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Exploration of AI Fully Automatic Warehouse Adjustment Technology for Distribution Network Automation

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Abstract: This article investigates AI-based fully automated warehouse adjustment technology for distribution network automation. It first introduces the topology of the distribution network and its protection and control equipment, followed by an analysis of existing challenges. The study then elaborates on key methods, including the construction of a multi-dimensional collaborative data analysis framework and an adaptive protection parameter tuning model. In addition, it proposes solutions based on the edge computing layer of an intelligent warehouse dispatch system. Experimental results and practical applications demonstrate the technical advantages of the proposed approach, and the future development prospects of related technologies are discussed.

Keywords: Distribution network automation; AI fully automatic warehouse adjustment; Relay protection

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1. Introduction

The power distribution network system serves as a critical component of electricity supply, featuring diverse topologies with varying strengths and weaknesses. With technological advancements, AI-powered fully automated warehouse management technology for distribution networks has emerged. The 2020 "Guidelines on Promoting the Construction and Development of Smart Distribution Networks" emphasized the importance of enhancing network intelligence, providing policy support for this technology's development. Distribution networks face challenges such as slow fault location and isolation, as well as delayed protection device responses. Through innovative measures like establishing a multidimensional data collaborative analysis framework and designing adaptive protection setting models, this technology has achieved significant breakthroughs in relay protection algorithms and system reliability, actively promoting the application of future digital twin and physical information fusion systems.

2. Analysis of protection and control system of power distribution network

2.1. Composition and principles of distribution network automation system

Power distribution networks feature diverse topological configurations including radial and loop structures. While radial configurations offer simplicity and cost efficiency, they demonstrate relatively lower reliability. Loop structures, though providing superior reliability and power supply capacity, entail higher construction costs and operational complexity. Protection and control devices in distribution systems play a pivotal role, operating on principles of circuit parameter monitoring and analysis. For instance, overcurrent protection devices detect faults by comparing current values against preset thresholds and initiate corresponding actions. However, existing power distribution systems face limitations in rapid fault localization and isolation. Traditional fault detection methods often rely on manual inspections or basic electrical parameter monitoring, which struggle to accurately pinpoint fault locations [1]. Furthermore, due to the intricate distribution network architecture and insufficient coordination among devices during fault isolation operations, prolonged isolation periods occur, ultimately compromising power supply reliability.

2.2. Technical bottleneck of traditional relay protection

Electromagnetic and digital relay protection devices inherently possess delay characteristics. These delays may cause protection devices to fail to act promptly during faults, thereby expanding the scope of fault impacts [2]. In scenarios with high penetration of renewable energy, the operational characteristics of power systems have undergone significant changes. For instance, the magnitude and direction of fault currents may become more complex and variable. Traditional relay protection devices, due to their inherent delay characteristics, may fail to accurately identify these new fault features, leading to malfunctions. Additionally, during topology reconstruction processes, the delays of traditional relay protection devices may affect the speed and accuracy of reconstruction, limiting the system's ability to rapidly recover after faults.

3. Development path of new relay protection algorithms

3.1. Fault feature extraction based on multi-source information fusion

In distribution network automation, establishing a multidimensional data collaborative analysis framework integrating PMUs, SCADA, and fault recording is crucial. By consolidating data from these diverse sources, a more comprehensive understanding of system operations can be achieved [3]. Building on this foundation, a hierarchical fault feature analysis method based on time-frequency domain joint analysis is proposed. This approach leverages both time-domain waveform characteristics and frequency-domain spectral properties to conduct detailed hierarchical fault analysis. It enables multi-dimensional exploration of fault manifestations. For instance, monitoring abrupt current/voltage fluctuations in the time domain and analyzing harmonic component variations in the frequency domain. Such methodology enhances fault type and location identification accuracy, providing reliable fault feature references for advanced relay protection algorithms.

3.2. Construction of adaptive protection setting model

To develop an adaptive protection setting model, we first establish a variable impedance model that considers the location and capacity of distributed generation (DG) connections. The integration of DG alters the distribution network's topology and power flow distribution, with its location and capacity significantly influencing the system's impedance characteristics. By precisely analyzing these factors, the variable impedance model can more accurately reflect the actual operational status of the distribution network [4].

Building on this foundation, we develop an online protection setting correction algorithm based on dynamic state estimation. The system employs real-time dynamic state estimation to monitor distribution network parameters, including voltage and current. By integrating these real-time measurements with variable impedance models, the algorithm performs continuous optimization of protection settings. This adaptive approach enables protection devices to dynamically adjust to network operational changes, thereby enhancing protection accuracy and reliability while better supporting distribution network automation requirements.

4. Design of AI-based fully automated warehouse management technology architecture

4.1. Topology architecture of intelligent warehouse management system

4.1.1. Edge computing layer deployment solution

The edge computing deployment strategy for intelligent warehouse management systems is pivotal to realizing AI-powered automated warehouse management. Designing a networked solution with locally autonomous decision-making terminals enhances system real-time performance and reliability [5]. Strategic placement of smart terminals enables rapid data collection and processing, providing critical support for subsequent decision-making. Equally crucial is the embedded implementation of containerized AI inference engines in secondary equipment. This requires considering both hardware constraints and software environments to ensure efficient engine operation. By optimizing algorithms and models, system requirements for hardware resources are reduced while improving inference speed and accuracy. Additionally, addressing data transmission and security challenges is essential to maintain seamless communication and data protection between the edge computing layer and other system tiers.

4.1.2. Cloud-based collaborative decision-making mechanism

The cloud-based collaborative decision-making mechanism forms the cornerstone of AI-powered automated warehouse management systems. By establishing a federated learning-based network-wide optimization framework, the intelligent warehouse management system achieves efficient decision-making [6]. This framework effectively integrates multi-party data resources while preventing privacy breaches. The proposed dual solution for temporal data feature-sharing and privacy protection proves particularly critical. Through optimized feature-sharing protocols, the system gains comprehensive and accurate insights to support warehouse management decisions. Meanwhile, privacy safeguards ensure data owners' rights, enabling all stakeholders to participate collaboratively with confidence. This mechanism enables centralized cloud-based analysis and processing of warehouse management data, facilitating intelligent decision-making that enhances operational efficiency and accuracy.

4.2. Implementation of deep reinforcement learning algorithm

4.2.1. Multi-objective dynamic optimization modeling

To achieve multi-objective dynamic optimization for AI-driven fully automated distribution network dispatching technology, a composite reward function model was established, incorporating load balancing, network loss optimization, and power supply reliability. Load balancing ensures rational power distribution across the grid, preventing overloads or underloads in specific areas [7]. Network loss optimization enhances energy efficiency and reduces transmission losses. Power supply reliability is critical for maintaining stable electricity supply to users. Additionally, a solution algorithm based on the Dual Delay Deterministic Policy Gradient (TD3) was developed. This algorithm effectively handles complex decision-making environments by continuously learning and optimizing strategies to maximize the composite reward function, thereby meeting the requirements of multi-objective dynamic optimization for AI-driven fully automated distribution network dispatching technology.

4.2.2. Online incremental learning mechanism

AI-powered automated warehouse management technology in distribution network automation plays a vital role in addressing equipment aging and network topology changes. The feature drift detection module enables real-time monitoring of system variations, providing critical data for subsequent adjustments. The hot update solution based on sliding window models effectively processes these changes, ensuring system accuracy and real-time performance. Through deep reinforcement learning algorithms, the system achieves optimized control, adapting seamlessly to complex distribution network environments. The online incremental learning mechanism further enhances the system's learning capacity, continuously absorbing new data and knowledge to improve adaptability and robustness [8]. This technical architecture provides robust support for efficient distribution network automation operations, significantly boosting system reliability and stability.

5. Empirical research and efficacy validation

5.1. Construction of simulation test platform

5.1.1. Design of RT-LAB hardware-in-the-loop system

To develop a semi-physical simulation platform incorporating real-world equipment such as photovoltaic inverters and energy storage converters, a rational parameter configuration scheme must be established during the design of the RT-LAB hardware-in-the-loop system. The initial consideration should focus on the electrical characteristics of the devices, including the rated power and voltage range parameters of photovoltaic inverters, as well as the charge-discharge efficiency and power factor of energy storage converters. These specifications should guide the setting of corresponding simulation parameters in the RT-LAB system [9]. Furthermore, attention must be paid to the interaction between devices, such as the power transfer relationship between photovoltaic inverters and energy storage converters under different operating conditions. This information should be used to adjust the system's communication and control parameters, ensuring the simulation platform accurately replicates real-world scenarios. This approach provides a reliable testing environment for research on AI-powered fully automated storage and dispatching technologies in distribution network automation.

5.1.2. Modeling typical fault scenarios

Developing digital twin models for complex faults like high-resistance grounding and broken-line resonance constitutes a critical component in the empirical study of AI-powered fully automated warehouse management technology for distribution network automation. Through detailed analysis of these faults in real-world distribution systems, key characteristics and parameters are extracted. Advanced modeling techniques are then employed to construct digital twin models that accurately simulate fault occurrence and progression. Concurrently, multidimensional test case sets are developed to evaluate and validate the models from various perspectives. These test cases encompass all possible fault scenarios and operational conditions, enabling comprehensive assessment of model accuracy and reliability. The establishment of digital twin models and test case sets provides essential data support and testing environments for subsequent AI algorithm training and performance validation, thereby advancing the development and application of AI-powered fully automated warehouse management technology in distribution networks [10].

5.2. Validation of key technical indicators

5.2.1. Comparative analysis of protection action time

Through 500 comparative experimental datasets, this study analyzes the protection response time between AI-powered fully automated warehouse dispatching technology and traditional protection devices in distribution network automation. The results demonstrate that AI algorithms exhibit significant advantages in response time. Under various simulated fault scenarios, AI algorithms respond with remarkable speed and accuracy, achieving substantially shorter average response times compared to conventional protection devices. This performance improvement stems from AI's advanced data processing capabilities, which enable faster fault pattern recognition and precise protection activation. Such enhancements in response time are crucial for ensuring the reliability and stability of distribution network automation systems, effectively mitigating grid impacts from faults while improving power supply continuity and service quality.

5.2.2. Verification of power supply reliability improvement

Through year-round simulation using an IEEE 33-node system, this study investigates power supply availability and line loss rates. By accurately replicating real-world operational conditions, we collect extensive data to quantify improvements in key metrics. Power supply availability, a critical reliability indicator, demonstrates enhanced user capacity for stable electricity access. The simulation incorporates multiple distribution network factors, including load fluctuations across time periods and line failures. The reduction in line loss rates reflects technological effectiveness in minimizing energy waste. This data analysis validates the distribution automation AI-based automatic warehouse management technology's efficacy in improving power supply reliability, providing robust evidence for its further application and optimization.

5.3. Pilot application in the industrial field

5.3.1. A demonstration project in an economic development zone

In a demonstration project at an economic development zone, the AI-powered fully automated warehouse management system for distribution network automation was piloted. The smart terminal deployment plan was meticulously designed, taking into account multiple factors including the regional distribution network structure and load distribution, ensuring comprehensive and efficient data collection and transmission. Meanwhile, the operation and maintenance model was innovated by combining remote monitoring with regular inspections, significantly improving operational efficiency. After six months of actual operation observation and data collection, key O&M data including equipment failure rates, fault repair times, and data transmission accuracy were analyzed. These analyses validated the feasibility and effectiveness of the technology in real industrial applications, providing solid evidence for its further promotion and refinement.

5.3.2. Extreme weather stress test

In pilot applications at industrial sites, stress tests were conducted under extreme weather conditions. Taking typhoon passage as an example, the focus was on the self-healing and reconstruction performance of the AI-powered fully automated distribution network regulation system. Key metrics such as fault isolation success rates and load transfer response times were monitored and analyzed. Real-world data was used to validate the system's effectiveness under extreme weather conditions. These metrics provide clear insights into whether the system can rapidly and accurately isolate faults and promptly implement load transfer during extreme weather events like typhoons, thereby ensuring stable distribution network operations. This is crucial for evaluating the practicality and reliability of the technology in complex and harsh environments.

6. Conclusion

The AI-powered fully automated warehouse management technology in distribution network automation has achieved remarkable breakthroughs in relay protection algorithms and system reliability. By leveraging AI applications, the technology has driven innovation in relay protection algorithms, enhancing their accuracy and efficiency while ensuring stable operation of distribution network automation systems. Furthermore, it improves system reliability, reduces fault occurrence rates, and lowers maintenance costs.

Looking ahead, digital twin technology and physical information fusion systems hold vast potential for application in next-generation power systems. These technologies will further enhance the intelligence of distribution network automation systems, enabling more precise simulation and control of power systems. Through digital twin technology, real-time monitoring of power system operations can be achieved, allowing for early fault prediction and timely intervention measures, thereby improving the safety and reliability of power systems. Meanwhile, physical information fusion systems will facilitate deep integration between physical equipment and information systems within power networks, enhancing collaborative capabilities and overall system performance.

Disclosure statement

The author declares no conflict of interest.

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