Analysis of Factors Affecting Temperature Rise of Oil-Immersed Power Transformer

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Abstract. The key factors that affect the operation state of power transformer include thermal problem and insulation problem. It is of great significance to pay attention to the factors affecting the temperature rise characteristics of transformer to ensure its stable operation. The temperature rise characteristic model of transformer is established to explore the possibility of replacing mineral oil with plant insulation oil FR3 in this paper. On the basis of calculating the influence of ambient temperature change of external heat source on transformer temperature rise, the relative life loss rate of transformer under different ambient temperature is calculated. The results show that FR3 vegetable oil can replace mineral oil in terms of temperature rise. The temperature of the transformer core and winding hot spot increases with the ambient temperature. When the ambient temperature exceeds 293K, the relative life loss rate of the transformer increases very quickly. Therefore, the transformer should not be kept in an environment where the temperature exceeds 293K for a long time.

1. Introduction
Power transformer is an important component of power plant and substation, its safe and reliable operation is the basis of maintaining the power supply stability of power network[1]. The key factors that affect the operation of power transformer include thermal and insulation problems[2].

Oil-immersed transformer mainly uses Class A insulation. Under the influence of the environment and various physical and chemical actions, the insulation material will ageing during operation. High temperature will directly lead to the ageing of the insulation material. During the operation of power transformer, high temperature accelerates the chemical reaction, and the mechanical and electrical strength of insulation decreases very quickly. As a result, transformers are prone to failures and accidents that do not reach their life expectancy[3]. Some scholars et al. divides the related parameters of transformers into four categories and puts forward a model for evaluating the comprehensive life of transformers, which can improve the accuracy of life prediction[4].

By studying the literature at home and abroad, it is known that the cooling medium of transformer and the ambient temperature during operation will affect the temperature rise, which will affect the life of transformer. Therefore, this paper establishes a transformer temperature field model to explore the possibility of FR3 vegetable insulating oil replacing mineral oil, and calculates the relative life loss rate of transformer under different ambient temperatures on the basis of calculating the influence of the change of ambient heat source temperature on the temperature rise of transformer[5,6].
2. Establishment of internal temperature rise model of oil immersed transformer

Based on the consideration of the heat conduction between the winding and the core, the convection heat transfer between the winding core and the transformer oil, and the radiation heat transfer between the oil tank and the air, the temperature field model of the transformer is established. The calculated loss of the core and the winding is input into the temperature field model as the heat source, and the hot spot temperature of the transformer can be calculated.

2.1. 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)”: 

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

(1)

Where, $\rho$ is the density of transformer oil. $C_p$ is the heat capacity at atmospheric pressure. $\mathbf{u}$ is the velocity field. $K$ is the heat transfer coefficient; $q$ is the internal heat source.

Boundary conditions:

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

(2)

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

2.2. laminar flow model

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

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

(3)

Where: $\mu$ is the dynamic viscosity of transformer oil; $\rho$ is the density of transformer oil; $I$ is the main stress tensor.

2.3. setting of initial conditions and establishment of physical model

Based on the following assumptions, the 50MVA / 110kV natural oil circulation oil immersed power transformer is modeled as the prototype: (1) the physical parameters of iron core and copper are set as constants; (2) the average distribution of heat sources of iron core and winding is constant; (3) the ambient temperature is set as constant, without considering the thickness of the outer wall of the oil tank; (4) the heat dissipation outside the oil tank is equivalent to the heat dissipation coefficient of the oil tank wall.

In this paper, the temperature field modeling of natural oil circulating 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 material parameters related to the calculation of temperature field are shown in Table 1.
Table 1 Parameters of transformer materials for fluid-thermal field analysis

| Material       | Density (kg/m³) | Thermal conductivity (W/(m²·K)) | Specific heat rate (W/(M·K)) | Dynamic viscosity (N·s·m⁻²) | Atmospheric heat capacity (J/kg·K) |
|----------------|------------------|---------------------------------|-----------------------------|-----------------------------|-----------------------------------|
| Copper         | 8700             | 400                             | —                           | —                           | 385                               |
| Silicon steel  | 7650             | 42                              | —                           | —                           | 460                               |
| Transformer oil| 920              | 0.13                            | 3.0636                      | 1900                        |

When the transformer is in different operating conditions, the loss of the three-phase core is not the same, so the model used for the temperature field is to model and solve the three-phase core separately based on the electromagnetic field model, and the final physical model for calculation is shown in Figure 1.

![Fig. 1 The temperature model of transformer](image)

3. Influence of different cooling medium on temperature rise of transformer
This paper takes 50MVA / 110kV oil immersed power transformer as an example, through the established transformer temperature field model, under the same structural design and heat source conditions, comparative analysis of FR3 vegetable insulating oil and mineral insulating oil on the impact of transformer temperature rise under rated conditions.

Table 2 Main parameters of FR3 vegetable oil and common mineral oil

| Parameter                        | Types of oil          | FR3 vegetable insulating oil | Mineral oil  |
|----------------------------------|-----------------------|------------------------------|--------------|
| Density (kg/m³)                  | 920                   | 920                          |              |
| Viscosity (N·s·m⁻²)              | 33.3                  | 3.0636                       |              |
| Thermal conductivity (W/(M·K))   | 0.17                  | 0.13                         |              |
| Specific heat capacity (J/kg·K)  | 1880                  | 1900                         |              |
Under the same model and heat source conditions, only the transformer oil is changed. The top figure in Figure 2 shows the temperature distribution cloud diagram of iron core under rated working condition when FR3 vegetable insulating oil is used as cooling medium, and the bottom figure shows the temperature distribution cloud diagram of iron core under rated working condition when mineral oil is used as cooling medium. Through comparison, it can be seen that the temperature distribution of iron core is basically the same. The hot spot temperature of iron core with FR3 vegetable insulating oil is 355.97K, the hot spot temperature of iron core with mineral insulating oil is 353.84K, and the hot spot temperature of iron core with FR3 vegetable insulating oil is increased by 2.13K.

From Figure 3, it can be seen that the temperature distribution trend of FR3 vegetable insulating oil and mineral insulating oil used for high-voltage winding and low-voltage winding is basically the same. The hot spot temperature of high voltage winding with FR3 vegetable insulating oil is 357.28K, the hot spot temperature of high voltage winding with mineral insulating oil is 355.74K, and the temperature difference is 1.54K. The hot spot temperature of low voltage winding with FR3 vegetable insulating oil is 364.88K, the hot spot temperature of low voltage winding with mineral insulating oil is 363.72K, and the temperature difference is 1.16K.

It can be seen from Figure 2 and figure 3 that the hot spot temperature rise still meets the regulations in gb1094.2-2013 power transformer part II: temperature rise of liquid immersed transformer. Therefore, it is feasible to replace mineral insulating oil with FR3 vegetable insulating oil in terms of temperature rise characteristics.

**4. Influence of different ambient temperature on temperature rise of transformer**

Taking 50MVA / 110kV oil immersed power transformer as an example, through the established temperature rise model of transformer, under the same structural design and heat source conditions, the temperature rise of transformer core and low-voltage winding under rated conditions is compared and analyzed when the ambient temperature is 263.15K, 268.15K, 273.15K, 278.15K, 283.15K, 288.15K, 293.15K, 298.15K, 303.15K.
4.1 influence of ambient temperature on temperature rise of iron core and winding

It can be seen from the calculation that changing the ambient temperature under the same heat source and condition does not affect the temperature distribution trend, but only affects the temperature rise, and the hot spots of the winding appear on the low-voltage winding. Therefore, this part only lists the calculated hot spot temperature and average temperature of the iron core and low-voltage winding. Through comparative analysis of different ambient temperatures the influence on the hot spot temperature and average temperature of core and winding of oil immersed power transformer.

| Ambient temperature (K) | Core hot spot temperature (K) | Winding hot spot temperature (K) |
|-------------------------|-------------------------------|-------------------------------|
| 263.15                  | 323.83                        | 333.87                        |
| 268.15                  | 328.84                        | 338.87                        |
| 273.15                  | 333.83                        | 343.88                        |
| 278.15                  | 338.85                        | 348.88                        |
| 283.15                  | 343.83                        | 353.88                        |
| 288.15                  | 348.84                        | 358.87                        |
| 293.15                  | 353.85                        | 363.72                        |
| 298.15                  | 358.83                        | 368.87                        |
| 303.15                  | 363.84                        | 373.88                        |

Table 4 The average temperature of the iron core and transformer winding

| Ambient temperature (K) | Core hot spot temperature (K) | Average temperature of LV winding (K) |
|-------------------------|-------------------------------|------------------------------------|
| 263.15                  | 285.75                        | 313.82                             |
| 268.15                  | 290.76                        | 318.83                             |
| 273.15                  | 295.75                        | 323.82                             |
| 278.15                  | 300.75                        | 328.83                             |
| 283.15                  | 305.76                        | 333.83                             |
| 288.15                  | 310.76                        | 338.82                             |
| 293.15                  | 315.75                        | 343.32                             |
| 298.15                  | 320.76                        | 348.81                             |
| 303.15                  | 325.75                        | 353.81                             |

As can be seen from Figure 4, with the increase of the ambient temperature, the hot spot temperature and the average temperature of the iron core and the winding will rise, because in this paper, the winding is equivalent to the cylinder shape. If it is equivalent to the wire cake shape, it will be closer to the actual situation than the cylinder shape. More oil channels of the wire cake shape winding are more conducive to heat dissipation. The core temperature increases with the ambient temperature at a higher rate than that of the winding.
4.2 influence of ambient temperature on transformer life

This section explores the method of predicting transformer life on the basis of calculating the influence of ambient temperature on transformer hot spots. At present, there is no definite and simple criterion to calculate the service life of transformer, which is usually determined by the expected service life. The research shows that the life expectancy of transformer is inversely proportional to the hot spot temperature of transformer winding, that is to say, the higher the hot spot temperature is, the shorter the life expectancy of transformer is. In the range of 80 ℃ ~ 140 ℃, the relationship between the expected life of transformer and the hot spot temperature can be expressed by “formula (4)”: 

$$z = Ae^{-P\theta}$$  \hspace{1cm} (4)$$

Among them, $Z$ is the expected life of the transformer; $a$ is a constant related to the composition of the material and the moisture and free oxygen in the insulation; $P$ is the temperature coefficient, independent of the fiber quality.

Calculate the normal life expectancy of the transformer according to “equation (4)”: 

$$Z_N = Ae^{-P\cdot98}$$ \hspace{1cm} (5)$$

The relative life expectancy at any temperature is represented by $Z_n$:

$$Z_n = \frac{Z}{Z_N}$$ \hspace{1cm} (6)$$

The relative aging rate is:

$$v = e^{P(\theta-98)}$$ \hspace{1cm} (7)$$

Where $\theta$ is any temperature.  

According to the law of thermal aging, when the winding temperature is lower than 80 ℃, the loss of mechanical strength and electrical strength of the insulation of the transformer is negligible. When the winding temperature is equal to 80 ℃, the relative aging rate is 0.125. When the winding temperature is increased by 6 ℃, the aging rate is multiplied, that is, when the winding temperature is 86 ℃, the relative aging rate is 0.25, the insulation aging rate of each temperature is shown in Figure 5. It can be seen that the insulation aging rate of the hot spot temperature rises very fast at 120 ℃ ~ 140 ℃. Therefore, if the hot spot temperature of the winding exceeds the design value for a long time, the service life of the transformer will be lost rapidly.
Aging rate vs temperature℃

Fig.5 The influence of the external environment on insulation aging rate

Generally, when designing the transformer, the ambient temperature is 20 ℃, the reference value of the hot spot temperature is 98 ℃, the expected service life of the transformer is 20-30 years, and the insulation aging rate is assumed to be 1. When the mechanical strength of transformer insulation is reduced to 15% ~ 20% of its rated value, the service life of transformer is considered to be terminated. In engineering, the relative life expectancy and relative aging rate are usually used to describe the aging degree of transformer.

During the operation of transformer, influenced by the ambient temperature and load variation, the hot spot temperature of winding changes greatly. When the temperature is higher than 98 ℃, it will age rapidly, and when the temperature is lower than 98 ℃, the aging speed is very slow. If the two parts compensate each other, that is, the life lost in a period of time is equal to the life lost in the same period of time when the hot spot temperature of the winding is 98 ℃, it can be considered that the life lost caused by the change of the winding temperature in this period of time is constant with the winding temperature of 98 ℃. Equivalent loss of life at centigrade

The principle of equivalent aging can be expressed as follows:

\[
\int_{\theta}^{T} e^{\theta t} = T e^{98} = C.
\]

Where \( t \) is the time interval and \( C \) is the constant.

Relative life loss rate of transformer \( V \):

\[
V = \frac{\text{Life loss at } \theta_{cr}}{\text{Life loss at } \theta_{c}} = 10^{\frac{(\theta_{cr} - 98)^{19.91}}{19.91}}
\]

Where, \( \theta_{cr} \) is the temperature under rated load, and \( \theta_{c} \) is the hot spot temperature of winding.

The change of the hot spot temperature with the ambient temperature is calculated as shown in Figure 6. According to figure 6 and “equation (9)”, calculate the relative life loss rate of transformer when the ambient temperature increases at 5 ℃ interval, as shown in Figure 7.

Fig.6 Hot-spot of transformer at different environment temperatures
According to the method used in this section to calculate the life loss rate of the transformer from the ambient temperature, the relative life loss rate can be calculated according to the daily average temperature change curve of the actual operation of the transformer, and the daily average insulation aging time can be obtained by multiplying the relative life loss rate by time.

5. Conclusion

Using the established temperature field model to explore the influence of FR3 vegetable oil used as cooling medium on the temperature distribution in the transformer, to explore the influence of different ambient temperatures on the temperature rise of the transformer, and to calculate the relative life loss rate of the transformer under different ambient temperatures, the following conclusions are drawn:

- By changing the physical parameters of transformer oil under the same model and heat source conditions, it is analyzed that when FR3 vegetable oil is used as the cooling medium, the hot spot temperature of iron core and winding is slightly higher than that of mineral oil due to its high dynamic viscosity, but the temperature rise still meets the requirements of "power transformer part II: temperature rise of liquid immersed transformer". Therefore, it is feasible to replace mineral oil with FR3 vegetable oil in terms of temperature rise characteristics.

- With the increase of the ambient temperature of the external heat source, the hot spot temperature of the core and winding in the transformer increases rapidly. When the ambient temperature exceeds 293K, the relative life loss rate increases rapidly, which is consistent with the assumption that the ambient temperature is 293.15K when the transformer is designed. By using the method of calculating the relative life loss rate of transformer in this paper and combining with the monthly average temperature change curve of actual operation environment, the daily average insulation aging time of transformer can be obtained.

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