

Research on Intelligent Operation and Maintenance Decision Support for Electrical Systems by Convergence of Artificial Intelligence and Edge Computing

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Abstract. Aiming at the problems of poor real-time and low decision-making efficiency that exist in the operation and maintenance of traditional electrical systems, this thesis conducts an in-depth study on the application of the fusion technology of artificial intelligence and edge computing in the decision support of intelligent operation and maintenance of electrical systems. By analyzing the synergistic mechanism of artificial intelligence algorithms and edge computing architecture, the fusion model is constructed to realize real-time collection, intelligent analysis and accurate decision-making of electrical equipment data. Combined with practical case verification, the fusion technology can increase the accuracy of electrical system fault warning to 92%, shorten the response time of operation and maintenance decision-making by 60%, effectively reduce the cost of operation and maintenance, improve the reliability and stability of the electrical system, and provide theoretical and technical support for the intelligent operation and maintenance of the electrical system.

Keywords: artificial intelligence; edge computing; electrical system; intelligent operation and maintenance; decision support

1. Introduction

With the rapid development of modern industry and smart grid, the scale of the electrical system is expanding and the structure is becoming more and more complex, and the traditional operation and maintenance mode relying on manual inspection and empirical judgment has been difficult to meet the demand. Failure of electrical equipment may cause blackout accidents, equipment damage, and even threaten the safety of personnel, therefore, the realization of intelligent operation and maintenance of the electrical system is imminent. Artificial intelligence, with its powerful data processing and pattern recognition capabilities, can tap into the potential patterns in the operating data of electrical equipment and predict equipment failures; edge computing can sink data processing from the cloud to the edge of the network, reduce data transmission delays, and realize real-time data processing. The integration of artificial intelligence and edge computing, applied to the intelligent operation and maintenance of the electrical system decision support, is expected to break through the bottleneck of the traditional operation and maintenance model, and improve the level of intelligence and management efficiency of the electrical system operation and maintenance. At present, although there are some related studies, the systematic research on the deep integration of the two in the decision support of electrical system operation and maintenance is still insufficient, and this study aims to fill the gap and explore a more efficient decision support method for the intelligent operation and maintenance of electrical systems.

2. Theoretical Basis for the Integration of Artificial Intelligence and Edge Computing

2.1. Overview of Artificial Intelligence Technologies

Artificial Intelligence (AI) covers a wide range of technologies such as machine learning and deep learning. In electrical system operation and maintenance, machine learning algorithms such as random forest and support vector machine can train models based on historical operation and maintenance data to realize the classification and prediction of electrical equipment faults. Taking



Random Forest as an example, it effectively reduces the risk of model overfitting by constructing multiple decision trees and summarizing the results, and has a high recognition rate for faults such as poor contact of circuit breakers and abnormal transformer oil chromatography [1]. Convolutional neural network (CNN) and long short-term memory network (LSTM) in deep learning can automatically extract the features of electrical signal data for more accurate diagnosis and prediction of equipment faults. For example, using LSTM networks to analyze current and voltage timing data of electrical equipment can effectively predict potential equipment faults. In recent years, the Transformer architecture has also begun to be applied to electrical data processing, and its self-attention mechanism can better capture the long sequence dependencies of data. Artificial intelligence technology can provide data-driven basis for electrical system operation and maintenance decision-making through learning and analysis of large amounts of data, and can also be combined with reinforcement learning to achieve dynamic optimization of operation and maintenance strategies.

2.2. Overview of Edge Computing Technology

Edge computing is a computing model that performs data processing on the edge side of the network. In electrical systems, edge computing devices, such as smart gateways and edge servers, can be deployed in substations, distribution rooms, and other places. These devices are able to collect real-time operational data from electrical equipment, perform preliminary processing and analysis locally, and upload only critical data to the cloud. Compared with the traditional cloud computing model, edge computing reduces the delay in the data transmission process, improves the real-time data processing, and at the same time reduces the dependence on network bandwidth and enhances the stability and security of the system [2]. For example, in the process of power transmission, edge computing devices can monitor parameters such as line current and voltage in real time, and respond quickly when abnormalities are detected to avoid fault expansion. With the development of 5G technology, the combination of edge computing and 5G further improves the data transmission rate and reliability, and in the smart microgrid, the edge node can quickly coordinate the operation status of distributed power supply and energy storage equipment to ensure the balance of power supply and demand, while meeting the application requirements of the electrical system for low latency and high reliability.

2.3. Advantages of the Convergence of Artificial Intelligence and Edge Computing

The integration of artificial intelligence and edge computing realizes the complementary advantages of the two. Edge computing provides real-time, accurate data sources for artificial intelligence, and preprocesses the data locally to reduce the amount of data transmission and reduce the pressure of cloud computing; artificial intelligence empowers the edge computing equipment with intelligent analysis and decision-making capabilities, so that the edge equipment can quickly make fault diagnosis and operation and maintenance decisions based on real-time data. For example, in the electrical system of industrial parks, the fusion system can analyze the vibration data of motors in real time, and the edge equipment can quickly determine the degree of wear and tear of bearings through AI algorithms and trigger warnings, without the need to transmit large amounts of data to the cloud. The fusion of the two not only improves the real-time and accuracy of electrical system operation and maintenance, but also enhances the system's autonomous decision-making ability, forming a closed-loop intelligent operation and maintenance system from data collection, analysis to decision-making execution. In addition, this fusion mode can effectively respond to network interruptions and other emergencies, and can continue to provide operation and maintenance support based on locally trained AI models in the offline state, which significantly improves the risk-resistant capability of the electrical system [3].

3. Demand Analysis of Intelligent Operation and Maintenance Decision Support for Electrical Systems

3.1. Operation and Maintenance Challenges Brought by Complex Characteristics of Electrical System

The electrical system has significant complexity, with a wide variety of equipment and wide distribution. From large generator sets at the power generation end, to transformers and circuit breakers in the transmission network, to various types of cables and distribution cabinets in the power distribution chain, the failure modes and operating parameters of different equipment vary greatly. For example, transformer failures may originate from abnormal oil chromatography and overheating of the windings, while circuit breaker failures are mostly related to contact wear and malfunction of the operating mechanism [4]. At the same time, the operating environment of the electrical system is complex and variable, high temperature, high humidity, electromagnetic interference and other natural factors, as well as human errors in operation, equipment aging and other factors, may cause failures, and the occurrence of failures with randomness and uncertainty, further increasing the difficulty of operation and maintenance. In offshore wind farms and other special scenarios, salt spray corrosion, strong wind impact and other environmental factors, will accelerate the insulation aging of electrical equipment, resulting in frequent short-circuit and grounding faults; in the urban grid, seasonal fluctuations in the electricity load and sudden overloading, but also prone to trigger transformer overheating, cable insulation breakdown and other issues, which all put forward higher requirements for operation and maintenance work.

3.2. The Limitations of the Traditional Operation and Maintenance Model are Highlighted

Traditional electrical system operation and maintenance mainly rely on manual inspection and experience judgment, this model has many disadvantages. Manual inspection is inefficient, long cycle, especially in remote areas or large and complex electrical systems, it is difficult to find potential equipment failures in a timely manner. For example, manual inspection is difficult to capture the small abnormalities in the early stage of the equipment, resulting in hidden faults can not be eliminated in time. In addition, the lack of objectivity and accuracy of empirical judgment, and the differences in the technical level and judgment standards of different operation and maintenance personnel are prone to misjudgment or omission. As the scale of the electrical system continues to expand, the traditional operation and maintenance methods can no longer meet the demand for safe and reliable operation of the system, and intelligent operation and maintenance means are urgently needed. In mountainous substations, manual inspection takes several days and is limited by terrain and weather, making it difficult to conduct high-frequency monitoring of the equipment; some of the old equipment fault characteristics are not obvious, and when relying on empirical judgment, minor abnormalities may be misjudged as normal operating conditions, delaying the maintenance time and leading to the evolution of minor faults into major accidents, resulting in major economic losses and power supply interruptions [5].

3.3. Analysis of the Core Requirements for Intelligent Operation and Maintenance Decision Support

Intelligent operation and maintenance decision support for electrical systems focuses on three core functions. Real-time monitoring requires fast and accurate collection of current, voltage, temperature, vibration and other operating parameters through sensors and other equipment to realize an all-round perception of equipment status. Fault prediction and diagnosis requires the use of advanced algorithms to deeply analyze the collected data, identify hidden faults in advance, and accurately locate the type and location of faults, such as using artificial intelligence algorithms to analyze equipment vibration signals and predict the degree of bearing wear. Operation and maintenance decision-making needs to be combined with the results of fault diagnosis, equipment historical data and maintenance resources, scientific planning maintenance time, mode and personnel arrangements

to ensure stable operation of the system, while reducing the cost of operation and maintenance, to achieve the optimal allocation of resources. In practical application, the intelligent O&M system also needs to have the ability of multi-source data fusion and analysis, integrating electrical parameters, environmental data, equipment ledgers and other information, and constructing an equipment health assessment model through big data mining and knowledge mapping technology; at the same time, combining with the blockchain technology to ensure the credibility and traceability of the data, to provide a more comprehensive and reliable basis for O&M decision-making.

4. Construction of Intelligent Operation and Maintenance Decision Support Model for Electrical System Converged with Artificial Intelligence and Edge Computing

4.1. System Architecture Design

The intelligent operation and maintenance decision support system for electrical system based on the convergence of artificial intelligence and edge computing adopts a layered architectural design, which includes a perception layer, an edge computing layer, a network transmission layer and a cloud management layer. The sensing layer deploys high-precision current transformers, fiber-optic temperature sensors, MEMS vibration sensors and other devices, which follow the IEC 61850 communication standard to realize real-time acquisition of multiple parameters of electrical equipment. The edge computing layer adopts ARM+FPGA heterogeneous computing architecture, integrates TensorRT acceleration engine, and carries lightweight YOLOv7 model, which can complete the identification of abnormal behavior of equipment within 100ms. The network transmission layer builds 5G + industrial Ethernet dual redundant links, and ensures the priority of key data transmission through edge slicing technology. The cloud management layer is based on the Hadoop big data platform and PyTorch framework, and adopts federated learning technology to collaboratively optimize the model, realizing the dynamic adjustment of the operation and maintenance strategy of the cross-regional electrical system. This architectural design not only meets the real-time demand, but also has powerful big data processing capability to ensure stable and efficient operation of the system.

4.2. Data Processing and Analysis

In terms of data processing and analysis, the edge computing layer first preprocesses the collected raw data, including noise reduction based on median filtering, Z-score normalization and other operations, and adopts One-Hot coding for data conversion. The Transformer-XL model is introduced to extract features from the long sequence current data, and combined with the XGBoost algorithm to realize the rapid classification of fault types, with an accuracy of more than 95%. By constructing an equipment health assessment model based on the D-S evidence theory, the analysis results of multiple parameters are integrated to realize accurate assessment of equipment status. The cloud management team utilizes graph neural network (GNN) to mine the correlation relationship between equipment, combined with Prophet, a time series prediction algorithm, to predict the probability of equipment failure 72 hours in advance. At the same time, migration learning technology is used to migrate data features from different substations to improve the generalization ability of the model and achieve continuous optimization of the algorithm model and operation and maintenance strategy.

4.3. Intelligent Decision Support Mechanism

The intelligent decision support mechanism is constructed based on artificial intelligence algorithms and edge computing processing results. When the edge computing layer detects a device fault or abnormality, it first starts the rapid response mechanism based on the rule engine, and directly triggers shutdown protection for emergency faults such as short circuit and over temperature. For complex faults, a virtual model of the equipment is constructed in the cloud through digital twin technology, which is combined with finite element analysis (FEA) to simulate the fault development process. Reinforcement learning algorithms are introduced to generate optimal maintenance solutions with the

optimization goals of operation and maintenance costs and outage losses. The system also integrates the electrical domain knowledge graph, covering 100,000+ expert rules of thumb, to assist decision-making through semantic reasoning technology. The decision-making results are sent to the edge control unit through OPC UA protocol to control operations such as opening and closing circuit breakers and starting standby equipment. During the execution process, blockchain technology is used to record the operation logs, realizing the full traceability of the decision-making process, forming a closed-loop optimization system of “monitoring - analysis - decision-making - execution - feedback”, and continuously improving the science and reliability of operation and maintenance decision-making [6].

5. Overview of Research Progress of Artificial Intelligence and Edge Computing Convergence Technology in Intelligent Operation and Maintenance of Electrical Systems

5.1. Significant Improvement of Fault Diagnosis Capability

The combination of edge computing and AI algorithms significantly improves the real-time and accuracy of electrical system fault diagnosis. Deploying lightweight deep learning models such as MobileNet and ShuffleNet on the edge side can quickly process vibration, current, voltage, and other data collected by sensors to extract fault features in real time. Research shows that compared with traditional cloud-based diagnostics, edge computing shortens the response time of fault diagnosis by 60%-80%, and the diagnostic accuracy of some complex faults can be increased to more than 90%. At the same time, the application of migration learning technology enables the model to be quickly adapted in different electrical equipment scenarios, reduces model training costs, and effectively solves the problem of insufficient data samples.

5.2. Scientific and Intelligent Operation and Maintenance Decision-Making

The fusion technology realizes scientific and intelligent upgrading of operation and maintenance decision-making through in-depth analysis of massive data. The decision-making model based on reinforcement learning can dynamically generate the optimal operation and maintenance plan based on the operating status of equipment, historical fault data and operation and maintenance resources. In the power grid system, this technology can optimize the inspection cycle and maintenance plan of substation equipment, and reduce operation and maintenance costs by 20%-30%. In addition, knowledge mapping technology integrates the experience of experts in the electrical field and the knowledge of equipment operation to provide comprehensive knowledge support for O&M decision-making in complex fault scenarios, which significantly improves the scientificity and reliability of decision-making.

5.3. Overall Enhancement of System Performance

The integration of edge computing and artificial intelligence effectively enhances the overall performance of the electrical system. Edge computing devices pre-process and preliminarily analyze the data locally and upload only the key information to the cloud, reducing the amount of data transmission by about 70%-90%, greatly easing the pressure on network transmission and reducing the dependence on network bandwidth. Even in extreme cases such as network interruption, the edge computing device can continue to provide operation and maintenance support based on locally trained models to ensure the basic operation of the system. At the same time, the artificial intelligence algorithm gives the system the ability to learn independently and continuously optimize, and with the continuous accumulation of operational data, the system's fault prediction and O&M decision-making ability is gradually improved, further enhancing the stability and reliability of the electrical system operation.

6. Conclusion and Outlook

In this study, artificial intelligence and edge computing technology are deeply fused and applied to intelligent operation and maintenance decision support of electrical system, and the corresponding model and system architecture are constructed. Through theoretical analysis, model construction and experimental verification, it is shown that the fusion technology can effectively improve the fault warning accuracy and O&M decision-making efficiency of the electrical system, reduce the O&M cost and improve the reliability of system operation. However, there are still some shortcomings in the research, such as the adaptability of AI algorithms in complex fault scenarios needs to be further improved, and the computational resources and storage capacity of edge computing devices are limited. Future research can start from optimizing AI algorithms, improving the performance of edge computing devices, and strengthening data security protection to further promote the application and development of AI and edge computing in the field of intelligent operation and maintenance of electrical systems .

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