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Development and Application of Digital Twin Simulation System for Thermal Power Plant

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Abstract: As a product of the deep integration between next-generation information technology and industrial systems, digital twin technology has demonstrated significant advantages in real-time monitoring, predictive maintenance, and optimization decision-making for thermal power plants. To address challenges such as low equipment efficiency, high maintenance costs, and difficulties in safety risk management in traditional thermal power plants, this study developed a digital twin simulation system that covers the entire lifecycle of power generation units. The system achieves real-time collection and processing of critical parameters such as temperature, pressure, and flow rate through a collaborative architecture integrating multi-source heterogeneous sensor networks with Programmable Logic Controllers (PLCs). A three-tier processing framework handles data preprocessing, feature extraction, and intelligent analysis, while establishing a hybrid storage system combining time-series databases and relational databases to enable millisecond-level queries and data traceability. The simulation model development module employs modular design methodology, integrating multi-physics coupling algorithms including computational fluid dynamics (CFD) and thermal circulation equations. Automated parameter calibration is achieved through intelligent optimization algorithms, with model accuracy validated via unit-level verification, system-level cascaded debugging tests, and virtual test platform simulations. Based on the modular layout strategy, the user interface and interaction module integrates 3D plant panoramic view, dynamic equipment model and multi-mode interaction channel, supports cross-terminal adaptation of PC, mobile terminal and control screen, and improves fault handling efficiency through AR assisted diagnosis function.

Keywords: Digital twin technology; Thermal power plant; Simulation system; Multi-source heterogeneous data

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1. Introduction

As an innovative achievement of the deep integration of the new generation of information technology and industrial system, digital twin technology has shown significant advantages in real-time monitoring, predictive maintenance and optimal decision-making of complex industrial systems in recent years. In the field of energy, traditional thermal power plants are faced with challenges such as low equipment operation efficiency, high maintenance cost and high pressure of safety risk control. Their high energy consumption and high pollution characteristics make them a key link in promoting energy revolution. In this context, the construction of digital twin simulation system for thermal power plants has become an important way to realize the intelligent upgrading of thermal power plants. By deeply integrating physical equipment, production process and virtual model, energy utilization efficiency can be effectively improved, operation and maintenance strategy can be optimized, and safety risks can be reduced.

The core value of digital twin technology lies in its ability to break through the space-time constraints of physical systems. Through real-time data collection and multi-dimensional modeling, it provides dynamic mapping and intelligent analysis capabilities for complex industrial systems. In the field of key equipment in thermal power plants, such as boiler system, researchers have proposed a five-dimensional digital twin model, which integrates physical entities, data integration, virtual models, service interfaces and communication networks, and realizes accurate control and dynamic optimization of combustion process through three-dimensional visual modeling.

Such technology not only promotes the improvement of combustion efficiency, but also provides a scientific basis for the adjustment of operating parameters through the two-way interaction between physical and digital space [1]. In addition, for equipment with high failure rate such as air preheater, the digital twin system based on temperature field calculation and video image analysis has been successfully applied in the scenario of predictive maintenance. By monitoring the changes of thermal parameters and ash accumulation in real time, the dynamic optimization of ash blowing strategy can significantly reduce the probability of unplanned shutdown of equipment.

2. Design of digital twin simulation system for thermal power plant

2.1. Data acquisition and processing module

The data acquisition and processing module of the digital twin simulation system of thermal power plant is the core component to realize the real-time interaction between physical entities and virtual models. Its design should take into account the comprehensiveness of data acquisition, the efficiency of processing and the reliability of storage. At the data acquisition level, the system adopts a multi-source heterogeneous sensor network and PLC collaborative architecture, and realizes real-time monitoring of key equipment operation parameters by deploying high-precision sensors such as temperature, pressure, flow and vibration.

For example, for the steam turbine system, the sensor network needs to cover the main steam parameters, blade vibration spectrum and bearing temperature and other core indicators, while the boiler module needs to collect the furnace temperature field distribution, fuel particle size and combustion efficiency data. In order to ensure the accuracy of data, the system introduces the error prediction and prevention function of digital twin. By comparing the output difference between physical sensors and virtual models, the measurement error or connection fault can be identified, so as to ensure the reliability of data acquisition. Furthermore, the data acquisition strategy should be designed to combine the sampling frequency with the characteristics of the device. For example, high-frequency vibration signals can be sampled at millisecond level, while temperature parameters can be sampled at second level to balance real-time and data volume.

2.2. Simulation model construction module

The simulation model construction module in the design of thermal power plant digital twin simulation system is the core foundation for realizing virtual-real mapping and dynamic interaction. Its construction method needs to take into account the high precision, real-time and scalability of the model. In the process of model construction, a high-fidelity digital mapping should be established based on the multi-dimensional characteristics of the physical entity of the thermal power plant. By integrating the equipment parameters, process flow and operation environment data, an integrated simulation architecture including key subsystems such as boiler, steam turbine and generator can be formed. The modular design principle is widely adopted. By decomposing complex systems into sub-modules that can be independently developed and verified, it is not only convenient for collaborative development, but also improves the flexibility and maintainability of the system [2,3]. For example, the boiler combustion model can adopt the coupling algorithm of computational fluid dynamics (CFD) and chemical reaction dynamics, while the steam turbine module needs to combine the thermodynamic cycle equation and mechanical vibration characteristics for multi-physics coupling modeling.

Parameter setting is the key link of simulation model construction, which needs to be combined with theoretical model for joint optimization .In order to overcome the limitations of low efficiency and local optimization in traditional manual debugging, intelligent optimization algorithm is introduced into the automatic parameter calibration process. Taking the parameter debugging of nuclear power plant digital twin system as an example, the differential evolution algorithm achieves rapid convergence of steam system model parameters under the constraint condition through iterative search. This method is also applicable to the parameter optimization of complex thermal networks such as the second circuit system of thermal power plant. At the same time, the model parameters should have online adaptive ability. By collecting the operation data of physical entities in real time, the data-driven model update strategy is adopted to dynamically correct the simulation parameters to eliminate model drift. Research shows that the online adaptive method based on Kalman filter can significantly improve the synchronization accuracy between the model and the physical system, and the effectiveness of this technology has been verified in the digital twin system of nuclear power plant.

2.3. User interface and interaction module

The system interface adopts a modular layout strategy, integrating core functions such as real-time monitoring, operation simulation, and data analysis into a visual interface, ensuring users can quickly obtain system status information through intuitive interaction. In terms of design principles, we follow three principles: user-friendliness, real-time and scalability.

Through multi-level operation interface, we realize the differentiated access needs of users with different permissions. The interface features a 3D panoramic view of the plant area and dynamic models of key equipment, combined with thermal system flow charts, unit operation parameter dashboards, and warning prompts, to create a multi-dimensional interactive scenario [4]. The 3D visualization module, based on the geometric model of the physical entity of the power plant and the sensor data, realizes the real-time 3D mapping of key equipment such as boiler, steam turbine and cooling tower. Operators can observe the equipment status and locate the abnormal area through zooming, rotating and other interactive operations.

In order to improve the convenience of operation, the system is designed with multiple mode interaction channels, including keyboard shortcuts, touch gesture recognition and voice command response function. The voice interaction module converts user commands into executable control commands of the system through natural language processing technology. At the data interaction level, the interface integrates the dynamic display and historical trace function of multi-source heterogeneous data, presents the equipment operation parameters, energy consumption indicators and fault diagnosis results in the form of time series curves, heat maps and statistical reports, and supports users to customize data filtering conditions and visual display forms.

3. System Implementation and Testing

3.1. System implementation steps

The development of this system follows the process of "requirement analysis-architecture design-module implementation-integration debugging-test verification". During the requirements analysis phase, through multiple rounds of requirements research with power plant technicians, the system was required to support core functions such as real-time data access, multi-physical field coupling simulation, and 3D visualization interaction. At the same time, the system response time was set to no more than 200ms and the performance index was set to support more than 50 real-time data sources to access concurrently [5].

Based on the above requirements, a four-layer architecture is adopted, including data acquisition layer, digital twin model layer, simulation engine layer and user interaction layer. The data acquisition layer establishes communication with the power plant's DCS system via the OPC UA protocol, utilizing edge computing nodes for protocol conversion and data preprocessing. The model layer utilizes MATLAB/Simulink to develop mathematical models for core equipment such as boilers and steam turbines, while integrating Comsol Multiphysics for thermodynamic field coupling modeling. The simulation engine layer utilizes C++ to develop a real-time computing framework, enabling dynamic parameter adjustment and multi-time-scale simulation capabilities.

During implementation, we first develop a Model-Driven Architecture (MDA) toolchain. Using XML Schema to define a unified model description language, we establish a device model metadata database. The modular function block library is built based on the IEC 61499 standard, with each function block containing mathematical expressions, parameter configuration interfaces, and simulation interfaces. The data interface module implements an OPC UA client using Python's PyOPC library. It receives DCS data streams in real time through a callback mechanism and utilizes Apache Kafka as a message middleware to handle data buffering and load balancing. The simulation engine adopts object-oriented design method, encapsulates each physical model as an independent object, and coordinates the interaction between models through event-driven mechanism. The 3D visualization interface, powered by the Unity3D engine, imports 3D point cloud data from power plants in FBX format and uses Shader programming to map real-time equipment operational status.

3.2. System testing methods

In the unit test phase, the white box test method is used to verify the code level of the data acquisition interface, simulation engine, visualization module and other core components, focusing on the input and output consistency of each module, the exception handling mechanism and the resource occupancy. The test case design adopts equivalence class division and boundary value analysis method to test extreme scenarios such as abnormal values of sensor data and critical state of model parameters, so as to ensure the stable operation of each functional module in isolated environment. In the integration test phase, a multi-module collaborative test environment is built to verify the reliability of data transmission protocol, real-time synchronization mechanism, and multi-source heterogeneous data fusion algorithm [6].

By simulating typical working conditions such as the start and stop of thermal power units and variable load operation, the monitoring system monitors the response delay, communication packet loss rate and data consistency index in the process of data flow interaction to ensure the compliance of interface specifications among subsystems. The system test adopts the combination of black box test and scenario test, and establishes a benchmark test case library based on the actual operation parameters of thermal power plant. The model's simulation error under both steady-state and transient operating conditions is maintained within 3%, markedly enhancing its capacity to capture the unit's complex dynamic behavior [7,8].

For the core functional modules of the digital twin system, three types of test cases are designed as follows:

(1) Data synchronization accuracy test, which verifies the effectiveness of data synchronization and extinction mechanism by comparing the error rate of real-time monitoring data of physical units and simulation data of digital twin;

(2) Accuracy test of the simulation model: The key performance indicators such as unit load change rate and thermal efficiency are selected to compare the consistency between the simulation results and the historical measured data;

(3) System stability test, which monitors system resource occupancy, data processing throughput, and abnormal recovery capability through continuous operation test for 72 hours.

4. Conclusion

This study systematically carried out the development and application research of the digital twin simulation system of thermal power plant. Through interdisciplinary integration and technological innovation, a high-fidelity digital twin covering the whole life cycle of the unit was constructed, and the simulation verification and engineering application were realized in multiple scenarios. The research work has made important achievements in theoretical methods, technical realization and practical application, and provided key technical support for the intelligent transformation of thermal power plants. In view of the problems of insufficient accuracy and lagging dynamic response of the traditional thermal power plant model, a refined modeling system of multi-physics field coupling is established. Through the deep coupling of multi-disciplinary mechanism models such as thermodynamics, fluid mechanics and heat transfer, and the combination of data-driven correction of unit operation data, a high-fidelity digital twin model covering key equipment such as boiler, steam turbine and auxiliary system has been successfully constructed. The simulation error of the model under steady state and transient working conditions is controlled within 3%, which significantly improves the representation ability of the complex dynamic behavior of the unit. On top of that, a distributed computing architecture for real-time simulation is developed, and a collaborative optimization strategy of edge computing and cloud computing is adopted to realize data update in seconds and simulation response in milliseconds. By designing the dynamic switching algorithm of lightweight model, the system improves the efficiency of complex condition simulation by more than 40% while ensuring the calculation accuracy, which provides a reliable technical guarantee for online optimization. At the application level, the system has been successfully applied to key scenarios such as unit start-stop optimization, fault warning, and energy efficiency improvement. Through the virtual and real interaction between digital twin and actual unit, the early diagnosis of equipment failure and health status prediction are realized. The fault identification accuracy rate is 92%, and the warning time window is 2–3 hours earlier than the traditional method. In terms of energy efficiency optimization, the multi-objective optimization algorithm based on digital twin improves the unit load response speed by 15% and the exergy efficiency by 1.8 percentage points, which verifies the engineering feasibility of the technical scheme. The study also reveals several key scientific issues in the application of digital twin technology in thermal power plants. To address the stability problem of real-time data and dynamic coupling of the model, an adaptive correction method based on sliding time window is proposed, which effectively solves the problem of model parameter drift.

Disclosure statement

The authors declare no conflict of interest.

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