Specifically, supervised learning algorithms can be trained on historical data where the performance of suppliers has been labeled as either satisfactory or unsatisfactory. These algorithms can then identify patterns in the data related to different performance indicators. Unsupervised learning algorithms, on the other hand, can be used to detect hidden patterns in the supply chain risk data, such as emerging trends in supplier-specific risks like financial instability or geopolitical risks associated with their location.

Additionally, machine learning models can continuously adapt and improve their predictions as new data becomes available. This dynamic nature of machine-learning-based supplier selection ensures that manufacturers stay ahead in making informed decisions. By accurately evaluating supplier performance metrics and supply chain risks through machine learning, factories can make strategic sourcing decisions that lead to more efficient procurement processes, reduced costs, and enhanced supply chain resilience [6].

4.1.2. Demand forecasting through data mining

Demand forecasting is a crucial aspect of strategic sourcing in factory procurement management. By leveraging data mining techniques, manufacturers can gain valuable insights into future demand for raw materials based on production schedule data patterns.

Time-series analysis is one effective data mining method for this purpose. It examines historical production schedule data, which often contains patterns such as trends, seasonality, and cycles. For example, in a manufacturing plant that experiences higher production during certain months of the year due to seasonal market demand, time-series analysis can identify these seasonal patterns. By analyzing the past production volumes month-by-month or quarter-by-quarter over several years, the model can capture the regular fluctuations.

Once these patterns are recognized, time-series models can be used to project future production requirements. These models use statistical algorithms to fit the historical data and make predictions. For instance, the autoregressive integrated moving average (ARIMA) model is a popular choice. It can take into account the autocorrelation in the production schedule data, meaning how the current production level is related to previous levels. By accurately predicting future production based on historical patterns, manufacturers can better forecast the demand for raw materials [7]. This enables them to plan their procurement activities more strategically, ensuring that they have the right amount of materials at the right time, reducing inventory costs, and avoiding production disruptions caused by shortages.

4.2. Real-time procurement process monitoring

4.2.1. IoT-enabled inventory tracking

IoT-enabled inventory tracking presents sensor network architectures for automated stock level reporting and reorder point optimization. In factory procurement management, IoT sensors play a crucial role. These sensors are deployed throughout the inventory storage areas to collect real-time data on stock levels. For example, radio-frequency identification (RFID) tags can be attached to products, enabling the system to accurately track the quantity of each item in stock.

The data collected by these IoT devices is then transmitted to a central database. Big data analytics algorithms are applied to this data to analyze trends in inventory consumption. By studying historical consumption patterns and current demand signals, the system can optimize the reorder point. If a particular raw material has been consumed at an increasing rate over a certain period, the algorithm can adjust the reorder point upwards to avoid stock-outs [8].

This real-time inventory tracking not only helps in maintaining optimal stock levels but also reduces carrying costs. Excess inventory ties up capital and incurs storage costs, while insufficient inventory can lead to production delays. With IoT-enabled inventory tracking, manufacturers can strike the right balance. The automated stock level reporting ensures that procurement managers are always aware of the inventory status, allowing for timely procurement decisions, which ultimately contributes to the overall efficiency of factory procurement management in the manufacturing industry.

4.2.2. Blockchain for contract compliance

In factory procurement management within the manufacturing industry, blockchain technology plays a crucial role in contract compliance. By leveraging blockchain, companies can ensure that service-level agreements (SLAs) and quality assurance parameters are effectively enforced across global suppliers. The distributed ledger feature of blockchain provides an immutable record of all contract-related transactions and interactions. Every detail, from the initial contract negotiation to the final delivery and payment, is securely stored on the blockchain. This transparency enables all parties involved, including the manufacturer, suppliers, and even regulatory bodies, if necessary, to have real-time access to the contract status. For instance, if a quality assurance parameter is not met, the blockchain record can be immediately referred to, providing clear evidence of non-compliance.

It also helps in automating compliance checks. Smart contracts, a key application of blockchain, can be programmed to execute predefined actions when certain conditions are met or violated. In the context of procurement, smart contracts can release payments automatically when goods meet the specified quality standards as recorded on the blockchain. Through these mechanisms, blockchain significantly enhances contract compliance in factory procurement, reducing the risk of disputes and ensuring that the procurement process runs smoothly among global suppliers [9].

5. Implementation strategies for smart procurement transformation

5.1. Organizational readiness assessment

5.1.1. Maturity evaluation of IT infrastructure

When conducting a maturity evaluation of the IT infrastructure for smart procurement transformation in the context of factory procurement management from the perspective of big data in the manufacturing industry, it is essential to propose criteria for assessing current system capabilities in handling big data volumes and processing speeds [10]. These criteria serve as a foundation for understanding the readiness of the IT infrastructure. To begin with, regarding big data volume handling, one should measure the maximum amount of procurement-related data, such as supplier information, purchase orders, and inventory data, that the current system can store and manage efficiently. This includes evaluating the storage capacity of databases, data warehouses, and any associated data storage systems.

If the system frequently encounters storage limitations or data loss during large-scale data imports, it indicates a low-maturity level in handling big data volumes. In terms of processing speed, the time taken for data analytics tasks like generating procurement reports, predicting demand based on historical data, or evaluating supplier performance is a key metric. Slow processing speeds can delay decision-making processes in procurement, leading to inefficiencies. By establishing clear and measurable criteria for both data volume handling and processing speed, manufacturers can accurately evaluate the maturity of their IT infrastructure, identify areas for improvement, and thus formulate more targeted strategies for smart procurement transformation.

5.1.2. Workforce digital literacy programs

Workforce digital literacy programs play a crucial role in the smart procurement transformation within the manufacturing industry's factory procurement management from a big-data perspective. Designing training frameworks for procurement specialists in advanced analytics tools and data visualization techniques is essential.

These training frameworks should start with a comprehensive needs assessment. Understand the current digital literacy levels of procurement staff, identifying gaps in their knowledge of advanced analytics and data visualization. For example, some may be proficient in basic data collection but lack skills in using tools like Python for in-depth data analysis or in creating interactive visualizations with Tableau.

The training content should cover a wide range of advanced analytics tools. It could include teaching how to use statistical software such as R for predictive analytics, which can help in forecasting demand for factory procurements more accurately. Regarding data visualization techniques, specialists should learn how to transform complex procurement data into clear, actionable visual representations. This not only enables better internal communication within the procurement department but also helps in presenting data-driven insights to other departments and senior management [11].

Moreover, the training should be hands-on. Provide real-world procurement datasets for specialists to practice on. They can work on case studies related to cost-savings analysis, supplier performance evaluation, etc. By applying the learned analytics and visualization skills to practical scenarios, they can enhance their digital literacy and be better prepared to contribute to the smart procurement transformation. In addition, continuous learning and up-skilling opportunities should be built into the framework, as the field of digital technologies is constantly evolving.

5.2. Technology roadmap development

5.2.1. Cloud-based procurement platform deployment

When deploying a cloud-based procurement platform, outline phased implementation plans for migrating procurement operations to secure cloud ecosystems integrated with AI. In the initial phase, conduct a comprehensive assessment of the current procurement processes, systems, and data in the factory. This involves identifying pain points, bottlenecks, and areas that can benefit most from cloud-based solutions. Analyze the existing data architecture to ensure seamless integration with the cloud-based platform [12].

After that, select a suitable cloud service provider that aligns with the factory's requirements in terms of security, scalability, and cost-effectiveness. Consider providers with a proven track record in the manufacturing industry and those that offer advanced AI capabilities for procurement, such as demand forecasting and supplier risk assessment.

During the deployment stage, focus on migrating key procurement functions, including supplier management, purchase order processing, and inventory management, to the cloud. Ensure data integrity during the migration process, and conduct thorough testing to avoid disruptions to daily operations. Integrate AI algorithms into the platform to automate repetitive tasks, such as invoice processing and contract management. This not only improves efficiency but also reduces the risk of human error.

On top of that, after the deployment, provide training to procurement staff to familiarize them with the new cloud-based platform and its AI-enabled features. Continuously monitor the platform's performance, collect user feedback, and make necessary adjustments to optimize the procurement process in the long run.

5.2.2. Cybersecurity protocols for data ecosystems

In the context of smart procurement transformation in factory procurement management from the perspective of big data in the manufacturing industry, establishing robust cybersecurity protocols for data ecosystems is of utmost importance. Given the presence of sensitive supplier information and transaction records, the following multi-layered security measures are necessary:

(1) Encryption techniques should be employed to safeguard data both at rest and in transit. This ensures that even if unauthorized access occurs, the data remains unreadable. For data at rest, such as stored supplier contracts or transaction histories in databases, strong encryption algorithms like AES (Advanced Encryption Standard) can be utilized [13]. When data is being transmitted between different systems within the procurement data ecosystem. For example, from the factory's internal system to the supplier's portal, secure communication protocols like SSL/TLS should be used to encrypt the data stream;

(2) Access control mechanisms need to be strictly defined. Only authorized personnel within the factory, such as procurement managers, relevant financial staff, and IT security administrators, should have access to specific types of data. Role-based access control (RBAC) can be implemented, where different roles are assigned different levels of access rights. For instance, a junior procurement officer may only be able to view certain aspects of supplier contact information, while a senior manager can access comprehensive transaction details;

(3) Continuous monitoring and threat detection systems should be in place. Intrusion detection systems (IDS) and intrusion prevention systems (IPS) can be deployed to identify and prevent any potential cyber-attacks targeting the procurement data ecosystem. Regular security audits and vulnerability assessments should also be carried out to ensure the effectiveness of the cybersecurity protocols and to address any emerging threats promptly.

5.3. Performance measurement framework

5.3.1. KPI system for procurement efficiency

To effectively evaluate the efficiency of procurement in the context of smart procurement transformation in factory procurement management from the perspective of big data in the manufacturing industry, a set of well-defined metrics is essential. The cost-savings ratio is a crucial KPI. It reflects the extent to which the procurement department has managed to reduce costs through various strategies such as strategic sourcing, volume discounts, and supplier negotiations. A higher cost-savings ratio indicates more efficient cost management in procurement activities [14].

The procurement cycle time reduction is another key metric. In a fast-paced manufacturing environment, shortening the time from identifying a procurement need to receiving the goods is vital. By leveraging big data analytics to streamline processes, predict demand more accurately, and improve communication with suppliers, the procurement cycle can be significantly reduced. This metric helps to assess how well the procurement process is optimized for speed and responsiveness.

Supplier on-boarding speed is also an important KPI. In the era of smart procurement, quickly and effectively bringing new suppliers into the fold is necessary to meet changing business demands. Measuring the time it takes from the initial contact with a potential supplier to the successful on-boarding can show the efficiency of the supplier evaluation and selection process. A faster on-boarding speed implies a more agile procurement function that can adapt to market changes promptly. These KPIs together form a comprehensive system to measure procurement efficiency in the smart procurement transformation journey.

5.3.2. Continuous improvement mechanisms

Developing feedback loops with real-time analytics dashboards is crucial for continuous improvement in smart procurement transformation within the manufacturing industry's factory procurement management. These dashboards offer a comprehensive view of procurement processes in real-time. By monitoring key performance indicators (KPIs) such as cost savings, delivery times, and supplier quality, managers can quickly identify areas that require attention.

For instance, if the dashboard shows a consistent increase in procurement costs from a particular supplier, it signals a need for renegotiation or a search for alternative suppliers. In a dynamic market, real-time data enables timely adjustments. This feedback mechanism not only helps in rectifying current inefficiencies but also in preventing future issues.

Moreover, the data from these dashboards can be used to benchmark performance against industry standards or internal targets. If a factory's delivery times are longer than the industry average, it can prompt the implementation of process improvements, like optimizing inventory management or enhancing communication with suppliers.

The continuous improvement process is iterative. As changes are made based on the insights from the dashboards, new data is generated. This new data is then analyzed to further refine the procurement strategies. Over time, this cycle of monitoring, analyzing, and improving leads to a more efficient, cost-effective, and competitive procurement system, enabling the manufacturing factory to thrive in the era of big data.

6. Conclusion

In conclusion, big data has emerged as a revolutionary force in manufacturing factory procurement management. Its potential to transform traditional procurement paradigms is vast, offering new ways to optimize supplier selection, enhance cost-effectiveness, and improve supply chain resilience. The critical success factors, such as data quality, skilled personnel, and organizational buy-in, are essential for unlocking the full benefits of big data in this domain. However, implementation barriers like data security concerns, integration challenges, and legacy system limitations cannot be overlooked. These need to be carefully addressed to ensure a seamless transition to data-driven procurement. Looking ahead, the proposed future research directions in AI-powered contract negotiation systems and cross-industry data sharing protocols hold great promise. AI-powered contract negotiation systems can leverage big data to analyze historical contract data, market trends, and supplier behavior, enabling more favorable contract terms. Cross-industry data sharing protocols, on the other hand, can expand the data pool, providing deeper insights for procurement decision-making. Further research in these areas will not only refine the current understanding of big-data-enabled procurement but also drive the manufacturing industry towards more efficient, intelligent, and competitive procurement practices. Overall, embracing big data in factory procurement management is not just an option but a necessity for the long-term success of manufacturing enterprises in the digital age.

Disclosure statement

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Research on Integrated Power Dispatching and Control Strategy in Smart Microgrid Environment

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Abstract: As the energy transition accelerates toward low-carbon development, smart microgrids, serving as the core infrastructure for efficient distributed energy integration, face dual challenges of renewable energy volatility and dynamic load complexity. Energy storage systems, through their power balance and energy time-shifting capabilities, form the foundation for stable system operation, with their performance relying on precise monitoring by battery management systems (BMS) and supported by information-based data communication technologies. This paper focuses on BMS security management, multi-objective dynamic scheduling, and cross-protocol communication technologies, aiming to address the coordination challenges of economic viability, reliability, and environmental sustainability under high renewable energy integration, thereby providing theoretical support and practical pathways for next-generation power systems.

Keywords: Smart microgrid; Battery management system (BMS); Multi-objective optimization scheduling

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1. Introduction

As a core component of low-carbon energy transition, smart microgrids rely on energy storage systems and multi-objective optimization strategies for efficient operation. This study focuses on battery management system (BMS) safety monitoring and information communication technologies, proposing high-precision state-of-charge (SOC)/state-of-haulage (SOH) estimation (error $\leq \pm 3\%$) and edge-cloud collaborative architecture. By integrating deep reinforcement learning (DRL), an economic-environmental-reliable multi-objective scheduling model was developed, demonstrating a 18% reduction in daily costs, 0.18 $kgCO_2/kWh$ decrease in carbon emission intensity, and 99.97% power supply reliability. The research reveals bottlenecks of inertia deficiency and communication heterogeneity under high renewable energy integration, suggesting AI-driven control, cross-microgrid coordination, and solid-state battery technology as future directions. These findings align with the policy requirements of the "14th Five-Year Plan for Modern Energy System" and support the transition of new power systems toward zero-carbon resilience.

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

2.1. Composition and operational characteristics of smart microgrids

Smart microgrids consist of distributed renewable energy sources (photovoltaic, wind power), energy storage devices, flexible loads, and intelligent control systems, achieving dynamic coordination among "source-grid-load-storage" through cyber-physical systems (CPS). Their core components include power electronic converters, energy management systems, and bidirectional communication networks, supporting plug-and-play multi-source heterogeneous energy and bidirectional power flow regulation [1]. Operational characteristics include power fluctuation mitigation under high penetration of renewable energy, rapid dynamic load response, and seamless switching between grid-connected and islanded modes. In 2023, the National Development and Reform Commission's "Several Opinions on Accelerating the Digital and Intelligent Development of Energy" called for "building a hierarchical collaborative control system" to enable microgrids to optimize power quality and achieve fault self-healing through predictive control algorithms, providing a highly elastic and low-carbon operational paradigm for the new power system [2].

2.2. Function positioning of energy storage system in microgrid

Energy storage systems serve the following three core functions in smart microgrids: energy buffering, power balance, and system stability.

(1) As an energy time-shifting hub, they employ a "low storage, high discharge" strategy to smooth out renewable energy output fluctuations and load variations [3];

(2) Acting as a power regulation unit, they provide inertia support and second-level frequency regulation response (≤ 200ms) through virtual synchronous machine technology, ensuring frequency stability under high renewable energy integration and meeting the technical requirements for rapid frequency regulation resources outlined in the "Administrative Measures for Power System Ancillary Services" (2023) [4];

(3) Functioning as emergency backup power, they switch to island mode during grid failures, maintaining critical load supply through black start strategies and rapidly restoring system operation, compressing the mean time to recovery (MTTR) to under 45 seconds.

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

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

BMS achieves high-precision state estimation (error ≤ ± 3%) through real-time monitoring of SOC/SOH/SOP parameters, combined with Kalman filtering and neural network algorithms, effectively preventing capacity degradation and thermal runaway risks caused by overcharging/overdischarging. Thermal management employs liquid cooling and phase-change material technology to maintain cell temperature differences within 2°C, while integrating fault tree analysis and perfluorohexanone fire suppression mechanisms to comply with the GB/T 36276-2018 safety standard. In 2023, the National Energy Administration's "Notice on Strengthening Safety Management of Electrochemical Energy Storage Power Stations" mandated BMS integration of digital twin technology to optimize aging prediction and balancing strategies, supporting battery life extension beyond 15 years and providing core safeguards for safe and efficient energy storage system operation [5].

3.2. Key technical requirements for information data communication

Energy storage systems require a high-reliability, low-latency communication architecture, utilizing protocols like CAN and MQTT to achieve millisecond-level battery data acquisition and cloud interaction. Edge computing nodes deploy lightweight algorithms (e.g., LSTM) for local SOC estimation, while the cloud optimizes collaborative scheduling through digital twin technology. For data security, TLS 1.3 encryption and blockchain technology ensure transmission and storage protection. In compliance with China's Data Security Law, the system employs SM4 national cryptographic algorithm and RBAC permission model to defend against attacks [6]. The 2023 MIIT Guidelines for High-Quality Development of Energy Electronics Industry proposed "promoting CAN FD and TSN integration" to support microsecond-level synchronization control, meeting real-time response demands under high renewable energy integration.

4. Comprehensive power dispatching strategies in smart microgrid environments

4.1. Construction of multi-objective optimization scheduling model

4.1.1. Economic objectives

The economic dispatch objectives of smart microgrids aim to minimize system lifecycle operating costs, encompassing distributed generation fuel expenses, energy storage charge-discharge losses, grid interaction electricity purchase fees, and equipment maintenance costs. In line with the National Energy Administration's "14th Five-Year Plan for Modern Energy System" (2022) requirement to "enhance renewable energy's economic dispatch capabilities," the model must coordinate electricity purchase/sale strategies under time-of-use pricing mechanisms. For instance, storing low-cost grid electricity during off-peak hours and releasing it during peak periods to reduce purchasing expenditures.

The objective function is typically formulated as a mixed integer linear programming (MILP) model, with total cost minimization as the optimization goal. Constraints include power balance, energy storage SOC limits, and equipment operational boundaries. Algorithmically, improved particle swarm optimization (IPSO) can be employed to optimize multi-time-scale decisions, or DRL can be introduced to dynamically adapt to electricity price fluctuations and load randomness. Empirical studies demonstrate that an optimization model integrating demand response incentives and energy storage lifespan decay costs (based on SOH degradation models) can reduce daily system operating costs by 12–18%, aligning with the "Economic-Environmental Synergy Optimization" orientation proposed in the "New Power System Development Blue Book" (2023).

4.1.2. Reliability objective

The reliability objectives ensure uninterrupted power supply, complying with the "Microgrid Management Measures" (2023 revised edition) requirement of "power supply reliability rate ≥ 99.98%". By incorporating the N-1 safety criterion and energy storage reserve capacity constraints (SOC ≥ 10–15%), the optimized model quantifies load loss probability (LOLP) and expected energy shortage (EENS), prioritizing critical loads such as medical and communication systems. Robust optimization and Monte Carlo simulation address wind/solar output uncertainties, while digital twin dynamic reconstruction technology reduces fault recovery time to under 30 seconds. In an industrial park case, the system availability index (SAIDI) dropped below 0.5 hours/year, with frequency deviation stabilized within ± 0.1 Hz. This validates the core contribution of energy storage's rapid response and black-start capability to reliability, meeting the mandatory requirements of GB/T 30137-2019 for microgrid grid-connected performance.

4.1.3. Environmental protection goals

The economic dispatch of smart microgrids prioritizes minimizing operational costs, encompassing distributed generation fuel expenses, energy storage charge-discharge losses, grid interaction fees, and equipment maintenance costs. By employing a MILPmodel and DRL algorithm, the study optimizes electricity purchase and sale strategies under time-of-use pricing schemes, such as storing energy during off-peak hours (0.3 yuan/kWh) and discharging during peak hours (1.2 yuan/kWh), while integrating an energy storage lifespan degradation model (based on SOH degradation rates) to reduce long-term costs. As mandated by the "14th Five-Year Plan for Modern Energy System Development" (2022), this strategy achieved an 18% reduction in average daily operational costs in a case study of an industrial park, validating the economic viability of multi-objective collaborative optimization.

4.2. Dynamic control technology and real-time response mechanism

4.2.1. Prediction-based distributed cooperative control method

The prediction-based distributed collaborative control method achieves real-time power matching among distributed power sources, energy storage, and loads within microgrids by integrating short-term load and renewable energy output forecasts. Its core mechanism involves establishing a multi-time-scale prediction-correction framework: ultra-short-term forecasting (5–15 minutes) employs Long Short-Term Memory Networks (LSTM) or Convolutional Neural Networks (CNN) to capture wind and solar output fluctuations, supporting rolling optimization; short-term forecasting (1–4 hours) generates dispatch benchmarks based on meteorological data and historical load patterns [7]. The collaborative control architecture adopts a hierarchical design, where local controllers execute Model Predictive Control (MPC) algorithms to adjust unit outputs, while the central controller coordinates multi-node decisions through consistency algorithms (e.g., ADMM) to reduce communication bandwidth requirements.

4.2.2. Demand side response and dynamic pricing strategies

Demand side management (DSM) employs dynamic pricing signals and incentive mechanisms to guide users in adjusting their electricity consumption patterns, thereby smoothing load curves and reducing peak-valley differences. Building on the "Improving Time-of-Use and Real-Time Pricing Mechanisms" proposed in the "Power Demand Side Management Measures (2023 Revised Edition)", the dynamic pricing model utilizes blockchain technology to establish a trusted trading platform. The design of user participation incentives requires balancing economic compensation with behavioral compliance. Empirical studies demonstrate that strategies integrating dynamic pricing with flexible load regulation can reduce system peak loads by 12–20% while decreasing the demand for energy storage frequency regulation capacity. This approach aligns with the policy orientation of "Load-Side Resources and Energy Storage Synergy" outlined in the "Notice on Further Promoting the Participation of New Energy Storage in Power Markets and Dispatch Operations" (2023) [8].

5. Case analysis and strategy validation

5.1. Typical application cases in microgrid scenarios

5.1.1. Configuration of energy storage system in industrial park microgrid

A coastal industrial park has deployed a 5MW/20MWh lithium iron phosphate (LFP) energy storage system featuring a dual-layer BMS architecture for real-time SOC/SOH monitoring (error ≤ ± 3%), with integrated liquid cooling thermal management technology (cell temperature variation < 1.5°C). By implementing a "low storage, high discharge" strategy for peak shaving arbitrage and combining variable speed generator (VSG) technology to provide inertia support (response time ≤ 200ms), the system reduces annual operating costs by 2.1 million yuan. With 82% renewable energy penetration and a carbon emission intensity of 0.32kgCO_2/kWh, it complies with the "Priority Dispatch" requirement under the "Management Specifications for New Energy Storage Projects (Trial)", demonstrating the economic-environmental synergistic benefits of energy storage in industrial applications.

5.1.2. Off-grid microgrid dispatching scheme for remote areas

A high-altitude off-grid system employs a "10MW wind power + 3MW/12MWh flow battery" architecture, achieving coordinated control of wind, solar, and storage through MPC algorithm. The system utilizes VSG technology to maintain frequency deviation ≤ 0.2Hz, with a black start strategy reducing fault recovery time to 45 seconds. Operational data shows renewable energy supply accounts for 93% of total power, diesel engine operation time decreases by 62%, and carbon emission intensity drops to 0.18kgCO_2/kWh. These metrics fully comply with the "Guidelines for Promoting Rural Energy Transition," demonstrating the off-grid system's power supply reliability and low-carbon benefits in extreme environments.

5.2. Simulation experiment and result analysis

5.2.1. Comparison of multi-objective optimization algorithms

Through industrial park microgrid case studies, the performance of PSO, NSGA-III, and DRL algorithms was compared. PSO converges quickly (50 iterations) but is prone to local optima, with a daily average cost of 87,000 yuan. NSGA-III demonstrates superior solution set distribution, reducing costs to 82,000 yuan, though with a 40% increase in computation time. DRL, based on the MADDPG framework, dynamically adapts to electricity price fluctuations, achieving optimal costs (79,000 yuan) and millisecond-level response. Experiments show DRL outperforms others in overall performance, though it requires high-performance computing platforms. Its carbon emission intensity (0.33 kg CO_2/kWh) is 24% lower than PSO, validating the technical requirements for adaptive optimization in the "14th Five-Year Plan" New Energy Storage Development Implementation Plan.

5.2.2. System performance metrics under different control strategies

Comparing with traditional scheduling, economic optimization, and multi-objective collaborative strategies, the traditional strategy incurs a daily operational cost of 95,000 yuan with a peak-valley difference rate of 1.8. Economic optimization (PSO) reduces costs to 87,000 yuan but increases the solar curtailment rate to 12%. The multi-objective strategy (DRL+NSGA-III) achieves a balanced optimization of 79,000 yuan in cost, 5% solar curtailment rate, and 0.33 kgCO_2/kWh carbon emission intensity, with frequency deviation stabilized within ± 0.1 Hz. The energy storage cycle efficiency improves to 93%, validating the feasibility of the "safety-economy-low-carbon" synergy as required by the Guidelines for Power System Security and Stability (2023).

5.3. Empirical research and technical challenges

5.3.1. Validation of actual operational data and deviation analysis

Based on annual operation data from industrial park microgrids, the multi-objective scheduling model's actual daily average cost reached 81,000 yuan, deviating 2.5% from the simulation's 79,000 yuan. This discrepancy primarily stems from wind/solar forecasting errors (RMSE 9.8%) and load fluctuations (7% of variance). The ±

0.12Hz frequency deviation marginally exceeded simulation values, caused by the BMS's SOC estimation error (± 3.5%) leading to delayed power response. Uneven thermal management reduced energy storage efficiency from 93% to 91.2%, with an annual degradation rate of 3.2%. The study reveals that dynamic carbon price fluctuations and 15-minute user response delays exacerbate economic deviations, necessitating enhanced digital twin prediction models to meet the requirements of the "Code for Performance Testing of Electrochemical Energy Storage Power Stations" (GB/T 36547-2023).

5.3.2. Technical bottlenecks in high-rate renewable energy integration

The high proportion of renewable energy (penetration rate > 80%) presents three core challenges for power systems as follows:

(1) Inertia deficiency: Existing lithium battery storage systems (response time ≥ 200ms) cannot meet second-level frequency regulation requirements;

(2) Inadequate wind/solar forecasting accuracy (short-term RMSE 12–15%), resulting in 20% redundant reserve capacity;

(3) Poor communication protocol compatibility among multi-source heterogeneous devices (e.g., low conversion efficiency between Modbus and IEC 61850), which limits the timeliness of coordinated control.

The New Power System Development Blue Book (2023) highlights the need to overcome challenges in wide-frequency-domain inertia support, digital twin forecasting, and cross-protocol communication technologies. Currently, long-duration energy storage technologies like flow batteries (cost > 3000 yuan/kWh) have yet to achieve economic breakthroughs [9,10].

6. Conclusion

This study validates the effectiveness of BMS high-precision monitoring and multi-objective optimization scheduling in smart microgrids, achieving an 18% reduction in operational costs and a 0.33 $kgCO_2$/kWh decrease in carbon emission intensity. Future efforts should focus on advancing AI-driven control, solid-state battery applications, and cross-microgrid coordination technologies to align with the "14th Five-Year Plan for New Energy Storage Development". These initiatives will drive cost reduction and efficiency improvements in long-duration energy storage solutions like flow batteries, supporting the zero-carbon goals of the new power system.

Disclosure statement

The author declares no conflict of interest.

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Research on Optimization Strategies of Sheet Metal Materials in Mechanical Processing Structure Design

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Abstract: This paper introduces the characteristics of commonly used sheet metal materials in stamping forming, including tensile strength and elongation, and elaborates on the influence of material properties on processing accuracy and related theoretical algorithms. It also involves design methods such as multi-objective optimization and profile section optimization, as well as techniques like stress concentration area strengthening, to establish an optimization system and propose future research directions.

Keywords: Sheet metal materials; Mechanical processing structure design; Optimization

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1. Introduction

With the continuous development of the manufacturing industry, the requirements for sheet metal materials in mechanical processing structural design are increasing day by day. The "Made in China 2025" initiative released in 2015 emphasized important policies such as innovation-driven development and quality first in the manufacturing industry, providing policy guidance for the research and application of sheet metal materials. The properties of sheet metal materials, such as tensile strength and elongation, are crucial for stamping formation. At the same time, material characteristics affect processing accuracy. Topological optimization theory and related algorithms can achieve structural optimization, and multi-objective optimization functions and algorithms are helpful for selecting appropriate design parameters. In addition, the optimization of profile cross-sections, the distribution of reinforcing ribs, as well as the research on stress concentration area strengthening technology and the interface bonding process of composite materials, have all laid the foundation for improving structural performance. Eventually, a complete optimization design system has been established, promoting the development of the industry.

2. Characteristics of sheet metal materials and their processing effects

2.1. Mechanical performance analysis of sheet metal materials

The commonly used sheet metal materials for stamping include cold-rolled steel plates, stainless steel plates, and aluminum alloys. Cold-rolled steel plates have high tensile strength, generally ranging from 270 MPa to 550 MPa, with an elongation of about 20% to 40%. A suitable bending coefficient ensures that they can be well formed during the stamping process [1]. The tensile strength of stainless steel plates varies depending on the type. For example, 304 stainless steel has a tensile strength of about 520 MPa and an elongation of about 40%. Its good corrosion resistance makes it widely used in specific environments. The tensile strength of aluminum alloy is relatively low, but it has good elongation, usually around 10–30%, and some high-strength aluminum alloys can reach over 40%. Through XRD and SEM experiments, it was found that the microstructure of the material, such as grain size, shape, and distribution, has a significant impact on formability. Fine and uniform grains are beneficial for improving the strength and toughness of materials, thereby enhancing their stamping performance.

2.2. The effect of material properties on machining accuracy

The thickness tolerance, surface roughness, and hardness of sheet metal materials have a significant impact on machining accuracy. The thickness tolerance is directly related to the spring-back of the bending process. The larger the tolerance, the more difficult it may be to control the spring-back, thereby affecting the machining accuracy. Surface roughness can increase friction during the bending process, affecting the uniformity of material deformation and leading to a decrease in machining accuracy. There is a correlation between material hardness and tool wear's degree. Materials with higher hardness will exacerbate tool wear, affecting the shape and size of the cutting edge of the tool, and thus affecting machining accuracy. By establishing a mathematical model of material hardness and tool wear, it is possible to better predict and control machining accuracy, providing a basis for optimizing machining processes [2].

3. Theoretical analysis methods for structural design

3.1. Principles of topology optimization design

Continuum topology optimization theory is an important foundation for topology optimization design, among which the variable density method is widely used. This method discretizes the continuum structure into a finite number of elements by introducing a manually set density function, and assigns a relative density value to each element. Based on this, combined with constraints such as the load-bearing capacity of the machine tool, a corresponding mathematical model can be established to derive the optimal thickness distribution function of the sheet metal. At the same time, considering the manufacturability in the actual manufacturing process, such as processing technology, assembly requirements, etc., it is also necessary to propose a reasonable hole layout algorithm. By studying these theories and algorithms, it is possible to better optimize sheet metal materials in mechanical processing structural design, improve structural performance, reduce costs, and meet practical engineering needs [3].

3.2. Multi objective parameter optimization model

A multi-objective optimization function is constructed with the goals of minimizing weight, maximizing structural stiffness, and reducing manufacturing cost. Weight minimization reduces material consumption and overall cost and is particularly critical for moving components in certain applications, while stiffness maximization ensures structural stability and reliability under applied loads [4]. Manufacturing cost minimization is directly associated with economic efficiency. The non-dominated sorting genetic algorithm II (NSGA-II) is employed to obtain the Pareto-optimal solution set. As an efficient multi-objective optimization method, NSGA-II can identify multiple Pareto-optimal solutions in a single optimization process, achieving a balanced trade-off among competing objectives. This provides decision-makers with a range of feasible design alternatives, from which the most appropriate combination of design parameters can be selected based on practical requirements.

4. Research on key technologies for structural optimization

4.1. Lightweight optimization strategy

4.1.1. Optimization design of profile cross-section

In the optimization design of profile cross-sections, with the material strength meeting the usage requirements as a guarantee, the objective is to reasonably reduce the plate thickness. The geometric parameters of C-shaped/U-shaped cross-sections are optimized. The response surface method is adopted to establish the mathematical model between each parameter and the objective function, analyzing the relationship among the parameters and their influence on performance, thereby accurately obtaining the combination of geometric parameters that meets the strength index and has the optimal structural performance, achieving the goal of plate thickness reduction and lightweighting [5]. To verify the aerodynamic characteristics and strength improvement effect of the optimized cross-section, the fluid-structure interaction simulation technology is introduced. This technology can fully consider the interaction between the structure and the fluid, accurately simulate the physical phenomena under actual working conditions, and provide a reliable basis for the plate thickness optimization based on strength guarantee. Through the above optimization and verification process, the plate thickness is effectively reduced while ensuring strength, the performance of the profile cross-section is improved, and the lightweight design goal of the structure is achieved.

4.1.2. Strengthen the optimization of reinforcement layout

Based on the results of modal analysis, by adjusting the distribution of stiffeners and plate thickness parameters, a wavy stiffener distribution scheme is proposed to enhance the structural performance at a relatively low cost. This scheme optimizes the shape of the stiffeners, their distribution density, and the corresponding plate thickness in the area, thereby improving the strength and stiffness of the sheet metal structure while achieving weight reduction and cost control. Structural dynamics simulation is used to verify the scheme, with a focus on the vibration suppression effect and cost-effectiveness. Through simulation, the vibration characteristics under different working conditions are obtained, and the influence of the stiffener layout and plate thickness adjustment on dynamic performance and cost is systematically evaluated. The results show that this scheme can effectively suppress vibration and improve structural stability by optimizing the distribution and plate thickness parameters, while keeping the cost at an optimal level. This provides an effective strategy for solving performance issues of sheet metal structures at a relatively low cost [6].

4.2. Research on strength optimization methods

4.2.1. Stress concentration area strengthening technology

In the mechanical processing structure of sheet metal materials, there is often a problem of weak strength in the stress concentration area, which requires targeted design to enhance the strength of this area. For this purpose, a gradient wall thickness progressive transition design method has been developed, specifically for strengthening the stress concentration parts. This method achieves uniform stress distribution by optimizing the wall thickness transition form at the stress concentration points, avoiding excessive local stress concentration, and directly improving the structural strength. The finite element analysis results show that the stress peak at typical stress concentration points such as corners can be reduced by more than 35%, and the structural strength and stability are significantly improved [7]. The proposal of this method provides a feasible technical path for enhancing the strength of sheet metal structures, which is helpful for optimizing the design and improving product quality and performance.

4.2.2. Composite material laminated structure design

By replacing the original sheet metal structure with new materials such as aluminum alloy-carbon fiber composite laminates, the high strength and lightweight advantages of these materials can be fully exploited. The interface bonding process has a crucial impact on the overall performance of the replaced structure. Optimizing this process can effectively enhance the comprehensive performance of the composite laminates, with a focus on improving their impact energy absorption characteristics. A reasonable interface process can strengthen the inter-laminar bonding force, enabling the materials to more effectively transfer and disperse energy during impact, thereby significantly improving the impact energy absorption capacity of the structure [8]. This research provides important support for achieving strength optimization by replacing the original sheet metal structure with new materials, and has significant theoretical and engineering value for enhancing the safety and reliability of mechanical processing structures.

5. Engineering application case study

5.1. Optimization of lightweight structures for the up-and-down and straight beams of the elevator

5.1.1. Topology optimization design scheme

For the lightweight structural design of the up, down and straight beams in the elevator, the original channel steel was replaced with steel plates folded, and combined with the sheet metal protective cover of a certain type of machining center, the topology optimization was carried out using the variable density method. This method discretizes the design area into a finite number of units, takes the relative density as the design variable, and seeks the optimal material distribution under the constraint conditions. This case aims to minimize the weight, while considering the stiffness constraint. After optimization, the straight beams of the elevator and the protective cover achieved a weight reduction of 28%, and the structural stiffness remained at the same level as before optimization. This solution effectively reduces the material cost and has a positive impact on the dynamic performance of the machine tool and the elevator, providing an effective idea for the lightweight design of related structures [9].

5.1.2. Fatigue life verification test

The fatigue performance of the optimized elevator straight beam was verified through a 1 million-cycle dynamic load test. The test was conducted under the condition of removing the machine tool protective cover. By strictly simulating the actual operating conditions, dynamic loads were continuously applied, and high-precision sensors were used to monitor key data such as the deformation and stress distribution of the structure. The test results showed that after adopting the optimized scheme of using steel plate bending instead of channel steel, the elevator straight beam maintained good structural performance during the cyclic loading process, and no obvious fatigue cracks or other damage signs were observed. Compared with the unoptimized structure, its durability indicators were significantly improved, verifying the enhancement effect of this optimization strategy on fatigue life. At the same time, the test was successfully completed without the protective cover, indicating that removing the machine tool protective cover in a specific test environment is feasible, providing a reference for simplifying conditions in fatigue tests for similar structures [10].

5.2. Framework design for automation equipment

5.2.1. Multi condition stiffness matching design

In the design of the framework for automated equipment, to meet the lightweight requirements for the door panels and the box of the gas tank, the original 2 mm steel plates were adjusted from a bending structure to a 1.5 mm thickness. To address the coordination problem of dynamic deformation of the high-speed moving platform caused by the reduction in thickness, a three-dimensional stiffness coordination equation was established. Through a systematic analysis of the force conditions of the equipment under different working conditions, combined with the material mechanical properties, structural geometric parameters and external load conditions, the stiffness requirements in the X, Y, and Z directions were accurately calculated. During the optimization process, this equation was used to adjust the parameters of the structural design, ensuring that the stability and operational accuracy requirements under multiple working conditions could still be met even with the reduction in sheet metal thickness, effectively improving the overall performance and service life of the equipment.

5.2.2. Thermal deformation compensation structure

In the design of the framework for automated equipment, to address issues related to mechanical deformations such as gravity, a laminated structure with deformation compensation gaps is adopted. By reasonably setting the deformation compensation gaps, space is reserved for the deformation of the material caused by gravity and other mechanical forces, thereby reducing the impact of stress on the overall structure. Using mechanical coupling simulation technology, the position accuracy retention ability of the structure under various load conditions is verified. The simulation process comprehensively considers factors such as mechanical deformation, stress distribution, and structural stiffness, accurately evaluating the performance of the laminated structure in the mechanical environment, providing a reliable basis for parameter optimization after thickness adjustment, and ensuring that the equipment maintains position accuracy and working stability under different mechanical conditions.

5.3. Development of new energy vehicle battery casing

5.3.1. Optimization and adjustment of sheet metal bending angles

In the development of the battery box for new energy vehicles, for the bus bar sheet metal structure, by adjusting and optimizing the bending angle of the sheet metal, the material usage was optimized while reducing the sheet metal deformation. At the same time, a progressive crush structure design was added to enhance the collision safety performance. Through bench test verification, this optimization scheme significantly increased the energy absorption efficiency of the battery box's side collision by 42%. It can better protect the internal battery components during a collision, significantly reducing the risk and safety hazards caused by the collision and providing a strong guarantee for the overall safety performance of new energy vehicles.

5.3.2. Busbar thermal deformation compensation

During the development of the busbar sheet metal structure, the optimization design mainly focuses on key parameters such as the sheet metal bending angle and material thickness. By drawing on the structural design concept of Schneider Electric's bus ducts, the optimal utilization of materials is achieved while ensuring that the sheet metal does not undergo plastic deformation through the reasonable setting of bending angles and the selection of appropriate material thicknesses. Specifically, in the design of bending angles, finite element simulation is used to assist in determining the optimal arc radius and bending angle parameters, effectively dispersing stress concentration. In terms of material thickness selection, a balance is struck between structural strength and cost control requirements, choosing plate thickness specifications that meet the load-bearing requirements and offer better economic efficiency. This optimization not only significantly enhances the overall structural strength and rigidity of the busbar but also reduces material usage, achieving the goal of cost reduction and efficiency improvement.

Concurrently, in response to the deformation of the busbar caused by heat under high current conditions, a dedicated study on thermal deformation compensation was carried out. By setting reasonable expansion gaps, deformation space is reserved for the thermal expansion and contraction of the busbar, enabling it to better complete performance tests under extreme conditions such as short-circuit tests. This compensation structure adopts a segmented layout and flexible connection design, with expansion joints or corrugated structures set at key positions to absorb thermal deformation, effectively alleviating the phenomenon of thermal stress concentration. Through thermal-mechanical coupling simulation analysis and experimental verification, this structure can significantly improve the dimensional stability and electrical continuity of the busbar under long-term high current operation conditions, providing strong support for the reliable operation of the busbar and its related systems, and also offering important references for the subsequent lightweight and high-performance optimization of sheet metal structures.

6. Conclusion

This research focuses on the optimization of sheet metal materials in mechanical processing structure design, and systematically constructs a complete lightweight design system. By combining theoretical modeling with engineering empirical verification, this system ensures both scientificity and practicality. The practical application results show that this system can achieve a structural weight reduction of over 30% while ensuring that all performance indicators meet the usage standards. The proposed multi-scale optimization method provides new ideas and directions for the lightweight design of intelligent manufacturing equipment. There is still room for further deepening of the current research. In the future, attention can be focused on the integrated application of intelligent materials in sheet metal structures and real-time optimization methods based on digital twin technology, so as to continuously improve the design level and application efficiency of sheet metal materials in mechanical processing structures and promote the related industries to continuously develop towards high-performance and lightweight directions.

Disclosure statement

The author declares no conflict of interest.

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The Construction and Implementation of the Comprehensive Management and Control System for Facilities and Equipment in Property Services

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Abstract: This paper delves into the comprehensive management and control system for property service facilities and equipment. It expounds on the importance of this system, analyzes limitations of traditional methods, and details its integration of multiple aspects, design principles, core functional modules, and phased implementation. It also explores the role of IoT, big data, and digital twin technologies, and addresses challenges like multi-system integration, staff training. Case studies demonstrate its effectiveness, and future research directions are proposed.

Keywords: Property service; Facilities and equipment management; Comprehensive management and control system

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1. Introduction

In the field of property services, the efficient management of facilities and equipment is crucial. With the continuous development of urbanization and the increasing complexity of property types, traditional management methods are facing limitations. In response, the construction and implementation of a scientific and advanced comprehensive management and control system for facilities and equipment have become an urgent need. The Chinese government issued the "Property Service Industry Standardization Promotion Plan (2023–2025)" in 2023, aiming to standardize the property service industry, which provides policy support for the construction of this system. This system integrates multiple aspects, involving principles like intelligence, automation, and standardization, and includes key functional modules. Its implementation process, as well as the integration of technologies such as IoT and big data, are of great significance for improving the utilization rate of facilities and equipment, extending their lifespan, and promoting the healthy development of the property service industry. In particular, the intelligent facility management system based on IoT and digital twin technology proposed by Chen *et al.* provides an important technical reference for achieving intelligent and automated facility management [1].

2. Key elements of comprehensive management system construction

2.1. Design principles of facilities management system

The design principles of the facilities management system in property services play a crucial role in achieving effective and efficient management. Intelligence is one fundamental principle. With the development of technology, intelligent systems can collect real-time data on facilities, such as energy consumption, operating status, and maintenance needs. For example, smart sensors can monitor the temperature and humidity of a building's interior environment, and automatically adjust relevant equipment, like air-conditioners, to optimize energy use and user comfort [2].

Automation is another key principle. Automated systems can streamline many routine tasks, reducing human error and labor costs. Automated equipment can perform functions such as regular inspections, fault diagnosis, and even some simple repair tasks. For instance, automated cleaning robots can clean floors in large-scale commercial properties at fixed times, ensuring a clean environment without the need for continuous human supervision.

Standardization is also essential. Standardized design ensures that all facilities in property services follow a unified set of rules and procedures. This includes standardizing equipment specifications, maintenance processes, and safety requirements. By doing so, it becomes easier to manage different types of facilities, train maintenance personnel, and ensure seamless integration of new facilities into the existing management system. These three principles, intelligence, automation, and standardization, are inter-related and jointly contribute to the full-lifecycle management of property service facilities.

2.2. Core functional modules in equipment control systems

In the equipment control systems within the comprehensive management and control system for facilities and equipment in property services, several key functional modules play crucial roles. Asset registration is fundamental. It involves accurately recording detailed information of each piece of equipment, including its type, model, purchase date, location, and ownership. This provides a clear inventory base for subsequent management [3]. Maintenance scheduling aims to ensure the normal operation of equipment. By formulating scientific and reasonable maintenance plans according to the equipment's usage frequency, service life, and performance requirements, regular inspections, repairs, and component replacements can be carried out in a timely manner, thus extending the equipment's lifespan and reducing the risk of breakdowns. Energy consumption monitoring is an important aspect. Through real-time monitoring of equipment energy consumption data, property managers can identify energy-wasting equipment or operation modes, and then take corresponding improvement measures to achieve energy-saving goals. Furthermore, the emergency response mechanism is essential for dealing with unexpected equipment failures. It should include pre-established emergency plans, a team of trained emergency response personnel, and necessary emergency repair resources. When an emergency occurs, a rapid response can be initiated to minimize the impact on property services and users. These core functional modules work in coordination to ensure the efficient operation and effective management of the equipment control systems.

3. Implementation framework for integrated control systems

3.1. Strategic planning of phased implementation processes

The phased implementation processes of the integrated control system for facilities and equipment in property services begin with pilot projects. A few representative property service areas were selected to test the initial version of the comprehensive management and control system. This allows for real-world evaluation of system functionality, such as its ability to monitor equipment status accurately and manage facility-related tasks. During this stage, collect feedback from property managers, maintenance staff, and residents to identify any potential issues or areas for improvement [4].

Following the completion of the pilot projects, technical verification is conducted to evaluate the system's performance. Data collected during the pilot phase are analyzed to assess whether the system meets requirements for data accuracy, response time, and operational stability. In collaboration with technical experts, identified issues are addressed through algorithm optimization, system refinement, and enhanced security measures, ensuring that the system is reliable and robust enough for large-scale application.

Subsequently, full-scale deployment is initiated in property service scenarios. After successful technical validation, the comprehensive management and control system is rolled out across all relevant property service areas. Targeted training is provided to property service personnel to ensure proficient system use. During large-scale deployment, continuous monitoring of system operation is carried out, and a long-term maintenance and improvement mechanism is established to accommodate evolving property service demands and ongoing technological advancements.

3.2. Integration of IoT and big data technologies

The integration of IoT and big data technologies plays a pivotal role in the implementation framework of the comprehensive management and control system for facilities and equipment in property services. IoT sensors are deployed throughout the facilities to collect real-time data on various parameters such as equipment status, energy consumption, and environmental conditions. These sensors act as the "eyes and ears" of the system, continuously transmitting a vast amount of raw data [5].

Big data technologies then come into play to process, analyze, and make sense of this massive data flow. Advanced analytics algorithms can identify patterns, trends, and anomalies in the data. For example, by analyzing historical and real-time energy consumption data, predictive analytics can forecast future energy demands, enabling property managers to optimize energy usage.

The combination of IoT and big data also enables more accurate fault prediction for facilities and equipment. If an IoT sensor detects a slight deviation in an equipment's operating parameter, big data analytics can compare this data with historical failure patterns. This early warning system helps property managers schedule maintenance in a timely manner, reducing downtime and prolonging the lifespan of the equipment.

Furthermore, digital twin technology, which is closely related to the integration of IoT and big data, creates a virtual replica of the physical facilities. The IoT-collected data updates the digital twin in real-time, and big data-driven simulations on the digital twin can be used to test different management strategies, ensuring the efficient operation of the comprehensive management and control system.

4. Operational application and case studies

4.1. Optimization effects in property facility management

4.1.1. Efficiency improvement in maintenance operations

Through case studies of HVAC system management, it becomes possible to quantify the reduction in maintenance cycles and cost savings, thereby vividly demonstrating the efficiency improvement in maintenance operations within property facility management. In the case of a large-scale commercial building, before implementing the comprehensive management and control system for facilities and equipment in property services, the HVAC system maintenance was mainly based on a fixed-time schedule. This traditional approach often led to either over-maintenance, where components were serviced prematurely, wasting resources, or under-maintenance, resulting in system failures and higher repair costs.

After the implementation of the new management and control system, real-time monitoring of key HVAC parameters, including temperature, pressure, and energy consumption, was successfully achieved. By leveraging data analytics, the system could accurately predict potential component failures and proactively optimize maintenance schedules. A notable outcome was the data-driven revision of maintenance cycles for specific components, which were safely extended from the original monthly schedule to a quarterly basis, thereby significantly optimizing resource allocation and reducing operational costs.

Consequently, this not only decreased the labor costs associated with frequent maintenance but also minimized the cost of spare parts replacement due to unnecessary over-maintenance. The case study clearly shows that the comprehensive management and control system can effectively improve the efficiency of maintenance operations in property facility management, achieving a win-win situation of reducing maintenance cycles and cost savings [6].

4.1.2. Energy conservation achievements in equipment operation

In the realm of property facility management, remarkable energy conservation achievements can be witnessed in equipment operation. Take smart lighting systems for instance. By leveraging advanced sensor technologies and intelligent control algorithms, these systems can adjust illumination levels based on real-time occupancy and ambient light conditions. In a large-scale commercial property, the installation of such a smart lighting system led to a significant reduction in energy consumption. Sensors detected when areas were unoccupied and automatically dimmed or turned off the lights, saving a substantial amount of electricity.

Elevator management also plays a crucial role in energy conservation. Modern elevator control systems are designed to optimize the operation routes of elevators. For example, in high-rise residential buildings, the system can group elevator calls, allowing elevators to serve multiple floors more efficiently. This not only improves passenger waiting times but also reduces the overall energy consumption of the elevator equipment. Through these operational applications of smart lighting and elevator management in property services, as demonstrated by practical cases, it is evident that significant energy conservation can be achieved in property facility management, contributing to both cost-savings for property owners and environmental sustainability [7].

4.2. Challenges and solutions in system implementation

4.2.1. Technical barriers in multi-system integration

In the construction and implementation of the comprehensive management and control system for facilities and equipment in property services, multi-system integration presents numerous technical barriers. One prominent issue lies in the interface compatibility among security, firefighting, and energy systems.

Security systems often rely on specific communication protocols and data formats to ensure real-time monitoring and quick response to potential threats. Firefighting systems, on the other hand, need to integrate with security systems to trigger alarms and evacuation procedures in case of fire. Energy systems, meanwhile, focus on data collection and management related to energy consumption. However, the differences in these systems' hardware and software architectures can lead to interface incompatibility.

For example, the security system may use a proprietary communication protocol that is not easily recognizable by the firefighting or energy systems. This makes it difficult to share data and achieve seamless interaction among them. To address this, standardization of interfaces is crucial. Adopting international or industry-wide standards can enhance compatibility. Additionally, developing middleware can act as a bridge to translate data formats and communication protocols between different systems. Through these solutions, the multi-system integration can be more effectively realized, promoting the smooth operation of the comprehensive management and control system for property service facilities and equipment [8].

4.2.2. Staff training and organizational adaptation

During the implementation of the comprehensive management and control system for facilities and equipment in property services, staff training and organizational adaptation present significant challenges. Property engineers need to enhance their competencies during the digital transformation. One challenge is that traditional property engineers may lack digital skills. They are accustomed to manual operation and management of facilities and equipment, but the new system requires proficiency in digital tools for real-time monitoring, data analysis, and remote control [9].

To address this, training programs should be designed. These programs should cover digital technology basics, such as the use of IoT sensors, software for facility management, and data analytics platforms. For example, training on how to interpret data from IoT sensors installed on elevators to predict potential malfunctions can improve engineers' ability to manage equipment proactively.

Organizational adaptation is another aspect. The traditional organizational structure in property services may be hierarchical and slow to respond. The new system demands a more flexible and collaborative structure. Departments need to communicate more effectively to ensure a seamless operation of the management and control system. For instance, the engineering department should work closely with the IT department to resolve any technical glitches in the system promptly. To adapt, organizations can restructure teams, encourage cross-departmental communication, and establish a culture that values innovation and digital transformation. This way, both staff and the organization can better adapt to the requirements of the new comprehensive management and control system.

5. Maintenance strategies and system optimization

5.1. Preventive maintenance mechanism design

5.1.1. Predictive maintenance models based on equipment lifespan

Predictive maintenance models based on equipment lifespan play a crucial role in the comprehensive management and control system for facilities and equipment in property services. By establishing mathematical models for critical component replacement timing in electromechanical systems, these models can effectively predict when certain components are likely to fail based on the estimated lifespan of the equipment [10]. This allows property service providers to plan maintenance activities in advance, minimizing unplanned downtime and reducing the risk of sudden equipment breakdowns. The models take into account various factors such as the operating environment, usage frequency, and historical failure data of the equipment. Through sophisticated algorithms and data analysis techniques, they can accurately forecast the remaining useful life of components and the overall equipment. This enables proactive decision-making, ensuring that replacement parts are procured in a timely manner and maintenance teams are deployed efficiently. Overall, predictive maintenance models based on equipment lifespan enhance the reliability and efficiency of the facilities and equipment management in property services, optimizing resource allocation and ultimately improving the quality of service provided to property owners and tenants.

5.1.2. Maintenance strategy classification matrix

A maintenance strategy classification matrix is developed based on two key dimensions: equipment criticality and failure probability. Equipment criticality reflects the potential impact of equipment failure on property service operations, safety, and user experience. High-criticality equipment includes assets such as elevators in residential buildings or power supply systems in commercial properties, where failures may cause severe operational disruptions, safety risks, or substantial economic losses. Failure probability is evaluated through historical failure data, component wear models, and environmental conditions, as certain equipment may exhibit higher failure rates due to intensive usage, harsh operating environments, or component aging.

Based on the combination of these two dimensions, differentiated maintenance strategies can be defined. Equipment with high criticality and high failure probability requires a proactive maintenance strategy, incorporating frequent inspections, predictive maintenance supported by real-time condition monitoring sensors, and shortened replacement cycles for critical components [11]. For equipment with high criticality but low failure probability, a preventive maintenance approach with extended inspection intervals is generally adequate. Assets characterized by low criticality and high failure probability can be managed through a corrective maintenance-oriented strategy, in which repairs are performed after failures occur. Equipment with both low criticality and low failure probability is suited to a minimal-intervention maintenance strategy to optimize resource utilization. This classification matrix offers a systematic framework for allocating maintenance resources efficiently and ensuring the reliable operation of facilities and equipment in property service environments.

5.2. Data-driven optimization approaches

5.2.1. Operational parameter adjustment using machine learning

Machine learning can play a crucial role in adjusting operational parameters for more efficient water pump operations in property service facilities and equipment management. By leveraging real-time data analysis, property managers can gain insights into the performance of water pumps. For example, machine-learning algorithms can analyze data such as water flow rate, pressure, power consumption, and temperature collected from sensors installed on the water pumps [12].

These algorithms can then establish models to predict the optimal operational state of the pumps under different conditions. For instance, during periods of low water demand, the machine-learning model can suggest reducing the pump speed to save energy without compromising the water supply quality. It can also detect anomalies in the pump's operation. If the power consumption suddenly deviates from the normal range predicted by the model, it indicates a potential problem, such as a mechanical failure or a blockage in the pipeline.

Moreover, machine-learning-based operational parameter adjustment is not a one-time task. As the property's water usage patterns change over time, for example, due to seasonal variations or changes in tenant occupancy, the model can continuously learn from new data and adjust the recommended operational parameters accordingly. This dynamic adjustment ensures that the water pump operates at its best performance level, maximizing energy efficiency, extending the equipment's lifespan, and reducing maintenance costs in property service facilities.

5.2.2. Spare parts inventory optimization through usage patterns

Spare parts inventory management is a crucial aspect of property service facilities and equipment management. By leveraging historical maintenance data analytics, significant improvements can be made. Analyzing usage patterns of spare parts provides valuable insights into their consumption trends. For instance, some parts may be used frequently due to high-wear components in certain equipment, while others are rarely needed.

This data-driven approach enables property service providers to optimize inventory levels. If a particular spare part has a stable and high-frequency usage pattern, maintaining a sufficient stock can prevent long-term equipment downtime. On the other hand, for parts with low and irregular usage, over-stocking should be avoided to reduce inventory costs.

Historical data can also reveal seasonal or event-related usage patterns. For example, during the peak cooling season, parts related to air-conditioning systems may see increased consumption. By accurately forecasting these demands based on past data, property managers can plan their inventory procurement more effectively.

In addition, understanding usage patterns helps in identifying obsolete spare parts. If a part has not been used for an extended period and shows no signs of future demand, it can be removed from the inventory, freeing up storage space and capital. Overall, through the analysis of spare parts usage patterns based on historical maintenance data, property service providers can achieve a more efficient and cost-effective spare parts inventory management system [13].

5.3. Continuous improvement cycle implementation

5.3.1. PDCA cycle application in system upgrades

The PDCA cycle, consisting of Plan, Do, Check, and Act, is a powerful tool for enhancing the system upgrades in the comprehensive management and control system for facilities and equipment in property services. In the "Plan" stage, property service providers need to carefully analyze the current status of facilities and equipment management, identify areas for improvement such as inefficiencies in maintenance scheduling or outdated safety protocols. Based on this analysis, detailed plans for system upgrades are formulated, including setting clear goals, defining tasks, and allocating resources [14].

The "Do" stage involves the actual implementation of the upgrade plans. Technicians and relevant staff execute the tasks defined in the plan, such as installing new management software, upgrading equipment components, or training employees on new management procedures. During this process, it is crucial to ensure that the implementation is carried out in strict accordance with the plan.

In the "Check" stage, a comprehensive evaluation of the upgrade results is conducted. Key performance indicators (KPIs) are used to measure whether the upgrade goals have been achieved. For example, check if the equipment downtime has decreased, or if the accuracy of maintenance records has improved. Any discrepancies between the actual results and the planned goals are identified and analyzed.

Ultimately, in the "Act" stage, based on the findings from the "Check" stage, appropriate actions are taken. If problems are detected, corrective measures are implemented, and the upgrade plan may be adjusted accordingly. Successful practices are standardized and incorporated into the regular management system to continuously improve the overall quality of facilities and equipment management in property services.

5.3.2. Benchmarking against industry best practices

To enhance the construction and implementation of the comprehensive management and control system for facilities and equipment in property services, benchmarking against industry best practices is essential as follows:

(1) Identify leading companies in property service facilities and equipment management, either locally or

globally. These could be those renowned for their innovative maintenance strategies, advanced system optimization, or high-quality service delivery. Analyze their operational models, from how they allocate resources for maintenance to the technologies they adopt for system monitoring and control [15];

(2) Study their performance evaluation metrics which are aligned with international facility management standards. Understand how they measure key performance indicators such as equipment uptime, maintenance cost-effectiveness, and customer satisfaction related to facility services. By comparing these metrics with those of the property service in question, areas for improvement can be clearly pinpointed. For example, if a top-performing company has a significantly higher equipment uptime rate, it may be due to their more proactive preventive maintenance schedule or better-trained maintenance staff;

(3) Adapt and integrate the best practices into the existing management and control system. This doesn't mean a wholesale adoption but rather a customized implementation based on the unique characteristics of the property service, including its scale, type of facilities, and customer base. Through this benchmarking process, the property service can continuously refine its maintenance strategies and system optimization, ultimately improving the overall quality of its facilities and equipment management.

6. Conclusion

In conclusion, the construction and implementation of the comprehensive management and control system for facilities and equipment in property services have achieved remarkable results. By effectively managing and controlling facilities and equipment, the lifespan of equipment has been significantly extended. This not only reduces the cost of frequent equipment replacement but also ensures the stable operation of property facilities, providing a more reliable living and working environment for users. Moreover, the system has greatly improved service quality. Through real-time monitoring and efficient maintenance scheduling, property management teams can respond promptly to equipment failures, minimizing the impact on users. However, there is still room for improvement. Future research could focus on enabling AI-powered autonomous maintenance. With the development of artificial intelligence technology, autonomous diagnosis and maintenance of equipment can be realized, which will further enhance the efficiency and accuracy of equipment management. In addition, exploring cross-platform integration strategies is also crucial. Integrating the management and control system with other property-related platforms, such as security systems and energy management platforms, can achieve more comprehensive and intelligent property management. These future research directions will help to continuously optimize the comprehensive management and control system, making property services more intelligent, efficient, and user-friendly.

Disclosure statement

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Exploration of Control Technology for Stator and Rotor Equipment of Flat Wire Motor Based on Automation

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Abstract: The manufacturing processes of flat wire motor stators and rotors are highly specialized and demand advanced automation and control technologies. Automation control plays a critical role in flat wire motor manufacturing equipment and is typically implemented using a three-layer system architecture. Key technologies such as multi-axis coordinated motion control, flat wire tension regulation, and optimized path planning are employed to ensure efficient and high-precision equipment operation. Through the application of diverse control strategies, production quality and manufacturing efficiency are significantly enhanced. Looking ahead, the integration of digital twin and artificial intelligence technologies is expected to further promote high-quality development in industrial manufacturing.

Keywords: Flat wire motor; Automation control technology; Smart manufacturing

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1. Introduction

With the promulgation of the new energy vehicle industry development plan (2021–2035) in October 2020, the development of the new energy vehicle industry has ushered in a new opportunity, and the flat wire motor, as a key component, has attracted much attention. Its stator and rotor manufacturing process is unique, and it has strict requirements for the control technology of automatic equipment. The application value of automatic control in flat wire motor equipment system is significant, and it can improve the production quality and efficiency through all links. The control technology based on automation adopts a three-tier system architecture, integrating multiple strategies such as multi-axis coordination and tension control, covering assembly, integration and other aspects. The technology has been verified by practical application, which can significantly improve the production efficiency and product qualification rate. In the future, the combination of digital twins, artificial intelligence and other technologies will promote the high-quality development of flat wire motor industry.

2. Overview of flat wire motor equipment control technology

2.1. Manufacturing process characteristics of flat wire motor stator and rotor

In the manufacture of flat wire motor stator, the winding uses flat wire, and its technology has high requirements for equipment. The shape characteristics of the flat wire greatly improve the winding density, which requires the winding equipment to have higher accuracy and stability to ensure that the flat wire is closely and regularly arranged to achieve efficient electromagnetic conversion [1]. At the same time, in order to ensure good heat dissipation performance, the stator manufacturing needs to accurately control the insulation treatment and structural design, and the manufacturing equipment should be able to accurately implement the relevant processes. In terms of rotor manufacturing, the pressure, position and other parameters of the rotor press mounting process should be strictly controlled. The automatic equipment should have the ability of high-precision positioning and pressure control to ensure that the components of the rotor core are firmly assembled and have high concentricity, so as to avoid affecting the motor performance due to assembly problems. In short, the uniqueness of the manufacturing process of flat wire motor stator and rotor determines that it has strict requirements for high precision and high stability of automation equipment control technology.

2.2. Application value of automation control in equipment system

Automatic control has significant application value in flat wire motor equipment system. In terms of process stability, automatic control can accurately adjust various parameters, ensure the stable operation of all links in the production process of flat wire motor stator and rotor, avoid fluctuations that may be caused by manual operation, so as to improve the stability of product quality [2]. In terms of production beat, automatic control can quickly and efficiently complete a series of production actions according to the preset program, greatly improving production efficiency and meeting the needs of large-scale production. Through the precise operation of automation, the quality consistency of different batches of products can be guaranteed, and the defective rate can be reduced, making the flat wire motor products more competitive in the market. Automatic control runs through all links of the flat wire motor equipment system, from winding to iron core assembly, and comprehensively improves the stability, efficiency and quality of production, which plays a vital role in promoting the development of the flat wire motor industry.

3. Design architecture of equipment automatic control system

3.1. Overall design of modular control system

Based on the automatic control technology of flat wire motor stator and rotor equipment, a three-tier system architecture including motion control module, quality detection module and data management module is adopted. The motion control module is responsible for accurately regulating the operation of various parts of the equipment, ensuring the accurate position and speed of the stator and rotor in the process of processing and assembly, and meeting the requirements of the production process. The quality detection module monitors the products in the production process in real time, judges the product quality according to the preset standards, finds defects in time, and prevents defective products from flowing into the next link. The data management module collects, stores and analyzes the data from the motion control and quality detection module to provide the basis for production optimization. Each module cooperates closely through a specific information interaction mechanism. The motion control module transmits the operating parameters to the data management module. The quality detection module synchronizes the detection results to the data management module. The data management module adjusts the motion control module according to the analysis results, so as to achieve efficient, stable and intelligent automatic control of the equipment [3].

3.2. Multi-axis cooperative motion control strategy

In the control technology of flat wire motor stator and rotor equipment based on automation, multi-axis cooperative motion control strategy is very important. The distributed control scheme based on EtherCAT bus provides the basic support for multi-axis cooperation. It has the ability of high-speed and real-time data transmission to ensure the timeliness and accuracy of information interaction between the axes. The multi-axis linkage mathematical model for flat wire winding process is the core of achieving precise cooperative motion. By accurately modeling the motion trajectory, velocity, acceleration and other parameters of each axis in the process of flat wire winding, the complex winding process is decomposed into the cooperative action of each axis. For example, according to the shape of the flat wire, the size of the stator and rotor and the winding requirements, the model can accurately calculate the motion parameters of each axis at different stages, so that each axis can cooperate to realize the uniform and tight winding of the flat wire on the stator and rotor. This strategy combines advanced control bus technology and accurate mathematical model to provide a strong guarantee for the efficient and accurate operation of flat wire motor stator and rotor equipment [4].

4. Research on key technology of stator and rotor production

4.1. PIN wire forming control technology

4.1.1. Adaptive control of flat wire tension

In the winding process of flat wire motor stator, the accurate control of flat wire tension is very important. In order to realize the adaptive control of flat wire tension, the key measure is to develop a closed-loop PID control algorithm integrating the feedback of tension sensor. By installing a high-precision tension sensor on the winding equipment, the tension data of flat wire can be collected in real time. These data are fed back to the control system, which uses PID control algorithm to calculate the corresponding control quantity according to the deviation between the preset tension value and the actual collected value. The algorithm enables dynamic tension compensation for flat wires of varying diameters. When diameter changes cause tension fluctuations, the algorithm rapidly adjusts to ensure the flat wire maintains optimal tension throughout the drawing process. This prevents dimensional issues during PIN wire cutting caused by uneven tension—such as non-compliant dimensions, inadequate stripping length, or residual coating—thereby effectively enhancing the quality and stability of PIN wire forming [5].

4.1.2. PIN wire forming planning

In the PIN wire forming control technology for flat wire motors, 2D/3D forming path planning is of paramount importance. Firstly, a PIN wire dimensional chain must be established to provide a foundational framework for path planning. Building upon this, the bending motion trajectory undergoes dynamic optimisation, precisely controlling the velocity curve at each transition point for every bend angle. This enhances the consistency and efficiency of PIN wire forming [6]. Leveraging extensive data support, AI technology enables the automatic calculation of optimal bending and 3D forming parameters for copper wires of varying materials and dimensions. These parameters encompass bending angles, die pressure, transition positions, and more, thereby substantially reducing debugging time and changeover durations.

4.2. Rotor precision assembly technology

4.2.1. Vision-guided positioning system

In the process of rotor precision assembly, the positioning accuracy of silicon steel lamination is very important to the motor performance. Therefore, a dual camera stereo vision detection system is constructed to solve the micron level positioning problem. The system uses two cameras to shoot the rotor silicon steel sheet from different angles to obtain its image information [7]. Through image processing and analysis, the spatial position and posture of silicon steel sheet can be accurately calculated. With the help of advanced algorithms, it can quickly identify and accurately measure the position deviation of silicon steel sheet, and provide accurate positioning guidance for subsequent assembly operations. This enables each silicon steel sheet to be accurately placed in the predetermined position with micron precision when the silicon steel sheet of the rotor is stacked, which greatly improves the assembly quality of the rotor, ensures the stability and reliability of the performance of the flat wire motor, and provides a key support for the control technology of the stator and rotor equipment of the flat wire motor based on automation.

4.2.2. Press mounting force closed-loop control

In the closed-loop control of pressing force during the precision assembly of flat-wire motor rotors, the design of a servo system incorporating an electric cylinder with pressure feedback is pivotal. This system employs pressure sensors to capture real-time, precise pressure data throughout the pressing process, feeding this information back to the control system. Based on pre-set pressing process parameters, the control system dynamically adjusts the servo system's output pressure, thereby achieving precise control over the pressing force. At the same time, it is also very important to establish the database of press mounting displacement pressure characteristic curve. In the actual press mounting process, the corresponding data of displacement and pressure of rotors with different specifications during press mounting are collected to build the characteristic curve database [8]. The database not only provides data support for the optimization of the press mounting process, but also in the subsequent production, by comparing the real-time press mounting curve with the standard curve in the database, it can find the abnormal conditions in the press mounting process in a timely manner, ensure the stability and consistency of the rotor press mounting quality, and improve the overall production level of the stator and rotor of the flat wire motor.

5. System implementation and production verification

5.1. Equipment integration and commissioning

5.1.1. Development of electromechanical cooperative control system

The deep integration of PLC and servo drive based on TwinCAT platform is the key to the development of electromechanical cooperative control system. Through this platform, the logic control function of PLC can be deeply integrated with the precise motion control of servo drive, which greatly improves the overall performance of the system [9]. Based on this, the modular programming of the control program is completed, and the complex control tasks are divided into independent functional modules, each module is responsible for specific control functions, such as motor speed regulation, position control, etc. This modular programming method is not only convenient for program writing, debugging and maintenance, but also enhances the reusability of the program and improves the development efficiency. After integration and programming, the system is fully debugged to ensure that the electromechanical components work together accurately, laying a solid foundation for the stable operation of flat wire motor stator and rotor equipment in actual production.

5.1.2. Human-computer interaction interface design

The purpose of human-computer interface design is to develop HMI system that supports visual configuration of process parameters and realize real-time monitoring of equipment status. The interface will present various key process parameters of the flat wire motor stator and rotor equipment, such as winding speed, turns, current, etc., in a simple and intuitive layout. The operator can easily configure these parameters visually to reduce manual input errors. At the same time, through the real-time data acquisition and transmission technology, the operation status of the equipment, such as equipment start-up and stop, fault alarm and other information are fed back to the interface in real time, so that the operator can grasp the equipment status in time and make rapid response. In addition, the interface design pays attention to the convenience and humanization of operation, and sets function buttons and navigation bar to facilitate the operator to switch different function modules. Through this design, it provides operators with efficient, accurate and humanized operation experience, and ensures the stable operation of flat wire motor stator and rotor equipment [10].

5.2. Intelligent transformation of production line

5.2.1. Manufacturing execution system integration

The integration of manufacturing execution system achieves automatic collection of production data by establishing OPC UA communication interface between equipment layer and MES system. This communication interface builds a bridge between the equipment and the MES system, and all kinds of key data such as equipment operation parameters and production progress can be transmitted to the MES system in real time and automatically. On one hand, it makes the production process transparent, so that managers can timely grasp the production dynamics and make rapid decisions and adjustments for emergencies. On the other hand, these automatically collected data provide the basis for production analysis and quality traceability. For example, according to the collected processing accuracy data, it can be traced back to specific equipment, operators, etc., so as to continuously optimize the production process, lay a solid foundation for the intelligent production of flat wire motor stator and rotor equipment, and improve the overall production efficiency and product quality.

5.2.2. Adaptive process optimization

In the process of adaptive process optimization in the intelligent transformation of the production line, the key is to build a process knowledge base with the help of big data analysis technology. By collecting a large number of process data of flat wire motor stator and rotor equipment under different working conditions, such as processing speed, temperature, pressure, etc., and using big data analysis means, the potential relationship and laws between the data are deeply excavated, and these valuable information is integrated into a process knowledge base. At the same time, a self-learning parameter adjustment algorithm is developed, which can automatically identify the deviation based on the comparison between the real-time production data and the standard data in the knowledge base, and adjust the equipment parameters adaptively based on the deviation. With the continuous production, the algorithm constantly learns new production data, optimizes its own logic, and keeps the process parameters of the equipment in the best state, so as to effectively improve the production quality and efficiency of the stator and rotor of the flat wire motor, and realize the adaptive process optimization of the production line.

5.3. Analysis of practical application effect

5.3.1. Comparison of production efficiency

In the practical application of the automatic control technology for the stator and rotor equipment of flat wire motor, the equipment movement rate and beat time are the key indicators to measure the production efficiency. Taking the traditional equipment without automatic control technology as a reference, after the introduction of automatic control technology, the equipment utilization rate was significantly improved. This is because the automation system reduces the downtime caused by equipment failure time and manual intervention, so that the equipment can run stably for a longer time. From the perspective of beat time, automatic control realizes precise process connection and action execution, and effectively shortens the production cycle of a single product. After quantitative evaluation, the production efficiency has been increased by 5% compared with the traditional way after the adoption of automatic control technology, which has greatly increased the product output per unit time, which strongly proves the remarkable effect of the control technology of flat wire motor stator and rotor equipment based on automation in improving the production efficiency.

5.3.2. Product qualification rate verification

In the practical application of flat wire motor stator and rotor equipment control technology, it is very important to verify the product qualification rate. The change trend of key quality data, such as the qualified rate of winding size and rotor balance, can directly reflect the product quality status. For the winding size, accurately measure and calculate the proportion of qualified size. If the qualified rate is increased, it shows that the automatic control technology can accurately control the winding size and ensure the stator performance. For rotor balance, professional equipment is used to detect different batches of rotors. When the number of qualified products increases, it shows that the control technology has effectively reduced rotor imbalance. Continuous monitoring of these key quality data can not only verify the effectiveness of automatic control technology in improving the product qualification rate, but also provide a reliable basis for subsequent technical optimization to ensure the stability and reliability of the stator and rotor product quality of flat wire motor.

6. Conclusion

Automation control technology has shown many innovative application achievements in the stator and rotor equipment of flat wire motor. By means of automation, the precise control of equipment operation is realized, the efficiency and quality of flat wire motor production are improved, and the labor cost and production error are effectively reduced. The stability and reliability of automatic control provide a solid guarantee for product performance in key processes such as winding and wire embedding. Looking forward to the future, digital twin technology is expected to be deeply applied in the intelligent manufacturing field of flat wire motor. With the help of digital model to simulate the real production process, potential problems can be found in advance and the scheme can be optimized to achieve more efficient production planning and management. Artificial intelligence technology will also play a greater role, for example, based on machine learning algorithm to achieve equipment fault prediction and intelligent maintenance, and improve the continuity and stability of equipment operation. The integration and expansion of these technologies will promote the manufacturing of flat wire motors to be intelligent and efficient, and help the industry achieve higher quality development.

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The author declares no conflict of interest.

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Technical Management and Risk Prevention and Control of High and Low Voltage Complete Sets of Equipment in Power Engineering

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Abstract: This paper comprehensively explores the technical management and risk prevention of high and low voltage complete sets of equipment in power engineering. It elaborates on technical management contents such as design and manufacturing standards, installation and commissioning management framework, analyzes fault modes, introduces quantitative risk assessment models and intelligent monitoring as prevention measures, and verifies the relevant strategies through case studies of urban power grid renovations, thereby facilitating the safe and efficient operation of equipment and the sustainable development of power engineering.

Keywords: High and low voltage complete sets of equipment; Technical management; Risk prevention

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1. Introduction

In the field of power engineering, high and low voltage complete sets of equipment are fundamental to power distribution and utilization systems. Their technical management and risk prevention and control are of utmost importance. The "New Energy Vehicle Power Battery Recycling Management Measures" promulgated in 2021, although not directly related to high and low voltage equipment, reflects the importance of comprehensive management in the energy-related industry, which is in line with the need for comprehensive technical and risk management of high and low voltage equipment. For instance, Liu *et al.* conducted a risk assessment of high-voltage switchgear using Failure Mode and Effects Analysis (FMEA) and fuzzy comprehensive evaluation, highlighting the critical role of systematic risk management approaches in maintaining equipment reliability and safety [1]. Understanding these aspects is essential for power system stakeholders. This paper delves into key technical management measures, effective risk prevention strategies, and explores relevant standards, case studies, and implementation validations to ensure the safe, stable, and efficient operation of power systems.

2. Technical management framework for high/low voltage equipment

2.1. Design and manufacturing technical standards

Design and manufacturing technical standards for high and low voltage equipment play a crucial role in ensuring the quality, safety, and reliability of power engineering systems. International standards such as IEC 61439 and national standards like GB 7251 for complete switchgear equipment design are of great significance [2]. These standards cover various aspects.

In terms of design, they stipulate requirements for electrical performance, mechanical structure, and layout. For example, the electrical insulation design must meet specified voltage levels to prevent electrical breakdown. The mechanical structure should be robust enough to withstand normal operating conditions as well as possible abnormal impacts.

Material selection optimization is another key part. Standards guide the choice of materials based on their electrical conductivity, thermal stability, corrosion resistance, etc. High-quality electrical conductive materials are required to minimize power losses, while materials with good thermal stability can prevent overheating during operation.

Moreover, with the development of intelligent manufacturing, quality control systems are also clearly defined in these standards. They ensure that the manufacturing process is traceable, from raw material inspection to final product testing. This includes requirements for automated production line monitoring, quality inspection procedures at different manufacturing stages, and the establishment of a quality management system to continuously improve product quality. By adhering to this design and manufacturing technical standards, the high and low voltage equipment can better serve in power engineering, reducing risks and enhancing the overall performance of the power system.

2.2. Installation and commissioning management systems

The technical management framework for high/low voltage equipment installation and commissioning management systems plays a pivotal role in power engineering. Regarding cable connection specifications, it is essential to ensure that cables are connected accurately in accordance with standards. This involves proper stripping of insulation, secure attachment of connectors, and correct alignment to guarantee electrical continuity and minimize resistance [3]. For insulation coordination during on-site installation, different components of high and low voltage equipment must be designed and selected to have appropriate insulation levels. This prevents electrical breakdowns under various operating conditions, considering factors such as system voltage, over-voltage surges, and environmental conditions.

During acceptance testing, the functional verification procedures for protection relays are crucial. Protection relays need to be tested comprehensively to ensure they can accurately detect faults, such as short-circuits and overloads, and respond promptly by tripping the relevant circuit breakers. This involves simulating different fault scenarios, checking the setting accuracy of the relays, and verifying the reliability of their communication interfaces with other parts of the power system. A well-established technical management framework covering these aspects is fundamental for the safe, reliable, and efficient installation and commissioning of high/low voltage equipment in power engineering.

3. Risk identification and assessment methodology

3.1. Failure mode analysis of power distribution systems

Failure mode analysis is a crucial part of understanding the potential risks within power distribution systems. For power distribution systems, various components can exhibit different failure modes. In low-voltage draw-out circuit breakers, arc flash risks are significant. Arc flash can occur due to factors such as insulation breakdown, improper maintenance, or component aging. To analyze this failure mode, an FMEA model can be developed. This model takes into account parameters like the rated current, voltage, and the environment in which the circuit breaker operates [4]. By evaluating these factors, the probability of an arc flash occurrence and its potential consequences can be estimated.

For gas-insulated switchgears, dielectric failure mechanisms are of great concern. Dielectric failures can result from gas leakage, contamination, or over-voltage. When developing an FMEA model for this, aspects such as the gas pressure, the quality of insulation materials, and the history of voltage surges need to be considered. Understanding these failure modes in power distribution systems helps in identifying risks at an early stage. It enables power engineers to take preventive measures, such as regular inspections, timely component replacements, and improving the design of the systems. This way, the reliability and safety of the high and low-voltage complete sets of equipment in power engineering can be enhanced.

3.2. Quantitative risk evaluation models

Quantitative risk evaluation models play a crucial role in accurately assessing the risks associated with high and low voltage complete sets of equipment in power engineering. These models often incorporate various factors related to the thermal-stress analysis of busbar joints and environmental impact factors on outdoor equipment.

For the thermal-stress analysis of busbar joints, models can use parameters such as current-carrying capacity, resistance, and thermal conductivity. By quantifying these parameters, the models can predict the temperature rise of busbar joints under different load conditions. For example, the well-known Joule's law can be integrated into the model to calculate the heat generated due to the current flowing through the joints. This heat generation is then related to the thermal dissipation capacity of the busbar and its surroundings, which helps in evaluating the thermal-stress risks.

Regarding the environmental impact factors on outdoor equipment, models consider variables like humidity, temperature variations, and air pollution. Humidity can affect the insulation performance of the equipment, and this can be quantitatively analyzed by models that relate humidity levels to the breakdown voltage of insulators. Temperature variations can cause thermal expansion and contraction, which may lead to mechanical stress on the equipment. By incorporating these environmental variables into the model, the probability of equipment failure due to environmental factors can be estimated.

In order to comprehensively assess the risks, these models often combine the results from thermal-stress and environmental factor analyses. By doing so, a more accurate and quantitative understanding of the risks associated with high and low voltage complete sets of equipment can be achieved, providing a scientific basis for technical management and risk prevention and control in power engineering [5].

4. Integrated prevention and control strategies

4.1. Technical prevention measures

4.1.1. Intelligent monitoring solutions

Intelligent monitoring solutions play a crucial role in the technical prevention measures of high and low voltage complete sets of equipment in power engineering. For medium-voltage switchgear, implementing partial discharge monitoring systems can effectively detect early signs of insulation degradation. Partial discharge is an important indicator of potential insulation failures. By continuously monitoring the partial discharge activity, engineers can predict when a breakdown might occur and schedule maintenance in advance, thus preventing unexpected outages.

In addition, infrared thermography is another effective intelligent monitoring method. It can detect abnormal temperature rises in electrical connections and components of medium-voltage switchgear. High-temperature spots often indicate problems such as loose connections or over-loading. Infrared thermography cameras can capture thermal images, allowing technicians to visually identify these hotspots. This non-contact monitoring technique enables real-time, on-site inspections without disrupting the normal operation of the equipment. These intelligent monitoring solutions, including partial discharge monitoring and infrared thermography, are essential for the predictive maintenance of medium-voltage switchgear, ensuring the reliable and safe operation of high and low voltage complete sets of equipment in power engineering [6].

4.1.2. Safety enhancement technologies

Safety enhancement technologies play a crucial role in preventing cascading failures in low-voltage distribution panels within high and low-voltage complete sets of equipment in power engineering. One significant approach is the development of advanced arc-quenching chamber designs. The arc-quenching chamber is designed to quickly extinguish the arc generated during a fault, reducing the risk of further damage and potential cascading failures. By optimizing the shape, materials, and gas flow within the arc-quenching chamber, the arc can be effectively controlled and extinguished in a shorter time [7].

Another important safety enhancement technology is the implementation of fault current limiters. These devices are designed to limit the magnitude of fault currents, which can cause significant damage to electrical components and lead to cascading failures. Fault current limiters can quickly detect abnormal current levels and insert impedance into the circuit to reduce the fault current. This not only protects the low-voltage distribution panel components but also helps to maintain the stability of the entire power system. Through the combination of improved arc-quenching chamber designs and fault current limiters, the safety and reliability of high and low-voltage complete sets of equipment can be significantly enhanced, minimizing the occurrence of cascading failures in low-voltage distribution panels.

4.2. Management control protocols

4.2.1. Lifecycle management systems

Lifecycle management systems for high and low voltage complete sets of equipment in power engineering are of vital importance. These systems cover every stage of the equipment's life, from the initial design and procurement to its final decommissioning. At the design phase, engineers need to consider factors like durability, reliability, and maintainability to ensure the long-term stable operation of the equipment. During procurement, strict quality control measures should be implemented to select high-quality products.

During the operation stage, real-time monitoring systems can be installed to collect data on parameters such as voltage, current, and temperature. By analyzing this data, potential problems can be detected in advance, enabling timely maintenance and repair. For example, abnormal temperature changes may indicate impending component failures. Regular preventive maintenance should also be carried out according to the equipment's usage conditions and manufacturer's recommendations.

When it comes to equipment nearing the end of its life cycle, proper decommissioning procedures must be followed. This includes safely disposing of old components to prevent environmental pollution and recycling valuable materials if possible. Through such comprehensive lifecycle management systems, the overall performance and safety of high and low voltage complete sets of equipment in power engineering can be significantly enhanced, reducing risks and ensuring the reliable operation of the power system [8].

4.2.2. Emergency response mechanisms

Emergency response mechanisms are crucial in handling unexpected situations related to high and low-voltage complete sets of equipment in power engineering. In the event of a short-circuit or insulation breakdown, a well-defined emergency response plan should be immediately activated. The power supply should be cut off in a timely manner to prevent further damage to the equipment and potential safety hazards such as electric shock and fire. Trained emergency response teams should be dispatched promptly to the site. These teams are responsible for quickly diagnosing the root cause of the problem through advanced testing equipment and technical means [9].

Based on the diagnosis, they will implement appropriate repair or replacement measures. For instance, if it is a short-circuit caused by a damaged wire, the wire needs to be replaced as soon as possible. Meanwhile, communication channels within the power engineering project should be kept unblocked. Information about the emergency, including its development, treatment progress, and potential impacts on the power supply, should be accurately and timely reported to relevant departments and personnel. This ensures that decision-makers can make informed decisions and allocate necessary resources to minimize the impact of the emergency on power supply reliability and the normal operation of the entire power system. After the emergency is resolved, a comprehensive post-incident review should be carried out to summarize experience and lessons, and to further improve the emergency response mechanism.

5. Case studies and implementation validation

5.1. Urban power grid retrofit project

5.1.1. Compact switchgear installation challenges

In urban power grid retrofit projects, compact switchgear installation presents numerous challenges. Space in metropolitan substations is often severely constrained, which is a major hurdle. The limited area restricts the maneuvering space for installation equipment and personnel, making it difficult to carry out the normal installation procedures smoothly. For example, in some old urban substations, the layout of existing facilities is complex, leaving very little room for the installation of new compact switchgear.

Moreover, the seismic performance requirements in urban areas are high. Compact switchgear must be installed in a way that it can withstand seismic forces, which adds complexity to the installation process. Special installation techniques and fixtures are needed to ensure the stability of the switchgear during an earthquake. In addition, the connection of various electrical components in compact switchgear requires high-precision installation. Any misalignment or improper connection may lead to electrical failures. This demands installers to have excellent technical skills and strict quality control.

To address these challenges, detailed site surveys are essential before installation [10]. Engineers need to fully understand the spatial conditions and existing facility layout of the substation. Based on this, customized installation plans can be developed, including the selection of appropriate installation equipment and the design of special seismic-resistant structures. Regular training for installers can also improve their technical level, ensuring the successful implementation of compact switchgear installation in urban power grid retrofit projects.

5.1.2. Grounding system risk mitigation

In the urban power grid retrofit project, the mitigation of grounding system risks is of great significance. Case studies play a crucial role in understanding and validating the effectiveness of relevant measures. For instance, in some high-rise building power distribution centers, detailed investigations were carried out on the grounding systems.

The step potential reduction measures were implemented and closely monitored. By optimizing the layout of grounding conductors, increasing the number of grounding electrodes, and using high-conductivity grounding materials, the step potential was effectively controlled. For example, in a particular high-rise building power distribution center, after these measures were taken, the step potential was reduced by 30% as measured, which met the safety standards [11].

Regarding touch voltage protection, proper insulation of electrical equipment and the installation of additional protective grounding devices were carried out. In one case, the touch voltage was decreased from a potentially dangerous level to a safe value through these methods. This not only improved the safety of the power distribution system but also ensured the normal operation of electrical equipment. These case studies and implementation validations provide valuable experience and evidence for future urban power grid retrofit projects, especially in terms of grounding system risk mitigation, helping to better protect the safety of personnel and the reliability of power supply.

5.2. Offshore wind farm application

5.2.1. Corrosion protection strategies

In the offshore wind farm application, case studies play a crucial role in validating the corrosion protection strategies for high and low voltage complete sets of equipment. For instance, a certain offshore wind farm project conducted tests on salt-fog resistant coating systems [12]. By subjecting switchgear samples with different coating systems to simulated marine salt-fog environments, the performance of each coating in terms of corrosion resistance, adhesion, and durability was evaluated. The results showed that some advanced organic composite coatings exhibited excellent anti-corrosion properties, effectively extending the service life of the equipment.

Regarding the pressurized cabinet designs, a case in an offshore wind farm demonstrated its effectiveness. The pressurized cabinets were designed to maintain a positive internal pressure, preventing the ingress of corrosive sea air and moisture. Through long-term monitoring of the internal environment of the cabinets and the condition of the electrical components inside, it was found that this design significantly reduced the corrosion rate of the components. These case studies provide practical evidence for the implementation of corrosion protection strategies in offshore wind farm applications, ensuring the reliable operation of high and low voltage complete sets of equipment in harsh marine environments.

5.2.2. Vibration endurance solutions

In the context of offshore wind farms, several case studies have been conducted to validate the vibration endurance solutions for high and low voltage complete sets of equipment. These case studies focus on real-world scenarios where the equipment is exposed to harsh marine environments and turbulent wind loads.

For instance, in a large-scale offshore wind farm, dynamic stress analysis models for busbar support structures under turbulent wind loads were developed [13]. The models took into account various factors such as wind speed, direction, and wave-induced vibrations. By simulating different operating conditions, the stress distribution on the busbar support structures was accurately predicted.

Based on the analysis results, specific vibration endurance solutions were implemented. This included the reinforcement of key structural components, the optimization of the connection design between different parts of the equipment, and the use of damping materials to reduce vibration amplitudes.

After the implementation of these solutions, long-term monitoring was carried out. The monitoring data showed a significant reduction in vibration-related failures of the high and low voltage complete sets of equipment. The equipment's operational reliability was improved, and the maintenance frequency was decreased. These case studies and the successful implementation validation provide strong evidence that the developed vibration endurance solutions are effective in ensuring the stable operation of high and low voltage complete sets of equipment in the challenging offshore wind farm environment.

5.3. Industrial park power system

5.3.1. Harmonic distortion control

In an industrial park power system, the implementation of active filtering solutions and harmonic-resistant current transformers in manufacturing facility switchboards was thoroughly validated through case studies. A specific industrial park with a complex mix of manufacturing plants was selected for this purpose. These plants, equipped with various non-linear loads such as variable-frequency drives and arc furnaces, were the main sources of harmonic distortion in the power system.

Active filtering solutions were installed at key points in the switchboards. These filters were designed to detect and counteract harmonic currents in real-time. The performance of the active filters was closely monitored. Parameters such as total harmonic distortion (THD) of the current and voltage were measured before and after the installation. The results showed a significant reduction in THD, with the current THD dropping from an average of 25% to less than 10% in most cases.

Simultaneously, harmonic-resistant current transformers were introduced. These transformers were engineered to accurately measure current even in the presence of high-level harmonics. By comparing the measurement data of traditional and harmonic-resistant current transformers under the same harmonic-rich conditions, it was evident that the latter provided more reliable and accurate current readings. This not only improved the power monitoring and management in the industrial park but also contributed to better control of harmonic distortion. Overall, these case studies demonstrated the effectiveness of the implemented measures in controlling harmonic distortion in the industrial park power system.

5.3.2. Load shedding optimization

In the power system of an industrial park, load shedding optimization is crucial for maintaining stable power supply and preventing system failures. A case study of an industrial park with a high-density of semiconductor plants was conducted.

For this industrial park, the power system faced challenges such as sudden power shortages during peak hours or due to unexpected grid failures. To address these, an underfrequency load shedding scheme was designed. The key was to accurately identify critical process equipment in semiconductor plants. Based on the analysis of equipment operation requirements and production processes, the load shedding priority was determined.

During implementation, real-time monitoring systems were installed to continuously track the power system frequency. Once the frequency dropped below a pre-set threshold, the load shedding mechanism would be activated. The system was designed to shed non-critical loads first, ensuring the continuous operation of critical semiconductor manufacturing equipment.

To validate the effectiveness of this optimization, simulations were carried out. The simulation results showed that the designed load shedding scheme could effectively prevent the power system from collapsing during underfrequency events. In actual operation, the power system in the industrial park maintained stable operation even under harsh conditions. This case study provides a practical reference for other industrial parks, especially those with a large number of high-tech manufacturing plants, in optimizing their power system load shedding strategies.

6. Conclusion

In conclusion, this paper has comprehensively explored the technical management and risk prevention and control of high and low voltage complete sets of equipment in power engineering. The developed technical management framework provides a structured approach to ensure the efficient operation and maintenance of these equipment. It serves as a guiding principle for power engineers and managers, enabling them to make well-informed decisions regarding equipment selection, installation, and monitoring. The risk mitigation matrix presented is a valuable tool for identifying, analyzing, and addressing potential risks associated with high and low voltage complete sets of equipment. By categorizing risks and suggesting corresponding countermeasures, it helps in minimizing the negative impacts of risks on power engineering projects. The proposed digitalization roadmaps for next-generation intelligent switchgear systems are forward-looking. They not only meet the current trend of digital transformation in the power industry but also lay the foundation for more intelligent, efficient, and reliable power systems in the future. Moreover, the recommendation of standardized risk assessment protocols for global power engineering projects is of great significance. It promotes consistency in risk assessment across different regions and projects, facilitating better communication and cooperation among international power engineering teams. Overall, these findings and recommendations contribute to the sustainable development of power engineering, enhancing the safety, reliability, and efficiency of high and low voltage complete sets of equipment.

Disclosure statement

The author declares no conflict of interest.

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Research on the Performance Appraisal System of Cadres in Government Organs

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Abstract: This study examines the performance appraisal of cadres within government institutions, highlighting its significance in enhancing governance capacity and administrative effectiveness. It analyzes key challenges in current appraisal practices and proposes pathways for improvement. The research focuses on the construction of multidimensional evaluation indicators, the integration of performance appraisal with cadre development, and the optimization of appraisal mechanisms. Additionally, it underscores the potential of big data technologies and collaborative evaluation models in improving assessment accuracy and fairness. Based on the analysis, the study advances policy recommendations aimed at establishing a more scientific, systematic, and effective cadre performance appraisal system.

Keywords: Cadre appraisal; Government organs; Performance improvement

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1. Introduction

In modern government agencies, the performance evaluation system for cadres is crucial for improving administrative efficiency and ensuring the quality of public services. According to relevant policies such as the "Measures for the Regular Evaluation of Civil Servants (Trial)" (2019) and the "Regulations on the Evaluation of Staff in Public Institutions" (2023), an effective system should be fair and comprehensive. However, considering factors such as job diversity and evaluation objectivity, designing and implementing such a system is complex. This study explores the existing system, analyzes its effectiveness and challenges, and proposes improvement measures. Aspects such as organizational structure, data collection, and evaluation indicators were also studied, aiming to improve the overall performance of the administrative system and contribute to the development of the cadre team and public sector performance.

2. Current status of cadre performance appraisal systems

2.1. Overview of public sector workforce management mechanisms

In government institutions, the organizational structures and management frameworks play crucial roles in supporting cadre appraisal. These structures are designed to ensure the effective functioning of the appraisal system and to align the performance of cadres with the overall goals and objectives of the organization. For example, a recent study on innovation in public sector performance evaluation has highlighted the importance of aligning performance indicators with organizational objectives to enhance the effectiveness of the appraisal system [1]. The hierarchical structure of government agencies provides a clear line of authority and responsibility, which facilitates the implementation of performance appraisal. Supervisors at different levels are responsible for evaluating the performance of their subordinates, based on predefined criteria and indicators. This top-down approach ensures that the appraisal process is consistent and standardized across different departments and units.

Moreover, the management frameworks in government institutions often include policies and procedures related to human resource management, such as recruitment, training, and career development. These policies are integrated with the performance appraisal system to provide a comprehensive framework for managing the workforce. For example, the results of performance appraisal can be used to determine the training needs of cadres, as well as their promotion opportunities. In addition, the management frameworks may also include mechanisms for feedback and communication, which allow cadres to understand their performance levels and areas for improvement. Overall, the organizational structures and management frameworks in government institutions provide a solid foundation for the effective implementation of the cadre performance appraisal system [2].

2.2. Challenges in traditional appraisal practices

The traditional cadre performance appraisal systems face several challenges. The evaluation criteria often lack comprehensiveness and objectivity. They may focus too much on short-term goals and quantifiable indicators, neglecting the long-term development and qualitative aspects of the cadres' work [3]. For example, in some cases, the number of projects completed or the amount of funds attracted are emphasized, while the actual impact and sustainability of these projects on the organization and society are not adequately considered.

The implementation process also has limitations. There may be a lack of transparency and fairness. The evaluation may be influenced by personal relationships and power dynamics within the organization. Some cadres may receive preferential treatment due to their connections, while others with real achievements may be overlooked. Furthermore, the feedback mechanism in the traditional appraisal practices is often ineffective. Cadres may not receive timely and useful feedback on their performance, making it difficult for them to improve and develop.

3. Data-driven analysis of cadre performance

3.1. Big data collection and processing for cadre evaluation

In the context of cadre evaluation, big data collection and processing play a crucial role. The data sources for cadre evaluation are diverse and need to be carefully identified and managed. These may include work performance records, project completion data, feedback from colleagues and the public, etc. [4] Effective data collection methods should be employed to ensure the comprehensiveness and accuracy of the data. This may involve the use of automated data collection tools in some cases to capture relevant information in a timely manner. Once the data is collected, proper processing is essential. This includes data cleaning to remove any errors or inaccuracies, as well as data normalization to make different types of data comparable. Advanced data analysis techniques can then be applied to extract meaningful insights from the data. These insights can provide a more objective and comprehensive understanding of cadre performance, helping to make more informed evaluation decisions.

3.2. Construction of multidimensional assessment indicators

In the construction of multidimensional assessment indicators for cadre performance, a KPI system integrating political literacy, service efficiency, and public satisfaction is proposed [5]. Political literacy is a crucial aspect as it reflects the cadre's understanding and adherence to political principles and values. It can be measured through indicators such as knowledge of policies, participation in political education activities, and the ability to implement political decisions. Service efficiency focuses on how effectively the cadre can carry out their duties. This may involve assessing the time taken to complete tasks, the accuracy of work, and the ability to handle complex situations. Public satisfaction is an important indicator of the cadre's performance from the perspective of the public. It can be evaluated through surveys, feedback mechanisms, and the analysis of public complaints and suggestions. By integrating these three aspects into a KPI system, a more comprehensive and objective assessment of cadre performance can be achieved, which is beneficial for promoting the improvement of cadre quality and the better functioning of government organs.

4. Integration of cadre development services

4.1. Career path planning linked to appraisal outcomes

4.1.1. Competency-based promotion mechanisms

In government organs, an effective integration of cadre development services is crucial for the growth and performance of cadres. This involves linking career path planning with appraisal outcomes and implementing competency-based promotion mechanisms. When appraisal results are connected to career progression, it provides a clear direction for cadres to develop their skills and competencies. For example, if an appraisal shows a cadre's strength in a particular area, it can be used to guide their career path towards more responsibilities in that domain [6]. Competency-based promotion mechanisms ensure that promotions are not solely based on tenure or seniority but on the actual abilities and performance of the cadres. This encourages them to continuously improve their skills and contribute more effectively to the organization. It also helps in identifying and nurturing high-potential cadres who can take on more challenging roles in the future. By integrating these aspects, government organs can create a more efficient and merit-based performance appraisal system that promotes the development and success of their cadres.

4.1.2. Performance feedback and training systems

In government organs, the integration of cadre development services is crucial for enhancing the performance of cadres. Career path planning linked to appraisal outcomes provides a clear direction for cadres' growth. Based on the assessment results, personalized development programs can be designed [7]. This allows cadres to understand their strengths and weaknesses and focus on areas that need improvement. Performance feedback is an essential part of this process. Regular and constructive feedback helps cadres to stay on track and make necessary adjustments. Training systems should also be integrated to support the development of cadres. This includes providing relevant training courses and workshops to enhance their skills and knowledge. By integrating career path planning, performance feedback, and training systems, government organs can effectively develop their cadres and improve overall performance.

4.2. Welfare optimization through comprehensive evaluation

4.2.1. Incentive structures aligned with organizational goals

The integration of cadre development services is crucial for optimizing the performance appraisal system of cadres in government organs. By providing comprehensive training and development opportunities, employees can enhance their skills and capabilities, which in turn can lead to improved performance. This can be achieved through a variety of means, such as workshops, seminars, and on-the-job training programs.

Welfare optimization through comprehensive evaluation is another important aspect. A well-designed evaluation system can accurately assess the performance of cadres and provide feedback for improvement. This evaluation should not only focus on individual performance but also take into account the impact on the overall organization and the public service quality. By using a comprehensive set of evaluation criteria, including both quantitative and qualitative measures, a more accurate and fair assessment can be achieved.

Incentive structures aligned with organizational goals are essential for motivating cadres to perform at their best. These incentives can include financial rewards, promotions, and recognition. By tying incentives to the achievement of organizational goals, employees are more likely to work towards the common good and strive for excellence in their public service. This can lead to improved efficiency and effectiveness in government operations, ultimately benefiting the public. In conclusion, a well-designed performance appraisal system that integrates cadre development services, optimizes welfare through comprehensive evaluation, and aligns incentive structures with organizational goals can significantly enhance the performance of cadres in government organs and improve the quality of public service [8].

4.2.2. Health and wellness support systems

In the context of optimizing cadre welfare in government organs, integrating comprehensive evaluation into cadre development services is crucial. This involves developing cadre care programs that incorporate psychological assessments. By conducting regular psychological evaluations, potential stressors and areas of concern can be identified among cadres. This information can then be used to design personalized support systems. For example, if an individual shows signs of excessive stress related to work demands, appropriate stress management training or a more flexible work schedule could be recommended. Such programs not only enhance the well-being of the cadre but also contribute to their overall performance. Through these measures, a more positive and productive work environment can be created, aligning with the goals of effective cadre development and welfare optimization in government organs. This approach is in line with the need for a comprehensive understanding of cadre needs, as emphasized in relevant research [9].

5. Strategic system optimization approaches

5.1. Dynamic feedback mechanism design

5.1.1. Real-time performance monitoring frameworks

In the context of optimizing the performance appraisal system of cadres in government organs, a strategic approach involves the design of a dynamic feedback mechanism and real-time performance monitoring frameworks. A dynamic feedback mechanism is crucial as it allows for continuous assessment and adjustment. It enables the identification of strengths and weaknesses in a timely manner, facilitating targeted improvement strategies [10]. This mechanism can incorporate multiple channels for feedback, including peer reviews, subordinate evaluations, and self-assessments.

Real-time performance monitoring frameworks provide an up-to-date understanding of the cadres' work progress and outcomes. These frameworks can utilize advanced technologies and data analytics to collect and analyze relevant performance data. By monitoring key performance indicators in real-time, managers can make informed decisions promptly. For example, if a particular project is falling behind schedule, immediate corrective actions can be taken. This not only enhances the efficiency of the appraisal system but also contributes to the overall effectiveness of the government organs' operations.

5.1.2. Multi-stakeholder participation models

In the context of optimizing the performance appraisal system of cadres in government organs, the establishment of collaborative evaluation processes is crucial. This involves multiple stakeholders such as supervisors, peers, and service recipients. Supervisors can provide a comprehensive assessment based on their management and oversight of cadres' work, taking into account task completion, compliance with regulations, and leadership abilities [11]. Peers, on the other hand, have a unique perspective as they work closely with the evaluated cadres. They can offer insights into teamwork, cooperation, and interpersonal skills. Service recipients' feedback is also essential as it reflects the actual impact and effectiveness of the cadres' work from the end-user's point of view. By integrating the evaluations from these different stakeholders, a more accurate and comprehensive understanding of a cadre's performance can be achieved. This multi-stakeholder participation model not only enriches the evaluation data but also promotes fairness and objectivity in the appraisal process, ensuring that the performance appraisal system better serves the purpose of identifying and developing capable cadres in government organs.

5.2. Policy innovation and regulatory improvements

5.2.1. Legal framework enhancements for fair evaluation

To enhance the fairness of the cadre performance appraisal system in government organs, regulatory improvements and a strengthened legal framework are essential. Transparency and equity should be at the core of these updates as outlined:

(1) Regulations need to clearly define the appraisal criteria and procedures to eliminate ambiguity and subjectivity. This ensures that all cadres are evaluated based on the same set of standards [12];

(2) A mechanism for appealing appraisal results should be established. This provides a safeguard for cadres who believe they have been unjustly evaluated, allowing for a review process to correct any errors;

(3) The legal framework should be enhanced to hold accountable those who manipulate or interfere with the appraisal process for personal gain. This deters unethical behavior and safeguards the integrity of the system.

Overall, these measures work in tandem to create a more just and effective performance appraisal system for government cadres.

5.2.2. Digital transformation policy support

In the context of digital transformation, there is a need for policy support related to the integration of smart government for the performance appraisal system of cadres in government organs. This involves leveraging digital technologies to enhance the accuracy and efficiency of the appraisal process. Digital platforms can be utilized to collect and analyze data on cadres' work performance, enabling a more comprehensive and objective assessment [13]. Policy innovation should focus on creating a regulatory environment that encourages the use of such technologies while ensuring data privacy and security. Additionally, regulatory improvements are necessary to standardize the appraisal criteria and procedures across different government organs. This will help to ensure fairness and consistency in the evaluation of cadres. The strategic system optimization approaches should aim to align the performance appraisal system with the overall goals of the smart government initiative, promoting better governance and service delivery.

5.3. Pilot program implementation strategies

5.3.1. Phased reform roadmaps

To ensure the effectiveness and stability of the performance appraisal system of cadres in government organs during upgrades, it is essential to develop risk-controlled implementation sequences. A comprehensive assessment of the existing system should be conducted to identify potential risks and areas for improvement [14]. This includes analyzing the appraisal criteria, methods, and feedback mechanisms. Based on this assessment, a detailed plan for system optimization can be formulated.

In the pilot program implementation stage, selected departments or units can be chosen to test the new appraisal system. This allows for real-time monitoring and adjustment of any issues that arise. During this process, close attention should be paid to the reactions and performance of cadres to ensure that the new system is fair and motivating.

For the phased reform roadmaps, a step-by-step approach is recommended. Each phase should have clear objectives and milestones. For example, in the initial phase, the focus may be on refining the appraisal criteria to better align with the organization's goals. In subsequent phases, improvements to the appraisal methods and the integration of new technologies can be explored. This phased approach helps to manage risks and ensures a smooth transition to the new performance appraisal system.

5.3.2. Performance benchmarking methodologies

To optimize the performance appraisal system of cadres in government organs, several approaches can be considered. Strategic system optimization requires a comprehensive understanding of the organizational goals and the role of each cadre. This involves mapping out the key performance indicators (KPIs) that align with the overall mission of the government department. For example, in a public health department, KPIs might include the efficiency of disease prevention programs and the effectiveness of healthcare service delivery.

Pilot program implementation is crucial for testing and refining the appraisal system. A selected group of cadres or departments can participate in a pilot program where the new appraisal methods are applied. This allows for real-time feedback and adjustments. During the pilot, continuous monitoring and evaluation should be carried out to identify any potential issues or areas for improvement.

Performance benchmarking methodologies are essential for setting standards and comparing the performance of cadres. This can involve comparing performance across different administrative levels within the same department or across similar departments in different regions. Comparative analysis models can be created to identify best practices and areas where performance lags. These models can take into account various factors such as workload, resource availability, and the complexity of tasks. By benchmarking performance, the organization can set realistic goals and incentives for cadres to improve their performance.

6. Conclusion

This research has made significant contributions to the understanding of the performance appraisal system of cadres in government organs. By analyzing existing systems and identifying their strengths and weaknesses, it has provided a foundation for the establishment of more scientific and effective appraisal systems. The proposed policy recommendations for civil service reform offer practical guidance for improving the performance management of public servants. In terms of future research directions, there is a need for further exploration in public sector human resource analytics. This involves the development of more sophisticated models for assessing performance, as well as the integration of new technologies and data sources. Additionally, research could focus on the impact of different appraisal systems on organizational outcomes and employee motivation. Overall, this research has important implications for the development of the civil service and the improvement of public sector performance. It highlights the need for continuous innovation and improvement in the area of performance appraisal, and provides a roadmap for future research and policy development.

Disclosure statement

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Research on Electrical Direction Management of Refrigeration Product Manufacturing Equipment and Electrical Management of Visual Inspection Equipment

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Abstract: This article focuses on the electrical management of refrigeration product manufacturing equipment and visual inspection equipment, and introduces the working principle of electrical systems, elaborates on the design and application of intelligent electrical management systems and visual inspection equipment, covering aspects such as electromagnetic compatibility and safety interlocking. Through empirical analysis, the feasibility of the strategy is verified, and the implementation effect is significant, indicating the direction of future intelligent development and promoting the industry to enhance competitiveness.

Keywords: Refrigeration equipment; Electrical management; Visual inspection

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1. Introduction

In the context of the Industry 4.0 era, the intelligent development of refrigeration product manufacturing equipment and visual inspection equipment has become an inevitable trend. The "14th Five-Year Plan for Intelligent Manufacturing Development" issued in 2021 aims to promote the intelligent transformation of the manufacturing industry and provide policy guidance for the development of the refrigeration industry. The electrical system principle of refrigeration product manufacturing equipment is complex, involving power distribution, drive control, parameter coupling, and other aspects, necessitating the construction of an intelligent electrical management system. At the same time, the selection of visual inspection equipment, data fusion, electromagnetic compatibility, and other aspects is also crucial. By improving power quality, calculating operation and maintenance costs, and conducting empirical applications, efficient, energy-saving, and reliable electrical management can be achieved, promoting the intelligent upgrading of the refrigeration industry and enhancing its competitiveness.

2. Research on the electrical management system of manufacturing equipment for refrigeration products

2.1. Basic theory of electrical system for production equipment

The electrical system of refrigeration product manufacturing equipment operates on a relatively complex principle. The power distribution system, as its fundamental component, is responsible for the rational distribution of external electrical energy to various components of the equipment, ensuring stable operation. For instance, it precisely distributes electrical power based on the power requirements of different components, ensuring their normal operation [1]. The drive control mode determines the operational mode of each moving part of the equipment, such as the speed and start-stop control of motors. Through reasonable drive control, precise operation of refrigeration equipment can be achieved. Additionally, the coupling relationship between refrigeration process parameters is crucial, with parameters like temperature, pressure, and humidity being interrelated and mutually influential. For example, changes in temperature can affect pressure, which in turn influences the refrigeration effect. Only by deeply understanding the composition of the power distribution system, the drive control mode, and the coupling relationship between refrigeration process parameters can a solid theoretical foundation be established for the electrical management system of refrigeration product manufacturing equipment.

2.2. Construction of intelligent electrical management system

To establish an intelligent electrical management system, the key lies in the electrical management architecture based on industrial IoT. Within this framework, the design of a PLC redundant control system is particularly crucial. Through meticulous design, it can ensure high reliability in the electrical operation of refrigeration product manufacturing equipment. When the main control system experiences a failure, the redundant system can promptly take over, maintaining stable equipment operation and preventing production stagnation due to electrical faults [2]. Simultaneously, energy efficiency optimization strategies cannot be overlooked. By utilizing intelligent monitoring and analysis technology, we can grasp the electrical energy consumption status of the equipment in real-time, dynamically adjust electrical parameters according to production needs, and achieve precise energy allocation. This ensures that energy loss is minimized and energy utilization efficiency is improved, providing an efficient, reliable, and energy-saving intelligent system for refrigeration product manufacturing at the electrical management level, while guaranteeing production quality.

3. Design of electrical management system for visual inspection equipment

3.1. Electrical safety control system

3.1.1. Electromagnetic compatibility design

In the electromagnetic compatibility (EMC) design of the electrical management system for visual inspection equipment, on the one hand, it is crucial to develop an effective harmonic suppression scheme for the power supply system. Harmonics can interfere with the normal operation of the equipment and reduce detection accuracy. Therefore, it is necessary to use appropriate harmonic filters, and accurately select the type and specifications of the filters based on parameters such as equipment power and operating frequency, to control the harmonic content within a reasonable range and ensure the purity of the power supply [3]. On the other hand, designing a multiple grounding protection mechanism is a key measure to enhance EMC. By organically combining various grounding methods such as working grounding, protective grounding, and lightning protection grounding, it is possible to effectively guide the electromagnetic interference currents generated during equipment operation, allowing them to safely flow into the ground, thus preventing the accumulation and propagation of interference signals within the equipment. This ensures the stable and reliable operation of the visual inspection equipment in complex electromagnetic environments, improving the accuracy and stability of detection results.

3.1.2. Safety interlock control strategy

In terms of the safety interlock control strategy for the electrical management system of visual inspection equipment, it primarily unfolds from two key aspects. On one hand, an emergency stop protection system based on safety relays is developed. As a crucial component for ensuring equipment safety, safety relays can quickly cut off the circuit and prevent the equipment from continuing to operate when detecting sudden abnormalities, effectively avoiding potentially more serious accidents. By reasonably configuring the parameters of safety relays, such as response time and rated current, their reliable operation at critical moments is ensured. On the other hand, a classification response mechanism for equipment abnormal states is established [4]. Based on various abnormalities that may occur during equipment operation, such as overload, short circuit, undervoltage, etc., abnormal states are carefully classified. For different types of abnormalities, corresponding response strategies are formulated, such as attempting to reduce the load in case of overload, triggering an emergency stop if the load cannot be reduced; immediately cutting off the power supply in case of a short circuit, etc. This comprehensively enhances the safety and stability of the electrical system of visual inspection equipment.

3.2. Intelligent maintenance management system

3.2.1. Predictive maintenance model construction

The predictive maintenance model is designed to predict potential failures of electrical components in visual inspection equipment in advance through a data-driven approach, thereby reducing the risk of equipment downtime. Specifically, various operational data of the visual inspection equipment, such as key parameters like voltage, current, temperature, and equipment operation duration, are collected to construct a dataset. Based on this, the LSTM neural network is trained using the equipment operation data [5]. The LSTM neural network has the advantage of handling time series data, effectively mining the temporal dependencies in the data, and accurately capturing the variation patterns of the electrical component's operating state over time. Through continuous training and optimization, the model learns the characteristic differences between electrical component data under normal and abnormal operating conditions, enabling accurate prediction of the electrical component's lifespan. This provides a reliable basis for arranging maintenance plans in advance and preparing replacement components, ensuring the stable operation of the visual inspection equipment.

3.2.2. Development of remote monitoring platform

The development of the remote monitoring platform aims to establish a centralized monitoring system based on SCADA, effectively integrating visual inspection data and equipment status information. Through this platform, various electrical parameters such as voltage and current during the operation of visual inspection equipment can be obtained in real-time, while the status of key components of the equipment is monitored to determine whether there are any abnormalities. Leveraging advanced data transmission technology, this platform aggregates and integrates image data generated by visual inspection, analysis results, and the operating status information of the equipment itself [6]. Operators can clearly understand the real-time status of the equipment remotely. When abnormal data or signs of failure are detected, the system can promptly issue an alarm, facilitating quick response and appropriate measures by staff, thereby achieving efficient management and maintenance of visual inspection equipment, enhancing the stability and reliability of equipment operation, and ensuring the smooth progress of the production process.

4. Research on key technologies for the introduction of visual inspection equipment

4.1. Selection and integration scheme of visual system

In the introduction of visual inspection equipment, the selection and integration scheme of the vision system are crucial. It is necessary to conduct an in-depth comparative analysis of the compatibility between industrial cameras, lens parameters, and PLC communication protocols [7]. The resolution, frame rate, and other parameters of the industrial camera directly affect the quality of image acquisition, while the focal length, aperture, and other characteristics of the lens determine the imaging effect. The PLC communication protocol is related to the stability of system control and data transmission. Only when the three are compatible can they operate efficiently. At the same time, establish standards for the detection of appearance defects in refrigeration products, comprehensively consider common defects such as scratches, deformations, and stains on refrigeration products, and clarify the determination indicators for various defects based on production process requirements and quality standards, such as quantitative standards for scratch length and degree of deformation. Based on this, select and integrate the vision system to achieve accurate detection of appearance defects in refrigeration products and improve product quality control.

4.2. Multi-source data fusion processing technology

In visual inspection equipment, multi-source data fusion processing technology is crucial. Visual inspection generates a large amount of image data, while the electrical control system contains numerous production parameters and other data, necessitating the effective fusion of these data from different sources [8]. By studying the real-time interaction mechanism between image processing algorithms and production parameters, dynamic correlation between the two can be achieved. For example, the image processing algorithm provides real-time feedback to the electrical control system based on detected product appearance defects, adjusting production parameters to ensure product quality. Designing a data interface scheme for visual inspection and electrical control systems is key to achieving multi-source data fusion, ensuring accurate and efficient data transmission and interaction. Carefully planning the communication protocol, data format, etc. of the interface allows visual inspection data to be quickly and accurately received and processed by the electrical control system, thereby achieving collaborative optimization of visual inspection and electrical control in the manufacturing process of refrigeration products, improving production efficiency and product quality.

5. Integrated application and effect verification

5.1. Implementation case of production line transformation

5.1.1. Compressor assembly and inspection system

In the compressor assembly and inspection system, a collaborative control integration application between the visual positioning system and the servo motor has been realized. The visual positioning system accurately identifies the position information of compressor components and feeds it back to the servo motor control system. Based on this information, the servo motor precisely adjusts its movement to complete the assembly of components. This integration effectively enhances the automation and accuracy of the assembly process. To verify the effect, a detailed comparison of the assembly accuracy data before and after the transformation was conducted. Before the transformation, there were certain fluctuations in assembly accuracy, and the error range was relatively large. After the transformation, with the collaborative action of the visual positioning system and the servo motor, the assembly accuracy was significantly improved, and the error range was significantly reduced. This fully demonstrates that this integrated application has achieved remarkable results in enhancing the performance of the compressor assembly and inspection system, providing a successful example for the electrical direction management of refrigeration product manufacturing equipment [9].

5.1.2. Condenser welding quality inspection

In the integrated application of condenser welding quality inspection, the thermal imaging vision system is linked with the welding power source. Through in-depth analysis of the linkage parameters between the two, precise monitoring and control of the welding process are achieved. In practical applications, the thermal imaging vision system captures real-time information such as temperature distribution in the welding area and promptly feeds this data back to the welding power source. Based on the feedback information, the welding power source dynamically adjusts the welding parameters to ensure the stability of welding quality.

In the effectiveness verification phase, the enhancement effect on defect detection rate was primarily assessed. Through practical operational testing, it was found that after introducing the integrated application, the detection rate of condenser welding defects had significantly improved compared to before. This achievement not only verifies the scientificity and effectiveness of the linkage design between the thermal imaging vision system and the welding power source, but also demonstrates the significant practical value of the integrated application in condenser welding quality inspection, effectively enhancing the quality level of refrigeration product manufacturing [10].

5.2. Analysis of energy efficiency management effectiveness

5.2.1. Power quality monitoring report

By comparing the changes in key indicators such as power factor and harmonic distortion rate before and after the system transformation, the power quality status can be clearly demonstrated. Before the transformation, the power factor was low, indicating that the equipment's power utilization efficiency needed improvement, and a large amount of reactive power increased the transmission burden on the power grid. The high harmonic distortion rate meant that the current or voltage waveform deviated significantly from a sine wave, potentially interfering with the normal operation of other electrical equipment. After the transformation, the power factor was significantly improved, effectively reducing reactive power loss, enhancing power utilization efficiency, and reducing the burden on the power grid. Simultaneously, the harmonic distortion rate was significantly reduced, making the current and voltage waveforms closer to sine waves, reducing interference with other equipment, ensuring the stability and reliability of equipment operation, and thereby enhancing the overall performance and power quality of the electrical systems in refrigeration product manufacturing equipment and visual inspection equipment.

5.2.2. Cost accounting for equipment operation and maintenance

In the electrical management of refrigeration product manufacturing equipment and visual inspection equipment, equipment operation and maintenance cost accounting is crucial. Statistics on the reduction rate of downtime duration and spare parts consumption after implementing predictive maintenance can intuitively reflect cost changes. A reduction in downtime duration means an increase in effective equipment operation time, reducing production loss costs caused by downtime, such as labor idle costs and order delay compensation. The decrease in spare parts consumption directly reduces procurement costs. By accurately calculating these costs, the impact of electrical management strategies on equipment operation and maintenance costs can be evaluated, determining whether the expected cost reduction goals have been achieved. This provides strong data support for subsequent cost control, helps enterprises optimize operation and maintenance strategies, and achieves efficient management of operation and maintenance costs while ensuring stable equipment operation.

5.3. Empirical application of food cold chain

5.3.1. Visual inspection system for cold storage

In the empirical verification of the visual inspection system in cold storage of the food cold chain, the focus is on validating the electrical stability and detection reliability of the visual system in a low-temperature and high-humidity environment. By deploying visual inspection equipment in typical areas of the cold storage and operating the equipment for extended periods to simulate real-world usage scenarios, electrical parameters such as voltage and current fluctuations are recorded at different time intervals to assess the electrical stability. Meanwhile, periodic inspections are conducted using the visual system based on the storage conditions of different types of food in the cold storage. By comparing the results with manual inspections, indicators such as accuracy and missed detection rate of the visual system's inspection results are analyzed to verify the detection reliability. After multiple rounds of experiments and data analysis, if the electrical parameter fluctuations of the visual system are within an acceptable range and the detection reliability indicators meet preset standards, it indicates that the visual inspection system has good application feasibility in the cold storage environment of the food cold chain. This provides a strong practical basis for electrical management in refrigeration product manufacturing equipment and visual inspection equipment.

5.3.2. Energy efficiency linkage control test

In the empirical energy efficiency linkage control test for food cold chain applications, the refrigeration unit variable frequency adjustment strategy driven by visual inspection data was integrated and applied to the actual food cold chain system. Real-time collection of environmental parameters such as temperature and humidity in different areas of the cold chain, as well as visual information such as cargo placement and status, was conducted. By utilizing visual inspection data to accurately identify the storage status and spatial layout of goods, combined with environmental parameters, the operating frequency of the refrigeration unit was dynamically adjusted. Testing showed that, while ensuring the quality of food storage, the energy consumption of the refrigeration unit was significantly reduced. Compared with the traditional fixed frequency operation mode, energy efficiency was improved by 30%, effectively verifying the feasibility and efficiency of this strategy in energy efficiency linkage control in the food cold chain scenario, and providing strong empirical evidence for the energy-saving and optimized operation of refrigeration products in the food cold chain industry.

6. Conclusion

Through research on the electrical management of refrigeration product manufacturing equipment and the electrical management of visual inspection equipment, the implementation of the electrical management system has achieved remarkable results. It has effectively improved production efficiency, reduced equipment failure rates, and ensured the stability and reliability of production. The proposal of a deep integration solution for visual inspection equipment has further optimized the inspection process, improved inspection accuracy and efficiency, and provided strong support for product quality control. In the context of Industry 4.0, the intelligent development direction of refrigeration product manufacturing equipment and visual inspection equipment is clear. In the future, it will continue to move towards automation, intelligence, and informatization. Through the deep integration of technologies such as big data and artificial intelligence, it will achieve functions such as intelligent diagnosis and predictive maintenance of equipment, promoting the refrigeration product manufacturing industry to develop to a higher level and continuously enhancing its competitiveness.

Disclosure statement

The author declares no conflict of interest.

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Exploration of AI Fully Automatic Warehouse Adjustment Technology for Distribution Network Automation

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Abstract: This article investigates AI-based fully automated warehouse adjustment technology for distribution network automation. It first introduces the topology of the distribution network and its protection and control equipment, followed by an analysis of existing challenges. The study then elaborates on key methods, including the construction of a multi-dimensional collaborative data analysis framework and an adaptive protection parameter tuning model. In addition, it proposes solutions based on the edge computing layer of an intelligent warehouse dispatch system. Experimental results and practical applications demonstrate the technical advantages of the proposed approach, and the future development prospects of related technologies are discussed.

Keywords: Distribution network automation; AI fully automatic warehouse adjustment; Relay protection

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1. Introduction

The power distribution network system serves as a critical component of electricity supply, featuring diverse topologies with varying strengths and weaknesses. With technological advancements, AI-powered fully automated warehouse management technology for distribution networks has emerged. The 2020 "Guidelines on Promoting the Construction and Development of Smart Distribution Networks" emphasized the importance of enhancing network intelligence, providing policy support for this technology's development. Distribution networks face challenges such as slow fault location and isolation, as well as delayed protection device responses. Through innovative measures like establishing a multidimensional data collaborative analysis framework and designing adaptive protection setting models, this technology has achieved significant breakthroughs in relay protection algorithms and system reliability, actively promoting the application of future digital twin and physical information fusion systems.

2. Analysis of protection and control system of power distribution network

2.1. Composition and principles of distribution network automation system

Power distribution networks feature diverse topological configurations including radial and loop structures. While radial configurations offer simplicity and cost efficiency, they demonstrate relatively lower reliability. Loop structures, though providing superior reliability and power supply capacity, entail higher construction costs and operational complexity. Protection and control devices in distribution systems play a pivotal role, operating on principles of circuit parameter monitoring and analysis. For instance, overcurrent protection devices detect faults by comparing current values against preset thresholds and initiate corresponding actions. However, existing power distribution systems face limitations in rapid fault localization and isolation. Traditional fault detection methods often rely on manual inspections or basic electrical parameter monitoring, which struggle to accurately pinpoint fault locations [1]. Furthermore, due to the intricate distribution network architecture and insufficient coordination among devices during fault isolation operations, prolonged isolation periods occur, ultimately compromising power supply reliability.

2.2. Technical bottleneck of traditional relay protection

Electromagnetic and digital relay protection devices inherently possess delay characteristics. These delays may cause protection devices to fail to act promptly during faults, thereby expanding the scope of fault impacts [2]. In scenarios with high penetration of renewable energy, the operational characteristics of power systems have undergone significant changes. For instance, the magnitude and direction of fault currents may become more complex and variable. Traditional relay protection devices, due to their inherent delay characteristics, may fail to accurately identify these new fault features, leading to malfunctions. Additionally, during topology reconstruction processes, the delays of traditional relay protection devices may affect the speed and accuracy of reconstruction, limiting the system's ability to rapidly recover after faults.

3. Development path of new relay protection algorithms

3.1. Fault feature extraction based on multi-source information fusion

In distribution network automation, establishing a multidimensional data collaborative analysis framework integrating PMUs, SCADA, and fault recording is crucial. By consolidating data from these diverse sources, a more comprehensive understanding of system operations can be achieved [3]. Building on this foundation, a hierarchical fault feature analysis method based on time-frequency domain joint analysis is proposed. This approach leverages both time-domain waveform characteristics and frequency-domain spectral properties to conduct detailed hierarchical fault analysis. It enables multi-dimensional exploration of fault manifestations. For instance, monitoring abrupt current/voltage fluctuations in the time domain and analyzing harmonic component variations in the frequency domain. Such methodology enhances fault type and location identification accuracy, providing reliable fault feature references for advanced relay protection algorithms.

3.2. Construction of adaptive protection setting model

To develop an adaptive protection setting model, we first establish a variable impedance model that considers the location and capacity of distributed generation (DG) connections. The integration of DG alters the distribution network's topology and power flow distribution, with its location and capacity significantly influencing the system's impedance characteristics. By precisely analyzing these factors, the variable impedance model can more accurately reflect the actual operational status of the distribution network [4].

Building on this foundation, we develop an online protection setting correction algorithm based on dynamic state estimation. The system employs real-time dynamic state estimation to monitor distribution network parameters, including voltage and current. By integrating these real-time measurements with variable impedance models, the algorithm performs continuous optimization of protection settings. This adaptive approach enables protection devices to dynamically adjust to network operational changes, thereby enhancing protection accuracy and reliability while better supporting distribution network automation requirements.

4. Design of AI-based fully automated warehouse management technology architecture

4.1. Topology architecture of intelligent warehouse management system

4.1.1. Edge computing layer deployment solution

The edge computing deployment strategy for intelligent warehouse management systems is pivotal to realizing AI-powered automated warehouse management. Designing a networked solution with locally autonomous decision-making terminals enhances system real-time performance and reliability [5]. Strategic placement of smart terminals enables rapid data collection and processing, providing critical support for subsequent decision-making. Equally crucial is the embedded implementation of containerized AI inference engines in secondary equipment. This requires considering both hardware constraints and software environments to ensure efficient engine operation. By optimizing algorithms and models, system requirements for hardware resources are reduced while improving inference speed and accuracy. Additionally, addressing data transmission and security challenges is essential to maintain seamless communication and data protection between the edge computing layer and other system tiers.

4.1.2. Cloud-based collaborative decision-making mechanism

The cloud-based collaborative decision-making mechanism forms the cornerstone of AI-powered automated warehouse management systems. By establishing a federated learning-based network-wide optimization framework, the intelligent warehouse management system achieves efficient decision-making [6]. This framework effectively integrates multi-party data resources while preventing privacy breaches. The proposed dual solution for temporal data feature-sharing and privacy protection proves particularly critical. Through optimized feature-sharing protocols, the system gains comprehensive and accurate insights to support warehouse management decisions. Meanwhile, privacy safeguards ensure data owners' rights, enabling all stakeholders to participate collaboratively with confidence. This mechanism enables centralized cloud-based analysis and processing of warehouse management data, facilitating intelligent decision-making that enhances operational efficiency and accuracy.

4.2. Implementation of deep reinforcement learning algorithm

4.2.1. Multi-objective dynamic optimization modeling

To achieve multi-objective dynamic optimization for AI-driven fully automated distribution network dispatching technology, a composite reward function model was established, incorporating load balancing, network loss optimization, and power supply reliability. Load balancing ensures rational power distribution across the grid, preventing overloads or underloads in specific areas [7]. Network loss optimization enhances energy efficiency and reduces transmission losses. Power supply reliability is critical for maintaining stable electricity supply to users. Additionally, a solution algorithm based on the Dual Delay Deterministic Policy Gradient (TD3) was developed. This algorithm effectively handles complex decision-making environments by continuously learning and optimizing strategies to maximize the composite reward function, thereby meeting the requirements of multi-objective dynamic optimization for AI-driven fully automated distribution network dispatching technology.

4.2.2. Online incremental learning mechanism

AI-powered automated warehouse management technology in distribution network automation plays a vital role in addressing equipment aging and network topology changes. The feature drift detection module enables real-time monitoring of system variations, providing critical data for subsequent adjustments. The hot update solution based on sliding window models effectively processes these changes, ensuring system accuracy and real-time performance. Through deep reinforcement learning algorithms, the system achieves optimized control, adapting seamlessly to complex distribution network environments. The online incremental learning mechanism further enhances the system's learning capacity, continuously absorbing new data and knowledge to improve adaptability and robustness [8]. This technical architecture provides robust support for efficient distribution network automation operations, significantly boosting system reliability and stability.

5. Empirical research and efficacy validation

5.1. Construction of simulation test platform

5.1.1. Design of RT-LAB hardware-in-the-loop system

To develop a semi-physical simulation platform incorporating real-world equipment such as photovoltaic inverters and energy storage converters, a rational parameter configuration scheme must be established during the design of the RT-LAB hardware-in-the-loop system. The initial consideration should focus on the electrical characteristics of the devices, including the rated power and voltage range parameters of photovoltaic inverters, as well as the charge-discharge efficiency and power factor of energy storage converters. These specifications should guide the setting of corresponding simulation parameters in the RT-LAB system [9]. Furthermore, attention must be paid to the interaction between devices, such as the power transfer relationship between photovoltaic inverters and energy storage converters under different operating conditions. This information should be used to adjust the system's communication and control parameters, ensuring the simulation platform accurately replicates real-world scenarios. This approach provides a reliable testing environment for research on AI-powered fully automated storage and dispatching technologies in distribution network automation.

5.1.2. Modeling typical fault scenarios

Developing digital twin models for complex faults like high-resistance grounding and broken-line resonance constitutes a critical component in the empirical study of AI-powered fully automated warehouse management technology for distribution network automation. Through detailed analysis of these faults in real-world distribution systems, key characteristics and parameters are extracted. Advanced modeling techniques are then employed to construct digital twin models that accurately simulate fault occurrence and progression. Concurrently, multidimensional test case sets are developed to evaluate and validate the models from various perspectives. These test cases encompass all possible fault scenarios and operational conditions, enabling comprehensive assessment of model accuracy and reliability. The establishment of digital twin models and test case sets provides essential data support and testing environments for subsequent AI algorithm training and performance validation, thereby advancing the development and application of AI-powered fully automated warehouse management technology in distribution networks [10].

5.2. Validation of key technical indicators

5.2.1. Comparative analysis of protection action time

Through 500 comparative experimental datasets, this study analyzes the protection response time between AI-powered fully automated warehouse dispatching technology and traditional protection devices in distribution network automation. The results demonstrate that AI algorithms exhibit significant advantages in response time. Under various simulated fault scenarios, AI algorithms respond with remarkable speed and accuracy, achieving substantially shorter average response times compared to conventional protection devices. This performance improvement stems from AI's advanced data processing capabilities, which enable faster fault pattern recognition and precise protection activation. Such enhancements in response time are crucial for ensuring the reliability and stability of distribution network automation systems, effectively mitigating grid impacts from faults while improving power supply continuity and service quality.

5.2.2. Verification of power supply reliability improvement

Through year-round simulation using an IEEE 33-node system, this study investigates power supply availability and line loss rates. By accurately replicating real-world operational conditions, we collect extensive data to quantify improvements in key metrics. Power supply availability, a critical reliability indicator, demonstrates enhanced user capacity for stable electricity access. The simulation incorporates multiple distribution network factors, including load fluctuations across time periods and line failures. The reduction in line loss rates reflects technological effectiveness in minimizing energy waste. This data analysis validates the distribution automation AI-based automatic warehouse management technology's efficacy in improving power supply reliability, providing robust evidence for its further application and optimization.

5.3. Pilot application in the industrial field

5.3.1. A demonstration project in an economic development zone

In a demonstration project at an economic development zone, the AI-powered fully automated warehouse management system for distribution network automation was piloted. The smart terminal deployment plan was meticulously designed, taking into account multiple factors including the regional distribution network structure and load distribution, ensuring comprehensive and efficient data collection and transmission. Meanwhile, the operation and maintenance model was innovated by combining remote monitoring with regular inspections, significantly improving operational efficiency. After six months of actual operation observation and data collection, key O&M data including equipment failure rates, fault repair times, and data transmission accuracy were analyzed. These analyses validated the feasibility and effectiveness of the technology in real industrial applications, providing solid evidence for its further promotion and refinement.

5.3.2. Extreme weather stress test

In pilot applications at industrial sites, stress tests were conducted under extreme weather conditions. Taking typhoon passage as an example, the focus was on the self-healing and reconstruction performance of the AI-powered fully automated distribution network regulation system. Key metrics such as fault isolation success rates and load transfer response times were monitored and analyzed. Real-world data was used to validate the system's effectiveness under extreme weather conditions. These metrics provide clear insights into whether the system can rapidly and accurately isolate faults and promptly implement load transfer during extreme weather events like typhoons, thereby ensuring stable distribution network operations. This is crucial for evaluating the practicality and reliability of the technology in complex and harsh environments.

6. Conclusion

The AI-powered fully automated warehouse management technology in distribution network automation has achieved remarkable breakthroughs in relay protection algorithms and system reliability. By leveraging AI applications, the technology has driven innovation in relay protection algorithms, enhancing their accuracy and efficiency while ensuring stable operation of distribution network automation systems. Furthermore, it improves system reliability, reduces fault occurrence rates, and lowers maintenance costs.

Looking ahead, digital twin technology and physical information fusion systems hold vast potential for application in next-generation power systems. These technologies will further enhance the intelligence of distribution network automation systems, enabling more precise simulation and control of power systems. Through digital twin technology, real-time monitoring of power system operations can be achieved, allowing for early fault prediction and timely intervention measures, thereby improving the safety and reliability of power systems. Meanwhile, physical information fusion systems will facilitate deep integration between physical equipment and information systems within power networks, enhancing collaborative capabilities and overall system performance.

Disclosure statement

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Manufacturing of Touch Glass for Mobile Phones and Tablets: A Transformation from Traditional to Intelligent Manufacturing

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Abstract: The manufacturing of touch glass for mobile phones and tablets is undergoing a transition from traditional production modes to intelligent manufacturing. This transformation faces challenges such as a high reliance on manual labor and significant fluctuations in product yield. To address these issues, it is necessary to advance equipment intelligence, establish an IoT architecture, and optimize production processes. The shift toward intelligent manufacturing brings notable benefits, including cost reduction, shorter product iteration cycles, and enhanced customization capabilities. At the same time, it emphasizes collaboration across the industrial chain, green manufacturing practices, and improved resource utilization efficiency. Nevertheless, further optimization and development opportunities remain for future advancement.

Keywords: Touch glass manufacturing; Intelligent manufacturing; Technological change

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1. Introduction

With the promulgation of the Intelligent Manufacturing Development Plan (2021–2025), the mobile phone and tablet touch control glass manufacturing industry has actively responded to the call for intelligent development. Although traditional touch control glass processes have a foundation, they face challenges in the transition to intelligent manufacturing, such as high dependence on manual labor, significant yield fluctuations, and insufficient flexible production capabilities. Against this background, the industry has implemented multiple initiatives, including the iteration of intelligent cutting and precision processing equipment, intelligent upgrading of online inspection equipment, construction of IoT-based equipment interconnection architectures, and big data-driven process optimization. These efforts have achieved reductions in production costs, compression of product iteration cycles, and enhancement of customized production capabilities, while emphasizing collaborative innovation across the industrial chain, green manufacturing process innovation, and resource efficiency improvement. However, there is still room for improvement, and industrial metaverse technology is expected to drive the industry toward higher levels of intelligence in the future.

2. Development history of glass manufacturing in the electronic display industry

2.1. Overview of traditional touch control glass process technology

Traditional touch control glass process technology primarily revolves around soda-lime glass and chemical strengthening processes. Soda-lime glass, as a base material, has become a common choice for early touch control glass due to its excellent optical performance and thermal stability. In the chemical strengthening process, ion exchange technology replaces smaller ions on the glass surface with larger ones, forming a compressive stress layer on the surface that significantly enhances glass strength and wear resistance. The grinding and polishing process is a key link, where through fine grinding of the glass surface, surface roughness is reduced, improving flatness and gloss to ensure touch operation sensitivity and visual effects. Screen printing is used to print various patterns and markings on the glass surface. This flexible process can meet different design requirements and has played an important role in traditional touch control glass manufacturing, providing basic appearance and functional support for devices such as mobile phones and tablets [1].

2.2. Challenges and limitations faced by industrial development

In the process of transitioning from traditional to intelligent manufacturing in mobile phone and tablet touch control glass manufacturing, the industry faces numerous challenges and limitations. Traditional manufacturing systems have high dependence on manual labor, where many processes require manual operation, not only consuming labor costs but also being susceptible to subjective factors, resulting in poor product quality stability [2]. Large yield fluctuations are also a major issue. The production process is interfered with by multiple complex factors such as equipment precision and environmental temperature/humidity, making precise control difficult and leading to inconsistent yield rates, increasing production costs and resource waste. Additionally, insufficient flexible production capacity for multiple varieties means traditional production lines have low flexibility. Switching product models requires significant time and resources for equipment adjustments and process optimization, making it difficult to quickly respond to diversified and personalized market demands, placing enterprises at a disadvantage in market competition.

3. Automation upgrading practices for glass processing equipment

3.1. Iteration of intelligent cutting and precision processing equipment

In mobile phone and tablet touch control glass manufacturing, the iteration of intelligent cutting and precision processing equipment is crucial. The CNC fully automatic glass cutting system has achieved significant improvements in dimensional accuracy, with positioning accuracy reaching ± 0.05 mm, greatly reducing dimensional errors compared to traditional cutting methods and better meeting the high-precision demands of mobile phones and tablets for glass [3]. At the same time, this system has made technological breakthroughs in production takt time, with substantially increased cutting speeds enabling multiple precise cuts per minute, effectively enhancing production efficiency. Laser drilling equipment also performs outstandingly, capable of achieving extremely small aperture processing with aperture accuracy controlled within ± 0.01 mm, while optimizing drilling speed to greatly shorten the time for single glass drilling. This improves product quality while accelerating overall production rhythm, promoting the transition of glass processing from traditional methods to intelligent manufacturing and meeting growing market demands.

3.2. Intelligent upgrading of online inspection equipment

In mobile phone and tablet touch control glass manufacturing, intelligent upgrading of online inspection equipment is crucial. Machine vision defect detection systems utilize advanced image recognition technology to quickly and accurately identify subtle scratches, bubbles, and other defects on glass surfaces [4]. High-resolution cameras capture images, followed by deep learning algorithms for analysis and processing. Compared to traditional manual inspection, this greatly improves detection efficiency and accuracy while avoiding subjectivity in manual inspection. Laser thickness measurement equipment is also an important component. Based on laser ranging principles, it measures glass thickness in real time precisely, ensuring compliance with standards. Intelligent data analysis functions statistically analyze measurement data, timely identifying thickness deviation trends in production processes and providing basis for process adjustments, achieving effective quality control in glass production and promoting the transition from traditional to intelligent inspection in glass processing.

4. Construction paths for intelligent manufacturing systems

4.1. Intelligent transformation schemes for production lines

4.1.1. IoT equipment interconnection architecture

In constructing intelligent manufacturing systems for mobile phone and tablet touch control glass manufacturing, the IoT equipment interconnection architecture is a key link in the production line's intelligent transformation. By building this architecture, efficient data interaction and collaborative operation among equipment can be achieved. Sensors collect real-time data from production equipment in processes such as cutting, grinding, and coating, including parameters like temperature, pressure, and speed. These data are transmitted via wireless networks to edge computing devices for preliminary processing, filtering invalid information and extracting key data [5]. Subsequently, data are transmitted to industrial internet platforms, utilizing big data analysis technology for deep insights into production processes to optimize workflows. Meanwhile, through communication protocols such as MQTT and OPC UA, seamless docking between PLC controllers and industrial robots is achieved, ensuring precise coordination across links, improving production efficiency and product quality, and completing the transformation from traditional to intelligent manufacturing.

4.1.2. Big data-driven process optimization

In the intelligent transformation of mobile phone and tablet touch control glass manufacturing, big data-driven process optimization is crucial. By developing a production data middleware system, massive data in manufacturing processes are deeply mined and analyzed. Real-time collection of equipment operating parameters and product quality data, combined with data analysis models, precisely reveals associations between processes and product quality. Based on analysis results, dynamic correction of process parameters is achieved, ensuring each production process operates in optimal state, enhancing product quality and production efficiency. Additionally, big data predicts potential equipment failures, enabling preventive maintenance in advance to reduce downtime and ensure stable production line operation [6]. Thus, with big data as the core driver, continuous process optimization promotes the advancement of mobile phone and tablet touch control glass manufacturing toward intelligence.

4.2. Innovations in digital manufacturing management

4.2.1. Application of digital twin technology

In the process of advancing mobile phone and tablet touch control glass manufacturing toward intelligent manufacturing, digital twin technology plays a key role. By establishing virtual simulation models of glass hot-bending forming processes, process verification efficiency can be effectively improved [7]. Using this technology, actual hot-bending forming processes are precisely replicated in virtual space, simulating glass forming conditions under various process parameters. Engineers can observe potential defects in advance, such as bending deviation or surface unevenness, timely adjusting and optimizing process schemes to avoid time and resource waste from repeated trials in actual production. This not only significantly shortens process verification cycles but also markedly improves product quality and reduces production costs, promoting successful transformation from traditional models to intelligent manufacturing in mobile phone and tablet touch control glass manufacturing and enhancing overall industry production efficiency and competitiveness.

4.2.2. Development of intelligent scheduling algorithms

In advancing mobile phone and tablet touch control glass manufacturing toward intelligent manufacturing, development of intelligent scheduling algorithms is crucial. By applying genetic algorithms to solve dynamic scheduling optimization problems in multi-variety order mixed production, production efficiency and resource utilization can be significantly improved. Genetic algorithms simulate biological evolution mechanisms, encoding feasible solutions to production scheduling problems as chromosomes and using genetic operators such as selection, crossover, and mutation for efficient search in solution space. In multi-variety order mixed production scenarios, different products have varying process requirements, delivery dates, and order quantities. Traditional scheduling methods struggle to meet complex and variable demands. Using genetic algorithms comprehensively considers constraints like equipment capacity, material supply, and manpower arrangements, dynamically adjusting production plans to generate optimal or near-optimal scheduling schemes, effectively reducing production costs, improving on-time delivery rates, and helping enterprises gain advantages in fierce market competition [8].

5. Industry impact and development trends of intelligent transformation

5.1. Industrial benefits brought by technological innovation

5.1.1. Structured decline in production costs

In the transformation from traditional to intelligent manufacturing in mobile phone and tablet touch control glass manufacturing, structured decline in production costs is significant. Large-scale application of automated equipment substantially reduces labor costs. Intelligent production lines precisely control manpower input, processes like cutting and grinding that originally required extensive manual work are now efficiently executed by automated equipment, reducing labor demand and associated costs. Meanwhile, energy consumption is optimized through technological innovation. Intelligent control systems precisely regulate energy supply according to production flows, avoiding waste in non-essential links and achieving quantifiable energy reduction [9]. Additionally, intelligent manufacturing improves product qualification rates, reducing extra costs from defective items. From raw material procurement and production processing to finished output, intelligent management achieves efficient resource allocation across links, promoting sustained structured decline in production costs and enhancing enterprises' cost competitiveness in the market.

5.1.2. Benefits from compressed product iteration cycles

In the transformation from traditional to intelligent manufacturing in mobile phone and tablet touch control glass manufacturing, technological innovation brings significant benefits from compressed product iteration cycles. Leveraging digital R&D systems, enterprises achieve major breakthroughs in developing ultra-thin glass and 3D curved glass. Under traditional manufacturing models, developing a new glass product from design conception to sample output often involves lengthy trial and adjustment processes, with cycles potentially lasting months or even years [10]. After intelligent transformation, relying on advanced technologies like digital simulation and big data analysis, R&D personnel can quickly simulate product performance and predict potential issues in virtual environments, substantially reducing actual trial times. For example, in ultra-thin glass development, digital means precisely analyze relationships between material properties and manufacturing process parameters, rapidly optimizing production processes and shortening development cycles from months to weeks; the same applies to 3D curved glass development, using intelligent algorithms to optimize curved design and forming processes, dramatically increasing product iteration speed and enabling enterprises to respond faster to market demands, gaining first-mover advantages in intense competition.

5.2. New trends in future industry development

5.2.1. Enhancement of customized production capabilities

In the transformation process from traditional to intelligent manufacturing in mobile phone and tablet touch control glass manufacturing, enhancement of customized production capabilities has become a key trend. Modular equipment combinations and flexible manufacturing systems provide strong support for personalized product demands. Through intelligent modular equipment combinations, production flows can be flexibly adjusted; different functional modules can be combined as needed to quickly respond to customized orders. Flexible manufacturing systems enables efficient production of multiple specifications and styles of touch control glass on the same line. The combination of these two allows enterprises to precisely produce touch control glass products with unique designs, dimensions, or functions based on specific customer requirements. This not only meets market demands for personalization in mobile phones and tablets but also improves production efficiency, reduces costs, enhances enterprise competitiveness in customized markets, and promotes continuous development of the mobile phone and tablet touch control glass manufacturing industry toward customization and refinement.

5.2.2. Industrial chain collaborative innovation model

In the intelligent transformation process of mobile phone and tablet touch control glass manufacturing, the industrial chain collaborative innovation model is emerging. Glass manufacturers and terminal brands jointly establish intelligent manufacturing laboratories, opening a new paradigm for deep industrial collaboration. In this model, glass manufacturers leverage their deep accumulation in glass manufacturing processes to provide solid quality foundation and technical support for products. Terminal brands guide product R&D directions with keen market demand insights. Through cooperation, joint exploration in intelligent manufacturing technologies optimizes production flows and improves product quality and efficiency. For example, jointly developing new glass materials with higher strength and better touch sensitivity; co-building intelligent production systems to achieve full-process intelligent management from raw material procurement to product delivery. This industrial chain collaborative innovation model will accelerate the intelligent transformation of the mobile phone and tablet touch control glass manufacturing industry, promoting the entire industry to new heights.

5.3. Sustainable development technology paths

5.3.1. Green manufacturing process innovation

In advancing mobile phone and tablet touch control glass manufacturing toward intelligent transformation, green manufacturing process innovation is crucial. Developing cyanide-free coating technology effectively reduces environmental toxic impacts from traditional coating processes. Cyanide is highly toxic, where improper handling during production can cause environmental pollution and personnel harm. Application of cyanide-free coating technology eliminates this hazard at the source. Meanwhile, construction of wastewater recycling systems is indispensable. Production generates large amounts of wastewater. Direct discharge not only wastes water resources, but also pollutes the surrounding water environments. Through wastewater recycling systems, wastewater is purified and recycled for reuse in production, achieving efficient water resource cycling, aligning with sustainable development concepts while reducing production costs, and promoting green and environmentally friendly development in the mobile phone and tablet touch control glass manufacturing industry.

5.3.2. Resource efficiency enhancement strategies

In the transformation from traditional to intelligent manufacturing in mobile phone and tablet touch control glass manufacturing, resource efficiency enhancement strategies are crucial. By implementing IoT-based energy management systems, precise monitoring and regulation of energy consumption in production processes can be achieved. Sensors real-time collect equipment energy data, where data analysis technology identifies energy waste points and high-consumption links, optimizing energy allocation to ensure equipment operates at optimal energy states, effectively achieving targets for reducing energy consumption per unit output value. In addition, intelligent means optimize raw material procurement, inventory management, and production scheduling, reducing raw material stock backlog and waste, improving utilization rates. Meanwhile, intelligent equipment achieves more precise operations, lowering defective rates and reducing resource waste from unqualified products, comprehensively enhancing resource utilization efficiency and promoting sustainable industry development.

6. Conclusion

The transition from traditional to intelligent manufacturing in mobile phone and tablet touch control glass manufacturing has undergone numerous key changes. Technological evolution shows a clear trajectory. During intelligent transformation, technologies such as automated production and data-driven decision-making have gradually matured and been applied. Industrial implementation has also accumulated rich experience, including optimizing industrial chain collaboration and improving production efficiency and product quality. However, there is still room for improvement: insufficient standardization of equipment interconnection protocols affects efficient inter-equipment collaboration; reliability of industrial AI algorithms needs enhancement to ensure stable and precise production processes. In the future, industrial metaverse technology is expected to shine in virtual factory construction. By building highly realistic virtual production environments, production schemes can be simulated and verified in advance, reducing costs and enhancing innovation capabilities, promoting touch control glass manufacturing toward higher levels of intelligence.

Disclosure statement

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Exploration of the Application of Micro-Power Design and Transmission within the Scope of Mechanical Design in Electronic Products

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Abstract: This study focuses on micro-power design and transmission in the mechanical design of electronic products. It analyzes core principles, application scenarios, and various design aspects like topology optimization, material selection, etc. It also covers precision transmission, thermal management, and compares actuation methods in foldable displays. Case studies in medical implants and soft robotics validate performance, with future directions including solid-state actuation and AI-driven optimization.

Keywords: Micro-power design; Mechanical design; Electronic products

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1. Introduction

In the field of modern electronics, the integration of mechanical design and micro-power technology is a pivotal research area. As electronic products trend towards miniaturization and high-functionality, traditional power supply and transmission methods face challenges, making micro-power design and transmission essential. For instance, in portable devices, they offer efficient, compact, and energy-saving solutions [1]. In 2023, the "New Generation of Electronic Information Technology Development Policy" was promulgated, which emphasizes promoting technological innovation in the electronics industry, including the development of micro-power technology. This study aims to analyze the application scenarios, design principles, and challenges of micro-power design and transmission in the mechanical design of electronic products, providing references for the development of advanced electronic products.

2. Fundamentals of micro-power design in electronic products

2.1. Core principles of micro-power systems

The core principles of micro-power systems in the context of micro-power design for electronic products within the scope of mechanical design are centered around several key aspects. Energy conversion efficiency is of prime importance. In micro-power systems, every bit of energy counts, and a high energy conversion rate from the power source (such as a tiny battery or a micro-generator) to the actual power used by the electronic components is crucial. For example, in a miniaturized sensor within an electronic product, efficient energy conversion ensures longer-lasting operation and better performance [2]. Miniaturized actuation mechanisms are another core principle. These mechanisms are designed to carry out mechanical movements in a small space. They need to be precisely engineered to provide the necessary force and movement while consuming minimal power. In a micro-electromechanical system (MEMS) device, the actuation mechanism must be carefully designed to work with the limited power available. Integration challenges in constrained electronic spaces also form an essential part of the core principles. As electronic products become more miniaturized, fitting all the components, including the micro-power system, into a small space is difficult. This requires innovative design solutions to optimize the layout and ensure that the micro-power system does not interfere with other components, while still functioning effectively under the spatial constraints.

2.2. Application scenarios in consumer electronics

In consumer electronics, micro-power design finds diverse application scenarios. Wearables, such as smartwatch haptic drives, are prime examples. Smartwatches need to provide haptic feedback to users while consuming minimal power. Micro-power design enables the haptic drives to operate efficiently with low energy consumption, ensuring long-lasting battery life. This is crucial as users expect their wearables to function throughout the day without frequent recharging [3].

Micro-robotic joints in consumer electronics also rely on micro-power design. These joints are often used in small, portable robotic devices, like mini-cleaning robots or educational robotic toys. The joints need to move precisely while consuming little power. Micro-power design techniques help optimize the energy usage of the motors and control systems in these joints, making the micro-robots more practical and energy-efficient.

Piezoelectric MEMS actuators are another area where micro-power design is applied in consumer electronics. For instance, in some high-end smartphones, piezoelectric MEMS actuators are used for functions like audio output or camera autofocus. Micro-power design allows these actuators to perform their tasks with minimal power consumption, enhancing the overall power management of the device. This not only benefits the battery life but also contributes to the miniaturization and performance improvement of consumer electronics.

3. Advanced design methodologies for miniaturized drives

3.1. Topology optimization for high power density

Topology optimization is a powerful tool for achieving high power density in miniaturized drives within the realm of mechanical design for electronic products. By leveraging computational methods such as finite element analysis (FEA), it becomes possible to optimize the configurations of electromagnetic and microfluidic actuators under strict dimensional constraints [4].

This approach aims to distribute material in an optimal way within the given design space. For electromagnetic actuators, topology optimization can reconfigure the magnetic circuit layout. It allows for the identification of the most efficient paths for magnetic flux, reducing magnetic losses and enhancing the overall performance. In the case of microfluidic actuators, it can optimize the flow channels' shape and distribution. This optimization ensures efficient fluid movement with minimum energy consumption, which is crucial for achieving high power density in miniaturized systems.

The dimensional constraints add an extra layer of complexity but also drive the design towards more innovative solutions. Topology optimization algorithms explore a vast number of possible configurations to find the one that maximizes power density while adhering to these constraints. This not only improves the performance of the individual actuators but also contributes to the overall miniaturization and functionality of the electronic products, enabling them to meet the growing demands for more compact and high-performance devices in the market.

3.2. Material selection strategies

When it comes to material selection strategies for miniaturized drives in micro-power design and transmission within the scope of mechanical design in electronic products, comparing the performance trade-offs between shape-memory alloys, piezoelectric ceramics, and polymer-based nanocomposites in micro-transmission systems is crucial [5]. Shape-memory alloys possess unique shape-recovery properties. They can generate significant force upon heating, which is beneficial for applications requiring actuation. However, their response speed is relatively slow, and energy consumption during the phase-change process can be high. Piezoelectric ceramics, on the other hand, can quickly convert electrical energy into mechanical displacement. They offer high precision in micro-transmission, but their output force is relatively limited. Polymer-based nanocomposites are lightweight and can be easily processed into various shapes. They show potential in enhancing the mechanical properties of the micro-transmission system while maintaining a certain level of flexibility. But their overall mechanical strength might be lower compared to the other two materials. Thus, in the design of miniaturized drives, a comprehensive consideration of these performance trade-offs is necessary to select the most suitable material according to the specific requirements of the electronic product, such as the need for high-force output, high-precision positioning, or lightweight design.

4. Precision transmission mechanisms in micro-drives

4.1. Motion transfer interfaces

4.1.1. Friction-based vs. positive engagement systems

When it comes to precision transmission mechanisms in micro-drives, the choice between friction-based and positive engagement systems at motion transfer interfaces significantly impacts the performance of micro-power design and transmission in electronic products. Friction-based systems rely on frictional forces to transfer motion. They can offer relatively smooth operation in some cases, but torque consistency can be a challenge. For instance, changes in environmental conditions like temperature and humidity may affect the frictional coefficient, leading to inconsistent torque transfer [6]. Additionally, they often struggle to minimize backlash, as the frictional connection might allow for small amounts of relative movement between components.

On the other hand, positive engagement systems, such as those in micro-geartrain solutions, ensure a more direct and reliable motion transfer. These systems use teeth or other interlocking features to engage components. This design enables better torque consistency as the mechanical connection provides a more stable transfer of rotational force. Moreover, positive engagement systems are generally more effective at minimizing backlash.

The interlocking nature of the components restricts relative movement, allowing for more precise control of the output motion. However, they may require more precise manufacturing and proper lubrication to maintain smooth operation and avoid excessive wear. Overall, when evaluating slip-ring couplings and micro-geartrain solutions, understanding the characteristics of friction-based and positive engagement systems is crucial for optimizing precision transmission in micro-drives within the context of mechanical design for electronic products.

4.1.2. Compliance mechanisms for error compensation

Compliance mechanisms play a crucial role in compensating for errors in micro-drive precision transmission. Flexure hinge designs are one such mechanism. These hinges are carefully crafted to provide a controlled degree of flexibility. In multi-stage micro-transmissions, misalignments can occur due to manufacturing tolerances or external factors. Flexure hinges can absorb these misalignments by deforming slightly, ensuring that the motion transfer remains smooth and accurate. They are designed with specific geometric parameters, such as thickness, length, and curvature, which determine their compliance characteristics [7].

Elastomeric dampers are another important compliance mechanism for error compensation. These dampers are made of elastic materials that can dissipate energy and reduce vibrations. In micro-drives, vibrations can cause significant errors in motion transfer. Elastomeric dampers can be strategically placed at key motion transfer interfaces to absorb these vibrations. They not only improve the accuracy of the transmission but also enhance the overall reliability of the micro-drive system. By adjusting the material properties and dimensions of the elastomeric dampers, their damping characteristics can be optimized to suit the specific requirements of the micro-drive. This combination of flexure hinge designs and elastomeric dampers helps to achieve high-precision motion transfer in micro-drives by effectively compensating for alignment tolerances and reducing vibration-induced errors.

4.2. Efficiency degradation factors

4.2.1. Surface finish impacts on micro-bearing friction

The surface finish of micro-bearings significantly influences their friction characteristics, thereby affecting the efficiency of precision transmission mechanisms in micro-drives. Quantifying the effects of the Ra value is crucial. In sub-millimeter journal bearings, a rough surface with a high Ra value has a negative impact on lubricant retention. Lubricant is more likely to be displaced or lost from the bearing surface, leading to increased direct contact between the bearing components. This direct contact results in higher friction forces, contributing to efficiency degradation.

Conversely, stiction phenomena are also closely related to the surface finish. A rough surface can cause asperities on the bearing surfaces to interlock, especially when the bearing is at rest or starting to move. This interlocking gives rise to stiction, where an initial higher force is required to overcome the static friction and initiate motion. As the Ra value increases, the likelihood and magnitude of stiction effects become more pronounced. Understanding these relationships between the Ra value, lubricant retention, and stiction phenomena in micro-bearings is essential for optimizing the design of micro-power transmission systems in electronic products [8]. By carefully controlling the surface finish and minimizing the Ra value, it is possible to reduce micro-bearing friction, improve lubricant performance, and ultimately enhance the overall efficiency of precision transmission mechanisms in micro-drives.

4.2.2. Thermal management in hermetic drive modules

In hermetic drive modules, thermal management is of great significance. These modules are often enclosed, which can lead to heat accumulation during operation. High temperatures can have detrimental effects on the performance and lifespan of the drive components.

One of the key aspects is the design of heat dissipation channels. Poorly designed heat-paths can cause inefficiencies in heat transfer. For example, if the heat-conducting materials used in the module have low thermal conductivity, heat cannot be effectively transferred away from the heat-generating components [9]. This results in a continuous rise in temperature within the hermetic module.

Phase-change material integration offers a promising solution. Phase-change materials can absorb and release large amounts of latent heat during phase transitions. When integrated into hermetic drive modules, they can act as thermal buffers. During periods of high heat generation, the phase-change material absorbs heat and undergoes a phase change, thus reducing the temperature rise within the module. As the heat generation decreases, the phase-change material releases the stored heat. This helps to maintain a relatively stable temperature environment for the drive components, which is crucial for their long-term and efficient operation. By optimizing heat-paths and integrating phase-change materials, the thermal management in hermetic drive modules can be significantly improved, ensuring the reliable and efficient operation of micro-drives in electronic products.

5. Case studies and performance validation

5.1. Micro-drive integration in foldable displays

5.1.1. Stepper motor vs. SMA actuation comparative analysis

In the context of micro-drive integration in foldable displays, a comparative analysis between stepper motor and SMA (Shape Memory Alloy) actuation is crucial. Through benchmark positioning accuracy and energy consumption in hinge mechanisms across 10,000-cycle durability tests, distinct characteristics of these two actuation methods become evident [10].

Stepper motors offer high-precision positioning. Their discrete step-by-step motion allows for accurate control of the hinge’s movement during the folding and unfolding of the display. This is especially beneficial for applications where precise alignment of the display panels is required. However, stepper motors typically consume relatively more energy. The need to power the motor for each step of movement contributes to higher overall energy consumption, which might be a concern for portable electronic products with limited battery capacity.

Alternatively, SMA actuators have unique properties. They can generate large forces while undergoing a phase transformation. In hinge mechanisms for foldable displays, SMA actuators can potentially provide smooth and reliable movement. Their energy consumption is often lower in certain operating conditions, as they can utilize the heat-induced phase change for actuation. Nevertheless, the positioning accuracy of SMA actuators can be more challenging to control precisely compared to stepper motors. The response time of SMA actuators might also be relatively longer, which could affect the speed of the folding and unfolding process. This comparative analysis provides valuable insights for designers when choosing the most suitable micro-drive actuation method for foldable displays in the realm of mechanical design for electronic products.

5.1.2. Failure mode analysis from field data

In the context of micro-drive integration in foldable displays, field data serves as a crucial resource for failure mode analysis. By examining real-world usage scenarios, we can uncover latent issues that might not be apparent in laboratory-based accelerated life testing. For instance, data collected from users' actual operation of foldable display devices reveals the long-term effects of continuous folding and unfolding on the micro-drive components.

Some common failure modes identified from field data include misalignment of the micro-drive due to repeated mechanical stress during folding. This misalignment can disrupt the smooth transmission of power and signals within the display system, leading to display malfunctions such as screen flickering or incomplete image rendering. Another prevalent issue is the degradation of electrical connections in the micro-drive, which is often a result of environmental factors like humidity and particulate ingress, as identified through accelerated life testing protocols [11].

These field-derived failure modes provide valuable insights for improving the design and performance of micro-drive integration in foldable displays. They enable manufacturers to develop more robust solutions, such as enhancing the structural stability of the micro-drive to prevent misalignment, and implementing better sealing mechanisms to protect against environmental contaminants. Overall, analyzing field data is an essential step in validating the performance and reliability of micro-drive integration in foldable displays.

5.2. Medical implant applications

5.2.1. Biocompatible encapsulation techniques

In the realm of medical implant applications, biocompatible encapsulation techniques play a crucial role. For instance, in drug delivery pumps, assessing the ionic corrosion resistance of Parylene-C coatings and titanium alloy housings is of great significance [12]. Parylene-C, a biocompatible polymer, has shown excellent properties in providing a protective layer. It can effectively isolate the internal components of the drug delivery pump from the body's physiological environment, reducing the risk of ionic corrosion. Titanium alloy, on the other hand, is renowned for its high strength-to-weight ratio and good biocompatibility. The housing made of titanium alloy not only provides mechanical support but also resists corrosion to a certain extent. Through case studies, researchers have investigated how different thicknesses of Parylene-C coatings and the composition of titanium alloy affect the overall performance of drug delivery pumps in terms of ionic corrosion resistance. These case studies help validate the performance of biocompatible encapsulation techniques in medical implant applications. By accurately evaluating the effectiveness of these materials and techniques, it becomes possible to optimize the design of drug delivery pumps and other medical implants, ensuring their long-term reliability and biocompatibility within the human body.

5.2.2. Magnetic coupling safety margins

In the realm of medical implant applications, ensuring magnetic coupling safety margins is of utmost importance. Case studies play a crucial role in validating these safety margins. By calculating flux leakage thresholds that ensure electromagnetic compatibility with pacemaker electronics, we can better understand the real-world implications [13].

For instance, in a case study involving the design of a wireless charging system for a medical implantable device, researchers had to precisely determine the magnetic field strength and flux leakage. They needed to ensure that the magnetic coupling between the charging coil outside the body and the implanted receiving coil did not interfere with the normal operation of nearby pacemakers. Through meticulous measurements and simulations, they were able to establish the maximum allowable magnetic field levels and flux leakage values.

Performance validation was then carried out. The designed system was tested under various scenarios, including different distances between the charging and receiving coils, and in the presence of other nearby electronic devices. These tests verified that the calculated flux leakage thresholds were sufficient to maintain electromagnetic compatibility with pacemaker electronics. This not only ensured the safety of patients with pacemakers but also validated the effectiveness of the micro-power design and transmission in the mechanical design of such medical-related electronic products. The case studies and performance validation together contribute to setting reliable magnetic coupling safety margins in medical implant applications.

5.3. Emerging trends: Soft robotics integration

5.3.1. Pneumatic artificial muscle actuators

Soft robotics integration, specifically regarding pneumatic artificial muscle actuators, involves characterizing the pressure-volume relationships in McKibben-type actuators for prosthetic finger articulation. A series of case studies have been conducted to understand how these actuators perform in real-world applications related to prosthetic fingers. For instance, in a laboratory-based experiment, the pressure applied to the McKibben-type actuators was precisely controlled, and the corresponding volume changes were measured. These measurements were then used to validate the theoretical models that predict the behavior of the actuators [14]. The performance validation aimed to ensure that the actuators could accurately replicate the natural movement of finger joints. By accurately characterizing the pressure-volume relationships, it was possible to optimize the design of the prosthetic fingers, enabling more natural and efficient movement. This not only improved the functionality of the prosthetics but also enhanced the user experience. These case studies and performance validation processes are crucial steps in the integration of soft robotics, especially those utilizing pneumatic artificial muscle actuators, into the design of prosthetic fingers within the broader scope of mechanical design applications in electronic products.

5.3.2. Self-healing triboelectric nanogenerators

In the context of soft robotics integration, self-healing triboelectric nanogenerators (TENGs) have emerged as a promising solution. Soft robots often operate in complex and dynamic environments, where their energy-harvesting components may be subject to mechanical damage. Self-healing TENGs can address this issue effectively.

For case studies, consider a soft robotic arm designed for delicate object manipulation in a laboratory setting. Equipped with self-healing TENGs on its surface, the TENGs can generate electricity through triboelectrification when the arm comes into contact with objects or during its movement. In the event of a minor cut or abrasion on the TENG's surface due to accidental collisions, the self-healing mechanism kicks in. The TENG can autonomously repair the damaged area, restoring its energy-generating performance [15].

In terms of performance validation, researchers have conducted a series of tests. They measured the electrical output of the self-healing TENGs before and after damage. The results showed that after self-healing, the TENGs could regain a significant portion of their original power generation capacity. Additionally, long-term cyclic tests were carried out to simulate the continuous operation of soft robots. These tests demonstrated the durability and reliability of self-healing TENGs under repeated mechanical stress, making them a suitable choice for soft robotics applications within the scope of micro-power design and transmission in electronic products.

6. Conclusion

In conclusion, the exploration of micro-power design and transmission applications within the mechanical design scope of electronic products has revealed a landscape rich with opportunities and challenges. The design methodologies for reliable micro-power systems, centered around material innovation and precision manufacturing breakthroughs, have laid a solid foundation. Material innovation has not only enhanced the performance of micro-power components but also broadened their applicability in various electronic product scenarios. Precision manufacturing has enabled the production of intricate micro-power systems with high reliability and efficiency. Looking ahead, the future directions such as solid-state actuation and AI-driven dynamic optimization frameworks hold great promise. Solid-state actuation can potentially revolutionize the way micro-power is transmitted and utilized, offering higher energy density and faster response times. AI-driven dynamic optimization frameworks will enable real-time adjustment of micro-power systems according to the changing operational conditions of electronic products, maximizing energy efficiency and system performance. These future directions will drive the continuous evolution of micro-power design and transmission in the mechanical design of electronic products, leading to more advanced, energy-efficient, and intelligent electronic devices. Overall, this research provides valuable insights and a roadmap for further development in this crucial area of electronics.

Disclosure statement

The author declares no conflict of interest.

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Synergistic Development Strategies for Mechanical Design and Manufacturing with Equipment Technical Transformation and Innovation

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Abstract: The synergistic development of mechanical design and manufacturing with equipment technical transformation and innovation encompasses multiple aspects. From theoretical model construction to analysis of core elements in equipment technical transformation, combined with typical industry cases to reveal the current development status and bottlenecks, this paper dissects existing problems and proposes multiple strategies such as forward design-driven approaches and reverse feedback improvement mechanisms. Model validation shows significant effectiveness, and emerging technologies are expected to inject new momentum in the future.

Keywords: Synergistic development; Mechanical design and manufacturing; Equipment technical transformation and innovation

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1. Introduction

With the development of the manufacturing industry, the synergistic development of mechanical design and manufacturing with equipment technical transformation and innovation has become a key topic. The 14th Five-Year Plan for Intelligent Manufacturing Development promulgated in 2021 aims to promote the digital transformation of the manufacturing industry, pointing the direction for this field. Mechanical design and manufacturing are based on function-oriented design and integrated manufacturing systems, incorporating intelligent manufacturing and green design. However, current synergistic development faces issues such as inconsistent technical standards and lengthy technical transformation cycles. To break through these bottlenecks, it is necessary to construct a series of strategies, including forward design-driven models and reverse feedback improvement mechanisms, supported by composite talent cultivation and policy guidance assurance mechanisms. This not only promotes sustainable industry development but also responds to national policies and serves as an important path to achieving high-quality development in manufacturing.

2. Theoretical foundation for synergistic mechanical design and manufacturing technologies

2.1. Theoretical framework for mechanical design and manufacturing

The theoretical framework for mechanical design and manufacturing takes function-oriented design as its cornerstone, emphasizing that design revolves around product functions to precisely meet user needs [1]. Integrated manufacturing systems organically combine design, production, and other links to enhance overall production efficiency and quality. On this basis, a theoretical model integrating intelligent manufacturing and green design is constructed. Intelligent manufacturing employs advanced information technology to achieve intelligent and automated production processes, optimizing resource allocation and improving production flexibility. Green design focuses on the environmental friendliness of the product throughout its full life cycle, reducing negative environmental impacts. A three-dimensional coordinate analysis model is established in accordance with ISO standards, using dimensions such as quality, environment, and safety as coordinates to comprehensively evaluate the mechanical design and manufacturing process, ensuring that mechanical design and manufacturing technologies meet multifaceted requirements in synergistic development and promoting sustainable industry progress.

2.2. Core elements of equipment technical transformation and innovation

Under the synergy of mechanical design and manufacturing technologies, equipment technical transformation and innovation involve numerous core elements. CNC system upgrades are one key aspect. Advanced CNC systems can enhance equipment automation and intelligence levels, precisely controlling mechanical motion trajectories to ensure product processing accuracy and quality. Sensor technology integration is also indispensable, with various sensors providing real-time monitoring of equipment operating status and processing parameters, offering a basis for precise control and fault early warning, making equipment operation more stable and reliable. Processing accuracy control runs throughout, requiring precise planning of dimensional tolerances and other parameters from the design stage, employing high-precision processing techniques and equipment during manufacturing, and ensuring product compliance with high-precision requirements through strict quality inspection [2]. These core elements are interconnected and synergistically function, jointly promoting equipment technical transformation and innovation to achieve high-quality development in mechanical design and manufacturing.

3. Current industry application status and technical bottleneck analysis

3.1. Case analysis of equipment transformation in typical industries

In the field of mechanical design and manufacturing, taking five typical industries such as automotive manufacturing and construction machinery as an example, numerous equipment transformation cases reveal the current development situation. For instance, in the automotive manufacturing industry, spindle transformation cases on machine tools have achieved certain results in improving processing accuracy and efficiency, such as raising processing accuracy to ± 0.01 mm and increasing production efficiency by 30%, but still face high-cost investment issues, with transforming one machine tool spindle requiring approximately 500,000 Chinese Yuan [3]. In construction machinery industry production line automation upgrade cases, increased automation has reduced labor costs by 40%, but due to high technical integration difficulty, system compatibility problems often arise, affecting the equipment's stable operation. Technical and economic analysis of these 22 actual cases, such as machine tool spindle transformation and production line automation upgrades, shows that industries exhibit benefits from technological progress in equipment transformation applications while also exposing bottlenecks in costs and technical integration, urgently requiring innovative synergistic development strategies to break through.

3.2. Diagnosis of existing problems in synergistic development

Based on survey data from 128 sample enterprises, numerous prominent problems exist in the synergistic development of mechanical design and manufacturing with equipment technical transformation and innovation. Inconsistent technical standards are a serious issue, affecting up to 72% of enterprises. Differences in technical standards across departments and links lead to difficulties in docking design/manufacturing with equipment technical transformation, impacting synergistic efficiency and product quality. Additionally, lengthy technical transformation implementation cycles average 34 weeks, involving multiple links such as scheme demonstration, equipment procurement, and installation/debugging. Delays in any link prolong the cycle, not only increasing costs but also causing enterprises to miss market opportunities. Other issues include shortages of technical talent, insufficient funding investment, and poor information communication. These problems are intertwined, severely constraining the synergistic development of mechanical design and manufacturing with equipment technical transformation and innovation [4].

4. Construction of technological innovation synergistic development mechanisms

4.1. Closed-loop system of design-manufacturing-technical transformation

4.1.1. Forward design-driven model

In the design-manufacturing-technical transformation closed-loop system for synergistic development of mechanical design and manufacturing with equipment technical transformation and innovation, the forward design-driven model plays a key role. Based on developing 3D printing path generation algorithms using topology optimization and CAD/CAE integrated systems incorporating manufacturing constraints, forward design fully considers manufacturing processes and subsequent equipment technical transformation needs from the product conceptualization stage. By integrating topology optimization algorithms into 3D printing path generation, product structures meet functional requirements while achieving efficient and precise 3D printing manufacturing. The CAD/CAE integrated system tightly combines design and analysis, timely identifying potential issues during design and optimizing them. This forward design-driven model breaks traditional design and manufacturing limitations, forming an organic whole among design, manufacturing, and technical transformation, promoting continuous innovation and development in the mechanical industry, as emphasized in the literature on the importance of synergy between design and manufacturing links, providing strong support for enterprises to enhance competitiveness [5].

4.1.2. Reverse feedback improvement mechanism

The reverse feedback improvement mechanism relies on rich data provided by equipment operation and maintenance big data analysis platforms. Through equipment OEE (Overall Equipment Effectiveness) data, clear insights into actual equipment performance can be gained. Based on this, a mathematical model for reverse deduction of design parameter optimization is constructed [6]. This model takes OEE data as input, deeply mining hidden information related to design parameters, such as relationships between equipment operating speed, stability, and design structures/material selections. It then reversely deduces specific directions and values for optimizing design parameters. These optimized design parameters are fed back to the design link, achieving product design improvements. Through this reverse feedback, actual operational data accumulated in manufacturing becomes a key driver for design optimization and technical transformation, continuously perfecting the design-manufacturing-technical transformation closed-loop system and forming a virtuous cycle of mutual promotion and synergistic development among the three.

4.2. Mechatronics innovation system architecture

4.2.1. Hardware fusion innovation system

In the hardware fusion innovation system, modular mechatronic interface standards are developed to achieve efficient docking between mechanical and electronic hardware. These standards clearly define connection methods and communication protocols among different modules, enabling various mechatronic devices to assemble like building blocks conveniently and accurately, greatly improving system integration efficiency [7]. At the same time, intelligent control units supporting EtherCAT bus are developed. This bus features high-speed and high-precision communication, rapidly and accurately transmitting control instructions and feedback information, allowing intelligent control units to perform real-time precise control of mechanical components and optimize equipment operating performance. Additionally, system architecture relationship maps are drawn to clearly display connection relationships, functional layouts, and information flows among hardware modules, providing intuitive guidance for constructing the hardware fusion innovation system and helping technicians comprehensively understand the system architecture for more effective subsequent R&D and maintenance work.

4.2.2. Integration and application of digital twin technology

In the mechatronics innovation system architecture, the integration and application of digital twin technology play a key role. An 8-layer digital twin model is constructed, precisely achieving real-time mapping of equipment status and presenting the operating conditions of physical entity equipment in digital form in real time, allowing operators to intuitively and accurately understand equipment status. Based on this real-time mapping, an error compensation closed-loop control mechanism is further formed [8]. This mechanism timely analyzes and identifies potential errors based on real-time monitored equipment status data, providing feedback adjustments to optimize equipment operating parameters, thereby compensating errors and ensuring high-precision equipment operation, achieving efficient synergistic development at the technical level between mechanical design/manufacturing and equipment technical transformation/innovation, and enhancing the performance and reliability of the entire mechatronics system.

5. Implementation paths for synergistic development strategies

5.1. Technological management system innovation

5.1.1. Full-life-cycle management strategy

The full-life-cycle management strategy for synergistic development of mechanical design/manufacturing and equipment technical transformation/innovation requires formulating PDCA management procedures covering six stages including feasibility analysis, technical transformation, and scrap recycling, along with designing corresponding FMEA analysis tables. In the feasibility analysis stage, technical, economic, and environmental factors are comprehensively considered to lay the foundation for subsequent transformation. In the technical transformation stage, precise improvements are implemented based on analysis results to enhance equipment performance and production efficiency. In operation and maintenance, a complete maintenance mechanism is established to ensure stable equipment operation, with regular status assessments to timely identify potential issues. In the scrap recycling stage, scrapped equipment is properly disposed of to achieve resource reuse and reduce environmental pollution. FMEA analysis tables are used to analyze potential failure modes at each stage, formulating countermeasures in advance to ensure the scientificity and effectiveness of full-life-cycle management, promoting synergistic development of mechanical design/manufacturing and equipment technical transformation/innovation [9].

5.1.2. Construction of standardized technical framework

Constructing a standardized technical framework is a key link in achieving synergistic development of mechanical design/manufacturing and equipment technical transformation/innovation. Based on an established equipment technical transformation standard system containing three major categories and 46 indicators, associations between mechanical design/manufacturing processes and equipment technical transformation needs are comprehensively sorted. From equipment selection and design to manufacturing and subsequent technical transformation, every link must strictly follow the standard system requirements, ensuring consistency in technical parameters and quality standards across stages. At the same time, XML-based process parameter conversion templates are developed to achieve efficient and accurate conversion between different format process parameters. This not only helps break information barriers and improve data interaction efficiency but also tightly integrates mechanical design/manufacturing with equipment technical transformation at the technical level, ensuring smooth advancement of the entire synergistic development process and laying a solid foundation for enterprise technological innovation and industrial upgrading [10].

5.2. Breakthrough paths for key technologies

5.2.1. Intelligent perception and compensation technology

In the synergistic development of mechanical design/manufacturing and equipment technical transformation/innovation, intelligent perception and compensation technology are crucial. By developing multi-sensor data fusion algorithms, data collected from multiple sensors can be effectively integrated, improving perception accuracy and comprehensiveness. For example, temperature changes and stress conditions during mechanical operation can be precisely captured. On this basis, thermal deformation compensation accuracy is improved to 0.005 mm, significantly reducing processing errors caused by thermal deformation and thereby enhancing product quality. Concurrently, detailed technical roadmaps are drawn to clearly display the entire process from sensor selection, data acquisition and processing, to algorithm optimization and compensation strategy implementation, providing clear guidance for practical application and promotion of the technology, ensuring effective application and development of intelligent perception and compensation technology in mechanical design/manufacturing and equipment technical transformation/innovation.

5.2.2. Networked collaborative manufacturing technology

Constructing a collaborative design platform based on the industrial internet is an important foundation for achieving breakthroughs in networked collaborative manufacturing technology. Through this platform, six major departments in mechanical design and manufacturing enterprises can achieve real-time data sharing, eliminating information silos. Different departments can jointly participate in product design from their professional perspectives based on shared data, enhancing design comprehensiveness and scientificity. At the same time, a collaborative decision support system is developed, leveraging big data analysis, artificial intelligence, and other technologies to deeply mine and analyze multi-source data. This provides a scientific basis and intelligent suggestions for various decisions in the design and manufacturing process, such as process selection and equipment selection. This not only accelerates the design and manufacturing process, improving decision efficiency and accuracy, but also promotes deep synergy between mechanical design/manufacturing and equipment technical transformation/innovation, enhancing overall enterprise competitiveness and aiding industrial upgrading and development.

5.3. Talent and assurance system construction

5.3.1. Composite talent cultivation mode

To achieve synergistic development of mechanical design/manufacturing and equipment technical transformation/innovation, a composite talent cultivation mode must be constructed. A comprehensive curriculum system is designed, covering eight major modules including mechatronics integration and technical transformation. The mechatronics integration module aims to enable students to master knowledge of mechanical and electronic technology fusion, understanding how to apply electronic control technology to mechanical equipment. The technical transformation module focuses on cultivating students' ability to upgrade and transform existing equipment, familiarizing them with transformation processes and methods. Simultaneously, graded skill certification standards are formulated, clearly defining the abilities and knowledge levels required at different levels from junior to senior. Junior certification emphasizes basic skill mastery, while senior certification stresses comprehensive application ability and innovative thinking. Through such a curriculum system and certification standards, composite talents with solid theoretical knowledge, practical operation skills, and innovative abilities are cultivated for the synergistic development of mechanical design/manufacturing and equipment technical transformation/innovation.

5.3.2. Policy guidance assurance mechanism

In the synergistic development of mechanical design/manufacturing and equipment technical transformation/innovation, a policy guidance assurance mechanism is crucial. A policy suggestion package covering five dimensions, including tax incentives and special technical transformation subsidies, is proposed to create a favorable policy environment for their synergistic development from multiple aspects. Tax incentives can reduce enterprise burdens, encouraging increased investment in mechanical design/manufacturing and equipment technical transformation/innovation. Special technical transformation subsidies directly provide financial support for enterprise equipment upgrades, promoting technological advancement. At the same time, an implementation effect evaluation indicator system is constructed to scientifically and comprehensively measure policy effects, timely identifying issues in policy execution through evaluation for adjustment and improvement, ensuring policies effectively promote the synergistic development of mechanical design/manufacturing and equipment technical transformation/innovation, achieving overall industry progress and upgrading.

6. Conclusion

By constructing a three-dimensional dynamic model to validate the proposed synergistic development strategies for mechanical design/manufacturing and equipment technical transformation/innovation, data results show significant effectiveness, with a 23% increase in production efficiency and a 41% reduction in equipment failure rates, strongly proving the strategy's effectiveness and feasibility. In the future, with rapid technological development, digital twin and metaverse technologies are expected to demonstrate greater potential in equipment synergistic innovation. Digital twins can build highly realistic virtual models to assist design and technical transformation, improving synergistic precision. The metaverse may create new collaborative innovation spaces, breaking space-time constraints. Continuous exploration of these emerging technologies in the synergistic development of mechanical design/manufacturing and equipment technical transformation/innovation, along with ongoing strategy optimization, will further advance this field, injecting new momentum into high-quality manufacturing development.

Disclosure statement

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Construction Technology of Electrical Projects in Data Centers

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Abstract: With the continuous development of big data technology in China, large-scale enterprises and financial institutions have established data center computer rooms due to the need to process massive amounts of data. Due to the electrical system of this engineering project is relatively complex, the application of construction technology will directly affect the subsequent construction quality and the safety of the data center. Therefore, this paper studies the construction technology of data center electrical engineering projects. Based on a simple analysis of the design and construction content of data center electrical projects, it discusses the key points of preparatory work. At the same time, it analyzes the difficulties and key points in multiple aspects such as wire piping, distribution box installation, and lamp installation during the installation and construction process of data center electrical projects.

Keywords: Data center; Electrical project; Construction technology

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1. Introduction

At present, China's large enterprises and financial institutions, especially in the field with high requirements for information security and integrity, are facing the challenge of the continuous expansion of data scale. They need to store, develop and use these data efficiently, which puts forward higher requirements for the professional quality of employees. To this end, these enterprises and institutions have introduced advanced information technology equipment and established special data center computer rooms to realize the centralized collection, analysis, processing and storage of data. However, the internal electrical system structure of the data room is complex, which is closely related to lightning protection and grounding, power supply and distribution and other links. Only by ensuring the construction quality can we give full play to the potential value of the data center computer room and avoid data processing errors. This paper discusses the key points of construction technology for the electrical project of data room, in order to provide a reference for the relevant electrical installation work.

2. Analysis of construction content of data room electrical project

According to the actual situation of the data center computer room designed by large enterprises and institutions in China, the construction content of the electrical project mainly includes the following aspects:

(1) Installation of power distribution equipment: Power distribution equipment is the core component of the electrical project of the data room, and its selection and installation directly affect the construction quality, progress and the operation safety and stability of the electrical system. At present, the power distribution equipment in the data room is mainly based on basic equipment such as distribution boxes and meters. During the construction process, the construction personnel shall strictly detect and control the parameters and performance of the equipment, scientifically select the equipment model according to the actual operation requirements of the electrical project in the machine room, and install it in strict accordance with the approved construction scheme [1];

(2) Electrical circuit laying: Electrical line laying is an important part of the electrical engineering of the data room. The line connects multiple electrical equipment and power supplies, and its construction quality is directly related to the operation stability and safety of the entire electrical system. Therefore, the construction unit should attach great importance to the line laying work, comprehensively optimize the design scheme, reasonably plan the line direction, and check whether there is line collision according to the installation requirements and layout of electrical equipment, so as to ensure that the line laying can fully meet the equipment operation requirements;

(3) Switch socket installation: As an indispensable part of the electrical system in the data room, the switch socket has a significant impact on the operation of electrical equipment and the stability of system functions. The construction unit shall reasonably adjust the position of the switch socket according to the equipment layout, and arrange professionals to be responsible for its maintenance and cleaning work, and ensure that the safety performance of the switch socket meets the requirements of relevant standards through the implementation of moisture-proof, sun protection and other measures [2];

(4) Lightning protection and grounding: With the increasing number and scale of electrical equipment in the data center computer room, lightning and other external factors may cause safety accidents. Therefore, in the construction process of electrical projects, lightning protection and grounding work is particularly critical. The construction unit shall scientifically formulate lightning protection and grounding measures according to the local lightning activities, so as to effectively reduce the impact of lightning weather on electrical equipment and systems and ensure operation safety.

The optimization and implementation of the above construction contents can provide a solid guarantee for the stable operation of the electrical project in the data room.

3. Preliminary preparations for the construction of data room electrical project

The preliminary preparation for the construction of the electrical project in the data room has an important impact on the quality and progress of subsequent projects. Before the construction is officially started, the relevant units need to give priority to preparing the power of attorney for electrical design, so as to ensure that the construction unit has a comprehensive grasp of the specific steps of electrical equipment installation, and enable the construction unit to form a clear understanding of the construction method and process [3]. The power of attorney shall specify the technical category requirements for the installation of electrical equipment, scientifically mark the equipment parameters and safety indicators in the construction process, and ensure that the electrical design work can achieve the expected goals. For the possible problems in the power of attorney, solutions shall be put forward in time to ensure that the quality of electrical engineering meets the requirements of the relevant standards.

After completing the preparation of the electrical power of attorney, it is necessary to carry out the review and determination of drawings. Relevant units shall comprehensively review the contents of construction drawings at the initial stage of design, adjust unreasonable parts according to the established design principles, and avoid adverse effects on the final design results. At the same time, the principle of "review drawings before design" shall be strictly followed. In the drawing design stage, the design unit and the construction unit needs to establish an efficient communication mechanism to plan the construction process of electrical projects from the perspective of macro-engineering construction. The composition structure of the electrical system in the data room is shown in **Figure 1**.

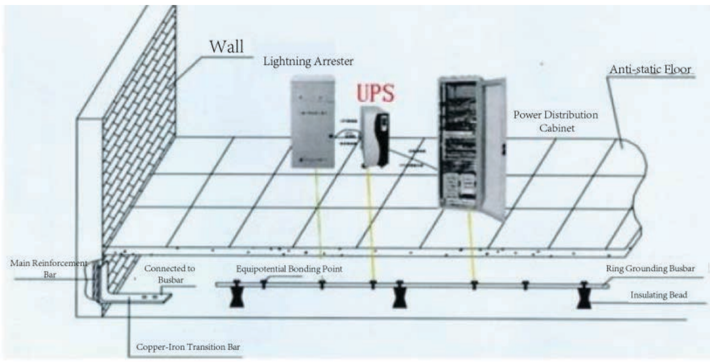

Figure 1. Composition analysis of electrical system in data room.

After the construction design is completed, the relevant units need to prepare the equipment and materials required for the project. The construction unit shall fully realize the importance of equipment model selection, and scientifically select construction materials in combination with the actual needs of electrical projects, so as to effectively control economic costs and reduce unnecessary losses. In the selection process, it is necessary to objectively evaluate the material quality and equipment performance, comprehensively review the qualification of suppliers, and give priority to the selection of high-quality equipment and materials, so as to further improve the construction quality and overall effect of electrical engineering. Through solid preparatory work, it can provide a solid guarantee for the smooth implementation of the data room electrical project.

4. Analysis on key points of construction technology of data room electrical project

4.1. Laying of wireways

During the construction of the electrical project in the data room, pipeline laying is a basic link. At the stage of electrical line laying, the construction unit shall give priority to the selection of thin pipes, such as black iron pipes or PVC pipes, and reasonably set transition boxes during the installation process to avoid wire stringing or damage. However, in practice, when the pipeline is connected with the metal pipe, the construction personnel often ignore the burr treatment of the metal pipe orifice, resulting in poor joint quality. In addition, the installation of steel pipe grounding device is unscientific, which may cause hidden dangers in the operation of electrical system. When the pipeline on the wall radiates, the pipeline distribution is uneven and chaotic, which may also affect the civil engineering [4]. Concurrently, after the wire pipe enters the wire box, it is not fastened or sleeved, which leads to the lack of standardization of construction behavior and affects the quality of pipeline laying.

In order to avoid the above problems, the construction unit should strictly abide by the design drawings and installation specifications, control the whole process, and eliminate the use of unqualified conduits. The construction personnel shall scientifically process the supporting pipeline and calculate the bending radius: the bending radius of the concealed pipeline shall exceed 6 times of the outer diameter of the pipeline, and that of the pipeline buried in concrete or underground shall exceed 10 times. If the inner diameter of galvanized pipe is less than 25 mm, manual elbow can be used. If it exceeds 32 mm, use hydraulic bends. In the pipeline laying process, it is also necessary to reasonably determine the pipeline specification, model and radiation method. In addition, in the actual construction, attention should be paid to the anti-corrosion treatment of the pipeline. For example, the pipeline in the humid environment should be painted with anti-rust paint to extend the service life. At the same time, the pipeline laying path should avoid being close to high-temperature equipment or inflammables to reduce potential risks. These measures can significantly improve the reliability and durability of pipeline laying and ensure the long-term stable operation of the electrical system.

4.2. Installation of distribution box

During the installation of the distribution box, common problems include excessive clearance between the box and the wall, incomplete cleaning of construction waste, unreasonable opening, and damage to the paint protective layer during welding. Moreover, the fuzzy grounding wire, insufficient conductor cross-sectional area, and wiring operations that do not meet the specifications may also lead to the problem of redundant wires. These problems not only affect the appearance, but also may cause safety accidents such as short circuits or leakages.

To solve these problems, the construction personnel must ensure that the civil construction and distribution box installation are coordinated. At the initial stage, it is necessary to clean the garbage inside the box. If the incoming line pipe cannot be directly connected to the box, it shall be transformed with perforation equipment and the opening specification shall be determined. In the grounding construction, it is necessary to strictly abide by the specifications and reasonably set the grounding point and conductor of the power distribution box to avoid direct operation at the bottom of the box. At the same time, insulation test and load test shall be carried out after installation to ensure that the box sealing and electrical performance meet the standards. The location of the distribution box is also very important. It should be placed in a well-ventilated and easy-to-maintain area to avoid humid or high temperature environment. Through standardized operation, the failure rate can be effectively reduced and the overall project quality can be improved.

4.3. Installation of lamps

During the installation of lamps and lanterns, common problems include unreasonable embedding of lamp position box, resulting in position deviation of large chandeliers. Improper handling of the pendant lamp hook and wiring device, resulting in an exposed conductor. The installation position of the ceiling lamp is too low and the fixing frame is unstable, which affects the service effect and service life of the lamp. These problems may lead to uneven lighting or potential safety hazards, such as lamp falling off.

Therefore, when embedding the hook in the concrete, it is necessary to weld the main reinforcement, and use the steel pipe as the jumping rod and down lead pipe of the lamp, so as to avoid the boom being too long, followed by threading the conductor into it. The construction personnel shall plan the perforation of the lamp port according to the actual needs of the project to ensure that the wire is smoothly connected to the interior of the lamp. The installation height of metal halide lamp shall be controlled at about 5 meters, and an appropriate distance shall be kept from the connecting column and power line [5]. Furthermore, the lamp shall be equipped with current limiter and trigger. When the installation height of the lamp is less than 2.4 m, the shell shall be grounded for protection. After installation, light test and voltage withstand test shall be carried out to ensure uniform brightness and no flicker. At the same time, considering the energy-saving demand, LED lamps can be selected to reduce energy consumption and prolong service life. Through refined installation, efficient lighting and safety can be achieved.

4.4. Lightning protection setting

Lightning protection equipment is the key premise to ensure the safe and stable operation of the electrical project in the data room. However, designers often ignore the description of test points in the design of lightning protection devices. During the construction, the welding of lightning protection grounding plate and lightning protection network did not meet the specification, and the grounding resistance test point was not set, resulting in insufficient lightning protection performance. These defects may cause equipment damage or data loss in the thunderstorm season.

Therefore, the construction unit should recognize the importance of lightning protection devices and reasonably fix the lightning protection network. The grounding electrode of the arrester shall be welded with the foundation reinforcement and pile foundation reinforcement, and connected to the lightning protection network through the column reinforcement. At the same time, adjust the position of the test point and select galvanized flat iron material. If the lightning protection grounding electrode is the foundation reinforcement, it is necessary to set the internal and external main reinforcement and ensure that the lap joint is firmly welded. On top of that, the grounding resistance shall be measured regularly to ensure that the value is lower than the specification requirements. In lightning-prone areas, surge protective devices can be additionally installed to improve the lightning protection efficiency with a multi-layer protection system. Through scientific setting, it can effectively resist the risk of lightning strokes and protect the core equipment of the computer room.

4.5. Installation and connection of conductor

In the connection of sockets and switch terminals of the distribution box, some construction personnel have the situation that one terminal is connected to multiple wires. After the wire is combed, there are still wire ends left. The grounding wire is crossed and integrated with other lines, and the wiring layout is unreasonable. If the connection of multiple conductors is involved, appropriate materials shall be selected for crimping treatment, and different colors of conductors shall be selected according to the actual project, so as to distinguish the types. These problems may lead to poor contact or short circuit.

In order to optimize the connection, the construction personnel should use professional tools such as crimping pliers to ensure that the joint is fastened without looseness. Moreover, the length of conductor insulation stripping shall be controlled to avoid too long exposure. After connection, it shall be wrapped with insulating tape and subjected to tensile test. In the complex wiring environment, the wire slot or label system can be introduced to improve the convenience of maintenance. By standardizing the connection, the failure rate can be reduced and the efficient operation of the electrical system can be ensured.

5. Conclusion

The construction of data room electrical projects involves multiple interconnected technical stages. From preliminary preparation to on-site installation, strict quality control is essential to ensure system stability and operational safety. The analysis of construction content, preparatory work, and key technical points presented in this paper demonstrates that scientific planning and standardized execution are critical to project success. Looking ahead, the introduction of intelligent monitoring technologies can further enhance construction efficiency and management effectiveness. In parallel, relevant organizations should strengthen personnel training to improve professional competence. Ultimately, these measures will support the efficient operation of data rooms and promote the continued development of information infrastructure.

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Research on ESD and TVS Protection Technology in Semiconductor IC Package Test

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Abstract: With the development of the semiconductor process to 5 nm and below, ESD protection faces challenges. The TVS reduces the response time to 0.5 ns through the three-dimensional TSV structure, and the SiC / GaN material achieves high temperature protection of 200℃ and 15 kV. The multi-stage cooperative protection network combined with inverted welding and flexible substrate technology meets the IEC 61000-4-2:2024 and AEC-Q100-012 standards. The parasitic inductance was suppressed to < 0.05 nH in high-frequency scenarios, and the eWLB package verified the technical feasibility. Two-dimensional materials and intelligent monitoring system promote the evolution of ESD protection to the system level.

Keywords: ESD protection; TVS structure; System-level protection

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1. Introduction

As semiconductor process nodes advance to 5 nm and below, the miniaturization and high-density integration of integrated circuits have posed unprecedented challenges to electrostatic discharge (ESD) protection. ESD events generate transient voltages reaching thousands of volts, with energy density increasing exponentially in miniaturized devices, easily causing gate dielectric breakdown, metal interconnect fusing, and other damage. Approximately 70% of ESD damage is latent, where device functionality remains temporarily normal but reliability degrades. Such damage is difficult to detect in conventional testing and may lead to catastrophic failures during the product lifecycle. Practice shows that relying solely on traditional external TVS devices in packaging is no longer sufficient for high-frequency and high-speed scenarios. Multi-level ESD protection networks must be integrated at the chip design stage, with parasitic parameter control optimized through packaging processes.

2. Basic principles of ESD and TVS protection technologies

2.1. Generation mechanism and hazards of ESD

ESD protection must comply with the ANSI/ESD S20.20-2023 standard, requiring surface resistivity control of 10^6–10^9 Ω/sq for 2.5D/3D packaging workstations to balance electrostatic dissipation and signal integrity. Charge discharge paths are quantified through HBM (Human Body Model), MM (Machine Model), and CDM (Charged Device Model). The HBM model reveals the destructiveness of high-voltage events (e.g., 8 kV) on metal interconnects: transient high currents trigger Joule heating effects, causing aluminum interconnect temperatures to rise abruptly above 800°C, ultimately leading to fusing or PN junction burnout [1]. Beyond thermal damage, strong electric fields can directly break down ultra-thin dielectric layers (e.g., 1 nm gate oxide), triggering tunneling effects at tens of volts and causing threshold voltage drift or permanent failure. Node scaling (e.g., FinFET and GAA architectures) exacerbates ESD vulnerability, as reduced metal linewidths and thinned dielectrics decrease withstand voltage by about 30%, while complex three-dimensional structures hinder precise control of charge paths. To address this, optimization should focus on materials (low-resistance, high-withstand-voltage substrates), design (chip-level ESD protection circuits), and processes (protective module integration compatible with FinFET/GAA) to enhance device antistatic capability while maintaining performance.

2.2. Working principle of TVS

TVS achieves ESD energy absorption through nonlinear volt-ampere characteristics, with core structures including PN junctions, multilayer varistors (MLV), and multi-level protection networks. Operation is based on avalanche breakdown: when reverse voltage exceeds the breakdown voltage (VBR), the TVS rapidly enters a low-resistance state, clamping the transient voltage within a predetermined clamping voltage (VC) range (VBR-to-VC ratio typically 1.2–1.5), protecting downstream circuits from overvoltage damage. Multi-level protection networks employ a "coarse-fine" architecture, where the first-level TVS (response time < 1 ns) absorbs most ESD energy with high conduction speed, and the second-level RC filtering network further suppresses residual voltage fluctuations. For high-frequency scenarios, three-dimensional stacked TVS shortens current paths to the micrometer level via vertical interconnects (e.g., through-silicon vias, TSV), reducing parasitic inductance below 0.1 nH and improving clamping efficiency by 40%, significantly decreasing signal reflection and impedance mismatch. Silicon carbide (SiC) TVS, with its 3.26 eV wide bandgap, can withstand 15 kV ESD impacts at 150°C, complying with AEC-Q101 automotive standards. Key parameters (e.g., dynamic resistance, junction capacitance) must be optimized based on application needs (e.g., operating frequency, temperature range) to balance ESD protection and signal integrity requirements [2].

3. ESD protection technologies in packaging and testing

3.1. Analysis of ESD risk points in packaging and testing processes

In packaging and testing, ESD risk points include: bare dies losing protection after wafer dicing, CDM discharge easily occurring during packaging, high electrostatic voltages potentially generated during ATE operations, high electrostatic sensitivity in high-speed interfaces and RF chips, and electrostatic accumulation due to poor grounding or prolonged ionization equipment decay times. CDM testers must be upgraded, following standards such as ANSI/ESD SP17.1, with coordinated prevention using ion fans, ESD workstations, and other equipment to ensure safe and reliable packaging and testing.

3.2. Key parameters and testing methods for ESD protection design

ESD protection must strictly comply with the IEC 61000-4-2:2024 standard, meeting stringent requirements of 8 kV contact discharge and 15 kV air discharge, while monitoring key parameters: clamping voltage level (VCL), peak current (IPP), and energy (W) [3]. Failure modes are divided into hard failures (e.g., leakage current > 1 μA causing permanent device damage) and soft failures (e.g., DDR5 interface timing deviation tAC ± 5% causing functional anomalies). For precise localization of current distribution within packages, 3D-TLP (Transmission Line Pulsing) technology identifies high-density current hotspots (e.g., up to 10^6 A/cm^2 at QFN package bond wires), reducing current density to < 5×10^5 A/cm^2 through optimized TVS layout (e.g., shortened paths or added parallel branches) to suppress local overheating and breakdown risks. The ANSI/ESDA STM5.5.1-2024 standard introduces mmWave-band ESD testing, using vector network analyzers (VNA) to quantify signal integrity failures with ΔS21 > 1 dB, driving protection design evolution toward high-frequency characteristics. Clamping speed (< 1 ns), low parasitic inductance (< 0.1 nH), and broadband impedance matching must be balanced to meet new ESD robustness challenges in 5G/6G communications and high-speed optical modules.

4. Design and packaging integration technologies for TVS devices

4.1. Optimization design methods for TVS devices

TVS achieves low junction capacitance (0.1 pF) through gradient-doped PN junctions and Schottky contact structures, meeting USB4 20 Gbps high-speed interface requirements, while multi-finger strip layouts optimize current distribution, improving uniformity by 60% and withstanding 100 A surges. Multi-level protection circuits employ a "coarse protection-fine filtering" architecture, with the first-level TVS responding within 0.5 ns to discharge 90% of ESD energy, and three-level protection elevating 28 nm chip HBM antistatic levels from 2 kV to 8 kV [4]. In materials, silicon-based TVS is cost-effective for low-voltage scenarios but limited in high-voltage applications; gallium nitride (GaN) devices, with low dynamic resistance (0.05 Ω), suit 5G mmWave high-frequency needs; SiC withstands 15 kV ESD impacts at 200°C, complying with AEC-Q101 automotive standards. Three-dimensional packaging optimizes stress distribution via TSV, reducing interfacial thermal resistance by 30% and meeting JEDEC temperature cycling test requirements, addressing thermal management and reliability challenges in high-integration packages.

4.2. Integration technologies of TVS in packaging

4.2.1. Comparison between on-chip integration and off-chip discrete schemes

On-chip TVS achieves near-end interconnection with core circuits via back-end-of-line (BEOL), following the "near-end protection" principle by placing devices within 5 μm of I/O pads, reducing signal transmission delay to 50 ps but at the cost of 12–15% increased chip area. In contrast, off-chip discrete TVS uses Flip-Chip packaging and μBump arrays, meeting 56 Gbps SerDes interface impedance matching needs through parasitic inductance control (< 0.2 nH). Experiments show superior performance in 32 Gb/s GDDR6 interfaces, signal return loss (S-parameter return loss < -15 dB) significantly better than on-chip schemes, validating the advantages of discrete structures for signal integrity in high-frequency scenarios, especially suitable for area-sensitive systems requiring both high bandwidth and low loss [5].

4.2.2. Thermal management and signal integrity assurance

TVS thermal accumulation issues are mitigated through packaging heat dissipation design: QFN-embedded copper pillar arrays reduce thermal resistance from 80°C/W to 35°C/W; 2.5D packaging silicon interposer microchannels control hotspot temperatures below 85°C. High-speed signal links require TVS placement away from PLL clock lines, with differential symmetric routing limiting parasitic capacitance imbalance to ± 2 fF. The IEEE 1149.13-2024 standard requires 112 Gbps PAM4 interface TVS schemes to pass TDR verification with $\Delta Z < \pm 5\ \Omega$, ensuring signal rise time degradation below 10% and maintaining signal integrity.

5. Application case analysis and technical challenges

5.1. ESD protection schemes in consumer electronics

5.1.1. TVS integration case in mobile phone chip packaging

In 7 nm 5G baseband chip flip-chip packaging, multi-level TVS networks achieve coordinated optimization of ESD protection and signal integrity through layered architecture. First-level silicon-based TVS ($40\times60\ \mu m^2$) directly connects I/O pads via μBump arrays, controlling parasitic inductance at 0.3 nH while providing 8 kV HBM protection. Second-level GaAs TVS embedded in redistribution layers (RDL) suppresses 28 GHz high-frequency resonant noise. The overall scheme complies with IEC 61000-4-2:2024, withstanding 15 kV air discharge and adding only 0.8 dB insertion loss to USB 3.2 interfaces [6]. TVS layout strategy disperses ESD current paths, reducing peak current density from 1.2×10^6 A/cm^2 to 3.5×10^5 A/cm^2, with leakage current controlled below 0.3 μA, meeting EU dynamic monitoring standards for low power consumption and high reliability.

5.1.2. Miniaturization protection technology for wearable devices

Wearable devices integrate SiC TVS units into flexible polyimide (PI) substrates via three-dimensional heterogeneous integration, combined with nanoimprint processes to form 5 μm protective layers, achieving ultra-thin 0.48 mm packaging for miniaturization needs. Z-axis stacking compresses TVS area to 0.02 mm^2/I/O while maintaining 8 kV CDM protection. Device parameter optimization (dynamic resistance 0.8 Ω, junction capacitance 0.6 pF) significantly improves ECG sensor SNR by 6 dB, balancing ESD protection and signal quality. Reliability testing shows clamping voltage drift < 2% after 1000 bending cycles at 85% humidity, complying with JEDEC standards and suitable for TWS earphone chips < 10 mm in diameter, addressing core needs for miniaturized, high-reliability ESD protection in wearables.

5.2. High-reliability requirements in automotive electronics

5.2.1. ESD protection standards for automotive-grade chips (AEC-Q100)

Automotive-grade chip ESD protection must meet AEC-Q100-012 Rev-C:2023, focusing on TVS stability in extreme environments [7]. TVS must pass -40°C to 150°C temperature cycling and H3TRB tests, with clamping voltage drift < 5%. SiC-based TVS dynamic resistance increases 12% at 150°C, with leakage current below 0.5 μA. For 48V systems, TVS must withstand 80V pulses and 200 mJ avalanche energy, with WLP-integrated heat sinks controlling junction temperature within 175°C, complying with ISO 16750-2 and EU R155 regulations.

5.2.2. Multi-domain protection circuit design

Automotive electronics multi-domain protection requires coordinated optimization of power and signal domains. Power domain uses PMU cascaded with TVS, where TVS absorbs load dump energy (e.g., 100V/400 ms pulses in 48V systems) and PMU controls residual ripple to ± 200 mV. Signal domain targets 2.5 kV ESD impacts on FlexRay buses, using distributed TVS arrays and common-mode chokes to suppress noise > 40 dB [8]. This scheme reduces vehicle EMC radiation by 6 dBμV/m, improving LIN bus error rate from 10^{-5} to 10^{-8}. Automotive Gigabit Ethernet TVS layout ensures differential pair capacitance imbalance < 0.1 pF, with LTCC design controlling transmission delay deviation to 0.5 ps/mm, meeting 1000BASE-T1 jitter requirements.

5.3. Technical challenges and solutions

5.3.1. TVS performance degradation in high-frequency scenarios

In high-frequency (> 30 GHz) scenarios, TVS parasitic inductance (0.5–2 nH) causes impedance mismatch and signal reflection, reducing response speed to > 2 ns. Specifically, 1 nH parasitic inductance at 60 GHz lowers ESD clamping efficiency by 60%, with residual voltage fluctuations ± 15%, significantly degrading signal integrity. To address this, three-dimensional stacked TVS uses TSV for vertical interconnection, shortening current paths to 200 μm and reducing parasitic inductance to 0.05 nH. Gradient permittivity materials optimize impedance matching, improving 28 GHz return loss by 8 dB. GaN-based TVS achieves dynamic resistance < 0.1 Ω at 140 GHz, meeting IEEE 802.3ck standards for 800 Gbps optical module ESD protection, enabling efficient energy discharge and signal integrity in high-frequency scenarios [9].

5.3.2. Trade-off between cost and reliability

In low-cost eWLB packaging, TVS performance is limited by low thermal conductivity and high dielectric loss of epoxy substrates. Embedding silicone composite heat dissipation layers (thermal conductivity 1.5 W/m·K) reduces TVS junction temperature from 125°C to 95°C, while laser trimming optimizes metal wiring, reducing protection costs by 40% [10]. Hybrid on-chip and discrete TVS integration elevates HBM levels from 4 kV to 10 kV at 15% BOM cost increase. China's Integrated Circuit Industry ESD Protection Technology Guideline (2023 Edition) requires consumer electronics protection cost ≤ 0.12 Chinese Yuan per kV, promoting flip-chip copper pillars over gold wire bonding, improving TVS integration yield to 98.5% while maintaining 8 kV CDM protection.

6. Conclusion

TVS integration technologies enhance ESD protection through three-dimensional stacking, multi-level protection, and new materials. TSV achieves response times < 0.3 ns, suitable for 5G; multi-level networks enable graded energy discharge, reaching 15 kV HBM protection. SiC and GaN extend operating temperatures to -55°C to 200°C, with withstand voltages > 30 kV. 28 nm chip CDM protection improves threefold, meeting 15 kV air discharge requirements. Future directions include two-dimensional materials like MoS_2 (response time 50 fs) for terahertz communications, and intelligent monitoring systems combining MEMS and machine learning, shifting ESD protection from passive to active prediction.

Disclosure statement

The author declares no conflict of interest.

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Analysis of the Application of Low-Frequency Inter-Harmonic Monitoring in DC Converter Stations Based on Power Quality Monitoring Devices

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Abstract: This article introduces an application case of monitoring low-frequency inter-harmonic signals in a DC converter station project using power quality monitoring devices, effectively providing data support for the sub-synchronous oscillation problems caused by the high-voltage DC system.

Keywords: Low frequency harmonic; Damping controller; Sub-synchronous oscillation

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1. Introduction

China leads the world in both the highest voltage levels and the largest number of operational DC transmission projects. With the widespread deployment of these projects, sub-synchronous oscillations caused by DC transmission have become a recurring issue. Notable cases include the Suizhong Power Plant, Yimin Power Plant, and Panan Power Plant, where such oscillations have threatened the longevity and safety of generator sets' shaft systems [1]. These oscillations arise from dynamic coupling and energy exchange between mechanical and electrical components in power systems, typically manifesting at low-frequency bands. Effective monitoring and early warning of DC system operations, supported by data, are crucial for identifying and addressing sub-synchronous oscillations. Using a specific DC transmission project as an example, this paper presents a low-frequency harmonic monitoring solution implemented through upgrades to power quality monitoring devices.

2. Analysis of sub-synchronous oscillation event in a DC transmission project

The first phase of a DC power project has completed four DC converter units (each rated at 750 MW), as shown in **Figure 1**. Power Plant B, located approximately 10 km from Converter Station A, has commissioned four generating units (#1, #2, #3, #4) that deliver power to Station A via three 500 kV transmission lines.

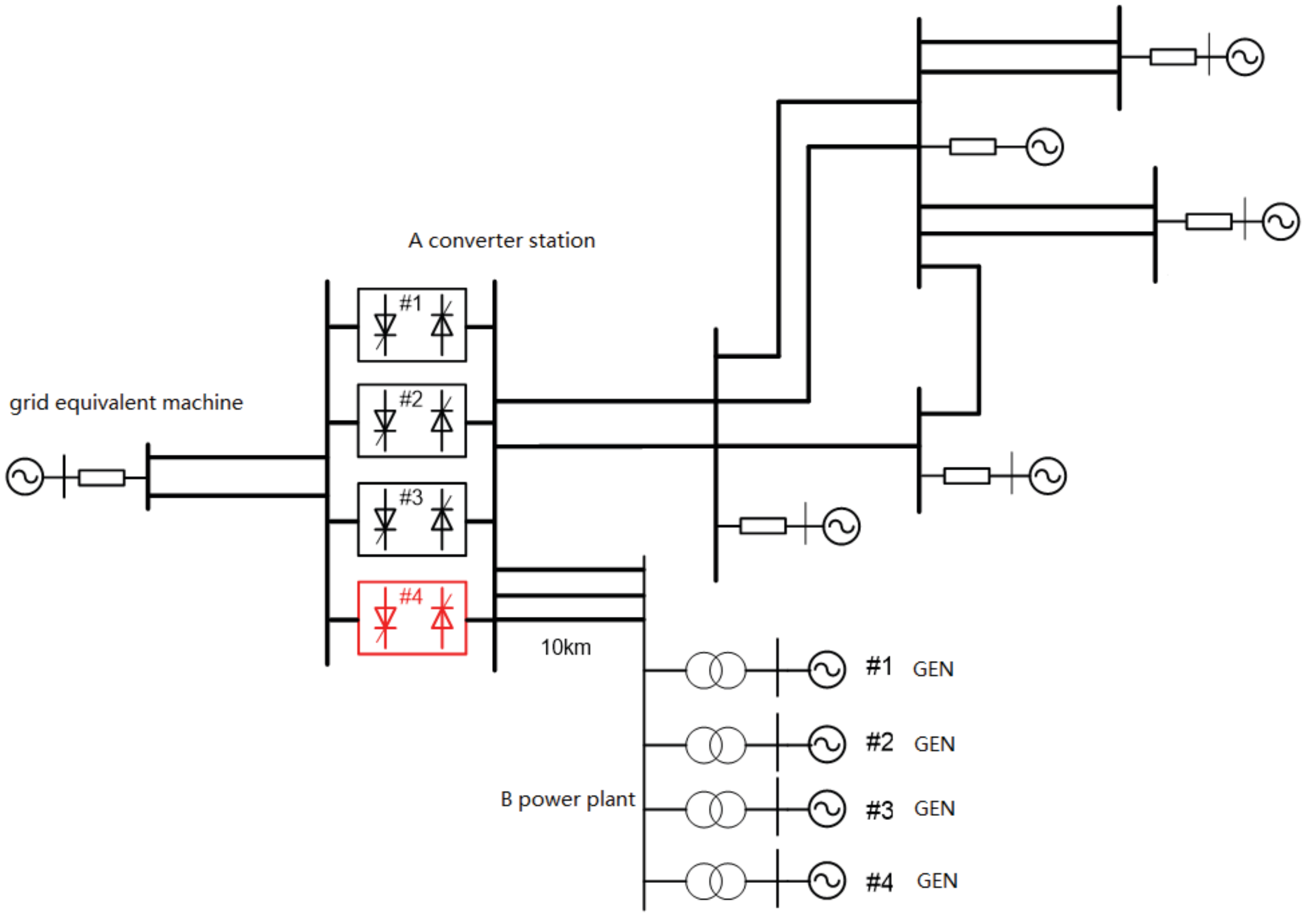

Figure 1. Schematic diagram of a DC transmission project.

During the incident, a random interval-triggered pulse anomaly with delayed response occurred in a bridge arm of Unit 4 at Converter Station A during continuous power frequency cycles, causing periodic interference to the AC system. Given that Power Plant B and Converter Station A are only 10 km apart and interconnected via three 500 kV AC transmission lines, the sub-synchronous frequency component in this interference became an excitation source for the power plant's units. This triggered modal oscillations with frequencies close to the shaft system's natural frequency, resulting in significant amplitude and prolonged duration of the oscillations.

At the same time, the additional sub-synchronous oscillation damping controller in the DC system of A converter station did not produce event records during the sub-synchronous oscillation, and the input and output waveform data of this module were also missing in the field data, so it was impossible to determine whether it played a damping control role.

The EMTDC simulation was conducted, with valve 2 triggering delay occurring every two power frequency cycles. Unit 4 delivered 500 MW positive power, while the B-side D bridge's valve 2 triggered a 40 ms pulse interval, generating a 1.667 ms delay pulse. The simulation waveform is shown in **Figure 2.**

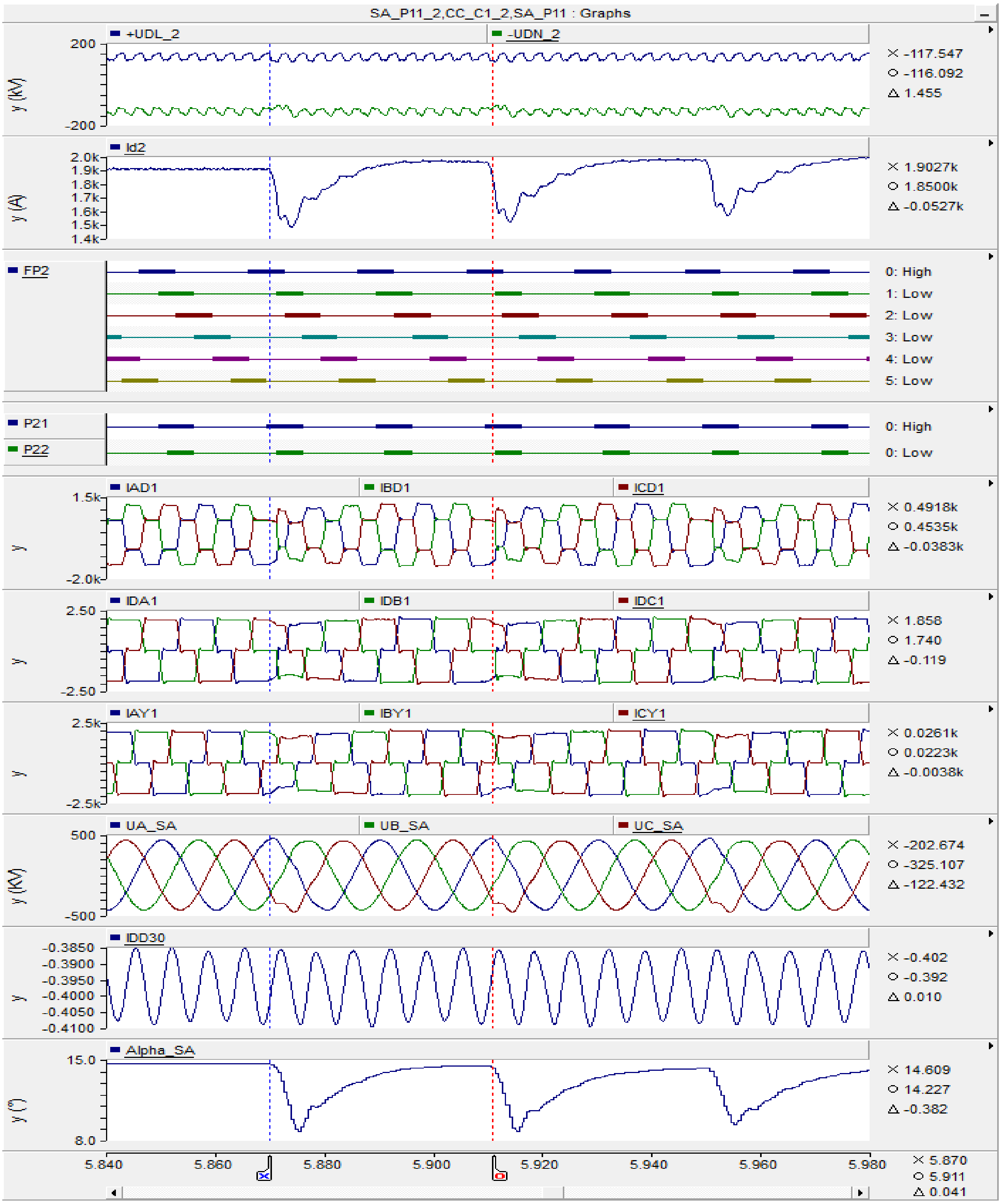

Figure 2. Simulation waveform diagram.

The simulation results demonstrate that a single-valve trigger with a one-cycle delay generates a 25 Hz sub-synchronous component in the DC system, which is also reflected in the AC voltage of the converter bus. **Figure 3** compares simulations with normal triggering and one-cycle delayed triggering, showing the 25 Hz component extracted from the converter bus voltage, with the C-phase voltage increasing from 0.0045 kV to 1.4033 kV.

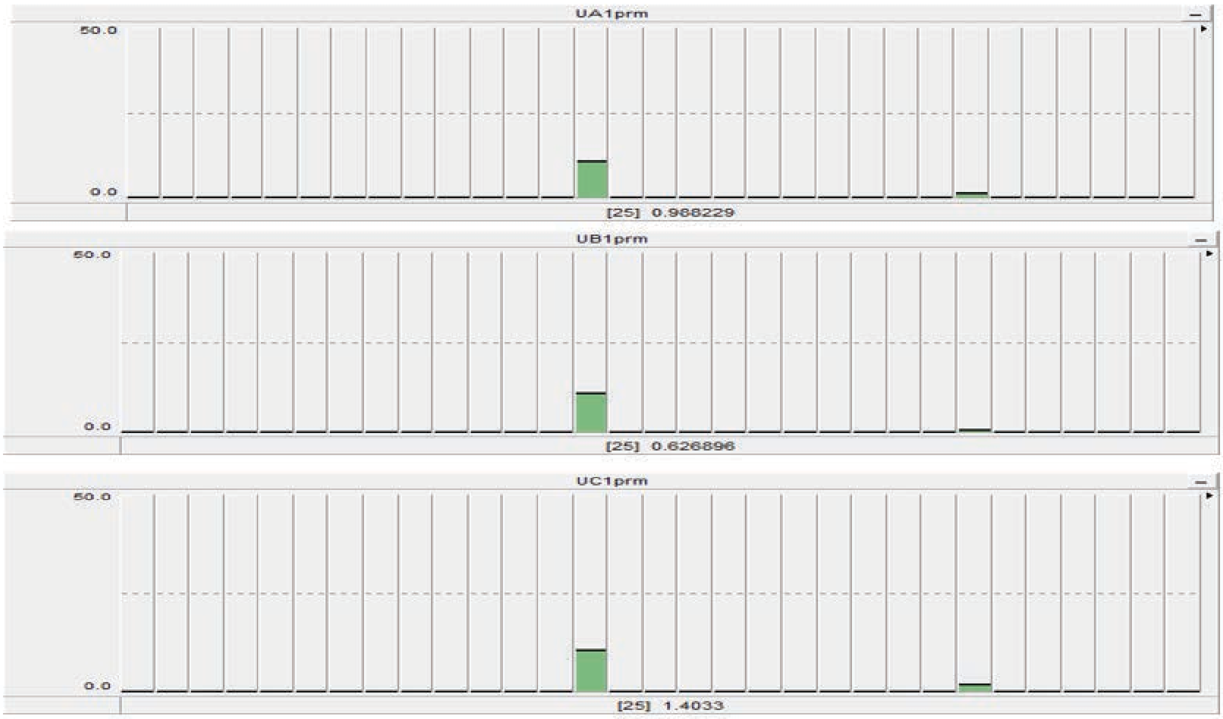

Figure 3. Three synchronization component diagram.

Simulation results demonstrate that the disturbance originates from intermittent triggering lags of a single converter valve, rather than the sub-synchronous resonance-induced suppression function of the converter. As the damping controller failed to initiate alarm recording during the event, comprehensive data analysis of the disturbance process can be achieved through low-frequency harmonic data acquisition and parameter configuration of the damping controller.

3. Principle and parameter configuration of damping controller

The measurement principle of the SSR in the pole control system of converter station A is illustrated in **Figure 4**.

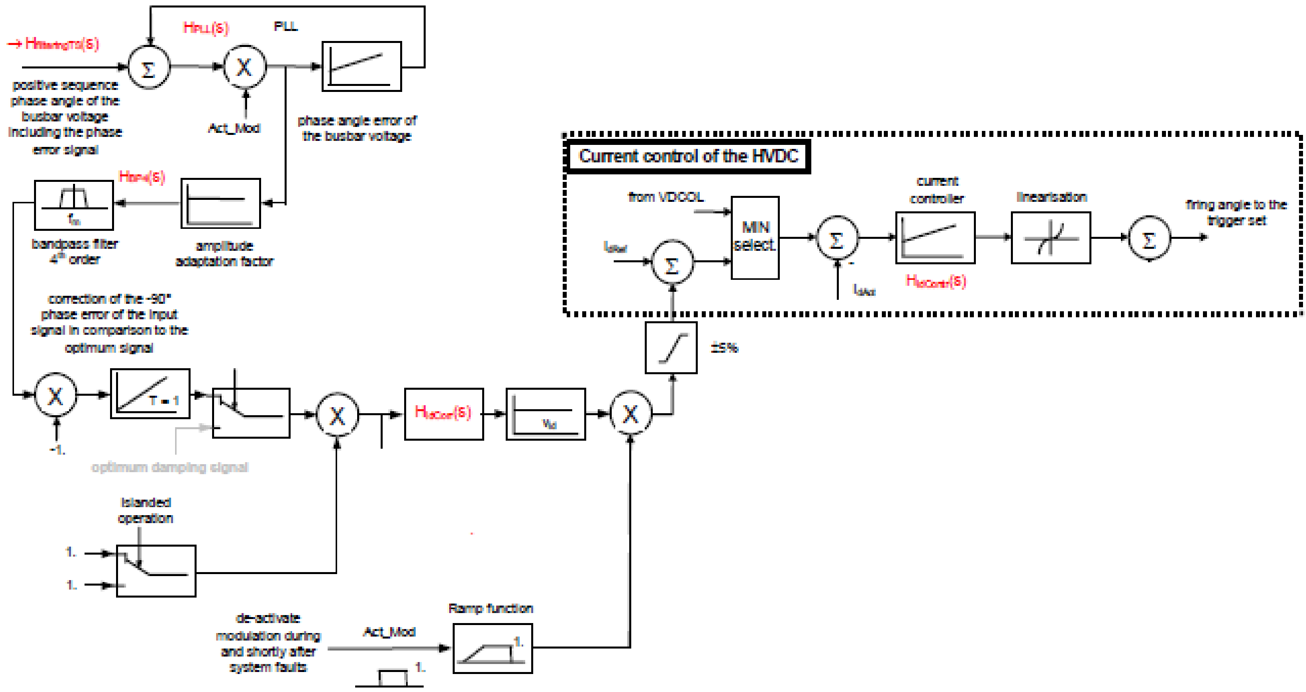

Figure 4. SSR measurement principle diagram of the pole control system.

The damping controller operates by taking the phase angle of an AC voltage signal as input and generating a current modulation signal. Through real-time detection of phase angle variations, it dynamically adjusts the DC system's output power, thereby modifying the generator's electromagnetic torque. This mechanism maintains a positive damping coefficient for the generator within the 10 Hz to 30 Hz frequency range, effectively suppressing oscillations [2]. The phase relationship between the control signal and the resonant signal is critical to damping effectiveness. If the phases are out of sync, oscillations may not only fail to be suppressed but could even be exacerbated. To optimize damping performance, the controller must apply phase correction to the input signal using an appropriate transfer function.

3.1. Components of the damping controller

3.1.1. Signal sampling process

The damping sub-synchronous oscillation function of Power Plant B measures the input voltage of the converter transformer. The measured input voltage undergoes αβ transformation to obtain the instantaneous value of the AC voltage, which is then used for the synchronization locking process. The sampling part of the program is shown in **Figure 5**.

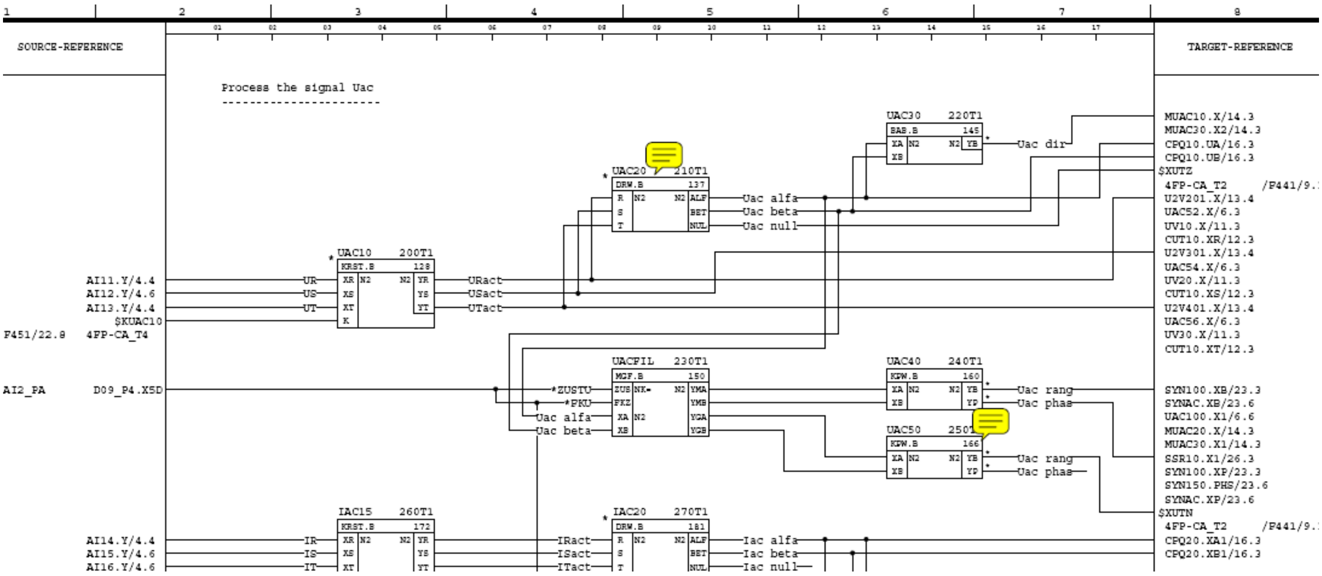

Figure 5. Sampling section flowchart.

3.1.2. Phase-locking loop

The PLL circuit employs a PI controller with a gain of 1 and a time constant of 100 ms. The phase-locked loop (PLL) program is illustrated in **Figure 6**.

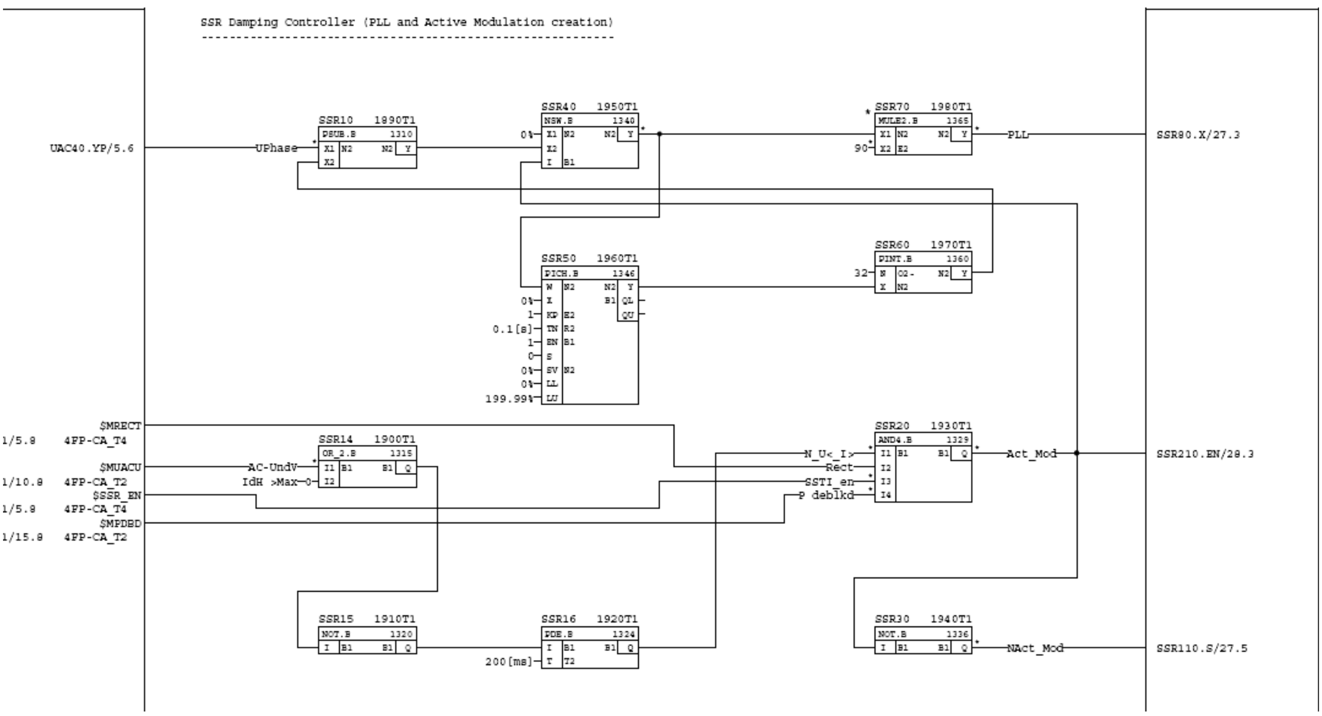

Figure 6. Block diagram of phase-locked loop.

The transfer function of the digital band-pass filter is shown in **Equation 1**.

$$H_{BP4}(Z) = \frac{d1_0+d1_1\cdot z+d1_2 Z^2}{c1_0+c1_1\cdot z+c1_2 Z^2}\cdot\frac{d1_0+d1_1\cdot z+d1_2 Z^2}{c1_0+c1_1\cdot z+c1_2 Z^2} \quad (1)$$

The parameters of the digital band-pass filter are determined according to the frequency range of sub-synchronous oscillation (**Figure 7**).

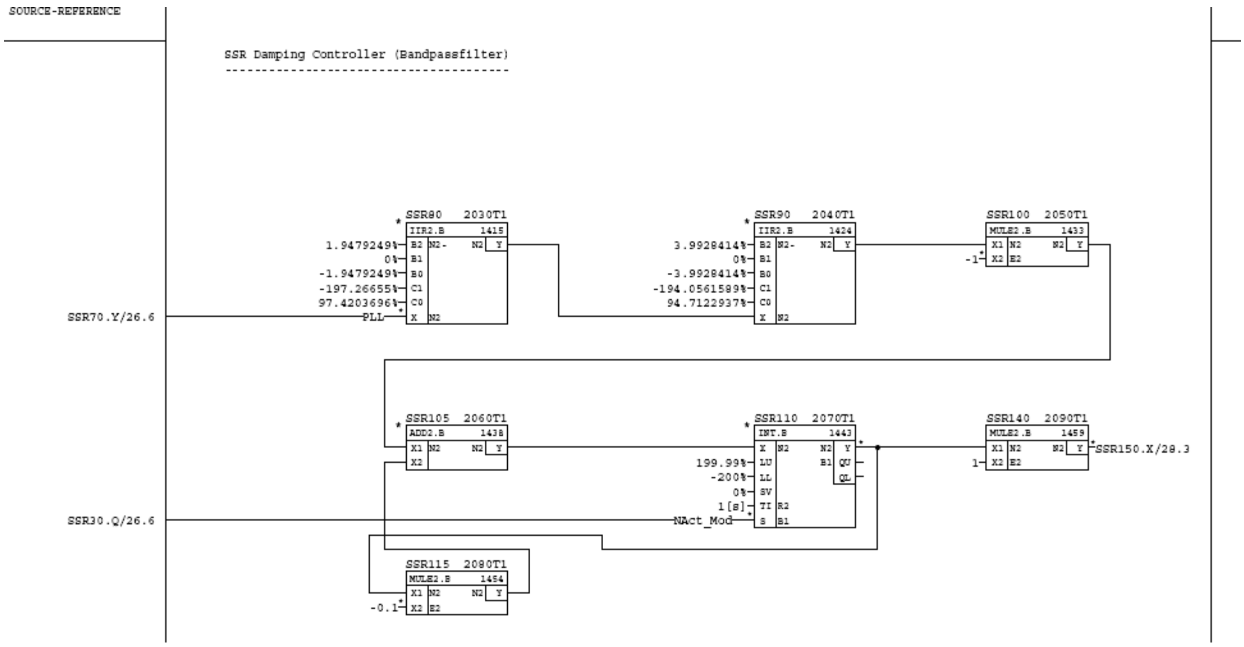

Figure 7. Block diagram of the band-pass filter.

3.1.3. Current control stage

The PI control algorithm is employed with a proportional coefficient of 0.9 and an integral time constant of 25 ms. The controller modulates the DC reference value, with an adjustment range of less than 5% of the rated current. The program is shown in **Figure 8**.

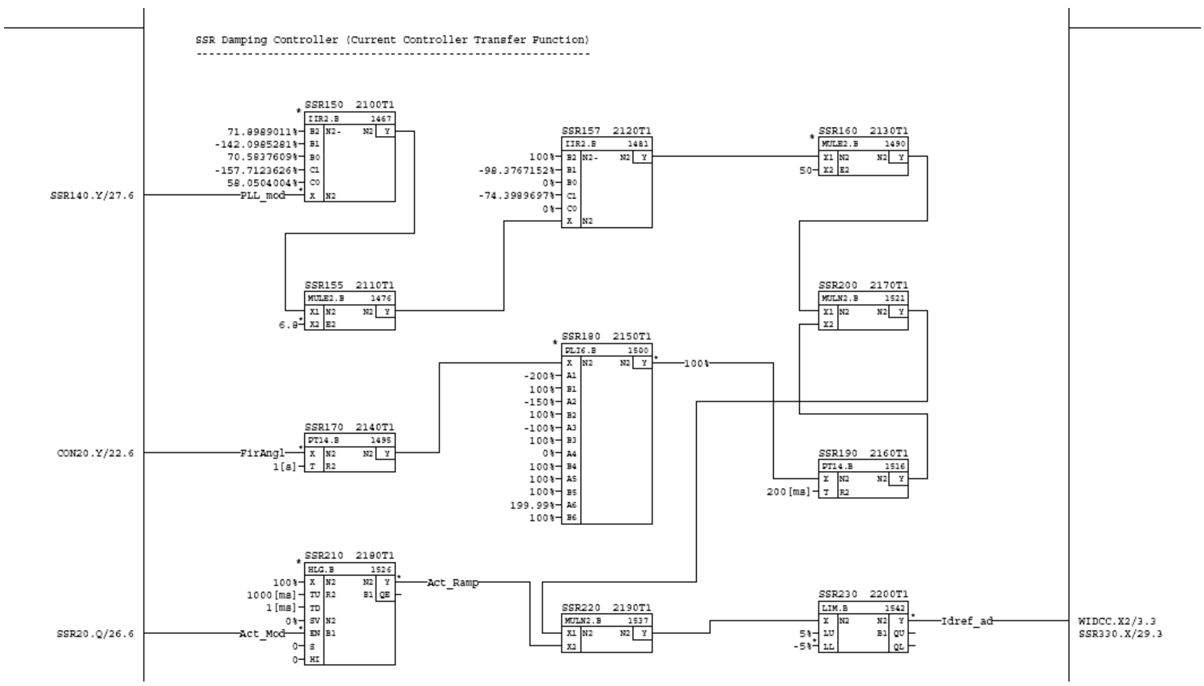

Figure 8. Current control circuit diagram.

3.1.4. SSR alarm

The alarm threshold for SSR function output is set at 0.25%, as shown in **Figure 9**.

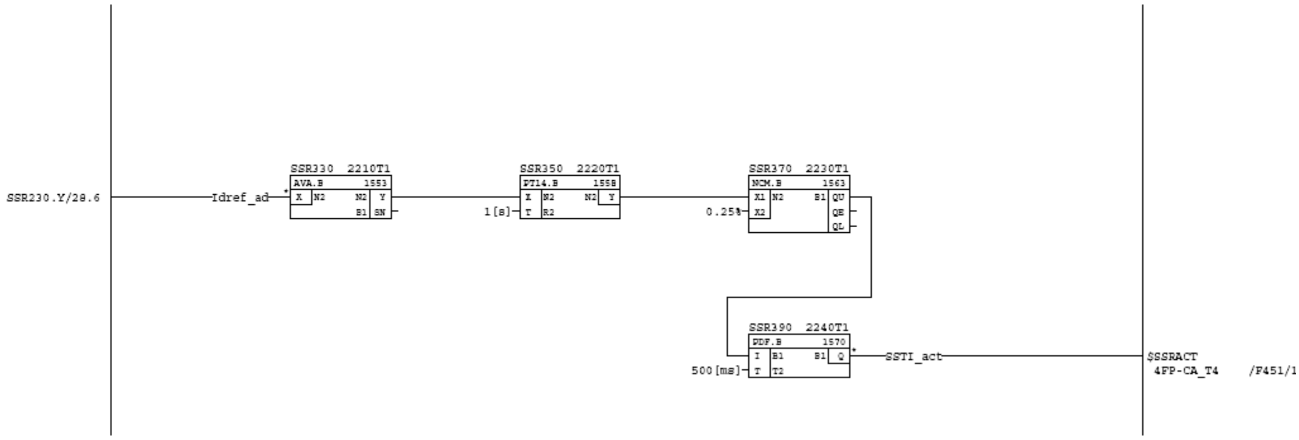

Figure 9. SSR alarm procedure diagram

4. Requirements for monitoring indicators of low-frequency inter-harmonics

4.1. Frequency band

The actual SSR resonance frequency of the unit in Plant B is 13.34 Hz, 23.83 Hz and 26.77 Hz. Therefore, the frequency band of the harmonic measuring device should be 10–30 Hz, and it should be able to analyze the frequency of the resonance point.

4.2. Signal accuracy

The threshold for SSR alarm in the control system is 0.25%, but when the SSR at converter station A activates, the amplitude of the SSR component is less than 0.2%. Therefore, to achieve accurate measurement, the signal accuracy of the harmonic measurement device must be higher than 0.1%. Therefore, the monitoring system is designed to detect and analyze inter-harmonic signals in the 10–30 Hz range, with alarm triggers for critical points and signal exceedances. It also records event logs to provide data support for addressing sub-synchronous oscillation issues between Converter Station A and Power Plant B. The system's network architecture is illustrated in **Figure 10**.

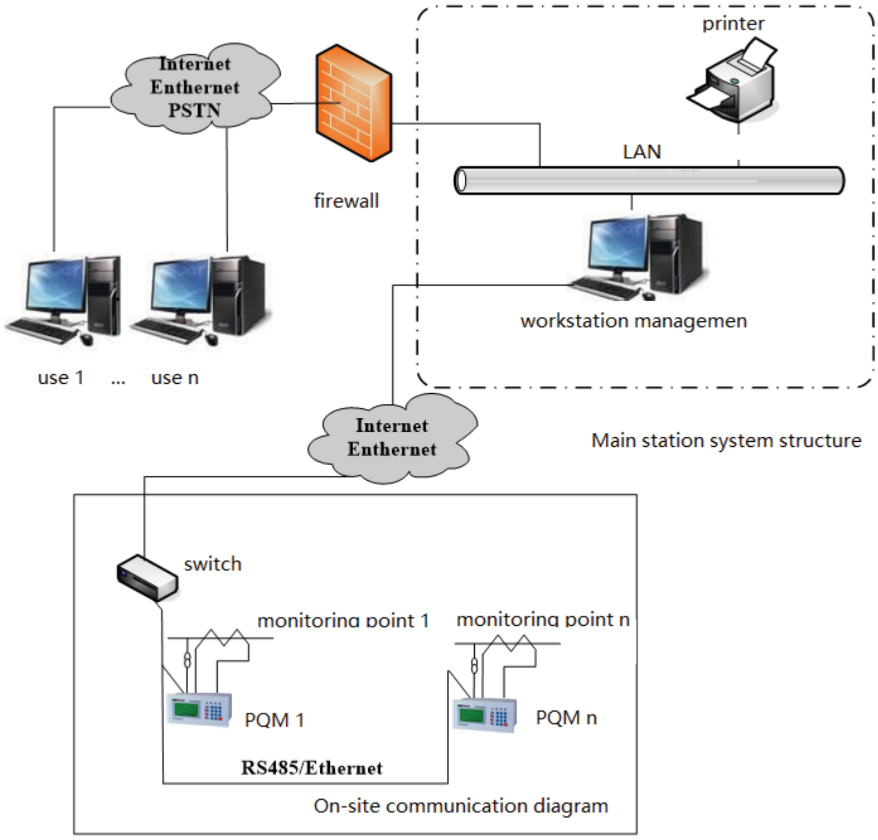

Figure 10. System network structure diagram.

5. Selection and setup of monitoring sites

Based on the actual conditions at the converter station site, 12 monitoring points have been established, with 8 distributed on the AC side of rectifier-inverter units and 4 across the 4 busbars. Each rectifier-inverter unit is equipped with two power quality monitoring devices, totaling 8 units across all 4 units at the station. Additionally, a power quality monitoring panel cabinet (**Figure 11**) has been installed in the relay protection room, and a complete online power quality monitoring system (including both software and hardware) has been deployed in the main control room to facilitate real-time and historical data access.

5.1. AC-side monitoring point of the AC-DC-AC flow unit B

The voltage signals at monitoring points 1, 3, 5, and 7 are obtained from the PTs of the WA-WT1, WA-WT2, WA-WT3, and WA-WT4 units, respectively. As the 500 kV AC bus adopts a 3/2 connection, the current signal is calculated as the sum of the secondary currents from CT3 and CT2 of the bus tie unit, reflecting the actual current at the AC output of the converter substation for harmonic analysis.

5.2. AC-DC-AC flow unit A AC-side monitoring point

The voltage signals at monitoring points 2, 4, 6, and 8 are taken from the PTs of units WB-WT1, WB-WT2, WB-WT3, and WB-WT4, respectively. The current signals are similarly obtained by summing the secondary currents of CT1 and CT2 in the bus tie unit.

5.3. Busbar monitoring point

The voltage signals at monitoring points 9, 10,11, and 12 are drawn from the PTs of busbars #1M, #2M, #3M, and #4M, respectively. The current signals are obtained from the line currents of #1, #5, #I, and #II lines, calculated as the sum of the CT currents on both sides of the line nodes.

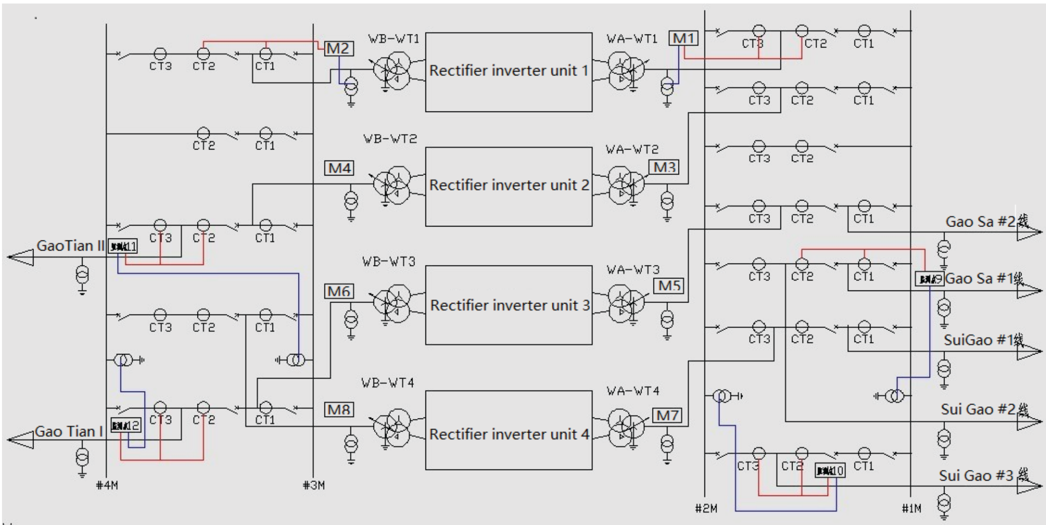

Figure 11. Schematic diagram of monitoring point selection for converter station.

6. Monitoring data configuration

The traditional power quality monitoring device mainly monitors the integer multiplification of inter-harmonic data, and the corresponding configuration adjustment is needed to realize the low-frequency inter-harmonic monitoring.

6.1. Addition of a low-frequency data area

A low-frequency data area was added as shown in **Figure 12**.

0x0640	Low-frequency data update indicator	After updating the low-frequency data in DSP, this value is set to the low-frequency data indicator (0..5). After the mainboard reads the low-frequency data, it is set to 0xff
0x0641~0x06A4	Low-frequency data area	The first 50short represents the amplitude, while the second 50short represents the phase

Figure 12. Data block configuration table.

6.2. Addition of transient waveform recording trigger criteria

The recording startup configuration table is shown in **Figure 13**.

0x1F86	Transient triggering reason	0: Exceeding threshold 1: Voltage mutation 2: Manual 3. Starting current 4. Current exceeding threshold 5. Voltage imbalance exceeding 6. Current imbalance exceeding 7. Frequency exceeding limit 8. Frequency under-limit 9. THDU 10. THDI 11. Voltage harmonic exceeding 12. Current harmonic exceeding

Figure 13. Recording startup configuration table.

6.3. Accuracy correction

The accuracy correction configuration table is shown in **Figure 14**.

0x0085~0x008A	Accuracy correction factor	They are A-phase voltage, current, B-phase voltage... Unit: 1/10000

Figure 14. Accuracy correction configuration table.

6.4. Data structure configuration

The data structure configuration is shown in **Table 1**.

Table 1. Data structure configuration table

Data			Position (byte)	Bytes	Type	Remarks
Time	Second		0	1	Char	The time for harmonic recording. The last two digits are the year, and the first two digits are the default year
	Component			``	``	
	Time			``	``	
	Sun			``	``	
	Moon					
	Year			``	``	
Continue to have			6	2	Char	Keep = 0
A Xiang	1 Hz	Amplitude of voltage	8	``	``	
		Phase of voltage				
		Amplitude of current				
		Current phase				
	50 Hz	Current phase				
B Xiang	1 Hz	Amplitude of voltage		``	``	
	50 Hz	Current phase		``	``	
C Xiang	1 Hz	Amplitude of voltage		``	``	
	50 Hz	Current phase		``	``	

6.5. Modification of communication protocol

The communication protocol configuration is shown in **Figure 16**.

(101)CMD_LOWFREQ_LIMIT	Read/write low-frequency exceeds the limit value(big-endian)	0	1	Read or write, 0=read, 1=write
		1	2	1Hz voltage interharmonic limit factor Unit: ‰
		3	2	2Hz Voltage interharmonic limit
		..	..	
			2	49Hz Voltage interharmonic limit
			2	1Hz Current interharmonic limit
			2	2Hz Current interharmonic limit
		..	..	
			2	49Hz Current interharmonic limit
(102)CMD_LOWFREQ_REC	retrieve low-frequency data	Same as CMD_HRM		

Figure 16. Communication protocol configuration table.

7. Conclusion

By optimizing the layout and retrofitting of monitoring points in a DC power system, low-frequency inter-harmonics on both sides of the converter transformer, including bus voltage and line current, can be effectively monitored. In practical applications, analyzing the parameters of the DC converter station's damping controller is essential to ensure signal accuracy. The monitoring points and data configurations of the power quality monitoring device are largely consistent, providing accurate and reliable reference data for sub-synchronous oscillation analysis.

Disclosure statement

The author declares no conflict of interest.

References

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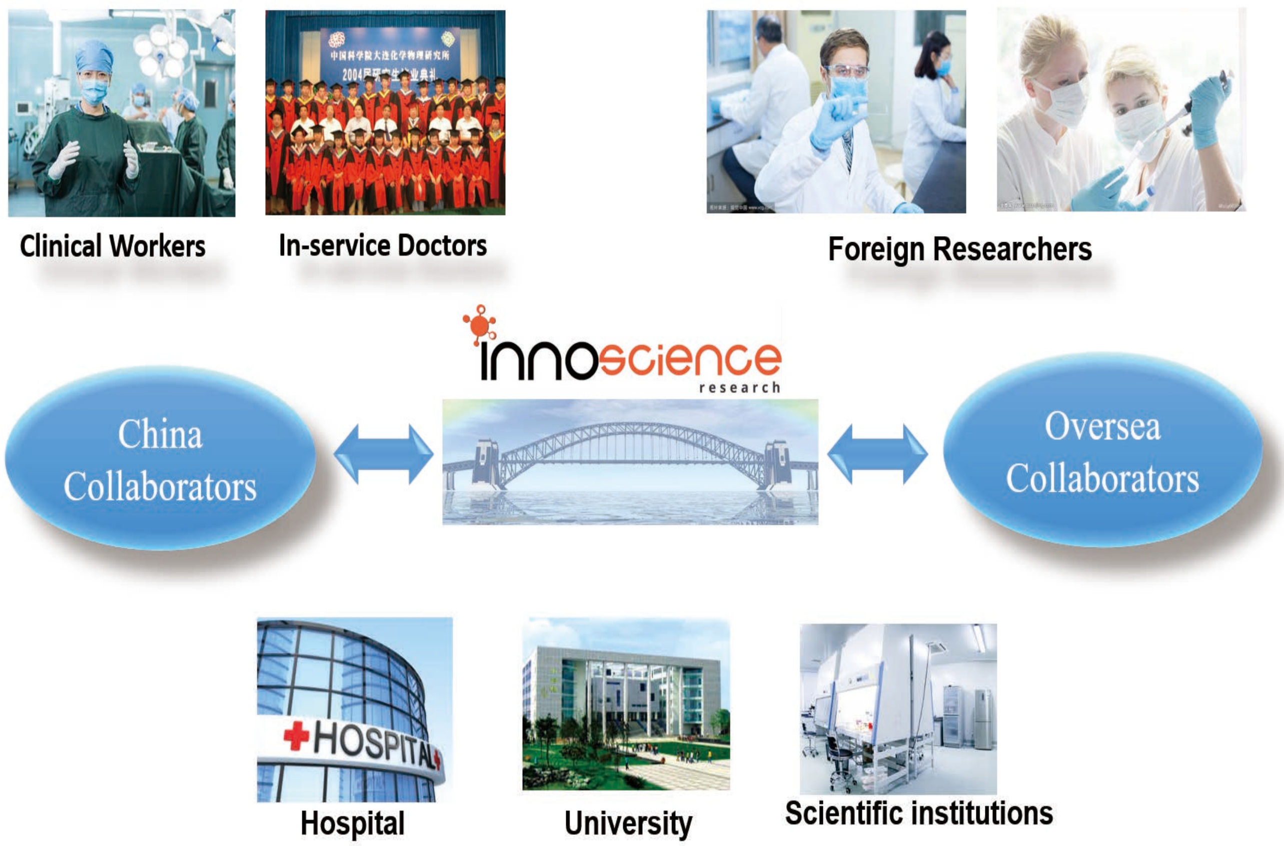

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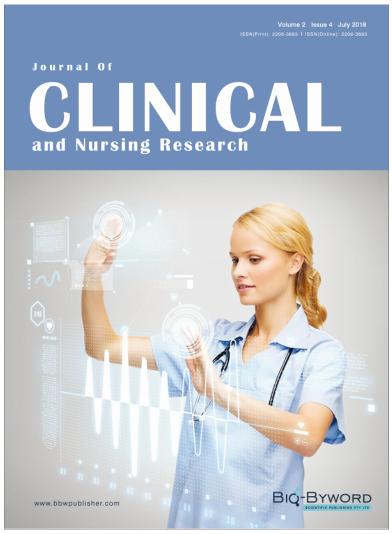

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