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Exploration of Automated Operation Technology for Power Transmission, Distribution, and Utilization Engineering

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Abstract: The rapid development of the socio-economy has driven a continuous increase in electricity demand, placing higher requirements on the operation of the power system. Power transmission, distribution, and utilization engineering play a crucial role in the entire power system, with their operational efficiency directly affecting the overall stability of the power supply. This paper analyzes the application advantages of automated operation technology in power transmission, distribution, and utilization engineering, and examines specific applications of relevant technologies, such as holographic perception and real-time monitoring technology, edge computing and cloud computing collaboration technology, multi-source data integration technology, adaptive control technology, and network security defense technology. Based on this, strategies for the efficient automated operation of power transmission, distribution, and utilization engineering are proposed, providing valuable references for the long-term development of power engineering.

Keywords: Power transmission and distribution; Utilization engineering; Real-time monitoring; Network security defense; Intelligent perception

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1. Introduction

Electricity is a vital energy source that supports the long-term development of various industries, and the stability of power operation is closely related to socio-economic development. With the continuous increase in electricity demand, the role of power transmission, distribution, and utilization engineering has become increasingly prominent. Traditional operation modes of power transmission, distribution, and utilization engineering struggle to cope with the current complex power grid architecture, while the application of automation technology can leverage sensing and computer control technologies to meet the intelligent management and control needs of power transmission, distribution, and utilization engineering. Therefore, in-depth exploration of automated operation strategies for power transmission, distribution, and utilization engineering holds significant practical importance for technological reform in the power industry.

2. Application advantages of automated operation technology for power transmission, distribution, and utilization engineering

2.1. Enhanced precision control capability

Automated operation technology for power transmission, distribution, and utilization engineering can effectively enhance precision control capability by collecting various types of data in real-time and accurately from power transmission, distribution, and utilization engineering, providing reliable data support for subsequent precision control. Automated operation technology has the advantage of rapid response, enabling it to quickly perceive and automatically adjust operating parameters in the event of system abnormalities or faults. Automation technology also supports remote precision control, allowing staff to remotely adjust power transmission and distribution equipment from the control center, reducing the risk of human operational errors and providing strong guarantees for the stable operation of the power system. Additionally, automatic generation control and automatic voltage control strategies based on cloud-edge collaboration can effectively coordinate peak-shaving resources in the transmission grid with distributed energy storage in the distribution grid, establishing a rigid foundational guarantee for real-time interaction in the power transmission, distribution, and utilization system.

2.2. Reduced power loss

Automated operation technology for power transmission, distribution, and utilization engineering can minimize power loss. Intelligent sensors and data acquisition systems can swiftly capture key parameters such as voltage and current in the lines, arranging maintenance and inspections at the first sign of potential risks to prevent further loss expansion. Automation technology enables automatic compensation for reactive power, reducing the flow of reactive current in the lines and thereby decreasing active losses caused by line resistance. Furthermore, by integrating the advantages of the Internet of Things (IoT) and edge computing, automated technology for power transmission, distribution, and utilization engineering can automatically optimize the open-loop operating points of the distribution network during fluctuations in distributed power output, finely enhancing the efficiency of transmission and distribution for every unit of electricity.

3. Automated operation technologies for power transmission, distribution, and utilization engineering

3.1. Holographic perception and real-time monitoring technology

The holographic perception and real-time monitoring technology in automated operation technologies for power transmission, distribution, and utilization engineering integrates modern technological means such as the IoT and big data. Based on intelligent sensor clusters deployed on transmission lines, substations, and distribution equipment, this technology enables millimeter-level precise collection of key parameters such as line temperature, ice thickness, and partial discharges in equipment. The holographic perception platform can construct a three-dimensional model of the power grid using digital twin technology, deeply integrating the status of physical equipment, environmental parameters, and operational data. The real-time monitoring system primarily integrates functional modules of SCADA, EMS, and DMS, dynamically displaying power grid topology, power flow distribution, and equipment status through a visual interface. It supports millisecond-level responses to commands such as switch operations and load adjustments. Upon detecting a line fault, the system can complete fault location and restore power supply to non-fault areas within 100 milliseconds. This technology integrates phasor measurement units and wide-area measurement systems, enabling synchronous capture of disturbance propagation trajectories and oscillation modes in complex power grids. It transforms the traditional passive repair and maintenance mode into a proactive warning and minute-level response self-healing ecosystem, propelling the power transmission, distribution, and utilization system towards a highly resilient and blind-spot-free transparent power grid.

3.2. Edge computing and cloud computing collaboration technology

The edge computing and cloud computing collaboration technology in automated operation technologies for power transmission, distribution, and utilization engineering leverages the RTOS real-time operating system and FPGA hardware acceleration to complete fault feature extraction, type identification, and preliminary location within 10 milliseconds. It uploads streamlined fault information to the cloud, reducing the daily data transmission volume per device from 10 GB to 50 MB, effectively alleviating core network bandwidth pressure [1]. The central cloud platform can identify the geographical distribution and seasonal characteristics of faults based on network-wide fault statistics, reducing fault handling delays from 500 milliseconds in traditional modes to 10 milliseconds, meeting the real-time handling requirements for new energy faults. For example, in a pilot project by State Grid in the high new energy penetration region of North China, the deployment of 300 edge node devices covered 1,500 kilometers of transmission lines. After one year of operation, communication bandwidth occupation was reduced by 99.5%, validating the advantages of cloud-edge collaboration technology in enhancing power grid real-time performance.

The application of this technology also achieves in-depth defense in terms of security. Edge nodes are responsible for terminal identity authentication, data encryption, and initial screening of abnormal traffic, while the cloud implements global intrusion detection and cross-site attack analysis. With the continuous maturation and development of low-latency 5G/6G networks, edge and cloud computing collaboration technology will drive the fault handling of power transmission and distribution systems towards proactive pre-defense and adaptive in-event responses.

3.3. Multi-source data integration technology

The primary function of multi-source data integration technology in the automated operation of power transmission, distribution, and utilization engineering is to deeply integrate real-time monitoring data from SCADA systems and load data collected by smart meters, constructing a unified data view across the entire chain. From a security perspective, this technology employs national cryptographic algorithms for encrypted transmission of collected data and implements fine-grained permission management through an Attribute-Based Access Control (ABAC) model, ensuring that only personnel with corresponding permissions can view sensitive data. The practical value of this technology has been validated in multiple scenarios. In extreme weather conditions, it can integrate meteorological radar data with power grid topology information to predict potentially affected line segments in advance, significantly improving the efficiency of emergency repair resource allocation. Additionally, in the context of distributed energy accommodation, this technology can integrate data such as numerical weather forecasts and ultra-short-term photovoltaic power forecasts to achieve voltage and reactive power optimization in distribution networks. The maturity of multi-source data integration technology directly determines the intelligence level of automated systems for power transmission, distribution, and utilization engineering.

3.4. Adaptive control technology

Adaptive control technology in the automated operation of power transmission, distribution, and utilization engineering can monitor power grid operating parameters in real-time and dynamically correct control models using online parameter identification algorithms, enabling the system to automatically adapt to uncertain factors such as sudden load changes and line aging. Adaptive control technology can incorporate the time-varying characteristics of power transmission and distribution equipment parameters, introducing Lyapunov stability theory into the adaptive control loop to design adaptive laws and ensure the convergence of controller parameter adjustment processes. With the deep integration of edge computing and digital twin technology, modern adaptive control systems are evolving towards a cloud-edge-end collaborative architecture. The cloud platform can pre-simulate control strategies through digital twin models and then transmit optimized parameters back to on-site controllers, effectively improving power grid operational efficiency. Furthermore, adaptive control technology can actively adjust the inertia and damping coefficients of virtual synchronous generators (VSGs) by identifying line impedance in real-time, enabling grid-connected inverters to maintain the same dynamic response quality at different operating points and promoting the formation of a closed-loop intelligent operation paradigm for automated systems in power transmission, distribution, and utilization engineering [2].

3.5. Network security defense technology

Network security defense technology in automated operation technologies for power transmission, distribution, and utilization engineering can effectively ensure the stable operation of the power system. This technology employs network diode technology in the physical isolation segment to achieve unidirectional data transmission between the power monitoring system and enterprise management information systems, meeting real-time requirements while avoiding reverse penetration risks. In wireless public network communication scenarios, this technology primarily uses APN+VPN virtual private network technology to achieve logical isolation of data channels, allowing only terminals with security authentication to perform switch operations, effectively resisting security risks such as network attacks and data breaches, and providing comprehensive protection for the stable operation of automated systems in power transmission and distribution. To better respond to the disruptive threats posed by future quantum computing to existing public key systems, the field of power transmission and distribution automation has begun exploring hybrid deployment experiments of power-specific key supply channels based on quantum key distribution and post-quantum cryptography. Network security defense technology has evolved from passive patch-based protection to an intelligent immune system deeply coupled with power physical processes, ensuring that the power system can maintain resilient operation even under sustained high-intensity cyberattacks.

4. Strategies for efficient and automated operation of power transmission, distribution, and consumption engineering

4.1. Building an intelligent perception system

To achieve efficient and automated operation of power transmission, distribution, and consumption engineering, an intelligent perception system should be established. This involves strengthening the diversified layout and deep integration of sensing devices, widely deploying high-precision and highly reliable sensors at key nodes of transmission and distribution lines to achieve comprehensive data collection on equipment operation status and environmental parameters. Furthermore, based on the electricity consumption characteristics and demands of different users in consumption engineering, intelligent meters, electricity consumption monitoring terminals, and other devices should be reasonably configured on the user side to accurately capture key information such as changes in electricity load and fluctuations in power quality, laying a solid data foundation for the intelligent perception system. The construction of the intelligent perception system should also be matched with data models and algorithm libraries to continuously optimize data analysis accuracy and efficiency, providing precise bases for automated operation decisions in the later stages and enhancing the intelligence level of the entire power transmission, distribution, and consumption engineering. Additionally, power transmission, distribution, and consumption engineering should integrate satellite remote sensing, unmanned aerial vehicle inspection images, and data from micro meteorological stations to construct an extended layer for environmental perception of power transmission and distribution channels, establish a unified data perception platform for the entire network, and deploy distributed stream processing engines for online fusion of real-time measurements, historical statistics, and simulation data. To ensure the engineering feasibility of the perception system, strategies should strengthen the application of self-powering technologies, develop plug-and-play protocols and remote firmware upgrade mechanisms for perception terminals at the operation and maintenance level, and truly provide a data foundation for the efficient and low-carbon operation of new power systems.

4.2. Implementing full lifecycle equipment management

To achieve efficient and automated operation of power transmission, distribution, and consumption engineering, full lifecycle equipment management should be thoroughly implemented, constructing a comprehensive management system covering equipment planning, procurement, and maintenance from a holistic perspective [3]. During the planning stage, reasonable equipment selection criteria should be formulated based on grid load forecasting and regional electricity consumption characteristics, prioritizing the selection of technologically advanced intelligent equipment to provide a data benchmark for subsequent full lifecycle management. During the operation and maintenance stage, an intelligent operation and maintenance model combining condition monitoring and predictive maintenance should be constructed, with online monitoring devices deployed to collect key parameters such as equipment temperature and partial discharge in real-time. Full lifecycle equipment management should also involve building a digital platform to ensure the effective implementation of management strategies throughout the equipment's lifecycle. Additionally, power transmission, distribution, and consumption engineering should leverage the remote control capabilities of automated systems to map some diagnostic conclusions back to operation control strategies, and build a unified data platform covering the entire equipment lifecycle to effectively extend the equipment's trouble-free operation time.

4.3. Strengthening the construction of a composite talent team

The efficient operation of power transmission, distribution, and consumption engineering automation requires a matching composite talent team. This process involves constructing a talent cultivation system with deep integration of "industry-university-research-application," relying on advantageous disciplines such as electrical engineering and automation control in universities, and formulating talent cultivation plans through university-enterprise collaboration. This integrates cutting-edge theoretical courses such as power transmission and distribution system modeling and smart grid scheduling with practical projects in substation automation operation and maintenance, and introduces virtual simulation technology to build a digital training platform to exercise talents' practical skills in automation system operation and maintenance and data analysis. The construction of a composite talent team should establish an internal talent mobility mechanism, encouraging technical personnel to participate in cross-departmental work throughout the entire process of power transmission and distribution planning and electricity service design, incorporating indicators such as automation system operation efficiency and energy conservation and consumption reduction in consumption engineering into the assessment scope, and encouraging talents to obtain professional qualifications such as registered electrical engineers and power demand-side managers to ensure that the talent team can master the core technologies of power transmission and distribution automation. Additionally, strengthening the cultivation of safety culture and psychological resilience is equally important. The construction of a composite talent team must cultivate talents who can independently tackle challenges and collaborate innovatively, enabling power transmission, distribution, and consumption engineering to leap from automation to intelligence.

4.4. Optimizing the dynamic regulation mechanism for power loss

During the efficient and automated operation of power transmission, distribution, and consumption engineering, optimizing the dynamic regulation mechanism for power loss involves constructing a multi-dimensional collaborative intelligent strategy framework [4]. This process can leverage the IoT and big data technologies to build a global perception network, combined with artificial intelligence algorithms to construct a dynamic loss prediction model, accurately identifying high-loss areas through deep learning of historical operation data and real-time monitoring information to provide data support for the formulation of regulation strategies. Automated operation of power transmission, distribution, and consumption engineering should also utilize technologies such as infrared thermal imaging and ultrasonic partial discharge detection for online diagnosis of core equipment, promptly identifying hidden dangers such as insulation aging and poor contact to avoid unplanned outages and additional losses caused by equipment failures. Additionally, blockchain technology can be combined to build a transparent energy trading platform, encouraging users to participate in virtual power plant aggregation and regulation, achieving a transition from passive monitoring to active regulation of the power transmission and distribution system, and ultimately constructing a dynamic regulation system for power loss covering the entire lifecycle. Furthermore, distribution companies should establish a cloud-edge collaborative digital twin, deploy offline-trained strategy models to edge gateways through containerization, introduce blockchain technology to record the loss responsibilities and regulatory contributions of each node, and incentivize diverse entities to actively participate in loss optimization, forming a closed-loop ecological regulation system.

4.5. Improving the safety protection system

The automated operation of power transmission, distribution, and consumption engineering should establish a comprehensive safety protection system. Distribution companies should construct a comprehensive and multi-layered physical safety protection architecture to enhance the mechanical strength and natural disaster resistance of lines. On this basis, cybersecurity protection should be strengthened by deploying advanced firewalls, intrusion detection systems, and other cybersecurity protection measures to ensure real-time encrypted transmission and storage of system data. Distribution companies should provide complete and qualified personal safety protection equipment for staff and formulate detailed emergency plans to enable staff to respond quickly in the face of sudden safety accidents and reduce accident losses [5]. Distribution companies should formulate scientific and reasonable equipment replacement plans, establish and improve safety management systems covering all aspects of the automated operation of power transmission, distribution, and consumption engineering, and regulate personnel behavior through systems to ensure that the automated operation of power transmission, distribution, and consumption engineering always operates on a safe track. Additionally, the automation of power transmission, distribution, and consumption engineering should actively promote secure access zones under wireless private networks or 5G virtual private networks, focus on investigating high-risk vulnerabilities such as weak passwords in IEC 104 protocols and unauthorized access to PLCs, and improve the operational efficiency of power transmission, distribution, and consumption engineering automation through a strategy combining boundary protection and ontology controllability.

5. Conclusion

In summary, automation technology in power transmission, distribution, and consumption engineering provides a key driving force for the high-quality development of the power industry, reshaping the operation mode of the power system with its precision and efficiency. In the future, automation technology in power transmission, distribution, and consumption engineering should closely follow trends, deeply promote technological innovation and practical application, construct an efficient and secure intelligent power network, provide a basic guarantee for the high-quality development of the power industry, and enable electricity to play its maximum advantage in serving society.

Disclosure statement

The authors declare no conflict of interest.

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