

Research on Reliability Improvement of Primary Equipment in Substation

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Abstract

Substation primary equipment is the material basis for power system to realize power transmission and conversion, and its reliability is directly related to the safe and stable operation of power grid and the quality of power supply. In this paper, the reliability improvement of primary equipment in substation is systematically studied. Firstly, the fault status of core equipment is analyzed, and the operation and maintenance dilemma of traditional maintenance mode and intelligent transformation, as well as the constraints of aging equipment, weak basic conditions and insufficient data support are sorted out. Secondly, the key technology system of reliability improvement is constructed from four dimensions: condition monitoring, fault diagnosis and prediction, design and manufacturing optimization and operation and maintenance strategy optimization, covering multi-parameter collaborative monitoring, intelligent fault diagnosis model, digital twin simulation and life cycle cost optimization. Finally, systematic reliability management strategy suggestions are put forward from three aspects: life cycle management, standardization and standardization construction, personnel training and technical exchange, and a closed-loop reliability guarantee mechanism covering the whole process of design, manufacturing, operation and maintenance and retirement is constructed.

Keywords

Substation; Primary Equipment; Reliability Improvement.

1. Introduction

As the core hub of power system, substation undertakes key functions such as voltage conversion, power distribution and system control, and its safe and stable operation is directly related to the reliability of power grid and the quality of power supply. Primary equipment is the material basis for substation to realize power transmission and conversion, but it is prone to insulation aging, mechanical wear, overheating and other problems when it is operated for a long time under high voltage, high current, strong electromagnetic interference and complex environmental conditions.

With the acceleration of smart grid construction, large-scale access to new energy and wide application of power electronic equipment, the operation mode of power grid is becoming increasingly complex, which puts forward higher requirements for the reliability of primary equipment [1]. The traditional "regular maintenance" mode gradually fails due to over-maintenance or missed inspection, and intelligent operation and maintenance technology based on state perception and prediction has become the direction of industry transformation [2]. The existing sensors have insufficient accuracy and low data acquisition frequency, so it is difficult to capture early fault characteristics. There is a lack of dynamic modeling of equipment degradation process, and the residual life evaluation error is large. The links of design, manufacturing and operation and

maintenance are separated, and the reliability index does not run through the whole cycle of the equipment.

Improving the reliability of primary equipment in substation has multiple values, which can reduce the sudden failure of equipment and reduce the risk of large-scale power outage. Condition-based maintenance replaces regular maintenance, saving manpower and material input. Adapt to the high proportion of new energy access scenarios, and improve the flexibility and adjustment ability of the power grid. Promote the deep integration of IoT (Internet of Things), big data, AI technology and power equipment. This study constructs a reliability improvement system covering the whole life cycle of equipment, providing theoretical support and practical guidance for smart grid construction.

2. Analysis of Reliability Status of Primary Equipment in Substation

Substation primary equipment is the core hub of power system, and its reliability directly affects the stability and security of power supply. At present, with the continuous growth of power demand and the iteration of power grid technology, the primary equipment in substation has made progress in technical upgrading and operation and maintenance management, but problems such as aging equipment, frequent failures and lagging maintenance mode are still prominent, and reliability improvement faces multiple challenges. The specific status quo is as follows:

(1) The core equipment problem is outstanding

As the core equipment of substation, the fault risk of transformer has both internal and external characteristics. The internal winding is often short-circuited, and the external winding is prone to thermal failure caused by local overheating or electrical failure caused by external environment and electromagnetic interference. Oil leakage and oil leakage caused by quality problems are common, and the hidden danger of loose lead directly affects the normal operation of the equipment, so it is necessary to rely on strict condition monitoring and maintenance data to ensure safe operation [3].

High-voltage and low-voltage switchgear undertakes the key function of quick short-circuit fault removal, but there are some typical problems in operation, such as refusing to operate, misoperation, abnormal sound and local overheating, and hidden dangers such as insufficient battery capacity and poor closing contact, which will directly affect the fault response ability of circuit breakers, and may lead to power grid cascading failures in severe cases, which requires extremely high equipment reliability.

Current and voltage transformers are the core equipment of power system signal acquisition, and the circuit disconnection is its high-frequency fault. In operation, the iron core is prone to abnormality due to the influence of secondary impedance, accompanied by abnormal sound and heating [4]. Traditional transformers have been difficult to meet the needs of power grid development in terms of insulation performance and fault response speed. Although electronic transformers have achieved breakthroughs in performance with optoelectronic technology, they have not been fully popularized, and equipment iteration and reliability balance still need to be optimized.

(2) Traditional mode and intelligent transformation coexist

At present, the primary equipment maintenance is still based on regular maintenance and fault maintenance, which easily leads to insufficient or excessive maintenance. Some equipment has not reached the maintenance period but lacks effective monitoring. Frequent maintenance of low-risk equipment wastes resources, and the maintenance plan is not scientific and targeted enough to match the actual operation state of equipment.

With the popularization of intelligent technology, infrared thermography, ultrasonic detection and oil pollution analysis are gradually applied, which can collect key parameters such as equipment temperature, vibration and current in real time and provide support for fault diagnosis [5]. However, most monitoring systems have not yet formed a complete data closed loop, and the linkage between equipment health status assessment and maintenance decision-making is insufficient, and the value of monitoring data has not been fully exerted.

Intelligent diagnosis, IoT and cloud computing technologies began to be integrated into the operation and maintenance system, realizing on-line monitoring and remote diagnosis of equipment, and improving the ability of fault early warning. However, the application of technology is still in its infancy, the accuracy of multi-source data fusion analysis and intelligent algorithm needs to be improved, and there is still room for improvement in operation and maintenance efficiency and timeliness of fault handling.

(3) Basic conditions restrict reliability

The aging problem of equipment is common in old substations. The problems of wear and leakage caused by long-term operation significantly reduce the reliability of equipment. The primary design capacity of some substations cannot match the increasing load demand, and the equipment is overloaded for a long time, which further aggravates the failure risk and becomes an important hidden danger of power supply reliability. The unreasonable distribution system layout and unscientific equipment connection in some substations lead to the increase of power transmission loss and the decrease of efficiency, which not only affects the stability of power grid operation, but also may lead to the spread of local faults due to structural defects and enlarge the influence range of faults on power grid.

(4) System shortcomings affect decision-making efficiency

The formulation of equipment maintenance plan lacks accurate adaptation to load characteristics and operating environment, and the rationality of maintenance cycle is insufficient, which makes it difficult to effectively cover the potential risks of equipment. Incomplete maintenance records and inadequate data analysis make it impossible to accurately identify the failure law, which restricts the dynamic optimization of operation and maintenance strategy [6]. The collection and analysis of equipment operation data is not systematic, and massive operation data has not been transformed into an effective basis for equipment health assessment, which is difficult to support the accurate formulation of maintenance plan and risk prediction, resulting in the lack of data support for operation and maintenance decision-making, and it is difficult to realize the transition from passive disposal to active prevention.

3. Research on Key Technologies to Improve Reliability

Improve the reliability of primary equipment is a systematic project, which must take condition monitoring, fault diagnosis and prediction as the analysis core; Take design and manufacturing optimization as the source guarantee; Operation and maintenance strategy optimization as implementation means; Through multi-technology collaborative promotion to make primary equipment in substation develop in a more reliable, intelligent and economic direction.

3.1 Equipment Condition Monitoring Technology

As the scale of power grid continues to expand and the operation requirements continue to improve, the failure reliability of primary equipment like transformer, circuit breaker, disconnecter and transformer in substation has a direct impact on safe and stable operation of power system. Equipment condition monitoring is the basis of reliability improvement. Through real-time and multi-dimensional data collection, the transparency and visualization of equipment operation state can be realized [7]. Multi-parameter collaborative monitoring integrates electrical, mechanical, thermal and chemical parameters to build a comprehensive monitoring system to improve the comprehensiveness and accuracy of state assessment. The application of high-precision, low-power and passive intelligent sensors, combined with IoT communication technology, realizes the real-time acquisition and remote transmission of equipment data, and provides data basis for state analysis. Optimize the anti-interference ability, environmental adaptability and long-term stability of the monitoring device to ensure continuous and reliable monitoring data.

3.2 Fault Diagnosis and Prediction Technology

The intelligent analysis means are used to realize early fault diagnosis and residual life prediction according to the monitoring data, changing the operation and maintenance mode from post-maintenance to active prevention [8]. Using signal processing and machine learning methods, fault-sensitive features are extracted from massive monitoring data, and high-resolution state indicators are constructed (Figure 1). Combining expert knowledge, physical model and data-driven method, a high-precision fault diagnosis model is established to realize accurate identification of fault type, location and severity. Based on the equipment degradation mechanism and historical data, a life prediction model is constructed to realize early warning of failure risk and residual service life evaluation, and support maintenance decision optimization.

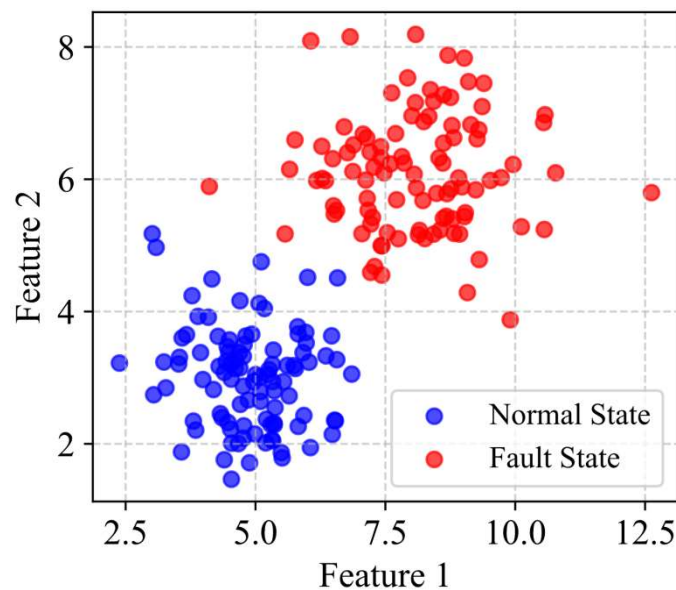


Figure 1. Fault sensitive feature extraction

3.3 Equipment Design and Manufacturing Optimization

Source capacity of equipment, improve the inherent reliability of equipment well models design, materials and technology optimization in tolerance long-term performance stability. Based on failure mode and impact analysis and reliability simulation, the design of electrical, insulation and mechanical structures is optimized to improve the adaptability of equipment under severe working conditions [9]. Research and development of high-performance insulation materials, arc-resistant contact materials, anti-corrosion coatings, etc., optimize the key processes of pouring, welding and assembly, and reduce the manufacturing defect rate. Using digital twinning, multi-physical field simulation and other technologies, the running state and stress distribution of equipment are simulated in the design stage, and the potential weak links are found in advance and improved.

3.4 Operation and Maintenance Strategy Optimization

According to the real-time status and forecast information of equipment, scientific and economical operation & maintenance strategies are formulated under the condition of balancing reliability improvement with good cost control. Combined with the fault prediction results, equipment importance and resource constraints, the maintenance plan is dynamically generated to improve the pertinence and timeliness of maintenance. Considering the cost of equipment purchase, operation, maintenance and scrapping as a whole, aiming at maximizing the reliability of the whole life cycle, the most economical operation and maintenance strategy is formulated. Integrate the functions of monitoring, diagnosis, prediction and decision support, and build an intelligent operation and maintenance system integrating data management, analysis and early warning, operation and

maintenance control, so as to improve the digital and intelligent level of operation and maintenance management.

4. Suggestions on Reliability Management Strategy

The primary equipment in substation is the core part of power system, and its reliability is directly related to two aspects: safe operation of pusers grid b and operation stability. In order to systematically improve the reliability of equipment, it is necessary to construct a comprehensive management strategy from three dimensions: life cycle management, standardization and standardization construction, personnel training and technical exchange, and form a reliability guarantee system covering the whole process of design, manufacturing, operation and maintenance, and retirement (Figure 2).

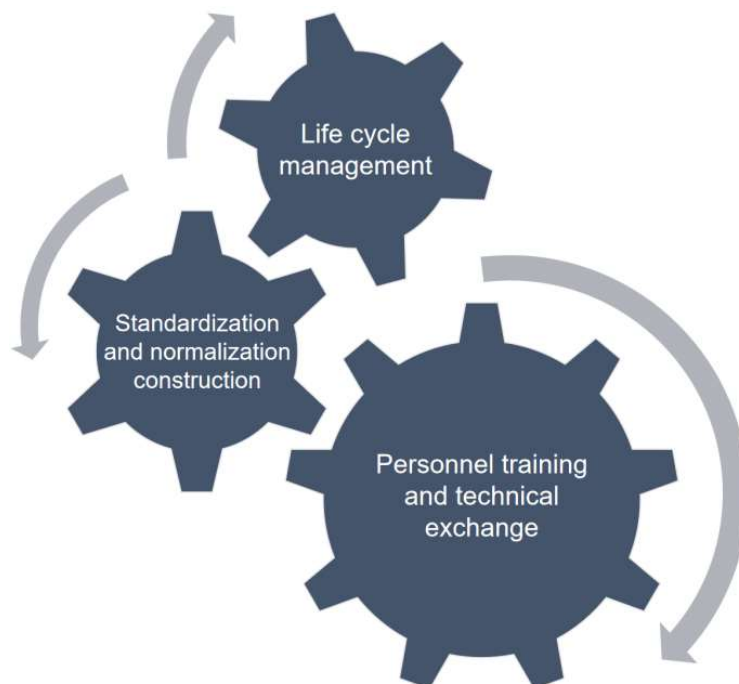


Figure 2. Reliability guarantee system

(1) Life cycle management

The equipment topology, material selection and redundancy design are optimized through reliability modeling and simulation analysis; the reliability index requirements of key components are specified. Establish supplier classification management system, strengthen raw material incoming inspection, production process quality traceability and ex-factory test standards, and ensure the equipment manufacturing process meets the reliability requirements. Intelligent detection technology is introduced to realize early defect identification. Deploy an online monitoring system, and establish an equipment health assessment model by combining big data analysis. The remaining life is predicted by AI algorithm, and the differentiated maintenance strategy is formulated to avoid excessive maintenance or disrepair. Establish equipment decommissioning evaluation standards, remanufacture repairable parts, and disassemble unrepairable parts in an environmentally friendly way to reduce the life cycle cost. Feedback design improvement through fault root cause analysis, forming closed-loop management. As shown in Figure 3, a closed-loop reliability improvement mechanism is constructed.

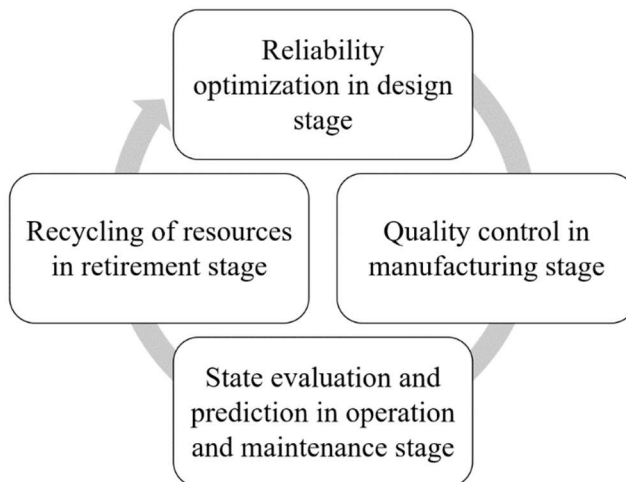


Figure 3. Closed-loop reliability improvement mechanism

(2) Standardization and standardization construction

Launch a combined technical specification, determine the performance characteristics of the device, testing standards and interface requirements, to avoid a parameter mismatch leading to compatibility problems. Develop standardized operating procedures (SOP) to refine the operational steps and quality standards for equipment inspection, testing, and maintenance. According to the DL/T 596 "Preventive Testing Code for Power Equipment" standard, establish an equipment status evaluation matrix and quantitatively evaluate the health index. Based on the risk assessment model of the power grid, develop differentiated operation and maintenance strategies to prioritize the reliability of high-risk equipment. Build a database of equipment life cycle, integrate design, manufacturing and operation and maintenance data, and realize dynamic tracking and visual analysis of reliability indicators. Real-time uploading of field operation data is realized through APP to improve management efficiency.

(3) Personnel training and technical exchange

Create specific courses for operation and maintenance personal, as well as technical managers and decision makers (see Table 1).

Table 1. Hierarchical and classified training system

Personnel hierarchy	The course focuses on direction
Operation and maintenance layer	Principle of equipment structure, fault phenomenon identification and emergency treatment skills
Management hierarchy	Reliability data analysis, condition evaluation method and maintenance strategy formulation ability
Decision-making level	Life cycle cost analysis, technical and economic evaluation and risk decision-making methods

Build a simulation training base, according to the common fault scenarios of circuit breaker refuse to operate and transformer oil leak, improve personnel emergency handling ability. Regularly carry out skill competitions to stimulate learning initiative. Participate in the formulation of international standards, join industry technical alliances, and share fault case base and solutions. Cooperate with scientific research institutions to carry out research on key technologies of reliability and promote iterative upgrading of technologies. Establish expert database and experience case database, and promote the manifestation of tacit knowledge through "mentoring system" and technical salon. Compile the Equipment Reliability Management Manual to systematically precipitate best practices.

5. Conclusion

Current substation main equipment operating conditions facing three difficulties, such as the comprehensive treatment of old equipment, frequent fault occurrence and so on traditional maintenance mode lag behind and intelligence level is low. In order to effectively improve its reliability, it is necessary to build a comprehensive technology and management framework covering the whole life cycle. Through multi-parameter collaborative monitoring and intelligent sensing, the equipment state transparency is realized; Integrate data-driven and physical model methods to improve fault diagnosis accuracy and residual life prediction ability; Optimize the equipment structure, materials and technology from the source of design and manufacture to enhance the inherent reliability; And dynamically optimize the operation and maintenance strategy based on the state evaluation results, and promote the transformation of maintenance mode to predictive maintenance. Relevant departments should strengthen the whole life cycle management mechanism, promote standardization and standardization construction, and enhance the professional ability of personnel through hierarchical training and technical exchange.

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