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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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