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Application of Internet of Things Technology in Remote Monitoring of Smart Grid Distribution Transformers

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ABSTRACT
This paper focuses on the application and design of Internet of Things technology in remote monitoring of smart grid distribution transformers. It first explains the background and significance of IoT technology, smart grids, and remote monitoring of distribution transformers. It then analyzes key technologies, including sensor technology, wireless communication technology, cloud computing, and big data analysis. The system architecture design is detailed, covering the perception layer, network layer, platform layer, and application layer. The hardware platform construction and software platform development are explained, and practical application results are demonstrated through application cases. Finally, the challenges and future development trends are discussed. The goal is to provide an effective IoT technology application solution for remote monitoring of smart grid distribution transformers.

KEYWORDS
Internet of things (IoT) technology; Smart grid; Distribution transformer; Remote monitoring; Aapplication design

1 Introduction

1.1 Research background and significance

With the continued growth of global energy demand and the transformation of the energy structure, the importance of smart grids, as a core component of the modern energy system, is becoming increasingly prominent. By integrating advanced information technology, communications technology, and automation technology, smart grids enable intelligent, efficient, and reliable operation of power systems. As key equipment in smart grids, distribution transformers undertake the important tasks of voltage conversion and power distribution, and their operating status directly affects the stability and power supply quality of the grid.

Traditional distribution transformer monitoring methods rely primarily on regular manual inspections and local monitoring. These methods suffer from low efficiency, poor real-time performance, and inaccurate data, making them unable to meet the real-time monitoring and refined management requirements of modern smart grids. The rise of IoT technology provides a new approach to addressing these issues. By connecting various devices to the internet, the Internet of Things (IoT) enables real-time data collection, transmission, and analysis. This technology can provide comprehensive, accurate, and real-time information support for remote monitoring of distribution transformers, thereby improving grid efficiency and reliability and reducing operation and maintenance costs. This technology holds significant practical significance.

1.2 Current research status internationally

Many developed countries have pioneered research and application of IoT technology for remote monitoring of distribution transformers in smart grids. Power companies in countries like the United States and Germany have successfully deployed IoT-based distribution transformer monitoring systems, enabling real-time monitoring of transformer operating conditions, fault warnings, and remote control. These systems use sensors installed on the transformers to collect parameters such as temperature, current, and voltage in real time and transmit this data to a monitoring center via wireless communication networks. This allows maintenance personnel to promptly understand the transformer's operating status, proactively identify potential problems, and implement appropriate measures to address them, effectively improving grid reliability and power supply quality.

China has also made some progress in applying IoT technology to remote monitoring of distribution transformers in smart grids. In recent years, with strong national support for smart grid development and the rapid development of IoT technology, several domestic research institutions and enterprises have initiated related research. Some power companies have begun piloting IoT-based distribution transformer monitoring systems, achieving some success. However, compared with other countries, China still lags behind in system integration, in-depth data analysis, and application, requiring further research and improvement.

1.3 Research content and objectives

This paper aims to study the application and design of IoT technology in remote monitoring of distribution transformers in smart grids. Specific research content includes: analyzing key IoT technologies for remote monitoring of distribution transformers; designing the overall system architecture, including the perception layer, network layer, platform layer, and application layer; building the hardware platform and developing the software platform; and verifying the system's effectiveness and feasibility through practical application cases.

The research objective is to achieve real-time and accurate monitoring of the operating status of distribution transformers through the application of IoT technology, improve fault warning capabilities, and implement remote control and intelligent management, thereby providing strong support for the safe and stable operation of smart grids.

2 Key technologies of iot in remote monitoring of distribution transformers

2.1 Sensor technology

Sensors are the core devices in the IoT perception layer, used to collect real-time operating parameters of distribution transformers. In remote monitoring of distribution transformers, commonly used sensors include temperature sensors, current sensors, voltage sensors, and partial discharge sensors. Temperature sensors can monitor transformer winding and oil temperatures in real time to prevent equipment damage due to overheating. Current and voltage sensors can accurately measure the transformer's input and output current and voltage, providing data support for energy metering and grid operation analysis. Partial discharge sensors can detect partial discharge within the transformer, proactively identifying insulation faults.

Sensor performance directly impacts the accuracy and reliability of data acquisition. Therefore, it is important to select sensors with high precision, good stability, and strong anti-interference capabilities, and to perform regular calibration and maintenance to ensure they are always in good working condition.

2.2 Wireless communication technology

Wireless communication technology is key to transmitting sensor data to the monitoring center. Commonly used wireless communication technologies for remote monitoring of distribution transformers include 4G, 5G, LoRa, and NB-IoT. 4G and 5G technologies offer high speeds and large capacity, making them suitable for scenarios requiring real-time data transmission, but they consume relatively high power. LoRa and NB-IoT technologies offer low power consumption and wide coverage, making them suitable for scenarios requiring lower power consumption and wider coverage.

In practical applications, the appropriate wireless communication technology must be selected based on factors such as the distribution of distribution transformers, monitoring requirements, and cost. For example, for densely populated urban areas, 4G or 5G technologies can be used; for remote areas or scenarios with higher power consumption requirements, LoRa or NB-IoT technologies can be used.

2.3 Cloud computing and big data analysis technology

Cloud computing technology provides powerful data storage and processing capabilities for remote monitoring systems of distribution transformers. Through cloud computing platforms, large amounts of collected data can be centrally stored and managed, and the elastic scalability of cloud computing can be leveraged to flexibly adjust computing resources based on actual needs. Big data analysis technology can deeply mine and analyze data stored on cloud computing platforms to extract valuable information.

In remote monitoring of distribution transformers, big data analysis technology can be used for fault prediction, load forecasting, energy efficiency assessment, and other aspects. For example, by analyzing historical and real-time transformer operating data, a fault prediction model can be established to predict potential transformer failures in advance, providing decision support for operations and maintenance personnel. By analyzing load data, the transformer's operating mode can be rationally adjusted to improve the power grid's power supply efficiency.

2.4 Edge computing technology

Edge computing technology is a computing model that places computation and data storage close to the data source. In remote monitoring of distribution transformers, edge computing devices can be deployed near the transformer to process and analyze sensor data in real time. Edge computing technology can reduce data transmission latency, improve system response speed, and reduce the burden on the cloud computing platform.

For example, edge computing devices can monitor the transformer's operating status in real time. When an anomaly is detected, an alarm is immediately issued and the processed data is uploaded to the cloud computing platform for further analysis. This enables rapid response and handling of transformer faults, improving power grid reliability.

3 System architecture design

3.1 Overall architecture

The IoT-based smart grid distribution transformer remote monitoring system adopts a layered architecture, primarily consisting of the perception layer, network layer, platform layer, and application layer, as shown in Figure 1. IoT Technology Architecture for Smart Grid Distribution Transformer Remote Monitoring.

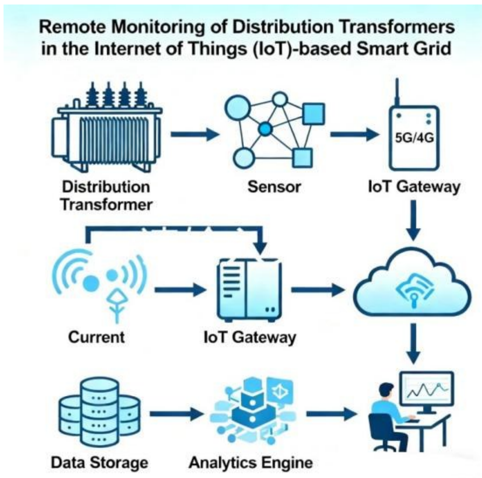

Figure 1 IoT technology architecture for smart grid distribution transformer remote monitoring

The perception layer is the system's data acquisition layer, primarily composed of various sensors. It is responsible for collecting real-time operating parameters of distribution transformers, such as temperature, current, and voltage, and transmitting this data to the network layer.

The network layer is responsible for transmitting data collected by the perception layer, using wireless communication technology to transfer data from the transformer site to the monitoring center. The network layer must select an appropriate communication method based on actual conditions to ensure reliable and real-time data transmission.

The platform layer is the system's data processing and storage center, primarily consisting of a cloud computing platform and a big data analysis platform. The cloud computing platform is responsible for receiving, storing, and managing the data collected by the sensors, while the big data analytics platform conducts in-depth data mining and analysis to extract valuable information.

The application layer is the user interaction layer of the system, providing users with various application services such as real-time monitoring, fault warnings, remote control, and energy efficiency management. Users can access the application layer through web or mobile applications to remotely monitor and manage distribution transformers.

3.2 Perception layer design

The key to the perception layer design lies in sensor selection and layout. Select the appropriate sensor type and specifications based on the monitoring requirements of the distribution transformer. For example, for temperature monitoring, you can choose a high-precision platinum resistance temperature sensor; for current and voltage monitoring, you can choose a current transformer and voltage transformer with high accuracy and good linearity.

Regarding sensor layout, it is necessary to consider the structure and operating characteristics of the transformer and arrange the sensors in a reasonable position to ensure comprehensive and accurate collection of transformer operating parameters. For example, temperature sensors should be installed in key locations such as the transformer windings and core; current and voltage sensors should be installed at the transformer's incoming and outgoing terminals.

3.3 Network layer design

The network layer design requires selecting the appropriate wireless communication technology based on actual conditions. In urban areas, due to the dense distribution of base stations and good signal coverage, 4G or 5G technologies can be selected for data transmission; in remote areas, due to insufficient base station coverage, LoRa or NB-IoT technologies can be selected for data transmission.

Regarding network topology, star, tree, or mesh topologies can be adopted. A star topology is simple and easy to manage and maintain, but requires high reliability for the central node. A tree topology can expand network coverage, but it also incurs significant data transmission latency. A mesh topology offers high reliability and flexibility, but also high network complexity and cost.

3.4 Platform layer design

The platform layer design primarily includes the construction of a cloud computing platform and a big data analytics platform. The cloud computing platform can adopt a public, private, or hybrid cloud approach. Public clouds offer the advantages of low cost and good scalability, but relatively low data security. Private clouds offer the advantages of high data security and strong controllability, but are more expensive. Hybrid clouds combine the advantages of public and private clouds, allowing for flexible resource allocation based on actual needs.

The big data analytics platform requires the establishment of a data warehouse and data mining models to clean, transform, and mine collected data. Through data analysis, functions such as real-time evaluation of distribution transformer operating status, fault prediction, and energy efficiency management can be achieved.

3.5 Application layer design

The application layer design should provide users with an intuitive and easy-to-use interface. Web applications can adopt a BS architecture, allowing users to access the system through a browser without installing client software. Mobile applications can be developed on Android or iOS platforms, allowing users to monitor the operating status of distribution transformers anytime, anywhere.

The application layer's functions primarily include real-time monitoring, fault warning, remote control, and energy efficiency management. The real-time monitoring function displays the operating parameters and status of the distribution transformer in real time; the fault warning function issues fault alarms in advance based on data analysis results; the remote control function enables remote operation of the distribution transformer, such as opening and closing the circuit breaker and adjusting operating parameters; and the energy efficiency management function analyzes and optimizes the transformer's energy consumption to improve energy efficiency.

4 Hardware platform construction

4.1 Sensor selection and installation

Select appropriate sensors based on the monitoring requirements of the distribution transformer. For temperature sensors, choose high-precision, fast-response platinum resistance temperature sensors and install them at the transformer's windings and oil temperature monitoring points. For current and voltage sensors, choose products with high precision and good linearity and install them at the transformer's incoming and outgoing terminals. For partial discharge sensors, choose products with high sensitivity and strong anti-interference capabilities and install them inside the transformer.

Sensor installation must strictly follow installation specifications to ensure accurate and secure positioning of the sensors to avoid inaccurate data collection due to improper installation. Sensors must also be regularly calibrated and maintained to ensure stable performance.

4.2 Data acquisition terminal design

The data acquisition terminal is a key device connecting sensors to the network layer, collecting, processing, and transmitting sensor data. It must possess high-speed data acquisition, data processing, and wireless communication capabilities.

The hardware design of the data acquisition terminal primarily includes a microprocessor, data acquisition module, and communication module. A high-performance, low-power microprocessor is responsible for data processing and control. The data acquisition module is responsible for collecting sensor data and performing analog-to-digital conversion. The communication module is responsible for transmitting the processed data to the network layer via wireless communication technology.

The software design of the data acquisition terminal primarily includes the data acquisition program, data processing program, and communication program. The data acquisition program controls the data acquisition module to collect sensor data. The data processing program is responsible for filtering and calibrating the collected data. The communication program is responsible for transmitting the processed data to the network layer via the communication module.

4.3 Communication network construction

Build a suitable communication network based on the network layer design requirements. For systems using 4G or 5G communication technology, it is necessary to work with the operator to apply for the appropriate SIM card and network service, and configure the communication parameters of the data acquisition terminal. For systems using LoRa or NB-IoT communication technology, it is necessary to build the corresponding base stations and networks, and configure the communication parameters between the data collection terminals and the base stations.

When establishing a communication network, factors such as network coverage, signal strength, and data transmission rate must be considered to ensure stable and reliable data transmission. Furthermore, regular monitoring and maintenance of the communication network is required to promptly detect and resolve network failures.

5 Software platform development

5.1 Platform architecture design

The software platform adopts a distributed microservices architecture to improve system scalability and maintainability. Key components include data acquisition services, data processing services, storage services, alarm services, and user interface services.

The data acquisition service is responsible for receiving sensor data from data acquisition terminals and performing preliminary processing; the data processing service utilizes big data analytics algorithms to conduct in-depth data mining and analysis; the storage service utilizes distributed database technology for efficient data storage and management; the alarm service issues timely fault warnings based on data analysis results; and the user interface service provides users with an intuitive and easy-to-use interface.

Services communicate with each other via message queues, ensuring real-time data transmission and processing. The message queues utilize highly reliable middleware, such as Kafka or RabbitMQ, to ensure data loss and duplication.

5.2 Data acquisition and processing module development

The data acquisition and processing module is responsible for receiving data from data acquisition terminals and performing data cleansing, conversion, and storage. This module utilizes multi-threading technology to achieve parallel data acquisition and processing, improving system processing efficiency.

For data cleansing, rule engine technology is used to analyze and correct data according to specific rules, removing abnormal and erroneous data. In terms of data conversion, the collected raw data is converted into a unified format to facilitate subsequent analysis and processing. In terms of data storage, a distributed file system and database are combined to achieve efficient data storage and querying.

5.3 Data analysis and early warning module development

The data analysis and early warning module utilizes big data analysis algorithms and machine learning techniques to conduct in-depth mining and analysis of collected data, enabling assessment of the operating status of distribution transformers and fault early warning.

In terms of data analysis, algorithms such as cluster analysis and association rule mining are used to discover underlying patterns and regularities in the data. In terms of fault early warning, algorithms such as time series analysis and neural networks are used to establish a fault prediction model, predicting potential transformer faults based on historical and real-time data.

When the system detects an abnormal situation or predicts a possible failure, it will issue a warning message in a timely manner and notify the operation and maintenance personnel via SMS, email, APP push, etc.

5.4 user interface development

The user interface combines web and mobile platforms, providing users with a convenient operation and monitoring interface. The web interface adopts a responsive design, adapting to screens of different sizes. Users can access the system through a browser and view the real-time operating status, historical data, alarm information, and more of the distribution transformer.

The mobile application utilizes native development technology to provide a smoother and more convenient user experience. Users can monitor the operating status of distribution transformers, receive early warning information, and perform remote control operations anytime, anywhere via their mobile phones or tablets.

6 Application analysis

6.1 Case study

A city faced problems such as aging power grid equipment, insufficient power supply reliability, and high operation and maintenance costs, urgently needing to improve grid management through intelligent means. To address these issues, the city decided to use IoT technology to build a remote monitoring system for distribution transformers. This system enables real-time monitoring, fault warnings, remote control, and energy efficiency optimization for distribution transformers citywide. The project covers the city center, industrial parks, and remote mountainous areas, involving over 2, 000 distribution transformers, 30% of which are located in remote areas with complex communication conditions.

6.2 System implementation plan

The system adopts a layered architecture design. The specific implementation plan is as follows:

Perception Layer: Diverse sensors are deployed for different scenarios. Transformers in central urban areas are equipped with high-precision temperature sensors (accuracy ±0.5°C), three-phase current and voltage sensors (accuracy 0.2), and partial discharge monitoring modules; transformers in remote mountainous areas are additionally equipped with vibration sensors (frequency response 0.1-10kHz) and ambient temperature and humidity sensors. All sensors support the Modbus RTU TCP protocol, with a sampling frequency set to 1 second, and a local data cache capacity of ⩾24 hours.

Network Layer: A hybrid communication solution is adopted. Urban areas utilize 4G networks for low-latency transmission (end-to-end latency <500ms), while remote mountainous areas utilize LoRaWAN technology (transmission distance >3km). Both are connected to a unified IoT platform via the MQTT protocol. To ensure data security, the communication link utilizes AES-256 encryption, and a VPN tunnel is deployed.

Platform Layer: A data processing center is built on the Alibaba Cloud IoT platform, utilizing the Flink real-time stream processing engine to process 100,000 data points per second. A fault prediction model is constructed using Spark MLlib, integrating historical SCADA system data (including five years of operation records) for model training, achieving a prediction accuracy of 92%. The platform provides a visual cockpit that supports device status mapping, parameter trend analysis, and alarm event tracing.

Application Layer: A web-based management platform and mobile app are developed, integrating functions such as device inventory management, work order dispatching, and energy efficiency analysis. Operations and maintenance personnel can receive real-time alarms (push response time <3 seconds) and perform remote closing and opening operations (control command execution latency <1 second) through the app. The system also provides energy efficiency diagnosis reports and automatically generates optimization suggestions (such as reactive power compensation adjustment plans).

6.3 Implementation results

After six months of operation, the system achieved significant results:

(1) Improved Reliability: Through real-time monitoring, 47 equipment overheating risks and 23 insulation degradation warnings were detected, resulting in a 38% year-over-year decrease in the failure rate. During the 2024 summer peak electricity demand period, three potential regional power outages were successfully avoided.

(2) Optimized Operation and Maintenance Efficiency: The remote control function shortened the average operation and maintenance response time from 2.3 hours to 0.8 hours, reducing the frequency of equipment inspections in remote areas by 60%, and saving approximately 4.2 million yuan in annual operation and maintenance costs.

(3) Effective Energy Efficiency Management: Through optimized reactive power compensation, the system's average power factor increased from 0.82 to 0.95, line losses decreased by 1.2 percentage points, and annual electricity bill savings reached 1.8 million yuan. Transformer load balance improved by 25%, extending equipment life by 15%.

(4). Decision Support Capabilities: The platform's accumulated 210 million operational data points provide a basis for power grid planning, identifying five heavily loaded lines and three areas of concentrated equipment aging, and guiding the completion of a 220kV substation capacity expansion and renovation.

7 Challenges and future development trends

7.1 Challenges

Although IoT technology holds broad application prospects in remote monitoring of smart grid distribution transformers, it also faces certain challenges. For example, data security issues arise. With the increasing number of devices connected to the IoT, security risks in data transmission and storage increase, necessitating effective encryption and access control measures to ensure data security. There are also issues with inconsistent standards. Devices and sensors produced by different manufacturers may use different communication protocols and data formats, leading to difficulties in system integration and interoperability. Furthermore, the application of IoT technology requires significant investment in hardware, communication, and software development costs, which may pose a financial burden for some economically underdeveloped regions.

7.2 Future development trends

In the future, IoT technology will develop towards greater intelligence, integration, and security in remote monitoring of distribution transformers in smart grids. On the one hand, with the continuous development of technologies such as artificial intelligence and big data, systems will have stronger data analysis and decision-making capabilities, enabling more accurate fault prediction and energy efficiency management. On the other hand, the IoT will be more efficient, energy-efficient, and easy to install and maintain. Meanwhile, communication technologies will continue to upgrade, improving data speed and reliability. Furthermore, with the development of blockchain technology, its application in data security will gradually increase, providing more reliable protection for the data security of remote monitoring systems for distribution transformers.

8 Conclusion

This paper studies the application design of Internet of Things technology in remote monitoring of smart grid distribution transformers. Through the analysis of key technologies, the design of system architecture, the construction of hardware platform and the development of software platform, the functions of real-time monitoring, fault warning, remote control and energy efficiency management of distribution transformers are realized. Actual application cases show that the system can significantly improve the reliability and operation efficiency of the power grid and reduce operation and maintenance costs. However, the Internet of Things technology also faces some challenges in the application process, which need further research and solutions. In the future, with the continuous development of technology, the application of Internet of Things technology in remote monitoring of smart grid distribution transformers will be more extensive and in-depth, providing strong support for the construction and development of smart grids.

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Yanbin Hou, Bachelor's Degree; Research Interests are embedded development and applications.

References

[1] Lu Lining, Zhu Weiguang. Application of power Internet of Things technology in online monitoring of power equipment [J]. Information Technology, 2021(07):17-19.

[2] Cui Xiangjun. Internet of Things technology helps the construction of smart grid [J]. Shandong Industrial Technology, 2015(13):99-102.

[3] Xu Guanglu. Application of Internet of Things technology in smart grid [J]. Science and Technology Innovation and Application, 2022(05):4-8.

[4] Ou Xingliang, Dai Yongchun. Application of Internet of Things Technology in Emergency Material Allocation of Power System[J]. Electronic Technology and Software Engineering, 2020(12):65-68.

[5] Shi Zhongqiang, Zheng Yunpeng, Zhang Qiang, Wang Qianqian. Internet of Things technology helps the construction of smart grid [J]. Shandong Industrial Technology, 2017(13):32-34.

[6] Liu Haimei. Research and analysis of the application of Internet of Things technology in smart grid [J]. Science and Technology Innovation and Application, 2016(30):4-6.

[7] Yin Cheng, Xia Yunfeng, Yang Wu. Application of information Internet of Things in online monitoring of power transmission and transformation equipment [J]. Shandong Industrial Technology, 2015(06):23-24.

[8] Liu Fujun. Application of Internet of Things technology in smart grid [J]. Technology and Market, 2015(11):11-12.

[9] Chai Yukun. Application of Internet of Things technology in smart grid [J]. China Electric Power (Technology Edition), 2014(02):72-74.

[10] Ren Yi. Internet of Things technology and its application in smart grid construction [J]. Communication World, 2014(13):88-89.