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Analysis of Life Cycle Characteristics of Power Transformer Based on Linear Regression

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Abstract: How to determine the insulation status of transformers reasonably which is very important for the life management of transformers. Electrical data, oil chromatograph data and oil test data are important parameters for measuring the insulation state of transformer. In this paper, the relationship between electrical, chromatographic and oil test data and transformer operating years in production operation is analyzed by means of regression analysis and hypothesis testing. The results show that the relationship between the absorption ratio, oil breakdown voltage and hydrogen hydrocarbon content is very weak between the operation years of the transformer and the CO and CO_2 gas content is strictly related to the operation years of the transformer. The former mainly reflects the insulation performance of transformer oil, and can effectively identify the integral fault of transformer, but it cannot effectively reflect the residual life of transformer by the influence of filter oil and oil transfer. The latter reflects the state of transformer solid insulation and is an old characteristic of transformer life prediction. An example verifies the validity of the above conclusion.

1. Introduction

Transformer is one of the most valuable equipment in the power system. It is of great significance to realize the state monitoring and life prediction of the transformer and change the transformer to the end of life in time. It is of great significance to the realization of the full utilization of the resources of the power equipment and the unity of the safe and stable operation of the power grid. The guidance for state evaluation of oil immersed transformer (reactor) is divided into four states of normal, abnormal, abnormal and serious according to the degree of deterioration and weight of each state. The transformer is divided into four states of normal, abnormal, abnormal and serious [1-2]. The domestic and foreign scholars introduced the comprehensive fuzzy evaluation method [3-4]. According to the basic information of the transformer, the oil color spectrum data, the oil experiment data, the electrical test data and the corresponding standard [1-2], the state evaluation was carried out, and the life prediction of the transformer was predicted according to the results of the evaluation. It is found that the correlation between the results of the test project and the prediction of the transformer life end is different. Some parameters change with the end of the transformer life, and some parameters are not obvious in the whole life cycle of the transformer, and the residual life of the transformer cannot be reflected effectively. In this paper, on the basis of the field test data, the change of the characteristic quantity with time is analyzed, and the relationship between the characteristic quantity and the life of the transformer is discussed [5-9]. The analysis shows that the electrical experimental data can effectively respond to the transformer fault, but it cannot effectively depict the position of the

transformer in the life cycle. As the life of the transformer decreases, the carbon oxygen compounds show significant changes, which can reflect the residual life of the transformer.

2. Linear regression and hypothesis test

In this paper, linear regression and hypothesis test are used to analyze the relationship between transformer aging characteristics and time [10]. The linear regression equation model is as follows:

$$\begin{cases} y = \beta_0 + \beta_1 x + \varepsilon \\ \varepsilon \sim N\left(0, \delta^2\right) \end{cases} \tag{1}$$

Where, it is an unrelated unknown parameter. Using the least square method to obtain the parameters of beta 0, beta 1. The Clem (Cramer) rule can be obtained:

$$\begin{cases} \hat{\beta}_1 = \dfrac{l_{xy}}{l_{xx}} = \dfrac{\sum\left(x_i - \bar{x}\right)\left(y_i - \bar{y}\right)}{\sum\left(x_i - \bar{x}\right)^2} = \dfrac{\sum\left(x_i - \bar{x}\right)y_i}{\sum\left(x_i - \bar{x}\right)^2} \\ \\ \hat{\beta}_0 = \bar{y} - \hat{\beta}_1 \bar{x} \end{cases} \tag{2}$$

Correlation coefficient is a relative index of goodness of fit between regression line and sample observation. Let S_R be the sum of squares of regression and S_T as the sum of squares of total deviations.

Correlation coefficient is a relative index of goodness of fit between regression line and sample observation. Let S_R be the sum of squares of regression and S_T as the sum of squares of total deviations.

Its specific meaning can be seen in document [10]. The greater the $\dfrac{s_R}{s_T}$ proportion, the better the return effect. Let

$$R = \sqrt{\dfrac{s_R}{s_T}} = \dfrac{l_{xy}}{\sqrt{l_{xx} l_{xy}}} = \dfrac{\sum\left(x_i - \bar{x}\right)\left(y_i - \bar{y}\right)}{\sqrt{\sum\left(x_i - \bar{x}\right)^2 \sum\left(y_i - \bar{y}\right)^2}} \tag{3}$$

Because, R^2 is used as a parameter to describe the effect of linear regression. When the closer to 1, the linear correlation between Y and X is stronger. Whether the linear regression equation of a single variable really describes the statistical law between variables and whether the regression coefficient is 0 is also significant tested by [6]. In this paper, the regression coefficient is tested by the test method, and the significance level is 0.05. The value P indicates the probability of the sample observation or the more extreme result obtained when the original hypothesis is true. When $P < \alpha$, the regression effect is significant, and variables are linearly correlated.

3. Electrical Characteristic Analysis

The transformer is mainly used in the form of oil paper insulation. Under the effect of high temperature and strong electromagnetic environment and electric power, the transformer is aging gradually. The main performance is the aging of insulation paper and insulation oil and the degradation of insulation performance, until the transformer cannot work normally and the life is terminated. The state evaluation and life prediction of transformer are mainly derived from the test project of the preventive test regulations of DL/T596-1996 power equipment, which mainly include gas chromatography analysis, DC resistance detection, insulation resistance and absorption ratio detection, insulating oil pressure test [2]. The above test items measure the performance of transformer insulation medium from different aspects. The above test items can effectively detect all kinds of insulation defects and faults in transformer. For in-service transformers, preventive tests should be carried out regularly to check the insulation status of transformers. This paper collects and analyzes the preventive test data of some transformers in a power supply bureau of a city. These data, the

earliest derived from the handover test data before the operation of the transformer, the latest for 22 years of transformer data, that is, the data represented by the transformer from 0 to 22 years.

3.1. Absorption ratio

The absorption ratio has a high sensitivity to check the overall insulation of the transformer, and can effectively detect the integral defects of the transformer as a whole to be affected by moisture or aging, moisture or fouling on the surface of the components and the penetration of the transformer. The large absorption ratio indicates that the insulation condition of the transformer is excellent. Regulation stipulates that the absorption ratio of the transformer is not less than 1.3. A total of 80 absorption data were collected, including 45 500kV data and 35 220kV data. As shown in Table 1.

Table 1. Absorption ratio at different running times

	time/year	0	0	0	0	0	0	2	2	2	2	2	4	4	4	4
	absorption	1.	1.	1.	1.	1.	1.	2.1	2.2	2	2.	2.	1.	1.	1.	1.
500 kV	time/year	4	5	5	5	5	5	5	8	8	8	8	8	8	11	11
	absorption	1.	1.	1.	1.	1.	2.	2.5	2.5	2.	2.	1.	1.	1.	2	3
	time/year	11	11	11	13	13	16	16	17	17	19	19	19	21	21	21
	absorption	2.	3	1.	2	2	1.	1.5	2	2	1.	1.	1.	1.	1.	1.
	time/year	3	3	3	5	5	5	6	8	8	8	8	8	9	9	9
	absorption	1.	2	1.	1.	2	1.	1.6	1.7	1.	1.	1.	1.	1.	1.	1.
220 kV	time/year	10	10	10	11	11	11	11	11	13	13	13	13	14	14	16
	absorption	1.	1.	1.	1.	2	2	1.5	2	1.	1.	2.	1.	2	2	1.
	time/year	16	17	17	19	19										
	absorption	1.	2	1.	2	1.										

The distribution of absorption ratio is not related to time. Further, regression analysis of absorbance data is done. 500kV voltage level transformer:

$$Y=0.0002x+1.9307 \quad R^2=1 \times 10^{-5} \quad P=0.873 \tag{4}$$

220kV voltage level transformer:

$$Y=0.0079x+1.643 \quad R2=0.0199 \quad P=0.3815 \tag{5}$$

The R^2 and P values can reflect the linear strong and weak relations between the variables. Under the same observation times, the smaller the P value, the closer to 1 of the R^2, the stronger the linear relationship between the two variables. In the three regression equations above, the P values are far greater than 0.05, while the linear correlation coefficients R^2 are relatively small. There is no linear relationship between absorptance and running time. Absorption ratio is an important index for insulation status of power equipment. It can reflect insulation defects such as wetting and so on. It is an important means of transformer fault diagnosis. When the transformer is dampened, the amount of water in the transformer oil increases, or when the transformer oil is polluted, the absorption ratio will drop sharply when the insulation performance is reduced, and the transformer can be diagnosed by using the absorption ratio. After transformer oil or oil change is eliminated, the insulation performance of transformer is recovered and the absorption ratio can return to normal after eliminating insulation fault. During operation, oil filters or oil changing processes are often carried out according to needs. So the absorption ratio is not a function of transformer operation time, and its numerical value is also affected by transformer insulation performance and transformer oil filtration or oil change. The absorption ratio reflects the insulation aging and is recoverable. The life of transformers should be determined by the aging of non recoverability, such as solid insulation aging, winding core deformation and so on. So the absorption ratio is not an effective index to judge whether the transformer reaches the life end point.

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3.2. Breakdown voltage

The breakdown voltage of insulating oil is another important electrical index of transformer preventive test. The breakdown voltage requirements of the insulation oil for all voltage levels are shown in Table 2. When the breakdown voltage does not meet the specified requirements, it should be treated or replaced with new oil.

Table 2. Voltage level insulation oil breakdown voltage warning value

voltage level	500kV	330kV	220kV	110kV
breakdown voltage	≥50kV	≥45kV	≥40kV	≥35kV

A total of 113 insulation oil breakdown voltage data were collected, including 46 (500kV voltage level) and 67 (220kV voltage level). Regression analysis shows that the breakdown voltage of insulating oil is independent of the running time linearity.

The breakdown voltage is restored to normal level. The breakdown voltage is mainly influenced by the transformer oil filtering or oil transfer, and has nothing to do with the operation time of the transformer, and it cannot be used as the characteristic of the transformer life prediction

3.3. Analysis for oil chromatographic data

The analysis of dissolved gases in transformer oil is an important means of transformer fault diagnosis. It is very sensitive and effective for the early diagnosis of latent faults and the development degree of transformer in transformer. Transformer oil and solid insulation gradually deteriorate and decompose the corresponding gas, dissolved and transformer oil, mainly including H_2, CH_4, C_2H_6, C_2H_4, C_2H_2, CO, CO_2 and so on. The study shows that the gas content of CO and CO_2 shows a rising trend with the increase of the operation years of the transformer, and it is basically linear, while the content of hydrogen hydrocarbon gas increases with the increase of the operation years of the transformer.

The aforementioned gas was regressed.

$$CO_2: y=348x+812.94 \quad R^2=0.8397 \quad P=8.33 \times 10^{-10} \qquad (6)$$

$$CO: y=33.17x+48.95 \quad R2=0.8841 \quad P=2.7 \times 10^{-11} \qquad (7)$$

The P value is far less than the significant level 0.05. The content of CO and CO_2 is closely related to the running time. With the increase of running time, the gas content increases steadily.

In the normal running state, the content of H_2 and hydrocarbon gas is very small. Only when the transformer fails, such as overheating failure or discharge fault, the content of the transformer increases significantly.

When the transformer fails, the hydrogen hydrocarbon content increases more than the attention value, and the transformer is treated with the fault. After filtering the oil, the content of hydrogen hydrocarbon is reduced to the normal value. Therefore, the hydrogen hydrocarbon content is mainly determined by the internal fault of the transformer and the oil filtering and oil transfer, but it is less associated with the operation life of the transformer, and cannot be used as the characteristic of the transformer life prediction. The change of gas content of CO and CO_2 reflects the aging or failure of solid insulation material in transformer, while solid insulation material determines the life of transformer.

The content of CO and CO_2 gas produced under the normal operation of the transformer increases with the increase of the operation years of the transformer, and the solid insulation material is gradually aging, and the trend of gas rising is slow. When the internal fault occurs in the transformer, the aging of solid insulation is accelerated and the gas content is accumulated rapidly. In conclusion, CO and CO_2 gas are products of solid insulation aging, and their contents increase with the deepening of aging. They can be used as characteristic quantities of transformer life prediction. However, it is worth noting that, if the transformer oil is treated, the content of CO and CO_2 gases in the oil will be reduced to varying degrees. After a long period of operation, the content of the transformer will increase to the original value, as shown in Figure 1. Figure 1 is Shenzhen Fuyong station #1

transformer. The transformer was put into operation in 2005, and quit in April 2015 due to aging. In March 2013, filtered oil treatment was carried out. The CO_2 content did not rise until 2013 before filtration. Therefore, to predict the residual life of the transformer and to judge the life end of the transformer, the other means, such as the content of furfural in the transformer oil and the degree of polymerization of the insulating paper, are also needed to make a comprehensive analysis of the aging degree of the transformer.
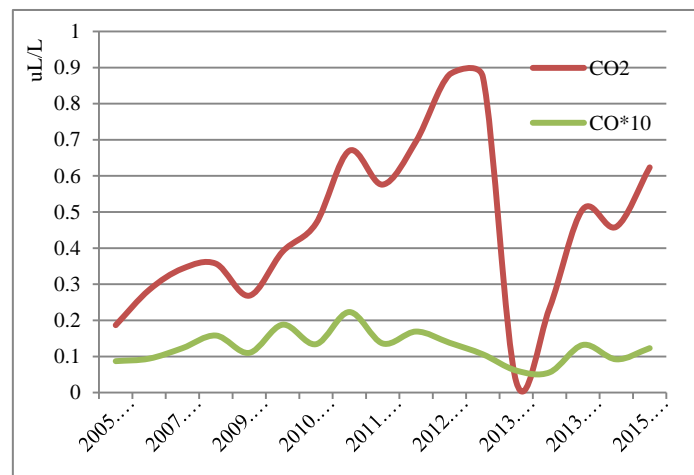

Figure 1. The track of CO_2 and CO in filtered oil

4. Conclusion
The electrical indexes such as absorption ratio and breakdown voltage are often used as the characteristics of transformer state evaluation, and the residual life of the transformer is predicted according to the results of state evaluation. It is found that the above electrical index is an important basis for measuring the insulation condition of the transformer and the fault diagnosis, but it is not an effective parameter for the life prediction of the transformer. The remaining life of transformers should be determined by the degree of solid insulation aging which is not recoverable. The electrical characteristics mentioned above reflect the insulation state of the transformer oil. The transformer oil can restore the good insulation performance by filtering oil or replacing the new oil. So the electrical index cannot effectively describe the position of the transformer in the life cycle, and cannot predict the life end of the transformer according to the above index. Carbon and oxygen compounds are mainly produced by aging of solid insulation. Their content is an effective index to predict the life of transformer and identify the end of life of transformer. However, as the filter oil or the replacement of new oil will cause the loss of carbon and oxygen compounds, the scientific and accurate determination of the end of the life of the transformer needs to be analyzed with the help of the rest of the means.

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