Evaluation of Oil Paper Insulation State of Traction Transformer

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Abstract. The improved grey target theory is applied to study the aging state of oil paper insulation of traction transformer. Firstly, the data are measured by the recovery voltage method and the related parameters are identified based on the ED equivalent circuit model, and the extracted parameters are used as the characteristic quantity to evaluate the oil paper insulation state. Secondly, according to the different influence of each characteristic quantity on the aging state of oil paper insulation, the combination algorithm of improved AHP and entropy weight method is used to allocate the weight of each characteristic quantity. Thirdly the paper insulation evaluation model of traction transformer is established. Finally, the data of several traction transformers are collected and the classification calculation of oil paper insulation state is carried out. The example shows that the method can effectively and reasonably evaluate the aging state of oil paper insulation of traction transformer, which can provide reference for condition based maintenance of traction transformer.

1. Introduction

At present, with the continuous development of China's railway transport, transport efficiency has been rapidly improved, and the national economy has also developed faster. In the railway system, the traction power supply system is a crucial link, and the most important core device is the traction transformer. Therefore, the performance requirements of the traction transformer need to be considered. The insulation aging problem of traction transformer is an important reason for its withdrawal from operation. It can effectively and accurately evaluate the insulation performance of traction transformer, find out the hidden danger of oil paper insulation as soon as possible and arrange maintenance reasonably, so as to prolong the service life of traction transformer and ensure the stability of traction power supply system.

In this paper, the improved grey target theory algorithm is adopted. Firstly, the data are measured by the recovery voltage method and the related parameters are identified based on the ED equivalent circuit model [1]. Secondly, the traditional grey target theory is improved, and the influence of each characteristic quantity on the bulls-eye degree is different in the diagnosis process [2]. By combining the improved AHP with entropy weight method, each feature is assigned the corresponding weight value, which improves the credibility of the evaluation results. Finally, the example shows that the method can effectively evaluate Oil paper insulation status of the transformer.
2. Return voltage method and selection of characteristic quantity

As a convenient and effective insulation diagnosis method, recovery voltage method is widely concerned by experts at home and abroad. When the voltage is applied to both ends of the insulating medium, the insulating medium will be polarized. If the voltage is removed and the medium is short circuited, the polarization charge on the surface of the dielectric will be released. At the same time, the depolarization reaction will occur inside the medium. After removing the two-stage line of the short connection medium, the depolarization reaction has not finished. At this point, the charge will form a potential difference between the electrodes, which is the recovery voltage, as shown in Figure 1.

After adjusting the charging time several times and measuring the voltage, the polarization spectrum of the return voltage can be obtained, as shown in Figure 2. The conclusions are as follows: the severity of insulation aging of traction transformer is positively correlated with the peak voltage $U_{\text{rmax}}$ of the corresponding return voltage polarization spectrum, and negatively correlated with the central time constant $\tau_{\text{cdom}}$. When the insulation condition is not good, the polarization speed will increase, resulting in a significant increase in the initial slope $S_i$.

At present, we establish an ED model composed of parallel RC series branches, which is integrated into the equivalent circuit, as shown in Figure 3. The complex polarization process of insulating medium is studied. The equivalent RC series circuit can be used to represent the relaxation process of insulating paper, insulating oil and insulation moisture. $R_g$ is the insulation resistance in the physical sense of transformer. The smaller the resistance value indicates the more serious the insulation aging condition, which shows the conductivity of the insulating medium. $C_g$ is the geometric capacitance of the insulating medium, and the smaller the capacitance value, the better the insulation performance of the insulating medium. In this paper, the time constant $\tau_i$ in the dielectric polarization equivalent circuit is proposed to reflect the state of the oil paper insulation system. The smaller the time constant is, the more serious the deterioration will be.
In summary, the six characteristics of peak voltage \( U_{\text{max}} \), central time constant \( \tau_{\text{cdom}} \), initial slope \( S_{\text{max}} \), insulation resistance \( R_g \) and geometric capacitance \( C_g \), and average time constant \( \tau \) of polarization branch in equivalent circuit are selected to evaluate oil paper insulation deterioration. After the characteristic quantity is determined, it is necessary to select the appropriate evaluation theory.

3. Improved grey target theory

The traditional grey target theory is the decision theory proposed by Professor Julong Deng [3]. The theory is used to reflect the mutual influence of various evaluation factors. In real life, the impact of each factor on the evaluation is different. Therefore, when analyzing the impact of various factors on the evaluation results, it is necessary to add different weight values to different factors. In this design, the comprehensive weight allocation method is adopted to assign weights to different factors, so that the evaluation results will be more in line with the reality [4].

3.1 Building a standard model

Since there are many states in transformer insulation system, we may as well set \( \omega_i \) as its \( i \)-th state mode, \( \omega_i = \{\omega_i(1), \omega_i(2), \ldots, \omega_i(n)\} \), Where \( \omega_i(n) \) represents the \( n \)-th characteristic quantity. In the established standard model, \( \text{POL}(\text{min}) \), \( \text{POL}(\text{men}) \) and \( \text{POL}(\text{max}) \) are expressed as minimum polarity, median polarity and maximum polarity respectively. Therefore, the formulas are as follows:

- \( \text{POL}_0(n) = \text{POL}(\text{min}) \), which represents the minimum polarity of the characteristic quantity of the standard mode, we can take \( \omega_0(n) = \min[\omega_i(n)], \omega_i(n) \in \omega(n) \).
- \( \text{POL}_0(n) = \text{POL}(\text{max}) \), which represents the maximum polarity of the characteristic quantity of the standard mode, we can take \( \omega_0(n) = \max[\omega_i(n)], \omega_i(n) \in \omega(n) \).
- \( \text{POL}_0(n) = \text{POL}(\text{men}) \), indicating that the characteristic quantity of the standard pattern is intermediate polarity, and the specified value is obtained.

The standard modes \( \omega_0 = \{\omega_0(1), \omega_0(2), \ldots, \omega_0(n)\} \).

3.2 Grey target transformation

When the difference between the values of different characteristic quantities is too large, the small values will be affected by the large values. This is because different dimensions need to be used between the characteristic quantities. Therefore, it is necessary to carry out a unified measure transformation for the characteristic quantities. The formula of grey target transformation is as follows:

\[
T[\omega_i(k)] = \frac{\min \{\omega_i(k), \omega_0(k)\}}{\max \{\omega_i(k), \omega_0(k)\}} = x_i(k) \tag{1}
\]

In this formula, \( T[\omega_i(k)] \in [0,1] \) is the transformed value, and the larger \( |\omega_i(k)-\omega_0(k)| \), the farther away \( T[\omega_i(k)] \) is from 1, otherwise, the closer \( T[\omega_i(k)] \) is to 1.

3.3 Determination of comprehensive weight

Improved analytic hierarchy process [5]: This method is to analyze the problem and divide it into several levels. Then combined with the experience of previous experiments, the opinions of experts in the field were adopted. Finally, the subjective judgment is quantified as a criterion to improve the accuracy of evaluation [6].

Entropy weight method: According to the definition of information entropy, the dispersion degree of an index can be judged by the entropy value. The smaller the entropy value is, the greater the dispersion degree of the index is, and the greater the influence of the index on the comprehensive evaluation. If the values of an index are all equal, the index has no role in the comprehensive evaluation.

The following describes the steps of determining the weight by entropy weight method:
The matrix \( X = [a_{ij}]_{m \times n} \) is established. The matrix is composed of \( m \) rows multiplied by \( n \) column elements. \( m \) represents the object to be evaluated and \( n \) represents the indexes participating in the evaluation.

\[
X = \begin{bmatrix}
a_{11} & a_{12} & a_{13} & \cdots & a_{1n} \\
a_{21} & a_{22} & a_{23} & \cdots & a_{2n} \\
\cdots & \cdots & \cdots & \cdots & \cdots \\
a_{m1} & a_{m2} & a_{m3} & \cdots & a_{mn}
\end{bmatrix}_{m \times n}
\]

(2)

The matrix \( X = [a_{ij}]_{m \times n} \) is standardized, and each element \( a_{ij} \) in the matrix \( X \) becomes \( b_{ij} \) after standardization, thus forming another different matrix \( K = [b_{ij}]_{m \times n} \). The proportion of the \( i \)-th element in the \( j \)-th evaluation element from the first calculation can be written as follows:

\[
P_{ij} = b_{ij} / \sum_{i=1}^{m} b_{ij}
\]

(3)

If \( P_0 = 0, P_{ij} \ln P_{ij} = 0 = 0 \). Under this premise, the entropy value of the \( j \)-th element is obtained as follows:

\[
I_j = - \frac{1}{\ln m} \sum_{i=1}^{\infty} P_{ij} \ln P_{ij}
\]

(4)

The entropy weight of the \( j \)-th element can be written as follow:

\[
\omega_j = \left(1 - I_j\right) / \left(n - \sum_{i=1}^{n} I_j\right)
\]

(5)

Combined with the above discussion, we can find that the improved AHP and entropy weight method are two different evaluation methods. Using these two methods at the same time will greatly improve the accuracy of the evaluation. This takes into account the importance of human experience and the objectivity of the data itself, so that the evaluation results are more real.

Therefore, the subject uses \( \alpha_k = \lambda \varepsilon_1 + (1-\lambda)\varepsilon_2 \) to calculate the weight value of each factor. Where, \( \lambda \) refers to the effect of human factors. Because the evaluation results are the combination of the two methods, the influence of human factors is the same as that of objective factors, so the value of \( \lambda \) is set as 0.5.

3.4 Bulls-eye degree calculation

The calculation formula of bulls-eye coefficient can be written as follows:

\[
\gamma(\omega_0(k), \omega_1(k)) = \frac{\min \min \Delta_{0i}(k) + \rho \max \max \Delta(k)}{\Delta_{0i}(k) + \rho \max \max \Delta_{0i}(k)}
\]

(6)

Where, \( \rho \) has the same meaning as \( \lambda \) in the previous chapters, so the value of \( \rho \) is 0.5, \( \Delta_{0i}(k) = |x_0(k)-x_i(k)| \).

In the improved calculation of bulls-eye degree, the influence of different factors on the evaluation of insulation state will be fully taken into account, so the calculation of bulls-eye degree will be improved to use the bulls-eye coefficient of each factor to determine the bulls-eye degree of each factor [7]. The new calculation formula of bulls-eye degree is:

\[
\gamma'(\omega_0, \omega_1) = \alpha_k \sum_{i=1}^{n} \gamma(\omega_0, \omega_1)
\]

(7)
3.5 Gradation

In the process of evaluation, the object to be evaluated is usually divided into several levels. These levels are different sets from 0 to 1. Each set represents a level, and the classification of these levels is based on the bull's-eye coefficient. According to the principle of information minimization, a conclusion is drawn, \( \gamma(\omega_0, \omega_i) \geq \rho/(1+\rho) \), the value of \( \rho \) in the above formula is 0.5. Therefore, \( \gamma(\omega_0, \omega_i) \geq 0.3333 \) is obtained. Only the evaluation level greater than 0.3333 is effective, and the rest has no practical effect. In this design, the oil paper insulation deterioration status of traction transformer is divided into three different levels, which are respectively:

- Severe insulation aging (the bulls-eye degree is in \([0.4,0.6]\)).
- Moderate insulation (the bulls-eye degree is in \([0.6,0.8]\)).
- Excellent insulation (the bulls-eye degree is \([0.8,1]\)).

4. Evaluation model of oil paper insulation state of traction transformer

- First of all, the recovery voltage test of the traction transformer to be studied is carried out to obtain the required test data.
- From a large number of experimental data, the best factors are selected. In this design, six important and effective characteristics are selected, which are insulation resistance \( R_g \), geometric capacitance \( C_g \), average time constant of polarization branch \( \bar{\tau} \), polarization peak voltage \( U_{rmax} \), central time constant \( \tau_{cdom} \) and peak initial slope ratio \( S_{max} \).
- The entropy weight method combined with the improved analytic hierarchy process is used to calculate the bulls-eye coefficient and the bulls-eye degree of each feature quantity, so as to realize the purpose of reasonable weight distribution for each feature quantity.
- After the weight of each characteristic quantity is reasonably assigned, these data are applied to the grey target theory, and the bulls-eye degree of the traction transformer is obtained.
- After the calculation of the bulls-eye degree of the transformer, the insulation deterioration status of the traction transformer is finally obtained by comparing with the evaluation level divided above.

5. Case analysis

The state characteristic quantity sequence of 7 traction transformers is selected, as shown in Table 1.

| Model           | Rg/GΩ | Cg/nF   | \( \bar{\tau} \) s | U_{rmax}/V | \( \tau_{cdom} \)/s | S_{max}/(V·s-1) |
|-----------------|-------|---------|---------------------|------------|----------------------|-----------------|
| SFL-50000/110   | 2.0031| 91.2478 | 54.216              | 220.0      | 665.000              | 46.0            |
| S21050000/110   | 9.4410| 46.990  | 101.227             | 256.0      | 1356.000             | 33.4            |
| SFSEZ-18000/220 | 10.0700| 101.5000| 138.900             | 165.0      | 2213.460             | 33.5            |
| SFPS-18000/220  | 2.9360| 214.5800| 192.000             | 132.5      | 1656.000             | 24.4            |
| cub-MRM         | 2.6892| 127.5615| 274.130             | 383.0      | 472.100              | 30.1            |
| SFP9-240000/220 | 1.0855| 164.3007| 38.450              | 189.5      | 823.600              | 78.7            |
| SFSE-240000/220 | 7.5946| 95.8900 | 225.980             | 202.1      | 1549.422             | 24.4            |

For the transformer of model cub-MRM in Table 1, according to the model calculation, the value of the bulls-eye degree is 0.528. Compared with the grading of the target value, target value of the traction transformer is 0.528 \([0.4,0.6]\), so it belongs to the severe insulation aging. At the same time, the furfural mass fraction of the transformer was tested, and the furfural mass fraction was 3.56mg/L. Compared with the regulations of preventive test procedures for power equipment, the furfural quality score belongs to the value of serious insulation deterioration interval.

Similarly, the same method is used to evaluate the condition of SFSE-240000/220 transformer. The calculated bulls-eye degree is 0.786 \([0.6,0.8]\), which belongs to the state of moderate insulation. At the same time, the furfural mass fraction test of the transformer shows that the furfural mass fraction is 1.63 mg/L. According to the regulations of preventive test code for electric power equipment, the furfural mass fraction belongs to the moderate range of insulation state.

The above analysis and diagnosis results show that the oil paper insulation state of traction...
transformer analyzed by improved grey target theory is consistent with the furfural mass fraction insulation detection report. Combined with its operation history, the improved grey target theory diagnosis algorithm can be effectively applied to the evaluation of oil paper insulation state.

6. Conclusion
In this paper, the characteristic quantities are measured by the recovery voltage method and analyzed and extracted based on the ED equivalent circuit. All the obtained characteristic quantities are taken as the basis for comprehensive evaluation of the insulation state of traction transformer oil-paper. Secondly, the improved grey target theory is proposed to evaluate the oil paper insulation state of traction transformer, which solves the problem that the accuracy of bulls-eye degree is affected by the same weight of each characteristic quantity in the traditional grey target theory. The subjectivity of the improved AHP and the objectivity of entropy weight method are comprehensively improved to ensure the weight calculation is more reasonable and scientific. Finally, the paper calculates the bulls-eye degree, evaluates the oil paper insulation status in different grades, and establishes the evaluation model of oil paper insulation state of traction transformer. The experimental results show that the improved grey target theory is highly consistent with the actual state of traction transformer. The method is practical and provides a new idea for the evaluation of oil paper insulation state of traction transformer.

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