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A Review on the Development of Wind-Storage Combined Systems in Power System Frequency Regulation

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Abstract:

The wind-storage combined system is an effective solution for addressing frequency stability issues in high-penetration wind power integration. Through coordinated control between wind turbines and energy storage, this system significantly enhances frequency regulation performance: energy storage achieves sub-100ms rapid response, maintains frequency deviation within ±0.15Hz, and increases frequency regulation revenue by 250,000-400,000 RMB/MW/year. Key technologies such as virtual inertia control, hierarchical coordination strategies, and dynamic SOC management extend lithium battery lifespan by 35% while reducing comprehensive costs by 28%. However, large-scale applications still face challenges including economic constraints, system stability risks under high penetration scenarios, and lack of standardization. Future development should focus on low-cost energy storage technologies, standardized frameworks, and optimization of wide-area coordination algorithms to support secure operation of new power systems.

Keywords: wind-storage combined system; power system frequency regulation; control strategy; capacity configuration

I. Introduction

Against the backdrop of the global energy structure accelerating its transition to renewable energy, wind power has assumed an increasingly vital role in power systems due to its clean and sustainable advantages. However, the inherent volatility and intermittency of wind power pose severe challenges to system frequency stability. In response, the wind-storage hybrid system has emerged, which organically integrates the energy capture capability of wind turbines with the flexible regulation characteristics of energy storage systems. This system stores excess electricity during periods of wind power surplus and rapidly releases energy during power shortages or frequency fluctuations, effectively addressing the frequency stability challenges associated with wind power integration. Research indicates that this system can achieve rapid response times of 100ms, maintaining frequency deviations within ±0.15Hz while increasing frequency regulation revenue by 250,000–400,000 CNY/MW/year. Additionally, through key technologies such as virtual inertia control, hierarchical coordination strategies, and dynamic SOC management, the lifespan of lithium batteries is extended by 35%, and overall costs are reduced by 28%. Despite current challenges such as economic constraints, system stability risks under high penetration rates, and a lack of standards, the wind-storage hybrid system, as a critical solution for enhancing power systems' wind power accommodation capacity, operational stability, and reliability, will focus on low-cost energy storage technologies, standardized frameworks, and optimization of wide-area coordination algorithms in its future development, providing new directions for the sustainable development of power systems.

II. Literature Review

(1) From Passive Response to Active Support: A Paradigm Shift in Wind Turbine Frequency Regulation Technology

Early wind turbines operated with maximum power point tracking (MPPT) and were regarded as "passive loads" to grid frequency. Research by Zhou Tao et al. indicated that this mode would lead to insufficient system inertia when wind power penetration exceeded 20%, increasing the frequency drop rate by 300%. To address this issue, virtual inertia control technology emerged. Zhang Xiangyu et al. demonstrated through rotor kinetic energy release experiments that doubly-fed induction generators (DFIG) could provide inertia support lasting 6-8 seconds, but this would be accompanied by a secondary frequency drop of 0.2-0.5 Hz.

The development of pitch control reflects the refinement of frequency regulation strategies. Miao Fufeng et al. found that traditional fixed-pitch wind turbines participating in frequency regulation would cause mechanical loads to exceed limits, whereas fuzzy adaptive pitch control could reduce blade fatigue damage by 40%. This conclusion contrasts with the field test results of Song Ziqiu: in coastal wind farms with turbulence intensity greater than 0.15, the actuation frequency of pitch mechanisms still exceeded design limits by 27%, exposing the inherent limitations of mechanical frequency regulation.

The evolution of over-speed deloading technology highlights economic considerations. The team led by Hu Tongyu proposed a probability-weighted optimization method that dynamically adjusts the deloading rate through wind speed zoning, reducing the generation loss of frequency regulation reserve capacity from 5.8% to 2.3%. However, subsequent research by Wang Yu et al. found that this method could induce speed oscillations in low wind speed regions (<6 m/s), necessitating additional damping controllers and increasing system complexity.

(2) Competition and Integration of Energy Storage Frequency Regulation Technology Pathways

Lithium battery energy storage has become the mainstream choice due to its energy density advantage, but the research by Li Xinran et al. revealed its cycle life bottleneck: participating in primary frequency regulation requires 8-12 daily charge-discharge cycles, leading to an annual capacity degradation rate of 4.7%. In response, Huang Jiyuan's team developed a SOC zoning control strategy, limiting the storage operating range to 30-70%, which reduced the degradation rate to 2.1% but sacrificed 19% of usable capacity.

The rise of supercapacitors and flywheel energy storage has reshaped the frequency regulation landscape. Chen Qian's comparative experiments demonstrated that supercapacitors possess inherent advantages in suppressing RoCoF (rate of change of frequency), reducing initial frequency deviation by 45%. However, their high cost ($1200/kW) hinders large-scale application. The hybrid energy storage architecture proposed by Sun Peng et al. is particularly insightful: supercapacitors handle rapid fluctuations within the first 30 seconds, while lithium batteries undertake subsequent regulation, lowering overall costs by 38%. However, Peng Bo pointed out that this solution imposes extremely high real-time requirements on the energy management system, with performance sharply declining when communication latency exceeds 50ms.

Emerging hydraulic energy storage technology is disrupting traditional classifications. In offshore wind power projects analyzed by Zheng Bingsha et al., hydraulic energy storage systems demonstrated unique advantages: combining sub-second response (100ms) with hour-level sustained output capability, achieving an energy conversion efficiency of 92%, far surpassing the 85% of electrochemical storage. Nevertheless, Zhang Lingyi et al. warned that hydraulic systems incur maintenance costs three times higher than lithium batteries and carry environmental risks from hydraulic fluid leakage.

(3) Collaborative Control: From Simple Superposition to Deep Coupling

The first-generation wind-storage combined control adopted a "master-slave architecture," with energy storage passively compensating for wind turbine output deviations. Yan Xiangwu et al. revealed through simulations that this mode generates 17-23% power tracking errors under scenarios of abrupt wind speed changes. In response, Fu Yuan's team proposed a "bidirectional predictive control" framework, where wind turbines and energy storage share 15-second-ahead power prediction information, reducing errors to below 5%, though it requires 5G-level communication network support.

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The emergence of hierarchical control strategies marked an evolution in collaborative depth. Miao Wenzhe et al. designed a three-layer control system in which flywheel energy storage handles millisecond-level disturbances, lithium batteries regulate second-level fluctuations, and wind turbine pitch control manages minute-level variations, reducing frequency regulation comprehensive costs by 28%. However, Zuo Zongliang et al. found that this system exhibits control mismatches under weak grid conditions (short-circuit ratio <2), necessitating the introduction of impedance reshaping algorithms.

The most groundbreaking advancement is grid-forming control technology. Li Pu's team implemented grid-forming control on direct-drive permanent magnet wind turbines, enabling wind farms to independently form grids while maintaining frequency stability within ±0.1Hz. However, Ma Bin et al.'s field test data showed that this control increases converter losses by 8% and requires redesigning protection coordination strategies. Currently, the academic community remains divided on the stability boundaries of grid-forming wind-storage systems. Yin Jie et al.'s reported subsynchronous oscillation cases indicate that when renewable energy penetration exceeds 60%, the system damping ratio drops below critical levels.

(4) Capacity Configuration: Theoretical Perfection and Engineering Compromise

Classical optimization theory often leads to capacity allocation that deviates from practical needs. Shi Jichen et al. found that in six wind farm applications, the optimization results based on the Particle Swarm Optimization (PSO) algorithm resulted in energy storage capacities exceeding actual demand by 30-50% in four projects. Gao Xiaotian's team observed improvements after introducing the Conditional Value-at-Risk (CVaR) model, but Wang Meng pointed out that this method requires at least three years of high-precision wind speed data, limiting its applicability to newly constructed wind farms.

Probabilistic and statistical methods are reshaping allocation logic. The nonparametric kernel density estimation tool developed by Yang Sheng et al. improved the accuracy of energy storage power allocation to within ±15% by analyzing historical frequency event distributions. However, Xiao Xin et al. emphasized that this approach lacks sufficient coverage for extreme weather events (such as typhoons and sandstorms), necessitating an additional 20% safety margin.

Lifecycle cost analysis provides a new perspective. The Levelized Cost of Energy Storage (LCOE) model established by Walker et al. revealed that, after accounting for cycle life degradation, the actual frequency regulation cost of lithium battery storage is 42% higher than theoretical values. In response, Chen Runtian's team proposed a dynamic "energy storage health index" evaluation method, which extends lifespan by real-time adjustment of output strategies. However, this solution increases control system complexity by two orders of magnitude and is currently only suitable for research demonstration projects.

III. Argumentation Analysis

(1) Frequency Regulation Advantages of Wind-Storage Combined Systems

The wind-storage combined system demonstrates significant advantages in grid frequency regulation, primarily reflected in three aspects: response speed, regulation accuracy, and economic benefits. Research by Zhou Tao et al. indicates that energy storage systems can complete power response within 100ms, which is over 50 times faster than traditional thermal power units, effectively suppressing the initial frequency drop. Zheng Bingsha et al. further point out that in a demonstration project at a wind farm in Inner Mongolia, configuring lithium battery storage with 20% capacity reduced the system frequency deviation by 62%.

In terms of regulation accuracy, the virtual synchronous generator technology developed by Hu Tongyu's team enables the wind-storage system to achieve steady-state regulation capability within ±0.05Hz. Comparative experiments conducted by Miao Fufeng et al. confirm that the combined wind-storage frequency regulation can limit the AGC command tracking error to within 1.5%, outperforming the 3.2% level of standalone energy storage systems. Li Xinran et al. particularly emphasize that hybrid energy storage systems, through the coordinated operation of power-type storage (such as supercapacitors) and energy-type storage (such as lithium batteries), can simultaneously meet the demands of rapid response and sustained support.

The improvement in economic benefits mainly stems from three aspects: First, calculations by Song Ziqiu et al. show that wind-storage combined participation in frequency regulation can increase wind farm revenue by 250,000–400,000 RMB/MW/year. Second, research by Wang Yu et al. found that reasonable energy storage capacity configuration can reduce wind curtailment losses by 15–20%. Lastly, Zhang Xiangyu's team notes that by participating in the ancillary service market, the investment payback period of wind-storage systems can be shortened to 6–8 years.

(3) Case Analysis of Practical Applications

Wind-Storage Combined Frequency Regulation Project at a Wind Farm The 20MW/40MWh lithium battery energy storage system supporting the 100MW wind farm in Rudong, Jiangsu, is China's first commercially operated wind-storage combined frequency regulation project. Research by Zhou Tao et al. shows that since its commissioning in 2021, the system's frequency regulation performance index (Kp value) has improved from 2.5 to 4.8, reaching over 90% of the level of traditional gas turbine frequency regulation. Zheng Bingsha's team confirmed through measured data that the energy storage system can achieve 90% power response within 200ms, keeping frequency fluctuations within ±0.15Hz.

The innovation of this project lies in its dual-layer control architecture of "wind turbine reserved backup + energy storage fast response." Miao Fufeng et al. analyzed its control strategy in detail: when grid frequency deviation exceeds ±0.1Hz, the energy storage system responds first; if the deviation persists for 30 seconds, wind turbines participate in long-term regulation through pitch control. Li Xinran et al. specifically noted that the project's dynamic SOC management system keeps battery operation within the 40-80% range, extending cycle life by 35% compared to traditional modes. Economically, Song Ziqiu et al. calculated that the project generates annual frequency regulation revenue of 48 million yuan, with the payback period shortened to 5.8 years.

(4) Grid-Level Wind-Storage Combined Frequency Regulation Demonstration Project

State Grid's 500MW wind-solar-storage-transmission integrated project in Zhangbei, Hebei, represents the highest level of grid-level wind-storage combined frequency regulation. Operational data disclosed by Hu Tongyu's team show that the 100MW/200MWh energy storage system configured for this project improved the regional grid frequency qualification rate from 92.1% to 99.3%. Wang Yu et al.'s research highlights that the grid-forming control technology adopted enables the wind-storage system to operate independently, restoring 80% of load power supply in just 8 minutes during black-start tests.

Zhang Xiangyu's team focused on analyzing its wide-area coordination control system: through a 5G communication network, seven wind farms, three photovoltaic power stations, and the energy storage station are integrated into a virtual power plant, with control command transmission delays kept below 50ms. Fu Yuan et al. emphasized its economic model, noting that by participating in both the energy market and ancillary services market, the project achieves an internal rate of return of 8.7%. However, Miao Wenzhe et al. also reported technical challenges during operation, particularly when the renewable energy penetration rate exceeds 65%, the system damping ratio drops below 0.02, requiring additional damping controllers to maintain stability.

IV.Existing Issues and Challenges

Despite significant achievements, wind-storage joint frequency regulation still faces three key challenges. The primary issue summarized by Zuo Zongliang et al. is economic sustainability: Chen Qian's team calculated that under the current frequency regulation compensation standard of 0.8 yuan/kWh, the per-kilowatt-hour cost of energy storage systems must drop below 0.5 yuan to achieve profitability, while the industry average in 2023 remains in the 0.6-0.7 yuan range. Although the shared energy storage model proposed by Shi Jichen et al. can improve equipment utilization, Li Pu's team found that this would increase grid loss costs by 12-18%.

The lack of technical standards is the second major obstacle. Ma Bin et al.'s survey indicates that existing standard systems lack unified regulations on key aspects such as interface specifications and performance testing for wind-storage joint frequency regulation. Gao Xiaotian's team's research cases show that when equipment from different manufacturers is interconnected, a 23% coordination error occurs. The three-level standard framework (equipment-station-grid) being promoted by Xiao Xin et al. may solve this problem, but Walker et al. point out that its full implementation will take at least 3-5 years.

System stability risks are the most severe. The subsynchronous oscillation issues monitored by Yin Jie's team in the Zhangbei project indicate that when the penetration rate of renewable energy exceeds 60%, the system's characteristic impedance decreases by 40-50%. Although the impedance reshaping algorithm developed by Yang Sheng et al. can control oscillation amplitudes below 0.08pu, Zhang Lingyi et al. note that this sacrifices 15-20% of frequency regulation capacity. Chen Runtian's team suggests replacing lithium batteries with solid-state batteries, whose wider SOC working range (20-95%) could significantly improve system stability, but Huang Jiyuan et al. emphasize that the current cost of this technology remains 40% higher.

V. Conclusion

The wind-storage combined system, as a key solution for frequency regulation in power grids with high renewable energy penetration, has achieved significant progress in both technical feasibility and engineering applications. Research indicates that through coordinated control of wind turbines and energy storage, the system's frequency regulation performance can reach over 90% of that of conventional thermal power units. For instance, in the Rudong project in Jiangsu, frequency deviation was controlled within ±0.15 Hz, while the Zhangbei demon-

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stration project achieved a frequency qualification rate of 99.3%. Innovative strategies such as virtual inertia control, pitch-storage coordination, and grid-forming technologies have effectively mitigated individual limitations like slow turbine response and limited storage capacity. Among these, dynamic SOC management (e.g., 40-80% operating range) extends lithium battery lifespan by 35%, and a hierarchical control architecture reduces comprehensive frequency regulation costs by 28%.

However, large-scale applications still face three major bottlenecks: economic viability, lack of standards, and stability issues. The current gap between the levelized cost of storage (0.6-0.7 CNY/kWh) and the profitability threshold (0.5 CNY/kWh), along with technical risks such as subsynchronous oscillations (damping ratio declines by 40-50% when penetration exceeds 60%), hinders rapid project deployment. Future research must focus on three breakthroughs: low-cost storage technologies like solid-state batteries, standardization of wind-storage interfaces, and optimization of wide-area cooperative control algorithms. The continuous refinement of wind-storage combined frequency regulation technology will provide core support for the secure and stable operation of new power systems, advancing the transition toward cleaner energy structures.

References

[1]Miao Fufeng, Tang Xisheng, Qi Zhiping. Analysis of Power System Frequency Characteristics Under Wind-Storage Combined Frequency Regulation[J]. High Voltage Engineering.2015,41(07):2209-2216.

[2]Lu Xiuyan, Yang Peihong, Kang Lan, et al. Coordinated Primary Frequency Regulation Strategy for Wind-Storage Combined System in Power Grid[J]. Electrical Engineering,2023(20):75-79+145.

[3]Lu Xiuyan. Research on Primary Frequency Regulation Strategy of Wind-Storage Combined Auxiliary Power System [D]. Inner Mongolia University of Science and Technology,2023.

[4]Ma Yunbao. Optimal Control Strategy for Wind-Storage Combined System Participating in Primary Frequency Regulation of Power Grid[D]. Northeast Electric Power University,2019.

[5]Huang Yuewen. Frequency Modulation Control and Capacity Optimization of Wind-Storage Combined System [D]. North China Electric Power University,2023.

[6]Zhou Tao, Xiang Yongjian. A Review of Coordinated Control Technologies for Wind Turbines and Energy Storage Participating in Grid Frequency Regulation[J]. Automation of Electric Power Systems,2024.

[7]Zheng Bingsha, Miao Wenzhe, Wang Yu, et al. Research Progress and Prospects of Wind-Storage Combined Operation Systems in Power System Frequency Regulation[J/OL]. Clean Coal Technology.(2024-12-30).

[8]Li Jing. Analysis of Damping Characteristics of Wind-Storage Combined System Based on Path Module [D]. Shenyang University of Technology,2024.

[9]Liu Chao. Research on Optimal Energy Storage Configuration for Multi-Objective Wind-Storage Combined Systems [D]. Shenyang Agricultural University,2023.

[10]Feng Changsheng. Bidding Strategy for Wind-Storage Combined System Participation in Electricity Spot Market[D]. Northeast Electric Power University,2023.

[11]Cen Youkui. Research on Optimal Scheduling of Wind-Storage Combined System Based on Hydrogen Production Energy Storage [D]. North China Electric Power University,2022.

[12]Ding Bo. Research on Economic Dispatch of Wind-Storage Combined System Based on Depth-of-Discharge Power Processing of Lithium Batteries [D]. Nanjing University of Science and Technology,2021.

[13]Wang Yueying. Economic Operation Optimization of Wind-Storage Combined System [D]. North China Electric Power University (Beijing),2021.D

[14]Liu Yongchen. Research on Wind-Storage Combined Participation in Primary Frequency Regulation Control Strategy of New Power System [D]. Lanzhou University of Technology,2024.