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Key Technologies and Challenges for Optimal Operation of Distribution Networks under High-Proportion Renewable Energy Integration

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Abstract: Driven by the "dual-carbon" goals, high-penetration renewable energy integration has become a critical trend in constructing a new power system. This research systematically reviews technical challenges of distribution network operation under high renewable energy scenarios, focusing on intermittency and diverse integration modes that cause voltage fluctuations and complex power flow dynamics. Key technologies are synthesized from existing studies, such as advanced forecasting algorithms, intelligent dispatch optimization, source-network-load-storage coordination, and AC/DC hybrid architecture design, etc. By integrating digital twin and artificial intelligence, a data- physics driven framework is proposed for multi-scale optimal operation. This framework addresses economy-reliability trade-offs through energy storage and multi-energy coupling, while interdisciplinary innovation promotes self-aware and self-decision-making distribution networks. This review provides a technical roadmap for optimizing high-penetration renewable energy systems by integrating state-of-the-art technologies and future research directions.This paper makes a comprehensive and in-depth analysis and research on the key technologies and challenges of distribution network optimization under the background of high proportion of new energy access, and puts forward some valuable insights and suggestions, which have certain significance for promoting its progress and development.

Keywords: High-penetration renewable energy, Distribution network, Optimized operation, Source-network-load-storage coordination, Digital twin

1. Introduction

The installed capacity of renewable energy sources, such as wind and photovoltaics, has continued to grow due to the global energy transition and the "dual carbon" goals. China's installed power generation capacity reached 2.92 billion kilowatts by the end of 2023, of which 1.47 billion came from renewable energy sources like solar, wind, and hydropower. billion kilowatts, which historically exceeds the capacity for thermal power generation and accounts for more than 50% of the installed capacity. The high-penetration integration of renewable energy has become an inevitable trend in the development of distribution networks [1]. While this transformative development improves the level of energy cleanliness, it also brings multidimensional challenges to the planning, operation, and protection of distribution networks. Therefore, it is essential to propose solutions to address the

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technical bottlenecks caused by high-penetration renewable energy integration, systematically analyze its impact mechanisms, and propose optimization strategies to provide theoretical support for the construction of new power systems.

There is substantial theoretical and practical significance to the optimal operation of distribution networks in the context of high penetration renewable energy integration.In addition to encouraging the change of the energy structure towards cleanliness, the extensive grid connection of renewable energy sources like solar and wind power also increases the demands on the efficient operation of distribution networks.From a theoretical perspective, traditional distribution network scheduling methods find it challenging to satisfy dynamic power balance needs due to the intermittent nature and unpredictability of renewable energy sources. Studies have shown that through demand response (DR) and coordinated optimization of intelligent soft switches, the capacity for renewable energy consumption can be improved, and the curtailment of wind and solar power can be reduced, verifying the theoretical value of multidimensional coordinated control[2]. Furthermore, an economic operational model considering energy storage configuration indicates that reasonably planning the penetration of renewable energy integration and storage capacity can balance system stability and supply costs, providing theoretical support for optimized scheduling in high-penetration scenarios[2].Renewable energy integration directly impacts the reliability and economy of power supply in distribution networks. For example, distributed generation integrated into the distribution network through microgrids can effectively alleviate load pressure and improve line losses and voltage quality[2]. Actual engineering cases have shown that active distribution network multi-timescale coordinated control technology can achieve dynamic optimization from minute-level to hour-level, significantly improving the ability to consume renewable energy locally [3]. Meanwhile, the AC/DC hybrid distribution network, using flexible DC technology, reduces energy losses and enhances controllability. Its engineering feasibility has been verified in offshore wind power grid connection and urban power supply. Therefore, the research on optimized operation strategies is not only key to technical breakthroughs but also a practical necessity for achieving energy transformation and high-quality development of power grids [4].

There are several aspects to the effects of high-penetration renewable energy integration on distribution networks. The fundamental characteristics of renewable energy are its unpredictability and intermittency.For instance, PV output fluctuates due to the influence of daylight and cloud cover changes, while wind power output is highly random due to abrupt changes in wind speed [3]. These characteristics challenge traditional reactive voltage control methods, which face issues with accuracy and require robust optimization models that account for prediction errors to improve scheduling robustness [5]. Regarding the integration methods, renewable energy grid connection exhibits centralized, distributed, and decentralized characteristics, each having different impacts on the distribution network.

In response to the impacts of high-penetration renewable energy integration on distribution networks, this researchresearchexplores the characteristics of high-penetration renewable energy and typical integration methods, analyzing their impacts and challenges on distribution network operation firstly. Then, it conducts in-depth research on key technologies for optimized operation of distribution networks, such as renewable energy forecasting, intelligent scheduling, synchronized source, network, load, and storage operations, and AC/DC hybrid architecture. Subsequently, the research proposes corresponding solutions to the technical, economic, and management challenges brought about by renewable energy integration. Finally, combining existing new technologies like artificial intelligence, the research outlines future development directions for optimized operation technologies of distribution networks under the high-penetration renewable energy integration context, aiming to provide theoretical support for the construction of new power systems.

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2. Impact of high penetration of renewable energy access on distribution networks

2.1. Characteristics of renewable energy and access modes

Significant unpredictability and intermittency are characteristics of renewable energy sources like solar and wind. For example, solar power output is influenced by day-night cycles and weather conditions, presenting a "high during the day - zero at night" fluctuation pattern. Wind power, on the other hand, experiences high randomness in output due to sudden changes in wind speed. Three common approaches can be used to integrate dispersed renewable energy sources into the distribution network: decentralized access, distributed access, and centralized access. Each mode has distinct technical characteristics, levels of integration, and impacts on the grid.

Centralized Access: This involves large-scale renewable energy generation units (such as wind farms, solar power plants, etc.) connecting to the high or medium-voltage bus of the distribution network through a booster station. Specific access methods include: (1) Dedicated Booster Station: After collecting power from generation units via gathering lines, the electricity is integrated into the distribution network's high-voltage side through a booster transformer [6]. (2) Centralized Inverter Control: Large-scale photovoltaic power stations use centralized inverters to achieve power output synchronization with the grid through PQ control or V/f control [7].

Distributed Access: This involves integrating distributed generation units (such as distributed photovoltaics, small wind turbines, energy storage, etc.) through microgrids or regional energy systems before connecting to the distribution network as a whole. Specific access methods include: (1) Microgrid Grid Connection Interface: The interface connects to the distribution network via the Point of Common Coupling (PCC), using VSC converters for voltage/frequency control [8]. (2) Layered Control Strategy: This includes primary droop control, secondary frequency and voltage regulation, and tertiary economic scheduling [9]. Decentralized Access: This involves small-scale distributed generation units (such as rooftop photovoltaics and electric vehicle charging stations) connecting directly to low-voltage distribution networks or customer sides. Specific access methods include: (1) Low Voltage Direct Grid Connection: Photovoltaic systems directly connect to 380V distribution lines via inverters, requiring compliance with harmonicand voltage deviationrequirements [9]. (2) V-dp/dv Droop Control: This method ensures penetrational power distribution among multiple photovoltaic sources without communication, preventing overvoltage [10].

2.2. Challenges faced by distribution networks

Many obstacles to the safe operation of distribution networks arise from the integration of a high penetration of renewable energy sources. The first challenge is voltage fluctuations and power quality issues.Voltage fluctuations are common when renewable energy sources are integrated into the distribution network on a wide scale because of their variability and intermittency. Traditional model-based reactive voltage optimization methods rely heavily on accurate grid modeling. However, their accuracy and calculation speed are insufficient to meet the voltage control requirements of distribution networks containing renewable energy sources [11]. Planning, scheduling, protection, and economic analysis of power networks are all impacted by the growing proportion of renewable energy generation, such as solar and wind. High penetrations of renewable energy sources increase system peak regulation pressures [12], often requiring conventional power sources to participate in system regulation more frequently, which can reduce their economic lifespan and place higher demands on flexible adjustment sources such as pumped storage and energy storage [13]. The development of new reactive power optimization technologies, flexible resource coordination, and market mechanisms is urgently needed to address these issues, which include voltage fluctuations,

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peak regulation pressures, and the shortcomings of traditional control methods. This will enable multi-dimensional collaborative regulation of generation, grid, load, and storage, ensuring the new power system operates safely and economically.

The second challenge is bidirectional power flow and protection configuration. The integration of distributed power sources changes the direction of short-circuit currents, causing traditional overcurrent protection to malfunction. Adaptive protection strategies rely on high-precision fault location technologies. However, due to limited installation of sensing devices and data transmission delays, accurate real-time parameters of the distribution network cannot be obtained, affecting the accuracy of traditional fault location methods. To address these issues, ref [14] proposed distribution network fault location method based on digital twin parameter self-correction technology, which dynamically corrects the positioning model with parameter changes, and effectively reduces the fault location error. With the popularization of distributed generation technology, the operation control of isolated wind storage network system has become the focus of research. The island mode is superior to the traditional network operation in terms of power supply flexibility and response efficiency, but the dynamic topology identification problem exists in the cooperative protection of microgrid and large grid. The research shows that the multi-source data fusion technology can optimize the protection strategy and achieve accurate fault location and isolation[15].Lastly, there are additional challenges posed by technological advances, such as digital twins and network security. The increasing digitalization of distribution networks and the corresponding increase in data interaction volumes have brought about significant information security risks. Although distributed forecasting frameworks based on federated learning can protect data privacy, the issue of standardizing communication protocols among heterogeneous devices still needs to be resolved [16]. When implementing synchronization between physical and virtual models on digital twin platforms, it is necessary to strengthen encryption algorithms to guard against potential cyberattacks. The comprehensive overload risk assessment algorithm for distribution networks based on digital twins effectively improves the accuracy of overload risk assessment, thereby enhancing the safety of the distribution network [17].

3. Key technologies of distribution networks optimization operation

3.1. Renewable energy power forecasting and optimal scheduling

In the key technologies of distribution networks optimization operation, renewable energy power forecasting and scheduling closed-loop optimization are crucial for achieving economic and safe operations. The intermittency and uncertainty of renewable energy sources present significant challenges to the scheduling of distribution networks. Therefore, advanced forecasting and optimization techniques are needed to address these challenges. Renewable energy power forecasting serves as the foundation for optimizing scheduling. By establishing accurate forecasting models, the operational risks caused by forecasting errors can be reduced. For example, model predictive control methods can achieve day-ahead, intra-day rolling scheduling and real-time feedback correction, thus reducing the impact of renewable energy intermittency and load forecasting errors on distribution network operation [5]. In the context of renewable energy integration, distribution networks need to adopt multi-time-scale optimization scheduling strategies, the multi-time-scale distributed power coordination control framework for active distribution networks includes long-time-scale global optimization control and short-time-scale regional autonomous control [18].

3.2. Source-network-load-storage coordinated optimization scheduling

The influence of forecasting mistakes on distribution network scheduling can be successfully mitigated through coordinated optimization scheduling of source-network-load-storage. A

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coordinated source-grid-load-storage active distribution network multi-time-scale optimization scheduling technique is suggested in the literature [19]. First, a response model for electric vehicles (EVs) participating in grid scheduling is established and classified according to the operational characteristics of flexible loads to adapt to multi-time-scale coordinated scheduling. By combining the entropy weighting method for target weighting, the balance between economic efficiency and renewable energy consumption is verified, reflecting the advantages of multi-time-scale scheduling. To study the impact of the cooperation mode between wind power providers and EV aggregators forming a virtual power plant (VPP) on market equilibrium results, a multi-period random game equilibrium model for the electricity market was established. The model analyzes the bidding competition of wind power providers and EV aggregators participating cooperatively as VPPs and independently as non-cooperative participants. Game theory models and the Shapley value method are used to optimize the revenue distribution between wind power providers and EV aggregators [20].

3.3. AC-DC hybrid distribution network technology

The voltage-source converter-based flexible DC transmission system, which is mostly utilized for islanded power supply, urban power supply, offshore wind power grid connection, and AC system interconnection, has the benefit of high controllability. To meet the needs of flexible DC converter station startup, operation, control, and maintenance, the design methodology, technical approach, and tools for flexible DC transmission systems were proposed. These provide strong support for the development and engineering application of multi-terminal flexible DC technology in China [21]. AC-DC hybrid distribution networks are favored due to their high flexibility, low energy loss, and ease of integrating distributed power sources such as photovoltaics. To address the optimization scheduling and economic evaluation challenges faced by high-penetration distributed photovoltaic demonstration areas in China, literature [16] proposes a coordinated optimization method for AC-DC hybrid distribution systems based on probabilistic energy tracking (PET). A multi-dimensional coupled model considering the randomness of photovoltaic output and the losses of grid-connected equipment was established. The method developed an economic dispatch system suitable for high-penetration scenarios, which was verified to effectively reduce system line losses under typical daily operating conditions.

3.4. Energy storage systems and DR

Demand response and energy storage systems are efficient ways to lessen the influence of uncertain renewable energy generation on distribution network operations. In the field of energy storage, innovation and demand are mainly reflected in sodium ion batteries. As a promising next-generation secondary battery system, SIBs are attracting attention in the energy storage market due to their abundant resources, low cost, and storage characteristics similar to lithium. Layered oxide materials, known for their high ionic conductivity, fast diffusion rate, and high specific capacity, are widely used. However, the structure of layered oxides is diverse, and inherent defects exist during the charging and discharging process. Literature [22] designed a multi-phase structure to overcome the limitations of a single structure and benefit from their advantages and synergistic effects. This reflects the innovation of energy storage systems. In addition to electrode materials, electrolytes are another key component of batteries. The composition of the electrolyte determines the solvation structure of Na^+, the diffusion rate of Na^+, and the composition and structure of the electrode-electrolyte interface film. Ref [23] provides strategies from the perspective of electrolyte optimization to address the performance limitations of SIBs in extreme low-temperature environments, promoting the sustainable development of energy-efficient storage.

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The three-stage bidding procedure of VPPs concurrently engaging in the bilateral contract market, day-ahead market, real-time market, and balancing market is examined in reference [16] with regard to DR. In light of this, a VPP three-stage bidding model that takes demand response and electric vehicles into account is developed for scenarios involving several kinds of power markets. The outcomes validate the model's efficacy by showing that it can efficiently regulate individual EVs and DR, save operating costs for the VPP, and improve the economic efficiency of the VPP.

4. Main challenges of distribution networks optimiztion operation

4.1. Technological challenges

Regarding technological challenges, the first issue is the insufficient accuracy of mid- and long-term forecasts for renewable energy, especially in the modeling of output fluctuations during extreme weather events, which still relies on empirical corrections. The instability and weather sensitivity of renewable energy generation are among the main difficulties in integrating renewable energy into the grid. To address this issue, it is necessary to have more precise forecasting of renewable energy output and adopt reasonable scheduling strategies to maximize the potential of renewable energy generation while ensuring the stable operation of the grid. Although this issue has garnered much attention and research, existing methods still have shortcomings. The strong correlation between renewable energy output and meteorological conditions requires predictive models that handle multidimensional nonlinear relationships. Current algorithms often use single models (e.g., traditional RNN or LSTM), which struggle to capture long-term dependencies in the data, especially when prediction errors expand significantly under extreme weather conditions [24].

The cost structure of energy storage devices presents the second difficulty.There is little study on the best capacity planning for energy storage systems from an economic standpoint, and most studies on energy storage systems based on the State of Charge (SOC) parameter of batteries concentrate on the control elements of storage systems [25]. Additionally, the high cost and unclear returns of energy storage systems are major barriers to their large-scale application. Economic analysis of energy storage typically focuses on specific beneficiaries, such as operators or users. For example, the benefits of user-side battery storage accrue to end users, with the primary benefit being reduced electricity costs. However, most cost/benefit models fail to adequately consider how factors such as the type of storage system, its technological characteristics, and its lifecycle affect its value [26].

4.2. Economic and policy challenges

Economic challenges primarily manifest in the nonlinear growth of renewable energy absorption costs and system flexibility demands. According to studies, the cost of a unit power supply rises as reserve capacity grows when the percentage of renewable energy surpasses 30%. Multi-time-scale production simulation optimization for the complementary generation of units containing renewable energy has become a hot topic in recent years. Researchers have proposed stochastic multi-scenario approaches, but the iterative process introduced by stochastic or robust scenarios often results in low computational efficiency. Furthermore, much of the existing research focuses on power systems with coal and wind generation, with less attention given to units such as hydropower and pumped storage [3]. Many scholars have studied the operation of high-penetration renewable energy systems but have not thoroughly analyzed the impact of renewable energy integration ratios on the system’s economic stability. The effects of renewable energy integration ratios on system operation remain to be explored [27].

Regarding policy challenges, policy tools must balance supply-side (e.g., technology development subsidies), demand-side (e.g., consumption incentives), and environmental measures (e.g., carbon taxes). The dual-credit policy for renewable energy vehicles aims to guide the development of the

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industry through market mechanisms but lacks incentives for corporate technological innovation. It needs to be used in combination with research and development subsidy policies [28].

The high penetration of renewable energy has led to a surge in the demand for grid upgrades. Current research on the coordinated operation optimization of transmission and distribution grids places more emphasis on overall benefits, often using integrated transmission-distribution economic dispatch models to study various distributed optimization methods. There is limited research from the perspective of different stakeholders on the coordinated economic dispatch strategies of transmission and distribution grids [29]. As the power system reform deepens and renewable energy generation is integrated on a large scale, it is necessary to balance and coordinate the reliable supply capability of the renewable energy power system with the investments in grid infrastructure. This ensures that the renewable energy power system can meet multiple requirements, including renewable energy absorption, electricity delivery, and high-quality services for users. Accurate assessment of the appropriate scale of construction and the effectiveness of user services during the construction of the renewable energy power system is one of the key challenges for the efficient and high-quality development of renewable energy power systems [30].

4.3. Challenges in system coordination and management

After the integration of a large number of distributed energy sources into the distribution network, the reactive voltage relationship between the transmission and distribution grids becomes closer, making traditional isolated reactive power optimization in the transmission and distribution networks unsuitable. To achieve effective utilization of reactive power resources on a larger scale, improve the economics of the transmission and distribution grids, and integrate reactive power optimization for transmission and distribution networks, it is crucial [31].

5. Outlook and future prospects

Under the background of high penetration of renewable energy, the intermittency and uncertainty of renewable energy generation present higher demands on the scheduling of the distribution network. In the future, renewable energy power forecasting models based on artificial intelligence and big data technologies will become more accurate. Combined with real-time feedback correction mechanisms, these models will effectively reduce the impact of forecast errors on scheduling. Furthermore, distributed power coordination control technologies based on multi-time-scale optimization will further develop, achieving dynamic optimization from minute-level to hour-level time scales. This will result in further improvements in renewable energy forecasting and scheduling optimization [5].

Energy storage technologies play a crucial role in balancing system stability and electricity supply costs. In the future, the configuration of energy storage capacity will be more scientific and rational. With the integration of DR and smart soft-switch technologies, the capacity for renewable energy absorption will significantly increase, while reducing the curtailment rates of wind and solar energy [5]. At the same time, the application of flexible DC technology in hybrid AC/DC distribution networks will further enhance the controllability and flexibility of the system.

As the degree of digitalization in distribution networks increases, digital twin technology will play a greater role in fault location, overload risk assessment, and other areas [32]. In the future, the integrated management platform of distribution networks based on digital twins will achieve a high degree of synchronization between physical models and virtual models. It will also strengthen encryption algorithms to resist potential network attacks, ensuring data security [33]. This will facilitate the integration of digital twins and cybersecurity technologies.

In the context of high renewable energy penetration, nuclear power, as a stable output source, will play an important role in peak shaving and frequency support in the power grid [32]. In the future,

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the coordinated development of nuclear power and renewable energy will provide strong support for the safe and stable operation of the power system. This will ensure the collaborative development of nuclear power and renewable energy.

6. Conclusion

This study offers focused answers after methodically examining the main technologies and difficulties in maximizing distribution networks' performance in the face of significant renewable energy penetration. The study shows that through technologies such as renewable energy power forecasting, intelligent scheduling, coordinated source-grid-load-storage integration, and hybrid AC/DC architectures, it is possible to effectively address issues such as voltage fluctuations and bi-directional power flow caused by renewable energy integration. At the same time, the application of energy storage technologies, digital twin platforms, and regional integrated energy systems will further enhance the economy and reliability of distribution networks.

As new technologies like digital twins, big data, and artificial intelligence continue to advance, distribution network operations optimization will shift in a more clever and effective path. This will not only help achieve the clean transformation of the energy structure but also provide a solid theoretical and technical foundation for the construction of new power systems.

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