

Distribution Network Planning under High Penetration of Renewable Energy: Key Technologies and Challenges

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Abstract: This paper systematically conducts key technology research on the impact of high proportion of new energy integration on distribution network planning. Firstly, it analyzes the mechanism of the impact of high penetration new energy output uncertainty on distribution network planning, revealing core issues such as aggravated system power fluctuations and surging reverse power flow in feeders caused by the integration of new energy. Then, by reviewing methods for multi-objective site selection and capacity optimization of new energy and cross-time-scale allocation strategies for flexibility resources, a planning framework balancing grid security and economic economy is established. Finally, addressing deep-seated contradictions such as the bottleneck of new energy absorption, voltage stability risks, and market mechanism lag, the work proposes multi-dimensional planning solutions across multiple time scales, providing theoretical support and technical paths for the planning of new distribution systems.

Keywords: Distribution network, Planning, High Penetration, Renewable Energy Randomness, Optimization

1. Introduction

Against the backdrop of global energy transition, with the increasing focus on sustainable development and the growing crisis of traditional energy sources, the new energy sector is developing at an impressive pace driven by policy incentives and technological innovations. The global energy transition has resulted in a rising penetration of renewable energy in power systems. By the end of 2024, China's new energy generation capacity is expected to reach approximately 1.41 billion kW, accounting for over 40% of the total national power generation capacity, surpassing coal-fired generation capacity [1]. With the iteration and upgrading of new energy technologies, large amounts of distributed energy sources are entering the distribution network. This change not only brings new opportunities for efficient energy use but fundamentally alters power flow patterns due to the inherent intermittency and volatility of high proportions of renewable energy [2], shifting the distribution network from a traditional "passive" mode to an "active" two-way interactive mode. In the face of the challenges brought about by high proportion new energy integration, distribution network planning urgently needs to shift from traditional passive planning to proactive and collaborative planning.

Traditionally, distribution networks have adhered to a "passive absorption" model, with planning and operation based on the stable characteristics of conventional power sources, primarily relying on unidirectional power distribution. This model has limited capacity to accommodate distributed energy sources, which is incompatible with the characteristics of new energy generation. The randomness of

new energy output leads to frequent violations of distribution network limits. Due to the significant influence of weather and environmental conditions on wind, solar, and other new energy sources, their output is highly random and difficult to predict accurately. After large-scale integration of new energy, it severely impacts the safe and stable operation of distribution networks. For example, in Europe, the rapid growth of distributed photovoltaics in some regions has led to an annual increase of over 30% in voltage violation events in distribution networks [3]. This has significant implications for distribution network planning.

Currently, significant progress has been made in key technologies related to distribution network planning: in the optimization of new energy site selection and capacity, methods such as Monte Carlo simulation and robust optimization are widely applied in scenario generation and uncertainty modeling. In the coordination of flexible resources, research on the capacity and layout optimization of energy storage systems focuses on improving power quality and alleviating economic pressure through energy storage devices. Furthermore, new methods for energy storage integration configuration have been proposed to achieve optimal configuration. In network topology reconstruction and upgrading, the optimization of hybrid AC/DC distribution network topology has gradually deepened. In the future, as new energy technologies continue to develop and planning theories improve, distribution networks will better adapt to the demands of energy transition, providing solid support for the realization of efficient, reliable, and sustainable energy systems. In the current field of distribution network planning, research mainly focuses on multiple aspects, including technology, economics, policy, and system coordination and management. On the technological front, the large-scale integration of new energy into distribution networks has made energy absorption and system stability a research hotspot [4]. At the same time, research on the monitoring, control, and operation complexity of distribution networks is continuously advancing [5]. For example, the volatility and uncertainty of new energy and distributed power sources have made the control and operation of distribution networks more complex, and existing technologies are insufficient to meet the needs, prompting the search for more efficient solutions. On the economic and policy front, the economic feasibility and investment benefits of planning [6], policy support, and market mechanism improvements are areas of great concern. In system coordination and management, insufficient collaboration between source, grid, load, and storage [7] and barriers to coordinated planning between distribution and transmission networks have resulted in low overall system operation efficiency [8]. High-proportion new energy distribution systems urgently need to overcome the bottlenecks of traditional planning technologies and establish a collaborative planning mechanism for source-grid-load-storage interaction.

This paper aims to explore the significant impacts brought about by the high proportion of new energy integration on distribution network planning. First, by analyzing the characteristics of new energy, the paper deeply investigates the impact of high proportion new energy integration on distribution network planning. Then, it examines the technical challenges of new energy site selection and capacity optimization, flexibility resource coordination, network topology reconstruction, and upgrading in the context of high proportion new energy integration. Finally, the paper proposes leading recommendations and measures for addressing the challenges faced by distribution network planning, covering aspects such as technological innovation, policy mechanisms, and future research directions, to support the future planning and development of distribution networks.

2. Impact of high proportion of new energy integration on distribution networks

2.1. Characteristics of new energy

This section analyzes the impact mechanism of new energy on distribution networks from two dimensions: intrinsic characteristics and development features. In terms of intrinsic characteristics,

the volatility and randomness of new energy generation alter the traditional operation modes of distribution networks. Wind power is dominated by wind speed turbulence intensity, exhibiting minute-level fluctuation characteristics, which can lead to deterioration of power quality. Photovoltaic output, on the other hand, has a strong correlation with solar irradiance, with daily fluctuations that can exceed 80% of installed capacity. According to literature [9], the fluctuating characteristics of new energy output make traditional load-based scheduling modes ineffective, requiring the introduction of probabilistic forecasting methods to improve prediction accuracy. The widespread integration of distributed generation (DG) fundamentally changes the power flow direction in distribution networks. For example, during the peak period of photovoltaic output at noon in an industrial park, the proportion of reverse power flow in the feeder is significant. As shown in literature [10], this can lead to frequent malfunctions of the original relay protection system. Furthermore, the power shift characteristics of electric vehicle clusters through demand response cause the load curve to exhibit both temporal and spatial uncertainty, further complicating system regulation.

Regarding the development features of new energy, its large-scale development has a structural impact on the evolution of distribution network forms. Statistical data shows that in 2022, China's newly installed distributed photovoltaic capacity reached 51.1 GW, and the DG penetration rate in some county-level distribution networks achieved significant breakthroughs [11]. This shift requires distribution network planning to achieve three breakthroughs: the topology must support dynamic reconstruction under bidirectional power flow, operating strategies need to adapt to multiple time scales, and technical standards urgently need to accommodate new networking modes such as microgrids and hybrid AC/DC networks [12]. Notably, the exponential growth of new energy penetration has triggered a fundamental change in the system's operating mode—shifting from the traditional "passive power receiving" model to an "active distribution" paradigm. This requires overcoming key technological bottlenecks such as cluster control and voltage coordination, as well as establishing planning methodologies that adapt to high-demand elasticity.

2.2. Impact of new energy integration on distribution networks

The integration of new energy into distribution networks faces multiple technical and management challenges, primarily in the following aspects: First, new energy integrated into the distribution network presents issues such as wind power outages and output abnormalities caused by cold waves [13], strong winds causing wind power fluctuations [14], and photovoltaic power declines due to desert dust [15], or high temperatures leading to varying degrees of light-induced/electrical degradation of photovoltaic modules, thus affecting photovoltaic generation efficiency [16]. The random fluctuations of both energy outputs can result in problems such as frequency deviations, voltage flicker, etc., particularly in weak grid areas where protection devices may malfunction, impacting power quality. Secondly, the complexity of distribution network planning will significantly increase due to the integration of distributed power sources. The traditional unidirectional planning model struggles to adapt to scenarios with high DG penetration. It is necessary to establish multi-time-scale forecasting models to coordinate the temporal and spatial matching of new energy output, load demand, and energy storage configuration, while also restructuring the network topology to optimize the capacity and location of distributed power integration. Additionally, as stipulated in China's national standard GB/T 29321-2012, the voltage at the end of the feeder should remain within a certain range. However, after the integration of new energy, the distribution network transforms from a radial single-source structure to a multi-source network, where reverse power flow may lead to line overloads and the voltage at the feeder's end may exceed the allowable range due to the reverse power feed from distributed energy sources. This necessitates the active development of distribution

network planning technologies to address these issues and ensure the safe absorption of high proportions of new energy.

3. Key technologies in distribution network planning

3.1. New energy site selection and capacity optimization

New energy site selection and capacity optimization are central to resolving the conflict between high penetration and system stability. The essence lies in optimizing spatial layout and capacity adaptability to achieve a dynamic balance between new energy absorption efficiency and grid security constraints. The intermittency and volatility of new energy generation are significant; improper site selection and capacity configuration can disrupt voltage stability in the distribution network, leading to voltage violations. However, scientific site selection and capacity planning can match generation and load distribution, reduce transmission losses and transformation costs, and enhance grid reliability and flexibility. This is further discussed below.

The high proportion integration of renewable energy such as photovoltaic and wind power may lead to issues such as voltage violations and increased network losses in the distribution network. To address these issues, literature [17] proposes a dual-layer optimization model for hybrid energy storage systems using batteries and supercapacitors as energy and power-type storage, respectively, taking full advantage of hybrid storage's efficient charging and discharging capabilities. The model solves the optimization problem through an adaptive genetic algorithm combined with mixed-integer second-order cone programming. Literature [18] proposes a site selection and capacity optimization method for energy storage systems, validating its effectiveness in improving system small disturbance stability from the perspective of grid strength, and presents an optimization model based on small disturbance stability margins and the gSCR conversion relationship. Literature [19] discusses the integrated energy planning approach based on resource optimization, demonstrating the advantages of this approach in improving the economic feasibility and renewable energy absorption rate compared to traditional energy supply models. Literature [20] presents an energy storage site selection method that improves the issue of voltage violations while ensuring frequency security, reducing operational costs, and enhancing new energy absorption. The volatility and intermittency of new energy generation, combined with mismatched integration locations and capacities, easily lead to voltage violations and increased network losses. Therefore, building a multi-dimensional collaborative optimization model for scientific new energy site selection and capacity planning is crucial. This model can effectively coordinate the temporal and spatial distribution characteristics of generation and load, ensuring safe and stable system operation while improving overall economic efficiency.

3.2. Collaborative configuration of flexible resources

Flexible resources are critical for the stability of distribution systems. They can supplement electricity during instability, regulate frequency during fluctuations, adjust load during peak and valley times, and respond urgently during system faults, providing comprehensive power security. As a key supporting technology to improve the power balance of distribution systems, energy storage systems can suppress feeder power fluctuations through their bidirectional power flow characteristics, thereby reducing network losses and improving power quality, alleviating the economic pressures associated with energy storage configuration in distribution networks. Thus, further research on the optimal configuration of energy storage systems in distribution networks is urgently needed [21]. Literature [22] uses an electricity planning model with a year-round 8760-hour panoramic time-series simulation, considering various flexible resource constraints, and optimizes the coordination of new energy sources, energy storage, and grid interconnection capacity across different time and spatial

scales. With the large-scale integration of distributed photovoltaics into distribution networks, voltage violation issues are becoming increasingly prominent, affecting power quality. Given that energy storage systems have flexible power regulation capabilities, literature [23] proposes an energy storage access configuration method based on voltage sensitivity correction, which is more cost-effective and adaptive in terms of voltage control compared to traditional storage configuration methods. Literature [24] considers the current main flexible resources and performs a techno-economic analysis, optimizing system flexibility resources based on the optimal economic performance, using particle swarm optimization combined with production simulation analysis. In the face of new energy integration into distribution networks, the collaborative configuration of flexible resources is key. While current technology is rapidly advancing, it still needs to be complemented with other relevant technologies.

3.3. Network topology reconstruction and upgrading

In the context of new energy integration, it is also essential to reconstruct and upgrade network topology. Literature [25] proposes a two-stage dynamic reconstruction strategy for distribution networks based on intelligent energy storage soft-switch optimization, effectively reducing system network losses and voltage deviations, and improving node voltages. This strategy achieves network topology optimization and power-reactive power coordination optimization, contributing to the economic and reliability objectives of distribution network operation. Literature [26], considering the operational characteristics of hybrid AC/DC distribution networks, constructs scenarios by combining the probability density function parameter variations of each source-load unit with Nataf transformation, generating source-load output samples with correlation and time sequence. The proposed approach for grid architecture and DG collaborative optimization planning lays the foundation for subsequent research. Through dynamic reconstruction strategies and grid architecture optimization methods, adaptive adjustments to the topology of high-penetration new energy distribution networks can be achieved, significantly enhancing the system's multi-objective coordination capabilities and providing foundational support for the economic and reliable operation of new power systems.

4. Challenges faced by distribution network planning

The multidimensional coupling effects caused by the high penetration of new energy have made modern distribution network planning face systemic challenges, including technical, economic and policy, and system coordination aspects. Despite the large-scale integration of new energy and the transformation of the power system, regions with high new energy penetration are prone to issues such as wind and solar curtailment, voltage violations, and capacity exceedance. In response to these challenges, literature [27] designed a case study based on an actual grid topology, incorporating high proportions of photovoltaic generation and load growth. Using the proposed optimal power flow method, the study solved issues such as wind and solar curtailment, voltage violations, and capacity exceedance that would otherwise arise. The study also proposed a multi-source coordination optimization control model for distribution networks, which aims to address potential future problems. The economic and policy challenges primarily lie in the mismatch between investment costs and policy support. Upgrading and transforming distribution networks require significant financial investment. However, the current electricity pricing mechanism and subsidy policies often fail to sufficiently incentivize investments in distributed generation and energy storage systems, leading to long investment return cycles. System coordination challenges span the entire distribution network planning process, particularly when multiple microgrids work in coordination with the distribution network. The divergent interests of various entities in this coordination need effective solutions.

Literature [28] proposes an optimization scheduling strategy involving microgrid leasing and shared energy storage to participate in the peak regulation of the distribution network. This approach constructs a game-theoretic model with one main and multiple sub-players to achieve win-win outcomes for all stakeholders. Addressing the challenges faced by distribution network planning requires coordinated efforts at the technical, economic and policy, and system coordination levels, providing solid technical support and policy backing for the integration of new energy into the distribution network.

5. Technological innovation and breakthroughs

Technological innovation in distribution network planning is transitioning from isolated breakthroughs to multidimensional collaboration. The evolution of this transition is deeply intertwined with three core driving forces: the iteration of intelligent algorithms, the reconstruction of topology structures, and the transformation of operational paradigms. This is pushing planning methods toward adaptive and holistic directions. Literature [29] studied the multi-source collaborative optimization scheduling objective function for active distribution networks and proposed an artificial intelligence-based scheduling method. The constructed multi-source collaborative optimization scheduling objective function, which considers generation costs, energy storage equivalent operation costs, and source-load supply costs, is highly extensible and flexible in terms of interaction. Simulation examples verified the effectiveness of this method and achieved optimal scheduling in active distribution networks. Regarding relevant policies, the current access rules for distributed renewable energy to the electricity market, electricity pricing mechanisms, and auxiliary service compensation policies are incomplete. There is a lack of economic incentives for flexible resources, which suppresses the potential for new energy absorption. Lastly, literature [30] analyzed distribution network planning and proposed an improved modulation strategy based on a novel parallel resonant DC link soft-switching inverter to overcome the issues of high current stress and high losses in the original modulation strategy. Literature [31] addressed the problem of complex influencing factors and poor analytical accuracy in distribution network operation management by combining grid-based methods with advanced algorithms, creating an intelligent fine-analysis model. This model integrates data through reasonable grid partitioning, improves analytical capabilities through algorithm optimization, and achieves intelligent, fine-grained analysis to provide strong support for the precise investment planning and analysis of distribution networks.

6. Conclusion

This paper investigates the impact of high penetration of new energy on distribution network planning, analyzing technical challenges such as new energy site selection and capacity optimization, flexible resource coordination, and network topology reconstruction, while proposing strategies to address these challenges. The analysis results show that the randomness and volatility of new energy pose higher demands on the safe and stable operation of distribution networks, requiring technological innovation and policy support to realize the transformation and upgrading of planning models. In the future, it is necessary to strengthen the integration of technologies such as artificial intelligence and big data with distribution network planning, improve policies and market mechanisms for new energy integration, and promote the development of efficient, reliable, and intelligent distribution networks to support energy transition and sustainable development.

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