Life Monitoring and Evaluation Strategy of Traction Transformer on Freight Line

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Abstract. The traction transformer is regarded as the core power equipment in the traction power supply system of railway freight-dedicated line. As the time goes on, lots of traction transformers are under the long-term service status in the domestic electrified railway. Nevertheless, based on the present time-based preventive test code for electric power equipment, it is difficult to conduct the decision-makings on theirs running status. Therefore, it is necessary to study and implement condition monitoring and diagnosis (CMD) technologies.

In this paper, some typical characteristics of aging conditions are described, such as tensile strength (TS), polymerization degree (DP), CO/CO² content, furfural concentration, water content. Some analysis methods with development prospect are analyzed based on dielectric response theories, such as recovery voltage (RV) method, polarization-depolarization current (PDC) method and frequency domain spectrum (FDS) method of the oil-immersed insulation traction transformer. However, the insulation aging of traction transformer is a complex kinetic process of chemical reaction, and it is definitely necessary to combine all the effective methods together and synthetically analyze the experimental data and parameters for obtaining a comprehensive conclusion.

1. Introduction

The traction transformer plays an important role in the traction power supply system of the railway freight line. Its operational reliability directly affects the operational safety of the entire traction power supply system. The failure process of traction transformers is rarely a quality problem of design and manufacture, and most of them are insulation aging problems caused by long-term service. Therefore, studying the life estimation and aging conditions of traction transformers has important practical significance for ensuring the operational safety of traction line power supply systems.

The traction transformer is composed of insulating materials, electrically conductive materials, magnetic conductive materials and structural materials. Its life depends on the condition of its own insulation system, and the stress effects such as heat, electricity, mechanical force and chemistry will also cause its deterioration during operation. Engineering practice has proved that the aging of the insulation system is the main cause of short-circuit faults in the traction transformer tank [1]. The oil-paper insulation system is the most commonly used insulation structure for traction transformers. Even if the traction transformer is used for more than 20 years, the insulation performance of the insulating oil is only reduced by about 10% and can be improved by purification or replacement. This shows from the side that the drop in insulation performance of the traction transformer is mainly concentrated on the solid insulation material, that is, the service life of the traction transformer mainly...
depends on the insulation period of the solid insulation material.

2. State evaluation of aging of traction transformer insulation system

In order to evaluate the aging state of the traction transformer insulation system, it is first necessary to select the characteristic parameters closely related to the insulation aging process, and then apply the appropriate algorithm for parameter analysis to finally determine the aging conditions.

2.1. Characteristic parameters of aging conditions of traction transformer solid insulation materials

The degree of aging of the traction transformer solid insulation material is mainly manifested in mechanical strength. The tensile strength (TS) of the insulation paper is usually defined as the characteristic parameter of the aging process of the solid insulation material [2]. The method of measuring the tensile strength TS is the most direct, but the on-site sampling of the insulating paper is difficult and the repeatability of the test results is not satisfactory. In addition, the degree of polymerization DP is selected as another characteristic parameter reflecting the degree of aging of the insulating paper, because some by-products such as carbon monoxide, carbon dioxide, furfural and water are generated as the aging progresses.

2.1.1. CO/CO2 content in oil

The short circuit in the tank of traction transformer is related to the solid insulation material, so the transformer will produce a large amount of carbon monoxide and carbon dioxide in its tank after short circuit. In this way, the aging degree of solid insulating materials is determined by the content and trend of CO/CO2 in oil [3]. At present, gas chromatography is generally used to determine the content of CO/CO2 in oil.

2.1.2. Furfural content in oil

Furfural is produced when the solid insulating material of traction transformer is heated, wet, acid and oxidized. Furfural can only be produced during aging and degradation of insulating paper of traction transformer, and its chemical properties are very stable and difficult to volatilize. Therefore, the content of furfural in oil can be used as a characteristic parameter to reflect the aging condition of solid insulating material [4]. Figure 1 is a schematic diagram of furfural content in oil of various transformers under different operating conditions. According to figure 1, (1) the furfural content of traction transformer increases with the increase of its working life, (2) the growth rate of furfural content of traction transformer is higher than that of similar power transformer; (3) the furfural content growth rate of heavy load traction transformer is higher than that of light load transformer.

![Figure 1. Curves of furfural content in transformer oils](image)

2.1.3. Degree of polymerization of cellulose paper

Because the mechanical strength of solid insulating materials mainly comes from cellulose bond, DP, which reflects the strength, can be chosen as the characteristic parameter. At present, it is obtained by measuring viscosity. Figure 2 shows the relationship between tensile TS and DP.
2.1.4. Water content of solid insulating material

Water is the main product in the aging process of solid insulating materials. Water acts as a catalyst to accelerate the aging of solid insulating materials, which makes the cellulose molecular chain composed of insulating paper or cardboard break faster. It not only reduces the degree of polymerization of paper DP, but also reduces the mechanical strength of insulation system. Therefore, the determination of water content in solid insulating material is the key to judge the aging condition of transformer. The determination of water content in oil and dielectric response are two effective methods for the determination of moisture content in solid insulating materials in recent years.

It is difficult to measure the moisture content of solid insulating material directly, but the water content of oil is proportional to the moisture content of paper after the internal balance is reached. Therefore, the moisture content of paper can be obtained by the water content of equilibrium. At present, Karl Fischer titration is the most reliable method for the determination of water content in oil [5].

Considering that the polarization characteristic of the insulating material is related to its water content, the polarization state can be measured nondestructive by the dielectric response. The measurement methods are divided into time domain method and frequency domain method, in which the time domain method includes the recovery voltage method (RVM) and the polarization-depolarization current (PDC) method, and the frequency domain method is the frequency domain energy spectrum method (FDS) [6].

2.2. Strategy for estimating the ageing State of solid Insulation Materials

According to the characteristic parameters of the aging conditions of solid insulating materials, two methods can be formed to evaluate the aging state, namely, simple comparison method and comprehensive evaluation method.

2.2.1. Simple comparison method

The simple comparison method is to compare the characteristic parameters of aging conditions with the preset reference values. If the results are larger (or less) than the reference values, the aging degree of the transformer can be determined. Obviously, the method is simple in form and clear in purpose.

Generally, the contents of CO and CO2 in the oil are taken as the characteristic parameters of aging conditions, and their ratios are specified as the criteria for evaluating the aging conditions. If the ratio is greater than 0.33 or less than 0.09, it may be the degradation problem that the aging degree of fiber insulation is only up to the standard of IEC60599. Although this method further improves the maneuverability of evaluating the aging state of transformer, CO and CO2, will also be produced when insulating oil is oxidized, and it is difficult to determine whether CO and CO2 are produced by insulating paper or insulating oil. Therefore, this method cannot be used directly to estimate the state of aging, it is only used as a stand-by Method. Table 1 lists the concentration criteria of furfural dissolved in oil. For transformers with different operating life, different furfural concentration standards are recommended.
Table 1. Criteria for judging aging status of traction transformers based on furfural concentration

| Operational life (year) | Different aging criteria (mg/L) |
|-------------------------|---------------------------------|
| 1~5                     | ≥0.1                            |
| 5~10                    | ≥0.2                            |
| 10~15                   | ≥0.4                            |
| 15~20                   | ≥0.75                           |

There was a linear relationship between the concentration of furfural lg (FUR) and the degree of polymerization (DP), and the relationship could be written as follows:

$$\text{Lg(FUR)} = 1.065 - 0.0027\text{DP}$$ (1)

Formula (1) shows that the degree of polymerization (DP) can be calculated by using furfural concentration and then the aging conditions of solid insulating materials can be estimated by DP method. The concentration of furfural can directly reflect the aging status of solid insulating materials, but it is easy to be affected by many factors, and its relative stability is poor.

Table 2 lists the criteria for the degree of polymerization of cellulose paper.

Table 2. Criteria for evaluating the aging degree of solid insulation materials of transformer based on the degree of cellulose paper polymerization

| degree of polymerization | Life(%) |
|--------------------------|---------|
| 1000~1200                | 100     |
| 500                      | 50      |
| 300                      | 0       |
| 50                       | -       |

In order to characterize the aging status of insulating paper, the DP of cellulose paper is the most suitable index, and it can be used as a reliable and accurate criterion. However, if the DP is used as the state characteristic, the transformer core needs to be suspended, and the insulation paper sampling cannot be located in the key part which can best reflect the actual insulation state of the transformer. In addition, different temperature and different winding positions will produce different cracking degree, that is, the distribution of DP is more dispersed, so the DP decision method is difficult to apply.

The standard for the moisture content of solid insulating material is as follows: new input transformer 0.2% / 0.7%; transformer with 25 years operation > 2.5%; Therefore, when the moisture content of insulating material is more than 3%, the transformer needs to be dried. It is necessary to calculate the water content in solid insulating materials by measuring the water content in the oil. It is obvious that the time is the maximum deficiency of the method, which requires the water to reach the equilibrium state in a long period of time. In contrast, dielectric response method is not limited by this time problem, so it has become a hot research topic.

2.2.2. Comprehensive evaluation method

In order to evaluate the aging state of insulation materials of traction transformer objectively, it is not possible to use simple set value and a small number of evaluation experiments, and a complex and comprehensive evaluation method must be adopted. The neural network method has this standard and can be used to estimate the aging status of transformer insulation materials. For example, reference [1] introduces the estimation strategy based on comprehensive characteristic parameters and its application in substations, and the application of expert system in the evaluation of transformer insulation aging state is emphatically introduced in reference [2], and an example is given.

3. Life assessment strategy for insulation system aging of traction transformer

After the aging state estimation of transformer insulation system is completed, the remaining working life of traction transformer after many years of service can be deduced by some definitions. At present, there are statistical method, reliability evaluation method, accelerated life measurement method, dynamic equation method and so on.
3.1. Statistical method
In this method, the average life of transformer is obtained by a large number of statistical data of transformer operation. It takes a long time to summarize the running state of traction transformer and to master their average life, so it is difficult to apply this method to new transformer.

3.2. Reliability evaluation method
Reliability evaluation method is based on the reliability characteristics of transformer in normal operation. The reliability of the transformer decreases with the deterioration of the aging state of the transformer. When the transformer reaches a certain threshold, the actual life of the transformer can be confirmed to be complete. The method uses probability and statistics as technical means to estimate the life of transformer by measuring the aging state of insulating material, which has high practical value, and enables technicians and operators to maintain the aging transformer more effectively. On the basis of this method, some foreign scholars put forward a new concept of describing transformer insulation aging and linked it with reliability. Other researchers at home and abroad will have artificial nerves the network method is applied to the reliability research of aging characteristic parameters in order to evaluate the aging life of transformer.

3.3. Accelerated life test method
For example, if the working stress of traction transformer is improved, its aging speed will be faster and its life will also be reduced. According to the accelerated aging model, the life of traction transformer under actual working stress can be deduced by accelerated aging test. This is a mature, destructive method, and the cost of the experiment is high. This method is mainly based on thermal aging model, electric aging model and electrothermal aging model.

Thermal aging model: \[ \ln L = \ln A + \frac{B}{T} \] (2)

Electrical aging model: \[ L = K E^{-n} \] (3)

Electrothermal aging model: \[ L = K e^{\frac{-n E}{T}} \] (4)

Among the three models, \( L \) is the insulation aging life of the transformer, \( T \) is the absolute temperature, \( E \) is the external electric field, and other parameters (\( A, B, K, n \)) are all constants of the specific working environment of the transformer. The above equation is just a formula for each aging model, and no other description is presupposed here.

3.4. Dynamic equation method
At present, some progress has been made in the study of the chemical reaction kinetics of cellulose degradation based on the concentration of DP and furfural. For DP, the typical dynamic equation is

\[ \frac{1}{DP_t} - \frac{1}{DP_0} = kt \] (5)

In this equation, \( DP_t \) and \( DP_0 \) represent the current value and initial value of DP, \( t \) is the aging time, and \( k \) is the constant of any particular aging environment.

By analyzing other researchers' test data, document [6] gives the water content curves of solid insulating materials (paper or board) at different temperatures, as shown in figure 3.
As can be seen from figure 3, the polymerization degree DP shows good linear characteristics over time, and the formula (5) is proved to be suitable for describing the aging process of transformer. Normally, $DP_t = 200$ is chosen as the complete fault mark of insulation system of traction transformer, then the aging period of transformer can be calculated by using formula (5). For furfural, the kinetic equation is

$$F_t = bt + ct^2$$

In the equation, $F_t$ is the current concentration of furfural, $t$ is aging time, $b$ and $c$ are constants of specific aging environment.

4. Conclusion
The change process of insulation system in traction transformer is very complicated, so it is difficult to quantify it by brief analysis. That is, when the transformer works, the different parts of the material bear different pressure, and the same part of the pressure is also time-varying, so a simple mathematical model is difficult to accurately describe the insulation aging process of traction transformer. In addition, it is not sufficient to use a single characteristic parameter to evaluate the aging degree of insulating materials. The only correct method is to analyze several characteristic parameters synthetically, and make a long-term investigation and horizontal comparison. In a word, the research on the service life of traction transformer can not be fully solved overnight. It is necessary to carry out solid theoretical and technical research on solid insulating material system, state assessment, aging assessment and evaluation strategy.

References
[1] Yang T F, Li J L, Zeng X J, etc. Fault diagnosis of large-scale transformer based on multi-method combination diagnosis model [J]. Power system Automation, 2009, 33 (20): 92 - 95.
[2] Mo J, Wang X, Dong M. Fault diagnosis method of power transformer based on rough set theory [J]. Chinese Journal of Electrical Engineering, 2004,24 (7): 162 -167.
[3] Dong M, Qu Y M, Zhou M G. Fault diagnosis of oil-immersed power transformer based on combinatorial decision tree [J]. Chinese Journal of Electrical Engineering, 2005,25 (16): 35 -41.
[4] Wang Y Q, Fang C. Fault diagnosis algorithm for transformer based on Bayesian network and dissolved gas analysis in oil [J]. Journal of Electrical Technology, 2004, 19 (12): 74 - 77.
[5] Zhou A H, Zhang B D, Zhang H X. Power transformer fault diagnosis based on artificial immune classification algorithm [J]. High Voltage Technology, 2007, 33 (8): 77-80.
[6] Zhao W Q. Research on transformer fault diagnosis and prediction based on data mining [D]. Doctoral thesis, North China Power University, 2009