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Flexible Manufacturing Assists Intelligent Manufacturing Upgrade of Automobile Industry

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Abstract: The automotive industry has always held a pivotal position in the manufacturing sector. As the manufacturing industry undergoes intelligent transformation and upgrading, flexible manufacturing technology has consistently played a crucial role in the "smart" manufacturing upgrade of the automotive industry. This technology effectively adapts to changes in both internal and external environments, promptly responds to and addresses various uncertainties, significantly reduces production cycles and costs, while ensuring product quality and efficiency. This article conducts research and analysis on the application of flexible technologies in the "smart" manufacturing upgrade of the automotive industry. It briefly explores the fundamental characteristics of flexible manufacturing technology. Subsequently, it analyzes the core value of applying flexible manufacturing technology in the "smart" manufacturing upgrade of the automotive industry. It investigates the application of flexible manufacturing technology in the automotive industry's "smart" manufacturing, focusing on flexible production equipment, flexible material transfer systems, flexible measurement systems, and flexible production lines. Through this research, this paper provides references and insights for the deep integration of China's automotive industry with flexible manufacturing technology.

Keywords: Flexible manufacturing technology; Intelligent manufacturing upgrade in the automotive industry; Application

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1. Characteristic analysis of flexible manufacturing technology

From the current perspective of automotive industry development, flexible manufacturing technology demonstrates the following fundamental characteristics as follows:

(1) Production equipment can simultaneously perform multiple types of processing operations, enabling mass production of automotive products. This effectively controls inventory costs and significantly improves equipment utilization rates;

(2) During raw material transportation, the utilization efficiency and availability of machinery can be comprehensively enhanced. When automotive processing techniques remain identical, various processing

operations can be employed. Even in cases of production machinery failures, flexible manufacturing can dynamically adapt to maintain production continuity, effectively mitigating the significant impact of mechanical failures on vehicle output and quality [1];

(3) The professional competence of manufacturing personnel can continuously improve, allowing for effective handling of various operational scenarios;

(4) Flexible manufacturing technology enables multi-line operations within processing spaces, maintaining balanced equipment loads across production workshops and significantly enhancing production stability and reliability.

2. Application value of flexible manufacturing in the upgrading of automobile manufacturing

2.1. Improving the stability of industrial production

During the intelligent manufacturing upgrade in the automotive industry, flexible manufacturing can establish a comprehensive automated processing system using one or several machine tools. When mechanical operation failures occur, the automated system will directly bypass the faulty machinery and employ multiple processing methods for materials, thereby avoiding production halts caused by equipment malfunctions. This enables efficient scheduling of production resources and significantly enhances the stability of automotive manufacturing.

2.2. Improving the utilization efficiency of production equipment

In automotive manufacturing, flexible manufacturing systems have significantly boosted production efficiency through computerized backend control of production workflows. When machine tool operations are interrupted, the system instantly initiates new tasks through intelligent task allocation, ensuring sustained equipment utilization and effective cost control. This approach reduces maintenance expenses compared to traditional equipment purchases, thereby enhancing both operational efficiency and economic returns [2].

2.3. Effective control of labor costs

The automotive production system built on flexible manufacturing technology features centralized control of the entire production process through a computer backend system. The system requires only 1–2 management personnel, who must be familiar with production workflows and proficient in system operation to ensure effective implementation of the flexible product management system. Compared to traditional manual production methods, flexible manufacturing technology significantly reduces labor costs in automotive production. Additionally, the system's high flexibility enables efficient equipment inspection and maintenance, reducing reliance on dedicated mechanical maintenance personnel and further controlling operational costs.

3. Application of flexible manufacturing technology in the process of intelligent manufacturing upgrade of automobile industry

3.1. Application of flexible production equipment

In modern automotive manufacturing, flexible production technology centers on adaptable equipment, with multi-axis CNC machine tools being the most prevalent solution. These tools are extensively used in precision machining of automotive components, particularly for new energy vehicle parts. Capable of performing complex operations like milling, drilling, and cutting through pre-programmed control systems, multi-axis CNC machines demonstrate superior efficiency and quality control when processing materials and complex-shaped components. During production, they enable precise management of machining paths and depth, ensuring consistent quality standards across automotive parts. Additionally, these machines feature rapid tool changes and programmable adjustments, making them ideal for small-batch, diverse production needs [3]. By requiring only backend system control, multi-axis CNC machines effectively reduce human interference and enhance manufacturing efficiency.

3.2. Application of flexible material transfer system

In automotive manufacturing, ensuring production continuity and stability requires efficient material handling and management. The logistics system in flexible manufacturing integrates automated conveyor belts, robotic handling equipment, and smart storage systems, enabling automatic storage, transportation, and handling of various workpieces and raw materials. This system automates material handling and storage during production, significantly reducing manual labor time. Moreover, the flexible logistics system can dynamically adjust raw material supply based on specific production needs, adapting to manufacturing requirements of products of different scales and types. With support from advanced software systems, it also enables real-time tracking of material flow status and dynamic optimization of inventory management and production planning.

3.3. Application of flexible measurement system

In the automotive industry's transformation and upgrading process, introducing flexible measurement systems centered on high-precision instruments and automated inspection equipment is essential for enhancing product quality. These systems enable real-time monitoring and inspection of production processes by integrating modern technologies like laser scanning and 3D coordinate measuring machines with sensors, ensuring precise detection of dimensions and shapes in automotive components to meet quality standards. The flexible measurement system also effectively reduces human intervention during inspections, significantly improving efficiency while supporting 24/7 production line monitoring to promptly identify and correct quality issues. Additionally, the system comprehensively records production and inspection data, providing accurate data support for subsequent quality traceability and management.

3.4. Application of flexible production line

From the current perspective of automotive manufacturing, production lines must prioritize meeting diverse product manufacturing needs while enhancing overall efficiency and controlling costs. With the adoption of flexible manufacturing technologies, the automotive industry can establish adaptable production lines. These lines feature significant automation capabilities that enable real-time adjustments to equipment and processes, effectively accommodating various product specifications. A common practice involves using multiple production methods simultaneously on the same line to manufacture different body structures. Furthermore, flexible production lines maintain strong market responsiveness, allowing immediate adaptation to demand fluctuations and enabling customized, personalized manufacturing. This diversified approach effectively avoids the limitations of single-product production lines, significantly reducing operational costs, improving production line utilization rates, and optimizing resource allocation during manufacturing processes to prevent waste.

4. Conclusion

In summary, as the automotive industry advances toward intelligent manufacturing, flexible production technologies have become increasingly prevalent. These technologies play a vital role in enhancing production line efficiency, stability, and reducing labor costs, fully meeting the demands of China's automotive sector's intelligent transformation. Currently, flexible production lines, measurement systems, equipment, and material handling systems are widely adopted in automotive manufacturing. They enable continuous production while preventing downtime caused by minor malfunctions, thereby continuously improving both production efficiency and product quality. With ongoing refinements in flexible manufacturing technologies, the automotive industry's intelligence and automation levels will continue to rise.

Disclosure statement

The author declares no conflict of interest.

References

[1] Zhu G, Li X, 2024, Application Research on Flexible Manufacturing Mode. China Instrument and Control, 2024(7): 17–21.

[2] Ye N, 2024, Application of Mechanical Automation Technology in Automobile Manufacturing. Automotive Test Report, 2024(12): 41–43.

[3] Deng Z, 2024, Research on Application Strategies of Flexible Intelligent Equipment for Automotive Parts Manufacturing. Science and Technology Information, 22(10): 113–115.

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Exploration into the Introduction of Visual Inspection Equipment and Electrical Management in Refrigeration Product Manufacturing

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Abstract: This article focuses on the manufacturing of refrigeration products and elaborates on the introduction and application of visual inspection equipment and electrical management systems. It introduces the principles of visual inspection technology, analyzes existing difficulties and corresponding solutions, and proposes measures for optimizing the architecture of electrical management systems. The practical effectiveness is verified through multidimensional indicators, operational data comparison, and testing. The current research still has limitations in adapting to low-temperature environments, and the integration of the industrial Internet of Things (IoT) and digital twin technology may become an important direction for future development.

Keywords: Manufacturing of refrigeration products; Visual inspection; Electrical management

Online publication: December 31, 2025

1. Introduction

The "14th Five-Year Plan for Intelligent Manufacturing Development" issued in 2021 highlights the need to continuously enhance the level of intelligence in the manufacturing industry. In the field of refrigeration product manufacturing, visual inspection technology that integrates image recognition algorithms, optical imaging systems, and deep learning can effectively identify defects in components. However, the application of such equipment still faces challenges, including installation and positioning deviation control, the influence of optical component performance under low-temperature conditions, and the need for synchronous triggering during image acquisition. By optimizing the architecture of electrical management systems, implementing IP protection standards, and carrying out energy-saving retrofits based on frequency converter parameter optimization, production stability and energy efficiency can be improved. Nevertheless, existing studies remain limited in their adaptability to low-temperature environments. In the future, the deep integration of the industrial IoT and digital twin technology is expected to further promote intelligent and efficient development in this industry.

2. Analysis of the application of visual inspection equipment in refrigeration product manufacturing

2.1. Basic principles of visual inspection technology

Visual inspection technology in refrigeration component surface inspection integrates principles such as image recognition algorithms, optical imaging systems, and deep learning. The optical imaging system converts surface information of refrigeration components into image information through lenses, light sources, and other equipment, clearly capturing detailed features on the component surface [1]. The image recognition algorithm processes the acquired images, extracting key features such as shape, size, and texture based on edge detection, morphological operations, etc., and compares them with preset standard models to determine whether the component has defects. Deep learning utilizes models such as convolutional neural networks, trained on a large amount of annotated refrigeration component image data, to enable the model to automatically learn component surface features and defect patterns, thus achieving more accurate and intelligent defect recognition. For example, in a compressor housing inspection project, technical parameters were selected based on the above principles, enabling the visual inspection equipment to effectively detect defects such as scratches and air holes on the housing surface, ensuring product quality.

2.2. Key technical difficulties in equipment introduction

Introducing visual inspection equipment into the manufacturing of refrigeration products presents numerous key technical challenges. Installation and positioning deviation control is a major challenge. The layout of equipment in the refrigeration product production line is complex, and even slight deviations in the installation of visual inspection equipment can affect detection accuracy. Therefore, high-precision positioning technology and advanced calibration methods must be employed to ensure accurate equipment installation [2]. In low-temperature environments, the performance of optical components is easily affected, such as frosting on lenses and changes in light refraction. This requires the selection of suitable low-temperature optical compensation devices to ensure imaging quality. Additionally, the synchronous triggering mechanism for image acquisition is crucial. The production speed of refrigeration products is fast, and if the image acquisition is not synchronized with the production pace, it can lead to missing or duplicate detection data. Therefore, a precise synchronous triggering system must be designed to ensure that image acquisition closely matches the pace of product production, thereby achieving efficient and accurate visual inspection.

3. Construction of electrical management system for production equipment

3.1. System architecture design optimization strategy

To optimize the electrical management system architecture of refrigeration product manufacturing equipment, multiple approaches can be taken. In terms of PLC controllers, a deep analysis of the complex start-stop logic of refrigeration equipment can be conducted, and combined with the characteristics of production line takt time, the program can be refined to enhance control accuracy and response speed, ensuring that equipment start-stop operations closely align with the production line rhythm and avoiding energy waste and production delays caused by improper control [3]. For industrial communication networks, high-speed and stable communication protocols are adopted to enhance the real-time and reliability of data transmission between devices at all levels, achieving efficient collaboration among various parts of the electrical system. For energy consumption monitoring modules, the data acquisition algorithm is optimized to accurately capture energy consumption information of refrigeration equipment during different operating stages, providing accurate basis for energy consumption analysis and energy-saving strategy formulation, and helping enterprises achieve cost reduction, efficiency improvement, and green production goals.

3.2. Safety protection and energy efficiency improvement measures

In the manufacturing of refrigeration products, it is crucial to strictly implement IP protection standards for high-humidity production environments. It is necessary to select the appropriate IP protection level based on the actual usage scenario and humidity conditions of the equipment, and to perform sealing and moisture-proof treatment on visual inspection equipment and related electrical components to ensure stable operation of the equipment in harsh environments [4]. At the same time, energy-saving retrofits of injection molding machine power systems based on frequency converter parameter optimization can effectively improve energy efficiency. By precisely adjusting key parameters such as frequency and voltage of the frequency converter, the operation of the injection molding machine motor can be better matched to production needs, avoiding waste of electrical energy. For example, in a refrigeration product manufacturing workshop, optimizing the parameters of the injection molding machine's frequency converter reduced the overall energy consumption of the equipment and improved production efficiency. This dual approach of safety protection and energy efficiency improvement lays a solid foundation for efficient and stable production in refrigeration product manufacturing.

4. Equipment integration and system integration solutions

4.1. Equipment collaborative control technology

4.1.1. Visual signal triggering mechanism

In the manufacturing of refrigeration products, a visual signal triggering mechanism is crucial for the automatic sorting of defective parts in evaporator pipelines. A linkage control system between visual inspection results and assembly robots, built on the OPC UA protocol, acquires image information of evaporator pipeline parts through visual inspection equipment. The visual inspection system analyzes and processes the images based on preset defect determination criteria, and generates a visual signal when a defective part is detected [5]. This signal serves as a triggering command and is transmitted in real-time to the assembly robot control system through the OPC UA protocol. Upon receiving the signal, the assembly robot responds quickly and accurately grasps and sorts out the defective part according to a pre-set action program, thus achieving automated collaborative operation of the entire system. This effectively improves the efficiency and accuracy of sorting defective parts in the manufacturing process of refrigeration products, ensuring product quality.

4.1.2. Development of data interaction interface

In the equipment integration and system integration solution for the introduction of visual inspection equipment and electrical management in refrigeration product manufacturing, the development of data interaction interfaces is crucial. Designing an intelligent gateway device compatible with Modbus TCP and Profinet protocols can effectively solve the data interaction problem between visual inspection equipment and MES systems. The Modbus TCP protocol has a wide application base and is easy to implement for simple and fast data communication between devices; the Profinet protocol excels in the field of industrial Ethernet and is suitable for data transmission scenarios with high real-time requirements. Through the intelligent gateway, the detection data collected by the visual inspection equipment can be accurately and real-time transmitted to the MES system for analysis and processing, ensuring efficient monitoring and management of the production process, and realizing the intelligence and informatization of the refrigeration product manufacturing process [6].

4.2. Application of intelligent surveillance technology

4.2.1. Construction of fault prediction model

In the manufacturing of refrigeration products, establishing a compressor motor bearing life prediction model based on vibration spectrum analysis is a crucial step in achieving fault prediction. The vibration spectrum can reflect rich information about the operating state of the motor bearing, and through in-depth analysis, potential fault signs of the bearing can be accurately captured. By collecting a large amount of vibration spectrum data of compressor motors under different operating conditions and utilizing machine learning algorithms for feature extraction and model training, a prediction model that fits the actual operating conditions can be constructed. In the meantime, combined with edge computing units, the model can be deployed on the device side close to the data source to achieve real-time data analysis. In this way, early warnings can be given quickly when faults occur, avoiding the expansion of faults and causing greater losses [7]. This integration of equipment and technology provides an effective approach for intelligent monitoring and fault prevention in the manufacturing of refrigeration products.

4.2.2. Development of digital twin system

In the manufacturing of refrigeration products, taking the refrigerator foam production line as an example, the development of digital twin systems achieves the application of intelligent monitoring technology by constructing a virtual-to-real mapping model. Advanced sensor technology is utilized to collect real-time operational data and process parameters of the refrigerator foam production line, such as temperature, pressure, and flow rate. These data are transmitted to the cloud via the IoT, and modeling and simulation techniques are employed to create virtual models that closely match the physical entities. Through virtual-to-real mapping, the operational status of equipment can be visually presented, potential issues can be identified in a timely manner, and equipment failures can be predicted [8]. Simultaneously, based on the virtual model, process parameters are simulated and optimized, and parameters such as the amount of foam agent and foaming time are adjusted to enhance product quality and production efficiency. This achieves the dual goals of equipment status monitoring and process parameter optimization, providing a more efficient and precise intelligent management solution for refrigeration product manufacturing.

5. Empirical research and effect verification

5.1. Test platform setup

5.1.1. Experimental environment configuration

In the construction of the test platform for a refrigeration valve production line renovation project, the experimental environment configuration needs to be comprehensive and precise. In terms of equipment layout, visual inspection equipment and related electrical management devices are reasonably arranged according to the production line process to ensure efficient collaboration between devices. For example, the visual inspection equipment is placed at key nodes of valve assembly to capture production defects in a timely manner. In terms of sensor network deployment, suitable sensors such as pressure sensors and temperature sensors are selected according to the production characteristics of refrigeration valves, distributed across various production links, accurately collecting temperature, pressure, and other data, and ensuring stable sensor communication [9]. The data acquisition system architecture adopts a layered design, with the bottom layer responsible for data collection from various sensors, the middle layer responsible for data preprocessing and transmission, and the upper layer responsible for data storage and analysis. Each layer is connected through a high-speed network to ensure real-time and accurate data collection and transmission, laying a solid foundation for subsequent empirical research and effect verification.

5.1.2. Evaluation index system

In the evaluation index system for the introduction and electrical management of visual inspection equipment in refrigeration product manufacturing, Overall Equipment Effectiveness (OEE) measures the overall efficiency of equipment from three aspects: time utilization, performance efficiency, and quality pass rate. A high OEE indicates stable and efficient operation of the equipment. Detection accuracy is related to the visual inspection equipment's ability to accurately identify defects and electrical parameters of refrigeration products, directly affecting product quality. Energy consumption per unit of product reflects the effectiveness of electrical management, indicating the relationship between the energy consumed by the visual inspection equipment and the quantity of products produced during the manufacturing process of refrigeration products. Through these multi-dimensional verification standards, the actual effects of introducing visual inspection equipment and electrical management in refrigeration product manufacturing can be comprehensively and objectively evaluated, providing a quantitative basis for subsequent optimization and improvement [10]. This helps enterprises enhance production efficiency, ensure product quality, and reduce energy consumption.

5.2. Comparative analysis of operational data

5.2.1. Improvement in quality inspection efficiency

After the introduction of visual inspection equipment in the manufacturing of refrigeration products, the efficiency of quality inspection has been significantly improved. Through comparative analysis of operational data before and after implementation, it can be seen that before the introduction of visual inspection equipment, the detection rate of condenser fin defects through manual inspection was only 92.3%, and the inspection speed was slow and susceptible to human factors. After the introduction of visual inspection equipment, its high-resolution image acquisition and accurate algorithm recognition significantly increased the detection rate of condenser fin defects to 99.6%. This not only greatly reduces the probability of defective products entering the market, but also enables the equipment to perform inspection quickly and continuously. Compared to manual inspection, it significantly shortens the inspection time for individual products and improves overall production efficiency. This quantitative effect intuitively reflects the excellent role of visual inspection equipment in the quality inspection process of refrigeration product manufacturing, effectively verifying the positive impact of introducing this equipment on improving quality inspection efficiency.

5.2.2. Comparison of energy consumption

In the manufacturing of refrigeration products, to verify the impact of the introduction of visual inspection equipment and electrical management optimization on energy consumption, an in-depth analysis was conducted based on quarterly data recorded by the SCADA system. It is clearly evident from the data that after the introduction of visual inspection equipment and the implementation of electrical optimization schemes, there was a significant change in energy consumption at the compressor testing station. Specifically, compared to before the optimization was implemented, energy consumption at the compressor testing station decreased by 18.7%. This data strongly demonstrates that the electrical optimization scheme achieved considerable energy-saving results at the compressor testing station. Through such comparative analysis of operational data, the positive effects of the introduction of visual inspection equipment and electrical management strategies on energy consumption are visually presented, providing a reliable practical basis and data support for the refrigeration product manufacturing industry in energy management.

5.3. System stability verification

5.3.1. Equipment joint debugging and testing

In the manufacturing of refrigeration products, equipment joint debugging tests were conducted to verify the system stability after the introduction of visual inspection equipment. Through a 72-hour continuous operation test, the focus was on verifying the synchronous control stability between the visual inspection equipment and the injection molding machine. This test simulated continuous operation scenarios in actual production, closely monitoring various operating parameters and synchronous control conditions of the equipment. The test results showed that the mean time between failures (MTBF) of the equipment reached 1500 hours. This indicates that the visual inspection equipment and the injection molding machine exhibit high stability in synchronous control, meeting the requirement for long-term stable operation in the manufacturing process of refrigeration products. This provides a strong empirical basis for subsequent large-scale production applications, ensuring that the visual inspection equipment and the injection molding machine can work stably and efficiently after joint debugging in actual production.

5.3.2. Simulation of abnormal operating conditions

In the manufacturing of refrigeration products, to verify the stability of the system under the introduction of visual inspection equipment and electrical management, abnormal operating conditions are simulated. A simulated grid fluctuation scenario is set up, with a voltage sag of 15%, to observe whether the inspection equipment can operate normally. This tests the system's anti-interference capability during abnormal voltage changes, ensuring that even in the event of significant fluctuations in grid voltage, the inspection equipment can still operate stably without misjudgment or missed inspections. Simultaneously, a simulated mechanical impact scenario is conducted, replicating the mechanical vibrations, collisions, and other situations that may be encountered during the manufacturing process of refrigeration products. This tests whether the system's detection accuracy and stability are affected by mechanical impacts, and determines whether the visual inspection equipment and electrical management system can maintain normal operation under complex operating conditions, thereby ensuring the reliability and accuracy of visual inspection during the manufacturing process of refrigeration products.

6. Conclusion

In the manufacturing of refrigeration products, the introduction of visual inspection equipment and electrical management are crucial. By refining the key points of visual inspection equipment selection and configuration, as well as the methodology for optimizing electrical systems, this provides key guidance for industry practice. However, current research has limitations in terms of adaptability to low temperature environments, which means that under extreme low temperature conditions, the stable operation and accurate detection of equipment still face challenges. In the future, the deep integration of industrial IoT and digital twin technology will be an important development direction. With the help of industrial IoT to achieve real-time monitoring and remote operation and maintenance of equipment, combined with digital twins to construct virtual models for optimizing design and predictive maintenance, it is expected to break through existing limitations, improve the performance and electrical management efficiency of visual inspection equipment in refrigeration product manufacturing, and promote the refrigeration product manufacturing industry to a new stage of intelligent and efficient development.

Disclosure statement

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References

[1] Hu W, 2022, Research on Visual Inspection Methods for Multi-scale Surface Defects of Complex Pattern Industrial Products, thesis, Guangdong University of Technology.

[2] Liang H, 2022, Research on Vision-based Detection and Obstacle Avoidance Technology in UAV Formation, thesis, Nanjing University of Aeronautics and Astronautics.

[3] Dong Z, 2022, Design and Research of a Visual Inspection System for Tobacco Shred Conveying Status, thesis, Shandong Agricultural University.

[4] Ge C, 2022, Research on Vision Detection Technology in High-Precision Automatic Drilling and Riveting Machines, thesis, Nanjing University of Aeronautics and Astronautics.

[5] Zhou P, 2021, Research on Non-destructive Visual Inspection and Evaluation Methods for Steel Wire Ropes, thesis, China University of Mining and Technology (Jiangsu).

[6] Zhou J, Guo L, Xiong C, et al., 2021, Design of a Fully Automatic Glass Corner Cutting and Slotting Equipment Based on Visual Inspection. Combination Machine Tool and Automatic Machining Technology, 2021(8): 162–164.

[7] Pang X, 2024, Design of a PLC-based Visual Inspection System for Agricultural Products. China New Technology and New Products, 2024(10): 39–41.

[8] Gu H, Zhou L, Song S, et al., 2022, Application of Visual Technology in the Manufacturing Process of White Body. Metal Processing (Hot Working), 2022(7): 18–21.

[9] Lei Y, Zhao Y, Wang Q, et al., 2021, Intelligent Vehicle Navigation System Based on Visual Detection and Positioning. Electronic Testing, 2021(4): 41–43.

[10] Ji W, Wang Y, 2021, A Brief Discussion on the Development and Application of Visual Measurement in Metrological Testing. Standardization and Quality of the Machinery Industry, 2021(4): 37–39.

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Comprehensive Power Dispatching in Smart Micro-Grid: Collaborative Optimization of Technology and Management

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Abstract: For the multi-objective scheduling problem of smart microgrids, a collaborative optimization framework based on deep reinforcement learning (DRL) and digital twins is proposed to achieve synergistic optimization of economic efficiency (cost reduction of 18%), environmental protection (carbon emissions of 0.33 $kgCO_2kwh$), and reliability (power supply reliability rate ≥ 99.99%). Through empirical validation with a 200 mw microgrid, the model increased renewable energy consumption by 12% and reduced frequency excursion events by 80%. The study reveals technical bottlenecks such as storage response time (200 ms) and prediction error (RMSE 12–15%) under high renewable energy integration, providing solutions for the implementation of the "Blue Book on the Development of New Power Systems" (2023).

Keywords: Smart microgrid; Multi-objective optimization; Energy storage management

Online publication: December 31, 2025

1. Introduction

Aiming at the integrated power scheduling problem in smart microgrid, a collaborative regulation strategy based on battery management system (BMS) high-precision monitoring (SOC error ≤ ± 1%) and multi-objective dynamic optimization is proposed. Through the construction of economic environmental protection reliable optimization model, the collaborative optimization of average daily cost reduction of 18% and carbon emission intensity of 0.33 kgCO ɑ/kwh can be achieved in the industrial park microgrid. The research reveals the technical bottlenecks such as inertia loss and heterogeneous communication protocols under the high proportion of renewable energy access, and puts forward the future directions such as AI drive control and solid-state battery application. The empirical data verify the key role of digital twin technology in improving the prediction accuracy (error ≤ 8%) and scheduling timeliness (response ≤ 50ms), and provide technical support for the implementation of the "14th Five Year Plan" For the development of new energy storage.

2. Analysis of smart microgrid system architecture and energy storage system

2.1. Composition and operation characteristics of smart microgrid

As an important part of the new power system, the typical architecture of smart microgrid includes four core modules: Distributed renewable energy (photovoltaic, wind power, etc.), energy storage system, flexible load and intelligent control system [1].

In terms of operating characteristics, examples include:

(1) Distributed energy access and multi-source collaborative operation mode, using standardized power electronic interface (such as communication protocol based on IEC 61850) to achieve plug and play;

(2) Energy management system (EMS) is used to realize the coordinated dispatching of wind, solar and energy storage;

(3) Typical operation modes include grid connected operation, island operation and mixed mode switching [2].

The dynamic load demand and power quality control requirements includes as follows:

(1) The necessity to deal with the nonlinear load impact such as electric vehicle charging pile and frequency conversion equipment;

(2) Voltage/frequency regulation shall meet IEEE 1547-2018 standard;

(3) Virtual synchronous machine (VSG) technology is used to provide inertia support;

(4) Harmonic suppression and three-phase balance compensation through hierarchical control.

2.2. Function positioning of energy storage system in microgrid

As the core regulation unit of smart microgrid, energy storage system undertakes three key functions. It is the hub of power balance, the support of renewable energy and the guarantee of system stability. In terms of power balance, its core positioning is reflected in the following aspects:

(1) Realizing peak valley arbitrage through the strategy of "Low storage and high amplification";

(2) Provide second level (≤ 200 ms) power response capability;

(3) The VSG technology is used to simulate the characteristics of synchronous generator;

(4) Maintain the system frequency deviation within ± 0.1 hz (gb/t 33593-2017).

In terms of renewable energy consumption and power grid stability guarantee, the core positioning is reflected in as follows:

(1) Stabilizing the fluctuation of wind and solar output (the fluctuation rate is reduced by more than 30%);

(2) Provide n-1 emergency reserve capacity (≥ 10% rated power);

(3) Support black start function (recovery time ≤ 1 minute);

(4) Improve the reliability of power supply to more than 99.98% (microgrid management measures 2023).

3. Key technologies of battery management and safety monitoring in energy storage system

3.1. The importance of BMS in battery safety and life management

BMS is the core technology to ensure the safe and efficient operation of energy storage system. Its key functions include as outlined.

3.1.1. Battery condition monitoring and fault diagnosis

The improved Kalman filter algorithm is used to realize SOC estimation (error ≤ ± 3%); SOH evaluation based on capacity decay curve and internal resistance analysis (accuracy ± 5%); SOP real-time calculation through multi-parameter fusion (refresh rate 1 hz); fault early warning with integrated voltage/temperature gradient detection (response time ≤ 100ms).

3.1.2. Thermal management and safety protection

The liquid cooling system maintains the temperature difference of the cell ≤ 2 ℃ (gb/t 36276-2018); active equalization circuit improves energy efficiency to more than 92%; three level protection system (electrical/thermal/chemical isolation); perfluorohexanone fire extinguishing system (trigger delay ≤ 30s).

3.2. Key technical requirements of information data communication

The data communication architecture of smart microgrid energy storage system needs to meet the requirements of high real-time, high reliability and strong security. Use can fd+tsn protocol to realizeμs device layer communication, support edge cloud collaboration based on 5g urllc (delay ≤ 1ms), and deploy lightweight AI model (TensorRT acceleration) to realize local SOC dynamic calibration (10 ms) [3]. In terms of security protection, a hybrid encryption system of sm9+quantum key is built to achieve dynamic authority control through a zero-trust architecture. Experiments show that the packet loss rate of this architecture is less than 0.001% at the scale of 200 nodes, which fully conforms to IEC 62351-3 standard, and provides a technical paradigm for the implementation of the provisions on safety protection of power monitoring system [4].

4. Integrated power dispatching strategy in smart microgrid environment

4.1. Construction of multi objective optimal scheduling model

The multi-objective optimal dispatching model of smart microgrid aims to achieve the goals of economy, environmental protection and reliability. Its core architecture includes three key dimensions as listed.

4.1.1. Economic optimization

With the objective of minimizing the operation cost, a mixed integer linear programming (MILP) model is constructed, covering the grid interaction cost (time of use price mechanism), distributed generation fuel cost, energy storage loss cost (based on SOH degradation model) and demand side response compensation cost. Through DRL to dynamically adapt to electricity price fluctuations, the case of an industrial park shows that the average daily cost is reduced by 18% [5].

4.1.2. Environmental protection constraint

Introduce carbon emission intensity index (≤ 0.35 kgCO ɑ/kwh) and renewable energy penetration constraint (≥ 70%), and use NSGA-iii algorithm to coordinate economic environmental protection conflict. The carbon flow tracking technology realizes the accurate responsibility sharing between the power generation side and the load side, and the wind and light rejection rate is reduced to less than 5% in the empirical study.

4.1.3. Reliability assurance

The n-1 safety criterion and reserve capacity of energy storage (≥ 15% of rated power) are embedded, and the uncertainty of wind and solar output is addressed through robust optimization. Fault reconstruction supported by digital twin technology reduces the recovery time to 30 seconds and improves power supply reliability to 99.99%

(SAIDI ≤ 0.5 hours/year).

For model innovation, multi-time-scale optimization is adopted, ranging from second-level frequency regulation to hour-level peak shaving. 5G edge computing enables real-time response at the 50 ms level. The model strictly complies with the requirements of "security, economy, and low carbon" coordination proposed in the Blue Book on New Power System Development (2023). The model has been verified in a 200 mw microgrid and provides an extensible scheduling framework for high proportions of renewable energy integration.

4.2. Dynamic control technology and real time response mechanism

4.2.1. Prediction based distributed cooperative control method

The distributed collaborative control of smart microgrid adopts a three-level architecture of "Prediction optimization execution" To achieve dynamic regulation. In the ultra-short-term forecasting layer, the attention LSTM hybrid model is used to forecast the wind and solar output for 5–15 minutes (error ≤ 8%), and the deep clustering algorithm is used for load forecasting (accuracy ≥ 90%). The local control layer deploys model predictive control (MPC) to achieve second-level adjustment, and the regional coordination layer reduces the communication bandwidth requirements by 60% based on ADMM algorithm. The system integrates the digital twin platform, compensates the prediction error through the VSG technology, and the key indicators show that the frequency regulation response is ≤ 200 ms, the voltage recovery is ≤ 500 ms, and the islanding switching is ≤ 2 s. The empirical results of a 200 mw microgrid show that this method improves the renewable energy consumption rate by 12%, reduces the frequency out of limit events by 80%, and fully meets the requirements of the technical specification for multi-level dispatching and collaborative control of power system (2023), providing a control paradigm of millisecond level response for a high proportion of new energy systems [6].

4.2.2. Demand side response and dynamic pricing strategy

In this study, a dynamic pricing platform for smart microgrid based on blockchain is constructed, which uses a 15 minute granularity real-time electricity price update mechanism and uses a two-stage auction model to match users' demand for flexible load regulation. An asymmetric incentive mechanism was innovatively designed to implement peak shaving compensation of 0.15 yuan/kwh for industrial users and step-by-step subsidies for residential users. The virtual power plant (VPP) aggregates adjustable resources such as electric vehicles and intelligent air conditioners, and combines fuzzy logic algorithm to optimize the charging and discharging timing, so as to achieve accurate load regulation under the premise of ensuring user comfort.

The empirical data show that the strategy successfully reduced the peak to valley load ratio of the microgrid in an industrial park from 1.8 to 1.3, reduced the peak load by 22%, and increased the user participation rate to more than 75%, fully meeting the requirements of the Power Demand Side Management Measures (2023), verifying the effectiveness of the market mechanism in promoting the interaction between sources and loads, and providing a scalable implementation example for the demand response of new power systems [7].

5. Case analysis and strategy verification

5.1. Application cases in typical microgrid scenarios

5.1.1. Configuration of micro-grid energy storage system in 1 industrial park

Based on a 20 mw/100 mwh smart microgrid demonstration platform in a coastal industrial park, this study innovatively constructs a "lithium iron phosphate battery + super capacitor" hybrid energy storage system. Among them, 15 mw/90 mwh lithium battery unit adopts digital twin BMS technology to achieve SOC estimation error ± 1% accuracy and 20 minute thermal runaway warning. 5 mw/10 mwh super capacitor has 50 ms rapid response capability. The system integrates SIC converter (conversion efficiency 98.5%) and 5g-mec edge control platform (command delay ≤ 10 ms). The empirical data show that through the time-sharing arbitrage strategy, the daily energy consumption cost can be saved by 236000 yuan, the power supply reliability rate can reach 99.991% (saidi 0.3 hours/year), the renewable energy penetration rate can be increased to 85%, and the carbon emission intensity can be reduced to 0.28 kgCO ɑ/kwh, which fully meets the standard of gb/t 36547-2023. It verifies the technical advantages of multi-time scale coordinated control of hybrid energy storage in industrial scenarios, and provides an effective solution for high proportion of renewable energy consumption.

5.1.2. Dispatching scheme of off grid microgrid in remote areas

For a plateau off-grid microgrid (10 mw wind power + 3 mw/12 mwh flow battery), this study proposes a "Prediction optimization correction" Dynamic scheduling framework. The ultra-short-term prediction of wind power output (error ≤ 10%) is achieved by LSTM algorithm. Combined with the deep charging and discharging characteristics of liquid flow battery (SOC working range 20–90%), the robust optimization model is used to coordinate the operation of source and storage. The system is configured with VSG technology, the frequency deviation is stable within ± 0.2 hz, and the black start time is ≤ 45 seconds. The actual operation data show that the renewable energy power supply accounts for 93%, the annual operation time of diesel engine is reduced by 68%, and the carbon emission intensity is reduced to 0.18kgCO ɑ/kwh, which fully meets the requirements of the technical specification for off grid microgrid (nb/t 10679-2021), and verifies the applicability of the scheme in high altitude and harsh environment.

5.2. Simulation experiment and result analysis

5.2.1. Comparison of multi-objective optimization algorithms

This study systematically compares the optimization performance of particle swarm optimization (PSO), improved non-dominated sorting genetic algorithm (NSGA-iii) and DRL for the industrial park microgrid scenario. Experimental data show that PSO algorithm has fast convergence speed (50 iterations), but it is easy to fall into local optimization, with an average daily cost of 87000 yuan; NSGA-iii achieves a better solution set distribution through the elite strategy, and the cost is reduced to 82000 yuan; DRL (MADDPG framework) performed best, achieving an average daily cost of 79000 yuan and a second level response, and reducing carbon emission intensity by 26.7% (0.33 vs 0.45 kgCO ɑ/kwh) compared with PSO. The results show that the comprehensive performance of DRL is outstanding in dynamic scenarios, but its high requirements for data quality and computing power still need to be broken through, which provides an important basis for the algorithm selection of the implementation plan for the development of new energy storage in the "14th Five Year Plan".

5.2.2. System performance indicators under different control strategies

This study reveals the key performance differences by comparing the traditional centralized, single economy and multi-objective coordination control strategies. The average daily cost of the traditional strategy is 95000 yuan, and the peak valley margin is 1.8. Although the cost of single economic optimization (PSO) was reduced to 87000 yuan, it resulted in 12% light rejection rate and 0.45kgCO ɑ/kwh carbon emissions; the multi-objective collaborative strategy (DRL + NSGA-iii) achieves the optimal balance: The cost is 79000 yuan, the light rejection rate is 5%, the carbon emission is 0.33kgCO ɑ/kwh, and the frequency deviation is stable within ± 0.1 hz. It is particularly noteworthy that this strategy improves the energy storage cycle efficiency to 93% and the source load matching degree to 22%, fully meeting the triple objective coordination requirements of the guidelines for power system security and stability (2023), and providing an empirical optimization model for a high proportion of renewable energy microgrids [8].

5.3. Empirical research and technical challenges

5.3.1. Verification and deviation analysis of actual operation data

This study reveals the key performance differences by comparing the traditional centralized, single economy and multi-objective coordination control strategies. The average daily cost of the traditional strategy is 95000 yuan, and the peak valley margin is 1.8. Although the cost of single economic optimization (PSO) was reduced to 87000 yuan, it resulted in 12% light rejection rate and 0.45kgCO ɑ/kwh carbon emissions; the multi-objective collaborative strategy (DRL + NSGA-iii) achieves the optimal balance: The cost is 79000 yuan, the light rejection rate is 5%, the carbon emission is 0.33kgCO ɑ/kwh, and the frequency deviation is stable within ± 0.1 hz. It is particularly noteworthy that this strategy improves the energy storage cycle efficiency to 93% and the source load matching degree to 22%, which fully meets the triple objective coordination requirements of the guidelines for power system security and stability (2023), and provides an empirical optimization paradigm for a high proportion of renewable energy micro grid [9].

5.3.2. Technical bottleneck under the high proportion of renewable energy access

This study reveals three major technical bottlenecks faced by microgrids with a high proportion of renewable energy (penetration rate > 80%): The 200 ms response speed of existing lithium battery energy storage is difficult to meet the second level frequency regulation requirements, resulting in an increased risk of frequency instability; the prediction error of wind and solar output (short-term RMSE 12–15%) caused 20% spare capacity redundancy, which significantly increased the operation cost; the conversion efficiency of heterogeneous protocols such as Modbus and IEC 61850 is low, which restricts the timeliness of multi-source collaboration. It is particularly noteworthy that the current cost of long-term energy storage technology of flow battery (>3000 yuan/kwh) has not reached the commercialization threshold, which directly limits the progress in achieving the goal of "Renewable energy penetration rate ≥ 80%" Proposed in the blue book for the development of new power systems (2023), and it is urgent to break through the key technologies such as wide frequency-domain inertia support and cross protocol communication [10].

6. Conclusion

This study verifies the effectiveness of the multi-objective optimal scheduling model for smart microgrid, and realizes the collaborative optimization of economy (cost reduction of 18%), environmental protection (0.33kgCO ɑ/kwh) and reliability (power supply reliability ≥ 99.99%). However, a high proportion of renewable energy access still faces technical bottlenecks such as insufficient inertia support and heterogeneous communication protocols. Future research will focus on solid-state battery and wide-band gap semiconductor technology to improve the response speed of energy storage; quantum communication enhances data security, promotes the realization of the objectives of the implementation plan for the development of new energy storage during the 14th Five Year Plan Period, and supports the low-carbon transformation of the new power system.

Disclosure statement

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References

[1] Zhang Y, 2015, Research on Scheduling Algorithm of Household Energy Management System in Smart Grid Environment, thesis, University of Chinese Academy of Sciences.

[2] Sun S, Su J, Yu P, et al., 2019, Key Technologies for Control and Operation of High Proportion Renewable Energy Microgrid. Electric Power Research Institute of State Grid Shandong Electric Power Company.

[3] Lei H, Zhou J, Zhu C, et al. 2023, A New Method for Intelligent Cognition and Resource Adaptability Optimization of Complex Systems. National University of Defense Science and Technology of the Chinese People's Liberation Army.

[4] Wang C, 2022, Research on Optimal Dispatch Strategy of Microgrid based on Intelligent Algorithm, thesis, Shandong University of Technology.

[5] Wu H, Wang Y, 2016, Economic Dispatch of Microgrid based on Intelligent Single Particle Algorithm. Power System Protection and Control, 44(20): 43–49.

[6] Song Q, 2022, Multi-Source Microgrid Optimal Scheduling Method based on Multi-Agent, thesis, North China University of Water Resources and Hydropower.

[7] Zhang H, 2022, Research on Optimization Strategy of Energy Storage Cost and Operating Profit in Microgrid Energy Management, thesis, Donghua University.

[8] Chen X, 2019, Research on Optimal Dispatch of Multi Energy Complementary Microgrid based on Improved Bat Algorithm, thesis, Xi'an University of Technology.

[9] Pan H, 2015, Research on Economic Dispatch of Microgrid and Reliability of Distribution Network with Microgrid, thesis, Hunan University.

[10] Long J, 2020, Research on Economic Operation Optimization of Microgrid with Distributed Generation, thesis, Nanchang University.

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Domestic Application and Risk Management of Bimetallic Self-Sealing Composite Gasket in High Temperature Petrochemical Equipment

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Abstract: This paper addresses the stringent requirements for sealing technology in high-temperature and high-pressure petrochemical equipment, and introduces the key technologies and performance studies for the domestication of bimetallic self-sealing composite gaskets. The gasket features a composite structure of a double-layer metal framework and flexible graphite, relying on the "pressure self-sealing" mechanism to maintain excellent sealing performance even under high-temperature conditions. The article systematically elaborates on its material process innovations, thermomechanical coupling experiments, and methods for verifying sealing integrity, and establishes a life prediction and engineering risk management system, providing a technical route and theoretical support for the reliable application of high-end sealing components in the petrochemical field in China.

Keywords: Double-layer metal skeleton self-sealing gasket; High-temperature petrochemical equipment; Graphite composite layer

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1. Introduction

As the petrochemical industry evolves towards high-temperature and high-pressure conditions, the sealing performance of equipment faces increasingly severe challenges. The petrochemical industry policy released in 2023 explicitly lists enhancing the reliability of key equipment as a key development direction. High-temperature environments impose stringent requirements on sealing materials. For instance, they need to possess excellent thermal stability, creep resistance, and corrosion resistance. Traditional sealing materials often struggle to meet these comprehensive performance indicators. The self-sealing composite gasket based on a double-layer metal skeleton structure effectively addresses this challenge through innovative design. It utilizes a double-layer metal-formed skeleton to establish rigid contact with the flange, and simultaneously fills micro-gaps with surfacecompounded graphite material, achieving a durable and reliable seal under high-temperature conditions. From skeleton structure optimization, graphite compounding process, to performance verification system, relevant research provides a complete technical path for enhancing the performance of domestic seals, which is of great strategic significance for ensuring the safe operation of petrochemical equipment.

2. Technical basis of bimetallic self-sealing composite gasket

2.1. Analysis of demand for high-temperature petrochemical sealing technology

Under high-temperature and high-pressure conditions, petrochemical equipment has stringent requirements for sealing materials. In terms of thermal stability, due to the high operating temperature of the equipment, the sealing material must maintain stable performance at high temperatures to avoid structural damage or degradation of sealing performance caused by temperature changes [1]. Creep resistance is also crucial. When subjected to long-term pressure, the material should prevent slow deformation to ensure the durability of the sealing effect. Regarding corrosion resistance, the petrochemical environment is complex, with various corrosive media present. The sealing material must be able to resist corrosion and prevent leakage. Traditional sealing materials fall short in these aspects. Their failure mechanisms include structural changes in the material at high temperatures, creep due to inability to withstand long-term pressure, and susceptibility to corrosion, which cannot meet the sealing requirements of high-temperature petrochemical equipment.

2.2. Innovative features of bimetallic composite structure

The design of the double-layer metal skeleton structure is innovative. In principle, it adopts a double-layer skeleton design composed of the same metal material, ensuring structural consistency through precision molding processes. Simultaneously, it utilizes the synergistic effects of temperature rise, internal pressure, elastic deformation, and plastic deformation to achieve self-sealing functionality [2]. The surface composite graphite layer closely adheres to the flange metal surface. The high-temperature stability and flexibility of graphite material effectively fill micro-gaps, maintaining long-lasting sealing under high-temperature and high-pressure conditions. Elastic deformation allows the gasket to quickly adapt to the unevenness of the flange surface when pressed, forming an initial seal. Plastic deformation further strengthens the sealing interface through local material flow, ensuring stable sealing performance even under long-term thermal cycling or stress fluctuations. This “double-layer metal skeleton-graphite layer” composite structure is one of the key innovative features of the gasket in adapting to complex working conditions in high-temperature petrochemical equipment.

3. Path to breakthroughs in key localization technologies

3.1. Innovation in material composite manufacturing process

The precision forming process of the double-layer metal skeleton is a crucial step in the manufacturing process. During the forming process, it is necessary to strictly control parameters such as mold precision, rotational speed, and temperature to ensure the consistency of the skeleton structure and dimensional stability [3]. To address the issue of residual stress, by optimizing annealing process parameters, such as temperature curve, holding time, etc., and combining mechanical sizing technology, the internal stress generated during processing is effectively eliminated, avoiding deformation or performance degradation caused by stress concentration. At the same time, advanced online detection methods are used to monitor the quality of the formed skeleton, ensuring that its geometric accuracy and mechanical properties meet the stringent requirements of high-temperature petrochemical equipment. This precision forming process provides an important guarantee for the reliability and durability of the bimetallic self-sealing composite gasket.

3.2. Surface modification technology

Graphite composite layer coating technology is a key aspect of surface modification treatment. By optimizing coating process parameters, such as coating pressure, temperature profile, and curing time, this technology can significantly enhance the bonding strength between the graphite layer and the metal skeleton [4]. The use of precisely controlled coating equipment ensures that the graphite layer is uniformly and densely coated on the surface of the metal skeleton, forming a stable interfacial bond. This graphite-metal composite structure exhibits excellent adaptability under high-temperature conditions. The graphite layer not only effectively fills the micro-defects on the flange contact surface, but its unique thermal stability and self-lubricating properties also significantly reduce thermal stress concentration. By optimizing the formulation of graphite materials and coating processes, the sealing reliability and service life of composite gaskets in high-temperature and high-pressure environments can be further improved, meeting the stringent requirements of petrochemical equipment.

4. Experimental study on performance under high-temperature conditions

4.1. Thermal-mechanical coupling test

4.1.1. Thermal cycle load test

A thermal shock cycle experimental model was established to test the double-layer metal skeleton self-sealing composite gasket. This model simulates the actual thermal cycling conditions in high-temperature petrochemical equipment, focusing on investigating the performance evolution of the graphite layer under repeated thermal shocks. During the experiment, the stability of the graphite layer at high temperatures was evaluated by monitoring the compression-rebound performance of the gasket and the changes in sealing interface contact stress. Microstructural analysis showed that the graphite layer can effectively buffer the thermal stress between the metal skeleton and the flange during thermal cycling, and its unique layered structure helps maintain tight contact at the interface. This design significantly improves the sealing reliability of the gasket under severe temperature fluctuations, providing important performance data support for domestic applications [5].

4.1.2. Creep relaxation behavior test

The high-temperature creep characteristics of double-layer metal skeleton gaskets were studied using a stepwise loading method, with a focus on the regulating effect of the metal skeleton and graphite layer on stress relaxation behavior. The experimental system simulated the complex stress-temperature coupling conditions in petrochemical equipment, and stress decay curves at different temperatures were obtained through precise control of the loading process. The results showed that the plastic flow characteristics of the graphite layer could effectively compensate for the creep deformation of the metal skeleton, maintaining stable sealing contact pressure. The constitutive model established based on experimental data accurately described the mechanical response law of the graphite-metal composite structure at high temperatures, providing a theoretical basis for predicting the long-term service performance of the gasket [6].

4.2. Verification of sealing integrity

4.2.1. Helium mass spectrometer leak detection experiment

A novel combined sealing surface testing device was designed for assessing the sealing performance of double-layer metal-framed self-sealing gaskets under high-temperature conditions. The experiment utilized 99.9% high-purity nitrogen as the medium and combined it with helium mass spectrometer leak detection technology to precisely measure the leakage rate under varying compressive stress conditions. The relationship between leakage rate and sealing performance was systematically analyzed. During the experiment, key parameters such as temperature and pressure were strictly controlled to simulate the actual high-temperature and high-pressure conditions of petrochemical equipment. The focus was on investigating the behavior of the graphite layer under thermal cycling and creep conditions. It was found that the graphite layer could effectively fill micro-gaps at high temperatures, significantly enhancing the sealing effect. By recording the leakage rate data and corresponding changes in compressive stress, a relationship curve was plotted, providing a reliable basis for evaluating the sealing integrity of the gasket under high-temperature conditions. This research offers important technical support for the localization and engineering risk management of such gaskets [7].

4.2.2. Service life prediction model

A fatigue propagation rate calculation based on the Paris formula is used to construct a life assessment equation. By studying the material fatigue propagation behavior of double-layer metal skeleton self-sealing gaskets under high-temperature conditions, the Paris formula is accurately applied to calculate their fatigue propagation rate [8]. Considering the actual service conditions of the gaskets in petrochemical equipment, including the influence of temperature, pressure, medium, and other factors on material fatigue behavior, the formula is appropriately modified. The modified propagation rate is combined with parameters such as the initial defect size and critical defect size of the gasket to construct a service life prediction model. This model can accurately predict the service life of the gasket in high-temperature petrochemical equipment, providing an important basis for the safe operation and maintenance of the equipment.

5. Engineering application risk management system

5.1. Risk identification and assessment

5.1.1. Design and material risks

In the risk assessment of double-layer metal skeleton self-sealing composite gaskets, graphite layer aging and metal skeleton fatigue are the primary risk factors. Under high-temperature conditions, the graphite layer gradually undergoes oxidation and structural loosening, leading to a decline in its sealing performance. Simultaneously, the metal skeleton may develop fatigue cracks under long-term cyclic loading, affecting the overall structural integrity [9]. Therefore, it is necessary to establish a high-temperature aging evaluation system for graphite materials, quantifying the performance degradation patterns through accelerated aging experiments. For the metal skeleton, fatigue life testing should be conducted to analyze the characteristics of crack initiation and propagation. By constructing a multidimensional evaluation matrix encompassing material, structure, and operating conditions, the failure risk of the gasket under different service environments can be systematically assessed, providing a basis for optimal design.

5.1.2. Production and manufacturing risks

In the manufacturing process, it is crucial to utilize the FMEA (Failure Mode and Effects Analysis) method to analyze the impact of process parameter fluctuations on product quality. Fluctuations in process parameters may arise from various factors, such as equipment accuracy, differences in raw materials, and the skill level of operators. These fluctuations can lead to various failure modes in products, such as dimensional deviations and decreased sealing performance, which in turn affect product quality. Through the FMEA method, these potential failure modes can be systematically identified and their impact on product quality can be assessed. This helps manufacturers take proactive measures, such as optimizing process parameters, strengthening equipment maintenance, and personnel training, to reduce risks, ensure product quality meets requirements, and improve the application reliability of products in high-temperature petrochemical equipment [10].

5.2. Risk control measures

5.2.1. Potential directions for condition monitoring and intelligent early warning

For the application of bimetallic self-sealing composite gaskets in high-temperature petrochemical equipment, a local state monitoring method based on fiber Bragg grating sensing can be explored. This technology utilizes the sensitive characteristics of optical fibers to temperature and stress, embedding sensors at the gasket or key flange connections to collect temperature and stress data in real time, thus achieving indirect perception of the sealing state. Long-term data can be used to analyze the evolution trend of gasket performance and provide early warning signals in case of abnormal temperature rise or stress mutation, providing a basis for regular maintenance and risk prevention and control at key sealing points.

This type of monitoring method is particularly suitable for core sealing areas with high temperature, high pressure, or frequent process fluctuations. Through limited deployment, it can achieve state visualization of key areas. However, at present, this technology is still in the research and pilot application stage. For its actual promotion, comprehensive considerations must be made regarding cost, reliability, and compatibility with existing equipment management systems. In the future, with the reduction in the cost of sensing technology and the promotion of intelligent operation and maintenance modes, this type of localized and refined monitoring approach is expected to become a beneficial supplement to the management of key sealing points in petrochemical plants.

5.2.2. Standardized management process

In the domestic application of bimetallic self-sealing composite gaskets in high-temperature petrochemical equipment, it is necessary to establish QHSE management system documents covering the entire cycle of design, manufacturing, and installation. During the design phase, the gasket structure and materials must be precisely designed based on the specific parameters and operating conditions of the high-temperature petrochemical equipment to ensure its sealing performance and high-temperature resistance. The manufacturing process strictly controls the quality of raw materials and adopts advanced processes to ensure the dimensional accuracy and performance consistency of the gaskets. In the installation process, detailed operating procedures are formulated, and professional training is provided to installation personnel to ensure correct installation. At the same time, a quality supervision and inspection mechanism is established to strictly inspect products at each stage and rectify non-conformities in a timely manner. Attention should also be paid to environmental, health, and safety management to reduce environmental impact and ensure personnel health and safety.

5.3. Emergency management mechanism

5.3.1. Stability enhancement strategy based on self-sealing mechanism

Focusing on the special sealing mechanism of double-layer metal skeleton self-sealing composite gaskets under high-temperature conditions, the long-term sealing stability can be further enhanced by optimizing their structural design and material system. The unique "pressure self-sealing" characteristic of this gasket enables it to generate self-reinforced sealing stress under the action of medium pressure. This inherent advantage provides a solid foundation for sealing reliability under complex high-temperature conditions. By improving the material compatibility and structural morphology of the double-metal skeleton, its adaptive compensation ability under temperature fluctuations can be significantly enhanced. The performance durability of the graphite sealing layer has a decisive impact on the overall lifespan of the gasket.

Using specially treated flexible graphite materials and enhancing their anti-aging and anti-creep characteristics through optimized composite processes can effectively maintain a long-term stable sealing state. Multiple experiments have shown that the comprehensively optimized gasket can maintain excellent sealing performance even after multiple thermal cycles under high-temperature conditions. This technical approach focuses on improving the performance of the gasket itself by fully utilizing its self-sealing characteristics and optimizing the durability of key materials, significantly enhancing its reliability and service life under high-temperature and high-pressure environments. This deep optimization based on inherent mechanisms provides a more fundamental and easily scalable solution for high-temperature flange sealing, with good engineering application prospects.

5.3.2. Quick replacement and emergency response plan

For the domestic application of bimetallic self-sealing composite gaskets in high-temperature petrochemical equipment, it is crucial to establish an efficient rapid replacement and emergency response system. Since the gasket will leak once damaged and cannot be repaired online, it is necessary to focus on improving the spare parts management mechanism and optimizing the gasket replacement process. Standardized replacement procedures should be pre-designed for different models and equipment operating conditions, and specialized disassembly and assembly tools and positioning fixtures should be equipped to achieve rapid positioning and safe replacement of damaged gaskets.

At the same time, it is necessary to establish a comprehensive emergency response plan, clarifying the operational procedures, personnel division, and safety precautions in case of a leakage. This ensures that a professional team can be quickly organized for efficient handling in emergencies. Through systematic technical training and emergency drills, the proficiency of on-site personnel in gasket replacement operations and their ability to handle emergencies can be improved.

This system is dedicated to minimizing equipment downtime, controlling maintenance costs, and ensuring the safe and stable operation of high-temperature petrochemical equipment, providing reliable technical support for the large-scale industrial application of bimetallic self-sealing composite gaskets.

6. Conclusion

The domestic application of double-layer metal skeleton self-sealing composite gaskets in high-temperature petrochemical equipment has achieved remarkable results. The core technological breakthrough is mainly reflected in the innovative combination of the design of the same type of metal double-layer skeleton and high-performance graphite composite technology. By optimizing the structural precision of the metal skeleton and the graphite layer coating process, the sealing reliability issue under high-temperature conditions has been successfully addressed, and large-scale applications have been realized in multiple petrochemical projects. Currently, there are still challenges such as the need to improve simulation methods for extreme conditions and deepen digital management throughout the entire life cycle. It is suggested to establish a collaborative innovation platform for industry, academia, research, and application, focusing on tackling key technologies such as high-temperature modification of graphite materials and intelligent monitoring, while accelerating the development of a domestic sealing component standard system aligned with international standards. These measures will further enhance product quality and competitiveness, providing more reliable technical support for the safe operation of petrochemical equipment.

Disclosure statement

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References

[1] Liu R, 2023, Research on the Low-Temperature Sealing Performance of Graphite Tooth Gaskets, thesis, Lanzhou University of Technology.

[2] Lin P, 2021, Research on Environmental Risk Management of Fujian Petrochemical Company, thesis, Nanhua University.

[3] Miao J, 2021, Development of a GIS-based Equipment Management Platform for Petrochemical Enterprises, thesis, Tianjin Polytechnic University.

[4] Zhu H, 2023, Research on Microstructure and Properties of Self-Resistant Heating 8090/2195 Al-Li Alloy Bimetal Composite Casting, thesis, Harbin Institute of Technology.

[5] Hao P, 2022, Simulation Analysis of the Influence of Seal Gasket Structure and Material on the Sealing Performance of Plate Heat Exchangers, thesis, Changchun University of Technology.

[6] Hu Z, Yu Y, Fan Z, et al., 2021, High-Temperature Resistant Plastic Ceramic Sealing Gasket and its Application in Steel Plants. Continuous Casting, 2021(1): 77–80.

[7] Wang J, Huang R, Shi B, 2022, IPv6 Transformation and Localization Application of the Back-end System of the Haihe River Water Resources Commission Portal Website. Haihe Water Conservancy, 2022(3): 35–37.

[8] Li X, 2021, Analysis on the Localization Application of Ultra-low Temperature Valves in LNG Receiving Terminal Projects. Petrochemical Technology, 28(8): 21–22.

[9] Xie D, 2024, Discussion on the Calculation and Design of Welded Sealing Diaphragm Gaskets for High-Pressure Equipment. Fertilizer Design, 62(1): 39–42.

[10] Hu H, 2021, Research on the Informatization of Risk Management for Petrochemical Equipment. China Equipment Engineering, 2021(5): 58–59.

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Key Technologies and Implementation Paths for Automation Transformation of Old Production Lines

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Abstract: The automation transformation of old production lines is of great significance for enhancing the competitiveness of enterprises. The transformation needs to first identify core requirements, attach importance to data collection and equipment interconnection, accurately consider technology selection, conduct process simulation verification, adopt a progressive implementation mode, design data connectivity solutions and implementation paths. The practice of transforming automobile and electronic assembly lines has verified its effectiveness, constructed a calculation model to evaluate economic benefits, analyzed non-economic benefits from multiple dimensions, and provided comprehensive solutions for the transformation.

Keywords: Old production line; Automation transformation; Technology selection

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1. Introduction

Made in China 2025 was promulgated in 2015 with the aim of promoting the transformation and upgrading of China's manufacturing industry. Against this policy background, the automation renovation of old production lines is of great significance for enhancing enterprise production efficiency and competitiveness. Currently, old production lines suffer from issues such as high energy consumption, frequent equipment failures, and poor production process continuity, which severely constrain enterprise development. During renovation, core needs must be identified from dimensions such as production take time matching, equipment compatibility, and human-machine collaboration requirements. Key technologies like data acquisition and equipment interconnection should be employed, with precise consideration of technology selection, validation through process simulation, implementation via progressive renovation paths, and analysis of both economic and non-economic benefits. This series of measures forms a comprehensive and systematic solution, helping enterprises achieve transformation and upgrading.

2. Current status and technical requirements of automation renovation for old production lines

2.1. Analysis of existing problems in old production lines

By comparing energy consumption data and equipment OEE indicators, numerous problems in old production lines can be clearly identified. From the perspective of energy consumption data, aging equipment in old production lines results in low energy utilization rates. The high-energy-consumption operating mode not only increases production costs but also exerts significant pressure on the environment [1]. In terms of equipment OEE indicators, frequent failures severely impact overall production efficiency. Due to long-term use, severe wear on mechanical components leads to high failure rates and prolonged maintenance times, reducing effective equipment operating time. Additionally, poor continuity in production processes results in unsmooth connections between various production links, with delays or blockages in material transfer and other stages creating production bottlenecks. These existing problems in old production lines severely restrict improvements in enterprise production efficiency and competitiveness, urgently requiring automation renovation to optimize production processes, increase efficiency, and reduce energy consumption and failure rates.

2.2. Identification of core requirements for automation renovation

When renovating old production lines for automation, core requirements can be identified from three dimensions: production take time matching, equipment compatibility, and human-machine collaboration requirements. In terms of production take time matching, the take time of old production lines may not adapt to new production scales and efficiency demands; precise calculation of time for each link is needed to ensure smooth take time after automation renovation and avoid bottleneck processes slowing the overall rhythm [2]. Regarding equipment compatibility, old equipment varies in brands and models, with non-unified interfaces and communication protocols; renovation must ensure effective docking and collaborative operation between new automated equipment and existing equipment, achieving data interaction and sharing. Human-machine collaboration requirements focus on the coordination between automated equipment and operators, leveraging the high-efficiency and accuracy advantages of automation while facilitating monitoring, maintenance, and intervention by operators through rational layout of operation interfaces and optimized workflows, thereby enhancing overall operational safety and efficiency.

3. Research on key technology systems for automation renovation

3.1. Data acquisition and equipment interconnection technologies

In the automation renovation of old production lines, data acquisition and equipment interconnection technologies are crucial. Based on an industrial IoT architecture, in-depth analysis of equipment data acquisition protocols is required. The OPC-UA protocol is key among them, offering advantages such as platform independence and high security, effectively enabling data interaction between different devices. Application examples of the OPC-UA protocol show that it can break data barriers between heterogeneous systems, achieving efficient data acquisition and transmission [3]. At the same time, for various heterogeneous systems in old production lines, integration schemes must be developed to enable interconnection among equipment of different brands and eras. Through rational selection of equipment data acquisition protocols and scientific design of heterogeneous system integration schemes, precise data acquisition and smooth interconnection of old production line equipment can be realized, providing a solid data foundation and equipment connection guarantee for subsequent automation renovation and promoting the intelligent upgrading of old production lines.

3.2. Technology selection for intelligent upgrading

In the intelligent upgrading process of old production lines, precise consideration of technology selection is necessary. For industrial robot applications, robot types and quantities should be selected based on factors such as operational complexity, repetition, and load requirements of the production line. For example, in an automotive parts assembly line requiring handling of multiple parts with high assembly precision, multi-joint high-precision robots are preferable. When selecting AGV scheduling systems, AGV load capacity, operating speed, and scheduling algorithms should be determined according to material transport volume, path layout, and transport frequency on the production line. For visual inspection devices, selection should be based on inspection precision, speed, and target features. For instance, in electronic chip inspection requiring extremely high precision, high-resolution and high-precision visual inspection equipment is needed. By comparing and analyzing adaptation standards for these technology combinations, scientific technology selection schemes can be provided for the intelligent upgrading of old production lines, ensuring efficient and stable operation after renovation [4].

4. Design of implementation paths for automation renovation

4.1. Phased implementation strategy for renovation projects

4.1.1. Preliminary process simulation validation

In the automation renovation of old production lines, preliminary process simulation validation is crucial. Using digital twin technology to build a virtual debugging environment for the production line enables feasibility verification of renovation schemes before actual implementation. By establishing digital models of production line equipment and process links, simulating their operating states and interactions, performance under different conditions can be precisely analyzed. For example, virtual testing of material transfer paths, equipment operating take times, and production process connections can identify potential issues such as collision interference or take time mismatches in advance [5]. This allows optimization of renovation schemes based on simulation results, avoiding delays, cost increases, and other issues due to unreasonable schemes during actual implementation, effectively improving the success rate and efficiency of renovation projects and laying a solid foundation for subsequent practical work.

4.1.2. Progressive renovation implementation mode

The automation renovation of old production lines adopts a progressive implementation mode to minimize the impact on production and steadily enhance automation levels. At the first step, conduct detailed assessments of each production line link and, based on results, select relatively independent modules with minimal impact for replacement. For example, start with the material conveying module by adopting new automated conveying equipment while ensuring transitional capacity through personnel adjustments and optimized production scheduling. After the material conveying module is renovated and operates stably, progressively advance automation in other modules such as processing and inspection. This mode makes the renovation process gradual, allowing employees to adapt to new equipment and processes step by step, while transitional capacity assurance measures effectively reduce negative impacts on overall production, laying a solid foundation for successful implementation of old production line automation renovation [6].

4.2. System integration and debugging schemes

4.2.1. Multi-level system docking architecture

A three-level data penetration scheme should be designed for ERP-MES-equipment control layers to build a multi-level system docking architecture. The ERP system focuses on enterprise resource planning and management, storing overall operational data such as orders and material plans. The MES system, as a production execution system, plays a bridging role at the workshop level, receiving production tasks from ERP and feeding back equipment status and production progress to ERP. The equipment control layer directly handles specific equipment operations and control. By establishing standardized data interfaces and communication protocols, smooth data interaction between levels is achieved, ensuring accurate delivery of production instructions to equipment and timely feedback of real-time equipment data to MES and ERP, providing an accurate basis for production decisions [7]. This multi-level system docking architecture effectively integrates data and functions across levels in old production lines, facilitating efficient advancement of automation renovation.

4.2.2. Whole-line joint debugging standards and acceptance

The design of automation renovation implementation paths must fully consider the current status of old production lines. Comprehensive assessments should be conducted to analyze efficiency and issues in each link. Based on identified problems, formulate detailed renovation schemes in combination with automation technologies, selecting suitable automated equipment and control systems. For system integration and debugging, ensure effective docking of automated equipment using modular integration approaches and progressively integrating parts. Debugging starts from single-machine, proceeds to unit debugging, and finally whole-line joint debugging. Whole-line joint debugging standards and acceptance are based on an established 22-item acceptance indicator system, covering production take time testing, fault simulation testing, etc., strictly checking production line stability, efficiency improvements, and fault response capabilities to ensure that renovated old production lines meet high-quality automated production requirements [8].

5. Engineering practice and benefit verification

5.1. Automotive parts production line renovation case

5.1.1. Specific implementation of renovation scheme

In the renovation of welding robot workstations on an automotive parts production line, process parameters were first optimized. Through extensive experiments and simulation analysis, welding current, voltage, speed, and angle were precisely adjusted to ensure stable welding quality and good weld formation, raising the welding yield rate from 85% to over 95% [9]. At the same time, emphasis was placed on upgrading the safety protection system. High-precision infrared sensing devices were installed to form sensing zones around the robot's operating radius, triggering alarms and pausing robot operation upon personnel entry. Additional protective barriers and light curtain sensors further ensured operator safety. Furthermore, the robot teach pendant interface was optimized to reduce mis-operation risks. After renovation, the production line's automation level significantly increased, boosting production efficiency by over 30%, markedly reducing labor costs and safety incident rates, and achieving excellent engineering practice outcomes and economic benefits.

5.1.2. Quantitative analysis of renovation effects

In this engineering practice of automotive parts production line renovation, quantitative analysis of effects is crucial. Taking a certain old automotive parts production line as an example, pre-renovation equipment comprehensive efficiency was low, with high product defect rates severely affecting production benefits and quality. Through automation renovation, applying key technologies and reasonable implementation paths, significant results were achieved. From key indicators, equipment comprehensive efficiency increased by 37%, meaning more qualified products could be produced per unit time, greatly enhancing production efficiency [10]. Meanwhile, the product defect rate dropped by 62%, effectively reducing costs from defective items and improving overall product quality. These quantitative data fully validate the success of this old production line automation renovation in improving production benefits and product quality, providing strong data support and practical reference for subsequent similar line renovations.

5.2. Electronic assembly line renovation practice

5.2.1. Experience in automated equipment selection

In the electronic assembly line renovation practice for old production line automation, technical-economic analysis is crucial for parallel robot selection in precision assembly links. Technically, focus on repeat positioning accuracy, which directly affects assembly precision, generally requiring ± 0.05 mm or higher to meet precision component needs. Motion speed is also critical, enabling completion of assembly actions within specified take times, such as a certain number of products per hour. Load capacity must adapt to different component specifications. Economically, calculate equipment procurement costs by comparing prices of different brands and models. Additionally, consider operating costs like energy consumption and maintenance, which differ significantly long-term. Comprehensively balancing technical and economic factors enables precise selection, meeting production needs while maximizing cost benefits.

5.2.2. Breakthrough in system integration difficulties

In the system integration process of electronic assembly line renovation practice, old production line automation faces many difficulties. Timing coordination between SMT equipment and AGV systems is one key issue. In practice, in-depth study of their operating logic and take times is needed. Precise analysis of SMT equipment mounting processes and time parameters in each link, along with detailed understanding of AGV transport path planning and start-stop time control. By building a simulation test environment and continuously adjusting parameters using advanced sensors and control algorithms, AGV can arrive at designated positions for material pickup and transport at precise times after SMT mounting completion. Through repeated testing and optimization, this timing coordination challenge was successfully resolved, significantly improving electronic assembly line operating efficiency and substantially shortening product production cycles, effectively validating the renovation scheme's feasibility and effectiveness in enhancing production benefits.

5.3. Comprehensive evaluation of renovation project benefits

5.3.1. Economic benefit calculation model

In constructing an economic benefit calculation model for old production line automation renovation projects, the payback period intuitively reflects the time needed to recover initial investment. By calculating renovation investment and subsequent annual net benefits, the payback period is derived, the shorter, the faster the recovery and better the project economics. Net present value discounts future net cash flows to present value at a certain rate and subtracts initial investment. If greater than zero, the project creates additional value considering time value of money, indicating economic feasibility. These parameters combined provide a comprehensive economic-level benefit assessment for old production line automation renovation, offering quantitative basis for decisions on project implementation viability.

5.3.2. Non-economic benefit analysis framework

In the non-economic benefit analysis framework for old production line automation renovation projects, production efficiency elasticity is an important dimension. Automation renovation enhances production's ability to respond to market demand changes. For instance, when orders suddenly increase, automated equipment can quickly boost capacity through flexible parameter adjustments, significant for adapting to volatile markets. In terms of technical reserve value, introduced advanced automation technologies lay the foundation for future product upgrades and business expansion. For example, application of intelligent control technologies enables mastery of key domain technologies, facilitating the launch of more competitive products and enhancing enterprise industry status and influence, yielding profound long-term non-economic benefits.

6. Conclusion

Automation renovation of old production lines is of great significance for enhancing enterprise production efficiency and competitiveness. During the process, technology selection decision trees enable more scientific and reasonable choices of suitable automation technologies, ensuring accurate renovation direction. Risk control checklists safeguard the entire project, identifying and mitigating potential risks in advance to reduce uncertainties. Renovation technology iteration directions proposed based on Industry 4.0 development requirements provide guidance for continuous upgrading of old production lines, maintaining adaptability and advancement in future production environments. These key technologies and implementation paths form an organic whole, offering a comprehensive, systematic, and forward-looking solution for old production line automation renovation, helping enterprises achieve transformation and upgrading in the automation wave and embark on a path of high-quality development.

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References

[1] Deng Y, 2022, Analysis and Implementation of Automation Transformation of LS Company's Lithium Battery System Production Line, thesis, Shandong University of Science and Technology.

[2] Ren Y, 2022, Automation Analysis and Improvement of CQK Factory Ball Sales Joint Production Line, thesis, Chongqing University of Technology.

[3] Gao S, 2023, Automation and Intelligent Transformation of Aluminum Profile Extrusion Forming, thesis, Dalian University of Technology.

[4] Zhang Y, 2022, Design and Research on Automation Transformation of Excitation Control System for Meishan Mining Ball Milling Synchronous Machine, thesis, Southeast University.

[5] Zhang W, 2021, Research and Application of Key Technologies for Automation and Informationization Transformation of Heavy Truck Differential Shell Production Line, thesis, Shandong University.

[6] Li J, Liu W, 2023, Analysis of Automation Transformation of Automobile Production Line. Special Purpose Vehicles, 2023(11): 75–77.
[7] Huang F, Wang Y, 2024, Automation Transformation and Implementation of Automobile Final Assembly Production Line. Era Automotive, 2024(13): 34–36.
[8] Red Y, Chen X, Lu M, et al., 2021, Research on Automation Transformation of Traditional Pipe Pile Production Line. Concrete and Cement Products, 2021(9): 35–38.
[9] Li X, 2022, Optimization Study on the Renovation Plan of Stamping Old Mold Automation Production Line. Paper Equipment and Materials, 51(9): 34–36.
[10] Gao Y, 2023, Exploration and Application of Automotive Welding Production Line Transformation. Automotive Practical Technology, 48(10): 181–18

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Research on Intelligent Management Mode of Property Electromechanical: A New Way to Improve the Efficiency of Property Management

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Abstract: Intelligent management of property mechanical and electrical systems integrates multiple technologies and concepts. While IoT enables device connectivity and data collection analysis, it also confronts inefficiencies in traditional management approaches. This paper elaborates on the deployment of sensor layer devices, construction of data platforms, energy consumption monitoring, emergency response protocols, evaluation models, talent optimization strategies, and future development directions.

Keywords: Property mechanical and electrical systems; Intelligent management; Technology application

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1. Introduction

With the rapid advancement of technology, the property management industry is transitioning to digitalization, where intelligent management of mechanical and electrical systems has become a key development direction. The "14th Five-Year Plan for Digital Economy Development" released in 2022 emphasized promoting industrial digital transformation, providing policy support for intelligent property management. This smart management approach integrates core concepts like IoT, big data, and cloud computing, encompassing a full lifecycle management philosophy for electromechanical facilities. However, challenges persist including inefficient traditional management methods, urgent demands for intelligent solutions, and insufficient system compatibility. Addressing these issues to establish efficient intelligent management systems and enhance property management efficiency has become a focal point of current research.

2. The theoretical basis of intelligent management of property electromechanical

2.1. Core concepts of intelligent management

Property management of mechanical and electrical facilities involves a variety of core concepts. Internet of Things

(IoT) technology enables interconnectivity between devices. It collects operational data of mechanical and electrical facilities through sensors and other devices, and transmits this data in real-time to the management system, providing fundamental data support for subsequent analysis and decision-making [1]. Big data technology, on the other hand, stores and analyzes the vast amount of equipment operation data, uncovering potential patterns and issues within it. For example, it can predict the probability of equipment failure and schedule maintenance in advance. Cloud computing provides powerful computing capabilities and storage space for data processing and storage, ensuring the efficient operation of the system. Meanwhile, the concept of the full life-cycle management of mechanical and electrical facilities emphasizes the management of the entire process from planning, design, procurement, installation, operation, maintenance to disposal of equipment, in order to optimize equipment performance and minimize costs, thereby improving the overall efficiency and effectiveness of property management [1].

2.2. Analysis of industry development status

With the rapid advancement of technology, the property management industry is also gradually moving towards digitalization. However, in this process, the management of mechanical and electrical systems still faces many problems. Traditional management methods of mechanical and electrical systems often rely on manual operations and experiential judgments, which lead to low efficiency and a high likelihood of errors [2]. For example, the inspection and maintenance of equipment may not be timely, and it is not possible to accurately predict equipment failures. At the same time, there is a lack of effective coordination between different mechanical and electrical equipment, and overall optimized operation cannot be achieved. In terms of intelligent management needs, as the functions of buildings become increasingly complex, the demand for intelligent management of mechanical and electrical systems is becoming more and more urgent. Intelligent management can improve the operating efficiency of equipment, reduce energy consumption, enhance the overall service quality of property management, and better meet the needs of property owners [2].

3. Intelligent management system architecture

3.1. Construction of the perception layer of the IoT

The IoT perception layer is the foundation of intelligent management systems and is crucial for the intelligent management of property mechanical and electrical equipment. At this level, it is necessary to reasonably deploy perception devices such as smart electricity meters, water pressure sensors, and elevator operation monitoring terminals. Smart electricity meters should be installed according to the power demand and circuit layout of different areas to ensure the accurate collection of electricity data [3]. Water pressure sensors need to be installed at key water supply nodes to monitor water pressure changes in real-time and ensure stable water supply. Elevator operation monitoring terminals should be installed in elevator cabins and machine rooms to comprehensively monitor the operating status of elevators, including speed, load, and fault information. At the same time, a unified data collection standard should be established to ensure that the data collected by various perception devices is formatted, accurate, and reliable, facilitating subsequent data processing and analysis.

3.2. Data center construction

In the construction of the data platform within the intelligent management system architecture for property mechanical and electrical equipment, it is necessary to focus on the integration and processing mechanisms of energy consumption data, equipment operating parameters, and maintenance records, and to establish a standardized data asset catalog [4]. Energy consumption data reflects the energy usage of mechanical and electrical equipment, equipment operating parameters indicate the real-time status of equipment operation, and maintenance records contain historical information on equipment maintenance and care. By integrating and processing these data, potential patterns and issues in equipment operation can be uncovered, providing a basis for intelligent management decision-making. Establishing a standardized data asset catalog helps to regulate the classification, storage, and retrieval of data, enhancing data usability and management efficiency, thereby better supporting the operation of the entire intelligent management system.

4. Typical application scenarios

4.1. Intelligent control of power supply and distribution

4.1.1. Dynamic monitoring of energy consumption

Energy consumption dynamic monitoring is crucial in the intelligent control and management of power supply and distribution. Smart electricity meters and other devices can be used to collect power usage data in real-time, including parameters such as voltage, current, and power [5]. This data can be transmitted to a monitoring system for visualization. On one hand, it allows management personnel to intuitively understand the energy consumption of different areas and equipment. On the other hand, the system can analyze based on historical and real-time data. For example, by constructing a power load forecasting model, future energy consumption trends can be predicted. When abnormal energy consumption data occurs, the system can promptly issue an alarm to achieve intelligent diagnosis of abnormal electricity usage. At the same time, the system can automatically generate energy efficiency optimization suggestions based on the analysis results, such as adjusting equipment operating hours and optimizing load distribution, thereby improving the energy efficiency of the power supply and distribution system and reducing energy consumption costs.

4.1.2. Emergency response mechanism

In the emergency response mechanism of intelligent control and management of power supply and distribution, the remote monitoring system of the distribution room plays a key role. The system integrates functions of fault early warning and automation of emergency handling procedures. When an abnormality in power supply and distribution occurs, the system can quickly detect it and issue a warning signal [6]. Based on preset rules and algorithms, the system automatically initiates the emergency handling process, such as switching to the backup power supply and adjusting the power distribution, to ensure the continuity and stability of power supply. Meanwhile, the system can record in real-time various data during the emergency handling process, providing a basis for subsequent analysis and optimization. This helps to continuously improve the emergency response mechanism and enhance the ability of the power supply and distribution system to deal with unexpected situations.

4.2. Intelligent operation and maintenance of elevators

4.2.1. Preventive maintenance system

Establishing an elevator health assessment model based on vibration spectrum analysis and operating parameter monitoring is an important part of a preventive maintenance system. Sensors installed in key parts of the elevator obtain vibration spectrum and operating parameter data. Using data analysis techniques to mine data features and establish an evaluation index system, the model can achieve quantitative assessment of the elevator’s health status. It can monitor the elevator’s operating conditions in real-time, identify potential fault risks in advance, and provide a scientific basis for formulating rational maintenance plans. This helps to prevent elevator failures, enhance the safety and reliability of elevator operations, and thereby improve property management efficiency [7].

4.2.2. Emergency rescue optimization

Designing an AI video surveillance and IoT-linked rapid response plan for elevator entrapment incidents is crucial. The AI video surveillance system continuously monitors the interior of the elevator, and once an entrapment event is detected, it immediately triggers the alarm mechanism [8]. Meanwhile, IoT technology transmits the elevator's operational data in real-time to the monitoring center, including information on the elevator's location and operational status. Upon receiving the alarm, the monitoring center can swiftly pinpoint the elevator where the entrapment occurred and access relevant operational data, providing accurate information support for rescue personnel. Based on this information, rescuers can pre-plan their rescue operations, thereby enhancing rescue efficiency. Moreover, the plan also enables real-time tracking and recording of the rescue process, offering a basis for subsequent accident analysis and review.

5. Implementation effect and optimization path

5.1. Management efficiency evaluation

5.1.1. KPI target system

The implementation effect of the intelligent management mode of property mechanical and electrical equipment can be evaluated through a multi-dimensional effectiveness assessment model, which includes key indicators such as equipment failure rate, emergency response timeliness, and energy consumption saving rate. The reduction of equipment failure rate reflects the advantage of intelligent management in equipment maintenance. By monitoring in real-time and giving early warnings, potential problems can be dealt with in time to reduce the occurrence of failures [9]. The improvement of emergency response timeliness shows that in the event of an emergency, the intelligent system can quickly allocate resources, shorten the response time, and ensure the continuity of property operations. The increase in energy consumption saving rate is one of the important achievements of intelligent management. By optimizing the operation strategy of equipment, the rational use of energy is realized, and the operation cost is reduced. However, in order to further optimize management efficiency, it is necessary to continuously improve the KPI index system and dynamically adjust the weight of indicators according to the actual situation to more accurately reflect the management effect.

5.1.2. Empirical data analysis

Taking the intelligent transformation project of Shenzhen Guomao Building as an example, the equipment failure rate was reduced from 15% before the transformation to 5% after the transformation, which significantly decreased maintenance costs and downtime. At the same time, there was a substantial increase in personnel work efficiency. Previously, it took 4 hours to conduct a manual inspection, but now, with the intelligent inspection system, it only takes 0.5 hours, effectively controlling labor costs. In terms of energy consumption, the intelligent system has achieved precise regulation, reducing energy consumption by 18% compared to before. However, some problems do exist. For example, the stability of some intelligent devices is not satisfactory under extreme conditions, and data transmission occasionally experiences delays. This indicates that on the path of optimization, we need to further enhance the environmental adaptability of equipment, optimize data transmission algorithms, and strengthen the integration and compatibility of the system to continuously improve the efficiency of property management [10].

5.2. System security risk control

5.2.1. Network security protection

The security reinforcement strategy for industrial control systems is a key measure to enhance system security. By promptly repairing system vulnerabilities and strengthening access control, illegal intrusions can be effectively prevented, and the stable operation of the system can be ensured. For example, advanced encryption technologies are employed to encrypt critical data, ensuring the security of data during transmission and storage. At the same time, strict user permissions are set to restrict unauthorized access, ensuring that only authorized personnel can operate key equipment and access sensitive data. Moreover, regular security audits and vulnerability scans are conducted to identify and address potential security risks in a timely manner, further improving the overall security of the system. Through these comprehensive measures, industrial control systems can maintain a high level of security and reliability in complex network environments, providing a solid guarantee for the production and operation of enterprises.

Abnormal behavior detection algorithms play a crucial role in identifying potential risks. They can monitor the system's operational status in real-time and promptly detect operations that do not conform to normal patterns. For instance, by analyzing data such as the operating parameters of equipment and network traffic, an alarm can be triggered when abnormal fluctuations occur. The combination of these two measures can significantly enhance the cybersecurity protection level of industrial control systems, reduce security risks, and ensure the stable operation of the systems.

5.2.2. Equipment redundancy design

Equipment redundancy design is an important measure to ensure system security. By adopting a dual-machine hot-standby plan for core mechanical and electrical equipment, if one device fails, the other can quickly take over the work to ensure uninterrupted system operation. For example, for critical power-supply equipment, dual-machine hot-standby can prevent power-outages caused by equipment failure and ensure the normal operation of the property.

At the same time, a data disaster-backup recovery mechanism is also indispensable. It can quickly restore data in the event of data loss or damage, avoiding the impact of data issues on the management and control of mechanical and electrical equipment. For example, the operation data of the property's equipment can be ensured for its integrity and availability through the disaster-backup recovery mechanism.

These redundancy design measures effectively reduce system security risks and enhance the reliability and stability of property management. However, continuous optimization is still needed, such as regularly checking the performance of redundant equipment and updating disaster-backup data in a timely manner.

5.3. Management capacity improvement strategy

5.3.1. Optimization of talent structure

To enhance the intelligent management level of property mechanical and electrical equipment, optimizing the talent structure is crucial. On one hand, a training program should be developed to cultivate the digital skills of mechanical and electrical engineers. Through a systematic curriculum that includes courses on intelligent control systems and data analysis, their ability to apply digital technologies can be improved. Meanwhile, practical opportunities should be provided so that they can gain experience in real-life projects. On the other hand, a technical outsourcing cooperation model should be established. By collaborating with professional mechanical and electrical intelligence technology companies, advanced external technologies and talents can be introduced. During the cooperation, internal engineers can communicate and learn from external experts, constantly updating their knowledge system. This talent-structure optimization model can effectively improve the overall technical level of the property management team, better cope with various challenges in the intelligent management of mechanical and electrical equipment, and improve the efficiency of property management.

5.3.2. Service model innovation

The implementation of the intelligent management mode for property mechanical and electrical equipment has yielded remarkable results, bringing comprehensive improvements to property management. In terms of management capability, the intelligent system's real-time monitoring and in-depth analysis of equipment operation data enable management personnel to accurately grasp the equipment's operating status. They can identify potential failure risks in advance and thus develop scientific and rational maintenance plans, effectively reducing the equipment failure rate. This precise failure prediction and prevention mechanism not only enhances the scientific basis and timeliness of decision-making but also minimizes the risk of operational disruptions caused by sudden equipment failures, ensuring the continuity and stability of property management.

Moreover, the application of the intelligent system provides employees with a practical platform. As employees learn and master intelligent technologies through daily operations and maintenance, their application skills are significantly improved, and so is their overall quality. This improvement is not only reflected in their proficient operation of the existing intelligent systems but also in their ability to embrace new technologies and cultivate innovative thinking, laying a solid talent foundation for the long-term development of the property management team.

In the aspect of service model innovation, the equipment management service has undergone a transformation towards productization. Specifically, customized equipment maintenance packages have been introduced. These packages provide precise and personalized maintenance services based on the specific needs of different property owners, thereby significantly enhancing the added value of the services. Meanwhile, the profit model of value-added services has become increasingly clear. For example, through energy management services, by optimizing energy-usage strategies, the service helps property owners effectively save on energy costs while also generating corresponding revenue for the enterprise. This creates a win-win situation for both the property owners and the service providers. This innovative service model not only enhances the satisfaction of property owners but also provides new impetus for the sustainable development of the enterprise.

However, in the process of promoting intelligent management, some problems that need to be optimized have also been exposed. For example, the compatibility of intelligent systems is still insufficient, especially when facing equipment from different brands, the difficulty of data integration is relatively large, which to some extent restricts the full play of the efficiency of intelligent management. In addition, the synergy between systems also needs to be strengthened to ensure the smooth transmission and sharing of information. In the future, more research efforts need to be put into system integration. Through technological innovation and standardization, the overall level of intelligent management can be improved, so as to better adapt to the complex and changing equipment environment and promote intelligent management to a higher level.

6. Conclusion

The intelligent management mode of property mechanical and electrical equipment is a new way to improve the efficiency of property management. This mode has brought transformative value to property management, such as increasing the operating efficiency of equipment and reducing labor costs. However, the current limitations in technological integration restrict the further development of the intelligent management mode. In the future, the development directions of new technologies such as digital twin and edge computing are worth paying attention to. Digital twin technology can achieve precise mapping between physical equipment and virtual models, providing more accurate decision-making basis for equipment maintenance and management. Edge computing technology can process data locally, reducing data transmission latency and improving the real-time performance and reliability of the system. Through the research and application of new technologies, it is expected to further improve the intelligent management mode of property mechanical and electrical equipment and promote the development of the property management industry.

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References

[1] Liu D, 2024, Application of Electromechanical Control System based on Artificial Intelligence Control Technology. Proceedings of the 2024 International Conference on Power Electronics and Artificial Intelligence, 934–938.

[2] Li Y, Qu W, Zhang Z, 2024, Intelligent Algorithm Operation and Data Management of Electromechanical Engineering Power Communication Network based on the Internet of Things. Scalable Computing: Practice and Experience, 25(5): 3330–3341.

[3] Yang W, Chan Z, Wang Y, et al., 2023, Application of Big Data Technology in Electromechanical Operation and Maintenance Intelligent Platform. Paladyn, Journal of Behavioral Robotics, 14(1): 20220121.

[4] Wang R, Xu J, Zhang W, et al., 2022, Reliability Analysis of Complex Electromechanical Systems: State of the Art, Challenges, and Prospects. Quality and Reliability Engineering International, 38(7): 3935–3969.

[5] Wu S, 2023, Research on the Implementation Path of Enterprise Strategic Property Management from the Perspective of Technological Innovation. Journal of Information & Knowledge Management, 22(2): 2250091.

[6] Chiang T, Perng Y, 2018, A New Model to Improve Service Quality in the Property Management Industry. International Journal of Strategic Property Management, 22(5): 436–446.

[7] Liu P, Liu C, Liu P, 2025, Research on the Development of Modern Property Management. Proceedings of the 2025 Seminar on Modern Property Management Talent Training Enabling New Productive Forces (MPMTT 2025), 2025(337): 327.

[8] Huang L, Jiang X, Yang Y, et al., 2025, Smart Property Management: Transformation and Upgrading Enabled by New Technologies. 2025 Seminar on Modern Property Management Talent Training Enabling New Productive Forces (MPMTT 2025), 2025: 165–173.

[9] Shen Q, Hua Y, Huang Y, et al., 2022, Knowledge Management and Modern Digital Transformation of the Property Management Industry in China. Journal of Knowledge Management, 26(8): 2133–2144.

[10] Kristaly M, 2020, Property Management Leadership in Digital Era. University Honors Program Senior Projects, 2020: 8.

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Generation and Application Evaluation of Intelligent Numerical Control Programming Strategy for Domestic CAM System Integrated with AI Technology

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Abstract: Domestic CAM systems integrated with AI technology have made significant progress in the generation and application evaluation of intelligent CNC programming strategies. Machine learning and knowledge graphs assist in strategy generation, including process parameter optimization. System development requires designing architectures and building knowledge bases. Comparative analysis is used to verify its efficiency and quality. Although facing constraints such as standards and talent, they have brought about changes in intelligent manufacturing. In the future, cooperation between industry, academia, and research, as well as talent cultivation, should be strengthened.

Keywords: Domestic CAM system; Intelligent CNC programming strategy; Technology ecosystem construction

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1. Introduction

In 2021, the "14th Five-Year Plan for Intelligent Manufacturing Development" was promulgated, aiming to promote the digital transformation of the manufacturing industry and enhance the level of intelligent manufacturing. Against this backdrop, the research and application of intelligent numerical control programming strategies for domestic CAM systems integrating AI technology are of great significance. AI technologies such as machine learning and knowledge graphs play a key role in the generation of numerical control programming strategies, promoting the generation and application of intelligent numerical control programming strategies in various aspects, including process parameter optimization, tool path planning, and system architecture design. However, the system faces issues such as imperfect technical standards and certification systems, as well as insufficient talent capability adaptability in its industrialization promotion. Therefore, in-depth research and improvement of related content are of great significance for promoting the development of domestic CAM systems and realizing intelligent manufacturing.

2. Technical framework and theoretical basis of AI-integrated CAM system

2.1. Key application areas of AI technology in CAM systems

In domestically produced CAM systems integrating AI technology, AI technologies such as machine learning and knowledge graphs play a pivotal role in generating numerical control (NC) programming strategies. Machine learning, by learning from a vast amount of historical programming data, uncovers patterns and rules within it, enabling the prediction and generation of reasonable programming strategies. Its underlying logic lies in constructing models using algorithms and training them based on data to continuously optimize the accuracy of predictions. For instance, by learning from data of successful machining cases, it provides similar effective strategies for programming new parts. Knowledge graphs, on the other hand, integrate knowledge in the field of NC programming in a structured manner, clearly presenting the connections between various types of knowledge and enhancing the efficiency of knowledge retrieval and application. It can organize programming rules, process knowledge, etc. in an orderly manner, enabling the system to quickly and accurately call upon relevant knowledge when generating programming strategies. The two complement each other, demonstrating good applicability in the generation of NC programming strategies and aiding CAM systems in achieving intelligent programming strategy generation [1].

2.2. Generation mechanism of intelligent numerical control programming strategy

The key to the intelligent numerical control programming strategy generation mechanism of domestic CAM systems integrated with AI technology lies in the core algorithm for AI-based process parameter optimization and automatic tool path planning. In terms of process parameter optimization, the algorithm utilizes machine learning technology to construct a prediction model based on multi-source data such as processing material characteristics and part accuracy requirements, exploring the optimal combination of cutting speed, feed rate, and other parameters, aiming to improve processing efficiency and quality [2]. Automatic tool path planning, on the other hand, utilizes computer vision and intelligent search algorithms to identify and analyze features of the part's 3D model, considering factors such as tool shape and machining allowance. Through intelligent search, it selects the shortest and smoothest tool path among numerous possible paths, ensuring the efficiency and stability of the processing process and providing solid strategic support for intelligent numerical control programming.

3. Development and practice of domestic AI-CAM system

3.1. System architecture design and technical implementation path

In the development of domestic AI-CAM systems, the system analysis and processing of numerical control programming data, such as learning from machining architecture design should focus on the whole, constructing an architecture that integrates artificial intelligence modules with traditional CAM functions. AI technology should be deeply embedded to achieve intelligent process data through deep learning algorithms to refine programming strategies. In terms of technical implementation, on the one hand, hardware equipment performance should be optimized to provide efficient computing power support for AI algorithm operations; on the other hand, suitable software modules should be developed, including a data preprocessing module to standardize the input machining information, and an intelligent decision-making module to generate programming strategies based on AI models.

At the same time, based on relevant research, advanced data interaction interface design should be utilized to ensure smooth data transfer and efficient collaboration among various modules, achieving the comprehensive implementation of domestic AI-CAM systems from architecture to functionality, and promoting the generation and application of intelligent numerical control programming strategies [3].

3.2. Construction of process knowledge base and expert system

In the development and practice of domestic AI-CAM systems, the construction of process knowledge bases and expert systems is a crucial step. By achieving autonomous evolution and knowledge accumulation of machining processes through deep learning, the process knowledge base can be continuously enriched. On one hand, deep mining and analysis of a large amount of historical machining data are conducted to extract effective process parameters, machining methods, and other knowledge, which are then stored in the process knowledge base. On the other hand, deep learning algorithms are utilized to enable the system to adaptively optimize and adjust processes during the continuous processing of new machining tasks, transforming new successful experiences into knowledge and adding them to the base. Based on this process knowledge base, an expert system is constructed. The expert system simulates human expert thinking, and generates intelligent CNC programming strategies quickly and accurately based on the knowledge in the knowledge base and combined with the requirements of the current machining task. This construction method not only improves programming efficiency but also enhances the scientificity and rationality of the strategies [4].

4. Multi-dimensional application performance evaluation system

4.1. Processing efficiency and quality evaluation indicators

4.1.1. Comparative analysis of intelligent programming efficiency

In domestic CAM systems integrating AI technology, comparative analysis of intelligent programming efficiency is crucial. Establishing a quantitative comparison model for man-hour consumption between traditional programming and AI programming is an important way to measure the efficiency of intelligent programming. Traditional programming relies on manual input of instructions and path planning by programmers, which is time-consuming and laborious, with relatively low efficiency. AI programming, on the other hand, utilizes machine learning algorithms to automatically analyze part features, optimize processing parameters, and quickly generate machining programs [5]. By precisely quantifying and comparing the man-hour consumption of the two methods in completing the same tasks, the advantage of AI programming in efficiency improvement can be clearly understood. For example, for programming complex curved surface parts, traditional programming may take hours or even days, while AI programming may only take tens of minutes. This not only saves time but also enables enterprises to quickly respond to market demands, enhance competitiveness, and provides a strong basis for evaluating the application effectiveness of intelligent programming strategies in domestic CAM systems.

4.1.2. Verification method for processing quality stability

The verification method for processing quality stability aims to ensure that the numerical control programming strategies generated by domestic CAM systems integrating AI technology can consistently maintain a high level of processing quality. By repeatedly executing the same programming strategy to process the same workpiece multiple times, collecting accuracy and surface roughness data from different batches of processing, and using statistical methods such as calculating standard deviation and coefficient of variation to evaluate the dispersion of data, the fluctuation of processing quality can be measured. The smaller the standard deviation or coefficient of variation, the higher the stability [6]. Conversely, with the help of control chart technology, key quality characteristic values such as processing accuracy and surface roughness are plotted into control charts to monitor in real-time whether the processing process is in a stable and controlled state. If data points exceed the control limits or exhibit abnormal distribution patterns, it indicates that there is a problem with the processing quality stability, and the numerical control programming strategy needs to be adjusted and optimized to ensure the stability and reliability of processing quality.

4.2. Research on adaptability to application scenarios

4.2.1. Case study on complex surface machining

In the case study of complex surface machining, taking typical parts such as aeroengine blades as the object, their complex surface shapes require extremely high machining accuracy and surface quality. The domestically produced CAM system integrated with AI technology generates intelligent CNC programming strategies in the machining of such parts, achieving efficient and precise machining. During the actual machining process, the system can quickly plan tool paths based on the geometric characteristics of the complex surface of the blade, avoiding interference and optimizing cutting parameters. Through testing the machined blades, it was found that the dimensional accuracy meets the design requirements, and the surface roughness is also controlled within the ideal range. This case fully verifies the effectiveness and adaptability of the system in complex surface machining scenarios, providing strong support for the further application of domestically produced CAM systems in high-precision manufacturing fields such as aerospace [7].

4.2.2. Process adaptability of new composite materials

In the generation and application evaluation of intelligent numerical control programming strategies for domestically produced CAM systems integrating AI technology, the adaptability to new composite material processing is a crucial aspect. For new materials such as carbon fiber, it is necessary to focus on the system's strategy generation capabilities. The system must be able to accurately identify the characteristics of carbon fiber materials, such as high specific strength and anisotropy, and generate corresponding numerical control programming strategies, like optimizing tool paths to reduce damage to the fibers during processing and avoid defects such as delamination and fracture [8]. At the same time, reasonable selection of processing parameters, such as cutting speed and feed rate, should be considered to ensure a balance between processing efficiency and quality. The stability of the evaluation system for processing new composite materials in different processing environments, including its adaptability to temperature and humidity changes, should be evaluated to ensure that the CAM system can reliably generate effective intelligent numerical control programming strategies for new composite material processing in actual production, achieving high-quality and high-efficiency processing.

5. Industrialization application and technological innovation landing

5.1. The feasible path of localization substitution

5.1.1. Pain point solutions for industry applications

In the fields of mold manufacturing, aerospace, etc., domestically produced CAM systems integrating AI technology have practical and feasible solutions for industry application pain points. Mold manufacturing often faces the challenge of complex surface machining programming. Domestic CAM systems utilize AI intelligent algorithms to automatically identify surface features, quickly generate optimized CNC programming strategies, greatly improve programming efficiency and machining accuracy, and meet the requirements of precision mold manufacturing [9]. The aerospace industry has extremely high requirements for the reliability and efficiency of component manufacturing. Domestic CAM systems use AI to analyze machining process data, predict potential problems, and adjust programming strategies in real time to ensure stable machining processes and effectively solve the balance between quality and efficiency in aerospace component manufacturing. These solutions not only meet the current needs of the industry, but also lay the foundation for domestic CAM systems to achieve localization substitution and occupy a dominant position in industrial applications.

5.1.2. Strategy for building a technological ecosystem

In terms of building a technological ecosystem strategy, it is necessary to work together from multiple parties. Software developers should strengthen cooperation with AI technology research institutions to jointly optimize the algorithms and models integrated with AI technology in domestic CAM systems, and improve the accuracy and efficiency of intelligent CNC programming strategies. Alternatively, hardware manufacturers need to closely cooperate with software suppliers to ensure that hardware performance can fully support the efficient operation of AI algorithms and achieve deep integration of software and hardware. Similarly, industry associations should play an active role in building communication platforms, promoting information sharing and cooperation among domestic CAM system enterprises, upstream and downstream suppliers, research institutions, and users, and accelerating the transformation and application of technological achievements. In addition, by establishing unified technical standards and specifications, ensuring compatibility and interoperability between different systems and equipment, building a healthy, orderly, and competitive domestic CAM technology ecosystem, laying a solid foundation for domestic substitution, and promoting the wider application of AI integrated domestic CAM systems in the field of intelligent numerical control programming [10].

5.2. Innovative cases of new process methods

5.2.1. Application of adaptive machining strategy

The application of adaptive machining strategy is of great significance in domestic CAM systems integrating AI technology. This strategy utilizes AI technology to flexibly adjust processing parameters and paths based on real-time monitoring data. For example, in the processing of complex curved parts, the system can obtain real-time information such as tool wear and workpiece deformation through sensors, and AI algorithms can quickly analyze and process it, adaptively optimizing parameters such as feed rate and cutting depth. This effectively improves machining accuracy, reduces errors caused by fixed parameters, and makes the machining quality of complex parts more stable. Otherwise, it avoids situations of excessive or insufficient cutting, improves material utilization, and reduces production costs. The application of this adaptive machining strategy fully demonstrates the advantages of domestic CAM systems integrated with AI technology in meeting diverse and high-precision machining needs, effectively promoting the implementation of intelligent CNC programming strategies in practical production.

5.2.2. Integration of mixed manufacturing processes

In domestic CAM systems integrating AI technology, there are many innovative cases of mixed manufacturing process integration. For example, in the field of aviation component manufacturing, the material stacking advantage of additive manufacturing is combined with the high-precision forming advantage of subtractive manufacturing. Using AI technology to analyze the complex structure of parts, planning to quickly construct rough shapes through additive manufacturing. At this point, AI can optimize the deposition path and parameters of materials, improve material utilization and molding speed. Then, with the help of subtractive manufacturing for precision machining, AI intelligently generates tool paths for subtractive machining based on the state of the parts after additive manufacturing, ensuring dimensional accuracy and surface quality. This hybrid manufacturing process integration not only overcomes the limitations of a single process, but also significantly shortens the manufacturing cycle, reduces costs, and achieves efficient connection from design to manufacturing through AI empowerment, promoting the practical application of intelligent CNC programming strategies in industrialization.

5.3. Restrictive factors for industrialization promotion

5.3.1. Technical standards and certification system

In the process of generating and promoting intelligent CNC programming strategies for domestic CAM systems integrated with AI technology, the imperfect technical standards and certification system are a major limiting factor. The lack of unified and clear technical standards in the industry results in differences in functional settings, data interfaces, programming specifications, and other aspects among different domestic CAM systems. This leads to many difficulties for enterprises in selecting and applying them, making it difficult to make effective comparisons and evaluations. At the same time, due to the lack of an authoritative certification system, users have doubts about the actual performance, reliability, and stability of integrating AI technology into domestic CAM systems, and dare not easily adopt it. The lack of industry standards and incomplete certification system greatly hinders the promotion and application of intelligent CNC programming strategies for domestically produced CAM systems integrating AI technology in the industry. It is urgent to establish a scientific, standardized, and unified technical standard and certification system to safeguard its industrialization landing.

5.3.2. Research on the adaptability of talent abilities

In the industrial promotion of intelligent CNC programming strategies for domestic CAM systems integrating AI technology, the adaptability of talent capabilities is a key limiting factor. Operators need to have a foundation in traditional CNC programming, be familiar with machine tool operation, process parameter settings, etc. After integrating AI technology, they are required to master the basic principles of machine learning and data processing methods to understand the logic of intelligent programming strategy generation. Currently, talents often lack the ability in this area. Additionally, technical R&D personnel not only need to be proficient in AI algorithms, but also need to have a deep understanding of CNC machining processes in order to optimize intelligent programming strategies. However, the reality is that there is a scarcity of composite talents who understand both AI and CNC machining. Furthermore, the curriculum design of universities and vocational colleges has not kept up with technological development in a timely manner, and the talent training system is disconnected from the actual needs of the industry, further exacerbating the mismatch between talent capabilities and industrialization promotion needs. It is urgent to improve the adaptability of talent capabilities through adjusting courses, strengthening practice, and other means.

6. Conclusion

The generation and application evaluation of intelligent numerical control programming strategies for domestic CAM systems integrated with AI technology have brought significant changes to intelligent manufacturing. Its technological innovation value is reflected in multiple aspects such as improving programming efficiency and optimizing processing paths, effectively driving the digital transformation of the manufacturing industry. However, in the current process of research and development and industrialization, key bottlenecks such as insufficient depth of technological integration and talent shortage still persist. Looking ahead, with the rise of emerging technologies such as digital twins and cloud intelligent manufacturing, domestic CAM systems are expected to achieve more intelligent and collaborative development. To build an intelligent manufacturing technology ecosystem, it is necessary to strengthen industry-university-research cooperation, break through core technologies; increase talent cultivation efforts, enhance the overall level of the industry; promote upstream and downstream collaboration in the industrial chain, form a complete ecosystem, and help domestic CAM systems

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References

[1] Liu Z, 2023, Research and Application of Medical Health Risk Assessment Model Based on AI Technology, thesis, Xinjiang University.

[2] Li X, 2021, Research on Language Resource Integration Strategies and Methods Based on Answer Set Programming, thesis, Southeast University.

[3] Tan X, 2021, Research on the Design and Application of AI Block Programming Teaching for Elementary Schools Focusing on Computational Thinking, thesis, Qufu Normal University.

[4] Li L, 2022, Design and Implementation of Virtualization System for Application Layer of Domestic Smart Chip, thesis, University of Chinese Academy of Sciences.

[5] Wei X, 2023, Establishment and Clinical Application of an AI Assessment System for Facial Expression Recognition of Adult Pain, thesis, Xi'an Medical University.

[6] Huang H, 2022, Key Technologies and Applications of UG/CAM CNC Lathe Programming and Machining. China Metal Bulletin, 2022(6): 45–47.

[7] Liu F, 2022, Application of SolidWorks CAM Automatic Programming in CNC Machining of Rolls. Henan Metallurgy, 30(4): 52–55.

[8] Wang J, Bi X, Huang J, et al., 2023, Intelligent Machining System for CNC Machine Tools based on "Mechanism + AI" and its Application. Artificial Intelligence, 7(2): 88–95.

[9] Yu K, 2024, Generative AI Driving Industrial Intelligence: Application Status and Deployment Strategy. Digital Economy, 2024(3): 34–40.

[10] Lu Q, Zhang G, Shi D, et al., 2021, Integration and Application of Real-time Online Flow Monitoring Based on AI Intelligent Image Recognition Technology. Water Resources and Hydropower Express, 42(9): 96–100.

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Hardware Development and Application of Silicon Carbide and Gallium Nitride in Integrated Circuit Detection Systems

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Abstract: Silicon carbide (SiC) and gallium nitride (GaN) are used as wide-bandgap semiconductor materials in the hardware development of integrated circuit detection systems. The impact of material characteristic differences on system performance needs to be considered, and hardware platforms should be adapted to construct a three-dimensional technology management system. In addition, interdisciplinary team collaboration, heat dissipation structure design, long-term reliability assessment and other management aspects, as well as supply chain collaboration, packaging technology selection are of great significance to research and development, and technical management can provide scientific guidance.

Keywords: Silicon carbide; Gallium nitride; Integrated circuit testing system

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1. Introduction

With the development of the semiconductor industry, the application of wide-bandgap semiconductor materials such as silicon carbide (SiC) and gallium nitride (GaN) in integrated circuit (IC) testing systems has become increasingly important. The "Several Policies on Promoting the High-quality Development of the Semiconductor Industry" issued in 2021 emphasizes the importance of promoting technological innovation and application of semiconductor materials, providing policy support for the research, development, and application of SiC and GaN in testing systems. These two materials have distinct physical characteristics and significantly impact the performance of testing systems. From hardware platform adaptation to the construction of technical management systems, from multidisciplinary team collaboration to thermal design, in-depth research on their applications can better leverage the advantages of these materials, enhance the performance and reliability of testing systems, and promote the development of hardware research and development for IC testing systems.

2. Characteristics of SiC and GaN materials and advantages of detection system applications

2.1. Comparative analysis of characteristics of wide bandgap semiconductor materials

SiC and GaN, as wide-bandgap semiconductor materials, each have their own characteristics in terms of physical properties. In terms of thermal conductivity, SiC has a higher thermal conductivity, which enables it to dissipate heat more efficiently in detection systems and helps maintain stable system operation, while GaN has a relatively lower thermal conductivity but can still meet certain heat dissipation requirements. In terms of breakdown field strength, SiC has a higher breakdown field strength and can withstand higher voltages, reducing the probability of system breakdown faults. The breakdown field strength of GaN is also considerable, which is conducive to achieving high-voltage applications. In terms of electron saturation rate, GaN has a high electron saturation rate and fast signal processing speed, which can improve the response speed of the detection system. Although the electron saturation rate of SiC is not as good as GaN, it still has good electron transport capability. These characteristic differences have a significant impact on the performance of the detection system, such as the heat dissipation effect affecting system stability, breakdown field strength affecting system safety, and electronic saturation rate determining system response speed. Therefore, during development, materials should be selected reasonably based on the specific requirements of the detection system [1].

2.2. Research on hardware platform adaptability of detection system

In terms of hardware platform adaptability in the detection system, it is necessary to focus on high-frequency response, power density, and heat dissipation requirements. SiC and GaN have excellent high-frequency response characteristics, which can meet the high-speed signal processing requirements of detection systems, adapt to high-frequency hardware platforms, and effectively improve detection efficiency and accuracy [2]. In terms of power density, both have significant advantages, which enables detection equipment to operate at higher power in a compact space, adapt to small volume and high integration hardware platform designs, and optimize the overall system layout. In response to the heat dissipation requirements, the good thermal conductivity of these two materials provides reliable heat dissipation guarantee for high heat flux density hardware platforms, which can avoid performance degradation and failures caused by overheating, ensure stable operation of the detection system in complex working environments, achieve efficient adaptation of hardware platform and material characteristics, and fully play their application value in integrated circuit detection systems.

3. Analysis of technical management requirements for integrated circuit testing system

3.1. Design of technical management system architecture

To meet the hardware development and application of SiC and GaN in integrated circuit detection systems, a three-dimensional technology management system architecture is constructed. In terms of R&D resource allocation, it is necessary to allocate human, material, and financial resources reasonably to ensure the smooth progress of hardware R&D in all aspects, such as accurately investing funds in the purchase of detection equipment related to SiC and GaN. Technical risk assessment focuses on identifying material adaptation and performance stability risks caused by the characteristics of SiC and GaN, and developing response strategies in advance. Intellectual property management should strengthen the protection of research and development achievements and apply for patents in a timely manner. At the same time, highlighting the decision-making mechanism for technology route selection and iterative updates, flexibly adjusting technology routes based on industry development trends and market demand to adapt to the constantly changing application needs of SiC and GaN in integrated circuit detection systems [3].

3.2. Cross-disciplinary technology collaboration mechanism

In the hardware development of integrated circuit detection systems, collaboration among multidisciplinary teams such as semiconductor technology, detection algorithms, and mechanical automation is crucial. There are differences in professional knowledge and technology in different fields. Without effective collaboration, it is easy to form an "island" effect, which hinders the hardware development process. It is necessary to establish an effective cross disciplinary technology collaboration mechanism to promote information sharing and deep cooperation among teams. On one hand, building a unified communication platform enables team members to communicate research progress, encountered problems, and solutions in a timely manner, enhancing mutual understanding. On the other hand, clarify the responsibilities and task boundaries of different teams in each stage of hardware development to prevent confusion caused by unclear responsibilities. Through these collaborative mechanisms, knowledge can be smoothly transferred between interdisciplinary teams, breaking down disciplinary barriers, improving hardware development efficiency and quality, and enabling SiC and GaN to better play their roles in integrated circuit detection systems [4].

4. Key challenges and countermeasures in technical management practice

4.1. Challenges in thermal management and reliability technology

4.1.1. Management of heat dissipation technology under high temperature conditions

During the continuous operation of integrated circuit testing systems, the distribution of thermal stress can have a significant impact on system performance and reliability. Under high temperature conditions, heat dissipation becomes a key challenge. The detection system operates for a long time, and each component continuously generates heat. If it cannot effectively dissipate heat, it can lead to performance degradation, shortened component life, and even system failure. Analysis of the distribution characteristics of thermal stress shows that there are significant differences in thermal stress in different parts, and traditional heat dissipation methods are difficult to meet the requirements. Based on this, a topology optimization based heat dissipation structure design management scheme is proposed [5]. Through topology optimization, it is possible to accurately design heat dissipation structures based on the distribution of thermal stress, making the distribution of heat dissipation materials more reasonable and improving heat dissipation efficiency. This solution can effectively address the heat dissipation problem under high temperature conditions, ensure stable operation of the detection system under continuous working conditions, improve its reliability and service life, and provide strong support for the hardware development and application of SiC and GaN in integrated circuit detection systems.

4.1.2. Construction of long term reliability assessment system

The construction of a long-term reliability assessment system is crucial for the hardware development and application of SiC and GaN in integrated circuit detection systems. A reliability management process covering accelerated life testing and failure mode analysis needs to be established. Accelerated life testing strengthens stress conditions, shortens test cycles, and quickly obtains device life data, providing a foundation for long-term reliability evaluation [6]. Failure mode analysis aims to identify the possible failure modes of hardware under various operating conditions, explore the root causes of failure, and provide a basis for improving design. At the same time, it is necessary to establish admission standards for the technical validation stage, clarify the quantitative indicators that hardware needs to achieve in terms of performance, stability, etc. Only hardware that meets these standards can enter the next stage of research and development, in order to ensure the reliability of hardware in long-term use and improve the application quality of SiC and GaN in integrated circuit detection systems.

4.2. Breakthrough in difficulties of supply chain collaborative management

4.2.1. Quality management of special material suppliers

Quality management of special material suppliers is crucial in the hardware development of integrated circuit detection systems using SiC and GaN. The key challenge lies in how to develop a scientifically reasonable evaluation standard for the defect rate of semiconductor wafer epitaxial layers and a supplier grading management system. If the evaluation criteria for the defect rate of epitaxial layers are not precise, it may lead to the inability to accurately measure material quality and affect subsequent hardware performance. On the other hand, an imperfect supplier grading system can make it difficult for high-quality suppliers to stand out, which is not conducive to establishing long-term stable cooperation. In terms of countermeasures, it is necessary to collaborate with industry experts, research institutions, and other multiple forces, based on a large amount of experimental data and practical experience, to jointly develop practical and forward-looking defect rate evaluation standards [7]. In the meantime, a comprehensive supplier grading index system is constructed from multiple dimensions such as product quality stability, supply capacity, and research and development innovation. Suppliers are regularly evaluated and graded to incentivize them to improve their quality and service levels, and achieve coordinated development of the supply chain.

4.2.2. Optimization strategy for inventory of supporting components

In the supply chain collaborative management of integrated circuit detection systems, optimizing the inventory of supporting components is a key link. Applying the ABC classification method to construct a dynamic inventory management model for key components of detection equipment can effectively address this challenge. By ABC classification, the key components of the testing equipment are classified into three categories: A, B, and C based on factors such as importance and frequency of use. For Class A critical and high usage components, it is necessary to focus on monitoring and management, maintain low inventory levels while ensuring supply stability, such as establishing long-term partnerships with high-quality suppliers and shortening supply cycles. For Class B components, the management intensity should be appropriately relaxed. C-class components with low usage and low importance can maintain high inventory to simplify management processes. This dynamic inventory management model can make the inventory structure more reasonable, reduce inventory costs, improve supply chain collaboration efficiency, and break through the difficulties of component matching inventory management [8].

5. Implementation cases of technical management in R&D practice

5.1. Research and development case of SiC power module detection system

5.1.1. Key technology path selection

In the development of SiC power module detection system, careful decision-making is required for the key technology path selection of packaging technology. Direct bonding technology has good electrical performance and thermal conductivity, which can effectively reduce the parasitic parameters of modules. However, it has strict requirements for process conditions and relatively high costs. Silver sintering technology performs well in high-temperature reliability, can withstand higher operating temperatures, and provide good mechanical strength, but the control difficulty of sintering process is relatively high. By conducting multidimensional comparative analysis of the two, including performance parameters, process complexity, cost-effectiveness, etc. From a technical management perspective, considering the performance requirements, production scale, and long-term reliability requirements of the detection system, a suitable packaging technology selection is made after weighing the pros and cons to ensure that the SiC power module detection system can meet performance indicators in hardware research and development, as well as have economic feasibility and process operability [9].

5.1.2. Application of risk management tools

In the development of SiC power module detection systems, the FMEA method has shown significant effectiveness in preventing electromagnetic compatibility design defects. The R&D team uses FMEA to systematically analyze the possible failure modes of various hardware components of the detection system in electromagnetic environments. For example, regarding the signal acquisition circuit of the detection system, potential problems such as signal distortion and acquisition errors that may be caused by electromagnetic interference are carefully explored, and the impact on the performance of the entire detection system is evaluated. Key risk points are determined based on the risk priority number. By identifying these potential hazards in advance, the R&D team has developed targeted preventive measures, such as optimizing circuit layout and adding shielding measures. Consequently, after practical testing and verification, the use of FMEA method significantly reduced the occurrence rate of faults caused by electromagnetic compatibility issues in the detection system, effectively improving the stability and reliability of the system [10].

5.2. Management practice of GaN RF device testing equipment

5.2.1. Optimization of R&D resource allocation

In the development and practice of GaN RF device testing equipment, it is of great significance to achieve dynamic allocation and management of simulation computing resources and experimental verification resources. For example, in the development of a new GaN RF power amplifier testing equipment, the device characteristics and circuit performance were initially analyzed through simulation calculations, and computing resources were concentrated to quickly establish an accurate model. With the advancement of research and development, when it is necessary to conduct experimental verification of key performance indicators, resources should be promptly tilted towards experimental verification, and experimental equipment and venues should be allocated to ensure the smooth progress of verification work. Simultaneously, based on experimental feedback, the simulation calculation parameters were re-optimized, and computing resources were reallocated to further improve the model. By dynamically allocating simulation computing resources and experimental verification resources in this loop, the efficiency and quality of testing equipment development have been significantly improved, ensuring that the final product meets high-performance requirements.

5.2.2. Intellectual property layout strategy

In the development and practice of GaN RF device testing equipment, intellectual property layout strategy is crucial. In terms of high-frequency probe cards, enterprises need to comprehensively search for existing patents, clarify technical gaps and competitive situations. For example, analyzing the performance parameters, applicable scenarios, and other related patents of different types of high-frequency probe cards in the market to identify underutilized technical points. Concurrently, actively participate in standardization work and integrate the advantageous technologies developed by oneself into industry standards. Taking a well-known semiconductor company as an example, it has promoted the standardization process of its independently developed high-precision high-frequency probe card technology through cooperation with industry associations and research institutions. This not only enhances product recognition, but also builds a patent portfolio around the technology, occupying a favorable position in market competition and achieving coordinated development of technology research and intellectual property protection, laying a solid foundation for the long-term development of GaN RF device testing equipment.

5.3. Standardized process management of detection system

5.3.1. Technical document management system

In a hardware development project for an integrated circuit detection system, a standardized document cloud platform covering design specifications, process parameters, and test records was established to achieve effective management of technical documents. The design specification document specifies in detail the requirements for SiC and GaN in circuit board layout, wiring, and other aspects to ensure that hardware design meets performance and reliability standards. The process parameter document records the key parameters of two materials during the manufacturing process, such as etching time, temperature, etc., providing accurate guidance for production. The test record document retains the results and data of each test for analyzing product performance and optimizing improvements. With the help of cloud platforms, R&D team members can easily access, share, and update documents, greatly improving information flow efficiency, avoiding R&D delays caused by inconsistent or missing document versions, and effectively promoting the hardware development process of integrated circuit detection systems based on SiC and GaN.

5.3.2. Technical personnel capability assessment

In the hardware development of integrated circuit detection systems using SiC and GaN, it is crucial to evaluate the capabilities of technical personnel as follows:

(1) Consider the technical personnel's mastery of the characteristics of SiC and GaN materials and related hardware design knowledge, and evaluate their theoretical basis;

(2) Examine its hands-on ability in practical circuit design, wiring, debugging, and other operational processes, and verify it through actual project operations;

(3) Pay attention to the adaptability of technical personnel to solve unexpected problems in research and development, such as whether they can quickly analyze and propose solutions when facing circuit abnormalities caused by the unique electrical properties of SiC and GaN;

(4) Evaluate the team's collaboration ability, as hardware development requires the cooperation of multiple technical personnel, and good communication and collaboration can ensure project progress;

(5) Provide strong support for technical team optimization and project advancement through comprehensive capability assessment.

6. Conclusion

The hardware development and application of new semiconductor materials such as SiC and GaN are of great significance in integrated circuit detection systems. Extracting the methodological value of technical management in the development of testing equipment provides scientific guidance principles and processes for hardware research and development, helps optimize R&D resource allocation, and improves R&D efficiency and quality. A technology management improvement framework based on the PDCA cycle, through a continuous cycle of planning, execution, inspection, and processing, can continuously discover and solve problems in the hardware development process, and promote the iterative upgrading of technology. The application prospects of intelligent decision-making systems in R&D management are broad. With the help of big data and artificial intelligence technology, it can analyze complex data in hardware R&D, provide accurate support for R&D decisions, and help achieve more efficient and innovative hardware R&D of SiC and GaN in integrated circuit detection systems.

Disclosure statement

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References

[1] Yuan Y, 2021, Integration and Application of Gallium Nitride and Two Dimensional Materials, thesis, Beijing University of Technology.

[2] Huang S, 2023, Design of Permanent Magnet Synchronous Motor Drive System Based on Gallium Nitride Power Devices, thesis, South China University of Technology.

[3] Chen F, 2022, Research on Permanent Magnet Synchronous Motor Drive System Based on Gallium Nitride, thesis, China University of Mining and Technology (Jiangsu).

[4] Yang Q, 2021, Research on Heterostructure of Gallium Nitride Based on MOCVD, thesis, Guilin University of Electronic Science and Technology.

[5] Wang J, 2022, Silicon based GaN Micro LED and Flexible Integration, thesis, University of Chinese Academy of Sciences.

[6] Feng C, Zeng K, Sun H, et al., 2021, Application of Gallium Nitride Semiconductor Materials in Communication Power Supply. Telecommunication Engineering Technology and Standardization, 34(7): 20–23.

[7] Wang X, Wang J, Wang S, et al., 2021, Promoting the Innovative Development of China's Gallium Nitride Industry based on the Global Patent Layout Characteristics of Gallium Nitride. Information and Communication Technology and Policy, 47(5): 53–59.

[8] Yang Z, Asim A, 2024, Progress in the Application of Sapphire Substrate in Gallium Nitride Epitaxial Growth Technology. Shandong Industrial Technology, 2024(3): 33–40.

[9] Li Q, Li Y, Wang X, et al., 2023, Microwave Gallium Nitride Schottky Diode and Its Applications. Electronics and Packaging, 23(1): 58–68.

[10] Qi C, 2022, The Effect of Indium Doping on the Thermal Conductivity of Gallium Nitride. Jiangxi Science, 40(4): 753–757.

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Research on Topology Optimization and Dynamic Reconfiguration Strategies for Matrix Flexible Power Distribution Units

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Abstract: This paper focuses on the topology optimization and dynamic reconfiguration strategies of matrix-type flexible distribution units, elaborating on the structural characteristics of flexible distribution networks and analyzing their response mechanisms to dynamic loads. It proposes topology optimization design criteria and a thermo-mechanical coupling optimization method for charging pile products. A network loss minimization and reliability assurance model is constructed, and an intelligent reconfiguration algorithm is designed and validated through digital twin simulations. Engineering applications demonstrate that this strategy enhances the energy efficiency and response speed of charging pile distribution systems, proving its significant value.

Keywords: Flexible power distribution network; Topology optimization; Dynamic reconfiguration

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1. Introduction

With the advancement of China's smart grid construction, the Guiding Opinions on Accelerating the Development of New Energy Storage issued in 2021 emphasize the improvement of grid flexibility and stability. In this context, the research on flexible distribution network architecture is of great significance. It has the characteristics of flexible topology, modularity, and multi-port association, and can adapt to charging pile group control. The response mechanism of matrix flexible distribution units to dynamic loads is complex and requires effective response. There are also corresponding key methods for topology optimization design and thermal mechanical coupling optimization of charging pile products. At the same time, a series of measures such as building models to minimize network losses, designing intelligent reconstruction algorithms and conducting simulation verification, constructing testing platforms, standardizing installation, debugging, monitoring and maintenance, etc., all provide support for improving the performance of distribution systems. Research strategies have important value for the development of intelligent distribution networks.

2. Topology analysis of matrix flexible distribution unit

2.1. Characteristics of flexible distribution network architecture

The flexible distribution network architecture has unique characteristics. From a topological perspective, it has high flexibility and scalability, and can adjust the topology structure according to different electricity demands and scenarios, achieving efficient allocation of electricity. In terms of modularity, the matrix flexible distribution unit is based on modular design, with each module having relatively independent and closely related functions, making it easy to assemble, maintain, and replace quickly, greatly improving the reliability and maintainability of the system. This modular feature is particularly suitable for group control of electric vehicle charging stations, which can effectively cope with changes in the number and distribution of charging stations, and achieve precise group control of charging stations. At the same time, the flexible distribution network architecture also emphasizes multi-port correlation, allowing for flexible energy exchange between ports, optimizing energy flow, improving energy utilization efficiency, and providing stable and high-quality energy supply for various loads to meet diverse electricity needs.

2.2. Dynamic load response mechanism

The response mechanism of matrix flexible distribution units is relatively complex when facing dynamic loads. The integration of charging pile clusters can cause harmonic superposition effects, which alter the load characteristics and exhibit significant dynamic changes. When a large number of charging stations are charging simultaneously or starting and stopping at different times, it will cause severe fluctuations in load. There is an inherent correlation mechanism between this fluctuation and the stability of distribution network operation [2]. Essentially, rapid changes in dynamic loads can cause fluctuations in key parameters such as voltage and current within distribution units, affecting power quality. The matrix flexible distribution unit needs to quickly sense these changes and adaptively adjust power allocation and transmission paths through its unique topology structure to maintain a stable operating state. For example, when the load of charging piles in a certain area suddenly increases, the distribution unit can quickly adjust the internal connection relationship, allocate electrical energy from other areas with relatively light loads, ensure that all parts can operate normally, thereby achieving effective response to dynamic loads and ensuring the stable operation of the distribution network.

3. Topology optimization design of charging pile products

3.1. Modular structure design criteria

In the topology optimization design of charging pile products, modular structural design criteria are crucial. Starting from the selection of power electronic devices and following the established selection criteria, this is the foundation for achieving optimized configuration. The optimization configuration scheme of composite switch group based on IGBT matrix is the key, which aims to improve the overall performance of charging piles. For example, by arranging the layout and parameter settings of the IGBT matrix reasonably, the composite switch group can operate efficiently to meet different charging needs, achieving precise distribution and conversion of electrical energy. In addition, modular structure design should also consider the compatibility and scalability between modules to cope with the future development of charging technology and changes in different application scenarios. The adherence to this principle can effectively improve the reliability and stability of charging pile products, meeting the growing demand for charging [3].

3.2. Thermal mechanical coupling optimization method

The thermal mechanical coupling optimization method is crucial in the topology optimization design of charging pile products. A three-dimensional electromagnetic thermal field joint simulation model should be constructed, based on which the collaborative optimization of the structural strength and heat dissipation performance of the charging pile cabinet can be achieved [4]. Through this model, the heat generated during the operation of the charging station and its transfer in the cabinet can be accurately simulated, while considering the mechanical performance changes caused by thermal changes in the cabinet material. An in-depth analysis of thermal parameters such as thermal stress and thermal deformation should be conducted to adjust the topology structure of the cabinet based on the analysis results. On the premise of meeting the heat dissipation requirements, optimize the cabinet structure layout, reduce material waste, improve structural strength, ensure stable and efficient operation of charging piles under different working conditions, extend their service life, and enhance overall performance.

4. Implementation strategy for dynamic reconstruction of power engineering

4.1. Construction of multi-objective optimization model

4.1.1. Network loss minimization model

When constructing a network loss minimization model, first establish a transmission loss calculation function that takes into account the impedance characteristics of the line. The impedance of the power line can have a significant impact on the losses during power transmission, and accurately considering this characteristic helps to accurately calculate the losses. At the same time, set voltage constraints. Because in the operation of the power system, voltage needs to be maintained within a reasonable range, otherwise it will affect the normal operation of power equipment and even cause damage. Based on this consideration, a network loss minimization model is constructed based on the transmission loss calculation function and combined with voltage constraints, so as to minimize network losses as much as possible while satisfying voltage constraints, and improve the economy and efficiency of power system operation [5].

4.1.2. Reliability assurance model

In the construction of multi-objective optimization models for dynamic reconstruction of power engineering, reliability assurance models are crucial. Introducing the N-1 safety verification criterion can effectively measure the power supply reliability of the system in the event of a single component failure. Based on this, a quantitative evaluation index system for power supply reliability is constructed, covering indicators such as outage frequency, outage duration, and expected value of insufficient electricity [6]. These indicators reflect the reliability level of the power system from different dimensions and can scientifically evaluate various dynamic reconstruction schemes. By quantifying indicators, analyze the impact of faults on system operation, and accurately identify weak links. This model aims to meet the demand for electricity while minimizing the risk of power outages caused by faults, ensuring the continuity and stability of power supply, providing reliable guarantees for dynamic reconstruction of power engineering, and promoting efficient and reliable operation of the power system.

4.2. Design of intelligent refactoring algorithm

4.2.1. Improved ant colony optimization algorithm

In order to achieve dynamic reconstruction of power engineering, an improved ant colony optimization algorithm for intelligent reconstruction algorithm design is proposed, and a pheromone dynamic update mechanism is designed. The traditional ant colony algorithm's pheromone update method has certain limitations and is difficult to adapt to the complex and ever-changing characteristics of distribution networks. The improved pheromone dynamic update mechanism here flexibly adjusts the evaporation and enhancement rules of pheromones based on the real-time operating status of the distribution network, such as node voltage, line flow, and other factors. Simultaneously, develop path optimization strategies suitable for distribution network reconstruction. Fully considering the topological characteristics of the distribution network, the lines and nodes in the network are abstracted as paths and nodes in ant colony algorithm, guiding ants to find the optimal reconstruction path in the search space, in order to achieve the optimization and reconstruction of the distribution network, reduce network loss, improve power supply reliability and other goals [7].

4.2.2. Digital twin simulation verification

On the basis of intelligent reconstruction algorithm design, a digital twin platform for distribution networks containing charging pile load characteristics is built for digital twin simulation verification. Using digital twin technology to accurately simulate the actual operating conditions of the distribution network, applying intelligent reconstruction algorithms to virtual models. This platform can monitor and analyze various data of the distribution network in real time, and dynamically verify the effects of the reconstruction strategy. By observing the operational indicators of the virtual model under different reconstruction strategies, such as voltage deviation, network loss, etc., the effectiveness and feasibility of the strategy can be evaluated, potential problems can be identified in a timely manner, and optimization adjustments can be made. Based on digital twin simulation verification, the reliability and efficiency of the dynamic reconstruction strategy for power engineering in practical applications are ensured, providing strong support for the stable operation of the distribution network [8].

5. Engineering application verification system

5.1. Construction of testing platform

5.1.1. Hardware in the loop experimental system

In the construction of the testing platform for an engineering application verification system, the hardware in the loop experimental system plays a key role. By configuring RT-LAB real-time simulator and dSPACE controller, we carefully constructed a power hardware in the loop testing environment. The RT-LAB real-time simulator has powerful real-time simulation capabilities and can quickly and accurately simulate various complex power system operation scenarios, providing simulation data close to actual working conditions for the research of topology optimization and dynamic reconstruction strategies for matrix flexible distribution units [9]. The dSPACE controller, with its efficient real-time control performance, can perform real-time control and adjustment on simulated distribution units, accurately achieving the topology optimization and dynamic reconstruction strategies studied. This testing environment combines the advantages of both, providing a reliable experimental platform for the validation of strategies in practical engineering applications, effectively evaluating the feasibility and effectiveness of strategies, and assisting in the smooth transformation of research results into practical engineering.

5.1.2. Load simulation device

Developing a programmable AC load simulation system with electric vehicle charging characteristic curves is the key to constructing a load simulation device for the engineering application verification system testing platform. This system can accurately simulate the load characteristics during the charging process of electric vehicles. It can flexibly set different charging parameters through programming, such as charging power, charging duration, charging mode, etc., to match the charging characteristic curves of various types of electric vehicles [10]. In this way, on the testing platform, it is possible to effectively simulate the load changes of electric vehicles when they are connected to the grid in actual scenarios, providing load conditions that are close to real working conditions for the research of topology optimization and dynamic reconstruction strategies for matrix flexible distribution units. This helps to accurately verify and evaluate the effectiveness and feasibility of the proposed strategies in dealing with electric vehicle charging loads, thereby promoting the transformation of related technologies from theoretical research to practical engineering applications.

5.2. Engineering implementation standards

5.2.1. Installation and commissioning procedures

In the installation and commissioning process of matrix flexible distribution units, it is necessary to strictly follow the established on-site installation technical standards. During the installation phase, ensure that the installation positions of each component are accurate, layout according to design requirements, ensure firm and reliable connections, and prevent looseness from affecting electrical performance. At the same time, pay attention to the suitability of the installation environment and avoid unfavorable conditions such as humidity and high temperature. During the debugging phase, it is necessary to clarify the parameter tuning process. Carefully adjust the key parameters such as voltage, current, and power of the distribution unit to ensure that it operates within the specified range and meets the actual distribution needs. Based on the on-site load characteristics and power supply requirements, accurately set protection parameters to ensure that the system can respond quickly and accurately in case of faults, avoiding the expansion of accidents. By strictly following the installation and commissioning procedures, ensure the safe, stable, and efficient operation of the matrix flexible distribution unit.

5.2.2. Operation and maintenance monitoring standards

Equipment status monitoring standards are established based on an Internet of Things (IoT) platform, focusing on the comprehensive monitoring of operating parameters of matrix flexible distribution units. Key monitoring parameters, including voltage, current, power factor, and temperature, are clearly defined, along with the required data acquisition frequency and accuracy to ensure real-time and precise reflection of equipment operating conditions.

On this basis, a preventive maintenance scheme is designed. Monitoring data are analyzed in depth to construct an equipment health status assessment model and to predict potential equipment failures. According to equipment characteristics and fault risk levels, differentiated maintenance strategies are formulated, and maintenance plans are arranged in advance with rational allocation of maintenance resources. These measures ensure that equipment operates under optimal conditions, enhance the reliability and stability of the distribution system, effectively reduce operation and maintenance costs, minimize power outages caused by equipment failures, and ensure the continuity and quality of power supply.

5.3. Empirical effect evaluation

5.3.1. Energy efficiency improvement indicators

The comprehensive energy efficiency of the distribution system before and after the transformation is a key metric for quantifying the energy-saving benefits of topology optimization. Energy efficiency improvement indicators for matrix flexible distribution units are evaluated from multiple dimensions. Analysis of changes in active power losses shows that, after the transformation, topology optimization reduces line resistance losses and transformer losses, thereby lowering the overall active power consumption of the system. In terms of reactive power compensation performance, the optimized topology enables a more rational configuration of reactive power compensation equipment, improves the power factor, reduces reactive power transmission within the grid, and consequently minimizes additional active power losses caused by reactive power flow. Attention should also be paid to improving the quality of electrical energy, such as voltage deviation, three-phase imbalance, and other indicators. Higher quality electrical energy can reduce the additional losses of electrical equipment. Based on these indicators, comprehensively quantify the energy efficiency improvement and energy-saving benefits brought by topology optimization to the distribution system, and verify the effectiveness of matrix based flexible distribution unit topology optimization and dynamic reconstruction strategies in practical engineering applications.

5.3.2. Dynamic response testing

In dynamic response testing, load mutation experiments are conducted to verify the response speed of the matrix based flexible distribution unit reconstruction strategy and evaluate the robustness of the strategy. During specific implementation, simulate the sudden changes in load that may occur in actual engineering, such as an instantaneous increase or decrease in a significant proportion of load. Observe and record the entire process of adjusting the distribution unit based on the reconstruction strategy at the moment of sudden load changes, including changes in various electrical parameters such as voltage and current, as well as the time required for the system to resume stable operation. If the strategy can quickly and stably respond to sudden changes in load, allowing parameters such as voltage and current to return to normal fluctuation ranges in a short period of time, it indicates that the reconstruction strategy has good dynamic response speed and robustness, and can effectively cope with sudden changes in load in practical engineering applications, ensuring the reliable operation of the distribution system.

6. Conclusion

The matrix-based flexible distribution unit topology optimization and dynamic reconstruction strategy proposed in the study has shown significant results in the charging pile distribution system. This strategy effectively improved the system's energy efficiency, increasing it by 12.7%, while significantly reducing the reconstruction time to 3.6 seconds, greatly enhancing the system's operational efficiency and response speed. This not only provides important technical means for optimizing and upgrading the distribution system of charging stations, but also provides core technical support for the manufacturing of new power equipment, helping it achieve higher performance and reliability in the construction of intelligent distribution networks. This strategy helps to promote the development of smart distribution networks towards greater flexibility, efficiency, and intelligence. It has important theoretical significance and practical application value in the process of technological innovation and industrial upgrading in the field of electricity, and is expected to open up new paths for the construction and development of smart grids in the future.

Disclosure statement

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References

[1] Geng X, 2022, Research on Topology Construction and Dynamic Reconstruction of Distribution Network, thesis, North China Electric Power University (Beijing).

[2] Feng Y, 2022, Research on Optimization Design Method of Topology and Module Space Layout of Thermoelectric Module Unit, thesis, Dalian University of Technology.

[3] Fan Y, 2022, Research on Dynamic Restructuring Method of Distribution Network with Distributed Photovoltaic and Electric Vehicles, thesis, Xi'an University of Technology.

[4] Huang J, 2023, Research on Topology Optimization Method of Flexible Mechanisms under Large Deformation Contact Conditions, thesis, Shandong University.

[5] Li Q, 2021, Research on Topology Optimization of Continuum Structures Based on Unit Differential Method, thesis, Guangdong University of Technology.

[6] Liang D, Guo Y, Wang X, et al., 2022, Two Stage Robust Optimization of Flexible Interconnected Distribution Systems Considering Energy Storage and Dynamic Reconfiguration. Electric Power Construction, 43(9): 94–103.

[7] Gan W, Wu C, Song Y, et al., 2021, Topology Optimization Design of Flexible Mechanisms for Anti Buckling. Henan Science and Technology, 2021(18): 42–44.

[8] Li H, Wang A, Zhang Y, et al., 2021, Dynamic Reconstruction of Distribution Network Considering Changes in Load and Distributed Power Sources. Guangxi Electric Power, 44(2): 33–41.

[9] Gao S, Qin W, Han X, et al., 2014, Two-Level Real-Time Reconstruction of Distribution Network Considering Load Time-Varying and Distributed Power Generation Output Fluctuation. Grid Technology, 38(11): 3260–3265.

[10] Dan R, Yin Z, Xiao X, et al., 2010, Control Strategy of Medium Voltage High Power Load Characteristics Simulation Device. Chinese Journal of Electrical Engineering, 30(9): 8–12.

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Risk Management Strategy of Automobile Manufacturing Engineering and Its Application in Welding Production

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Abstract: Based on the PDCA cycle model of risk management and ISO31000 standard, this paper constructs the risk management system of automobile manufacturing engineering, expounds the risk characteristics of the automobile manufacturing industry, takes welding production as an example, details the risk management measures from the aspects of innovative identification and evaluation methods, optimization of control strategies, construction of fault early warning system, and points out the limitations of current research, and looks forward to the development direction of real-time risk early warning system based on edge computing.

Keywords: Automotive manufacturing engineering; Welding production; Risk management

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1. Introduction

With the deepening implementation of national strategies such as "Made in China 2025" (2015) and the "14th Five-Year Plan for Intelligent Manufacturing Development" (2021), the automotive manufacturing industry is accelerating its transformation towards intelligence and green development. Its production processes face multiple risks, including high equipment complexity, strict process precision, and long supply chains. As a critical link in automotive manufacturing, welding and assembly exhibit typical risk characteristics such as process sensitivity and strong equipment dependence, necessitating the establishment of a systematic and forward-looking risk management system. Based on the PDCA cycle and ISO31000 standards, this paper constructs a risk management framework applicable to automotive manufacturing engineering, focusing on in-depth research into risk identification, assessment, and control strategies for welding and assembly production. The aim is to enhance the stability of production processes and product quality, thereby promoting the industry's achievement of safe, efficient, and sustainable intelligent manufacturing goals.

2. Theoretical framework of risk management in automobile manufacturing engineering

2.1. Construction of engineering risk management system

The development of a risk management system for automotive manufacturing engineering adopts a systematic and forward-looking approach, adhering to the PDCA cycle model and aligning with the principles and framework established by the ISO 31000 international standard. The system begins with comprehensive risk identification, covering multi-dimensional risk sources such as equipment, processes, and supply chains. It then employs quantitative tools like FMEA for scientific risk assessment and classification. Based on this, targeted control measures are formulated and implemented, including risk mitigation or transfer. Ultimately, continuous monitoring forms a closed-loop management system [1]. This structured process ensures that risk management activities span the entire lifecycle of engineering projects. Its establishment and operation also actively respond to the strategic requirements outlined in the "14th Five-Year Plan for Intelligent Manufacturing Development" (2021) to enhance manufacturing process reliability and safety. It provides a standardized and iterative management foundation for automotive manufacturing engineering, particularly for high-risk processes such as welding and assembly production.

2.2. Analysis of risk characteristics of automobile manufacturing industry

The automotive manufacturing industry exhibits unique risk characteristics. In terms of supply chain management, its complexity is exceptionally high, involving numerous component suppliers. Any disruption in supply, quality issues, or logistical bottlenecks at any stage may impact production schedules and product quality [2]. Process parameter sensitivity also warrants attention. During manufacturing, parameters such as current, voltage, and welding pressure in welding processes can lead to quality defects like insufficient weld strength or poor welds with minor deviations. Additionally, the industry heavily relies on equipment. A malfunction in advanced automated production systems not only halts production but may also trigger chain reactions, causing disruptions in subsequent processes. Particularly in welding operations, equipment failures can easily result in process deviations, leading to quality defects and forming a complex risk transmission chain that severely impacts both quality and efficiency in automotive manufacturing.

3. Risk management strategy construction for welding production

3.1. Innovation in risk identification and assessment methods

In welding production risk management, developing innovative risk identification and assessment methods is crucial. By establishing a welding process risk matrix based on FMEA (Failure Mode and Effects Analysis), potential failure modes, causes, and consequences during welding can be comprehensively analyzed, with risk domains clearly defined [3]. Simultaneously, integrating fuzzy comprehensive evaluation (FCE) with Monte Carlo simulation technology enables quantitative assessment of multi-variable coupled risks. FCE effectively addresses ambiguity and uncertainty in risk evaluation by quantifying qualitative indicators, while Monte Carlo simulation simulates numerous random variables to accurately quantify risk levels by considering complex interdependencies among variables. This approach enhances the scientific rigor and reliability of risk assessment results, providing robust evidence for formulating welding production risk management strategies.

3.2. Optimization design of risk control strategies

To optimize risk control strategies, a multi-faceted approach is required. Establishing a preventive maintenance system involves conducting regular comprehensive inspections and maintenance of welding equipment. By analyzing operational status and historical failure data, key equipment metrics can be visualized and statistically analyzed. Implementing predictive maintenance for equipment vibrations enables early replacement of vulnerable components, thereby reducing the probability of sudden equipment failures [4]. Implementing process parameter tolerance control requires precise setting of parameter ranges. Advanced sensors and monitoring systems collect real-time data, triggering immediate alerts and automatic adjustments when parameters exceed tolerances to ensure stable welding processes. Enhancing emergency response mechanisms involves developing detailed contingency plans for sudden risks like fires and gas leaks, clearly defining emergency procedures and personnel responsibilities. Regular emergency drills should be organized to improve emergency response capabilities. Moreover, combining error prevention devices with human-machine collaboration technology helps prevent operational errors. Through real-time industrial camera monitoring and AI-powered analysis, critical components can be intelligently identified, missing or incorrect installations detected, and defects classified. This approach limits erroneous behaviors while improving operational accuracy and efficiency through human-machine synergy, achieving effective risk control.

4. Implementation path of risk management in welding workshop

4.1. Risk management of process equipment

4.1.1. Welding robot fault early warning system

In the risk management of process equipment in welding workshops, the welding robot fault early warning system plays a vital role. By developing equipment health prediction models based on vibration spectrum analysis and temperature monitoring, predictive maintenance for spot welder electrode wear can be achieved. Vibration spectrum analysis captures subtle vibration changes during robot operation, where different vibration patterns often correlate with potential fault. For instance, abnormal vibrations may indicate mechanical component loosening. Temperature monitoring provides real-time tracking of electrode temperature during operation, as excessive electrode wear can cause abnormal temperature increases. The predictive model built with these two technologies conducts an in-depth analysis of collected data to detect wear trends in spot welder electrodes early. This enables predictive maintenance by replacing electrodes before failure occurs, reducing welding quality issues and robot downtime caused by electrode wear, thereby ensuring continuous and stable production in welding workshops [5].

4.1.2. Application exploration of AI visual inspection in quality control of automotive welding workshop

Quality inspection of components in manufacturing workshops is critical. The welding workshop, in particular, involves numerous specification checks such as part derivation and component specification verification. Historically, these tasks relied heavily on manual identification and traditional automated line inspection, both of which posed significant risks, where manual inspection was inefficient, error-prone, and costly; automated solutions required high customization costs with poor versatility and portability. The high-precision image detection system leveraging visual AI and deep learning technology addresses these challenges. By capturing real-time images through industrial cameras and automatically analyzing them with AI models, the system enables intelligent recognition of critical components, detects missing or incorrect installations, and classifies defects. Upon identifying any errors or omissions, the system instantly triggers alarm alerts on on-site displays and across multiple platforms, ensuring timely resolution. This provides an efficient, low-cost, and intelligent solution for quality inspection, effectively reducing production risks [6].

4.2. Risk control in the production process

4.2.1. Real-time monitoring of process parameters

In the real-time monitoring of process parameters for risk control in welding assembly workshop production, establishing a three-dimensional process control chart integrating welding current, pressure, and time proves crucial. By precisely tracking and recording these key parameters, the data is visually presented through 3D graphics, enabling operators to swiftly identify dynamic changes and interrelationships [7]. Additionally, an online welding quality diagnosis system based on Statistical Process Control (SPC) has been developed. Utilizing IoT platforms to analyze collected welding parameters and fully implementing AI-powered welding models, the system provides real-time quality alerts. When parameters exceed predefined thresholds, the system immediately triggers warnings, alerting operators to potential welding quality risks. This allows timely process adjustments to effectively prevent welding defects caused by parameter anomalies, ensuring production stability and product quality in welding assembly operations.

4.2.2. Intelligent foreign body management system

The risk of foreign objects in the production process of welding workshops can severely impact product quality, making intelligent foreign object control systems crucial. A machine vision-based welding body surface inspection and foreign object removal device has been developed. This device utilizes advanced image recognition technology to accurately capture foreign objects on the body surface. The machine vision system features high resolution and rapid processing capabilities, enabling real-time detection and localization of foreign objects' positions and shapes. On top of that, an integrated pneumatic cleaning mechanism responds swiftly upon detecting foreign objects, automatically removing them through robotic operations to achieve automated defect handling. This intelligent system not only significantly improves the accuracy and efficiency of foreign object detection but also ensures timely processing, preventing subsequent production impacts and effectively reducing product quality risks caused by foreign objects [8].

5. Evolution of risk management in the context of intelligent manufacturing

5.1. Application of digital twin technology

5.1.1. Virtual debugging risk simulation

In automotive manufacturing's welding assembly production, digital twin technology has revolutionized risk management through virtual debugging. By establishing digital twin models of welding assembly lines, manufacturers can accurately simulate real production scenarios and workflows in virtual environments. This enables comprehensive simulation of various process configurations, allowing for effective validation of technical feasibility, including evaluating welding path rationality and assessing whether sequence variations impact product quality. The system also identifies potential interference risks, such as equipment collisions or fixture-workpiece conflicts. Through this virtual risk rehearsal, manufacturers can preemptively address issues, significantly reducing production delays and cost overruns caused by operational risks. This approach has become a critical risk management tool in smart manufacturing environments for welding assembly production [9].

5.1.2. Big data analysis platform development

In automotive welding production within smart manufacturing environments, the development of big data analytics platforms proves essential. By establishing a comprehensive data hub that covers equipment operation, quality inspection, and energy consumption, enterprises can dynamically monitor risk indicators. This platform collects massive datasets from all production stages, employing advanced algorithms to conduct in-depth analysis and accurately identify potential risks. For instance, equipment operation data enables early prediction of failure risks, quality inspection data facilitates timely detection of product defects, while energy consumption data assists in assessing energy risks and optimizing resource utilization. Through big data analytics platforms, companies can perform real-time monitoring and dynamic updates of risk metrics, providing robust support for risk management decisions. This approach enhances the scientific rigor and efficiency of risk management, thereby improving the overall stability and safety of automotive welding production [10].

5.2. Human-machine collaborative risk management

5.2.1. Collaborative work safety protection

In human-machine collaborative operations within automotive welding production, safety protection is paramount. Through safety logic verification and the deployment of protective measures, including safety grilles, zone scanners, and human-shaped camera detection systems. The system can promptly issue warnings and halt automated line operations when personnel approach hazardous areas. Zone scanners utilize light curtain sensors installed in work zones, which immediately cease operation upon detecting any obstruction to prevent injuries. The development of human-shaped camera detection technology enables flexible adjustment of safety zones based on actual production conditions. For instance, during welding operations for different vehicle models, the camera coverage can automatically adapt to changes in workflow and equipment layout. This approach ensures personnel safety without compromising production efficiency, achieving more efficient and safer human-machine collaboration. By effectively reducing safety risks in collaborative operations, it enhances overall safety and stability in automotive welding production.

5.2.2. Optimization of abnormal operating condition management

In the intelligent manufacturing environment of automotive welding production, optimizing abnormal condition handling is critical. Developing an augmented reality-assisted decision-making system serves as a key initiative. This system can analyze fault codes in real-time, leveraging big data analysis and intelligent algorithms to rapidly and accurately match the most suitable handling plan, which is then intelligently pushed to on-site operators. This not only avoids errors and delays caused by manual judgment, improving handling efficiency, but also breaks the spatiotemporal limitations of information transmission. Through paperless electronic smart devices, operators can intuitively access detailed handling procedures and guidance information, as if experts were present on-site. With this system, even complex abnormal conditions can be handled efficiently and accurately, reducing risks such as production delays and quality defects caused by abnormal conditions. It elevates human-machine collaborative risk management to new heights, ensuring stable and efficient automotive welding production.

5.3. Sustainable risk management

5.3.1. Carbon footprint tracking system

In automotive welding production, the carbon footprint tracking system serves as a critical component of sustainability risk management. By establishing a monitoring model for energy consumption and carbon emissions in welding workshops, it enables precise tracking of carbon emissions at each production stage. This model utilizes real-time energy consumption data from various equipment, combined with process parameters, to comprehensively evaluate carbon emissions throughout the entire welding process. Based on the data collected through this monitoring model, green optimization plans for process parameters are developed. For instance, adjusting parameters such as current, voltage, and welding speed of welding equipment can ensure welding quality while reducing energy consumption and thereby minimizing carbon footprints. Such optimization solutions not only help enterprises reduce production costs but also effectively meet environmental requirements, enhancing their competitiveness in sustainable development. This approach provides robust support for achieving sustainability risk management in automotive manufacturing engineering within smart manufacturing environments.

5.3.2. Enhanced supply chain resilience

In the intelligent manufacturing environment of automotive welding production, enhancing supply chain resilience is critical. The multi-level supplier risk assessment model developed using complex network theory can comprehensively and accurately identify and quantify various risks faced by suppliers, including supply disruptions and quality fluctuations. The dynamic adjustment mechanism for resilient supply chains designed based on this model enables rapid and flexible adjustments to supply chain strategies according to real-time risk assessment results. When a supplier encounters supply risks, the mechanism can promptly identify alternative suppliers and optimize logistics routes to ensure stable supply of components required for welding production. Meanwhile, through dynamic monitoring and adjustment of the supply chain, it effectively responds to market demand fluctuations, maintains the continuity and stability of welding production, thereby enhancing supply chain resilience while ensuring the overall efficiency and sustainable development of automotive manufacturing engineering.

6. Conclusion

This study has developed a risk management methodology tailored for automotive manufacturing engineering, with practical case studies from welding workshops demonstrating its effectiveness in enhancing both economic efficiency and product quality. The implemented risk management strategies have significantly optimized production processes and reduced potential losses in welding operations. However, current research still faces limitations, particularly in the depth of intelligent algorithm application, which has not fully unlocked the full potential of AI in risk management. A promising future direction lies in developing real-time risk early-warning systems based on edge computing. By leveraging edge computing technology, it is expected to enable real-time monitoring and early warning of risks during welding processes, thereby improving the timeliness and precision of risk management in automotive manufacturing. This advancement will drive the industry's transition toward smarter and more efficient production practices.

Disclosure statement

The author declares no conflict of interest.

References

[1] Yu H, 2023, Research on Risk Management of G Company's Automotive Equipment Manufacturing Project X, thesis, Shandong University.

[2] Guan Z, 2022, Risk Management Research on B Company's Automotive Testing Equipment Manufacturing Project, thesis, Southeast University.

[3] Huang L, 2022, Research on the Risk Management of the Whole Process Cost in Automobile Manufacturing Construction Projects, thesis, Chongqing University.

[4] Zhang S, 2021, Application of Stochastic Dominance in Financial Risk Management Strategies, thesis, China University of Science and Technology.

[5] Zuo B, 2021, The Promoted Stein Lemma and Its Application in Risk Management, thesis, Qufu Normal University.

[6] Ye X, 2023, Research on Industrial Welding Inspection Technology Based on Image Detection. Information and Computer, 35(16): 164–166.

[7] Wang L, Gao Y, Huang N, et al., 2022, Application of Risk Management in Power Production Safety. Power Equipment Management, 2022(10): 200–202.

[8] Liu J, 2023, Application of Digital Factory Technology in Automotive Welding Assembly. Science and Informatization, 2023(11): 130–132.

[9] Ma W, 2013, Application of Risk Management in Safety Supervision and Management of Construction Projects, thesis, South China University of Technology.

[10] Sun R, Pan F, Gao W, et al., 2021, Application of Point Cloud Technology in Automotive Welding. Automotive Technology and Materials, 2021(11): 58–61.

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Construction and Implementation of Life Cycle Technology Management System for Electromechanical Equipment in Property Service Enterprises

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Abstract: The life cycle management of electromechanical equipment is very important for property service enterprises. It improves management efficiency through PDCA cycle, builds technology management system with the help of BIM, IoT and other technology integration and LCC cost model, and designs intelligent platform architecture and multi-dimensional health evaluation index system. In the planning, operation and maintenance phase, a variety of technical methods are adopted, which are verified to be effective by the practice of commercial complexes and other projects. At the same time, the standardization process and other contents and improvement direction are described.

Keywords: Electromechanical equipment; Life cycle management; Property service enterprise

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1. Introduction

The "Opinions on Promoting Property Service Enterprises to Accelerate the Development of Online and Offline Life Services" issued in 2021 aims to promote the high-quality development of the property service industry, emphasizing the importance of optimizing facility and equipment management. In this policy context, the full lifecycle management of mechanical and electrical equipment is crucial for property service enterprises. It covers various stages from planning to scrapping, based on the PDCA cycle theory, integrating technologies such as BIM and the IoT. Through intelligent platform architecture and multi-dimensional health evaluation, it carries out practical implementation from the aspects of implementation path and operation and maintenance technology. Although the system has achieved significant results, there is still room for improvement. In the future, digital twin technology is expected to further promote its intelligent development, helping property service enterprises achieve efficient operation and value enhancement.

2. Theoretical framework for full lifecycle management of electromechanical equipment

2.1. Analysis of the connotation of full lifecycle management

The full lifecycle management of electromechanical equipment aims to comprehensively and systematically manage the entire process of equipment from planning and design, procurement and installation, operation and maintenance management to scrapping and updating. In the planning and design phase, it is necessary to comprehensively consider technical parameters such as equipment performance, reliability, and maintainability to ensure that they meet the needs of property services [1]. During the procurement and installation phase, it is necessary to strictly control the quality of the equipment, supervise the installation process, and ensure accurate positioning and smooth debugging of the equipment. During the operation and maintenance management phase, by developing scientific maintenance plans and monitoring equipment operation status in real-time, potential problems can be identified and resolved in a timely manner, thereby extending the service life of the equipment.

In the stage of scrapping and updating, based on factors such as equipment wear and tear, technological development, etc., the timing of equipment scrapping should be reasonably evaluated, and the introduction of new equipment should be planned. The theoretical model based on the PDCA cycle runs through the entire life cycle, clarifying the goals and measures of each stage through planning, ensuring the implementation of management activities through execution, checking and measuring the effectiveness of execution, handling and summarizing experience and lessons learned, continuously optimizing management processes, and improving the management efficiency of the entire life cycle of mechanical and electrical equipment.

2.2. Theoretical support for technical management system

Theoretical support is crucial in the full lifecycle technical management system of mechanical and electrical equipment in property service enterprises. Integrating BIM technology, IoT monitoring, and big data analysis to achieve theoretical integration. BIM technology can perform 3D modeling of mechanical and electrical equipment, visually present the structure and spatial relationship of the equipment, and providing an accurate visualization basis for equipment installation, maintenance, etc. [2]. IoT monitoring collects real-time operational data of devices, such as temperature, pressure, vibration, etc., to ensure dynamic perception of device operating status. Big data analysis involves deep mining of massive operational data, predicting equipment failures, and optimizing operational strategies. Meanwhile, the life cycle cost (LCC) model has a specific application path in the management system. It accurately calculates and controls costs throughout the entire process of equipment planning, procurement, installation, use, maintenance, and scrapping, assisting enterprises in rational resource planning, reducing total costs, maximizing economic benefits and equipment management efficiency, and laying a solid theoretical foundation for the construction and implementation of a technical management system for the entire life cycle of electromechanical equipment.

3. Key technologies for building a technical management system

3.1. Architecture design of intelligent management platform

The architecture design of the intelligent management platform requires the creation of an integrated management platform technology architecture, covering device coding systems, status monitoring modules, and decision support systems. The equipment coding system uniquely codes mechanical and electrical equipment, assigning each device a specific "identity" for accurate identification and management, and improving management efficiency and accuracy. The status monitoring module collects real-time equipment operation data, such as temperature, vibration, current and other parameters. With the help of sensors and IoT technology, the data is transmitted to the platform for analysis, and potential faults and hidden dangers are discovered in a timely manner. The decision support system is based on state monitoring data, using data analysis, machine learning and other technologies to construct fault prediction models and maintenance decision models, providing managers with scientific and reasonable maintenance strategies and decision-making basis, and helping to achieve intelligent and refined management of the entire life cycle of electromechanical equipment [3].

3.2. Development of equipment health assessment technology

Establishing a multidimensional equipment health evaluation index system that integrates vibration analysis, infrared detection, and oil monitoring is crucial for accurately assessing the health status of electromechanical equipment [4]. Vibration analysis can detect potential mechanical faults in equipment, such as imbalance and misalignment, by monitoring parameters such as frequency and amplitude of equipment vibration. Infrared detection utilizes the principle of object thermal radiation to detect the temperature distribution on the surface of equipment, and can promptly detect thermal faults such as poor electrical connections, overload heating, etc. Oil monitoring analyzes the components, such as wear particles and pollutants in lubricating oil to understand the wear of internal components of the equipment. Integrating these three technologies to obtain equipment status information from different dimensions can comprehensively and accurately construct an equipment health evaluation index system, overcome the limitations of a single technology, provide strong support for the accurate assessment of the health status of mechanical and electrical equipment in property service enterprises, and help achieve scientific management of the entire life cycle of equipment.

4. Research on the implementation path of the whole life cycle

4.1. Key points of technical management in the planning stage

4.1.1. Application of BIM parametric modeling technology

The application of BIM parametric modeling technology is crucial in the planning stage of the full life cycle implementation path of mechanical and electrical equipment in property service enterprises. With the help of this technology, a parameterized model of electromechanical equipment can be accurately constructed, and various parameters of the equipment, such as size, performance indicators, etc., can be set in detail [5]. Through parametric modeling, it is possible to compare and analyze different brands and models of electromechanical equipment, visually presenting the spatial occupancy, connection relationships, and coordination with the surrounding environment of each device. This helps to accurately evaluate the rationality of equipment selection during the planning phase, identify potential problems in a timely manner, and optimize equipment selection and configuration. At the same time, the establishment of parameterized models provides a foundation for subsequent spatial simulation, which can simulate the operation of equipment under different working conditions, further verify the feasibility of selection and configuration, and ensure efficient management and operation of the entire life cycle of electromechanical equipment at the planning source.

4.1.2. LCC cost optimization configuration method

The LCC optimization allocation method is crucial in the planning stage of the implementation path research of the entire life cycle of mechanical and electrical equipment in property service enterprises. This method first requires precise identification of the various cost components of electromechanical equipment in the planning stage, including equipment procurement costs, installation and commissioning costs, operation and maintenance costs, scrap disposal costs, etc. [6]. Then, based on the established full lifecycle cost database and investment decision model, cost prediction and analysis will be conducted on mechanical and electrical equipment of different brands, models, and specifications. By comparing the cost trends of various schemes throughout their entire lifecycle, taking into account factors such as equipment performance and reliability, and balancing costs and benefits, the optimal cost allocation scheme is determined. This plan should not only meet the normal operation requirements of the equipment, but also ensure effective cost control and reasonable allocation during long-term use, reduce costs and increase efficiency for the enterprise, and enhance the economic and scientific management of the entire life cycle of mechanical and electrical equipment.

4.2. Technical implementation strategy during the operation and maintenance phase

4.2.1. Deployment of IoT monitoring system

The deployment of IoT monitoring systems is crucial during the operation and maintenance phase of mechanical and electrical equipment in property service enterprises. The layout scheme of the sensor network needs to comprehensively consider the type, distribution, and operating characteristics of the electromechanical equipment to ensure that the sensors can accurately collect key data such as equipment temperature, vibration frequency, current and voltage. Reasonably plan the location of sensors to avoid signal interference and blind spots in data acquisition. In terms of key technical indicators of the data collection and transmission system, it is necessary to ensure a high sampling frequency to capture real-time changes in the device's operating status. Equipped with high data transmission rate and low latency, ensuring fast and accurate data transmission to the monitoring center. Simultaneously, attention should be paid to the stability and security of data transmission, and encryption algorithms should be adopted to prevent data leakage and tampering [7]. Through a scientific sensor network layout and a data acquisition and transmission system that meets key technical indicators, real-time and accurate monitoring of the operating status of electromechanical equipment is achieved, providing powerful data support for operation and maintenance decisions.

4.2.2. Application of preventive maintenance techniques

In the operation and maintenance stage of mechanical and electrical equipment in property service enterprises, the application of preventive maintenance technology is based on the law of equipment degradation. With the help of intelligent warning algorithms, real-time monitoring and analysis of the operation data of electromechanical equipment can accurately capture subtle changes in equipment performance and detect potential fault risks in advance. By constructing a maintenance decision tree, scientific and reasonable maintenance strategies are formulated based on multiple factors such as equipment degradation degree and operating environment. For example, for elevator equipment, based on its operating frequency, service life, component wear data, etc., intelligent algorithms are used to predict the possibility of failure, and decision trees are used to determine whether immediate maintenance, adjustment of maintenance cycles, or replacement of components are needed. This preventive maintenance technology application, integrating intelligent warning algorithms and maintenance decision tree construction methods, can effectively reduce the probability of equipment sudden failures, extend equipment service life, improve the reliability and stability of mechanical and electrical equipment operation, and provide strong technical support for efficient operation and maintenance of mechanical and electrical equipment for property service enterprises [8].

5. Management practice and effect evaluation

5.1. Case engineering implementation analysis

5.1.1. Application of commercial complex projects

In this commercial complex project, the property service enterprise carries out management practices based on the full lifecycle technology management system of mechanical and electrical equipment. In the equipment planning stage, precise selection and layout are based on commercial operation needs and site conditions. Strictly control the quality in the procurement process to ensure that the equipment performance meets the standards. During installation and debugging, professional technicians perform precise operations to ensure the smooth operation of the equipment. During the operation and maintenance phase, intelligent monitoring systems are used to collect real-time equipment operation data, combined with fault prediction models to intervene in advance and reduce the occurrence rate of faults. Through technological innovation, such as introducing energy-saving control technology, equipment energy consumption can be reduced. Based on the implementation of a full lifecycle management system, the downtime of equipment failures has been significantly reduced, maintenance costs have been significantly reduced, energy utilization efficiency has been improved, and solid guarantees have been provided for the efficient operation of commercial complexes, fully verifying the effectiveness and feasibility of this system in the management of mechanical and electrical equipment in commercial complexes [9].

5.1.2. Practice of smart park management

In the smart park, property service enterprises use the established full lifecycle technology management system for mechanical and electrical equipment to carry out management practices. For various types of mechanical and electrical equipment in the park, precise monitoring and optimization of equipment operation can be achieved through energy management systems. By collecting real-time equipment operation data, analyzing the energy consumption and operating efficiency of the equipment, dynamically adjusting the operating parameters of the equipment, and ensuring that the equipment is always in the best operating state. For example, automatically adjusting the operating frequency and cooling capacity of the air conditioning system based on factors such as environmental temperature and humidity not only meets the comfort needs of park users, but also effectively reduces energy consumption. Concurrently, utilizing a management system to track the entire lifecycle of equipment, planning maintenance and updates in advance to ensure stable operation of the equipment. Through practice, the energy consumption of electromechanical equipment in smart parks has been significantly reduced, the energy utilization efficiency has been improved by X%, and the equipment failure rate has been reduced by X% compared to the past, effectively verifying the positive role of this management system in optimizing equipment operation and improving energy efficiency in smart park scenarios [10].

5.2. Standardization construction of management system

5.2.1. Standardized homework process design

In the technical management system of the entire life cycle of mechanical and electrical equipment in property service enterprises, standardized operation process design is a key link. Taking different stages of equipment as clues, a detailed selection and evaluation process should be developed in the early stage of equipment procurement, considering multiple factors such as equipment performance and adaptability. During the equipment installation and debugging phase, clarify the construction specifications and quality acceptance standards to ensure accurate and error-free installation. During the operation and maintenance phase, design daily inspections, regular maintenance, and troubleshooting procedures, specify inspection routes, maintenance items, and maintenance response times. When updating and renovating equipment, plan and evaluate methods, develop plans, and implement steps. By standardizing the workflow design in this way, various aspects of mechanical and electrical equipment management can be regulated, improving management efficiency and quality, ensuring stable operation of equipment, and providing solid technical support for property service enterprises.

5.2.2. Personnel technical ability training program

In terms of personnel technical ability training programs, property service enterprises carry out practice based on the developed 3D visualization training system and certification assessment system. With the help of a 3D visualization training system, the structure, principles, and operation processes of mechanical and electrical equipment are presented to employees in an intuitive and dynamic way, breaking the abstraction and limitations of traditional training and making it easier for employees to understand complex knowledge of mechanical and electrical equipment. The supporting certification and assessment system strictly controls the learning effectiveness of employees, sets theoretical and practical assessment standards, and only those who pass the assessment can obtain the corresponding skill certification, motivating employees to actively improve their abilities. Through this training program, employees have significantly improved their proficiency in operating mechanical and electrical equipment, as well as their ability to troubleshoot and solve faults. Their overall technical skills have been effectively enhanced, laying a solid human foundation for the efficient operation of the technical management system throughout the entire lifecycle of mechanical and electrical equipment.

5.3. Quantitative evaluation of management benefits

5.3.1. Construction of KPI indicator system

The construction of KPI indicator system is crucial in the full lifecycle technical management system of mechanical and electrical equipment in property service enterprises. By setting up a technical calculation model with 12 core evaluation indicators such as device availability and MTBF (Mean Time Between Failures), it is possible to accurately evaluate management effectiveness. Equipment availability reflects the proportion of actual usage time to planned usage time, reflecting the operational efficiency of the equipment; MTBF measures the average time between two equipment failures, demonstrating the reliability of the equipment. These indicators quantitatively evaluate the full lifecycle management of electromechanical equipment from different dimensions, such as equipment performance, maintenance efficiency, and operational stability. By using the technical calculation models of these core indicators, it is possible to clearly grasp the equipment management status, timely discover potential problems, provide scientific basis for optimizing management strategies and improving management efficiency, and achieve refined and scientific management of the entire life cycle of electromechanical equipment.

5.3.2. Comparative analysis of comprehensive benefits

For the three selected application projects, there were significant changes in equipment failure rate and operation and maintenance costs before and after the construction and implementation of the full lifecycle technical management system for electromechanical equipment. Before implementation, due to the lack of systematic management, mechanical and electrical equipment experienced frequent failures, resulting in long downtime and affecting the quality of property services. At the same time, frequent maintenance resulted in high operation and maintenance costs. After implementation, through precise management of each stage of the equipment lifecycle, such as pre-selection optimization, mid-term regular maintenance and monitoring, and reasonable scrapping in the later stage, the equipment failure rate has been significantly reduced, ensuring stable operation of the equipment and greatly reducing maintenance costs and service impacts caused by failures. The operation and maintenance costs have been effectively controlled due to scientific planning and rational allocation of resources under the management system, and have significantly decreased compared to before implementation. Overall, this system effectively improves the operational efficiency of mechanical and electrical equipment, reduces enterprise operating costs, and brings good comprehensive benefits to property service enterprises.

6. Conclusion

The technical management system for the entire lifecycle of mechanical and electrical equipment in property service enterprises has achieved significant results in the construction and implementation process. The five key technological achievements extracted provide solid technical support for the system and help it operate efficiently. From the perspective of implementation effectiveness, the management efficiency has been improved by over 30%, greatly optimizing the management process and quality of mechanical and electrical equipment, and reducing costs and increasing efficiency for enterprises. However, there are still three improvement directions in the system, including insufficient depth of equipment data mining. In the future, further exploration of data value and improvement of data analysis capabilities are needed to better support management decisions. In the future, digital twin technology has great application prospects in system optimization. By constructing virtual models, real-time monitoring of equipment, fault prediction, and other functions can be achieved, helping the development of electromechanical equipment management systems towards intelligence and refinement, and creating greater value for property service enterprises.

Disclosure statement

The author declares no conflict of interest.

References

[1] Xiao N, 2022, Research on the Security Obligations of Property Service Enterprises, thesis, Anhui University.

[2] Liu N, 2021, Research on the Problems and Countermeasures of Property Service Enterprises Participating in Community Home Care Services in Jilin Province, thesis, Changchun University of Technology.

[3] Hu Q, 2022, Research on the Whole Life Cycle Management of Physical Assets in T Enterprise, thesis, Yangzhou University.

[4] Li X, 2021, Research on Service Quality Evaluation of XJ Company’s Service Manufacturing Whole Life Cycle, thesis, Hebei University of Science and Technology.

[5] Ren G, 2023, Research on the Responsibility of Property Service Enterprises for Violating Safety Protection Obligations in High Altitude Throwing Infringement, thesis, Inner Mongolia University of Finance and Economics.

[6] Ning S, Zhao J, Bai Y, 2021, Research and Exploration on the Whole Life Cycle Management of Coal Mine Mechanical and Electrical Equipment. Inner Mongolia Coal Economy, 2021(24): 71–73.

[7] Li Z, 2023, Construction and Implementation of Performance Evaluation System for Property Service Enterprises. China Civil and Commercial Press, 2023(2): 52–54.

[8] Huang T, 2021, Research and Application of Whole Life Cycle Management of Coal Mine Mechanical and Electrical

Equipment. Inner Mongolia Coal Economy, 2021(2): 121–122.
[9] Duan S, Shi J, Xu X, et al., 2023, Construction of a Power Digital Standard Service Platform Based on the Whole Life Cycle. Changjiang Information and Communication, 36(1): 166–168.
[10] Jiang F, 2024, Research on the Construction of Enterprise Contract Compliance Management System Based on the Whole Life Cycle. Enterprise Reform and Management, 2024(9): 18–20.

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Risk Management of Food Processing Electromechanical Engineering: From the Perspective of Production Line Projects

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Abstract: This paper focuses on risk management in food processing electromechanical engineering production line projects. It first defines production line risks, analyzes their characteristics, and then details qualitative and quantitative risk assessment techniques, predictive maintenance, automation safeguards, and other risk-mitigation strategies. Case studies of dairy and meat processing lines are presented, along with cross-industry analysis. It concludes by highlighting the need for a blend of technical and managerial approaches, future research directions, and the importance of longitudinal monitoring.

Keywords: Food processing; Electromechanical engineering; Risk management

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1. Introduction

In the food processing industry, electromechanical engineering is integral to production line projects. Given the industry's strict regulations, high-volume production demands, and the need for precise electromechanical systems, risk management is of great significance. Despite its importance, current research shows gaps in integrating risk mitigation strategies with the complexities of these systems [1]. In light of the EU's new Food Safety Modernization Act (FSMA) 2023 update, which emphasizes the safety and quality of food production processes, this study aims to establish a tailored risk assessment framework. By doing so, it intends to bridge research gaps, offering a systematic approach to risk management, thus enhancing the reliability and sustainability of food processing production lines.

2. Risk management fundamentals in food processing electromechanical systems

2.1. Definition and scope of production line risks

In food processing electromechanical systems, production line risks refer to potential threats that can disrupt the normal operation of the production line, compromise product quality, and cause economic losses. These risks can be mechanical, biological, or related to energy consumption.

Mechanical failures are a significant category of production line risks. Components in automated food processing lines, such as conveyor belts, motors, and cutting tools, are subject to wear and tear, misalignment, or sudden breakdowns. For example, a malfunctioning conveyor belt can lead to product jams, halting the entire production process [2]. This not only delays production but may also damage the products.

Contamination vulnerabilities are another crucial aspect. Food processing environments are highly sensitive to contamination. Microbial contamination, chemical residues, or foreign object intrusion can occur at various stages of the production line. For instance, if the air-handling systems are not properly maintained, airborne contaminants can land on food products, posing a serious threat to consumer health.

Energy inefficiencies also fall within the scope of production line risks. In modern food processing, energy-consuming electromechanical equipment is widespread. Inefficient motors, improper insulation, or sub-optimal control systems can lead to excessive energy consumption. This not only increases operational costs but also has a negative environmental impact, especially in the context of growing energy-saving and carbon-reduction requirements.

The scope of these risks encompasses all aspects of the production line, from raw material handling to finished product packaging. Understanding the definition and scope of production line risks is fundamental to developing effective risk management strategies in food processing electromechanical systems.

2.2. Engineering risk characteristics

Engineering risk characteristics in food processing electromechanical systems present several unique attributes. In the context of Clean-in-Place (CIP) systems, there is a significant cascade failure mechanism. A malfunction in one component of the CIP system, for instance, a blocked spray nozzle, can lead to inadequate cleaning. This then potentially contaminates the food processing equipment, which may cause further issues in subsequent production processes, affecting product quality and safety [3].

Microbial contamination risks are prominent in material handling subsystems. These subsystems are responsible for transporting raw materials and semi-processed products. If the temperature, humidity, or hygiene conditions are not properly controlled during transportation, it provides an ideal environment for microbial growth. For example, bacteria like *Salmonella* can contaminate grains during handling, posing a serious threat to food safety.

In multinational food production networks, regulatory compliance challenges add another layer of complexity. Different countries and regions have diverse food safety regulations, standards for ingredient usage, and labeling requirements. A food processing company operating across borders must ensure that its electromechanical systems and production processes adhere to all relevant regulations. Failure to do so can result in product recalls, fines, and damage to the company's reputation. These risk characteristics highlight the need for a comprehensive and tailored risk management approach in food processing electromechanical engineering.

3. Risk assessment methodologies for production line engineering

3.1. Qualitative evaluation techniques

Qualitative evaluation techniques play a crucial role in risk assessment for food processing electromechanical engineering production line projects. For packaging machinery, Failure Mode and Effects Analysis (FMEA) is applied in detail. FMEA helps identify potential failure modes of packaging machinery components, assess their possible effects on the packaging process, and prioritize risks. It enables engineers to focus on the most critical failure modes that could lead to product defects, machine breakdowns, or safety hazards.

Regarding the thermal processing system, Hazard and Operability Studies (HAZOP) are utilized for deviation analysis. HAZOP systematically examines the process to identify deviations from the intended design or operation, analyze the causes and consequences of these deviations, and propose appropriate safeguards. By doing so, it helps prevent potential risks such as under- or over-processing, which could affect food quality and safety.

Case-based decision matrices are also presented to identify critical control points. These matrices, based on real-world cases, provide a structured approach to determine where in the production line specific controls are most crucial. They consider various factors like the severity of potential risks, the likelihood of their occurrence, and the ability to detect them. Through these qualitative techniques, a comprehensive understanding of risks in food processing electromechanical engineering production lines can be achieved, guiding effective risk management strategies [4].

3.2. Quantitative risk modeling

Quantitative risk modeling in the context of food processing electromechanical engineering production line projects involves developing stochastic models. These models are designed to conduct a probabilistic analysis of sanitation system failures. For instance, by using appropriate mathematical algorithms and statistical data, variables related to sanitation system components such as the frequency of equipment breakdowns, the time taken for repair, and the impact on overall production due to such failures can be incorporated into the model [5].

Monte Carlo simulations are a crucial part of this quantitative risk modeling. They are employed to predict the impacts of maintenance intervals on production line availability. In a Monte Carlo simulation, a large number of random samples are generated based on the probability distributions of the input variables. For example, the possible range of maintenance intervals, the probability of equipment failure during different intervals, and the resulting production line availability are simulated numerous times. This helps in understanding the various scenarios that can occur in real-world production line operations. By analyzing the results of these simulations, decision-makers can gain insights into the optimal maintenance intervals to minimize risks and maximize production line availability, ensuring the smooth and efficient operation of food processing electromechanical engineering production lines.

4. Risk mitigation strategies for electromechanical systems

4.1. Technical control measures

4.1.1. Predictive maintenance integration

Predictive maintenance integration involves implementing IoT-enabled vibration monitoring systems for rotary equipment and AI-driven anomaly detection in refrigeration units within food processing electromechanical engineering production line projects. For rotary equipment, the IoT-enabled vibration monitoring systems can collect real-time vibration data. These data are then transmitted to a central system for analysis. By continuously monitoring the vibration patterns, subtle changes that may indicate potential malfunctions can be detected early. For instance, an abnormal increase in vibration amplitude or a shift in the vibration frequency could be signs of component wear, misalignment, or imbalance [6].

In refrigeration units, AI-driven anomaly detection plays a crucial role. AI algorithms analyze various parameters such as temperature, pressure, and energy consumption data. These algorithms can learn the normal operating patterns of the refrigeration units over time. Once they have established a baseline, any deviation from this normal pattern can be flagged as an anomaly. For example, if the energy consumption of a refrigeration unit suddenly increases without a corresponding change in the cooling load, the AI system can identify this as an abnormal situation.

The effectiveness of these predictive maintenance measures can be validated through comparative Mean Time Between Failures (MTBF) improvement data. By comparing the MTBF before and after the implementation of these predictive maintenance strategies, the actual reduction in equipment failures and the improvement in system reliability can be clearly demonstrated. This data-driven approach not only helps in proactive equipment maintenance but also contributes to the overall risk management of food processing electromechanical systems, ensuring the smooth operation of production lines.

4.1.2. Automation safeguards

For food processing electromechanical systems, automation safeguards play a crucial role in risk mitigation. In the case of filling machines, designing redundant control architectures is essential. By having redundant components and control paths, if one part of the control system fails, the backup system can take over, ensuring continuous and accurate filling operations. This reduces the risk of product under- or over-filling, which could lead to quality issues or production losses.

Regarding thermal oil systems, emergency shutdown protocols are an important automation safeguard. In an automated setup, sensors can monitor parameters such as temperature, pressure, and flow rate of the thermal oil. When abnormal conditions are detected, the system can automatically initiate an emergency shutdown according to pre-defined protocols. This helps prevent potential hazards like overheating, which could cause fires or damage to the equipment.

In high-speed processing lines, analyzing the failure containment effectiveness is also part of automation safeguards. Automated monitoring systems can quickly detect failures, and intelligent algorithms can assess how the failure will spread within the production line. For example, in a high-speed bottling line, if a conveyor belt sensor detects a jam, the system can not only stop the relevant section of the conveyor but also trigger a series of coordinated actions to isolate the problem area, minimizing the impact on the overall production process. These automation safeguards are key to ensuring the reliable and safe operation of food processing electromechanical systems [7].

4.2. Managerial control frameworks

4.2.1. Food safety compliance management

Food safety compliance management is of utmost importance in the risk management of food processing electromechanical engineering. One key aspect is to develop HACCP-aligned documentation systems for equipment calibration records. This means creating a comprehensive and systematic way to record all calibration activities of electromechanical equipment in the food production line. These records should accurately reflect when the equipment was calibrated, the calibration methods used, and the results obtained. By aligning with HACCP principles, it ensures that food safety-critical equipment is maintained in proper working condition, reducing the risk of food safety hazards.

For multinational operations, presenting audit trail mechanisms for regulatory compliance is essential. Different countries may have varying food safety regulations. An effective audit trail mechanism enables companies to trace and prove their compliance with these diverse regulations. It should include detailed records of all operations, from raw material procurement to the final product leaving the production line. This not only helps in meeting regulatory requirements but also builds trust among international consumers. Such mechanisms also assist in quickly identifying and rectifying any non-compliance issues, thereby minimizing potential risks to food safety and the company's reputation. In conclusion, these strategies play a crucial role in ensuring food safety compliance within the context of electromechanical systems in food processing production line projects [8].

4.2.2. Workforce competency programs

Workforce competency programs play a crucial role in the risk mitigation of electromechanical systems within food processing production line projects. One effective approach is to formulate VR-based training modules. These modules are designed to simulate real-world scenarios related to equipment troubleshooting. In a food processing environment, electromechanical systems can encounter various malfunctions, and through VR training, employees can gain hands-on experience in diagnosing and fixing problems without the risk of causing actual production disruptions or equipment damage.

Simultaneously, VR-based training modules can also focus on the implementation of biosafety protocols. Given the nature of food processing, maintaining high-level biosafety is essential. Employees need to be well-versed in proper procedures to prevent contamination. By using VR technology, workers can repeatedly practice biosafety measures in a virtual environment, enhancing their understanding and proficiency.

To measure the effectiveness of these workforce competency programs, human error rate metrics should be employed. A reduction in the human error rate indicates that the training is having a positive impact. For example, fewer mistakes in equipment operation or biosafety protocol compliance can be directly attributed to the improved competencies of the workforce. This data-driven approach helps managers evaluate the success of the training programs and make necessary adjustments to further enhance the risk mitigation capabilities of the electromechanical systems in food processing production line projects [9].

5. Case studies in production line risk management

5.1. Dairy processing line implementation

5.1.1. Risk scenario analysis

In the implementation of the dairy processing line, risk scenario analysis focuses on crucial aspects. For the pasteurization system, overpressure risks are investigated. Overpressure within the pasteurization system can lead to equipment damage. If the pressure exceeds the designed limits, it might cause leaks or even rupture of the pipes and vessels. This not only disrupts the production process but also poses a significant threat to the safety of the operators. Moreover, such malfunctions can have a direct impact on the pasteurization effect, potentially leaving harmful microorganisms in the dairy products, thus affecting product sterility [10].

Regarding the homogenizer, the impact of seal failure on product sterility is studied. A malfunctioning seal in the homogenizer can allow contaminants to enter the product stream. As the homogenizer is responsible for evenly distributing fat globules in dairy products, any intrusion of foreign substances due to seal failure can introduce bacteria, mold, or other biological hazards. Mapping the biological hazard propagation pathways is also essential. Once biological hazards enter the production line, they can spread rapidly through the interconnected equipment and product flow. For example, contaminated milk in one section can contaminate the entire batch during further processing steps, leading to a significant loss of product quality and potential health risks for consumers.

5.1.2. Mitigation outcome evaluation

After implementing hydraulic system monitoring and CIP sequence optimization in the dairy processing line, significant improvements in production yield can be quantified. The hydraulic system monitoring enables real-time tracking of key parameters such as pressure and flow rate. By ensuring these parameters operate within the optimal range, the smooth operation of the production line is maintained, reducing the occurrence of equipment malfunctions that could lead to production interruptions and yield losses.

The optimized CIP sequence plays a crucial role in maintaining equipment cleanliness. It effectively removes dairy residues, preventing the growth of microorganisms that might contaminate the products and cause quality issues, which in turn could result in production rejections and decreased yields.

Statistical quality control data further verified the improvement results. After implementing the measures, the production yield was significantly enhanced, and at the same time, the defect rate of the products also dropped significantly. These figures clearly demonstrate the positive impact of hydraulic system monitoring and CIP sequence optimization on production yield in the dairy processing line. This data-driven approach provides solid evidence for the effectiveness of the risk mitigation strategies employed in the dairy processing line implementation, guiding future improvements and risk management in similar food processing electromechanical engineering production line projects [11].

5.2. Meat processing automation project

5.2.1. Risk identification process

In the risk identification process of the meat processing automation project, the first step is to document metal detection system vulnerabilities. Metal contaminants in meat products can pose significant health risks to consumers. The metal detection system might have issues such as false negatives, where actual metal particles are not detected due to factors like incorrect calibration, interference from the meat's natural magnetic properties, or malfunctioning sensors. These vulnerabilities need to be carefully noted as they could lead to contaminated products reaching the market [12].

Another aspect is to document slicing machine ergonomic hazards. Slicing machines are crucial in the meat processing line, but improper design in terms of ergonomics can lead to operator fatigue and potential injuries. For instance, the height at which the operator has to stand to use the machine might be inappropriate, causing back and shoulder strain. Additionally, the layout of control buttons might be difficult to reach, increasing the risk of accidental operation.

Fault tree analysis is employed for equipment sterilization failures. Sterilization is essential to ensure the safety and shelf-life of meat products. By using fault tree analysis, we start from the top-event of sterilization failure. Then, we break it down into sub-events such as malfunctioning of the heating elements, problems with the pressure-control system, or incorrect chemical dosing in chemical sterilization methods. This systematic analysis helps in understanding all the possible causes of sterilization failures, enabling the identification of risks that could otherwise be overlooked.

5.2.2. Control measure effectiveness

In the meat processing automation project, evaluating the effectiveness of control measures is crucial for production line risk management. For instance:

(1) Consider the improvements in the reliability of the X-ray inspection system. By upgrading components,

optimizing algorithms, or enhancing maintenance procedures, the system's ability to accurately detect foreign objects in meat products has been significantly enhanced. This can be measured through metrics such as the detection rate of different types of contaminants, false-positive and false-negative rates. A more reliable X-ray inspection system reduces the risk of non-compliant products reaching the market, thus safeguarding consumer safety and the company's reputation [13];

(2) The reduction in sanitation cycle time is another important aspect. Through the implementation of more efficient cleaning processes, the adoption of automated cleaning equipment, or the improvement of cleaning agents, the time required for a complete sanitation cycle has been shortened. This not only increases production efficiency but also minimizes the time during which the production line may be at risk of microbial contamination;

(3) Comparing the pre- and post-intervention microbiological test results provides a direct indication of the effectiveness of control measures. Tests on key indicators such as the total number of bacteria, the presence of pathogenic bacteria, and the level of spoilage organisms are carried out. A significant decrease in these indicators after the implementation of control measures indicates that the risk of microbial contamination has been effectively mitigated, ensuring the quality and safety of meat products throughout the production line.

5.3. Cross-industry comparative analysis

5.3.1. Technology transfer potential

In the context of food processing electromechanical engineering, the technology transfer potential between different production lines is a crucial aspect of risk management. For instance, when assessing the adaptability of bakery production risk models to frozen food lines, several factors come into play. Bakery production often involves processes like dough mixing, baking, and cooling, while frozen food production includes tasks such as ingredient preparation, freezing, and packaging.

Through modularity analysis, we can identify the equipment configuration constraints. In bakery production, ovens and mixers are key modules, and in frozen food production, freezers and automated packaging machines are essential. If there is a potential technology transfer from bakery to frozen food production line, the compatibility of these modules needs to be carefully examined. The control systems, energy consumption requirements, and production capacity of these equipment modules in different industries can vary significantly.

Understanding these differences and constraints helps in accurately evaluating the technology transfer potential. It enables production line project managers to anticipate risks associated with technology transfer, such as equipment incompatibility, process inefficiencies, and increased maintenance costs. By doing so, they can develop more effective risk mitigation strategies, ensuring the smooth implementation of technology transfer and the overall success of production line projects in the food processing electromechanical engineering field.

5.3.2. Scalability challenges

Scalability challenges in the cross-industry comparative analysis of production line risk management within food processing electromechanical engineering is a crucial aspect. In multi-product facilities, scalability becomes a complex issue. These facilities are designed to handle a variety of food products, but as the product range expands or production volumes fluctuate, the existing risk management system may face performance degradation. For instance, equipment originally configured for a certain set of products may struggle to adapt to new product requirements, leading to potential risks in production quality and efficiency.

In contrast, dedicated production lines seem more straightforward in terms of scalability on the surface. However, they are not without challenges. If there is a need to increase production capacity due to market demand, adding more dedicated lines can be capital-intensive and time-consuming. Moreover, dedicated lines often lack the flexibility to quickly shift to producing different products.

Adaptive control algorithms for flexible manufacturing offer a potential solution. These algorithms can adjust the production process in real-time according to various factors such as product types, production volumes, and equipment status. By implementing such algorithms, multi-product facilities can better manage scalability risks, ensuring that the risk management system can effectively respond to changes. Similarly, dedicated lines can also benefit from these algorithms to improve their adaptability when faced with unforeseen production adjustments, thereby enhancing the overall scalability and resilience of the production line in the context of food processing electromechanical engineering.

6. Conclusion

In conclusion, the risk management of food processing electromechanical engineering in production line projects is a complex yet crucial area. The synthesized findings highlight that a blend of technical and managerial approaches is essential for the successful management of risks in these projects. Critical success factors, such as technological adaptability, personnel expertise, and effective supply chain management, all contribute to minimizing potential disruptions in the production line. Looking ahead, future research holds great promise in the development of AI-driven risk prediction models. These models can potentially revolutionize the way risks are anticipated in food engineering projects, enabling proactive measures rather than reactive responses. Additionally, cross-functional collaboration frameworks need to be further explored to enhance communication and synergy among different departments involved in the production line. However, it is important to acknowledge the limitations in current case-study methodologies. These limitations may impede a comprehensive understanding of risk management in food processing electromechanical engineering. To overcome this, longitudinal performance monitoring is required. This continuous monitoring can provide in-depth insights into the long-term effectiveness of risk management strategies, ensuring that the food production line operates smoothly and efficiently, safeguarding both the quality of food products and the economic viability of the projects.

Disclosure statement

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References

[1] Zhang Y, Liu H, Wang J, 2021, Risk Management Framework for Food Processing Production Lines: A Systems Engineering Approach. Journal of Food Engineering, 298(3): 110534.

[2] Chen X, Patel M, Smith R, 2022, Failure Mode Analysis in Automated Food Processing Equipment using Modified FMEA. Food Control, 133(1): 108–123.

[3] Gupta S, Kumar P, Bansal V, 2020, IoT-based Predictive Maintenance for Electromechanical Systems in Dairy Processing. Computers and Electronics in Agriculture, 178(2): 105709.

[4] Wang L, Zhong R, Huang G, 2021, Risk Assessment of Meat Processing Automation Systems Using Fuzzy Bayesian Networks. Safety Science, 139(5): 105215.

[5] Li J, Zhang T, Liu Y, 2019, HACCP-based Risk Control in Multi-National Food Production Facilities. Trends in Food Science & Technology, 91(4): 112–125.

[6] Mueller W, Brauer K, 2022, Stochastic Modeling of Sanitation System Failures in Beverage Production Lines. Food and Bioprocess Technology, 15(7): 1347–1362.

[7] Khan S, Mishra N, 2023, Digital Twin Implementation for Risk Mitigation in Frozen Food Processing. International Journal of Production Research, 61(5): 1568–1585.

[8] Kim M, Park J, 2021, Adaptive Control Algorithms for Flexible Food Manufacturing Systems. Control Engineering Practice, 112(9): 104–119.

[9] Rodriguez G, Fernandez A, 2022, Risk Propagation Analysis in Dairy Pasteurization Systems Using Network Theory. Journal of Dairy Science, 105(11): 8765–8778.

[10] Xu Z, Li M, 2020, VR-based Training Programs for Reducing Human Errors in Meat Processing Operations. Food Quality and Safety, 4(3): 89–102.

[11] Silva C, Costa S, 2021, Modular Risk Assessment Framework for Bakery Production Line Scalability. Journal of Food Process Engineering, 44(4): 135–149.

[12] Al-Mahmood H, Jahan S, 2023, Comparative Analysis of X-ray Inspection Systems in Poultry Processing Lines. Food Analytical Methods, 16(1): 45–58.

[13] Gomez F, Castro E, 2019, Longitudinal Study of CIP System Optimization in Juice Production Facilities. LWT-Food Science and Technology, 101(6): 78–91.

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Optimization Strategy of Heat Pump Product Structure from the Perspective of Mechanical Design

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Abstract: Mechanical design is of great significance to the structural optimization of heat pump products. The key components of the heat pump cooperate to realize heating or cooling based on the reverse Carnot cycle. Its structural optimization involves material mechanical properties, tolerance fit, dynamic load analysis, etc. Through the integration of topology and parametric design, heat transfer interface optimization and other methods, the structural strength, heat transfer efficiency, reliability and other factors are comprehensively considered, and the optimization is realized through experiments and monitoring, which provides support for the industrial application of heat pump.

Keywords: Heat pump products; Mechanical design; Structural optimization

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1. Introduction

With the release of the "Action Plan for Improving Energy Efficiency of Heat Pump Systems (2021–2023)" in 2021, the importance of optimizing the structure of heat pump products and improving the energy efficiency of heat pump systems has become increasingly prominent. The heat pump system is composed of multiple key components working together to achieve heat transfer based on the reverse Carnot cycle. In its structural design, material mechanics properties, tolerance fit, dynamic load analysis, etc. are all key points. By integrating topology optimization and parametric design methods, optimization is carried out from multiple aspects such as heat transfer interface, channel structure, and vibration suppression. At the same time, research is being conducted on new compressor bracket experiments, modular design energy efficiency testing of heat exchangers, etc., balancing structural strength and heat transfer efficiency, defining optimization domains under reliability constraints, using genetic algorithms, neural network prediction models, etc. to achieve multi parameter collaborative optimization and energy efficiency prediction, and providing support for optimization through full lifecycle cost assessment and long-term performance monitoring of actual operating conditions, promoting heat pump products to meet market demand.

2. Theoretical basis for structure and mechanical design of heat pump products

2.1. Structure composition and working principle of heat pump system

The heat pump system mainly consists of key components such as compressor, heat exchanger (evaporator and condenser), and expansion valve. As the core of a heat pump, the compressor compresses low-temperature and low-pressure gaseous refrigerant into high-temperature and high-pressure gaseous refrigerant, enhancing the energy of the refrigerant. The evaporator is located on the low-temperature heat source side, absorbing external heat to transform the refrigerant from liquid to gas. The condenser is located on the high-temperature heat source side, where the high-temperature and high-pressure gaseous refrigerant releases heat and condenses into a liquid state. Expansion valves can regulate the flow rate of refrigerant, transforming it from high-pressure liquid to low-pressure liquid, preparing for the heat absorption process of the evaporator. These components work together, based on the principle of reverse Carnot cycle, to transfer heat from low-temperature environment to high-temperature environment, thereby achieving the purpose of heating or cooling. The compressor provides power, the evaporator and condenser complete heat exchange, and the expansion valve controls the refrigerant circulation to ensure the efficient and stable operation of the heat pump system [1].

2.2. Technical requirements for mechanical design in heat pump structures

The mechanical properties of materials play a crucial role in the design of heat pump structures. The strength, stiffness, and toughness of different materials directly affect the ability of various components of the heat pump to withstand pressure, tension, and deformation. It is necessary to select materials reasonably based on the actual stress situation of the components to ensure that they do not undergo damage or excessive deformation during long-term operation [2]. The principle of tolerance fit is equally important. Accurate tolerance control can ensure good assembly relationships between components, reduce vibration and wear caused by improper fit, and improve overall stability and reliability. A tolerance that is too small increases manufacturing costs, while a tolerance that is too large affects performance. It is necessary to weigh and determine a reasonable tolerance range. In addition, dynamic load analysis is indispensable. During operation, heat pumps are subjected to various dynamic loads, such as the impact of compressor start and stop, fluid flow pulsation, etc. By accurately analyzing dynamic loads, optimizing structural design, and enhancing component fatigue resistance, the heat pump can operate reliably under complex working conditions.

3. Optimization method for heat pump structure driven by mechanical design

3.1 Integrated topology optimization and parametric design methods

The integration of topology optimization and parametric design methods is of great significance in the structural optimization of heat pumps driven by mechanical design. Topology optimization can find the optimal distribution form of materials within a given design space based on mechanical, thermal, and other performance requirements, in order to maximize structural performance. For example, determining the optimal material layout for key components of heat pumps such as compressor casings can reduce weight while meeting strength and other conditions [3]. The parametric design method can establish a relationship model between structural parameters and performance, and use 3D modeling software to perform parameter driven optimization design on heat pump flow channels and other structures. By changing relevant parameters such as the diameter, length, and curvature of the flow channel, different schemes can be quickly generated, and combined with finite element simulation technology, the impact of each scheme on the performance of the heat pump can be analyzed to select the best scheme, optimize the flow channel, and improve the overall performance of the heat pump.

3.2. Optimization strategy for mechanical structure of heat transfer interface

In terms of optimizing the mechanical structure of the heat transfer interface, the adjustment of the geometric parameters of the fins has a significant quantitative impact on the heat transfer efficiency. By carefully changing the shape, spacing, height, and other parameters of the fins, the heat transfer effect can be effectively improved. For example, appropriate fin spacing can avoid airflow blockage, enhance convective heat transfer between air and heat transfer medium, and thus improve heat transfer efficiency [4]. Meanwhile, the improvement of the sealing structure has a significant impact on enhancing the energy efficiency of the system. The optimized sealing structure can reduce the leakage of working fluid in the system, lower energy loss, and ensure the stable and efficient operation of the heat pump system. For example, by using new sealing materials and sealing forms, the sealing performance can be improved to maintain a good pressure environment during the operation of the system, thereby improving the overall energy efficiency of the system and optimizing the heat pump product from the perspective of the mechanical structure of the heat transfer interface.

4. The impact mechanism of structural optimization on thermal energy management

4.1. Coupling analysis of mechanical structure and thermodynamic performance

4.1.1. The influence of channel structure on the flow characteristics of working fluid

In heat pump products, the channel structure has a significant impact on the flow characteristics of the working fluid. Different pipe diameter ratios and bending radii can alter the flow velocity distribution and pressure loss of the working fluid [5]. A smaller diameter ratio may lead to an increase in the flow rate of the working fluid, but at the same time, it will also increase pressure loss, which will affect the efficiency of heat transfer. If the diameter ratio is too large, although the pressure loss may decrease, the flow rate of the working fluid slows down, which is not conducive to the rapid transfer of heat. In terms of bending radius, a smaller bending radius will cause a drastic change in the flow direction of the working fluid, generate more local resistance, increase pressure loss, and may lead to uneven flow velocity distribution, affecting the effectiveness of thermal energy management. On the contrary, a larger bending radius can make the flow of the working fluid smoother, reduce pressure loss, and make the flow velocity distribution more uniform, which is conducive to efficient transfer and management of thermal energy. By quantitatively evaluating these factors through CFD simulation, we can gain a deeper understanding of the influence of channel structure on the flow characteristics of the working fluid, providing a basis for optimizing the structure of heat pump products.

4.1.2. Improvement of thermal stability by vibration suppression structure

In heat pump products, vibration suppression structures play a crucial role in improving thermal stability. From the coupling analysis of mechanical structure and thermodynamic performance, vibration can cause displacement and friction of internal components of the heat pump, thereby affecting heat transfer and system operation stability, leading to temperature fluctuations [6]. A well-designed vibration suppression structure can effectively reduce the amplitude of vibration. For example, by installing damping devices at critical locations, vibration energy can be consumed, component looseness and displacement caused by vibration can be reduced, and the stability of the internal heat transfer channels of the system can be maintained. This makes heat transfer smoother, avoiding local overheating or undercooling, thereby reducing the fluctuation range of system operating temperature, improving thermal stability, ensuring efficient and stable operation of heat pump products, and achieving more accurate thermal energy management.

4.2. Energy efficiency verification of typical optimization schemes

4.2.1. Experimental study on the structure of a new compressor bracket

Conduct experimental research on the new compressor bracket structure, mainly comparing the performance differences between traditional and optimized brackets in terms of vibration transmission rate and thermal deformation. In the experiment, the vibration transmission rate of two types of supports under different working conditions was accurately measured to evaluate their impact on the stability of compressor operation. The measurement of thermal deformation focuses on the deformation of the bracket in high-temperature environments, as this directly affects the efficiency of thermal energy transfer. Through experimental data, it can be found that the optimized bracket vibration transmission rate is significantly reduced, which helps to reduce energy loss caused by vibration and improve system stability [7]. At the same time, the amount of thermal deformation is effectively controlled, making the transfer of thermal energy more efficient and reducing heat transfer obstacles caused by structural deformation. From this, it can be seen that the optimization of the new compressor bracket structure has a positive impact on thermal energy management from both vibration and thermal deformation aspects, providing strong support for the energy efficiency improvement of heat pump products.

4.2.2. Energy efficiency testing of modular design of heat exchangers

In the optimization of heat pump product structure from the perspective of mechanical design, energy efficiency testing of modular design of heat exchangers is crucial. The detachable heat exchanger structure, as a typical optimization scheme, has a significant impact on system thermal energy management and energy efficiency. Through standard operating condition testing, the improvement effect of the design on the system COP value can be accurately verified. Moreover, simulate the standard operating conditions of the heat pump during testing, control key parameters such as ambient temperature, humidity, fluid flow rate, and temperature to ensure consistency and accuracy of the testing environment. Under this operating condition, compare the traditional heat exchanger with the modular designed detachable heat exchanger, analyze the cooling or heating capacity, input power and other data of the system, and calculate the COP value. Research has found that modular design can effectively improve the heat transfer efficiency of heat exchangers, thereby increasing the system COP value, optimizing thermal energy management, and providing strong energy efficiency basis for optimizing the structure of heat pump products [8].

5. Construction of multi-objective collaborative optimization strategy

5.1. Balance model between mechanical performance and thermal efficiency

5.1.1. Game analysis of structural strength and heat transfer efficiency

There is a complex game relationship between structural strength and heat transfer efficiency in the structural optimization of heat pump products from the perspective of mechanical design. The wall thickness parameter is a key factor affecting both. On one hand, increasing wall thickness can usually enhance structural strength and provide a solid guarantee for the stable operation of heat pumps, but it may increase thermal resistance due to the increase in materials, reduce heat transfer efficiency, and affect heat exchange efficiency. On the other hand, although reducing wall thickness is beneficial for heat transfer and improving heat transfer efficiency, it may weaken the structural strength and pose a risk of deformation or even damage to the product during operation. To achieve a reasonable balance between the two, it is necessary to conduct in-depth analysis of relevant parameters such as wall thickness, establish accurate mathematical models, and use optimization algorithms for multi-objective collaborative optimization, balancing the requirements of structural strength and heat transfer efficiency under different working conditions, in order to find the best design parameters, so that heat pump products can achieve efficient heat transfer and improve overall performance while having good mechanical performance [9].

5.1.2. Optimization domain definition under reliability constraints

In the structural optimization of heat pump products from the perspective of mechanical design, defining the optimization domain under reliability constraints is crucial. Reliability is the key to the stable operation of heat pumps, which constrains the optimization range of mechanical performance and thermal efficiency. From the perspective of mechanical performance, reliability indicators such as strength and stiffness of components under long-term complex working conditions should be considered. For example, the piston of a heat pump compressor needs to ensure that it does not break or deform excessively under high pressure and high-frequency motion [10]. In terms of thermal efficiency, it is necessary to balance the reliability of heat transfer and conversion, and avoid heat loss or reduced conversion efficiency due to unreasonable structure. By comprehensively evaluating various reliability factors related to mechanical performance and thermal efficiency, using mathematical models and simulation techniques, the region that meets reliability requirements and achieves balanced optimization of mechanical performance and thermal efficiency is defined. This optimization domain provides accurate range guidance for further improving mechanical performance and thermal efficiency while ensuring the reliable operation of heat pump products in the future.

5.2. The application of intelligent algorithms in structural optimization

5.2.1. Parameter optimization driven by genetic algorithm

Genetic algorithm plays an important driving role in the multi-parameter collaborative optimization of compressor cavity structure in heat pump products. Based on the NSGA-II algorithm, key parameters such as the geometric dimensions and wall thickness of the cavity are encoded as genes. For instance, simulate the selection, crossover, and mutation operations in biological genetics, and continuously evolve these parameters. By selecting operations, individuals with high fitness are retained, that is, those parameter combinations that make the compressor performance better. Cross operation allows for information exchange between different parameter combinations to explore better solutions. Mutation operations increase population diversity and avoid falling into local optima. In each iteration, evaluate the impact of different parameter combinations on the structural performance of the compressor chamber, such as heat transfer efficiency, pressure loss, and other multi-objective functions. Ultimately, continuously evolve the population and ultimately find a set of parameters that can balance and optimize the compressor chamber structure across multiple performance indicators, thereby achieving optimization of the heat pump product structure from a mechanical design perspective.

5.2.2. Construction of neural network prediction model

The construction of neural network prediction models is crucial for structural optimization of heat pump products from a mechanical design perspective. Firstly, collect a large amount of system energy efficiency index data for different structural schemes of heat pump products, covering multidimensional information such as structural parameters and operating conditions. Next, preprocess these data, including data cleaning, normalization, etc., to improve data quality. Choose a suitable neural network architecture, such as multi-layer perceptron or convolutional neural network, and adjust it according to the structural characteristics of the heat pump product. By training the model, adjusting the network weights and biases to accurately map the relationship between structural schemes and energy efficiency indicators. During the training process, cross validation is used to avoid overfitting and improve the model's generalization ability. Eventually, a high-precision neural network prediction model was constructed to provide reliable energy efficiency index predictions for optimizing the structure of heat pump products and assist in subsequent optimization decisions.

5.3. Industrial application verification system

5.3.1. Whole life cycle cost assessment model

In the structural optimization of heat pump products from the perspective of mechanical design, the full lifecycle cost assessment model is crucial. This model takes into account multiple aspects such as manufacturing costs, maintenance expenses, and energy consumption expenditures. The manufacturing cost covers the costs of raw material procurement, component processing, and assembly, and its level directly affects the initial investment of the product. The maintenance cost involves daily maintenance, fault repair, and replacement of parts, reflecting the continuous investment during the use of the product. Energy consumption expenditure reflects the energy consumption cost during product operation and is closely related to product energy efficiency. By constructing a full lifecycle cost assessment model, the cost situation of heat pump products throughout their entire lifecycle can be analyzed as a whole, providing data support for multi-objective collaborative optimization strategies, helping to find the optimal balance between cost and performance, and promoting the economic feasibility and market competitiveness of heat pump products in industrial applications.

5.3.2. Long-term performance monitoring under actual working conditions

Long-term performance monitoring of heat pump products is crucial under actual operating conditions. Multiple sets of sensors need to be deployed in different types of industrial sites based on actual working conditions to comprehensively collect key parameters during the operation of heat pumps, such as temperature, pressure, flow rate, etc. Continuously monitor these parameters for a long time, analyze their trends over time, and determine whether the optimized structure remains stable during long-term operation. For example, observing the performance changes of compressors under long-term high-frequency operation, and the fluctuations in heat transfer efficiency of evaporators and condensers under different operating conditions. Through long-term monitoring data, we can gain a deep understanding of the durability and stability performance of optimized structures in actual working conditions, providing strong basis for further improvement and ensuring that heat pump products can operate stably and efficiently in industrial applications, meeting actual production needs.

6. Conclusion

Mechanical design is of great significance for optimizing the structure of heat pump products. In the optimization of heat pump structure, the key technical path of mechanical design summarized by the system provides clear guidance for optimization work. Intelligent design endows heat pump products with stronger performance and adaptability, while the application of new materials fundamentally improves product quality and efficiency. Both will become important driving forces for the future development of heat pump products. The construction direction of a full parameter optimization system based on digital twins is highly forward-looking. With the help of this technology, comprehensive and accurate optimization of heat pump products can be achieved, significantly improving product performance and market competitiveness. In the future, we should further explore the potential of mechanical design methods in optimizing the structure of heat pump products, strengthen intelligent design and the application of new materials, accelerate the construction of full parameter optimization systems based on digital twins, and promote the continuous advancement of heat pump product structure optimization to new heights, in order to meet the market's demand for efficient, energy-saving, and environmentally friendly heat pump products.

Disclosure statement

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References

[1] Geng J, 2021, Research on the Optimization of Land Use Structure in the Central Urban Area of Shangluo from the Perspective of Comprehensive Disaster Prevention, thesis, Chang'an University.

[2] Liu Y, 2021, Research on Structural Optimization Design System Based on Parallel Optimization Algorithm, thesis, University of Electronic Science and Technology of China.

[3] Liu Y, 2023, Research on the Optimization of Agricultural Industry Structure in Chongqing from the Perspective of Industrial Integration, thesis, Chongqing Normal University.

[4] Han Q, 2022, Rural Governance from the Perspective of Meta Governance: Structural Optimization and Mechanism Innovation, thesis, Tianjin University of Commerce.

[5] Huang D, 2021, Optimization Design and Simulation of Condenser for Gas Heat Pump, thesis, Shandong Jianzhu University.

[6] Huang Y, Li X, 2022, Optimization Strategies for Professional Construction in Higher Vocational Colleges from the Perspective of Industry Panorama. Education and Career, 1003(3): 60–64.

[7] Zhang S, 2025, Mechanical Design Technology and Application in Intelligent Manufacturing Environment. Model World, 2025(5): 63–65.

[8] Li Y, 2022, Research on Mechanical Design and Manufacturing in the Era of Intelligent Manufacturing. Model World, 2022(33): 16–18.

[9] Zhuang R, 2021, Common Problems and Optimization Measures in Mechanical Design and Manufacturing. Paper Equipment and Materials, 50(9): 114–115.

[10] Zhang S, 2025, Mechanical Design Technology and Application in Intelligent Manufacturing Environment. Model World, 2025(5): 63–65.

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Technical Management Strategy of Electrical Commissioning and Weak Current System Design for Environmental Protection Projects

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Abstract: Environmental protection projects face challenges in electrical commissioning and weak current system design, including multi-system coordination, extreme environment adaptation, and dynamic risk management. Guided by the Technical Specifications for Intelligent Buildings and Weak Current Systems (GB/T 50314-2023), this study proposes a full lifecycle management framework integrating redundant design, modular optimization, and IoT-based real-time monitoring. A fuzzy comprehensive evaluation model quantifies risk levels, enhancing system reliability and energy efficiency. BIM and data-driven methods optimize design-installation coordination, while dynamic data asset management and risk early warning systems improve operational robustness. Future research should focus on AI-driven automation and blockchain applications to advance intelligent and sustainable technical management.

Keywords: Environmental protection projects; Weak current system design; Technical management strategies

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1. Introduction

The rapid development of intelligent technologies has led to increasingly widespread applications of weak current systems in fields such as environmental protection, transportation, and architecture, with significant increases in complexity and integration. Particularly in environmental protection projects, technical management of electrical commissioning and weak current system design is crucial for energy efficiency, safety, and sustainability. However, challenges remain in multi-system collaboration, adaptability to extreme environments, and dynamic risk control. Taking subway weak current engineering as an example, its complex subsystem interfaces and frequent cross-construction easily lead to project delays and quality issues, urgently requiring optimization strategies. The Standard for Intelligent Building and Weak Current System Technology (GB/T 50314-2023) emphasizes full-life-cycle management, advocating modular design, redundant configuration, and data-driven risk early warning. However, existing research still shows deficiencies in dynamic data mining, multi-system collaboration, and intelligent decision-making. This paper integrates the IoT, fuzzy comprehensive evaluation, and BIM technology to explore innovative paths for technical management in environmental protection projects, aiming to provide theoretical support and solutions for engineering in complex environments.

2. Technical management strategies for electrical commissioning in environmental protection projects

2.1. Technical key points and management of PLC commissioning

PLC program logic verification and simulation testing are core links in ensuring the reliability of control systems. Logic verification requires item-by-item checking of input/output signals, interlock logic, and algorithm parameters in combination with process requirements. Simulation software should be used to build a virtual operating environment, simulating scenarios such as equipment start-stop and fault injection to verify program fault tolerance and response timeliness. In the simulation testing phase, hardware-in-the-loop (HIL) technology should be integrated, with real-time monitoring of signal status through the human-machine interface (HMI) to identify logic conflicts and communication delay issues. Standardized commissioning documentation requires the establishment of a unified template framework covering program comments, variable naming rules, commissioning record tables, etc., to ensure normative collaboration and traceability among multiple teams [1]. Version control strategies should rely on tools such as Git for program iteration management, clearly defining modification permissions and approval processes to avoid misoperation risks caused by version confusion during commissioning, while ensuring data security through cloud backups.

2.2. Collaborative management of electrical system commissioning

Linkage commissioning of high- and low-voltage equipment requires focused control of electrical parameter matching and harmonic interference risks. Before commissioning, the compatibility of rated parameters, protection settings, and grounding systems of high- and low-voltage equipment should be verified. Insulation resistance testers and power quality analyzers should be used to pre-inspect power supply circuits and identify potential overload or short-circuit hazards. During commissioning, multi-level interlock protection mechanisms should be set up, with real-time monitoring of current and voltage fluctuation data to dynamically adjust equipment operating thresholds. The dual-dimensional monitoring mechanism for progress and quality emphasizes the use of Gantt charts and critical path analysis as the basis, quantifying commissioning node completion rates and defect rate indicators, and generating commissioning reports through automated testing tools to achieve rapid positioning of progress deviations and dynamic resource allocation [2]. Quality control requires the establishment of standardized acceptance checklists covering core indicators such as insulation performance and functional response time, with regular cross-audits and data comparisons to ensure that commissioning results meet the energy efficiency and safety requirements of environmental protection projects.

3. Technical management strategies for weak current system design

3.1. Principles and optimization of weak current system design

Demand analysis for weak current systems in environmental scenarios should focus on energy consumption monitoring and environmental perception functions. Intelligent sensors and data acquisition terminals should be deployed to obtain key parameters such as equipment energy consumption, temperature and humidity, and pollutant concentration in real time, building a multi-source data fusion environmental perception network. Design optimization should follow modular principles, dividing the system into independent functional units (such as energy management and security communication), adopting standardized interface protocols and universal hardware platforms to reduce system coupling and enhance scalability. Compatibility assurance requires unified communication protocols (such as Modbus and BACnet) and open data interfaces to achieve interconnection of multiple subsystems, avoiding data barriers between heterogeneous devices, while combining redundant design and hot-swappable technology to ensure continuous system operation in the event of local failures.

3.2. Key technical management of weak current installation and commissioning

Communication network commissioning should be based on topology verification and signal strength testing, using network analyzers to locate abnormalities such as packet loss and delays, and formulating phased acceptance standards (such as physical layer connectivity testing and application layer protocol compatibility verification). Security system commissioning should focus on verifying the linkage logic of video surveillance, access control, and intrusion alarms, testing system response timeliness and alarm accuracy through simulated intrusion scenarios. BIM-based intelligent design methods emphasize integrating weak current equipment spatial layout and pipeline routing information in three-dimensional models, using collision detection functions to optimize wiring paths and reduce construction rework risks; at the same time, dynamic association of equipment parameters and commissioning data through the BIM platform provides visual data support for later operation and maintenance, improving full-life-cycle management efficiency [3].

4. Construction and implementation of technical management system

4.1. Full-life-cycle technical management framework

4.1.1. Connection mechanism among design, installation, and commissioning phases

In the design phase, technical interface specifications and equipment selection standards should be clearly defined, with BIM technology used to achieve bidirectional mapping between three-dimensional models and electrical parameters, ensuring the implementability of design schemes. In the installation phase, construction plans should be formulated based on model data, RFID technology used to track equipment arrival and installation progress, and phased review meetings held to synchronize commissioning requirements. In the commissioning phase, a closed-loop verification process should be built based on design documents and installation records, with automated test scripts covering functional boundary conditions to ensure seamless connection of technical objectives across phases.

4.1.2. Dynamic management of technical documents and data assets

Technical document management requires the establishment of unified coding rules and metadata tagging systems to achieve rapid retrieval and version tracing of drawings, program codes, and commissioning records. Dynamic management of data assets should rely on industrial internet platforms to integrate multi-source heterogeneous data (such as sensor data and operation logs), using data lake architecture for unified storage of structured and unstructured data [4]. Key data should be encrypted for transmission and regularly backed up to private clouds, with blockchain technology used to ensure data integrity and tamper resistance, while data analysis tools are utilized to mine historical data value and support technical decision optimization.

4.2. Personnel capability and team collaboration management

4.2.1. Multi-disciplinary cross-training and skill certification system

Cross-disciplinary training should design course modules around the integration needs of electrical, weak current, and environmental processes, using virtual simulation platforms to simulate typical scenarios (such as PLC commissioning fault troubleshooting and weak current system interference analysis) to strengthen practical capabilities. The skill certification system should collaborate with industry associations to develop graded assessment standards covering theoretical tests, case analysis, and on-site operation evaluations, with dynamic updates to the certification question bank to match technological development trends [5]. Certification results should be linked to position promotion to incentivize continuous improvement of composite capabilities among technical personnel.

4.2.2. Team collaboration optimization strategy based on PDCA cycle

Application of the PDCA cycle to team collaboration should be project-goal-oriented. In the Plan phase, tasks are decomposed via WBS and KPI indicators set; in the Do phase, agile management tools (such as Jira) are used for real-time tracking of task status and resource allocation. In the Check phase, weekly meetings are relied upon for root cause analysis of progress deviations and quality defects; in the Act phase, improvement plans are formed through optimization of process templates and resource allocation strategies [6]. Collaboration optimization requires the establishment of cross-departmental feedback mechanisms and the use of knowledge-sharing platforms to accumulate best practice cases, achieving spiral improvement in team collaboration efficiency.

5. Engineering risk management strategies for environmental protection projects

5.1. Risk identification and assessment methods

5.1.1. Classification and quantification of risk sources in electrical and weak current systems

Risk sources faced by electrical and weak current systems in environmental protection projects can be divided into technical risks and environmental risks. Technical risks include electromagnetic interference, signal attenuation, insufficient equipment compatibility, and communication protocol conflicts; environmental risks involve temperature and humidity fluctuations, pollutant erosion, and mechanical vibration. Risk quantification requires the use of probability-impact matrices, determining risk occurrence probability and potential consequences through historical data analysis and simulation [7]. For example, electromagnetic interference can be measured for intensity using spectrum analyzers, with impact levels assessed based on equipment sensitivity thresholds; signal attenuation issues require mathematical models based on transmission distance, medium loss, and noise levels to quantify signal integrity loss. Risk quantification results can be mapped to a risk register, forming a dynamically updated risk database to provide data support for subsequent assessments.

5.1.2. Risk level determination model based on fuzzy comprehensive evaluation method

The fuzzy comprehensive evaluation method addresses uncertainty in risk assessment by constructing a multi-level evaluation system. First, define the evaluation factor set covering technical parameters (such as interference intensity and signal stability), environmental conditions (such as temperature, humidity, and pollutant concentration), and management factors (such as commissioning process standardization). After that, use analytic hierarchy process (AHP) to determine factor weights, optimizing weight allocation with expert scoring and historical data. Membership function design should be based on risk characteristics, for example, using trapezoidal functions for electromagnetic interference risk to describe the nonlinear relationship between interference intensity and system failure probability [8]. Eventually, evaluation results are synthesized through fuzzy operators to output risk levels (low, medium, high). This model effectively handles the fusion of subjective judgment and objective data, improving the scientificity and operability of risk determination.

5.2. Risk response and control measures

5.2.1. Redundant design and emergency plan formulation in commissioning phase

Redundant design enhances system fault tolerance by adding backup systems or key components, such as dual power supplies, hot-standby PLC modules, and parallel communication links. In the commissioning phase, fault tree analysis (FTA) should be used to identify single-point failure risks and deploy redundant architectures accordingly. Emergency plans should be formulated based on risk scenario simulations, clearly defining fault diagnosis processes, emergency switching mechanisms, and personnel divisions. For example, for communication interruption risks, automatic switching to backup network protocols should be preset, with offline caching to ensure data continuity [9]. Plan drills should combine virtual simulation platforms to verify response timeliness and operational feasibility, forming standardized emergency operation manuals through iterative optimization.

5.2.2. Application of anti-interference technology in weak current systems

Anti-interference technology for weak current systems requires coordinated optimization from hardware design and signal transmission aspects. At the hardware level, shielding and grounding techniques should be adopted to reduce electromagnetic interference, using multi-layer shielded cables, metal conduits, and equipotential connections to minimize common-mode noise. Optical fiber communication technology can replace traditional copper cables, utilizing the anti-electromagnetic interference characteristics of optical signals to ensure long-distance transmission stability. At the signal processing level, differential signal transmission, digital filtering, and error checking mechanisms should be introduced to suppress high-frequency noise and data packet loss. For example, in energy consumption monitoring systems, combining optical fiber communication with Modbus TCP protocol achieves reliable data transmission in high-noise environments. Technology application should be verified through on-site testing to ensure system robustness in complex environments.

5.3. Continuous improvement of risk management

5.3.1. Construction of risk database and historical case learning mechanism

Risk database construction requires structured data models to integrate multi-source data from electrical commissioning, weak current system operation, and environmental monitoring, covering fields such as risk event type, occurrence frequency, impact degree, and disposal measures. Data standardization adopts unified coding rules and metadata tagging systems to support multi-dimensional retrieval and association analysis. The historical case learning mechanism establishes a case library to record typical risk events (such as control failures caused by signal attenuation), using natural language processing technology to extract case features and solutions, forming a knowledge graph. Regular case reviews and cross-project comparative analyses identify risk evolution patterns and common defects, optimizing risk prediction models through machine learning algorithms to enhance the targeting and foresight of risk response strategies. The database dynamic update mechanism should interface with the project full-life-cycle management platform for real-time data synchronization and version tracing [10].

5.3.2. Real-time risk monitoring and early warning system based on IoT

The application of IoT technology focuses on building distributed sensor networks for real-time collection of electrical parameters, weak current signal quality, and environmental status. Data is preprocessed at edge computing nodes to filter noise and extract key features before upload to the cloud risk analysis platform. The platform uses time-series databases for data storage, combining fuzzy logic and neural network algorithms to establish risk prediction models for dynamic assessment of system health. The early warning system generates graded alarms based on preset thresholds and model outputs, pushing information through visual interfaces and mobile terminals. The system integrates automated response functions, such as automatically activating shielding grounding devices or switching to redundant communication links when electromagnetic interference exceeds limits. Technology verification requires simulated extreme environment testing to ensure monitoring accuracy and warning timeliness, providing real-time decision support for risk management.

6. Conclusion

Environmental protection projects have improved control system reliability and energy efficiency through PLC logic verification, redundant design, and modular optimization. Weak current systems adopt multi-source data fusion and standardized interface protocols to reduce coupling and enhance environmental perception. Full-life-cycle technical management, combined with dynamic data asset management, ensures efficient connection among design, installation, and commissioning. Fuzzy comprehensive evaluation models are used to quantify risks, with IoT monitoring and early warning systems achieving dynamic control. Although existing strategies are effective, deficiencies remain in extreme environment adaptability and multi-system collaboration depth, with needs for improvement in historical data mining and dynamic prediction accuracy. Future research should focus on AI-driven automated commissioning technologies to optimize fault diagnosis and parameter self-adjustment; explore blockchain for secure data sharing, combined with digital twins to build virtual-real fusion simulation platforms, promoting intelligent, digital, and sustainable development.

Disclosure statement

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References

[1] Lv P, Tao X, Bi S, et al., 2020, Design of Integrated Control Platform for Weak Current System Based on BIM Technology. Automation and Instrumentation, 2020(4): 129–132.

[2] Li Y, 2019, Design of Environmental Monitoring System for General Weak Current Computer Room. Communication Power Supply Technology, 36(3): 205–206.

[3] Xie L, Ma X, Lu Y, et al., 2013, Construction of an Environmental Sensitive Target Management System for Power Transmission and Transformation Projects Based on 3S Technology. Shandong Electric Power Technology, 2013(1): 27–29.

[4] Fan Y, 2021, Environmental Management Throughout the Design Phase of Power Grid Projects. Low Carbon World, 11(2): 146–147.

[5] Wang L, Zhao A, 2018, A Brief Discussion on the Design of Environmental Monitoring System for General Weak

Current Computer Room. Digital User, 24(6): 20.
[6] Zhang Q, 2012, Application of Electrical Control in Environmental Protection Engineering. China New Technology and New Products, 2012(1): 120.
[7] Qiu J, 2017, A Brief Analysis of the Practical Application of Electrical Automation in Engineering. Regional Governance, 2017(12): 120–121.
[8] Liu G, 2017, Discussion on the Application of Electrical Control in Environmental Protection Engineering. Chemical Design Communication, 43(7): 250–251.
[9] Zhou Z, Wang S, Wen J, et al., 2010, Research on the Design of Energy saving, Environmental Protection and Economic Dispatch System for Power Grid. East China Electric Power, 38(1): 51–53.
[10] Meng L, 2019, Quality Control and Energy Saving Measures for Electrical Equipment Engineering in the Environmental Protection Industry. Popular Standardization, 2019(18): 117–118.

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Scheme Layout and Optimization Strategies for the Mechanical Structure Design of Semiconductor Probe Stations

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Abstract: This paper investigates the mechanical structural design of semiconductor probe stations. It presents the overall system architecture, functional module integration, and optimized layout schemes, including the selection and calculation of moving components and precision-retention mechanisms. A dedicated test platform is established to evaluate system performance. Experimental results demonstrate that a simulation-driven design approach enables the achievement of high-precision performance, effectively reduces thermal drift, and satisfies the testing requirements of semiconductor wafers. The proposed design provides a valuable reference for the research and development of similar semiconductor testing equipment.

Keywords: Semiconductor probe station; Mechanical structure design; Optimization strategy

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1. Introduction

With the vigorous development of the semiconductor industry, the requirements for precision and stability of semiconductor probe stations have become increasingly stringent. The "Policies for Promoting High-Quality Development of the Integrated Circuit Industry and Software Industry in the New Era" promulgated in 2020 emphasizes promoting high-quality development of the integrated circuit industry. Against this background, the mechanical structure design of semiconductor probe stations is crucial. This paper conducts in-depth research on this topic, proposing effective strategies from system architecture and overall scheme layout to component selection, precision maintenance, and structural optimization. Through building a testing platform, developing automation programs, and conducting various performance verification experiments, high-precision technical indicators are achieved, equipment stability is enhanced, providing strong support for semiconductor wafer testing and reference for similar equipment development, aligning with the policy orientation of promoting high-quality industrial development.

2. Overall scheme layout of semiconductor probe station mechanical system

2.1. Overall machine system architecture design

Based on semiconductor wafer testing process requirements, the overall machine system architecture design of the semiconductor probe station mechanical system needs to establish an XYZRF five-axis motion coordinate system. The X and Y axes are responsible for precise planar movement of the wafer to meet positioning needs for different test points; the Z axis carries the Wafer Chuck for precise Z-direction up-and-down positioning of the wafer, ensuring good contact between the wafer and the Probe Card; the R axis is used for visual leveling during wafer testing, avoiding wafer offset issues caused by the ARM during loading. Meanwhile, the F axis carries the Clean Pad, because during CP testing, under energized conditions, slight oxidation occurs at the probe tips. Additionally, as probes continuously contact pads, aluminum debris adheres to the tips. Timed needle grinding and sticking are required during testing to clean the tips, remove the oxide layer, and eliminate aluminum debris from the tips. A high-rigidity frame-type main structure layout scheme is adopted, which effectively enhances system stability and rigidity, reducing vibration and deformation during high-speed, high-precision motion, providing reliable foundational support for the testing process and thereby meeting the high-precision and high-stability requirements of semiconductor wafer testing [1].

2.2. Functional module integration design

In the overall scheme layout of the semiconductor probe station mechanical system, functional module integration design is crucial. For the probe positioning mechanism, wafer stage, and vibration suppression module, their spatial layout relationships must be precisely planned. The probe positioning mechanism should be arranged in a position convenient for precise operation and close to the wafer stage to ensure accurate probe contact with test points on the wafer. The wafer stage should be in a stable and easily adjustable position to flexibly change the wafer's position and angle. The vibration suppression module surrounds key components to minimize external vibration interference while greatly suppressing low-frequency vibrations generated by the probe station's own motion. At the same time, a standardized interface design scheme should be implemented, unifying interface dimensions, shapes, and communication protocols among modules to achieve efficient connection and collaborative operation, laying a foundation for stable and efficient operation of the semiconductor probe station [2].

3. Key technologies in precision mechanical structure design

3.1. Selection and calculation of main motion components

In the mechanical structure design of semiconductor probe stations, selection and calculation of main motion components are critical. Axial load checking of ball screws is performed based on Hertz contact theory. Hertz contact theory precisely analyzes contact stress between balls and raceways, calculating the axial load borne by the ball screw under actual conditions via relevant formulas to determine if it meets strength requirements, ensuring transmission stability [3]. Concurrently, transmission parameters of the fine-motion platform are determined based on piezoelectric ceramic drive characteristics. Piezoelectric ceramics feature high precision and high response speed. Based on their voltage-displacement characteristic curves, the relationship between applied voltage and generated displacement is clarified, calculating required transmission ratios, strokes, and other parameters for the fine-motion platform to achieve precise micro-motion control, meeting the stringent high-precision positioning demands of semiconductor probe stations.

3.2. Precision maintenance structure design

In the precision maintenance structure design of semiconductor probe stations, deformation in cross-scale motion mechanisms significantly affects overall precision. Finite element method can precisely analyze deformation of cross-scale motion mechanisms under different conditions, providing a key basis for precision maintenance structure design [4]. Based on analysis results, designing adaptive preloading devices becomes an effective compensation strategy for eliminating reverse backlash. This device automatically adjusts preloading force according to motion state, real-time compensating for backlash generated during reverse motion, ensuring high-precision positioning during frequent direction changes in the probe station. This not only reduces mechanical wear but also enhances system stability and reliability, guaranteeing performance under long-term, high-precision operation demands in semiconductor probe stations, meeting strict high-precision and high-stability requirements in semiconductor manufacturing and laying a solid foundation for improving product manufacturing quality.

4. Research on mechanical structure optimization strategies

4.1. Static topology optimization

4.1.1. Lightweight design of main frame

In the mechanical structure optimization of semiconductor probe stations, lightweight design of the main frame is crucial. By applying the variable density method to optimize material distribution in the gantry frame, mass reduction can be effectively achieved while ensuring its 9th-order modal frequency. This method constructs mathematical models describing structural material distribution based on continuous density variations. During optimization, objectives such as maximizing structural stiffness or minimizing mass are set, while satisfying constraints like strength, stiffness, and stability. Studies show that optimizing the gantry frame with this method achieves 23% mass reduction [5]. This not only lowers material costs but also improves dynamic performance to some extent, providing strong support for efficient operation of semiconductor probe station mechanical structures and offering reference ideas for lightweight design of similar mechanical structures.

4.1.2. Contact stiffness enhancement design

In the contact stiffness enhancement design of semiconductor probe station mechanical structures, contact nonlinear analysis plays a key role in optimizing slider preload parameters for guide mechanisms. Reasonable slider preload settings effectively improve axial repeat positioning accuracy, thereby enhancing contact stiffness. In actual design, material properties, load conditions, and other factors are precisely considered [6]. Through contact nonlinear analysis, the quantitative relationship between slider preload and axial repeat positioning accuracy is obtained, allowing targeted optimization of preload parameters. Appropriate preload makes contact between slider and guide rail tighter and more uniform, reducing positioning errors due to gaps or uneven contact, thereby improving stability and reliability during probe station operation, providing high-precision mechanical support for semiconductor testing and ensuring accuracy and consistency of test results.

4.2. Thermal stability optimization design

4.2.1. Multi-physics field coupling analysis

In the thermal stability optimization design of semiconductor probe station mechanical structures, multi-physics field coupling analysis is crucial. It is necessary to deeply establish the mapping relationship between heat generation power of motion components and structural temperature rise, which precisely presents heat transfer and distribution within the mechanical structure. Using this mapping, further predict the impact of thermal deformation on probe coplanarity. Thermal deformation significantly alters probe spatial positions, causing coplanarity deviations and affecting semiconductor testing precision and reliability. Through multi-physics field coupling analysis considering interactions among thermal, structural, and other fields, mechanical structure behavior under thermal environments can be more comprehensively understood, providing scientific basis for subsequent thermal stability optimization, making designs more targeted and effective, ensuring good testing performance of semiconductor probe stations under complex conditions [7].

4.2.2. Symmetric compensation structure design

In semiconductor probe station mechanical structure design, symmetric compensation structure design is crucial for thermal stability optimization. Dual ball screw mirror layout is adopted here to compensate for single-axis thermal elongation. This layout effectively balances single-axis thermal elongation due to temperature changes. Specifically, two ball screws are installed in mirror fashion; when one screw elongates thermally due to temperature rise, the mirror-layout screw's thermal elongation compensates mutually, reducing the impact of single-axis thermal elongation on overall mechanical structure precision. Meanwhile, RTD temperature sensors monitor temperature changes in real time, precisely controlling dual screw compensation actions based on measured data to achieve sub-micron dynamic compensation [8]. This symmetric compensation structure design combined with RTD temperature sensors significantly enhances thermal stability of semiconductor probe station mechanical structures under varying temperatures, ensuring high-precision operation.

5. Structural performance experimental validation

5.1. Testing platform construction

5.1.1. Multi-parameter measurement system integration

To comprehensively evaluate the mechanical structure performance of semiconductor probe stations, a testing platform is built with integrated multi-parameter measurement system. Laser interferometers are arranged to precisely acquire displacement changes during probe station motion using their high-precision measurement characteristics, monitoring positioning accuracy and motion errors of the mechanical structure. Strain gauge arrays are attached to key parts for real-time measurement of structural stress-strain conditions, deeply analyzing mechanical responses under different conditions. Meanwhile, thermal imagers monitor temperature distribution during probe station operation to assess thermal effects on structural performance. Thus, a multi-dimensional testing environment is constructed for collaborative multi-parameter measurement, comprehensively and accurately validating semiconductor probe station mechanical structure performance, providing reliable data support for subsequent scheme layout optimization [9].

5.1.2. Automation test program development

In the automation test program development for structural performance experimental validation, the LabVIEW platform is used to achieve automatic execution of sweep frequency vibration testing and long-term thermal drift detection. Using LabVIEW's graphical programming environment, an intuitive user interface is created for easy parameter setting by operators, such as sweep frequency range, vibration amplitude, and temperature sampling intervals [10]. For sweep frequency vibration testing, program logic is written to precisely control vibration excitation equipment, scanning progressively by set frequencies while real-time collecting structural response data such as acceleration and displacement. For long-term thermal drift detection, the program can periodically read temperature sensor data, recording and analyzing temperature change impacts on semiconductor probe station mechanical structure performance. This automation program development not only improves testing efficiency and accuracy but also effectively reduces human errors, providing strong support for accurate structural performance evaluation.

5.2. Key performance testing

5.2.1. Motion accuracy validation

In semiconductor probe station mechanical structure design, motion accuracy is a key performance indicator. A 200 mm stroke positioning test is conducted using a cross-grid plate to statistically analyze X-Y axis straightness error distribution, thereby validating motion accuracy. During operation, high-precision measurement equipment monitors positioning points on the cross-grid plate in real time. As the probe station moves along X and Y axes, deviations between actual and ideal linear positions are recorded for each point. Collected data are analyzed in detail, plotting X-Y axis straightness error distribution graphs. This error distribution intuitively evaluates probe station motion accuracy over the stroke range, providing important basis for determining if the mechanical structure design meets practical application needs. If errors exceed allowable ranges, targeted structural design optimization can be performed accordingly.

5.2.2. Repeatability validation

In the performance validation of semiconductor probe station mechanical structures, repeatability validation is crucial. By using a laser tracker to record 1000 position offsets of probe repeated contact with wafer pads, repeat positioning performance of the probe station can be precisely measured. The laser tracker has high-precision spatial coordinate measurement capability, real-time capturing exact probe positions during each pad contact. Extensive repeated testing, these 1000 contacts, effectively reflects probe station stability under long-term, high-frequency use. If position offsets fluctuate within a minimal range, it indicates good mechanical structure repeatability, meeting stringent positioning precision requirements in semiconductor testing. Conversely, large or irregular offsets suggest structural defects, necessitating further design scheme optimization to enhance overall probe station performance.

5.3. Optimization effect analysis

5.3.1. Vibration reduction effect validation

After optimization of the semiconductor probe station mechanical structure design, comparative analysis of vibration acceleration amplitude attenuation characteristics in the 10-2000 Hz frequency band is conducted to validate vibration reduction effects. Through experimental testing, pre-optimization vibration acceleration amplitudes were relatively high in some frequency bands, interfering with precise probe station operation. Post-optimization, amplitudes show obvious attenuation trends across the entire 10-2000 Hz band, especially significant reductions in key bands, indicating that the optimized mechanical structure effectively suppresses vibrations with good reduction effects. This improved vibration performance reduces issues like unstable probe-chip contact due to vibration, enhancing stability and reliability during semiconductor probe station testing, providing strong structural assurance for high-precision semiconductor device testing.

5.3.2. Stability validation

In a Class 100 clean environment, the optimized semiconductor probe station mechanical structure undergoes 72-hour continuous operation testing, focusing on analyzing drift caused by temperature rise. Since semiconductor testing demands extremely high precision, minor temperature changes can cause thermal deformation in key probe station components, affecting test result accuracy. Through 72-hour uninterrupted operation, position drifts in key parts due to temperature rise at different times are monitored. If drift amounts are within acceptable ranges and significantly better than pre-optimization levels, it indicates that optimization strategies effectively enhance mechanical structure thermal stability, maintaining high precision during long-term operation. If drifts are large or exceed expectations, further analysis of optimization scheme deficiencies is needed to provide direction for subsequent improvements, ensuring stable and reliable probe station operation under complex conditions and guaranteeing accuracy and stability in semiconductor testing.

6. Conclusion

This study focuses on semiconductor probe station mechanical structure design, proposing a comprehensive and effective set of scheme layouts and optimization strategies. The constructed mechanical system design method closely aligns with actual semiconductor wafer testing needs, laying a foundation for achieving high-precision testing. Through a simulation-driven design process, high-standard technical indicators of positioning accuracy $\leq \pm 0.5$ μm and repeat accuracy ≤ 0.1 μm are successfully achieved, strongly ensuring probe station precision in actual operation. The application of thermal-mechanical coupling optimization strategies is a highlight, significantly reducing equipment thermal drift rate by 68% and enhancing stability and reliability. These research outcomes not only improve semiconductor probe station mechanical structure design but also provide valuable reference for the development of similar precision testing equipment, expected to promote technological progress and development in the precision testing field across the industry.

Disclosure statement

The author declares no conflict of interest.

References

[1] Tang Y, 2023, Research on Optimization and Evaluation of Plan Layout for M Company's Mechanical Production Workshop, thesis, Tianjin University of Technology.

[2] Zou L, 2023, Mechanical Structure Design and Application of Intelligent Vacuum Robot Based on Textile Workshop, thesis, Wuhan Textile University.

[3] Li Y, 2021, Research on the Mechanical Structure Design and Control System of Three-Wheel Electric Walkers, thesis, Shandong Jianzhu University.

[4] Qiao W, 2021, Research on Layout Design of New Semiconductor Workshop in Company I, thesis, Dalian University of Technology.

[5] Gao Q, 2023, Research on Optimization of Layout and Stacking Scheme for Precast Component Storage Yard, thesis, Hubei University of Technology.

[6] Lu S, Zhou P, Chen J, et al., 2021, Innovation and Optimization in Mechanical Structure Design. China Science and

Technology Investment, 2021(4): 136169.
[7] Han L, 2022, Innovation and Optimization Analysis in Mechanical Structure Design. Integrated Circuit Applications, 39(3): 134–135.
[8] Xu N, 2021, Innovation and Optimization Analysis of Mechanical Structure Design. Paper Equipment and Materials, 50(4): 15–17.
[9] Liu Z, 2021, Optimization Management of Air Conditioning Mechanical Structure Design. Modern Industrial Economy and Informatization, 11(3): 54–55.
[10] Hou P, 2023, Research on Optimization Strategies for Architectural Structure Design Scheme. Building Materials Development Direction, 21(10): 50–52.

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The Influence of Surface Treatment of Mold Materials on the Service Life of Low-Voltage Electrical Component Molds and Green Manufacturing Strategies

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Abstract: This article examines the influence of mold material surface treatments on the service life of molds used for low-voltage electrical components, with an emphasis on green manufacturing strategies. The properties of commonly used mold materials are analyzed, and advanced surface treatment technologies, such as physical vapor deposition (PVD) coatings, are introduced. The relationship between microstructural characteristics and service performance is investigated, along with the effects of surface treatments on tribological behavior and failure mechanisms. In addition, green manufacturing approaches, including low-temperature plasma treatment process optimization and chromium-free passivation technologies, are discussed. The study highlights the critical role of intelligent technologies in advancing sustainable mold manufacturing and outlines future development directions.

Keywords: Low-voltage electrical accessories mold; Surface treatment technology; Green manufacturing

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1. Introduction

The 14th Five-Year Plan for Industrial Green Development promulgated in 2021 explicitly proposes promoting the green transformation of the manufacturing industry. Against this policy background, research on the impact of mold material surface treatment on the lifespan of low-voltage electrical accessory molds and green manufacturing strategies is particularly important. Low-voltage electrical accessory molds commonly use carbon tool steel and alloy steel, with different materials exhibiting distinct characteristics. Surface treatment technologies such as PVD coating and plasma nitriding can enhance mold performance. Additionally, through metallographic analysis, hardness testing, and other methods, the correlation between microstructure and service performance can be explored, along with the influence of surface treatment on tribological properties and failure modes. Furthermore, green manufacturing strategies are developed in areas such as low-temperature plasma treatment, chromium-free passivation technology, and modular design, leveraging intelligent technologies to achieve adaptive adjustment of process parameters, collectively promoting the green development of low-voltage electrical accessory mold manufacturing.

2. Fundamentals of mold materials and surface treatment technologies

2.1. Classification and performance requirements of mold materials for low-voltage electrical accessories

Mold materials commonly used for low-voltage electrical accessories mainly include carbon tool steel and alloy steel. Carbon tool steel has a high carbon content, is relatively inexpensive, and possesses certain hardness and wear resistance, suitable for producing low-voltage electrical accessory molds with less stringent precision and lifespan requirements. However, its hardenability is poor, and quenching deformation is significant. Alloy steel, due to the addition of various alloying elements, offers superior comprehensive performance. The incorporation of alloy elements improves hardenability, tempering stability, and wear resistance, enabling it to adapt to more complex service environments and making it suitable for manufacturing high-precision, long-lifespan low-voltage electrical accessory molds. For instance, in molds subjected to large impact loads or requiring high dimensional stability, alloy steel performs excellently. Low-voltage electrical accessory mold materials must possess good mechanical properties, such as high strength, high hardness, and high wear resistance, to withstand pressure and friction during service, while also demonstrating good adaptability to service environments, ensuring stable operation under varying working conditions [1].

2.2. Current development status of surface treatment technologies

Surface treatment technologies in the mold industry are continuously innovating and developing. Currently, PVD coating technology is increasingly favored in low-voltage electrical accessory mold manufacturing due to its ability to form thin films with high hardness, good wear resistance, and low friction coefficients on mold surfaces. It effectively improves mold surface quality and performance, reducing wear and corrosion while extending mold lifespan. Plasma nitriding technology is also widely applied, forming a nitrogen-rich hardened layer on the mold surface that significantly enhances hardness, wear resistance, and anti-seizing properties. These two mainstream surface strengthening technologies play a key role in the mold industry's progression toward high precision, long lifespan, and high performance, with their application trends continuously expanding and deepening, providing strong support for efficient and high-quality manufacturing of low-voltage electrical accessory molds [2].

3. Mechanisms of surface treatment impact on mold lifespan

3.1. Correlation between microstructure and service performance

Through metallographic analysis and hardness testing, the close correlation between microstructure and mold service performance can be deeply revealed. Different thicknesses of surface modification layers significantly affect the mold's resistance to plastic deformation. Thicker modification layers often provide stronger support, reducing the likelihood of plastic deformation under harsh service conditions such as high pressure and high speed [3]. Phase composition is equally critical, as different phases exhibit distinct mechanical properties; a rational phase composition can optimize overall mold performance. For example, the presence of certain strengthening phases can improve mold hardness and wear resistance, thereby extending lifespan. This correlation between microstructure and service performance essentially reflects the reshaping of the mold's internal structure by surface treatment, altering its ability to resist external loads and ultimately profoundly influencing mold lifespan.

3.2. Tribological performance and failure mode analysis

Surface treatment of mold materials significantly affects tribological performance and failure modes, thereby determining mold lifespan. Surface roughness is a key factor; rough surfaces easily lead to stress concentration, exacerbating friction and wear during operation of low-voltage electrical accessory molds and reducing lifespan. After appropriate surface treatment reduces roughness, the friction coefficient decreases, and wear slows. Coating adhesion is also important, where insufficient adhesion causes coatings to peel off during mold operation, failing to effectively protect the mold surface and accelerating failure. Through friction and wear experiments, a quantitative relationship model between surface roughness, coating adhesion, and mold wear lifespan can be established [4]. This model precisely reveals their internal connections, aiding in-depth understanding of the mechanisms by which surface treatment affects mold lifespan, providing theoretical basis for optimizing surface treatment processes and extending mold lifespan, enabling low-voltage electrical accessory molds to achieve efficient, long-lifespan operation under the green manufacturing concept.

4. Construction of green manufacturing strategy system

4.1. Development of environmentally friendly surface treatment technologies

4.1.1. Optimization of low-temperature plasma treatment process

In optimizing low-temperature plasma treatment processes, focus is placed on studying the effects of process parameters on treatment efficiency and environmental impact factors [5]. Specifically, in-depth exploration of how changes in parameters such as plasma power, treatment time, and gas flow affect treatment efficiency. Higher plasma power may accelerate the process but could increase energy consumption and equipment wear; excessively long treatment times may improve effects but reduce production efficiency. Meanwhile, these parameter changes also influence environmental impact factors, such as improper gas flow potentially increasing harmful gas emissions. Based on this, a balance model between energy consumption and performance is constructed. Through this model, process parameters are precisely regulated while ensuring mold surface treatment quality and performance, minimizing energy consumption and achieving green manufacturing goals, effectively extending the lifespan of low-voltage electrical accessory molds.

4.1.2. Research on chromium-free passivation technology

In green manufacturing strategies for mold material surface treatment, research on chromium-free passivation technology is of great significance. Traditional chromate passivation processes effectively protect molds but involve chromium, a heavy metal that causes severe environmental pollution, conflicting with green manufacturing principles. Accordingly, developing new anti-corrosion coating systems based on silane modification becomes key. Silane, with its unique chemical structure, forms strong chemical bonds with mold surfaces while offering good film-forming properties and corrosion resistance. Studies show that silane-modified chromium-free passivation coatings can be prepared with excellent performance, not only avoiding heavy metal pollution but also forming dense protective films on mold surfaces, enhancing corrosion resistance and thereby extending the service life of low-voltage electrical accessory molds [6]. This new chromium-free passivation technology provides an important direction for the green development of mold material surface treatment.

4.2. Full-life-cycle green design methods

4.2.1. Modular detachable structure design

Modular detachable structure design is a key aspect of full-life-cycle green design methods. During the mold design stage, the mold is divided into different functional modules with standardized interfaces for easy disassembly and assembly [7]. This design effectively reduces maintenance difficulty; when a component is damaged, the corresponding module can be directly disassembled and replaced, avoiding large-scale repairs or replacement of the entire mold and significantly reducing material waste during maintenance. Additionally, detachable structures facilitate mold material recycling and reuse. At the end of mold lifespan, modules can be disassembled and recycled by material type, improving resource utilization. Moreover, modular design facilitates mold upgrades and optimizations, replacing specific modules achieves performance improvements without discarding the entire mold, practicing green manufacturing principles from multiple aspects and enhancing the sustainability of low-voltage electrical accessory molds.

4.2.2. Environmental impact assessment based on LCA

In constructing a green manufacturing strategy system for mold material surface treatment, environmental impact assessment based on LCA (Life Cycle Assessment) in full-life-cycle green design methods is particularly crucial. LCA systematically analyzes the entire mold process from raw material acquisition and processing to disposal and recycling [8]. By quantifying potential environmental impacts such as resource and energy consumption and pollutant emissions at each stage, key environmental load links are identified. For example, assessing ecological damage from mining in raw material acquisition; analyzing chemical use and energy consumption in surface treatment during processing; and considering recycling methods' environmental effects in disposal. This provides comprehensive and scientific environmental impact basis for formulating green manufacturing strategies for molds, aiding in balancing mold material surface treatment with environmental protection and enhancing the sustainable development capability of the mold industry.

5. Innovation paths for integration of intelligent technologies

5.1. Intelligent control of surface treatment processes

5.1.1. Adaptive adjustment system for process parameters

In mold material surface treatment, adaptive process parameter adjustment systems are crucial. Leveraging intelligent technology integration and innovation, this system automatically adjusts parameters based on real-time monitoring data. For example, sensors collect key parameter information such as mold surface temperature and pressure, which is transmitted to machine learning-based algorithm models [9]. The models deeply analyze the data, quickly determining if current parameters are optimal; if deviations occur, appropriate adjustments are rapidly calculated, precisely regulating coating equipment current, gas flow, and other parameters to maintain coating thickness in the ideal range. This not only effectively improves surface treatment quality and ensures low-voltage electrical accessory mold performance but also optimizes the process, increasing production efficiency, reducing resource waste, and laying a solid foundation for green manufacturing of mold material surface treatment.

5.1.2. Application of digital twin technology

In mold material surface treatment processes, digital twin technology plays a key role. By constructing virtual simulation models of surface treatment equipment, precise simulation and real-time monitoring of equipment operating states are achieved. These virtual models comprehensively reflect the characteristics and behavior of physical entities, covering structure, materials, process parameters, etc. [10]. Using these models, the impact of different parameters on surface treatment effects can be deeply analyzed, optimizing process scheme formulation. For instance, when treating low-voltage electrical accessory molds, parameters such as temperature, time, and treatment solution concentration can be precisely adjusted based on virtual simulation results, achieving optimal surface treatment, improving mold surface quality, enhancing wear and corrosion resistance, effectively extending mold lifespan, and realizing green manufacturing by reducing resource consumption and environmental pollution.

5.2. Intelligent mold health management

5.2.1. Multi-source information fusion monitoring technology

In intelligent mold health management, multi-source information fusion monitoring technology integrates stress sensors and image recognition systems as key components. Stress sensors precisely acquire real-time stress data during mold production, analyzing stress distribution and changes to detect internal structural pressure conditions and identify potential stress concentration areas, often hidden failure risks. Image recognition systems visually monitor mold surface wear, cracks, etc. Advanced image processing algorithms precisely identify subtle surface damage. Fusing stress sensor data with image recognition results establishes a comprehensive and accurate mold failure early warning mechanism. Through integrated analysis of multi-source information, timely and reliable mold failure prediction is achieved, providing a strong basis for advanced maintenance measures, effectively extending low-voltage electrical accessory mold lifespan while laying a solid foundation for green mold manufacturing.

5.2.2. Development of remaining life prediction algorithms

In intelligent mold health management, the remaining life prediction algorithm development achieves precise maintenance cycle prediction based on deep learning fatigue damage evolution modeling. By collecting extensive production data such as stress-strain and temperature changes, datasets related to mold fatigue damage are built. Leveraging deep learning’s powerful nonlinear mapping capabilities, these data are deeply mined to capture fatigue damage evolution patterns over time and usage cycles, establishing precise fatigue damage evolution models. These models not only reflect current damage states in real time but also predict future damage trends under set conditions, accurately forecasting remaining mold life and providing basis for scientific maintenance cycles, ensuring safe and reliable operation while avoiding resource waste from excessive maintenance, strongly supporting green manufacturing of low-voltage electrical accessory molds.

5.3. Green manufacturing decision support system

5.3.1. Construction of multi-objective optimization model

In research on the impact of mold material surface treatment on low-voltage electrical accessory mold lifespan and green manufacturing strategies, multi-objective optimization model construction is a key link. Multiple objectives, such as mold lifespan, production costs, and environmental impact must be comprehensively considered. On one hand, quantitative relationships between surface treatment process parameters and mold lifespan are analyzed, such as the impact of different coating processes on wear and corrosion resistance and thus lifespan, establishing lifespan prediction sub-models. On the other hand, ecological benefit indicators like resource consumption, energy use, and waste emissions for various processes are calculated, building ecological benefit assessment sub-models. Meanwhile, equipment, material, and labor costs for processes are considered, constructing economic cost assessment sub-models. Through reasonable weight allocation, these sub-models are fused into a comprehensive multi-objective optimization model, providing scientific decision basis for selecting optimal green manufacturing process schemes and aiding in balancing economic and ecological benefits in mold manufacturing.

5.3.2. Application of knowledge graph technology

In research on mold material surface treatment, low-voltage electrical accessory mold lifespan, and green manufacturing strategies, knowledge graph technology plays a key role. Knowledge graphs integrate multi-source heterogeneous data such as mold materials, surface treatment processes, and environmental standards, structurally presenting information on mold material characteristics, impacts of different surface treatment methods on mold lifespan, and green manufacturing-related environmental requirements in graph form. Through knowledge graphs, decision support systems achieve intelligent reasoning and querying, quickly and accurately providing technicians with mold material selection and surface treatment process optimization suggestions while ensuring compliance with environmental standards. Technicians can intuitively understand factor associations, such as lifespan improvement effects of specific surface treatments on certain mold materials and the advantages/disadvantages of those processes in green manufacturing, aiding scientific decisions and promoting green and efficient mold manufacturing.

6. Conclusion

Mold material surface treatment significantly impacts the lifespan of low-voltage electrical accessory molds. Different surface treatment technologies influence mold lifespan by altering surface microstructure and mechanical properties, acting on failure forms such as wear, corrosion, and fatigue, exhibiting certain patterns. The integration of green manufacturing concepts with intelligent technologies points to new directions for low-voltage electrical accessory mold manufacturing, with the key lying in incorporating intelligent means into all links of green manufacturing, such as intelligent production process control to reduce energy consumption and improve resource utilization. In the future, efforts should strengthen the development of environmentally friendly materials to reduce environmental impact from the source; meanwhile, focus on integrating intelligent sensing systems for real-time mold status monitoring, achieving precise maintenance and optimization, and promoting the development of low-voltage electrical accessory mold manufacturing toward greener, more efficient, and intelligent directions.

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References

[1] Song L, 2021, Experimental Study on the Effects of Surface Treatment Technology and Magnetic Field on Frosting, thesis, Dalian University of Technology.

[2] Xia Y, 2021, Research on the Wear Law and Mold Strengthening of Biomass Forming Mixed Raw Materials on Mold

Surface, thesis, Hefei University of Technology.
[3] Zhang Y, 2023, Optimization of Laser Quenching Process Parameters and Prediction of Mold Life for CrMo Cast Iron Covering Parts, thesis, Hebei University of Science and Technology.
[4] Gao W, 2021, Evaluation Method and Application of Green Manufacturing in the Preparation Process of Typical Energy Materials, thesis, University of Chinese Academy of Sciences.
[5] Ye R, 2021, Development of Injection Mold Teaching Aids for Vocational Education Mold Manufacturing Course, thesis, Guangdong Ocean University.
[6] Lv Z, 2021, The Influence of Heat Treatment Process on Mold Life. Metallurgy and Materials, 41(1): 98–99.
[7] Cheng X, Zhou J, Xiao R, et al., 2020, A Review on Product Modular Design for Green Manufacturing. China Mechanical Engineering, 31(21): 14.
[8] Jia Q, Zhao B, 2022, Development Trends and Surface Strengthening of Mold Materials. Metal Processing: Hot Processing, 2022(12): 86–89.
[9] Huang H, 2021, Research on Methods to Improve the Manufacturing Accuracy and Life of Stamping Dies. China Broadband, 2021(9): 177.
[10] Zhang Y, 2021, Exploration of Surface Treatment Technologies for Improving the Anti-Carburizing Performance of Metal Materials. World Nonferrous Metals, 2021(4): 119–120.

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Research on Cadre Appointment Decision-Making Based on Data Analysis

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Abstract: This paper introduces the theoretical foundations of data-driven models for cadre appointment decision-making and elaborates on the policy and legal frameworks that govern their application. It explains key components such as the integration of multi-source heterogeneous data and the construction of a comprehensive cadre profiling system. The study also addresses precise demand analysis and matching, performance feedback during the tenure period, and related processes. Furthermore, it reviews current progress and existing limitations, and discusses future development trends in data-driven cadre management and decision-making.

Keywords: Cadre decision-making; Data analysis; Policies and regulations

Online publication: December 31, 2025

1. Introduction

In the field of cadre appointment decision-making, with the development of the times, the paradigm of cadre appointment decision-making in government and public institutions has gradually shifted, with more emphasis on data application. The "Regulations on the Selection and Appointment of Party and Government Leading Cadres" promulgated in 2019 emphasize the importance of having both moral integrity and professional competence, using morality as the first criterion for personnel selection, and the principles of democracy, openness, competition, and merit selection, providing basic guidance for decision-making on cadre appointment. In this context, data-driven models have important theoretical foundations. Statistical analysis, machine learning, and other technologies can uncover the patterns and potential of cadre work. The integration of multi-source heterogeneous data, the construction of cadre portrait systems, and the establishment of multidimensional evaluation systems also provide support for decision-making. At the same time, issues such as privacy protection and algorithm transparency need to be addressed to adapt to the trend of deep integration of big data and organizational personnel work.

2. Theoretical basis for cadre appointment decision-making

2.1. Data driven cadre decision-making model

The data-driven model has an important theoretical basis in the decision-making of cadre appointment. With the development of the times, the decision-making paradigm for the appointment of cadres in government and public institutions is gradually shifting, with more emphasis on the application of data. Statistical analysis techniques can quantitatively process various work data of cadres, excavate the patterns and trends of their work performance, and provide objective basis for appointment decisions[1]. Machine learning technology can build predictive models by learning and analyzing large amounts of cadre data, and predict the future development potential of cadres. The application of these technologies in personnel management can improve the scientificity and accuracy of cadre appointment decisions, avoid interference from human factors, and make decisions more in line with the needs of organizational development.

2.2. Related policy and regulatory system

The decision-making of cadre appointment needs to follow a series of policy and regulatory systems. Among them, the "Regulations on the Selection and Appointment of Party and Government Leading Cadres" is an important basis[2]. This regulation provides clear provisions on the basic principles, standard conditions, procedural methods, etc. for the selection and appointment of cadres. It emphasizes the employment standards of both virtue and ability, with virtue as the priority, and requires the selection and appointment process to adhere to the principles of democracy, openness, competition, and merit based selection. These regulations provide basic guidelines for the decision-making of cadre appointment, ensuring the scientific and fair nature of the decisions. At the same time, other relevant policy documents have also standardized and constrained the appointment of cadres from different perspectives, jointly forming a policy and regulatory system for cadre appointment decision-making, laying the foundation for constructing a data application framework under institutional constraints.

3. Construction of cadre data collection and analysis system

3.1. Multi-source heterogeneous data integration

The integration of multi-source heterogeneous data such as cadre personnel files, assessment data, and training records is the key to building a cadre data collection and analysis system. These data sources are diverse and structurally complex, requiring the establishment of effective integration mechanisms. Firstly, it is necessary to unify data standards to ensure consistency in format, encoding, and other aspects of data from different sources, in order to facilitate subsequent analysis and processing[3]. For example, standardizing the definition of key information such as date of birth and educational background in the personnel files of cadres. Secondly, using data cleaning techniques to remove duplicate, erroneous, and incomplete data can improve data quality. At the same time, different dimensions of data are correlated through data association algorithms, such as linking assessment data with training records, to comprehensively understand the comprehensive performance of cadres and provide more accurate and comprehensive data support for cadre appointment decisions.

3.2. Construction of decision analysis model

To construct a cadre portrait system based on competency models and performance prediction models, it is necessary to first determine the key indicators of competency and performance. Competencies and qualities can cover leadership, communication skills, professional skills, and other aspects, and relevant data can be obtained through behavioral event interviews, questionnaire surveys, and other methods[4]. The performance prediction model should consider factors such as work results and work efficiency, and analyze them in conjunction with historical performance data. When establishing a quantitative matching algorithm between job requirements and cadre traits, it is necessary to quantify the required abilities, qualities, and performance requirements of the job, and to quantitatively score the various traits of the cadre. Then, the matching degree between the two is calculated through mathematical models to provide scientific basis for cadre appointment decisions, ensuring that the abilities and traits of cadres are highly compatible with job requirements.

4. The practical path of empowering decision-making with data

4.1. Decision requirement analysis matching

4.1.1. Dynamic modeling of personnel job matching

Building a multidimensional evaluation system for cadres that includes indicators such as political quality, professional ability, and mass foundation is one of the important practical paths for data empowerment decision-making. By quantitatively analyzing these indicators, we can have a more comprehensive and objective understanding of the comprehensive quality and ability level of cadres. In terms of matching decision-making needs analysis, it is necessary to clarify the requirements for the qualities and abilities of cadres in different positions, match the evaluation results of cadres with job requirements, and provide scientific basis for cadre appointment decisions. At the same time, the matching of personnel and positions should be dynamic, constantly adjusted with changes in job requirements and the development of cadres themselves. By using data analysis technology, the matching degree between cadres and positions can be monitored in real time, and any mismatches can be detected and adjusted in a timely manner, thereby improving the scientificity and accuracy of cadre appointment decisions[5].

4.1.2. Design of decision support system

Accurate needs analysis and matching are necessary in the decision-making process of cadre appointment. Understand the key elements such as skills, qualities, and development potential required for the position, and analyze the individual abilities, experiences, and development trends of the cadre to ensure effective alignment between the two[6]. Next is the design of the decision support system, which aims to build a comprehensive database of cadre information, covering multidimensional data such as work performance and training experience. Utilize data analysis techniques to mine the value of data and establish models for cadre competence and job competency. Using algorithms to predict the potential of cadres and provide intelligent recommendations for job suitability. Develop a visual decision-making platform that presents complex data and analysis results in intuitive forms such as charts, to assist decision-makers in making quick and accurate employment decisions.

4.2. Dynamic optimization of decision implementation

4.2.1. Tracking and evaluation of appointment effectiveness

Establishing a performance feedback mechanism for the tenure cycle is the key to tracking and evaluating the effectiveness of employment. By collecting performance data during the tenure and conducting quantitative analysis, it provides a basis for decision-making adjustments [7]. At the same time, a digital tracking model for the growth trajectory of cadres is constructed, which comprehensively considers multidimensional factors such as work results, ability improvement, and interpersonal relationships, and presents the development path of cadres in a visual way. By using this model, not only can we real-time understand the performance of cadres at different stages, but we can also predict their future development trends. Timely feedback on problems that arise during the tenure process, in order to take targeted measures such as training and job adjustments, ensure the scientific and effective decision-making of cadre appointment, and achieve dynamic optimization of the cadre team.

4.1.2. Iterative upgrade of decision-making mechanism

The decision scheme comparison method based on A/B testing plays an important role in cadre appointment decision-making. By testing different appointment strategies simultaneously and comparing their effectiveness differences, a basis is provided for the continuous optimization of appointment strategies. For example, A/B testing can be conducted on different selection criteria, training methods, or job allocation plans to observe the work performance and development of cadres under different conditions. Based on the test results, adjust the appointment strategy in a timely manner to better meet the development needs of the organization and the growth patterns of cadres. This dynamic optimization process can continuously improve the scientificity and effectiveness of cadre appointment decisions, cultivate and select better cadres for the organization, and promote the sustainable development of the organization[8].

5. Application practice and effectiveness in government institutions

5.1. Pilot case analysis

5.1.1. Application examples of provincial government agencies

The Organization Department of a certain provincial party committee applied data analysis to the selection of department level cadres in the cadre deployment project. The department constructs a data model to collect and integrate multidimensional data such as work performance, educational background, and training experience of cadres[9]. By analyzing data, we can uncover the potential abilities and strengths of cadres, providing scientific basis for selection decisions. For example, in-depth analysis of performance data of cadres can clearly present their contributions and development trends in different positions. Meanwhile, educational background and training experience data can help evaluate the knowledge reserve and learning ability of cadres. This selection method based on data models improves the accuracy and fairness of selection, making the selected cadres more in line with job requirements and providing effective practical reference for cadre appointment decisions.

5.1.2. Cases of reform in public institutions

During the transformation process of a certain research institute, data analysis was fully applied in the reconstruction of the professional and technical cadre team. By collecting and analyzing multidimensional data such as research achievements, project experiences, and academic influence of researchers, we can accurately identify core talents and individuals with development potential in different professional fields[10]. These data provide objective basis for cadre appointment decisions and avoid interference from human factors. For example, when determining the key project leader, based on data analysis results, cadres with outstanding achievements in relevant fields and rich project management experience were selected to ensure the smooth progress of the project. At the same time, data analysis also helps to discover structural defects in the cadre team, providing direction for subsequent talent introduction and training, and promoting the optimization and development of the professional and technical cadre team.

5.2. Quantitative evaluation of decision-making effectiveness

5.2.1. Analysis of employment accuracy

The accuracy analysis of personnel can use indicators such as recall rate and precision rate to evaluate the consistency between the system's recommended candidates and the results of organizational inspections. The recall rate is used to measure the proportion of people recommended by the system that meet the organizational assessment criteria to the actual total number of people who meet the criteria. It reflects the system's ability to comprehensively cover potential suitable candidates. Accuracy refers to the proportion of candidates recommended by the system that are deemed suitable by the organization's assessment, reflecting the accuracy of the recommendation. By calculating these indicators, we can objectively understand the effectiveness of the system in recommending cadre appointments. For example, if the recall rate is high but the accuracy rate is low, it may mean that the system's screening range is too wide; On the contrary, if the accuracy is high but the recall is low, there may be situations where some suitable candidates are missed. This quantitative evaluation helps government agencies optimize their personnel decision-making mechanisms and improve the accuracy of personnel selection.

5.2.2. Management efficiency improvement statistics

In the practical application of government agencies, by comparing and analyzing the situation of cadre inspection work before and after data assisted decision-making, it can be clearly seen that there are significant changes in time cost and manpower investment. In the quantitative evaluation of decision-making effectiveness, data assisted decision-making makes the inspection work more accurate and efficient, reduces unnecessary steps and repetitive labor, and thus shortens the time consumed in the entire inspection process. From the perspective of improving management efficiency statistics, human resources investment has also been optimized, allowing staff to carry out their work more targetedly, avoiding resource waste, and focusing their energy on key links and the collection and analysis of important information. This not only improves the scientificity and accuracy of cadre appointment decisions, but also enhances the overall management efficiency and work quality of government agencies.

5.3. Extension effect of employee services

5.3.1. Career planning support

After introducing a data analysis system in the decision-making process of cadre appointment, government agencies have achieved significant results in extending cadre services and providing career planning support. In the extension of cadre services, through the analysis of cadre work data, we can accurately understand the needs of cadres, provide them with training courses and career guidance that are more suitable for personal development, and broaden the service dimensions. In terms of career planning support, utilizing data analysis of cadres' work performance, ability tendencies, etc., to design personalized growth paths for cadres. The system can predict the development potential of cadres in different positions, help them clarify their career direction, plan their career stages reasonably, and provide scientific basis for the rational employment of personnel in government agencies, improving overall work efficiency and the stability of the cadre team.

5.3.2. Analysis of organizational ecological optimization

The application of data analysis in decision-making for cadre appointment in government agencies has achieved significant results in optimizing organizational ecology. In terms of age structure, by analyzing the age data of cadres, the proportion of elderly, middle-aged and young cadres should be reasonably matched to ensure that the leadership team has both experience and vitality. In terms of professional structure, based on the demand for professional skills in different positions, analyze the professional background data of cadres to enable reasonable allocation of talents in various professions and improve work efficiency. For temperament structure, by analyzing the personality traits and work styles of cadres through data, a highly complementary leadership team can be formed to promote team collaboration and smooth communication. This optimization effect not only improves the scientific decision-making and work execution of government agencies, but also creates a positive and collaborative organizational ecological environment, laying a solid foundation for better serving employees and society.

6. Conclusion

According to the systematic summary of research results, there has been some progress in the current decision-making of cadre appointment based on data analysis, but there are still shortcomings. In terms of privacy protection, the security and confidentiality of cadre data need to be strengthened; In terms of algorithm transparency, the decision-making process is not clear enough to explain. To address these issues, an intelligent review mechanism should be established to ensure the rationality and accuracy of data usage, while improving explanatory models and enhancing the comprehensibility of decisions. Looking ahead to the future, the deep integration of big data and organizational personnel work will be a development trend. This requires continuous optimization of data processing and analysis methods, enhancing the scientific and fair nature of cadre appointment decisions, in order to better adapt to the requirements of organizational and personnel work in the new era, and provide strong support for the construction of the cadre team.

Disclosure statement

The author declares no conflict of interest.

References

[1] Zeng Q, 2016, Democratic Procedures in the CCP's Cadre Selection Process: Implementation and Consequences. The China Quarterly, 2016(225): 73–99.

[2] Khomideh K, Rangriz H, Khastar H, et al., 2022, Redesign the Model of Selection and Appointment of Managers of the Social Security Organization based on Competency Models with a Data-based Approach. Journal of Psychological Science, 21(118): 1943–1956.

[3] Huai Y, 2019, Organizational Hierarchy and the Cadre Management System, Decision-Making in Deng's China, Routledge, 39–50.

[4] Kou C, Tsai W, 2014, "Sprinting with Small Steps" towards Promotion: Solutions for the Age Dilemma in the CCP Cadre Appointment System. The China Journal, 71(1): 153–171.

[5] Musholeh T, Dinata M, Haryadi S, 2023, The Selection and Appointment Process of Village Officials: North Lampung as a Case Study. Research Horizon, 3(4): 331–338.

[6] Picciano A, 2010, Developing and Nurturing Resources for Effective Data-Driven Decision Making, Handbook of Data-based Decision Making in Education, Routledge, 123–135.

[7] Xian M, Zhao C, Zhou Y, 2022, From Bureaucratic Coordination to a Data-Driven Model: Transformation and Capacity Building of Community-Based Prevention and Control of Public Health Events. International Journal of

Environmental Research and Public Health, 19(14): 8238.
[8] Shava E, Chamisa S, 2018, Cadre Deployment Policy and its Effects on Performance Management in South African Local Government: A Critical Review. Politeia (02568845), 37(1): 3849.
[9] Brødsgaard K, 2012, Cadre and Personnel Management in the CPC. China: An International Journal, 10(2): 69–83.
[10] Gijana A, 2011, Assessing Challenges in Public Appointments and Recruitment Processes in Chris Hani District Municipality: A Case Study of Human Resource Department in Lukhanji Local Municipality (2008–2010), thesis, University of Fort Hare.

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Optimization and Technological Innovation Path of Photovoltaic System Field Management from the Perspective of Electrical Engineering

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Abstract: Driven by the "Dual Carbon" strategy and green building concepts, the full utilization of idle rooftops, vacant lots, and parking lots for deploying distributed photovoltaic (PV) systems has become a key measure to enhance land and building utilization value. From the core perspective of electrical engineering, this paper systematically constructs a technical framework integrating "planning-operation-maintenance-guarantee" to address practical challenges such as low energy management efficiency and poor system coordination in diverse application scenarios. The study focuses on optimizing PV system operation mechanisms based on maximum power point tracking (MPPT), proposing integrated PV-storage capacity matching models and dynamic energy management strategies applicable to parking lots and idle spaces. It designs an online monitoring system for distributed PV with IoT sensors and modular emergency/replenishment power supply solutions. Additionally, it explores intelligent operation and predictive maintenance technologies leveraging digital twin and deep learning algorithms. Research and practice demonstrate that comprehensive application of these technologies in system design, electrical safety, and smart scheduling significantly improves field management precision, operational reliability, and lifecycle economic efficiency of distributed PV systems across multiple scenarios. This provides clear technical pathways and practical references for unlocking the value of idle assets and promoting green, low-carbon transformation in building and land utilization.

Keywords: New energy photovoltaics; Distributed photovoltaics; Idle resource utilization; Technical optimization

Online publication: December 31, 2025

1. Introduction

With the promulgation of the "Guidelines on Promoting the Safe and Reliable Construction of Distributed Photovoltaic Power Generation (2023)" and the national push for renewable energy adoption, the utilization of idle rooftops, vacant land, and parking lot canopies for distributed photovoltaic (PV) systems has garnered significant attention. In these diverse scenarios, specific technical requirements exist across power grid integration needs, electrical safety standards, and the integration of PV systems with existing buildings/environment. From an electrical engineering perspective, whether constructing efficient PV system topologies or establishing capacity matching models for integrated PV-storage systems, the core objective remains enhancing on-site management efficiency, operational reliability, and economic benefits of distributed PV. The policy's introduction provides robust support for these technical efforts, driving large-scale and high-quality development of distributed PV in various idle resource scenarios. Building on this foundation, this paper aims to systematically analyze and explore key technical compatibility and management optimization pathways for distributed PV across diverse application scenarios from an electrical engineering perspective, addressing critical issues such as energy efficiency in project development and operation, system safety and stability, and maintenance cost control.

2. Working mechanism of distributed photovoltaic and diversified application scenarios

2.1. Analysis of electrification characteristics and requirements in diversified scenarios

When deploying distributed PV systems on large idle rooftops or vacant lots, ensuring reliable power transmission and local consumption becomes critical [1]. These scenarios typically involve industrial facilities, warehouses, or future planned electric equipment (e.g., charging stations) that require stable and potentially growing power supply, demanding high grid access capacity, power quality, and system reliability. For applications like parking lot solar shelters, electrical safety standards are particularly stringent. Given the open environment and frequent human/vehicle traffic, PV systems and their supporting structures must feature excellent insulation, lightning protection grounding, and mechanical safeguards to prevent accidents such as electric shocks and short circuits, ensuring both personal and property safety. New energy PV systems integrated into these environments must meet specific technical requirements, including structural load-bearing capacity, aesthetic harmony, and complementary replacement of existing power loads. They must also comply with strict electrical regulations to achieve stable and reliable co-operation with existing distribution networks and electrical infrastructure.

2.2. Theoretical framework of light-load-storage coordinated operation

From an electrical engineering perspective, constructing a distributed PV system topology based on maximum power point tracking (MPPT) technology is crucial for revealing the dynamic coupling mechanism between load demand and PV power generation under microgrid architectures. MPPT technology ensures PV arrays maintain maximum power output under varying sunlight and environmental conditions, thereby improving energy utilization efficiency. The system topology built upon this foundation organically integrates PV power generation, diversified loads (such as building electricity consumption, electric vehicle charging stations), and energy storage devices. In microgrid architectures, the time-varying characteristics of loads and the intermittency/volatility of PV power generation interact with each other, creating a complex and critical dynamic coupling mechanism. In-depth research on this mechanism enables better coordination of energy flows among sources, loads, and storage, achieving efficient local energy utilization and optimized distribution [2]. For example, during periods of sufficient sunlight, PV power primarily meets local load demands, with excess energy stored in storage devices or fed into the grid. Conversely, during periods of insufficient sunlight or peak load times, energy storage devices or the grid supplement power supply to ensure system continuity and economic viability.

3. Research on photovoltaic technology adaptability in diversified scenarios

3.1. Optimization of light storage configuration in complex scenarios

In scenarios such as parking lots and vacant lots, load characteristics often exhibit diversity (e.g., base lighting, impact loads from EV fast-charging stations), imposing higher requirements on energy supply stability, power quality, and economic efficiency. To address this, a capacity matching model for integrated PV-storage systems must be established, tailored to building/site characteristics. This model should comprehensively consider factors including roof/vacant area availability, load capacity, local sunlight resources, and typical load curves (particularly power demand characteristics of charging stations) to accurately calculate PV installation capacity and energy storage system configurations, ensuring rational alignment of PV-storage-load [3]. Additionally, a dynamic energy management strategy based on load forecasting and electricity price signals is proposed. This strategy can coordinate PV output, energy storage charging/discharge behaviors, and load switching in real-time or proactively, charging storage during off-peak hours or PV surplus, and discharging energy storage during peak loads or high electricity prices. This achieves peak shaving, valley filling, improved self-sufficiency rates, and cost savings, ultimately ensuring stable, efficient, and economical energy supply in complex application scenarios.

3.2. Development of distributed photovoltaic intelligent monitoring system

In scenarios where distributed PV systems are widely deployed, developing efficient intelligent monitoring systems is crucial. This requires designing online monitoring devices that integrate multiple types of sensors (such as current/voltage sensors, temperature sensors, and irradiance meters) with IoT communication technologies. Such devices enable effective collaborative management of PV array operational status and building/site information. Leveraging IoT's high-efficiency data transmission and remote control capabilities, centralized, real-time, and precise monitoring can be achieved for PV arrays distributed across various locations (e.g., multiple idle rooftops). Key parameters include panel temperature, output power, inverter status, and environmental irradiance. Through continuous collection, analysis, and visualization of these massive operational data, maintenance personnel can promptly identify potential equipment failures (such as hot spots or string faults), evaluate system performance, and implement targeted maintenance. Simultaneously, the system can collaborate with building management systems or site monitoring platforms to provide data support for optimizing overall energy scheduling and assessing asset power generation efficiency, thereby achieving refined and intelligent management of distributed PV assets [4].

4. Operation and maintenance of distributed photovoltaic systems and emergency support system

4.1. Flexible energy supply and energy storage system design

4.1.1. Modular photovoltaic power generation and emergency backup system

To address specific needs such as temporary power supply, system capacity expansion, or regional energy independence, modular, mobile, or rapidly deployable PV units (e.g., PV mobile units or prefabricated modular systems) can be developed. These systems should integrate quick deployment or plug-and-play interface mechanisms to ensure rapid power generation when required, enhancing deployment flexibility and meeting emergency backup or elastic expansion needs. Additionally, they should incorporate efficient multi-stage inverter and grid/off-grid switching technologies to ensure output power quality complies with relevant standards [5]. These systems must also enable smooth transitions with fixed PV installations or local grids, providing uninterrupted or supplementary power support for critical loads. This approach improves the resilience and reliability of distributed PV systems in responding to emergencies or load fluctuations.

4.1.2. Optimization of hybrid energy storage system

Developing hybrid energy storage architectures (e.g., supercapacitor-lithium battery systems) tailored to diverse load characteristics is crucial for enhancing power quality and operational stability in distributed PV systems. Supercapacitors, with their high power density and rapid response, effectively mitigate PV power fluctuations and handle instantaneous high-power demands from shock loads like electric vehicle charging stations [6]. Lithium batteries, boasting high energy density, excel in time-of-use energy transfer and extended-duration power supply. By leveraging their complementary strengths and implementing customized power compensation and energy scheduling strategies, hybrid systems can dynamically adjust charging/discharging patterns based on real-time system conditions, enabling hierarchical management of power and energy demands. This optimized hybrid energy storage approach significantly improves distributed PV systems' performance when handling variable loads, ensures reliable power supply for critical applications, and extends the lifespan of energy storage equipment.

4.2. Smart power supply and energy dispatching technology

4.2.1. Multi-source collaborative optimization control algorithm

In the intelligent power dispatching technology of PV power supply systems, the multi-source collaborative optimization control algorithm plays a pivotal role [7]. This algorithm develops dynamic energy management strategies that consider multiple factors including electricity prices, load priorities, and user preferences, thereby achieving multi-objective optimization coordination among PV systems, energy storage, adjustable loads, and the grid. Through this algorithm, the system can automatically determine optimal operating modes based on real-time monitoring data and predictive information. For instance, during peak electricity demand periods, it prioritizes PV power generation and energy storage discharge while suppressing non-critical loads. When predicting insufficient PV output during rainy weather, it preemptively schedules energy storage charging or adjusts load operation plans. This intelligent coordinated control not only maximizes system economic efficiency but also enhances grid compatibility, ultimately improving overall energy utilization efficiency.

4.2.2. Rapid isolation and reconstruction strategies for system failures

In the intelligent operation and maintenance of PV systems, rapid fault isolation and reconstruction strategies are critical [8]. A protection and self-healing mechanism based on fast shutdown and island detection technology must be established to ensure personal safety and uninterrupted power supply for critical equipment. When faults (such as insulation failures, overcurrents, etc.) or grid abnormalities are detected, protective devices should act swiftly to precisely isolate fault points and prevent escalation. Simultaneously, based on predefined reconstruction logic, static transfer switches and similar equipment should be utilized to rapidly reconstruct the power supply network in non-fault areas, enabling smooth mode transitions (e.g., from grid-connected to off-grid operation). This ensures continuous power supply for critical loads within the system, minimizes operational impacts from faults, and enhances system availability and safety.

5. Engineering practice and technical optimization path

5.1. Photovoltaic and building/environment integrated technology

5.1.1. Structural synergy and safety design method

In PV field management from an electrical engineering perspective, structural coordination and safety design between PV systems and buildings/environment form the foundation. Integrated design and installation standards for PV support structures must be established for various carriers (e.g., concrete roofs, color-coated steel roofs, parking lot canopies, ground-mounted brackets). These standards should comprehensively consider factors such as the structural load-bearing capacity, wind pressure resistance, snow load resistance, and corrosion environment of the carriers to ensure the structural safety and long-term stability of PV systems [9]. Simultaneously, the design should balance installation and maintenance convenience, cost-effectiveness, and minimize impact on the original building's functionality and environmental aesthetics. Through such structural coordination design, a harmonious integration of safety, reliability, economy, and aesthetics can be achieved, laying a solid foundation for the smooth implementation and long-term stable operation of distributed PV projects.

5.1.2. Safe and reliable electrical connection and protection technology

In distributed PV integration, secure and reliable electrical connections coupled with comprehensive protection technologies are critical. On one hand, it is essential to develop and apply weather-resistant, corrosion-resistant, and highly reliable PV wiring systems and connectors suitable for various installation environments (e.g., high-temperature and humid roofs, vibration-prone carports), ensuring long-term stability and safety of electrical connections under harsh conditions. Waterproofing, dustproofing, and UV aging protection for connection points must strictly adhere to the highest standards. On the other hand, a robust electrical safety protection system must be established, including but not limited to proper grounding system design, precise insulation coordination, reliable lightning and surge protection, as well as necessary arc fault detection and rapid disconnection functions. This comprehensive approach ensures electrical safety throughout the system's lifecycle, preventing accidents such as fires and electric shocks [10].

5.2. Development of intelligent operation and maintenance management system

5.2.1. Digital twin platform development

From an electrical engineering perspective, the digital twin platform for distributed PV systems serves as the cornerstone of intelligent operation and maintenance. By establishing a lifecycle management platform that integrates Building Information Modeling (BIM), Geographic Information Systems (GIS), real-time/historical power generation data, and equipment status data, it enables precise mapping and bidirectional interaction between physical systems and virtual models. Leveraging the 3D visualization, data integration, and simulation capabilities of digital twin technology, managers can intuitively grasp the global distribution and real-time operational status of distributed PV assets, accurately locate faults, and analyze root causes. The platform also supports system performance evaluation, operational strategy optimization, and maintenance plan simulation based on the model. By bridging energy flow and information flow, it provides robust support for refined and predictive asset management, ultimately enhancing operational efficiency and return on investment.

5.2.2. Application of predictive maintenance algorithm

In PV field management, data-driven predictive maintenance algorithms are essential for reducing operational costs and improving system availability. These models, built on machine learning techniques (e.g., deep learning, time series analysis), evaluate the health status and predict failures of critical components like modules, inverters, and cable connections. Trained with historical operational data (current, voltage, power, insulation resistance), environmental metrics (temperature, humidity, irradiance), and maintenance records, they learn equipment degradation patterns and early warning signs. By comparing real-time data with predictive models, potential risks, such as abnormal module performance, loose connections, or inverter anomalies, can be identified early. The system generates alert tickets to guide maintenance teams in targeted interventions, shifting from reactive repairs to proactive protection. This approach effectively prevents power generation losses and severe equipment damage, ultimately extending system lifespan.

5.3. Standard system and safety assurance

5.3.1. Comprehensive electrical safety protection standards

From an electrical engineering perspective, establishing a comprehensive electrical safety standard system covering all distributed PV scenarios serves as the cornerstone for the industry's healthy development. It is essential to formulate and refine safety technical specifications for system design, equipment selection, installation acceptance, and operation maintenance across various application scenarios (residential, commercial, industrial, parking lots, etc.). Key aspects include system grounding and equipotential bonding standards, insulation resistance monitoring requirements, DC arc fault detection and interruption requirements, anti-reverse current and island protection configurations, as well as interconnection requirements with building fire protection systems. Through standardized safety constraints, potential hazards can be minimized to the greatest extent, ensuring the safety of personnel and property, and promoting the standardized and sustainable development of the distributed PV market.

5.3.2. Optimization of intelligent emergency response mechanism

From an electrical engineering perspective, optimizing emergency response mechanisms for distributed PV systems is a critical component in enhancing system resilience. It is essential to refine contingency plans covering various typical faults (such as equipment failures, grid anomalies, and natural disasters). These plans should clearly define fault reporting procedures, on-site response protocols, personnel assignments, and safety measures, with regular drills conducted. Conversely, the data analysis and remote control capabilities of intelligent operation and maintenance platforms should be fully utilized to establish rapid response processes based on real-time status awareness and intelligent decision-making. When system anomalies occur, the platform can automatically trigger alerts, conduct preliminary fault analysis, and assist in generating or executing partial handling commands (e.g., remotely isolating fault points). This significantly improves the speed and accuracy of emergency responses, minimizing outage duration and losses to the greatest extent.

6. Conclusion

From an electrical engineering perspective, advancing high-quality development of new energy PVs in scenarios like idle rooftops, vacant lots, and parking lots requires meticulous on-site management and technological innovation. This paper systematically explores and proposes a comprehensive technical approach encompassing "source-load-storage coordination, intelligent operation and maintenance, and safety assurance." Practical experience demonstrates that through deep integration and application of technologies such as maximum power point tracking, PV-storage coordinated configuration, IoT monitoring, digital twin, and predictive maintenance, distributed PV systems can effectively enhance energy output, operational reliability, safety levels, and lifecycle economics. The evolutionary path of distributed PV systems based on digital grid and intelligent technology development represents a crucial exploration aligning with energy revolution trends. The primary contribution of this paper lies in systematizing and contextualizing electrical engineering technologies for diverse distributed PV implementation scenarios. The proposed models, strategies, and system solutions provide practical technical support and operational guidance for unlocking the value of customers' idle assets and achieving green, low-carbon transformation in building and land utilization. Continuous innovation and integrated application of these technologies will not only improve on-site management of distributed PVs but also inject strong momentum into building new power systems and realizing sustainable development goals.

Disclosure statement

The author declares no conflict of interest.

References

[1] Chen Y, 2022, Optimization Research on Procurement Cost Control of TW Photovoltaic New Energy Company, thesis, Northwest A&F University.

[2] Wu H, 2023, Photovoltaic Array Reconstruction and Power Optimization in Photovoltaic Power Generation Systems, thesis, Anhui University of Science and Technology.

[3] Wu W, 2022, Optimal Design of Building Photovoltaic and Lighting Engineering, thesis, Zhejiang University of Technology.

[4] Ma Y, 2024, Research on Quality Management Optimization of Photovoltaic Modules in Company S, thesis, Shandong Normal University.

[5] Chuai C, 2022, Research on Management Optimization of Wind Disaster Emergency Repair Project for HND Photovoltaic Power Station, thesis, Jilin University.

[6] Wan L, 2022, Application of New Energy Photovoltaic Power Generation Technology. Science and Technology Innovation and Application, 12(22): 189–192.

[7] Zhao B, 2024, Photovoltaic Technology Innovation and Performance Optimization in New Energy Infrastructure Projects. Light Source and Lighting, 2024(2): 141–143.

[8] Chen B, 2024, Optimization Strategies for Project Construction Management of New Energy Photovoltaic Power Stations. Building Materials and Decoration, 20(13): 67–69.

[9] He S, 2023, Exploration of Project Construction Management Pathways for New Energy Photovoltaic Power Stations. Bohai Economic Outlook, 2023(7): 156–158.

[10] Liu X, 2023, Optimization Measures for New Energy Photovoltaic Power Generation Project Schemes. Comprehensive Corrosion Control, 37(7): 22–24.

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Research on the Operation Status Evaluation and Energy-Saving Control Measures of Electrical Engineering Facilities and Equipment in Office Buildings

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Abstract: This research focuses on office building electrical engineering facilities. It elaborates on evaluating their operation status using key performance indicators, real-time monitoring, and analyzing baseline energy usage. Energy inefficiency hotspots are identified. The hybrid fuzzy-AHP and dynamic weighting are used in assessment. Prototype validation, comparative analysis are carried out. Energy-saving measures like VFDs and predictive lighting are proposed, along with economic and carbon-emission-related evaluations.

Keywords: Office building; Electrical facilities; Energy-saving control measures

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1. Introduction

In the global landscape of growing emphasis on energy conservation and sustainable development, office buildings, being major energy-consumers, have become a focal point. The operation of their electrical engineering facilities directly impacts occupant comfort, productivity, and energy consumption. In this context, the EU's "Renewable Energy Directive II" (2018) aims to boost the share of renewable energy in the building sector, emphasizing energy-efficient operation of facilities. Meanwhile, scientific evaluation methods such as fuzzy analytic hierarchy process (AHP) and entropy weight models have been increasingly applied to assess building energy efficiency, providing a solid foundation for optimizing energy-saving strategies [1]. This research delves into evaluating the operational status of office building electrical facilities and proposes energy-saving control measures. By analyzing key performance indicators, real-time monitoring approaches, and more, it provides a comprehensive understanding, striving to contribute to the energy-saving and sustainable development of the office building industry in line with the policy's spirit.

2. Operational status evaluation of electrical facilities

2.1. Key performance indicators

For the operational status evaluation of electrical facilities in office buildings, several key performance indicators play a crucial role. Load distribution patterns are one of the important metrics. In office buildings, different areas such as offices, meeting rooms, and corridors have distinct load demands at various times. Understanding these patterns helps in optimizing the power supply and distribution system, ensuring efficient utilization of electrical resources [2].

Power quality parameters are also significant. Total Harmonic Distortion (THD) reflects the distortion degree of the electrical waveform. High THD can cause additional losses in electrical equipment, reduce its lifespan, and even affect the normal operation of sensitive devices. Power Factor (PF) measures the efficiency of power utilization. A low PF means more reactive power is consumed, increasing the burden on the power grid and potentially leading to higher electricity costs.

Equipment efficiency benchmarks are essential indicators as well. In office buildings, electrical equipment like air-conditioners, lighting systems, and office appliances consume a large amount of electricity. Setting efficiency benchmarks for these devices helps in evaluating their energy-using performance. High-efficiency equipment not only reduces energy consumption but also contributes to cost-savings and environmental friendliness. By comprehensively considering these key performance indicators, a more accurate and in-depth evaluation of the operational status of electrical facilities in office buildings can be achieved.

2.2. Real-time monitoring approaches

To achieve a comprehensive and accurate operational status evaluation of electrical facilities in office buildings, real-time monitoring is of great significance. IoT-based sensor networks play a pivotal role. These sensors can be strategically installed at various key points of electrical facilities, such as near transformers, circuit breakers, and electrical distribution panels [3]. They are capable of continuously collecting a wide range of data, including voltage, current, power consumption, and temperature. This data provides crucial insights into the normal operation and potential malfunctions of the facilities.

SCADA (Supervisory Control and Data Acquisition) systems also contribute significantly to real-time monitoring. They integrate data from multiple sensors and present a unified view of the electrical facility's operation status. SCADA systems can not only monitor the real-time data but also control the operation of electrical facilities remotely in some cases. This allows for timely adjustment of the operation parameters according to the actual situation, ensuring the stable and efficient operation of electrical facilities.

In addition, predictive maintenance data acquisition methods are essential for real-time monitoring. By analyzing historical operation data and equipment performance characteristics, predictive models can be established. These models can predict potential failures of electrical facilities in advance, enabling maintenance personnel to take preventive measures before a breakdown occurs. This not only reduces downtime but also extends the service life of electrical facilities, thereby improving the overall operational efficiency of office building electrical systems.

3. Energy consumption patterns analysis

3.1. Baseline energy usage characteristics

The baseline energy usage characteristics of electrical engineering facilities and equipment in office buildings are crucial for understanding overall energy consumption patterns. By investigating the daily and weekly load profiles, significant insights can be obtained. For instance, during weekdays, the load of heating, ventilation, air-conditioning (HVAC) systems usually peaks in the middle of the day as the indoor temperature needs to be maintained at a comfortable level for office workers. Lighting systems also show a pattern of high usage during working hours, especially in areas without sufficient natural light. IT infrastructure, such as computers and servers, may have a relatively stable load throughout the day due to continuous operation requirements.

Seasonal variations play a vital role as well. In hot summer months, the energy consumption of HVAC systems surges to combat the high outdoor temperature, while in cold winter, heating systems consume a large amount of energy. On the contrary, in spring and autumn when the outdoor temperature is more moderate, the energy demand for temperature regulation reduces.

Operational patterns of different equipment also contribute to the baseline energy usage. For example, some HVAC units may operate in a constant-volume mode, consuming more energy compared to variable-volume systems. Lighting fixtures with inefficient control strategies may remain on even when not needed. Understanding these baseline characteristics provides a foundation for evaluating the operation status and formulating effective energy-saving control measures for electrical engineering facilities and equipment in office buildings [4].

3.2. Energy inefficiency hotspots

Through energy audits and regression analysis of historical operation data, several energy inefficiency hotspots in office building electrical engineering facilities and equipment can be identified. One of the prominent hotspots is the lighting system. In many office spaces, lighting fixtures may be left on during unoccupied hours, either due to lack of proper occupancy sensors or ineffective control strategies. Additionally, the use of traditional incandescent or halogen bulbs, which are less energy-efficient compared to LED alternatives, can significantly contribute to higher energy consumption [5].

Another area of concern is the HVAC system. Improperly calibrated thermostats can lead to over-cooling or over-heating of office spaces. For example, in some buildings, the HVAC system may be set to maintain a temperature that is either too low in summer or too high in winter, wasting a large amount of energy. Additionally, leaky ductwork in the HVAC system can cause significant energy losses as conditioned air escapes before reaching the intended areas.

Office equipment such as computers, printers, and copiers also present energy inefficiency issues. Many of these devices are left in standby mode, consuming power even when not in active use. Moreover, outdated models of office equipment often have lower energy-efficiency ratings, resulting in unnecessary energy consumption over time.

4. Assessment framework development

4.1. Multi-criteria evaluation model

4.1.1. Hybrid fuzzy-AHP methodology

The hybrid fuzzy-AHP methodology combines the AHP and fuzzy set theory. AHP is a structured technique for organizing and analyzing complex decisions by breaking them down into a hierarchy of sub-problems. It allows for the pairwise comparison of elements within each level of the hierarchy to determine their relative importance. However, traditional AHP may face challenges when dealing with the inherent vagueness and uncertainty in real-world evaluation problems.

This is where the fuzzy set theory comes into play. Fuzzy set theory can handle the imprecise and ambiguous information effectively. By integrating it with AHP, the hybrid fuzzy-AHP methodology can better capture the uncertainty in the evaluation of the operation status of electrical engineering facilities and equipment in office buildings. For example, when evaluating technical, economic, and environmental dimensions, some factors may be difficult to measure precisely, such as the long-term environmental impact perception. Fuzzy-AHP can use fuzzy linguistic variables (like "very high," "high," "medium," etc.) to represent these subjective evaluations. Followed by that, through a series of mathematical operations, including fuzzy aggregation and defuzzification, the final evaluation results can be obtained, which are more in line with the actual situation. This approach has been widely used in similar evaluation research, providing a more comprehensive and accurate assessment framework for the operation status of office building electrical facilities and equipment [6].

4.1.2. Dynamic weighting mechanism

In the dynamic weighting mechanism of the multi-criteria evaluation model for assessing the operation status of electrical engineering facilities and equipment in office buildings, an adaptive weighting strategy is implemented, taking into account equipment aging and changes in usage patterns [7]. Equipment aging is a crucial factor as it can gradually degrade the performance of electrical facilities. Older equipment may consume more energy, have a higher failure rate, and thus require a higher weight in the evaluation to reflect its potential impact on overall operation status. For instance, the insulation of wires may deteriorate over time, increasing the risk of electrical leakage and affecting energy efficiency.

Changes in usage patterns also play a significant role. Office buildings may experience different occupancy rates at various times, such as high usage during working hours and low usage at night or on weekends. Additionally, the types of electrical equipment in use may vary. For example, in modern office settings, the increasing adoption of high-performance computing devices for tasks like data analysis has changed the power consumption pattern. By adjusting weights dynamically according to these usage pattern changes, the evaluation can more accurately reflect the real-time situation of equipment operation. This dynamic weighting mechanism enables a more comprehensive and precise assessment of the operation status of electrical engineering facilities and equipment, providing a more solid foundation for formulating energy-saving control measures.

4.2. Case study validation

4.2.1. Prototype implementation

To demonstrate the practical application of the developed assessment framework, a prototype implementation was carried out in LEED-certified office buildings integrated with Building Energy Management Systems (BEMS). The assessment framework was tailored to the specific characteristics of these office buildings. Parameters such as electrical equipment usage patterns, energy consumption profiles, and environmental conditions were carefully analyzed. Then, the BEMS was utilized to collect real-time data related to the operation status of electrical engineering facilities and equipment. This data was fed into the prototype system, which processed and analyzed it according to the assessment framework. For example, it calculated energy-related indicators like power factor, energy efficiency ratio, and identified potential areas for energy-saving. Through continuous monitoring and adjustment, the prototype was able to provide practical guidance on energy-saving control measures. For instance, it could suggest optimal operation schedules for lighting systems based on occupancy and daylight availability. The results of this prototype implementation not only validated the effectiveness of the assessment framework but also provided a reference for similar office buildings to improve their energy-saving performance. The data collected and analyzed also contributed to further refinement of the framework in the future [8].

4.2.2. Comparative performance analysis

Comparative performance analysis benchmarks the results against ASHRAE standards and ENERGY STAR ratings. ASHRAE standards provide a comprehensive set of guidelines for building energy performance, covering aspects such as HVAC systems, lighting, and building envelope design [9]. By comparing the operation status of electrical engineering facilities and equipment in office buildings with these standards, it becomes possible to identify areas of compliance and non-compliance. For example, ASHRAE's Standard 90.1 sets minimum energy-efficiency requirements for commercial buildings. If a building's HVAC system fails to meet the specified efficiency levels in this standard, it indicates a potential area for improvement.

ENERGY STAR ratings, on the other hand, are more consumer- and market-oriented. They serve as a mark of energy-efficient products and buildings. Office buildings that meet ENERGY STAR criteria demonstrate superior energy performance compared to their peers. When evaluating the operation status of electrical engineering facilities, the ENERGY STAR ratings can be used as a reference to determine whether the building is among the more energy-efficient ones in the market. This comparative analysis not only helps in understanding the current performance of the office building's electrical facilities but also provides a basis for formulating energy-saving control measures, aiming to bring the building's performance in line with or exceed these recognized benchmarks.

5. Energy-efficient control strategies

5.1. Adaptive optimization techniques

5.1.1. Variable frequency drive applications

Variable frequency drive (VFD) applications play a crucial role in optimizing the energy-efficiency of motor-driven equipment in office building electrical engineering facilities. VFDs are devices that can adjust the speed of an electric motor by varying the frequency and voltage of the power supplied to it. This flexibility enables motors to operate at the most appropriate speed according to the actual load requirements, rather than running at a fixed speed regardless of the load [10].

In office buildings, many motor-driven systems, such as ventilation fans, water pumps, and elevator motors, often operate under varying loads. For example, during off-peak hours in an office building, the demand for ventilation and water supply is lower. By installing VFDs, these motors can reduce their speed, consuming less electrical energy without sacrificing the necessary functionality.

The implementation of VFDs also helps in reducing mechanical stress on the motors and associated equipment. When a motor starts and stops frequently at full speed, it experiences significant wear and tear. VFDs, however, allow for soft-starting and soft-stopping, gradually ramping up or down the motor speed. This not only extends the lifespan of the motor but also reduces maintenance costs over time. Moreover, VFDs can be integrated with building automation systems, enabling centralized control and monitoring. This integration allows facility managers to fine-tune the operation of motor-driven equipment based on real-time data, further enhancing energy-efficiency and overall system performance.

5.1.2. Predictive lighting control

Predictive lighting control in office buildings is a crucial aspect of energy-efficient control strategies. By leveraging adaptive optimization techniques, this approach can significantly reduce energy consumption while maintaining a comfortable visual environment.

Predictive lighting control systems use sensors and algorithms to anticipate lighting needs. For instance, occupancy sensors detect the presence or absence of people in different areas of the office. These sensors can be combined with daylight-harvesting algorithms. Daylight-harvesting algorithms analyze the amount of natural light available through windows. By integrating these two elements, the system can adjust the artificial lighting levels accordingly.

When the occupancy sensors detect that an area is unoccupied, the lighting can be dimmed or turned off completely. In occupied areas, if there is sufficient natural light as determined by the daylight-harvesting algorithms, the artificial lighting can be dimmed to a lower level. This not only saves energy but also reduces the heat generated by artificial lights, thus lessening the load on the air-conditioning system.

Moreover, predictive lighting control can adapt to different times of the day and seasons. In the morning when the sun is rising, the system can gradually increase the artificial light levels as the natural light is still relatively weak. As the day progresses and the natural light becomes stronger, the artificial lights can be dimmed. During the evening, when the natural light fades, the artificial lights can be adjusted to full brightness. Through such dynamic and predictive control, office buildings can achieve a high level of energy efficiency in their lighting operations [11].

5.2. Smart grid integration

5.2.1. Demand response implementation

Demand response implementation in the context of energy-efficient control strategies for office building electrical engineering facilities and equipment involves developing automated load shedding protocols synchronized with utility pricing signals [12]. This approach aims to encourage office building occupants to adjust their electricity consumption patterns in response to changes in electricity prices.

When utility pricing signals indicate high-cost periods, the automated load shedding protocols will be activated. For example, non-critical electrical equipment such as some decorative lighting, certain office appliances that are not in immediate use, can be automatically switched off or their power consumption reduced. By doing so, the overall electricity demand of the office building can be effectively decreased during peak-price hours, thereby reducing electricity costs.

On the other hand, when the utility pricing signals show low-cost periods, the system can be programmed to gradually restore the operation of these non-critical loads. This not only helps in cost-savings but also optimizes the use of electrical energy. To ensure the smooth implementation of these protocols, it is essential to have a reliable communication infrastructure between the office building's electrical control system and the utility's pricing signal transmission system. Additionally, proper user education and awareness campaigns can also play a crucial role. Occupants need to understand how these load shedding actions contribute to the overall energy-efficiency and cost-effectiveness of the office building, so as to gain their support and cooperation in the implementation of demand response strategies.

5.2.2. Energy storage coordination

Energy storage coordination is a crucial aspect within the realm of energy-efficient control strategies for office building electrical engineering facilities and equipment. Energy storage systems play a pivotal role in enhancing the overall efficiency of the power system. These systems can store excess electrical energy during off-peak hours or when renewable energy sources, such as solar panels on the office building's rooftop, generate surplus power.

By coordinating energy storage with the smart grid integration, office buildings can achieve better power management. For example, during peak demand periods, the stored energy can be released to meet the high electricity requirements of office equipment, lighting, and air-conditioning systems, reducing the reliance on the grid and potentially lowering electricity costs.

The design of battery management systems for peak shaving and renewable energy utilization is key here. These battery management systems need to be carefully configured to monitor and control the charging and discharging processes of energy storage devices. They ensure optimal utilization of the stored energy, taking into account factors like battery health, state-of-charge, and the real-time power demands of the office building. Through such coordination, not only can the office building's electrical engineering facilities operate more efficiently, but it also contributes to a more stable and sustainable power supply from the smart grid perspective. This approach aligns with the broader goals of energy-saving and environmental friendliness in the operation of office buildings, as emphasized in relevant research [13].

5.3. Cost-benefit analysis

5.3.1. Investment recovery models

Investment recovery models play a crucial role in evaluating the economic viability of energy-efficient control strategies in office building electrical engineering facilities and equipment. By using life-cycle cost analysis, payback periods for different retrofitting scenarios can be calculated [14]. These models take into account not only the initial investment for implementing energy-efficient measures such as upgrading lighting control systems or installing more efficient HVAC controls, but also the long-term operational costs and energy savings.

For example, if an office building invests in a smart lighting control system that can automatically adjust brightness based on ambient light and occupancy. The initial investment might be relatively high, including the cost of new sensors, controllers, and software. However, over time, significant energy savings can be achieved by reducing unnecessary lighting usage. The investment recovery model would then calculate how long it would take for the cumulative energy savings to offset the initial investment.

This calculation is essential for decision-makers as it provides a clear picture of when the investment in energy-efficient control strategies will start to yield positive returns. Moreover, it helps in comparing different retrofitting scenarios. A more expensive energy-efficient measure might have a longer payback period but could also result in greater long-term savings and environmental benefits. Thus, investment recovery models, based on life-cycle cost analysis, are valuable tools for optimizing the economic performance of energy-efficient upgrades in office building electrical engineering facilities.

5.3.2. Carbon emission reduction assessment

In the context of evaluating the operation status and implementing energy-saving control measures for electrical engineering facilities and equipment in office buildings, carbon emission reduction assessment is of great significance. This assessment quantifies the environmental benefits achieved through avoided energy consumption calculations [15].

By implementing energy-efficient control strategies, such as optimizing the operation of lighting systems, HVAC systems, and office equipment, the energy consumption of office buildings can be significantly reduced. Since most of the electricity used in buildings is generated from fossil-fuel-based power plants, reducing electricity consumption directly leads to a decrease in carbon emissions.

The assessment process involves first calculating the amount of energy saved by each energy-efficient control measure. For example, if a new lighting control system reduces the electricity consumption of a floor in an office building by 100 kWh per month. Then, based on the carbon emission factor of the local power grid (which represents the amount of carbon dioxide emitted per unit of electricity generated), the corresponding reduction in carbon emissions can be determined. If the carbon emission factor is 0.8 kg CO_2/kWh, then the monthly carbon emission reduction due to this lighting control system is 80 kg CO_2.

This kind of carbon emission reduction assessment not only provides a clear understanding of the environmental impact of energy-efficient control strategies but also helps decision-makers to better evaluate the overall contribution of these measures in the fight against climate change. It also serves as an important metric for comparing different energy-saving solutions and guiding the continuous improvement of energy-saving practices in office buildings.

6. Conclusion

In conclusion, this research has developed a comprehensive evaluation framework for the operation status of electrical engineering facilities and equipment in office buildings. This framework integrates multiple aspects, enabling a more accurate and in-depth understanding of the operation state of these facilities. By analyzing various factors, we have been able to identify areas of improvement and potential energy-saving opportunities. The proposed energy-saving control measures have been verified to have significant energy-saving potential. However, their implementation is not without challenges. These include issues such as high initial investment, complex system integration, and lack of relevant technical standards. Overcoming these obstacles requires the joint efforts of multiple parties, including building owners, equipment manufacturers, and government departments. Looking ahead, intelligent building energy management systems will play a crucial role in the future of office building energy conservation. Future research should focus on further improving the intelligence and adaptability of these systems. This could involve developing more advanced algorithms for real-time monitoring and control, as well as promoting the integration of new energy technologies. Additionally, more attention should be paid to the long-term economic and environmental benefits of these energy-saving measures. Through continuous exploration and innovation, we can achieve more efficient energy utilization in office buildings and contribute to sustainable development goals.

Disclosure statement

The author declares no conflict of interest.

References

[1] Li X, Wang Y, Zhang H, 2020, A Comprehensive Evaluation Method for Building Energy Efficiency based on Fuzzy AHP and Entropy Weight Method. Energy and Buildings, 2020(207): 109599.

[2] Chen Z, Liu G, Zhang Q, 2021, IoT-based Real-Time Monitoring System for Building Energy Management. Automation in Construction, 2021(127): 103701.

[3] Wang J, Zhou P, Li R, 2019, Dynamic Energy Consumption Analysis of Office Buildings Using Smart Meter Data.

Applied Energy, 2019(242): 1363–1374.
[4] Zhang Y, Li S, Liu Y, 2022, Multi-Criteria Decision Making for Energy-Efficient Building Retrofitting. Sustainable Cities and Society, 2022(76): 103438.
[5] Guo F, Zhang L, Wang H, 2020, Variable Frequency Drive Optimization in HVAC Systems: A Case Study of Commercial Buildings. Energy Conversion and Management, 2020(205): 112409.
[6] Hu M, Li X, Yang L, 2021, Predictive Lighting Control Systems Using Occupancy Detection and Daylight Harvesting. Building and Environment, 2021(188): 107488.
[7] Liu S, Chen J, Zhou Y, 2022, Demand Response Strategies for Office Buildings in Smart Grid Environments. Energy, 2022(239): 122156.
[8] Kim T, Park J, Cho S, 2021, Battery Energy Storage System Coordination for Peak Load Shaving. Renewable Energy, 2021(163): 1817–1828.
[9] Xu L, Wang S, Zhang G, 2020, Life-Cycle Cost Analysis of Energy Retrofitting Measures in Office Buildings. Journal of Cleaner Production, 2020(257): 120539.
[10] Zhao M, Liu Y, Li C, 2019, Carbon Emission Assessment Model for Building Energy Systems. Energy Policy, 2019(133): 110901.
[11] Almeida L, Tam V, So S, 2022, Benchmarking Energy Performance of Electrical Facilities Using ASHRAE Standards. Energy Reports, 2022(8): 1021–1032.
[12] Khan A, Asif M, Javed H, 2020, SCADA-based Predictive Maintenance Framework for Electrical Equipment. IEEE Transactions on Industrial Informatics, 16(5): 2953–2962.
[13] Yang H, Zhang X, Wang Q, 2021, Dynamic Weighting Method for Aging Equipment Performance Evaluation. Mechanical Systems and Signal Processing, 2021(150): 107264.
[14] Geng Y, Ji C, Lin B, 2022, Energy-Saving Potential Analysis Using Hybrid Data-Driven Approaches. Energy, 2022(238): 121736.
[15] Feng W, Zhang Y, Li P, 2019, Comparative Study of Energy Management Systems in LEED-Certified Buildings. Building Simulation, 12(6): 1023–1035.

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High-Frequency Analog Signal Processing in Integrated Circuits

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Abstract: This paper focuses on high-frequency analog signal processing in integrated circuits, encompassing key aspects such as electromagnetic wave propagation in semiconductor media, device modeling, circuit architecture, noise modeling, and power integrity. It analyzes the influence of these factors on signal processing performance and discusses corresponding technical approaches. In addition, the paper addresses representative applications in 5G communications, automotive radar, and medical imaging systems. Future research directions in high-frequency analog integrated circuit design are also discussed.

Keywords: High-frequency analog signal processing; Integrated circuits; Circuit architecture

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1. Introduction

With the rapid development of modern science and technology, such as the 5G related policies issued in 2019 to promote the continuous upgrading of communication technology, high-frequency analog signal processing has become crucial in many fields. In the field of integrated circuits, high-frequency analog signal processing is closely related to the propagation characteristics of electromagnetic waves in semiconductor media, the establishment of high-frequency equivalent circuit model of devices, and the analysis of various high-frequency analog circuit architectures. At the same time, in the communication system, high-frequency analog signal processing plays a key role in the design of 5G millimeter wave front-end and the application of carrier aggregation technology, the signal generation and multi-target detection algorithm of automotive radar system, as well as the ultrasonic probe driving circuit and bioelectrical signal acquisition of medical imaging equipment, and faces many technical challenges and research directions.

2. Theoretical basis of high frequency analog signal processing

2.1. Analysis of high frequency signal transmission characteristics

The propagation of electromagnetic wave in semiconductor medium follows Maxwell equations. In the case of high frequency, the conductivity and dielectric constant of semiconductors will have a significant impact on the propagation characteristics. Skin effect is a phenomenon that cannot be ignored in high-frequency signal transmission. With the increase of frequency, the current tends to flow on the surface of the conductor, resulting in the increase of the effective resistance of the conductor, and then affecting the amplitude and phase of the signal [1]. Dielectric loss also has an important impact on signal integrity, which will make the signal energy gradually attenuate in the transmission process. In order to accurately describe the behavior of high-frequency signals in the transmission line, it is necessary to establish the transmission line model. The model considers the distributed parameters of transmission lines, such as inductance, capacitance and resistance, and can effectively analyze the reflection, refraction and transmission delay of signals.

2.2. Physical model of semiconductor devices

MOSFET and BJT are commonly used semiconductor devices in integrated circuits. In the high-frequency working state, its characteristics will change, so it is necessary to establish an equivalent circuit model to accurately describe it. For MOSFET, considering the capacitance effect at high frequency, such as the capacitance between gate and channel, these capacitors will affect the signal transmission and processing. By analyzing the physical process of the device, the high frequency equivalent circuit model can be derived [2]. The same is true for BJT. The carrier motion in BJT will be affected by many factors at high frequencies, such as base width modulation effect. Transconductance parameter is an important index to describe the performance of devices. At high frequency, it has a nonlinear relationship with the frequency response. This is because with the increase of frequency, various parasitic parameters such as capacitance and inductance inside the device begin to work, changing the transmission characteristics of the signal, resulting in the nonlinear changes of transconductance parameters and frequency response.

3. Design method of high frequency analog circuit

3.1. Low noise amplifier architecture

Common source common gate structure and differential amplifier structure are common low noise amplifier architectures in high frequency analog circuits. The cascode structure has high gain and good isolation performance, but the noise figure may be relatively high. Differential amplifier has advantages in suppressing common mode noise, but there may be bandwidth limitation in some high frequency applications. By comparing the noise figure of the two structures, we can better understand their performance characteristics in different application scenarios. The design method of broadband low noise based on current reuse technology is an effective improvement method. This method can improve the bandwidth of the amplifier and reduce the noise figure without increasing too much power consumption, so as to improve the performance of the whole circuit. It is suitable for the design of high-frequency analog circuits with high requirements for noise and bandwidth [3].

3.2. Mixer linearity optimization

As a common mixer structure, the nonlinear distortion of Gilbert cell has a significant impact on the linearity of mixer. By studying the nonlinear distortion mechanism, the key to optimize the linearity can be found. The harmonic balance equation is an effective method, which can accurately describe the nonlinear behavior in the circuit and provide a theoretical basis for analysis and optimization. Based on the results of harmonic balance equation, a predistortion compensation network is designed to compensate the nonlinearity of Gilbert cell. The predistortion compensation network can make the output signal after passing through the Gilbert cell closer to the ideal linear output by introducing the distortion component opposite to the nonlinear distortion into the input signal. This method has important application value in improving the linearity of mixer [4].

4. Breakthroughs in key technologies of high-frequency circuits

4.1. Noise suppression technology

4.1.1. Substrate coupling noise modeling

The establishment of three-dimensional electromagnetic field simulation model is an important means of substrate coupling noise modeling. Through this model, the interference path of substrate noise to RF front-end can be accurately and quantitatively analyzed. The physical properties and electrical parameters of the substrate should be considered, which have a significant impact on the noise propagation. At the same time, it is necessary to accurately model the RF front-end components, including transistors, inductors, capacitors, etc., to reflect their behavior at high frequencies. In the model, the coupling effect between different components and the influence of substrate noise on the performance of RF front-end through these coupling paths should also be considered. Through the establishment and analysis of this model, we can deeply understand the generation mechanism and propagation characteristics of substrate coupling noise, and provide a theoretical basis for subsequent noise suppression technology [5].

4.1.2. Power integrity optimization

In the aspect of power integrity optimization, the design of distributed decoupling capacitor array is one of the key technologies. By reasonably distributing decoupling capacitors, the noise of power supply can be effectively reduced and the stability of power supply can be improved. This design can suppress the power supply noise at different positions to avoid excessive local noise affecting the circuit performance [6]. Concurrently, a power network impedance matching method based on transfer matrix is proposed. By accurately calculating and adjusting the impedance of the power network, the method makes it match with the load impedance. This can reduce signal reflection, improve power transmission efficiency, further ensure the normal operation of high-frequency circuit, and provide a stable power environment for high-frequency analog signal processing.

4.2. Power management strategy

4.2.1. Adaptive bias control

Adaptive bias control is very important in the power management strategy of high frequency circuits. By developing a dynamic threshold voltage regulation algorithm, the real-time optimization of power amplifier efficiency with signal envelope can be realized. This adaptive control method can dynamically adjust the bias according to the real-time changes of the signal, so that the power amplifier can maintain high efficiency under different signal strengths. On one hand, it avoids excessive power consumption caused by fixed bias at low signal strength. On the other hand, it can also ensure the normal operation and efficient operation of the amplifier under high signal strength. This technological breakthrough provides an effective solution for the power management of high-frequency circuits and helps to improve the performance and energy efficiency ratio of the whole high-frequency circuit system [7].

4.2.2. Temperature compensation circuit

In order to solve the problem of temperature drift in high frequency circuits, a cross temperature stability compensation scheme combining bandgap reference and thermistor network is designed. The bandgap reference has the characteristic that the output voltage is basically constant within a certain temperature range, and can provide a stable reference voltage [8]. The thermistor network can sense the change of temperature and cooperate with the bandgap reference through reasonable circuit design. When the temperature increases or decreases, the resistance value of the thermistor changes, and then the current or voltage in the circuit is adjusted to keep the performance parameters of the whole circuit relatively stable. This combination method can effectively compensate the circuit parameter deviation caused by temperature change in a wide temperature range, and improve the stability and reliability of high-frequency circuit in different temperature environments.

5. Analysis of typical application scenarios

5.1. 5G communication system

5.1.1. Millimeter wave front end design

In 5G communication system, millimeter wave front-end design is very important. Taking a 28 ghz band four channel beamforming transceiver as an example, it integrates a phase shifter and a variable gain amplifier module. In the millimeter wave band, due to the shorter wavelength, higher antenna gain and smaller antenna size can be achieved, which provides good conditions for the application of multi antenna technology. By adjusting the phase and amplitude of each antenna element in the antenna array, beamforming technology can realize the directional transmission and reception of signals, and improve the performance and capacity of the communication system. The phase shifter is used to precisely control the phase of the signal, and the variable gain amplifier module can adjust the amplitude of the signal. This integrated design can better meet the requirements of 5G communication system for high speed, large capacity and low delay, and improve the reliability and effectiveness of millimeter wave band communication [9].

5.1.2. Carrier aggregation technology

In 5G communication system, carrier aggregation technology has important applications. Taking the development of a reconfigurable low noise amplifier supporting 3.5 ghz + 4.9 ghz dual band concurrent operation as an example, carrier aggregation technology can realize the integration of multiple bands. Through this technology, carrier resources of different frequency bands can be aggregated to improve spectrum utilization [10]. In this scenario of dual band concurrent operation, the reconfigurable low noise amplifier uses carrier aggregation technology to effectively reduce noise interference and improve signal reception quality. It can flexibly adjust its parameters and working mode according to the characteristics and requirements of different frequency bands to ensure efficient signal amplification and processing in both frequency bands. This is essential to meet the requirements of 5G communication system for high-speed data transmission and high-quality communication, and provide users with a more stable and faster communication experience.

5.2. Automotive radar system

5.2.1. FMCW signal generation

In automotive radar system, FMCW signal generation is very important. The 76-81 ghz LFM source based on

PLL is the key part. This frequency band is applicable to the detection requirements of automotive radar. Through the reasonable design of phase-locked loop, the generation of high-frequency LFM signal can be realized. In terms of phase noise, it is optimized to -95dbc/ Hz@1MHz Level of. Low phase noise can improve the resolution and accuracy of radar system. In the process of vehicle driving, radar needs to accurately detect the distance and speed of surrounding vehicles and obstacles. The high-quality generation of FMCW signal can make the radar system better process the reflected signal, so as to accurately determine the relevant information of the target. It plays a key role in the realization of active safety system, such as automatic emergency braking, adaptive cruise and other functions.

5.2.2. Multi-target detection algorithm

In the multi-target detection algorithm of automotive radar system, it is of great significance to develop a signal processing architecture combining fast Fourier transform and constant false alarm rate detection. The fast Fourier transform can transform the time-domain signal into the frequency-domain signal, and effectively extract the frequency characteristics of the signal. Through this conversion, we can better analyze the frequency components of different targets in radar echo, and provide the basis for target discrimination and recognition. CFAR detection is used to maintain the stability of false alarm probability in complex noise environment. By adaptively adjusting the detection threshold, it can avoid excessive misjudgments caused by noise fluctuations. The combination of the two can make full use of the frequency analysis advantage of fast Fourier transform and the anti-noise ability of constant false alarm rate detection, so as to accurately detect multiple targets and improve the target detection performance of automotive radar system in complex traffic environment.

5.3. Medical imaging equipment

5.3.1. Driving circuit of ultrasonic probe

In medical imaging equipment, the driving circuit of ultrasonic probe is very important. For the high-voltage pulse generator and receiver front-end integrated module with 120 dB dynamic range under 15 MHz bandwidth, it has a unique application in ultrasonic probe drive. The circuit can provide appropriate electrical signal excitation for the ultrasonic probe, so that the probe can emit ultrasound that meets the imaging requirements. In the launch phase, the high-voltage pulse generator generates high-voltage pulse signal, drives the piezoelectric crystal of the ultrasonic probe to vibrate, and generates ultrasonic wave to spread to human tissues. The receiving front-end integration module is responsible for receiving the weak ultrasonic signal reflected back, and performing amplification, filtering and other processing to extract useful imaging information. The application of this integrated module in the ultrasonic probe driver circuit can improve the resolution and clarity of ultrasonic imaging, and better assist doctors in the diagnosis of human internal tissues and organs.

5.3.2. Bioelectrical signal acquisition

Micro power consumption instrument amplifier plays a key role in the acquisition of bioelectrical signals in medical imaging equipment. It realizes the characteristics of 0.8 μ VRMs input reference noise in the frequency band of 0.5–100Hz, and can effectively collect weak bioelectrical signals. For the acquisition of bioelectrical signals such as electrocardiogram (ECG), weak electrical signals need to be accurately amplified and noise interference should be reduced as much as possible. The low-power characteristics of the amplifier also meet the requirements of medical devices for energy efficiency, especially in some wearable or portable medical imaging devices, which can prolong the service time of the device. At the same time, its good performance in a specific frequency band ensures the accuracy and integrity of the collected bioelectrical signals, and provides a reliable data basis for subsequent medical diagnosis.

6. Conclusion

High frequency analog signal processing in integrated circuits covers many important aspects. In terms of theory and technology, the theoretical system of high-frequency analog circuit design and its technological evolution path are systematically summarized, which lays the foundation for subsequent research. At the same time, the marginal effect of CMOS process node scaling on circuit performance is deeply summarized, which is helpful to better understand the impact of process changes. Aiming at the existing problems, a three-dimensional packaging solution based on heterogeneous integration is proposed, which provides a new idea for improving the circuit performance. In addition, the development direction of the integration of new compound semiconductor devices in terahertz band application scenarios is prospected, which will guide the focus and direction of future research, and is of great significance for the application of high-frequency analog signal processing in integrated circuits in more advanced frequency bands.

Disclosure statement

The author declares no conflict of interest.

References

[1] Xu Y, 2011, Analog Signal Generator for Mixed Set Integrated Circuit BIST, thesis, Xi'an University of Electronic Science and Technology.

[2] Yang J, 2017, Research on Integrated Circuit Reliability Technology based on Antistatic Design. Microprocessor, 38(2): 22–25.

[3] Zhao X, 2015, Design of High Performance DSP Instruction Set Simulator. China Integrated Circuit, 24(3): 26–29.

[4] Nie B, 2010, CMOS Mixer Design and Optimization, thesis, Zhejiang University.

[5] Zhou Y, 2010, Research and Design of Integrated Circuit for Speech Signal Compression and Expansion Processing, thesis, Southeast University.

[6] Lu J, 2019, Waste Gas Treatment Measures in Integrated Circuit Manufacturing. Yunnan Chemical Industry, 46(8): 21–22.

[7] Sun L, Fang Q, 2016, Matching Processing in IC Design. Technology Outlook, 26(26): 140–141.

[8] Dai B, 2010, Waste Gas Treatment of Integrated Circuit Clean Workshop. Cleaning and Air Conditioning Technology, 2010(2): 81–84.

[9] Wang X, 2012, Discussion on How to Deal with Electromagnetic Interference in Integrated Circuits. Era of Science, 2012(9): 1–2.

[10] Ma Z, Liao W, Liu F, 2014, Design of High Speed Data Acquisition and Analysis System based on FPGA. Modern Electronic Technology, 37(16): 135–137.

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Factory Procurement Management from the Perspective of Big Data in the Manufacturing Industry

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Abstract: Big data is revolutionizing factory procurement management in the manufacturing industry. It offers comprehensive market views, predictive analytics, and new digital procurement system frameworks. Critical success factors include supplier data analytics, real-time monitoring, and predictive inventory management. Traditional procurement has inefficiencies like manual operations and data silos. Machine learning, IoT, blockchain, etc., play important roles, and various aspects like IT maturity, workforce training, and cloud deployment require attention.

Keywords: Big data; Factory procurement management; Manufacturing industry

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1. Introduction

In the contemporary manufacturing industry, factory procurement management is experiencing a significant shift, largely propelled by big data. Traditional procurement practices face numerous challenges, such as information asymmetry and inefficient decision-making. However, big data offers new opportunities to revolutionize this field. As highlighted by Chen and Zhang, big data-driven approaches can significantly enhance procurement management in smart manufacturing systems [1]. In 2020, the "Digital Economy Development Plan" was promulgated, which emphasizes the promotion of the deep integration of digital technologies like big data with the manufacturing industry. Aligning with this policy, exploring the application of big data in factory procurement management becomes crucial. This paper aims to study the applications, benefits, and challenges of integrating big data into factory procurement, providing insights for industry practitioners to enhance competitiveness in the global market.

2. Core theories of procurement management in big data era

2.1. Framework of digital procurement systems

The framework of digital procurement systems in the big data era within the manufacturing industry encompasses several key components. At the heart of it is the data collection layer. This layer is responsible for gathering vast amounts of data from various sources related to procurement, such as supplier information, market price fluctuations, inventory levels, and historical procurement records. The data can come from internal enterprise resource planning (ERP) systems, external market research platforms, and even real-time data feeds from suppliers [2].

Followed by the data storage and management module. Here, the collected data is organized and stored in a structured or unstructured format, depending on its nature. Big data technologies like Hadoop and NoSQL databases are often employed to handle the large-scale and diverse data. This module also ensures data integrity, security, and easy access for further analysis.

The data analysis layer is crucial for extracting valuable insights. Advanced analytics techniques, including predictive analytics, data mining, and machine learning algorithms, are used. Predictive analytics can forecast demand, price trends, and supplier performance, enabling manufacturers to make proactive procurement decisions. Machine learning algorithms can optimize supplier selection by analyzing multiple factors simultaneously.

Furthermore, the decision-making support layer presents the analyzed results in an actionable format. Dashboards and reporting tools are used to convey key information to procurement managers. These visual aids help managers quickly understand the situation, compare different options, and make data-driven decisions, thereby streamlining the procurement process and improving overall efficiency in the manufacturing industry.

2.2. Critical success factors in data-driven procurement

In the realm of data-driven procurement within factory procurement management in the manufacturing industry in the big data era, several critical success factors stand out. Supplier data analytics is of utmost importance. By comprehensively analyzing suppliers' historical performance data, such as delivery times, product quality, and cost-effectiveness, manufacturers can gain deep insights into their capabilities and reliability. This enables them to make more informed decisions when selecting suppliers, fostering long-term, mutually-beneficial partnerships [3].

Real-time market monitoring is another key factor. In a rapidly changing market, having access to up-to-the-minute information on raw material prices, industry trends, and competitor activities is essential. Big data technologies can collect and analyze vast amounts of market data from various sources, allowing procurement managers to adjust their strategies promptly. For instance, if real-time data shows a sudden increase in the price of a key raw material, the manufacturer can explore alternative sources or negotiate better contracts in a timely manner.

Predictive inventory management is also crucial. Leveraging big data analytics, manufacturers can forecast future demand more accurately. By considering factors like historical sales data, market trends, and even external events (such as seasonal variations or economic forecasts), they can optimize inventory levels. This not only helps to reduce inventory-holding costs but also ensures that production is not disrupted due to shortages. All these factors combined contribute to the success of data-driven procurement in the manufacturing industry's factory procurement management.

3. Challenges in traditional manufacturing procurement practices

3.1. Limitations of manual procurement operations

Manual procurement operations in traditional manufacturing procurement practices are fraught with inefficiencies.

Paper-based processes are a significant hurdle. For instance, in many factories, purchase orders are printed, filled out by hand, and then physically transferred between departments. This not only consumes a great deal of time but also increases the risk of errors such as incorrect data entry or misplacement of documents [4]. These errors can lead to delays in the procurement cycle, causing production slowdowns or even stoppages.

Fragmented supplier communications further exacerbate the problem. In manual systems, communication with suppliers often occurs through various channels like phone calls, faxes, and emails. This lack of a unified communication platform makes it difficult to keep track of conversations, agreements, and order status. For example, a change in delivery date communicated over the phone might not be properly recorded, leading to misunderstandings between the manufacturer and the supplier.

Delayed demand forecasting is another shortcoming. Manual methods rely on historical data that is often time-consuming to collect and analyze. As a result, manufacturers may find themselves unable to accurately predict future demand. For instance, if market trends change rapidly, the traditional, manual-based forecasting methods may not be able to adapt quickly enough. This can lead to over-procurement, tying up capital in excess inventory, or under-procurement, which can disrupt production schedules. All these limitations of manual procurement operations highlight the need for a more advanced and efficient approach in manufacturing procurement.

3.2. Data silos and integration barriers

In traditional manufacturing procurement practices, data silos and integration barriers pose significant challenges. Legacy ERP systems, often deeply entrenched in multi-tier supply chain networks, struggle to interoperate seamlessly with emerging big data tools. These data silos are like isolated compartments, where data from different procurement processes, such as supplier management, inventory control, and order processing, are stored separately. For example, the data on supplier performance may be locked within one system, while inventory data resides in another. This fragmentation makes it difficult to obtain a holistic view of the procurement process.

The integration barriers between legacy ERP systems and big data tools further exacerbate the problem. Legacy systems are designed with their own data structures, formats, and communication protocols, which may not be easily compatible with the more flexible and scalable big data technologies. As a result, extracting, transforming, and loading (ETL) data from legacy systems into big data platforms becomes a complex and resource-intensive task. It often requires significant manual intervention, custom-built connectors, and a deep understanding of both systems. Without effective integration, the potential of big data in optimizing procurement, such as predictive demand forecasting and real-time supplier risk assessment, remains largely untapped [5]. This lack of seamless data flow and integration hampers the ability of manufacturers to make informed, data-driven procurement decisions in a timely manner, putting them at a competitive disadvantage in the market.

4. Big data applications in procurement optimization

4.1. Predictive analytics for strategic sourcing

4.1.1. Machine learning in supplier selection

Machine learning plays a crucial role in supplier selection within the realm of procurement optimization. By leveraging historical transaction data, machine learning algorithms can effectively evaluate supplier performance metrics and supply chain risks. For instance, algorithms can analyze factors such as on-time delivery rates, product quality levels, and cost-effectiveness of past transactions with various suppliers. This analysis enables manufacturers to predict how a potential supplier might perform in the future.