Calculation and Analysis of Heat Field of Large Capacity Epoxy Pouring Dry-type Transformer Based on Fluid-solid Coupling

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Abstract: Dry-type transformer had the advantages of simple structure, easy maintenance, small environmental pollution, safe and reliable operation. It was widely used in power system distribution network. With the increase of urban power load year by year, large capacity dry type transformer had been highly concerned by the power industry. In this paper, the fluid-solid coupling calculation equation of a large capacity epoxy casting dry-type transformer was expounded, and a two-dimensional axisymmetric model of the transformer was established. The finite element method was used to calculate the temperature distribution and hot spot temperature with different wind speed and load rate. The results showed that when the wind speed at the transformer inlet was 0.7m/s and the load exceeded 120%, the temperature rise of the low-voltage winding reached 136.41℃, which had exceeded the temperature limit of the material. Therefore, the ventilation volume needed to be increased and the running time needed to be reduced. The research results could provide technical support for the design and safe operation of large capacity epoxy casting dry type transformer.

1. Introduction

Power distribution was the link that connected directly with the user and distributed the electric energy in the electric power system. As the important electrical equipment in the electric power distribution, the dry type transformer undertook the function of converting high-voltage electric energy into daily life or industrial demand electric energy and played a decisive role in the distribution network. The heat dissipation of dry type transformer was one of the key technical problems to be considered in transformer design[1-2]. The heat production and heat dissipation of the transformer during operation had a great influence on its performance and reliability.

Dry-type transformer adopted epoxy resin as the insulating medium. Compared with the oil-immersed transformer, although its mechanical properties and electrical properties were improved and it was more safe and environmentally friendly, the thermal conductivity was poor, which was not conducive to the heat dissipation of the transformer windings. In the operation, when the winding temperature rose to a certain value, it would accelerate the aging of the insulation material and reduce the insulation performance, eventually leading to the thermal aging and breakdown of the insulation material, affecting the safe and stable operation and service life of the transformer[3-5]. Therefore, it was of great significance to research the temperature distribution and variation rules of transformer windings.
2. Calculation principle

The heat transfers of dry-type epoxy casting transformer mainly consisted of three parts: that were the heat conduction between winding and epoxy resin, heat convection between epoxy resin and external air, heat convection and radiation dissipation between iron core and external air. The heat from the core and winding first reached the solid surface through heat conduction, from which it was dissipated by air. In order to solve the distribution of temperature field in dry type transformer, the heat transfer problem of core, winding and the air flow problem should be solved together. The solution equation could be divided into two corresponding parts: one was the heat conduction equation; The other part was the air governing equation.

In order to simplify the model and reduce the amount of calculation, the steady state calculation was carried out on the two-dimensional axisymmetric model of dry type transformer. The following assumptions were made during calculation: the thermal conductivity, specific heat capacity and density of solid materials were all constant and did not change with temperature. In steady state, the temperature of each point in the transformer did not change, and the air velocity and pressure reached equilibrium. Under the condition of axisymmetric and steady state, the heat transfer equation could be simplified to formula.1:

\[ K\left(\frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial z^2}\right) + q_v = 0 \]  \hspace{1cm} (1)

Where: \( r \) —— radial direction/m; \( z \) —— axial direction/m; \( T \) —— temperature/K; \( K \) —— heat conductivity of the material/W·m\(^{-1}\)·K\(^{-1}\); \( q_v \) —— calorific value of per unit area/W·m\(^{-2}\).

Under the condition of axisymmetric and steady state, air temperature and velocity were affected by mass transfer, momentum transfer and energy transfer. The governing equation of air was shown as formula.2:

\[ \frac{\partial (\rho u)}{\partial r} + \frac{\partial (\rho v)}{\partial z} = 0 \]

\[ \rho u \frac{\partial u}{\partial r} + \rho v \frac{\partial u}{\partial z} = \mu \nabla^2 u - \frac{\partial P}{\partial r} + F_u \]

\[ \rho u \frac{\partial v}{\partial r} + \rho v \frac{\partial v}{\partial z} = \mu \nabla^2 v - \frac{\partial P}{\partial z} + F_v \]

\[ \rho c \left(\frac{\partial T_0}{\partial r} + \frac{\partial T_0}{\partial z}\right) = K_0 \nabla^2 T_0 \]  \hspace{1cm} (2)

Where: \( \rho \) —— air density /kg·m\(^{-3}\); \( u, v \) —— radial or axial velocity component/m·s\(^{-1}\); \( \mu \) —— kinematic viscosity coefficient/P; \( P \) —— air pressure/Pa; \( c \) —— specific heat capacity/J·kg\(^{-1}\)·K\(^{-1}\); \( K_0 \) —— air thermal conductivity/ W·m\(^{-1}\)·K\(^{-1}\); \( T_0 \) —— ambient temperature/K.
3. Temperature distribution in transformer under different wind speed and load rate

3.1. Calculation model and material parameters

The two-dimensional axisymmetric model of the dry type transformer was established as shown in figure 1. The model included core, presser, insulating paper, insulating cylinder, high voltage and low voltage windings. In order to improve modelling efficiency and avoid over-dense subdivision in unnecessary directions, a boundary layer grid was established in the thin air gap area on the surface of epoxy resin. In this paper, multi-layer flat long unit was used to replace the traditional over-discrete grid with low aspect ratio.

![Figure 1. Two-dimensional axisymmetric model of dry-type transformer.](image)

The ambient temperature and the initial temperature of the material were 293.15K, and the atmospheric pressure was 101.32kPa. The material properties of each part were shown in table 1.

| Material       | Heat coefficient (W/m·K) | Heat capacity (J/kg·K) | Density (kg/m$^3$) |
|----------------|--------------------------|------------------------|--------------------|
| Copper         | 386                      | 383.1                  | 8954               |
| Iron core      | 25                       | 490                    | 7600               |
| Air            | 0.026                    | 1005.7                 | 1.2                |
| Epoxy resin    | 0.5                      | 1700                   | 1400               |

3.2. Temperature distribution in transformer under different wind speed

The temperature distribution in the large capacity dry type transformer with different wind speed was calculated. The result was shown in figure 2. According to the figure, the hot spot temperature of the high-voltage winding was always lower than that of the core and low-voltage winding under different wind speeds. When the wind speed increases from 0.1m/s to 0.7m/s, the temperature of core, high and low voltage winding would drop sharply. The hot spot temperature of high voltage winding dropped from 228.72°C to 90.682°C, the hot spot temperature of low pressure winding dropped from 481.85°C to 115.7°C, and the hot spot temperature of core dropped from 462.11°C to 103.49°C. The change of hot spot of core and low pressure winding was relatively close.

When the wind speed increased from 0.7m/s to 1.2m/s, the transformer temperature decreased significantly, and the hot spot temperature of the low-voltage winding was the highest, followed by the core and finally the high-voltage winding. Especially when the wind speed reached 0.9m/s, the hot spot temperature changed at nearly the same rate with the wind speed. For every 0.1m/s increase in wind speed, the power required by the blower was multiplied, but the temperature inside the transformer changed very little and the cost performance was extremely low.

Due to the fact that the actual blowing efficiency of the blower could not reach 100%, so the inlet wind speed was set as 0.7m/s in consideration of the heat dissipation situation and the feasibility of
practical application. At this time, the temperature distribution and air velocity inside the transformer were shown in figure 3.

Figure 2. The hot-spot temperature on transformer iron core and windings under different wind speeds

It could be seen from figure 3 that the core temperature rose first and then decreased from the bottom to the top, with the highest temperature in the middle and upper part. Because the heat would flow with the air flow, when the air blowing in from the bottom, the heat dissipation of the bottom core was best and temperature was lowest; Although the air flow was disturbed in the transformer, it still formed a stable circulation between the air passage of the iron core and the insulating paperboard. With the upward flow of heat, the heat dissipation in the upper part became worse and the temperature increased due to the heat accumulation and the influence of the surrounding low-voltage winding high temperature. Because the core top was not affected by the high temperature of the low-voltage winding, and the air flow was no longer under the heat dissipation of the barrier, the temperature at core top would decrease.

Figure 3. The temperature distribution and air velocity in transformer under 0.7m/s inlet velocity

3.3. Temperature distribution in transformer under different load rate
Transformer load rate was not fixed, there were load peak and trough period. When the transformer was in the trough, the load rate was low and the temperature rise was small. In the case of peak period or accident, the transformer may be operating under overload state. At this time, the operating current of the transformer exceeded the rated current, and the load loss increased sharply, which was bound to
increase the temperature inside the transformer, accelerate the insulation aging, and cause great harm to the transformer operation and service life. Therefore, it was necessary to study hot spot temperature rise of large capacity dry type transformer under different load.[9]

Under different load rates, the no-load loss of the transformer remained unchanged, and the load loss of the winding could be calculated according to formula.3:

$$P_l = K_T \cdot \beta^2 \cdot P_k$$

(3)

Where: $P_l$ —— load loss/W; $K_T$ —— 1.05; $\beta$ —— load rate; $P_k$ —— short-circuit loss /W.

The inlet wind speed was set as 0.7m/s, and the change curves of the heat source maximum and minimum temperature inside the transformer under different load rates were shown in figure.4. By the figure, when load rate was low, the transformer's highest temperature was 103 °C and kept constant. The hot spot temperature appeared on the core, because the load rate change would affect the current size in the winding. When the load rate was low, winding heat production was low, temperature rise was small. But the core loss was almost not influenced by the winding current, and the iron core could keep high temperature constant. When the load rate exceeded 90%, the maximum temperature increased rapidly. When the load rate reached 120%, the maximum temperature reached 160 °C. The minimum temperature of heat source increased linearly and slowly with the increase of load rate.

![Figure 4. The temperature change curve of transformer under different load rates.](image)

The hot spot temperature variation curves of the core, low-voltage winding and high-voltage winding in the transformer under different load rates were shown in figure 5. According to the figure, the maximum temperature of the core was not affected by the load rate. Because the heat source of core was mainly from iron loss, the hysteresis loss and eddy current loss of core were related to frequency, hysteresis coefficient and maximum magnetic flux density, and the influence of load current change was very small. Since the heat source and wind speed remained unchanged, only the heat of the winding had a slight effect on the heat dissipation of the core. When the load rate was 70%, the highest temperature of the core was 103.13 °C. When the load rate was 120%, the highest temperature was 104.04 °C, and the temperature only increased by 0.91 °C.

The hot spot temperature of the low-voltage winding showed a linear growth trend with the increase of the load rate. For every 5% increase of the load rate, the hot spot temperature increased by 8 °C. When the load rate was 70%, the hot spot temperature of the low-voltage winding was only 68.765 °C, and when the load rate was less than 95%, the hot spot temperature of the low-voltage winding was lower than that of the core. When the load rate reached 120%, the hot spot temperature of the low-voltage winding was 156.41 °C and the temperature rise reached 136.41 °C, which was far beyond the maximum temperature rise of 125 °C allowed by the insulation material. Therefore, when transformer was operating...
under 120% over-load, the operating time must be strictly controlled and should not exceed 60 minutes according to relevant regulations.

![Figure 5. The temperature change curve of iron core and windings under different load rates.](image)

The hot spot temperature of the high voltage winding increased linearly. Because the heat dissipation of the high voltage winding was better than that of the low voltage winding, so the temperature increased slowly. When the load rate was 70%, the hot spot temperature of the high-voltage winding was only 55.425°C. When the load rate increased to 110%, the hot spot temperature was almost the same as that of the core. When the load rate was 120%, the hot spot temperature was 121.46°C, far exceeding the core temperature. The two-dimensional temperature distribution cloud maps in the transformer under 80%, 95% and 120% loading rates were shown in figure 6.

![Figure 6. The temperature distribution of dry-type transformer under different load rates.](image)

4. Conclusion
In this paper, the calculation equation of transformer thermal field was introduced. Based on the fluid-solid coupling calculation, the temperature distribution inside the transformer under different wind speed and load rate was obtained. The change rule of winding and core temperature with load rate was obtained. The following conclusions were obtained:

1) When the inlet wind speed of the transformer increased from 0.1m/s to 0.7m/s, the temperature of the core and windings would drop sharply. When the inlet wind speed exceeded 0.7m/s, the temperature decrease in transformer slowed down obviously. Considering the blower's blowing efficiency and cost performance, the inlet wind speed of the large-capacity dry type transformer
was set as 0.7m/s, and the hot spot of the high-voltage winding was 90.682 ℃, the hot spot of the low-voltage winding was 115.7 ℃, and the hot spot of the core was 103.49 ℃.

2) When the wind speed at the transformer inlet was 0.7m/s, the temperature distribution of the transformer changed under different load rates. When the load rate was lower than 90%, the hot spot was occurred at the core. When the load rate was higher than 90%, the hot spot would always appear in the low-voltage winding. When the load rate was 120%, the hot spot temperature of the low-voltage winding was 156.41 ℃ and the temperature rise was 136.41 ℃, which had exceeded the limit temperature rise of the insulation material. Therefore, the running time must be controlled and the ventilation volume must be increased.

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