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Application Value and Practical Reflection of High Voltage Test in Transformer Condition Evaluation System

Kun Feng

CHN ENERGY DADU RIVER REPAIR&INSTALLATION CO.LTD., Leshan, Sichuan, China

Abstract: In this paper, the mapping relationship between high voltage test items such as insulation resistance, dielectric loss, DC resistance, partial discharge and winding deformation test and transformer latent defects, overheating faults, mechanical deformation and weak insulation points is systematically sorted out, and the unique physical significance of high voltage test as "insulation mirror" and "structural stethoscope" is expounded. At the same time, the problems existing in current practice, such as multi-dimensional information fragmentation caused by data islands, time mismatch between fixed test period and dynamic evolution of equipment state, insufficient anti-interference ability in complex electromagnetic environment, and insufficient "fingerprint" feature mining of equipment by evaluation model, are deeply analyzed. On this basis, some improvement strategies are put forward, such as establishing a comprehensive diagnosis mechanism of multi-source data fusion, carrying out differentiated test strategy based on equipment health index, strengthening the anti-interference ability of field environment, introducing deep learning technology to improve fault prediction ability, and strengthening continuous monitoring and dynamic analysis of data, in order to promote the development of transformer condition evaluation in the direction of intelligence and accuracy.

Keywords: Transformer; Condition Evaluation; High Voltage Test; Application Value.

1. Introduction

In the long-term operation process, the transformer will inevitably be affected by electric field, thermal field, mechanical stress and environmental factors, which will lead to the decline of insulation performance, component aging and even sudden failure. Once a large transformer fails, it will not only have a long maintenance period and high cost, but also cause a large-scale power outage, resulting in huge economic losses and adverse social impact.

In the transformer condition maintenance system, accurate condition evaluation is the basis of decision-making. There are many means to obtain the internal state information of transformer, including high voltage test, oil chromatography analysis, operation condition monitoring and historical family defect investigation [1]. Among them, high voltage test (including insulation resistance, dielectric loss, DC resistance, partial discharge, winding deformation test, etc.) has always been regarded as the "gold standard" for transformer condition diagnosis because of its characteristics of directly reflecting the electrical insulation performance and the connection state of conductive loop.

Despite the increasingly rich technical means, in practical engineering applications, the role of high-voltage test in state evaluation system still faces many challenges [2]. The interference of complex electromagnetic environment on high voltage test data often leads to misjudgment; Insufficient data correlation analysis between different experimental items is easy to lead to one-sided diagnosis of "blind people touching the image" [3]; And how to effectively integrate historical data and similar equipment data for vertical and horizontal comparison, there is still a lack of unified and standardized operation paradigm. These problems make the value of high voltage test not fully released, which restricts the further development of transformer condition evaluation in the direction of intelligence and accuracy.

This paper will systematically sort out the mapping relationship between various high-voltage test items and different fault modes of transformers, clarify the unique physical significance of high-voltage test as "insulation mirror" and "structural stethoscope", and clarify its weight and position in the multi-dimensional state evaluation system. In view of the problems existing in current practice, such as data island, poor anti-interference ability and rigid evaluation strategy, this paper will put forward specific improvement strategies. Including the establishment of a comprehensive diagnosis mechanism of multi-source data fusion, the implementation of differentiated test strategy based on equipment health index, and the use of big data technology to mine the deep rules of test data.

2. Overview of Transformer Condition Evaluation System and High Voltage Test

2.1. Basic Composition of Transformer Condition Evaluation System

Transformer condition evaluation system is the core link to ensure the safe operation of power system. Through multi-dimensional data collection and analysis, it realizes the comprehensive diagnosis of equipment health status. The specific structure is as follows: Table 1 and Table 2.

Table 1. Transformer condition evaluation content

Evaluation content	Key technical indicators
Ontology evaluation	Including insulation performance (such as dissolved gas analysis in oil), electrical performance (winding DC resistance, dielectric loss tangent) and mechanical structure (vibration signal monitoring).
Casing evaluation	Pay attention to insulation performance and mechanical deformation, and identify defects by combining partial discharge detection and infrared thermal imaging technology.
Tap changer evaluation	The arc tolerance and mechanical characteristics during switching are tested.

Table 2. Key technical indexes of transformer

Key technical indicators	Describe
Oil chromatographic analysis	Judging internal overheating or discharge failure by detecting hydrogen content.
Vibration signal monitoring	Using accelerometer to capture the characteristics of winding looseness or core relaxation.
Health index model	Combining historical operation data, maintenance records and environmental parameters, a quantitative scoring system is constructed.

The innovative methods are mainly embodied in two aspects. First, multi-physical field coupling evaluation is adopted, and the synergistic effects of electrical stress, thermal stress and mechanical stress on insulation aging process are comprehensively considered, so as to reflect the actual operation state of equipment more comprehensively [4]; The second is to introduce deep learning technology and use neural network to efficiently process massive monitoring data, which significantly improves the accuracy and intelligence level of fault prediction.

2.2. Classification and Characteristics of High-Pressure Test

As the core means to verify the insulation performance of transformer, high voltage test can be divided into three categories according to the test properties. Among them, the insulation test is further divided into two categories: non-destructive test is carried out at low voltage to evaluate the overall insulation state of the equipment; However, the destructive test exposes concentrated defects by applying high voltage, which is effective but has the risk of damaging insulation [5]. In addition, the characteristic test is used to detect the electrical or mechanical performance parameters of the transformer, such as winding DC resistance, ratio error and opening and closing time of the circuit breaker, and provide supplementary information for the equipment state.

According to the different waveforms of applied voltage, high voltage test can be divided into three categories: power frequency AC test, DC withstand voltage test and impact test. Power frequency AC test is closest to the actual operating conditions of equipment, and is mainly used to test the stability of insulation under long-term working voltage; Because of the different voltage distribution characteristics, DC withstand voltage test is more suitable for finding penetrating defects, especially in large-capacity equipment. The impulse test includes two forms: lightning impulse and operation impulse, aiming at evaluating the withstand capacity of insulation system under transient overvoltage, which is of great significance to ensure the safe operation of equipment under extreme working conditions.

3. Deep Analysis of Application Value of High Voltage Test in Condition Evaluation

As the core technical means of transformer condition evaluation system, high voltage test provides key data support for equipment health management through multi-dimensional detection and analysis. As shown in Figure 1, its application value is mainly reflected in the following four aspects:

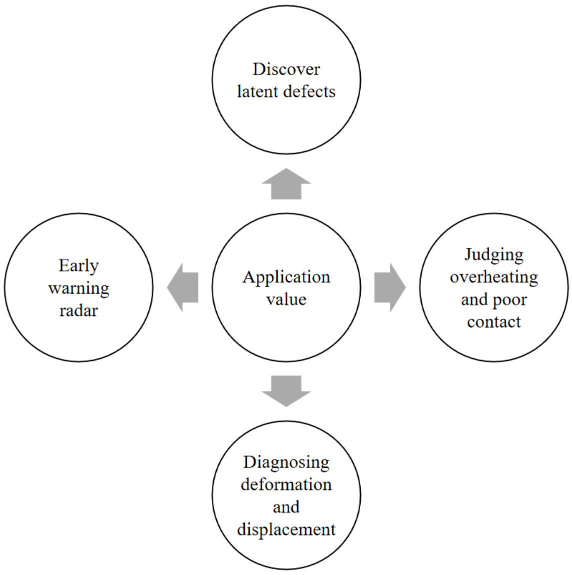

Figure 1. Application value of high voltage test in condition evaluation

1. Discover latent defects

The high voltage test can effectively identify the latent defects of insulation materials such as aging, moisture and bubbles by applying high voltage to simulate extreme working conditions. For example, the dielectric loss factor test can capture the early signal of insulation deterioration, and the withstand voltage test can expose local insulation weak links, providing scientific basis for preventive maintenance [6].

2. Judging overheating and poor contact

By means of DC resistance test and contact resistance measurement, the high voltage test can accurately locate the problem of poor contact, looseness or overload in the conductive circuit [7]. The unbalance rate analysis of winding DC resistance can quickly diagnose tap changer failure or lead breakage risk, and avoid equipment damage caused by overheating.

3. Diagnosing deformation and displacement

Techniques such as frequency response analysis (FRA) and short-circuit impedance testing can be used to non-invasively detect mechanical structural problems such as winding deformation and core looseness [8]. For example, FRA can identify the axial displacement or amplitude deformation of windings by comparing the frequency spectrum characteristics, and provide quantitative indicators for evaluating the short-circuit resistance of transformers (as shown in Figure 2).

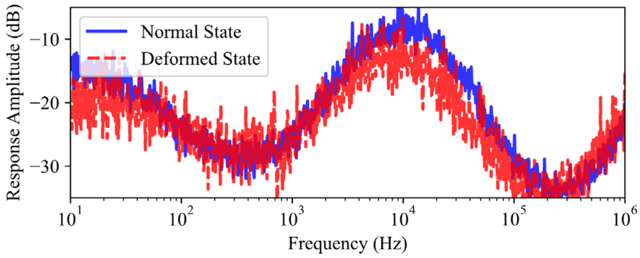

Figure 2. Comparison of FRA frequency response

4. "Early warning radar" for weak insulation points

Ultra-high frequency (UHF), ultrasonic and other partial discharge detection technologies can locate defects such as air gap and tip discharge in insulation in real time [9]. Through pulse waveform analysis, the discharge types can be distinguished, and the fault early warning can be realized by combining with trend monitoring, which significantly improves the reliability of insulation system operation.

4. Reflection and Problem Analysis in Current High Voltage Test Practice

4.1. Limitation of Data Dimension and "Information Island" Phenomenon

The current high voltage test mainly relies on off-line and periodic data, and lacks continuous monitoring of the whole process of transformer operation. The data of different test items (such as insulation resistance, dielectric loss and partial discharge) are often stored independently, and there are no unified data standard and interface, which makes it difficult to fuse and analyze the data, forming an "information island", which limits the comprehensiveness and accuracy of state assessment.

4.2. "Time Mismatch" between Test Period and State

There is a problem of "time mismatch" in the traditional periodic test mode. The test period is usually long, and the development of internal defects (insulation aging, partial discharge) of transformers is often dynamic and rapid. This fixed test period is difficult to capture sudden failure or rapid deterioration of state changes, resulting in the evaluation results lagging behind the actual operating state.

4.3. Insufficient On-site Environmental Interference and Anti-interference Ability

The field high voltage test environment is complex, which is easily affected by electromagnetic interference, temperature change, humidity and other factors. The anti-interference ability of some test equipment is weak, which leads to large fluctuation of test data, poor repeatability and even misjudgment. Especially in the strong electromagnetic environment of substation, the detection of weak signals such as partial discharge is easily disturbed, which affects the reliability of diagnosis results.

4.4. The Evaluation Model Ignores the Characteristics of "Fingerprint"

Traditional evaluation models mostly rely on threshold judgment or simple trend analysis, and lack of "fingerprint" feature mining for transformers [10]. Models often lack the ability to extract depth features after multi-source data fusion, which leads to insufficient sensitivity in identifying early latent faults and makes it difficult to achieve accurate state warning.

5. Strategies and Suggestions for Improving the Application Value of High Voltage Test

1) Establish a comprehensive diagnosis mechanism of multi-source data fusion

At present, there is an "information island" phenomenon in high-voltage test data, and the data of different test items are stored independently, so it is difficult to fuse and analyze them, which limits the comprehensiveness and accuracy of state evaluation. It is necessary to promote the establishment of unified data standards and interfaces to realize the integration of high voltage test data with other monitoring data. Through the comprehensive diagnosis platform, multi-source data are integrated to improve the comprehensiveness and accuracy of fault diagnosis.

2) Carry out differentiated test strategy based on equipment health index

The traditional periodic test mode has the problem of "time mismatch", so it is difficult to capture sudden failure or rapid deterioration of state changes. According to the historical operation data, maintenance records and environmental parameters of transformers, a health index model is constructed to quantify the equipment state. Based on the health index, the differentiated test strategy is implemented, the test frequency is increased for high-risk equipment, and the test period is extended for low-risk equipment to improve the test efficiency.

3) Strengthen the anti-interference ability of field environment

The field high voltage test environment is complex, which is easily influenced by electromagnetic interference, temperature change, humidity and other factors, resulting in large fluctuation and poor repeatability of test data. Develop test equipment with strong anti-interference ability, optimize test methods, and reduce the influence of environmental factors on test results. At the same time, strengthen the monitoring and management of field test environment to ensure the reliability of test data.

4) Introducing deep learning technology to improve fault prediction ability

Traditional evaluation models mostly rely on threshold judgment or simple trend analysis, and the sensitivity of identifying early latent faults is insufficient. Using deep learning technology, such as neural network, massive monitoring data are processed, deep features of data are extracted, and an intelligent diagnosis model is constructed. Through the deep learning model, the real-time monitoring and fault early warning of transformer state are realized, and the accuracy and intelligence level of fault prediction are improved.

5) Strengthen continuous monitoring and dynamic analysis of high voltage test data

The current high voltage test mainly relies on off-line and periodic data, and lacks continuous monitoring of the whole process of transformer operation. Popularize online monitoring technology to realize continuous and real-time monitoring of transformer state. Combined with big data analysis technology, the continuous monitoring data is dynamically analyzed, and the changing trend of equipment state is found in time, which provides more comprehensive and accurate data support for state evaluation.

Through the implementation of the above strategy, the application value of high voltage test in transformer condition evaluation can be effectively improved, and the transformer condition evaluation can be promoted to be intelligent and accurate, thus providing a strong guarantee for the safe operation of power system.

6. Conclusion

As the core technical means of transformer condition evaluation system, high voltage test shows irreplaceable application value in finding latent defects, judging overheating and poor contact, diagnosing deformation and displacement, and realizing early warning of insulation weak points by virtue of its unique advantages of directly reflecting electrical insulation performance and connection state of conductive loop. However, there are still some problems in practice, such as "information island" caused by data dimension limitation, "time mismatch" between periodic test and dynamic degradation, test error caused by field environmental interference, and insufficient mining of equipment "fingerprint" features by traditional evaluation models, which restrict its value release. In view of the above challenges, the research puts forward the following innovative paths: first, build a multi-source data fusion platform, integrate high-voltage test and other monitoring data through unified data standards and interfaces, and break through the information barrier; Secondly, the differentiated test strategy based on equipment health index is implemented, and the test cycle is dynamically optimized by using historical operation data, maintenance records and environmental parameters; Third, develop anti-interference test equipment and combine with online monitoring technology to improve data reliability in complex environment; Fourthly, the deep learning algorithm is introduced to mine the deep features of multi-dimensional data, and an intelligent diagnosis model is constructed to realize accurate early warning of faults. These improvement strategies provide theoretical support and technical path for promoting the development of transformer condition assessment in the direction of intelligence and accuracy, which is helpful to improve the operation and maintenance efficiency of power system and reduce the risk of sudden failure.

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