Research on the temperature rise characteristics of power transformers based on fluid-solid-thermal coupling

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Abstract. The problems of overheating and insulation are the main influencing factors to the operation status of power transformers. Based on the physical model of a 50MVA/110kV oil-immersed self-cooling transformer, the electromagnetic, temperature and fluid field are introduced to establish a three-dimensional temperature rise model of the transformer in this thesis. The loss obtained from the electromagnetic field calculation model is taken as a heat source and input into the transformer temperature rise model. The results show that the hot spot temperature occurs in the core column and increases with the maximum load current when the single-phase ground fault occurs, and the hot spot temperature in the transformer exceeds the limit value. The temperature distribution trends of the core and high and low voltage windings under rated conditions and overload conditions are similar. In addition, the average temperature rise of the windings under overload conditions exceeds the limit value.

1. Introduction
Reliable operation of power equipment is the basis of safe and stable operation of power grid. Power transformer is an important part of power plant and substation and it is also a key element for realizing long-distance transmission of electric energy and providing appropriate voltage to users [1]. The key factors that affect the working state of power transformers in actual operation are thermal problems and insulation problems. The temperature rise of transformers is an important indicator to measure whether transformers are in safe and stable working state [2]. Transformer manufacturers and transformer operation departments are concerned about the temperature rise and local overheating in transformer engineering [3].

The research on the thermal problems of oil-immersed power transformers mainly includes three methods. They are installing temperature sensors in transformers for direct measurement, calculating hot spot temperature by using top oil temperature, and establishing finite element model to calculate hot spot temperature by using numerical calculation methods [4,5].

The research on the temperature field in oil-immersed power transformers is mainly based on the heat transfer theory and fluid mechanics theory currently. By establishing the temperature field model of oil-immersed power transformers, the distribution of the temperature field inside transformers is solved by numerical calculation method [6]. The transient temperature field of transformer cold start under different temperature conditions is calculated based on the finite element simulation method. The temperature rise of winding hotspots when starting oil-immersed transformers at different ambient temperatures is investigated [7]. Analysis of heat problem and temperature field of a piezoelectric transformer, operated at steady-state conditions, is described. The resonance frequency of the transformer is calculated from impedance and electrical gain analysis using a finite-element method.
Because the results of heat grid method are not accurate enough, at present, more research is carried out by numerical modelling method, and the majority of calculation is carried out by two-dimensional model [9]. But the accuracy of the two-dimensional model is not as good as that of the three-dimensional model. Therefore, three-dimensional modelling is carried out for the transformer in this thesis, and the three phases are modelled separately considering the uneven distribution of core loss. The calculated core and winding losses are input into the three-dimensional temperature rise model as a heat source to study the temperature rise characteristics of the transformer.

2. Establishment of temperature rise model of transformer

2.1. Establishment of physical model in computational domain

In this paper, the high and low voltage windings of 50MVA/110kV natural oil circulation oil immersed power transformer are simplified as cylinder, and the thickness of insulation layer next to the winding is very thin, so the thickness is ignored. The iron core and yoke are simplified as cylinder. The electromagnetic relationship of transformer is mainly determined by the iron core and winding, so the influence of radiator and structure outside the oil tank is not considered. Therefore, a simplified physical model of transformer calculation domain is established, as shown in Figure 1.

![Figure 1. The model of the transformer](image)

The main parameters of the model are as follows. The core diameter is 600mm, the centre distance of the core column is 1140mm, and the window height is 1525mm. The model of silicon steel sheet used for transformer core is 30QG120, the thickness of lamination is 0.3mm, and the lamination coefficient is 0.97. The rated voltage of HV side winding is 110kV, the rated current is 262.43A, and the number of winding turns is 629. The rated voltage of low voltage side winding is 10.5kV, rated current is 2749.29A and winding turns are 104.

2.2. Establishment of field circuit coupling model

Field circuit coupling refers to the establishment of physical model of transformer to participate in the calculation of external circuit and electromagnetic field.

![Figure 2. The equivalent circuit model of the rated condition](image)
Therefore, it is necessary to establish the calculation model of external circuit at the same time to establish the calculation model of field, that is to say, the part marked by the finite element in the figure has been connected to the established physical model [10,11]. The equivalent circuit model of rated condition is shown in Figure 2. In the case of overload, the three-phase load on the right side is added and increased; in the case of single-phase grounding, the B-phase load on the right side is set for short circuit.

2.3. Establishment of temperature rise model of transformer

2.3.1. Solid heat transfer model

The solid heat transfer includes not only the heat transfer between the winding and the core, but also the convection heat transfer of the transformer. Therefore, it is necessary to introduce the fluid domain control equation, as shown in equation (1).

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \vec{U} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q$$

Where, $\rho$ is the density of transformer oil. $C_p$ is the heat capacity at atmospheric pressure. $\vec{U}$ is the velocity field. $k$ is the heat transfer coefficient. $Q$ is the internal heat source.

Set the boundary conditions of solid heat transfer to restrict the temperature rise characteristics.

$$q = -\hat{\lambda} \frac{\partial T}{\partial n} = -\hat{\lambda} (n \cdot \nabla T) = \begin{bmatrix} \lambda_{xx} & 0 & 0 \\ 0 & \lambda_{yy} & 0 \\ 0 & 0 & \lambda_{zz} \end{bmatrix} \frac{\partial T}{\partial x} n_x$$

Where $q$ is the heat flux and $n$ is the normal vector of the outflow on the boundary.

2.3.2. Laminar flow model

The research object of this paper is the natural oil circulation oil-immersed power transformer. The internal oil flow velocity is very small, which belongs to the laminar flow model. In engineering research, the transformer oil flow can be approximated as an incompressible fluid.

$$\begin{cases} \nabla \cdot \vec{U} = 0 \\ \rho \frac{\partial \vec{U}}{\partial t} + \rho (\vec{U} \cdot \nabla) \vec{U} \\ = \nabla \left[ -\mu \vec{I} + \mu \left( \nabla \vec{U} + \left( \nabla \vec{U} \right)^T \right) \right] + \vec{F} \end{cases}$$

Among them: $\mu$ is the dynamic viscosity of the transformer oil; $\rho$ is the density of the transformer oil; $\vec{I}$ is the main stress tensor.

2.3.3. Setting of parameters and initial conditions

The temperature field modeling of oil-immersed power transformer needs to set the physical parameters of winding, iron core and transformer oil. The winding material is copper, iron core material is silicon steel sheet, and transformer oil is mineral oil. The external heat source of the transformer is mainly related to the environment. The internal heat source of the transformer is mainly the core and winding. The loss of the core and winding has been calculated based on the electromagnetic field. The transformer model used in this paper has core diameter of 600mm, lamination thickness of 0.3mm, core angle weight of 2178kg and core weight of 20391kg. The heat source density can be obtained by dividing the loss by the equivalent volume. The calculation results are shown in Table 1 and Table 2.
Table 1. Heat source density of the three-phase iron core

| Iron core | Rated working condition (W/m³) | Overload (W/m³) | Single-phase ground fault (W/m³) |
|-----------|-------------------------------|-----------------|----------------------------------|
| A phase   | 10811                         | 7876            | 7631                             |
| B phase   | 11200                         | 8205            | 7427                             |
| C phase   | 10389                         | 7689            | 10431                            |

Table 2. Heat source density of the three-phase winding

| Winding   | Rated working condition (W/m³) | Overload (W/m³) | Single-phase ground fault (W/m³) |
|-----------|-------------------------------|-----------------|----------------------------------|
| Low voltage winding |                               |                 |                                  |
| A phase   | 130472                        | 387444          | 559073                           |
| B phase   | 130472                        | 384523          | 499647                           |
| C phase   | 130472                        | 385978          | 130946                           |
| High voltage winding |                              |                 |                                  |
| A phase   | 87937                         | 260603          | 375291                           |
| B phase   | 87937                         | 260453          | 338538                           |
| C phase   | 87937                         | 259555          | 88165                            |

3. Analysis of temperature rise characteristics of transformer under multiple working conditions

3.1. Analysis of iron core temperature rise under rated conditions

On the basis of heat source calculation and model assumption, the temperature distribution of iron core under different operating conditions of transformer is calculated and analysed. The temperature distribution results of iron core under rated conditions are shown in Figure 3.

It can be seen that the overall distribution of the temperature of the three-phase iron mandrels under the rated operating conditions of the transformer is similar. The temperature in the vertical direction decreases from the middle to both sides. The temperature of the horizontal mandrel is lower than that of the longitudinal mandrel. The phase core is 353.84K, and the minimum temperature appears at the end of the four corners of the core is 293.15K. The average temperature of three-phase iron core is 315.76k, that of phase A is 315.99K, that of phase B is 315.80K, and that of phase C is 315.48K.

Figure 3. Calculated temperature distribution of the iron core under rated condition

Figure 4. Calculated temperature distribution of the winding under rated condition

Figure 4 shows the temperature distribution results of HV and LV windings under rated conditions. It can be seen from Figure 4(a) that the maximum temperature of high-voltage winding under rated working condition is 355.74K, the minimum temperature is 297.99K and the temperature difference is
By analysing the temperature of each phase separately, the average values of the three-phase temperature of the high-voltage windings A, B, and C are 335.29K, 342.05K, and 334.67K.

It can be seen from Figure 4(b) that the maximum temperature of low-voltage winding under rated condition is 363.72K, the minimum temperature is 295.61K, and the temperature difference is 68.11K. By analysing the temperature of each phase separately, the mean value of three-phase temperature of low-voltage winding is about 342.08K, 345.35K and 342.53K. From the longitudinal observation of the low-voltage winding, the hot spot temperature appears in the middle part, the temperature decreases from the hot spot position to both sides, and the hot spot temperature and average temperature of the low-voltage winding are significantly higher than that of the high-voltage winding.

3.2. Analysis of temperature rise under overload

The maximum and minimum temperatures of the iron core are 359.69K and 293.15K by calculating the temperature of the transformer under overload in Figure 5. The maximum temperature occurs on the B-phase core column, and the hot spot temperature of the core is higher than the highest temperature of the core under rated conditions. The average temperature of the three-phase core is 315.76K. The average core temperature of the A-phase, B-phase and C-phase are 317.52K, 316.84K, and 317.70K respectively. As a whole, the temperature distribution is the same as the rated condition. The core loss has nothing to do with the load size. Under overload, the load current is larger than the rated condition, and the winding loss is larger. This part of heat is transferred to the core, so that the core temperature is higher than the rated condition.

![Figure 5. Calculated temperature distribution of the iron core under overload condition](image)

![Figure 6. Calculated temperature distribution of the winding under overload condition](image)

The results of winding temperature distribution are shown in Figure 6. The maximum temperature of the high voltage winding under overload is 474.08K, the minimum temperature is 305.27K in Figure 6(a), and the temperature difference is 168.81K. Through separate analysis of the temperature of each phase, the mean temperature of A, B and C of the high voltage winding is 414.92K, 434.15K and 412.77K. Compared with the rated working condition, the temperature distribution characteristics remain unchanged. The average temperature of phase B is slightly higher than the average temperature of phase A and phase C. The maximum and the average temperatures of each winding increase.

As can be seen from Figure 6(b), the maximum temperature of the low-voltage winding under overload condition is 494.49K, the minimum temperature is 300.18K, and the temperature difference is 194.31K. Through the separate analysis of the temperature of each phase, the mean temperature of the three phases of the low-voltage winding is about 433.61K, 441.59K and 434.62K, respectively. The highest and average temperature of the low voltage winding is significantly higher than that of the high voltage winding. Compared with rated working conditions, the temperature distribution characteristics remain unchanged, the average temperature of phase B is slightly higher than the average temperature of phase A and phase C. The maximum and minimum temperatures are both increased, the average temperature of each winding and the temperature difference are also raised.
3.3. Analysis of winding temperature rise when single-phase ground fault occurs

The core temperature distribution results under the condition of single-phase ground fault are shown in Figure 7. The maximum temperature of the transformer core is 366.217K and the minimum temperature is 293.155K by calculating the temperature of the transformer when the single-phase ground fault occurs. It is much higher than the maximum temperature of transformer core under rated condition and under overload condition. The highest temperature occurs on the A-phase core column, which is the phase with the maximum load current. The average temperature of the A-phase core is 321.48K, the average temperature of the B-phase core is 318.27K, and the average temperature of the C-phase core is 315.55K. The average temperature decreases gradually from left to right.

According to Figure 3, 5 and 7, the hot spot temperature and average temperature of the core under three different load conditions are shown in Table 3.

| Temperature | Rated condition | Overload condition | Single-phase ground fault |
|-------------|-----------------|--------------------|---------------------------|
| Maximum $T$ (K) | 353.845 | 359.693 | 366.217 |
| Average $T$ (K)  | 315.76  | 317.32  | 318.43  |

The winding temperature distributions when the transformer single-phase ground fault occurs are shown in Figure 8. The maximum temperature of the high voltage winding is 540.27K, the minimum temperature is 298.01K in Figure 8(a), and the temperature difference is 242.26K. Through analyzing the temperature of each phase, the mean temperature of the high voltage winding A, B and C is 468.26K, 475.97K and 335.13K respectively. Compared with the rated condition, the highest temperature and the average temperature of each winding both increase. The maximum and minimum temperature difference increases when the winding tends to steady state. The highest temperature of the winding appears in phase A, where the load current is the largest, and the temperature gradually decreases from left to right.

As can be seen from Figure 8(b), the highest temperature of the low-voltage winding is 573.87K, the lowest temperature is 296.36K, and the temperature difference is 277.51K when the single-phase ground fault occurs. The mean temperature of the three phases of the low-voltage winding is 494.92K, 485.32K and 342.68K, respectively. From the longitudinal observation of the winding, the maximum temperature in the middle of the winding, along the radial direction of the temperature gradually decreased. And the highest and average temperature of the low voltage winding is significantly higher than that of the high voltage winding. Compared with the rated conditions, the temperature distribution trend changes significantly, the hot spot temperature increases significantly, the difference between the hot spot temperature and the minimum temperature increases, the average temperature of phase A is greater than the average temperature of phase B, and the average temperature of phase B is greater than the average temperature of phase C.
Phase A ground fault occurred at the load side of the transformer, the magnetic flux of the A and B phase winding decreased, the current increased, the induced electromotive force decreased, and the magnetic flux, current and induced electromotive force of the C phase winding remained unchanged. In the case of triangular connection on the load side, if the ground fault of phase A occurs, it will only affect the winding of phase A and phase B of the transformer directly connected with the load of phase A, resulting in an increase in the load current, A decrease in the induced electromotive force of the winding, and A decrease in the magnetic flux used to generate the induced electromotive force. The flux, current and induced voltage of the c-phase winding, which are not directly connected to the a-phase winding, are not affected. Therefore, the temperature of phase A and phase B is high, and the temperature of phase C is low compared with that of phase A and phase B.

| Temperature | Rated working condition | Overload condition | Single-phase grounding |
|-------------|-------------------------|--------------------|------------------------|
| Maximum T (K) | 355.74 | 474.08 | 540.27 |
| Minimum T (K) | 297.99 | 305.27 | 298.01 |
| Average T (K) | 337.34 | 420.61 | 426.46 |

Table 4. Temperature peak and average temperature of the primary winding

| Temperature | Rated working condition | Overload condition | Single-phase grounding |
|-------------|-------------------------|--------------------|------------------------|
| Maximum T (K) | 363.72 | 494.49 | 573.87 |
| Minimum T (K) | 295.61 | 300.18 | 296.36 |
| Average T (K) | 343.32 | 436.61 | 440.97 |

Table 5. Temperature peak and average temperature of the secondary winding

4. Conclusion

The temperature rise conditions of core and winding in transformer under rated condition, overload condition and single-phase grounding fault are calculated and the following conclusions are obtained.

(a) The temperature distribution trend of iron core and winding is similar under rated conditions and overload conditions, in which the load is three-phase symmetrical. But the temperature distribution trend changes greatly when out-of-zone grounding fault occurs.

(b) The hot spot temperature rise and average temperature rise of the core are less affected by the working conditions than the winding, and the lowest temperature of the core appears at the four corners.

(c) The hot spot temperature of the high voltage winding is located in the upper part of the winding. The temperature increases with the rise of the position. The temperature at the top decreases slightly.

(d) The internal hot spot of the transformer is located in the middle section of the low-voltage winding. The hot spot temperature and average temperature of the low-voltage winding are higher than that of the high-voltage winding, but the difference is not large.

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