

Research on Robustness Control Technology for Wind Power System Operation in Northwest China under Extreme Weather Conditions

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Abstract: With the continuous advancement of China's new power system construction, the installed capacity of wind power in the vast Northwest China has continued to expand, with a constantly increasing proportion within the energy supply system; becoming an important cornerstone for the regional clean energy supply. Because of the vast territory and complex climate in Northwest China, it often occurs extreme severe weather such as typhoons, rain, snow and freezing conditions, which seriously disrupts the stable operation of wind turbines and the smoothness of wind power output, greatly reduces the operational reliability of the wind power system and poses great challenges to the safe and stable dispatch of the power grid. From the characteristics of extreme weather in Northwest China, this paper systematically analyzed the negative impact of different types of special weather conditions on the operation of wind turbine equipment and the output characteristics of wind power, carried out in-depth study on key robustness technology: optimization of centralized management mode of the wind power system, collaboration matching of energy storage systems, accurate prediction of wind power output, and anti-interference control of wind turbines. We verified the practical application effect of the multi-technology coupled control scheme through engineering examples. The research results show that the multi-technology coupled operational robustness control method is able to effectively enhance the power generation stability and efficiency of wind turbines under extreme weather conditions, increase the effective power generation during special weather, and reduce the failure rate of the power grid.

Keywords: Extreme Weather; Northwest China Wind Power; Operational Stability; Robustness Control; Multi-technology Coupling.

1. Introduction

Driven by the "dual carbon" goals, the energy structure of China is turning toward clean, low-carbon, and diverse development. As a clean energy source with mature technologies and abundant resources, the scale of development of wind power is ever-expanding^[1]. Due to its rich wind energy resources and vast land resources, northwest China has become the main part of wind power development in China, accounting for most of the country's onshore wind power installed capacity and plays a crucial role in the national energy supply and energy structure transformation. With the increasing proportion of grid-connected wind power, the random, volatile, and intermittent nature of wind power puts great pressure on grid operations. Besides, the frequent occurrence of extreme weather in this area aggravates the instability of wind power operation, becoming one of the core bottlenecks restricting the high-quality development of wind power in Northwest China^[2]. Climate and environmental characteristics in Northwest China are complicated and variable; compared with traditional inland regions, extreme weather (typhoon invasion, winter rain, snow and freezing condition, strong sandstorms) occurs at a very high frequency, over a broad range, and lasts for a long time^[3], directly affecting the core equipment like turbine blade, transmission system, and control system causing some problems such as sharp rise or fall of wind power output, unit shutdowns, and equipment failure, greatly reducing the utilization efficiency of wind power, and easily induce safety hazard such as grid voltage fluctuation and frequency deviation that threaten the stable operation of the regional power system^[4]. According to statistics, based on the operation and maintenance accident records of Northwest Power Grid, 72.6% of the unit off-grid and output abnormality issues were directly caused by extreme weather in the grid connection fault of wind power in Northwest China during 2018-2024. Among them, the ratio of faults caused by sandstorms, rain, snow and freezing condition, and extreme gales was 38.2%, 25.7%, and 8.7%. Extreme weather has become the primary trigger for instability in the Northwest China wind power system^[5]. Typical accident

cases happen often. For instance, in 2011, the Gansu Guazhou Ganhekou West Wind Farm suffered extreme gale and sandstorm weather, leading to a collective off-grid of 702 wind turbines, and the regional wind power output loss accounted for 54.17%, which directly caused a significant frequency drop in the Northwest Power Grid, seriously endangering the safety of the regional grid. In 2024, the Yili Wind Farm in Xinjiang faced sudden extreme gusty winds, resulting in resonance damage to turbine equipment and resulted in casualties and heavy economic losses, fully reflecting the fatal disturbance risk of extreme weather to wind power operation in Northwest China. At present, the research on wind power stability control in the industry focuses on conventional meteorological conditions, but there is still insufficiency regarding research on the robustness control system for wind power under coupled disturbances of various types of extreme weather in Northwest China. Single control technology cannot meet the operational needs under complex extreme weather conditions^[6].

Thus, based on the actual features of extreme weather in Northwest China: analyze the disturbance mechanism of different types of extreme weather on wind power operation; sort out the key control technologies of operational robustness of the wind power system; verify the application effectiveness of multi-technology coupling control by taking an engineering example as an illustration; summarize the current pain points in technology application and future development trend so that it can be used as theoretical support and practical basis for improving the anti-disturbance ability of the Northwest China wind power system under extreme weather and ensure safe and stable operation of the power grid.

2. Analysis of the Impact of Typical Extreme Weather in Northwest China on Wind Power Operation

Due to unique geographical location and climatic condition in Northwest China, different types of extreme weather will have different impacts on wind turbine equipment, output characteristics and grid adaptability with significant difference. Specific impact characteristic is as follows;

2.1 Disturbance Effects of Typhoon Weather

The open wind areas in northern Xinjiang and Hexi Corridor of Northwest China are susceptible to be affected by typhoon's peripheral circulation and strong cold air mass, experience extreme meteorology such as strong gusts, extreme gales and intense turbulence. The instantaneous wind speed exceeds 25 m/s which is far beyond the rated operating wind speed limit of conventional wind turbines. Drastic and abrupt change of wind speed and direction will bring significant aerodynamic effect on the turbine blades that easily leads to blade deformation, cracking and fatigue damage accumulated over time eventually triggering blade fracture accident; while the atmospheric turbulence brought by typhoons and extreme gales also brings severe fluctuation of wind power output. Pitch control system and yaw control system of the turbines are often started and adjusted, accelerating the equipment wear rate by more than three times and greatly increasing the possibility of fault trips and emergency shutdowns^[7](e.g., in October 2024, sudden extreme crosswind weather hit the million-kilowatt wind power project area in Yili, Xinjiang with an instantaneous wind speed above 22 m/s, triggered vortex-induced resonance of the turbine towers, resulting in equipment damage and casualties, with direct economic losses exceeding 3.75 million yuan). In 2019, the Minqin Wind Farm in Gansu suffered from extreme gale weather, led to loss of control of the turbines during blade pitching, resulting in overspeed and tower collapse, resulting in major casualties. Directly causing large gap in regional wind power output and disrupt the power balance of the grid, create a great hidden danger to the grid-connection safety of wind power in Northwest China. According to statistics, wind-induced structural damage and off-grid faults account for 8.7% of all extreme-weather related faults in Northwest China wind power, one large scale gale event can result in more than 30% of regional wind power output lost^[8].

2.2 Disturbance Effects of Rain, Snow and Freezing Weather

High altitude wind farms situated in Qinghai, Gansu and Xinjiang in Northwest China have long and cold winters where there is annual low temperature freezing weather that lasts for 60 days; they are high risk zones for rain, snow and freezing disaster. Rapid formation of ice layer (thickness ranging between 2 to 10 mm) on turbine blades' surfaces due to low temperatures change its aerodynamic profile which reduce wind energy capture efficiency by 20% to 45%; directly causes significant decrease in wind power output^[9], adhesion of ice layers increases blade's operating loads by 15% to 30%, causing excessive vibration of the units and exacerbates gearbox wear with an obvious increase in equipment failure rate. Rainy, snowy, humid and low-temperature conditions will reduce the insulation performance of electrical

equipment easily triggering faults like line leakage, short circuits or converter trips^[10]. Freezing weather may lead to icing and malfunction of wind speed and direction sensors resulting in monitoring data deviation higher than 40%, causing inefficient wind power output forecast and inaccurate grid dispatching. Based on the wind power operation and maintenance data collected at the Qinghai Power Grid from 2020 to 2024, the average availability of wind turbine units in the regional wind farms decreases by 18.3% when facing freezing weather, the output prediction error is increasing by 35.6% and the equipment failure downtime is 2.1 times longer compared to normal weather condition, thus, freezing weather becomes one of the key triggers for wind power instability in winter.

2.3 Disturbance Effects of Sandstorm Weather

The wind farms located in eastern Xinjiang, Hexi Corridor in Gansu and west part of Inner Mongolia have suffered over 30 sandstorms per annum on an average which has wide impact range, long duration and covert destructiveness that cause continual damages to the wind power equipment and output stability: High-speed scouring effect of suspended sand particles leads to coating shedding, surface roughness and degradation of aerodynamic performance, reducing the power generation efficiency of the units by 3% to 5% every year after prolonged operations; fine sand particles enter the nacelle, gearbox and electrical control cabinets, bearing wear, cooling blockage and short-circuit fault because of dust accumulation on circuits, greatly reducing the service life of the equipment. Disordered turbulent wind field occurs under sandstorm weather makes the wind speed fluctuate up to three or five times as compared with normal weather condition. Irregular and serious fluctuations happens in the wind power output easily inducing voltage and frequency fluctuations in the power grid. According to the operation and maintenance statistics from the Northwest Power Grid, the number of sandstorm-induced wind power faults accounts for 38.2%, the highest proportion among all kinds of extreme weather faults. A cascading off-grid accident happened at the Gansu Guazhou Ganhekou West Wind Farm in 2011 when 702 wind turbines are collectively shut down in a severe sandstorm event, more than half of the regional wind power output is lost. The grid frequency drops to a minimum value of 49.815 Hz, close to the safe operation threshold of the power grid, causing severe regional power disturbances.

3. Core Control Technologies for Operational Robustness of Wind Power System under Extreme Weather

In order to solve the problem that there are multiple disturbances of extreme weather on wind power operation in Northwest China, enhance the anti-disturbance ability of the wind power system and ensure the output stability; After reviewing the wind power robustness control technology which is suitable for complex extreme weather (such as: system management, energy storage adaptation, output forecasting, and equipment anti-interference) we build a comprehensive guarantee system for stable wind power operation through multi-technology coupling and coordination.

3.1 Optimization of the Centralized Management Mode for the Wind Power System

The traditional decentralized management mode of wind power has data silos, delay in dispatching and sluggish fault response which are not conducive to rapidly adapting to the regulation and control needs under extreme weather conditions; The centralization wind power management mode takes regional wind farm clusters as management and control objects, building an integrated intelligent control platform that integrates the operation data of all wind turbines in the whole region together with meteorological monitoring data and power grid dispatching data realize real-time perception, centralized monitoring and unified dispatching of wind power operation status: For extreme weather early warning information, forecast in advance the scope and degree of impact caused by weather disturbance, conduct group-based control and parameter pre-setting on wind turbines in the region and dynamically adjust the unit operation strategies according to changing weather. With centralized management mode, we can quickly locate the faults, accurately diagnose and handle them coordinately, greatly reducing the downtime of equipment failure due to extreme weather and improving the overall operational coordination and stability of wind power system.

3.2 Precise Matching and Coordinated Regulation of the Energy Storage System

The energy storage can smooth the fluctuation of wind power output and counteract the effect of extreme weather. In order to cope with the sharp increase/decrease of wind power output due to

typhoons/sandstorms and attenuation of output from freezing weather, we optimized the capacity configuration and charge/discharge strategy of energy storage system so that it could smoothly regulate wind power output: if there are sudden surges in wind power output triggered by extreme weather, then the energy storage system would quickly charge up and absorb excess wind power to avoid power surplus in the grid, while when the output suddenly drops or turbines shutdown, the energy storage system will discharge promptly to compensate for power deficit to ensure the stability of regional power supply. Meanwhile, considering the spatiotemporal distribution characteristics of extreme weather in Northwest China, this paper adopted a matching mode between distributed energy storage and centralized energy storage according to the disturbance characteristics of different wind areas, which enhanced the collaboration adaptability of the energy storage system and wind power output, thereby effectively smoothing out the power fluctuations arising from extreme weather.

3.3 Construction of a High-Precision Wind Power Output Forecasting Model

Wind speed, wind direction, temperature experience sudden and drastic changes during extreme weather. The traditional output forecasting models are inaccurate and do not meet the requirements of power grid dispatching. By combining historical meteorological data of extreme weather in Northwest China with wind turbine operation fault data and output fluctuation data, we build a high-precision wind power output forecasting model through meteorological feature classification. Correctly capture the change pattern of wind power output under extreme weather after parameter training in different weather scenarios (typhoons, freezing conditions, and sandstorms); Predict ahead the output fluctuation trend, fault risk, and power generation gap of the units. High precision output forecast provide data support for early grid dispatching, timely energy storage response, and advance protection of the units reduce the impact of extreme weather on the operational stability of wind power at the source level.

3.4 Enhancement of Anti-Interference Control Technology for Wind Turbines

In order to solve the physical effects and operating disturbance of extreme weather on wind turbine equipment, in this paper we optimize the anti-interference control strategy of the turbines themselves so as to enhance its adaptive operation ability: through optimization of the intelligent control algorithm for pitch system and yaw system, realize the fast adaptive regulation under extreme gale and turbulent weather condition, reduce the vibration load on blades and units; provide anti-icing and anti-sand protection device together with intelligent de-icing and dust removal control system for turbines, solving the degradation of equipment due to rain, snow, freezing or sandstorm weather; Optimization of anti-interference design of electrical systems improve the insulation, heat dissipation, and fault tolerance of electrical equipment in low temperature and sandy environment, decrease the frequency of equipment failure shutdowns and strengthen the stable operation capability of wind turbines in extreme working conditions.

4. Engineering Example Verification and Effect Analysis

To verify the practical application effect of the multi-technology coupling robustness control method, one of the plateau wind farms in Northwest China is chosen for our research. This wind farm has an installed capacity of 200 MW suffering from extreme weather (such as sandstorms, winter freezing, and short-duration gales) all year round that causes great fluctuation of wind power output, high rate of equipment failure and low level of power generation stability. We chose a multi-technology coupling scheme ("centralized intelligent management, coordinated energy storage regulation, high-precision output forecasting, and turbine anti-interference optimization"), and carried out a 12-month engineering pilot application; then we compared changes of wind power operation indicators under extreme weather before and after retrofit. To quantitatively evaluate the engineering effectiveness of the multi-technology coupling robustness control scheme, we compiled and analyzed the key operation indicators of the pilot wind farm's operations under extreme weather within 12 months before and after retrofit including four aspects: equipment failures, output stability, power generation, and grid disturbances. Here are some specific comparison results below:

	Before retrofit (conventional single	After retrofit (multi- technology coupling	Improvement margins:
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	control)	control)	
Number of turbine fault shutdowns under extreme weather (times/year)	83	48	A year-on-year decrease of 42.3%
Maximum fluctuation range of wind power output (%)	38.2		A decrease of 58.6%
Effective power generation under extreme weather (10,000 kWh)	2876.5	3414.3	A year-on-year increase of 18.7%
Number of grid wind power disturbance faults (times/year)	43	26	A year-on-year decrease of 39.5%
Average error of wind power output prediction (%)	27.4	8.9	An error reduction of 67.5%

By implementing our multi-technology coupling control scheme based on the table data, we found that all the core operation indicators of the wind farm are significantly optimized as follows: The frequency of turbine fault shutdowns during extreme weather was greatly reduced at the equipment level, thus improving both its operational safety and durability; the fluctuation range of output was greatly narrowed while the accuracy of output prediction was greatly enhanced at the output regulation level, completely solving the problem of disordered wind power output fluctuations under extreme weather; the effective power generation under extreme weather was significantly increased and the utilization rate of wind power resources was further improved at the power generation benefit level; the number of grid faults resulting from wind power disturbances was greatly reduced at the grid adaptation level, effectively ensuring the safe and stable operation of the regional power grid. Based upon the above-mentioned accident cases, we confirmed that the coupling control scheme could specifically solve the multiple disturbance problems caused by extreme weather (gales, freezing, and sandstorms), and is suitable for the complex meteorological environment of Northwest China, showing a high degree of engineering practicality and promotion value.

Conclusion

Frequent extreme weather such as typhoons, rain, snow and freezing conditions and sandstorms in Northwest China has continuously and destructively impacted the wind power system from different aspects (equipment structural safety, output stability characteristics and grid adaptation operation). Based on the industry statistics from 2018 to 2024 and typical accident cases, we see that extreme weather becomes an important factor limiting the stable and efficient operation of regional wind power and put pressure on grid dispatching. We analyzed the differential disturbance mechanism of various types of extreme weather on wind power equipment, output characteristics and grid-connected operation; constructed a multi-technology coupling robustness control system centered on centralized intelligent management, coordinated energy storage matching, high precision output forecast and anti-interference control of wind turbines. Practical application effect of this technical system were verified by engineering pilot data. Measured data showed that this coupling control method greatly reduced the failure rate of wind turbine equipment under extreme weather, narrow the range of output fluctuation, improve wind power generation efficiency, effectively avoid safety risk like wind power off-grid or grid disturbances caused by extreme weather, solve the prominent problem of poor stability and low controllability of wind power operation under extreme weather in Northwest China.

However there are still some problems such as lack of coordination, poor adaptability of old equipment, and weak intelligent prevention and control capabilities with respect to the technologies for wind power to withstand extreme weather in Northwest China at present; it should be further deepened to study the intelligent and integrated collaborative control technologies, strengthen the prevention and control system for extreme weather in wind power, transform the wind power in Northwest China from large-scale development into high-quality and high-stability development which can provide a solid clean

energy guarantee for building up China's new power system and achieving the "dual carbon" goals.

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