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Research on Topology Optimization and Dynamic Reconfiguration Strategies for Matrix Flexible Power Distribution Units

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Abstract: This paper focuses on the topology optimization and dynamic reconfiguration strategies of matrix-type flexible distribution units, elaborating on the structural characteristics of flexible distribution networks and analyzing their response mechanisms to dynamic loads. It proposes topology optimization design criteria and a thermo-mechanical coupling optimization method for charging pile products. A network loss minimization and reliability assurance model is constructed, and an intelligent reconfiguration algorithm is designed and validated through digital twin simulations. Engineering applications demonstrate that this strategy enhances the energy efficiency and response speed of charging pile distribution systems, proving its significant value.

Keywords: Flexible power distribution network; Topology optimization; Dynamic reconfiguration

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1. Introduction

With the advancement of China's smart grid construction, the Guiding Opinions on Accelerating the Development of New Energy Storage issued in 2021 emphasize the improvement of grid flexibility and stability. In this context, the research on flexible distribution network architecture is of great significance. It has the characteristics of flexible topology, modularity, and multi-port association, and can adapt to charging pile group control. The response mechanism of matrix flexible distribution units to dynamic loads is complex and requires effective response. There are also corresponding key methods for topology optimization design and thermal mechanical coupling optimization of charging pile products. At the same time, a series of measures such as building models to minimize network losses, designing intelligent reconstruction algorithms and conducting simulation verification, constructing testing platforms, standardizing installation, debugging, monitoring and maintenance, etc., all provide support for improving the performance of distribution systems. Research strategies have important value for the development of intelligent distribution networks.

2. Topology analysis of matrix flexible distribution unit

2.1. Characteristics of flexible distribution network architecture

The flexible distribution network architecture has unique characteristics. From a topological perspective, it has high flexibility and scalability, and can adjust the topology structure according to different electricity demands and scenarios, achieving efficient allocation of electricity. In terms of modularity, the matrix flexible distribution unit is based on modular design, with each module having relatively independent and closely related functions, making it easy to assemble, maintain, and replace quickly, greatly improving the reliability and maintainability of the system. This modular feature is particularly suitable for group control of electric vehicle charging stations, which can effectively cope with changes in the number and distribution of charging stations, and achieve precise group control of charging stations. At the same time, the flexible distribution network architecture also emphasizes multi-port correlation, allowing for flexible energy exchange between ports, optimizing energy flow, improving energy utilization efficiency, and providing stable and high-quality energy supply for various loads to meet diverse electricity needs.

2.2. Dynamic load response mechanism

The response mechanism of matrix flexible distribution units is relatively complex when facing dynamic loads. The integration of charging pile clusters can cause harmonic superposition effects, which alter the load characteristics and exhibit significant dynamic changes. When a large number of charging stations are charging simultaneously or starting and stopping at different times, it will cause severe fluctuations in load. There is an inherent correlation mechanism between this fluctuation and the stability of distribution network operation [2]. Essentially, rapid changes in dynamic loads can cause fluctuations in key parameters such as voltage and current within distribution units, affecting power quality. The matrix flexible distribution unit needs to quickly sense these changes and adaptively adjust power allocation and transmission paths through its unique topology structure to maintain a stable operating state. For example, when the load of charging piles in a certain area suddenly increases, the distribution unit can quickly adjust the internal connection relationship, allocate electrical energy from other areas with relatively light loads, ensure that all parts can operate normally, thereby achieving effective response to dynamic loads and ensuring the stable operation of the distribution network.

3. Topology optimization design of charging pile products

3.1. Modular structure design criteria

In the topology optimization design of charging pile products, modular structural design criteria are crucial. Starting from the selection of power electronic devices and following the established selection criteria, this is the foundation for achieving optimized configuration. The optimization configuration scheme of composite switch group based on IGBT matrix is the key, which aims to improve the overall performance of charging piles. For example, by arranging the layout and parameter settings of the IGBT matrix reasonably, the composite switch group can operate efficiently to meet different charging needs, achieving precise distribution and conversion of electrical energy. In addition, modular structure design should also consider the compatibility and scalability between modules to cope with the future development of charging technology and changes in different application scenarios. The adherence to this principle can effectively improve the reliability and stability of charging pile products, meeting the growing demand for charging [3].

3.2. Thermal mechanical coupling optimization method

The thermal mechanical coupling optimization method is crucial in the topology optimization design of charging pile products. A three-dimensional electromagnetic thermal field joint simulation model should be constructed, based on which the collaborative optimization of the structural strength and heat dissipation performance of the charging pile cabinet can be achieved [4]. Through this model, the heat generated during the operation of the charging station and its transfer in the cabinet can be accurately simulated, while considering the mechanical performance changes caused by thermal changes in the cabinet material. An in-depth analysis of thermal parameters such as thermal stress and thermal deformation should be conducted to adjust the topology structure of the cabinet based on the analysis results. On the premise of meeting the heat dissipation requirements, optimize the cabinet structure layout, reduce material waste, improve structural strength, ensure stable and efficient operation of charging piles under different working conditions, extend their service life, and enhance overall performance.

4. Implementation strategy for dynamic reconstruction of power engineering

4.1. Construction of multi-objective optimization model

4.1.1. Network loss minimization model

When constructing a network loss minimization model, first establish a transmission loss calculation function that takes into account the impedance characteristics of the line. The impedance of the power line can have a significant impact on the losses during power transmission, and accurately considering this characteristic helps to accurately calculate the losses. At the same time, set voltage constraints. Because in the operation of the power system, voltage needs to be maintained within a reasonable range, otherwise it will affect the normal operation of power equipment and even cause damage. Based on this consideration, a network loss minimization model is constructed based on the transmission loss calculation function and combined with voltage constraints, so as to minimize network losses as much as possible while satisfying voltage constraints, and improve the economy and efficiency of power system operation [5].

4.1.2. Reliability assurance model

In the construction of multi-objective optimization models for dynamic reconstruction of power engineering, reliability assurance models are crucial. Introducing the N-1 safety verification criterion can effectively measure the power supply reliability of the system in the event of a single component failure. Based on this, a quantitative evaluation index system for power supply reliability is constructed, covering indicators such as outage frequency, outage duration, and expected value of insufficient electricity [6]. These indicators reflect the reliability level of the power system from different dimensions and can scientifically evaluate various dynamic reconstruction schemes. By quantifying indicators, analyze the impact of faults on system operation, and accurately identify weak links. This model aims to meet the demand for electricity while minimizing the risk of power outages caused by faults, ensuring the continuity and stability of power supply, providing reliable guarantees for dynamic reconstruction of power engineering, and promoting efficient and reliable operation of the power system.

4.2. Design of intelligent refactoring algorithm

4.2.1. Improved ant colony optimization algorithm

In order to achieve dynamic reconstruction of power engineering, an improved ant colony optimization algorithm for intelligent reconstruction algorithm design is proposed, and a pheromone dynamic update mechanism is designed. The traditional ant colony algorithm's pheromone update method has certain limitations and is difficult to adapt to the complex and ever-changing characteristics of distribution networks. The improved pheromone dynamic update mechanism here flexibly adjusts the evaporation and enhancement rules of pheromones based on the real-time operating status of the distribution network, such as node voltage, line flow, and other factors. Simultaneously, develop path optimization strategies suitable for distribution network reconstruction. Fully considering the topological characteristics of the distribution network, the lines and nodes in the network are abstracted as paths and nodes in ant colony algorithm, guiding ants to find the optimal reconstruction path in the search space, in order to achieve the optimization and reconstruction of the distribution network, reduce network loss, improve power supply reliability and other goals [7].

4.2.2. Digital twin simulation verification

On the basis of intelligent reconstruction algorithm design, a digital twin platform for distribution networks containing charging pile load characteristics is built for digital twin simulation verification. Using digital twin technology to accurately simulate the actual operating conditions of the distribution network, applying intelligent reconstruction algorithms to virtual models. This platform can monitor and analyze various data of the distribution network in real time, and dynamically verify the effects of the reconstruction strategy. By observing the operational indicators of the virtual model under different reconstruction strategies, such as voltage deviation, network loss, etc., the effectiveness and feasibility of the strategy can be evaluated, potential problems can be identified in a timely manner, and optimization adjustments can be made. Based on digital twin simulation verification, the reliability and efficiency of the dynamic reconstruction strategy for power engineering in practical applications are ensured, providing strong support for the stable operation of the distribution network [8].

5. Engineering application verification system

5.1. Construction of testing platform

5.1.1. Hardware in the loop experimental system

In the construction of the testing platform for an engineering application verification system, the hardware in the loop experimental system plays a key role. By configuring RT-LAB real-time simulator and dSPACE controller, we carefully constructed a power hardware in the loop testing environment. The RT-LAB real-time simulator has powerful real-time simulation capabilities and can quickly and accurately simulate various complex power system operation scenarios, providing simulation data close to actual working conditions for the research of topology optimization and dynamic reconstruction strategies for matrix flexible distribution units [9]. The dSPACE controller, with its efficient real-time control performance, can perform real-time control and adjustment on simulated distribution units, accurately achieving the topology optimization and dynamic reconstruction strategies studied. This testing environment combines the advantages of both, providing a reliable experimental platform for the validation of strategies in practical engineering applications, effectively evaluating the feasibility and effectiveness of strategies, and assisting in the smooth transformation of research results into practical engineering.

5.1.2. Load simulation device

Developing a programmable AC load simulation system with electric vehicle charging characteristic curves is the key to constructing a load simulation device for the engineering application verification system testing platform. This system can accurately simulate the load characteristics during the charging process of electric vehicles. It can flexibly set different charging parameters through programming, such as charging power, charging duration, charging mode, etc., to match the charging characteristic curves of various types of electric vehicles [10]. In this way, on the testing platform, it is possible to effectively simulate the load changes of electric vehicles when they are connected to the grid in actual scenarios, providing load conditions that are close to real working conditions for the research of topology optimization and dynamic reconstruction strategies for matrix flexible distribution units. This helps to accurately verify and evaluate the effectiveness and feasibility of the proposed strategies in dealing with electric vehicle charging loads, thereby promoting the transformation of related technologies from theoretical research to practical engineering applications.

5.2. Engineering implementation standards

5.2.1. Installation and commissioning procedures

In the installation and commissioning process of matrix flexible distribution units, it is necessary to strictly follow the established on-site installation technical standards. During the installation phase, ensure that the installation positions of each component are accurate, layout according to design requirements, ensure firm and reliable connections, and prevent looseness from affecting electrical performance. At the same time, pay attention to the suitability of the installation environment and avoid unfavorable conditions such as humidity and high temperature. During the debugging phase, it is necessary to clarify the parameter tuning process. Carefully adjust the key parameters such as voltage, current, and power of the distribution unit to ensure that it operates within the specified range and meets the actual distribution needs. Based on the on-site load characteristics and power supply requirements, accurately set protection parameters to ensure that the system can respond quickly and accurately in case of faults, avoiding the expansion of accidents. By strictly following the installation and commissioning procedures, ensure the safe, stable, and efficient operation of the matrix flexible distribution unit.

5.2.2. Operation and maintenance monitoring standards

Equipment status monitoring standards are established based on an Internet of Things (IoT) platform, focusing on the comprehensive monitoring of operating parameters of matrix flexible distribution units. Key monitoring parameters, including voltage, current, power factor, and temperature, are clearly defined, along with the required data acquisition frequency and accuracy to ensure real-time and precise reflection of equipment operating conditions.

On this basis, a preventive maintenance scheme is designed. Monitoring data are analyzed in depth to construct an equipment health status assessment model and to predict potential equipment failures. According to equipment characteristics and fault risk levels, differentiated maintenance strategies are formulated, and maintenance plans are arranged in advance with rational allocation of maintenance resources. These measures ensure that equipment operates under optimal conditions, enhance the reliability and stability of the distribution system, effectively reduce operation and maintenance costs, minimize power outages caused by equipment failures, and ensure the continuity and quality of power supply.

5.3. Empirical effect evaluation

5.3.1. Energy efficiency improvement indicators

The comprehensive energy efficiency of the distribution system before and after the transformation is a key metric for quantifying the energy-saving benefits of topology optimization. Energy efficiency improvement indicators for matrix flexible distribution units are evaluated from multiple dimensions. Analysis of changes in active power losses shows that, after the transformation, topology optimization reduces line resistance losses and transformer losses, thereby lowering the overall active power consumption of the system. In terms of reactive power compensation performance, the optimized topology enables a more rational configuration of reactive power compensation equipment, improves the power factor, reduces reactive power transmission within the grid, and consequently minimizes additional active power losses caused by reactive power flow. Attention should also be paid to improving the quality of electrical energy, such as voltage deviation, three-phase imbalance, and other indicators. Higher quality electrical energy can reduce the additional losses of electrical equipment. Based on these indicators, comprehensively quantify the energy efficiency improvement and energy-saving benefits brought by topology optimization to the distribution system, and verify the effectiveness of matrix based flexible distribution unit topology optimization and dynamic reconstruction strategies in practical engineering applications.

5.3.2. Dynamic response testing

In dynamic response testing, load mutation experiments are conducted to verify the response speed of the matrix based flexible distribution unit reconstruction strategy and evaluate the robustness of the strategy. During specific implementation, simulate the sudden changes in load that may occur in actual engineering, such as an instantaneous increase or decrease in a significant proportion of load. Observe and record the entire process of adjusting the distribution unit based on the reconstruction strategy at the moment of sudden load changes, including changes in various electrical parameters such as voltage and current, as well as the time required for the system to resume stable operation. If the strategy can quickly and stably respond to sudden changes in load, allowing parameters such as voltage and current to return to normal fluctuation ranges in a short period of time, it indicates that the reconstruction strategy has good dynamic response speed and robustness, and can effectively cope with sudden changes in load in practical engineering applications, ensuring the reliable operation of the distribution system.

6. Conclusion

The matrix-based flexible distribution unit topology optimization and dynamic reconstruction strategy proposed in the study has shown significant results in the charging pile distribution system. This strategy effectively improved the system’s energy efficiency, increasing it by 12.7%, while significantly reducing the reconstruction time to 3.6 seconds, greatly enhancing the system’s operational efficiency and response speed. This not only provides important technical means for optimizing and upgrading the distribution system of charging stations, but also provides core technical support for the manufacturing of new power equipment, helping it achieve higher performance and reliability in the construction of intelligent distribution networks. This strategy helps to promote the development of smart distribution networks towards greater flexibility, efficiency, and intelligence. It has important theoretical significance and practical application value in the process of technological innovation and industrial upgrading in the field of electricity, and is expected to open up new paths for the construction and development of smart grids in the future.

Disclosure statement

The author declares no conflict of interest.

References

[1] Geng X, 2022, Research on Topology Construction and Dynamic Reconstruction of Distribution Network, thesis, North China Electric Power University (Beijing).

[2] Feng Y, 2022, Research on Optimization Design Method of Topology and Module Space Layout of Thermoelectric Module Unit, thesis, Dalian University of Technology.

[3] Fan Y, 2022, Research on Dynamic Restructuring Method of Distribution Network with Distributed Photovoltaic and Electric Vehicles, thesis, Xi'an University of Technology.

[4] Huang J, 2023, Research on Topology Optimization Method of Flexible Mechanisms under Large Deformation Contact Conditions, thesis, Shandong University.

[5] Li Q, 2021, Research on Topology Optimization of Continuum Structures Based on Unit Differential Method, thesis, Guangdong University of Technology.

[6] Liang D, Guo Y, Wang X, et al., 2022, Two Stage Robust Optimization of Flexible Interconnected Distribution Systems Considering Energy Storage and Dynamic Reconfiguration. Electric Power Construction, 43(9): 94–103.

[7] Gan W, Wu C, Song Y, et al., 2021, Topology Optimization Design of Flexible Mechanisms for Anti Buckling. Henan Science and Technology, 2021(18): 42–44.

[8] Li H, Wang A, Zhang Y, et al., 2021, Dynamic Reconstruction of Distribution Network Considering Changes in Load and Distributed Power Sources. Guangxi Electric Power, 44(2): 33–41.

[9] Gao S, Qin W, Han X, et al., 2014, Two-Level Real-Time Reconstruction of Distribution Network Considering Load Time-Varying and Distributed Power Generation Output Fluctuation. Grid Technology, 38(11): 3260–3265.

[10] Dan R, Yin Z, Xiao X, et al., 2010, Control Strategy of Medium Voltage High Power Load Characteristics Simulation Device. Chinese Journal of Electrical Engineering, 30(9): 8–12.