Evaluation Method of 500kV Transformer Bushing Insulation State Based on Active Power Loss

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Abstract. The bushing is one of the most important components of power transformer, and it is very important to find the internal defects of bushings as soon as possible, effectively and accurately diagnose its insulation state information. In this paper, the active power loss of 500kV transformer bushings have been analyzed, and the insulation state evaluation method based on active power loss is proposed. To verify the feasibility of evaluation method, one abnormal 500kV transformer bushing was selected to analyze its insulation state. The result shows that this method can be used as a powerful complement to tanδ.

1. Introduction
The bushing is one of the most important components of power transformer. With the continuous expansion of power grid scale and the continuous improvement of power transformer voltage level, higher requirements are put forward for the insulation performance of important components, such as bushings. During the long-term operation of bushings in complex environment, due to the combined action of mechanical pressure, chemical corrosion, surface pollution, over-voltage, humidity and other factors for a long time, the insulation of equipment will continue to decline, which may eventually lead to insulation breakdown and transformer fault [1-3]. Therefore, it is helpful to reduce the probability of equipment accident and ensure the safe operation of equipment to find the internal defects of bushings as soon as possible, effectively and accurately diagnose its insulation state information, and formulate a scientific operation and maintenance plan for bushings [4-5].

At present, the dielectric loss tangent, tanδ, is the most commonly used characteristic parameter to characterize the overall insulation condition of bushings. But this single evaluation method still can not comprehensively and effectively evaluate the insulation condition of Bushings. This is mainly because , tanδ is the intermediate parameter of insulation dielectric loss. It can not truly reflect the insulation aging and power loss of the medium without effectively unifying the factors, such as insulation size and capacitance [6-7]. In addition, Most of tanδ are tested under power frequency voltage, which only reflects the inherent insulation characteristics of insulating medium to power frequency voltage. In some cases, bushings will bear the effect of complex voltage waveform, the insulation characteristics are different from those at power frequency, and the applicability of power frequency detection parameters is greatly limited [8].
Therefore, by analyzing the essential causes of bushings insulation aging, it can be determined that the insulation aging process itself is gradually developed with the long-term active power loss process of insulating medium in this paper. The electrical and thermal properties of dielectric are closely related, and the thermal state of bushings will directly affect its electrical properties. Therefore, active power loss is an important characteristic parameter to characterize the insulation condition of bushings, which can well reflect the insulation condition of bushings. In addition, in some cases, bushings will bear composite voltage, including power frequency, DC, pulse and other voltage components, which aggravates the dielectric electro-thermal effect inside the insulation. Therefore, starting from the essential physical process that the active power loss reflects the insulation condition, the active power loss of bushings can be analyzed respectively, which can lay a foundation for the effective evaluation of the insulation condition of bushings.

2. Analysis of Active Power Loss of Bushings

Dielectric will produce energy loss under the action of voltage. These losses can be divided into two types, one is the loss caused by conductivity, the other one is the loss caused by polarization. The energy consumed by a dielectric per unit time, that is, the energy generated by dielectric heating, is called dielectric loss. Under a constant electric field, there is no periodic polarization process in the dielectric, so the dielectric loss is only caused by conductivity [9-10]. Under AC voltage, in addition to the loss caused by conductivity, there is periodic relaxation polarization related to thermal motion, resulting in energy loss [11].

![Figure 1. Equivalent circuit of dielectric](image1)

![Figure 2. Power loss triangle](image2)

Voltage U is applied at both ends of the dielectric in the bushings. Due to the loss of the dielectric, the current is not a pure capacitive current, but includes active and reactive components $I_R$ and $I_C$. Therefore, the apparent power supplied by the power supply is

$$S = P + jQ = UI_R + jUI_C.$$  (1)

Its dielectric loss is

$$P = Q \tan \delta = \omega CU^2 \tan \delta.$$  (2)

Although the active power loss of bushings is related to capacitance, voltage and frequency, it is mainly referred to the value of tanδ. This leads to the neglect of the main factor of capacitance in the evaluation of bushings insulation state. Even if the capacitance factor is considered, it is not related to the specific capacitance. Under different voltage levels, even if the active loss of bushings is the same, the difference of bushings insulation volume will lead to different active loss per unit insulation volume. In other words, the power loss density of bushings insulation medium is also different, and the insulation condition of bushings is also different. Therefore, the insulation volume of bushings is also an important factor affecting its insulation condition.

For 500kV transformer bushings, their capacitance is often greater than those of 110kV or 220kV transformer bushings. So, even their tanδ are similar, it also shows that the active power loss of 500kV transformer bushing is much greater than that of 110kV or 220kV transformer bushing. However, in this case, the insulation state of 500kV bushings can not be simply said to be poor, because their volume are also larger than 110kV or 220kV transformer bushings. At this time, the influence of
bushings insulation volume should be fully considered. Active power loss per unit volume is a more direct, effective and essential diagnostic parameter for insulation evaluation of bushings, which is directly related to the insulation state of bushings. The active loss per unit volume can be defined as $p = P/V$. The active loss density $p$ of bushings is small, indicating that the bushing insulation is in good condition. When the $p$ value is larger, it indicates that the active power loss per unit volume of the bushing increases, the heating is more serious, and there may be insulation defects.

$$p = \gamma + \frac{E_0 (\varepsilon_s - \varepsilon_s^\infty)}{1 + (\omega\tau)^2}\omega^2 E^2$$

$\approx \gamma E^2$.                                \hspace{1cm} (3)

When the frequency is high, the relaxation polarization cannot be established in time. As a result, the polarization mainly consist of displacement polarization. Besides, the dielectric constant $\varepsilon_s$ is more similar to the optical frequency dielectric constant $\varepsilon_s^\infty$. Meanwhile, no relaxation loss can be produced and loss caused in each week decreases. $p$ can be described by

$$p = (\gamma + g_s)E^2 = (\gamma + \frac{E_0 (\varepsilon_s - \varepsilon_s^\infty)}{1 + (\omega\tau)^2}\omega^2 \tau)E^2$$

$$= (\gamma + \frac{E_0 (\varepsilon_s - \varepsilon_s^\infty)}{\tau}) E^2$$

$$\approx (\gamma + g_s)E^2$$.                                 \hspace{1cm} (4)

It can be seen from the above formula that the bushings active power loss will surge at high frequency, thus accelerating the insulation deterioration.

3. Test Data and Discussions

The active power loss of 500kV bushings are analyzed in this paper. Firstly, the $\tan\delta$ and capacitance $C$ are obtained through manual preventive test or on-line monitoring data. Then, the active power loss of the bushing, and then converted to the power loss corresponding to the unit volume. It is assumed that the insulation volume of bushings at the same voltage level is approximately equal. According to the specific insulation structure of bushings, one 500kV capacitive bushings (phase A) data are selected for analysis in Shandong power grid, and the insulation volume is about 0.279m$^3$. As shown in Table 1, the test data of these two groups of bushings from 2006 to 2021 are selected for analysis, and their active loss and active loss density are calculated.
Table 1. Calculation and analysis of 500kV transformer bushing (phase A).

| Year | Rated voltage (kV) | Temperature (℃) | Rated capacitance (pF) | Measured capacitance (pF) | Deviation (%) | tanδ (%) | Active power loss (W) | Active power loss density (W/m³) |
|------|--------------------|-----------------|------------------------|--------------------------|---------------|----------|-----------------------|----------------------------------|
| 2006 | 500                | 23              | 679                    | 675                      | -0.59%        | 0.21     | 56.3                  | 201.8                            |
| 2009 | 500                | 21              | 679                    | 681                      | 0.29%         | 0.23     | 59.4                  | 212.9                            |
| 2012 | 500                | 19              | 679                    | 673                      | -0.88%        | 0.22     | 55.6                  | 199.3                            |
| 2015 | 500                | 21              | 679                    | 673                      | -0.88%        | 0.22     | 59.6                  | 212.9                            |
| 2018 | 500                | 18              | 679                    | 675                      | -0.59%        | 0.24     | 60.1                  | 215.4                            |
| 2021 | 500                | 17              | 679                    | 652                      | -3.98%        | 0.87     | 121.3                 | 434.8                            |

At present, tanδ is generally recognized as an important characteristic parameter to characterize the overall insulation condition of bushings, and is used to judge the insulation of equipment. By measuring the tanδ of bushings to roughly judge whether the main insulation of the bushing is good and how the insulation strength of the bushing is. We can see that the capacitance deviation of the bushing data in 2021 was -3.98%, which is much higher than before. Besides, its tanδ is also more than standard value. And its active power loss and active power loss density have also increased significantly compared with previous years. In order to further verify that there are problems in the insulation of the transformer bushing (phase A), the data of phase B transformer bushing data are calculated and analyzed, which is the same batch and model to phase A transformer bushing, as shown in table 2. We can see that there is no obvious fluctuations in the data of phase B transformer bushing in 2021.

Table 2. Calculation and analysis of 500kV transformer bushing (phase A).

| Year | Rated voltage (kV) | Temperature (℃) | Rated capacitance (pF) | Measured capacitance (pF) | Deviation (%) | tanδ (%) | Active power loss (W) | Active power loss density (W/m³) |
|------|--------------------|-----------------|------------------------|--------------------------|---------------|----------|-----------------------|----------------------------------|
| 2006 | 500                | 23              | 679                    | 673                      | -0.88%        | 0.22     | 58.4                  | 209.3                            |
| 2009 | 500                | 21              | 679                    | 680                      | 0.15%         | 0.21     | 57.5                  | 206.1                            |
| 2012 | 500                | 19              | 679                    | 674                      | -0.74%        | 0.22     | 59.6                  | 213.6                            |
| 2015 | 500                | 21              | 679                    | 675                      | -0.59%        | 0.23     | 62.8                  | 225.1                            |
| 2018 | 500                | 18              | 679                    | 673                      | -0.88%        | 0.22     | 58.5                  | 209.7                            |
| 2021 | 500                | 17              | 679                    | 674                      | -0.74%        | 0.23     | 60.9                  | 218.3                            |

The main cause of abnormal data is analyzed, and it is considered that the insulation of bushing is damp and aging. The poor quality of the sealing ring of the bushing leads to the lax sealing of the bushing, resulting in the gradual infiltration of water into the capacitor core through the outer insulation. After the paper fiber in the insulation absorbs water, the conductivity of the fiber increases and the mechanical properties become worse, which reduces the main insulation and outermost insulation resistance of the bushing, increases the conductivity of the insulation system and increases the conductivity loss. At the same time, water will participate in the chemical degradation of polymer materials such as oil, paper cellulose and so on. This increases the number of particles participating in polarization and polarization loss per unit volume of insulating medium. The dielectric loss of the insulation system consists of conductivity loss and polarization loss. The increase of the total active power loss will cause the dielectric to heat and further accelerate the deterioration of the insulation. The degradation of insulating paper cellulose and insulating oil will generate water, which further participates in the chemical degradation reaction of polymer materials such as oil and paper cellulose.
Thus, playing a ‘positive feedback’ role in insulation aging. Therefore, the active power loss analysis can effectively find the aging and moisture of bushings insulation. The greater the active power loss value, the worse the insulation medium state.

In addition, the active power loss fully considers the factors of bushing capacitance and insulation volume, which makes up for the conventional parameter tanδ in the effectiveness of bushing insulation state detection. Based on the analysis of abnormal bushings data of Shandong power grid, it is preliminarily considered that when the active power loss density of capacitive bushings exceeds 200 W/m³, the insulation may be aged and damp.

4. Conclusions
In this paper, the method based on active loss has been proposed and used for evaluating the insulation state of transformer bushings. One abnormal 500kV transformer bushing test data is used for the analysis of bushing insulation evaluation in Shandong power grid. And the feasibility of the evaluation method based on active loss has been verified. Based on the analysis of a large number of data, if the active loss density of bushings is more than 400 W/m³, there may be some problems in the bushings insulation. Using the method of active power loss evaluation, transformer bushings can be evaluated uniformly, and can be used as a powerful tool rather than tanδ.

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