Original Research Article

Impact of wind power integration on power system stability and optimization strategies for dispatch

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Abstract: With the continuous expansion of grid-connected wind power capacity, its output volatility, low inertia characteristics, and anti-peak regulation behavior pose significant challenges to power system stability. This paper investigates the impact mechanisms of wind power integration on both static and dynamic stability of power systems, analyzing voltage collapse risks and power flow redistribution caused by wind power randomness, as well as frequency instability and subsynchronous oscillations resulting from insufficient inertia support. Building upon this foundation, we construct a multi-timescale scheduling optimization model that balances economic efficiency with stability requirements, employing distributionally robust optimization to handle wind power output uncertainty and designing decomposition-coordination algorithms to improve solution efficiency. For stability enhancement, we propose coordinated "source-grid-load-storage" optimization strategies, including combined wind-PV-storage dispatch, flexible transmission technologies, and demand-side response mechanisms. This research provides theoretical support and practical solutions for ensuring secure and stable operation of power systems with high renewable energy penetration, offering significant implications for low-carbon energy transitions.

Keywords: Wind power integration; Power system stability; Dispatch optimization; Robust optimization; Inertia support; Voltage control

1. Introduction

Against the backdrop of global energy structure transformation, wind power—As a core component of clean energy—Has experienced continuous growth in grid-connected capacity. However, the strong randomness, volatility, and low-inertia characteristics of wind power introduce new challenges to power systems, including voltage instability and degraded frequency regulation capability. Traditional dispatch methods struggle to accommodate high-penetration wind power scenarios, necessitating novel optimization approaches that simultaneously address economic and stability requirements.

Current research predominantly focuses on wind power forecasting or isolated stability issues, lacking comprehensive "mechanism analysis-model development-strategy coordination" investigations. This paper systematically examines wind power integration's impact mechanisms on both static (voltage, power flow) and dynamic (frequency, oscillation) stability, establishes a multi-objective dispatch optimization model, and proposes cross-timescale, multi-resource coordinated stability enhancement strategies[1]. The research outcomes provide theoretical foundations for power system planning and operation, supporting the development of new-type power systems under carbon neutrality goals.

2. Mechanisms of wind power integration's impact on power system stability

The impact mechanisms of wind power integration on power system stability manifest across both static and dynamic dimensions. In terms of static stability, the inherent randomness and volatility of wind power output significantly alter power flow distribution characteristics, challenging the transmission capacity of existing power corridors. Concentrated wind farm integration can trigger reactive power imbalances in local grids, where sudden wind power drops at voltage-sensitive nodes may cascade into voltage collapse incidents. Moreover, wind power's anti-peak regulation characteristic exacerbates spinning reserve pressure during load peaks, intensifying the deep regulation demands on conventional thermal units. Insufficient regulation capacity directly threatens the system's N-1 security criterion[2].

Regarding dynamic stability, the inertia deficiency caused by wind integration poses particularly severe challenges. As synchronous generators are replaced by wind turbine converters, the system's equivalent inertia constant plummets, degrading frequency response characteristics. During large power deficits, the rate of frequency change may exceed traditional relay protection thresholds, potentially triggering misguided underfrequency load shedding. More critically, dynamic interactions between wind converters and synchronous units can induce subsynchronous oscillations, especially in weak grid conditions where resonance effects between converter control loops and grid impedance amplify oscillation risks. These wideband oscillations may damage generator shaft systems, while their nonlinear nature renders conventional damping controllers ineffective.

Wind power's spatiotemporal correlation further amplifies stability risks. Temporally, minute-scale wind fluctuations mismatch with system frequency regulation speeds, while hourly anti-peak characteristics compound with load curves. Spatially, output synchronization among regional wind clusters causes violent power swings across provincial interconnections. Such multidimensional uncertainties render traditional deterministic dispatch methods inadequate, necessitating probabilistic stability assessment frameworks incorporating spatiotemporal dependencies. Notably, wind integration doesn't solely introduce negative effects—its rapid power response capability, when properly controlled, can provide virtual inertia and fast frequency regulation services.

3. Construction of a wind-integrated power system dispatch optimization model

The dispatch optimization model for power systems incorporating wind power must comprehensively address the stochastic and volatile nature of wind generation while ensuring coordinated operation with conventional power sources. Due to the significant uncertainty in wind power output, traditional deterministic dispatch methods are inadequate, necessitating stochastic or robust optimization models to mitigate risks arising from wind power forecasting errors[3]. The objective function typically minimizes total system operating costs, including fuel costs, startup/shutdown costs of thermal units, penalty costs for wind curtailment, and spinning reserve costs. To align with low-carbon dispatch requirements, carbon emission costs can also be incorporated, forming a multi-objective optimization framework that balances economic and environmental considerations. In terms of constraints, beyond conventional power balance constraints, generation limits, and ramping constraints, the model must explicitly account for wind power uncertainty. Scenario-based analysis or chance-constrained programming is often employed to handle forecast deviations, ensuring secure operation across multiple possible scenarios.

Temporally, the dispatch optimization of wind-integrated power systems requires multi-timescale coordination. Day-ahead scheduling, based on wind power forecasts, determines unit commitment decisions to accommodate large-scale wind integration. Intraday rolling dispatch adjusts generation schedules using updated forecasts to address short-term wind fluctuations, while real-time dispatch relies on automatic generation control (AGC) to balance minute-to-minute variations. To enhance adaptability, model predictive control (MPC) can be applied, leveraging rolling optimization and feedback correction to dynamically adjust dispatch plans in response to actual wind power output.

4. Optimization strategies for enhancing wind power integration stability

To address the inherent intermittency and volatility of wind power and ensure the secure and stable operation of power systems, a multi-dimensional and multi-layered technical framework must be established.

On the generation side, the focus should be on improving the grid-support capabilities of wind turbines themselves. Advanced converter control strategies can enable active voltage regulation and inertia response functionalities. Modern doubly-fed and direct-drive wind turbines can employ Virtual Synchronous Generator (VSG) technology to emulate the rotational inertia and damping characteristics of conventional synchronous machines, providing short-term active power support during sudden frequency deviations. Additionally, coordinated reactive power and voltage control within wind farms should be optimized using a hierarchical control architecture, ensuring seamless interaction between station-level Automatic Voltage Control (AVC) systems and individual turbine controls to prevent circulating currents and oscillations during reactive power adjustments. For large-scale wind power bases, distributed synchronous condensers or STATCOMs should be deployed to provide rapid dynamic reactive power compensation during grid faults, maintaining point-of-connection voltage fluctuations within the national standard range of ±10%.

On the grid side, network reinforcement is essential to enhance wind power integration capacity. During the planning phase, priority should be given to strengthening transmission corridors between wind-rich regions and load centers, utilizing flexible HVDC technology to ensure stability in long-distance, high-capacity power transmission. During operation, adaptive protection settings and transient stability pre-decision systems should be developed to account for wind power uncertainty. Upon detecting grid faults, Low Voltage Ride-Through (LVRT) protection logic should be automatically triggered, leveraging active crowbar circuits and DC chopper circuits to ensure uninterrupted operation. In weak grid conditions with high wind power penetration, a wideband oscillation monitoring and suppression system must be established, employing impedance reshaping and additional damping control to mitigate sub-synchronous oscillations (SSO) and high-frequency resonance phenomena.

From a dispatch and control perspective, a "source-grid-load-storage" coordinated stability assurance system should be implemented. Multi-timescale dispatch optimization can smooth wind power fluctuations by reserving sufficient spinning reserves in day-ahead scheduling and utilizing millisecond-level response capabilities of energy storage systems to compensate for forecast errors in real-time operations. Centralized energy storage stations should be deployed at wind farm aggregation points, adopting a "power-type + energy-type" hybrid configuration to provide both short-term power support and peak/frequency regulation. On the demand side, Virtual Power Plants (VPPs) can aggregate flexible resources such as interruptible loads and electric vehicles to rapidly reduce load power during frequency dips. Furthermore, market mechanisms should incentivize wind farms to participate in ancillary services, including frequency and voltage regulation, through price signals.

With the advancement of digital transformation, digital twin technology should be widely adopted for wind farm stability analysis, enabling real-time simulation platforms to preemptively test fault scenarios and optimize control strategies. Notably, region-specific stability solutions must be developed—coastal areas prone to typhoons should prioritize extreme weather resilience, while northern regions must focus on preventing insulation failures caused by sandstorms.

5. Case study

The Gansu Wind Farm Cluster, one of the world's largest wind power bases, presents a compelling case for studying the challenges and solutions associated with high-penetration wind power integration. Located in China's arid northwest, the cluster has an installed capacity exceeding 20 GW, supplying a significant portion of renewable energy to the national grid. However, its rapid expansion has exposed critical stability issues, including voltage fluctuations, sub-synchronous oscillations (SSO), and frequency instability, particularly during periods of high wind generation and weak grid conditions.

A major challenge in Gansu stemmed from the intermittent nature of wind power, which led to frequent voltage sags and swells at the point of common coupling (PCC). To address this, operators implemented dynamic reactive power compensation using STATCOMs and synchronous condensers at key substations. These devices provided near-instantaneous voltage support during sudden wind power fluctuations, reducing voltage deviations to within ±5% of nominal levels. Additionally, wind turbines were retrofitted with enhanced Low Voltage Ride-Through (LVRT) capabilities, ensuring they remained connected during grid disturbances rather than tripping offline, which had previously exacerbated instability.

Another critical issue was the emergence of sub-synchronous oscillations (SSO), particularly in wind farms connected to series-compensated transmission lines. These oscillations, caused by interactions between wind turbine converters and grid impedance, threatened equipment safety and grid reliability. Engineers deployed wide-area monitoring systems (WAMS) to detect SSO in real-time, followed by active damping control strategies embedded in wind turbine converters. By adjusting converter control parameters and introducing supplementary damping signals, the system successfully suppressed oscillations below hazardous thresholds.

To further enhance grid stability, the Gansu project incorporated hybrid energy storage systems (ESS)—combining lithium-ion batteries for short-term frequency regulation and pumped hydro for longer-duration energy shifting. This approach smoothed wind power output variations and provided fast frequency response (FFR) during sudden generation drops. Additionally, predictive dispatch algorithms were introduced, leveraging high-resolution wind forecasts and demand-side management to optimize power flow and reduce curtailment.

The lessons from Gansu highlight the importance of multi-layered solutions—combining power electronics, energy storage, advanced control strategies, and predictive analytics—to ensure stable wind power integration. This case also underscores the need for adaptive grid planning, particularly in regions with rapidly expanding renewable capacity. Future expansions may explore grid-forming inverters and artificial intelligence-based stability prediction to further enhance resilience in high-renewable penetration scenarios.

6. Conclusion

This study addresses power system stability challenges induced by wind power integration by elucidating its static and dynamic impact mechanisms, developing robust optimization-based dispatch models, and proposing multidimensional coordinated solutions. Research demonstrates that coordinated "source-grid-load-storage" flexibility resources can effectively mitigate wind power fluctuations while enhancing system stability margins. Future work should further explore distributed control architectures for high-renewable systems and implement digital twin technology for dispatch simulation and risk prevention. The theoretical framework and optimization methods presented herein provide critical technical pathways for low-carbon transformation of power systems.

References

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