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Effect of DC Magnetic Biasing on the Temperature Rise of High-voltage Winding of Power Transformer

Abstract: The DC magnetic biasing can aggravate the core saturation and increase the temperature in the large power transformer. In this paper, a 240000 kVA/330 kA oil immersible power transformer is taken as a research object to analyze the variation of the temperature rise in the high-voltage windings under DC magnetic biasing. The effect of DC magnetic biasing current on the winding loss is analyzed at first. Using computational fluid dynamics and fluid network of power transformer, the fluid field and the temperature distribution in the power transformer are then obtained. The results show that the temperature rise is greatly affected by the DC magnetic biasing phenomenon. The calculation method proposed in this paper provides a theoretical basis for the structure optimization and the local over-heating suppression.

Keywords: DC magnetic biasing, Winding loss, Temperature rise

1 Introduction

HVDC power transmission over long distance may cause the DC magnetic biasing in power transformer, accelerating the transformer core saturation and forming the local overheating [1]. In addition, the geomagnetic ally induce current generated by the effect of the solar magnetic storm and the high-altitude nuclear electromagnetic pulse may also induce the presence of DC magnetic biasing in power transformer [2].

Many studies have been carried out to research the DC magnetic biasing phenomenon. The magnetization characteristic of transformer laminated core is analyzed under the DC magnetic biasing [3]. According to the field-circuit coupling method, the exciting current and the internal magnetic field distribution are analyzed under different levels of DC magnetic biasing [4–6]. In addition, the effect and its suppression method of DC magnetic biasing on the relay protection equipment in power system and transmission system operation are also considered [7]. However, very few studies have been carried out on the temperature rise of transformer wind-
ing caused by the DC magnetic biasing.

In this paper, the high-voltage winding loss of a 240000 kVA/330 kA oil immersible power transformer is firstly calculated under different DC magnetic biasing current. A calculation model of temperature field in power transformer is built and is used to obtain to the temperature rise of high-voltage winding. This study provides theoretical basis for the optimization design of winding insulation structure of high-voltage and high-capacity power transformer.

2 Calculation of High-voltage Winding Loss

Taking a 240000 kVA/330 kA oil immersible power transformer as the research object, the internal magnetic density distribution of power transformer is calculated and is used to obtain the loss density of high-voltage winding. According to the loss density, the eddy-current loss in each winding is calculated from the integration along the axial direction of the winding and is 35674 W. In addition, the resistance loss of high-voltage winding is 313602 W based on $P_R=I^2R$. Thus, the high-voltage winding loss of power transformer without DC magnetic biasing is $P=349276$ W.

The effective value of the rated current of this used power transformer is $I_n=514.34$ A, so the maximum allowable DC magnetic biasing current is about 2.56 A for calculating the high-voltage winding loss under DC magnetic biasing according to the DL/T5224–2005 technical specification. By setting different magnitude of DC magnetic biasing current, the high-voltage winding loss is obtained, as shown in Table 1.

<table>
<thead>
<tr>
<th>$I_d$ (A)</th>
<th>0</th>
<th>0.256</th>
<th>0.512</th>
<th>0.768</th>
<th>1.024</th>
<th>1.28</th>
<th>1.536</th>
<th>1.792</th>
<th>2.048</th>
<th>2.304</th>
<th>2.56</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$ (W)</td>
<td>34927</td>
<td>3659</td>
<td>38987</td>
<td>41269</td>
<td>43865</td>
<td>46562</td>
<td>49863</td>
<td>54246</td>
<td>58657</td>
<td>62985</td>
<td>675348</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>65</td>
<td>4</td>
<td>7</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

It can be learnt from Table 1 that the high-voltage winding loss is increased with the increasing magnitude of DC magnetic biasing current. This is attributed to the fact that the increasing DC magnetic biasing current accelerating the core saturation and aggravating the distortion of the winding exciting current.
3 Numerical Calculation of Fluid Field

The fluid field in the cooling circuit of power transformer plays an important role in the calculation of the whole temperature rise. According to the flow path of internal fluid and the physical structure of power transformer, the fluid field in power transformer can be divided into the oil circuit in the windings, the cooler and the oil circuit in the connecting structure, etc. By analyzing the fluid field in each physical structure, the corresponding internal flow resistance is obtained and then is lined up via fluid network to calculate the actual flow of oil circuit.

![Fig. 1: Schematic of the oil circuit in the windings](image)

The schematic of the oil circuit in the windings is shown in Fig. 1. The oil circuit consists of the vertical oil circuit between the winding and the folding screen, and the horizontal oil circuit between the winding and the insulating block. According to the thermodynamic principle [8], the heat quantity absorbed \(d\varphi\) by the oil in the AB cross section is defined as below,

\[
d\varphi = q_m c_{oil} dt
\]

Where \(q_m\) is the flow velocity of the oil, \(c_{oil}\) is the specific heat capacity of the oil and \(dt\) is the mean temperature difference of the oil in the cross section. The temperature rise of the winding oil circuit can be considered to be caused only by the winding loss. As the winding loss is not uniformly distributed in the windings and is larger in both ends of the windings, the actual temperature of the oil circuit in the windings is not linearly distributed in the vertical direction.

The heat quantity \(\Delta Q\) escaped from the windings to the surrounding oil is described as below,
\[ \Delta Q = k \Delta t \Delta A \tag{2} \]

Where \( \Delta t \) is the mean temperature difference of the winding against the surrounding oil, \( \Delta A \) is the heat radiating area of the windings and \( k \) is the mean convective heat transfer coefficient on the windings.

As the structure of the three-phase transformer windings is exactly the same, the fluid and thermal characteristics of the whole winding oil circuit can be obtained by analyzing the oil circuit in one phase windings. In the calculation of fluid field in the windings, the overall model of the winding oil circuit is simplified according to the repeatability of winding structure. The overall model of the windings is divided into eight sections by the internal oil baffle plate and the external one. The first and final four sections are the same whereas the middle four sections are the same. The whole oil circuit model is converted into two oil circuit models, and it is calculated by taking the circumference of the surrounding block in the circle direction 1/16.

The winding integral model is divided into eight sections, the first and final four sections are the same, whereas the middle four sections are the same. The integral oil circuit model is converted into two oil circuit models, and it is calculated by taking the circumference of the surrounding block in the circle direction 1/16.

The fluid field in the high-voltage windings is then calculated by using the computational fluid dynamics. The fluid field distribution in one section high-voltage winding is shown in Fig. 2 when the entrance velocity is 0.35 m/s.

![Fig. 2: Fluid field in 1/16 high-voltage winding](image)

4 Temperature Rise of the High-voltage Windings

According to the above winding loss and fluid field in the power transformer, the temperature rise of transformer winding can then be calculated. Due to the axial symmetric of the oil circuit in the windings, only one section winding is modeled.
This model consists of the internal oil baffle plate, the winding and the external oil baffle plate. The oil circuit in the windings is divided into two segments. Moreover, as the repetitive winding along the circumference of a circle can be divided into eight sections, where each section contains 15 winding discs with a mean height of 13.75 mm high, the 1/16 winding model as shown in Fig. 3 is chosen as the analysis model of temperature distribution. On the analysis of the temperature distribution in the winding, this established winding model replaces the whole winding. The temperature distribution of the remaining 7 sections windings can be calculated according to the oil flow and the flow velocity as well as the corresponding parameters obtained from each section winding model.

The solving conditions for the temperature distribution are set as follows. The entrance oil temperature is 298 K and is only used for calculating the convective heat transfer coefficient which is modified during the temperature distribution calculation. The winding oil velocity is 0.35 m/s, and the oil flow is 14.26 kg/s. The two sides of the model are symmetry boundary conditions, namely the geometric and physical properties on both sides of the boundary is symmetrical along the cross section. The oil baffle plate is set as an adiabatic boundary (the second boundary condition). The contact surface of the winding and the oil is set as a coupling boundary condition (the third boundary condition).

By solving the established model of temperature distribution with the above solving conditions, the 3D finite element results of single section high-voltage winding are obtained, as shown in Fig. 4, under the effect of different DC magnetic biasing current of 0, 1.28 and 2.56 A.
It can be seen from Fig. 4 that the temperature of the windings is increased with the increasing DC magnetic biasing current in the power transformer. When the DC magnetic biasing current is set as 2.56 A, the temperature in parts of the high-voltage winding approaches or exceeds 99 °C. For example, the temperature in the top winding is 102 °C which is larger than that of the bottom winding with a temperature of 99 °C. Whereas the temperature in the middle winding is about 100 °C. The above temperature exceeds the maximum allowable temperature of 98 °C, seriously threatening the safe operation of power transformer.

According to the above calculation of temperature distribution under DC magnetic biasing current, the internal heat exchange characteristics of the transformer can be known. The temperature rise of the whole high-voltage winding, as shown in Fig. 5, can be obtained based on the temperature distribution of single winding and the fluid network of power transformer.
As the temperature of cooling oil can be considered constant, the temperature rise of the windings is increased with the increasing DC magnetic biasing current, as shown in Fig. 5. When the applied DC magnetic biasing current is 2.56 A, the temperature rise in parts of the windings has exceeded 71 K, which is larger than the allowable temperature limitation of 65 K proposed in the national standard. Therefore, the local overheating phenomenon will occur in the power transformer under DC magnetic biasing and it is necessary to optimize the insulating structure design of the windings or to take some measures to suppress the DC magnetic biasing phenomenon.

5 Conclusion

The winding loss and temperature distribution of a 240000 kVA/330 kA oil immersible power transformer are calculated by using the finite element method and the computational fluid dynamics. The main conclusions are summarized as below.

1. With increasing the applied DC magnetic biasing current, the winding loss of high-voltage winding is increased. When the applied DC magnetic biasing current is set as the maximum allowable value, the transformer core appears the saturation or over-saturation.

2. The DC magnetic biasing phenomenon will accelerate the core saturation and aggravate the leakage magnetic field, which results in the increasing temperature rise in high-voltage winding. When the applied current is set as the maximum allowable of 2.56 A, the temperature rise in parts of the high-voltage windings has exceeded the allowable temperature limitation proposed in the national standard. This leads to the local overheating in the windings.

3. The calculation method proposed in this paper can provide a theoretical basis for judging the temperature rise in the power transformer under DC magnetic biasing.

References


