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Industrial Internet Platform Architecture Design and Implementation in Thermal Power Plant

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Abstract: As the global energy system transitions toward cleaner and low-carbon solutions, the thermal power industry faces dual challenges of improving efficiency and environmental protection. Industrial Internet technology, through integrating IoT, big data, and AI, provides crucial support for optimizing production processes, enabling intelligent equipment maintenance, and enhancing energy efficiency in thermal power plants. This paper focuses on the architecture design of industrial Internet platforms for thermal power plants, proposing a three-tier architecture model comprising edge layer, platform layer, and application layer. The edge layer integrates IoT protocol adaptation with edge computing technology to standardize access for multi-source heterogeneous devices and perform real-time data preprocessing, effectively addressing issues such as fragmented protocols and high latency in traditional thermal power plant equipment. The platform layer constructs a data middle platform and business middle platform using containerized microservices architecture, combining cloud computing and big data technologies to form a highly concurrent and available industrial PaaS platform that supports massive data storage, analysis, and service-oriented encapsulation. The application layer develops core modules including equipment health management, combustion optimization, and energy consumption analysis through digital twin technology and AI algorithms, establishing an intelligent decision support system that covers the entire production process.

Keywords: Thermal power plant; Industrial Internet platform; Hierarchical architecture; Edge computing

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1. Introduction

With the transformation of energy structure and the increasing requirements of environmental protection, the thermal power industry is facing unprecedented challenges and opportunities. As a product of the deep integration of the new generation of information technology and industrial system, industrial Internet technology provides a key support for the intelligent upgrading of thermal power plants. At present, the global energy system is accelerating to the direction of clean and low-carbon, thermal power plants need to achieve multiple goals, such as production efficiency improvement, operating cost reduction and carbon emission intensity control through digital transformation. In this context, the construction of industrial Internet platform for thermal power plants has become an important way to promote the high-quality development of the industry.

As a core component of energy supply, thermal power plants face challenges in traditional operations, including inefficient equipment maintenance, severe information silos, and suboptimal energy utilization. By integrating key technologies such as IoT, big data, and AI, industrial internet platforms enable digital modeling and intelligent management of the entire production process in thermal power plants [1]. For example, the coal transport control system based on the industrial Internet can monitor the status of the transport equipment in real time and optimize the dispatching strategy, significantly reducing the material loss and operation and maintenance cost; while the application of self-service repair technology can effectively improve the equipment maintenance response speed through intelligent fault diagnosis and resource coordination dispatching. In addition, predictive maintenance technology relies on the data collection and analysis capabilities of the industrial Internet platform to identify potential failure risks of key equipment such as pump system in advance, so as to avoid economic losses and safety risks caused by unplanned shutdown.

2. Design of industrial Internet platform architecture for thermal power plants

2.1. Data architecture design

The data architecture design of thermal power industrial Internet platform takes data life cycle management as the core, and realizes the in-depth mining of data value through multi-level technology integration. At the level of data acquisition, a perception network covering the whole plant is built by relying on the IoT technology, and equipment such as radio frequency identification, infrared sensor and laser scanning is used to obtain multi-dimensional data such as fuel unloading, equipment running status and smoke emission in real time. For example, in the fuel management process, the measurement and laboratory data of coal entering the plant are synchronized to the cloud platform through the self-service unloading system and automatic acceptance device, so as to ensure the efficiency and accuracy of the collection process. At the same time, the introduction of the new type of thermal polarization solid-state spin sensor, through the non-optical state preparation technology and microwave cavity readout architecture, significantly improves the sensitivity and environmental adaptability of key parameters such as flue gas composition detection, and solves the technical bottleneck of traditional optical methods limited by thermal load and optical power.

The data storage system adopts a distributed cloud platform architecture, combining relational database and non-relational storage solutions to realize the hybrid management of structured and unstructured data. To meet the real-time requirements of flue gas monitoring data in thermal power plants, a centralized storage system based on cloud platform is constructed, which ensures high concurrent writing and fast retrieval of massive data through dynamic load balancing strategy [2]. In fuel management, the system stores workflow data, equipment operation logs, and time series database, providing a reliable data foundation for long-term trend analysis.environmental parameters in a classified manner, and optimizes the efficiency of historical data query by combining

2.2. Application architecture design

The application architecture design of thermal power industrial Internet platform follows the principle of hierarchical decoupling, and builds a three-layer functional system covering data collection, business processing and intelligent decision-making. At the data acquisition layer, the IoT technology is used to realize the comprehensive perception of equipment operation parameters, environmental monitoring data and production process information. This layer employs an LPWAN-based IoT architecture for energy and power systems, enabling massive device connectivity and low-power data transmission. It effectively integrates sensors and actuators from critical equipment such as boilers, steam turbines, and desulfurization systems, forming a real-time data collection network that covers the entire production process. The system standardizes and analyzes multi-source heterogeneous data through standardized interface protocols with edge computing nodes [3].

The business processing layer is the core of the application architecture, including four core modules: production monitoring, equipment health management, energy efficiency optimization and environmental monitoring. The production monitoring module, built on a B/S architecture, integrates the functional design of the boiler safety decision support system. It displays real-time unit operation status and key parameter trends via the web interface, enabling rapid identification and early warning response to abnormal conditions. The equipment health management module integrates vibration analysis, temperature monitoring and life prediction algorithm, and establishes a multi-dimensional equipment health assessment model based on equipment operation data and historical maintenance records to provide data support for preventive maintenance. The energy efficiency optimization module adopts the operation efficiency analysis technology, collects the operation data of the operators and calculates the efficiency index to generate the operation suggestion information to improve the economy of the unit. Its technical route is highly coordinated with the correction set point optimization method. The environmental monitoring module focuses on the flue gas desulfurization system, integrating the desulfurization process parameters and emission monitoring data, and realizing the dynamic evaluation of the operating state of environmental protection equipment and the optimization of process parameters by comparing the performance indicators of different desulfurization technologies.

3. Key technologies implemented by the platform

3.1. Data acquisition and transmission technology

Data acquisition, as the basic link of industrial Internet platform, aims to realize the efficient, real-time and reliable acquisition of multi-source and heterogeneous equipment data in thermal power plants. To meet the needs of different scenarios, the platform adopts a hierarchical and collaborative collection architecture: The bottom layer monitors the temperature, pressure, vibration and flue gas composition of key equipment such as boiler, steam turbine and generator in real time by deploying intelligent sensor network. The sampling frequency is dynamically adjusted according to the characteristics of the equipment, such as vibration monitoring can reach 1000 times per second sampling.

The middle layer integrates the SCADA system with the DCS control system, enabling unified access to historical data archiving and real-time data streams through the OPC interface. The edge layer deploys lightweight edge computing nodes to perform data preprocessing, protocol conversion, and local storage functions, effectively reducing the transmission bandwidth pressure. The multi-level architecture ensures comprehensive data collection and improves system response speed by reducing cloud data redundancy through edge computing [4,5].

At the data transmission level, the platform builds a multi-protocol support system based on the compatibility requirements of industrial communication protocols. The physical layer combines fiber Ethernet and wireless Mesh networks to balance high bandwidth and redundancy. The transport layer selects appropriate protocols based on device types: Traditional control devices utilize Modbus TCP for stable communication, while smart meters employ PROFINET for real-time data exchange. New-generation devices with digital twin capabilities employ the OPC UA protocol to ensure semantic integrity of information models. For IoT terminal devices, the platform implements the MQTT protocol to establish a lightweight transmission channel, ensuring message reliability through QoS Level 2 service quality.

3.2. Big data processing and analysis technology

The efficient operation of thermal power industrial Internet platform depends on the ability of deep processing and intelligent analysis of massive multi-source data. The equipment operation parameters, environmental monitoring data and production management information obtained in the data acquisition layer are characterized by high dimension, unstructured and real-time, so it is necessary to realize value mining through systematic processing process. First of all, data preprocessing technology is the basic link of building analysis model, including data cleaning, standardization and feature engineering. In order to deal with the common sensor noise, missing values and abnormal pulse signals in thermal power plants, the statistical outlier detection method (such as 3σ criterion) and interpolation algorithm (such as cubic spline interpolation) are used to purify the data. In the feature engineering stage, the envelope features of equipment vibration signals are extracted through time-frequency domain transformations (such as wavelet decomposition and Fourier transform), and the sliding window technology is combined to construct time series feature vectors, which effectively improves the input quality of the subsequent model.

In the platform, data mining technology is primarily applied to equipment health status assessment and production process optimization. Cluster analysis methods are employed for pattern recognition of unit operating conditions, where the K-means algorithm clusters historical load curves to assist in developing differentiated maintenance strategies [6]. Association rule mining technology is applied to combustion efficiency optimization scenarios. Through the Apriori algorithm, potential correlations between coal quality parameters and boiler efficiency are identified, guiding dynamic adjustments to coal blending schemes. The classification prediction model has been outstanding in the field of fault diagnosis. Random forest and support vector machine (SVM) are used to predict the early warning of typical faults such as boiler coking and steam turbine blade crack. The key influencing factors are located through feature importance analysis, which significantly improves the diagnostic accuracy.

4. Platform implementation and testing

4.1. Platform development environment and tools

The platform's development environment and toolset are systematically designed to accommodate the multi-tiered architecture of industrial internet in thermal power plants, featuring four core components: hardware infrastructure, software development frameworks, integrated toolchains, and test/verification platforms. In terms of hardware infrastructure, the system employs a cloud-based distributed server cluster architecture with high-performance computing nodes and edge computing gateways. The main control server is equipped with dual-socket Xeon CPUs, 128GB ECC memory, and an NVMe SSD storage array. The edge nodes utilize industrial-grade embedded devices designed for power plant environments. The operating system uniformly deploys CentOS 7.6 LTS, with containerization technology enabling environment isolation. Core components are deployed via Docker containers, while Kubernetes orchestration manages elastic scaling and high availability.

The development toolchain employs a full-stack technology stack. Back-end development is centered on Java 11, utilizing the Spring Boot microservices framework to build core services. The database access layer is developed with MyBatis Plus, while Redis serves as a caching middleware for rapid high-frequency data access. The frontend development utilizes the Vue.js 3.2 framework to build a responsive interface, employs Element UI component library for industrial visualization component encapsulation, and leverages WebSockets protocol for real-time data transmission [7]. At the data processing layer, Apache Kafka is employed to build real-time data stream processing pipelines, while the Flink framework implements complex event processing logic. The time-series database InfluxDB stores operational parameters, and the relational database PostgreSQL manages configurations and business data.

4.2. Implementation steps and methods of the platform

The platform implementation process strictly follows the system engineering methodology, and is promoted through four stages: requirement analysis, system design, development integration, and test verification. In the requirements analysis phase, based on the business processes and equipment characteristics of thermal power plants, the Kano model was adopted to establish a function requirement priority matrix, focusing on identifying four core functional modules: real-time data acquisition, equipment health management, production optimization decision-making, and safety protection. By leveraging communication protocols of field devices, including DCS systems and PLC controllers, we developed a multi-protocol adaptation solution for OPC UA, Modbus TCP, and MQTT. The solution specifies critical performance metrics: system response time ≤ 200ms, data acquisition frequency 1Hz, and support for over 5,000 measurement points with concurrent access.

The system design adopts a layered architecture, consisting of three layers: edge layer, platform layer, and application layer. The edge layer deploys a lightweight edge computing gateway to perform protocol parsing, data cleaning, and local storage functions. The platform layer is built on the Kubernetes container cloud platform, featuring core components such as a data platform, algorithm engine, and service bus with a microservices architecture. The application layer develops web and mobile interfaces, integrating modules for data visualization, intelligent analysis, and alarm management. The interface design adheres to RESTful standards, with API documentation defined through Swagger to ensure decoupling and scalability among modules [8]. The security design adopts ISO/IEC 27001 standard to build a four-dimensional protection system, including identity authentication, access control, data encryption and log audit.

5. Conclusion

Based on the production and operation characteristics of thermal power plants and the development trend of industrial Internet technology, this study constructs a hierarchical and decoupled industrial Internet platform architecture system, and realizes the comprehensive interconnection and intelligent management of thermal power plant equipment, data and application through multi-dimensional technology integration. At the architectural design level, a three-tier system comprising edge layer, platform layer, and application layer is proposed. The edge layer integrates IoT protocol adaptation with edge computing technology, enabling standardized access and real-time data preprocessing for multi-source heterogeneous devices. This effectively resolves the issues of fragmented protocols and high data transmission latency in traditional thermal power plant equipment. The platform layer utilizes containerized microservices architecture to establish both data and business platforms. By integrating cloud computing and big data technologies, it creates a high-concurrency, high-availability industrial PaaS platform that supports massive data storage, analysis, and service-oriented encapsulation. The application layer developed core application modules such as equipment health management, combustion optimization, and energy consumption analysis based on digital twin and AI algorithm, forming an intelligent decision support system covering the whole production process.

Disclosure statement

The authors declare no conflict of interest.

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