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Research on comprehensive optimization strategy of transformer thermal life in digital substation

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Abstract: *With the national advocacy and vigorous promotion of new digital infrastructure, digital assessment of transformer operation state based on digital twin technology has become one of the hot issues in the power field. In this paper, taking an oil immersed transformer as an example, the magnetic, current and thermal multi field coupling numerical analysis method is used to simulate and analyze the operation state of the transformer, monitor the multi state characteristic parameters of the transformer through sensors, integrate the numerical simulation analysis results with the state monitoring results, and build a transformer thermal life loss evaluation system. This method can evaluate and analyze the operation status of transformers in real time, which is of great significance for power companies to formulate governance measures. It can effectively support the national new digital infrastructure strategy and contribute to the national strategy while satisfying the normal operation of power grid enterprises.*

Keywords: *Transformer; Digital twins; Thermal life loss; Multi-field coupling; Evaluating system*

1. Introduction

China's electric power industry is making great strides. At the same time, the "Fourteenth Five Year Plan" points out that building a digital China will drive the transformation of equipment management mode with digital. Through the digital twin technology, the operation state of the physical entity of the transformer in the whole life cycle can be analyzed. Transformer faults will affect the stable operation of the power system. According to incomplete statistics, more than 70 destructive thermal faults have occurred in transformers of 110 kV and above of China Southern Power Grid Corporation since 2015. Therefore, based on the requirements of digital transformation of power grid and safe and stable operation, it is an urgent problem to introduce digital twin technology to analyze the thermal life loss of transformers [1-2].

Digital twin technology has made some research achievements in the field of power system. Literature [3] built a digital twin framework of energy Internet, and looked forward to the feasible technical routes and typical applications. Literature [4] constructs the overall framework of digital twin power grid, and looks forward to the typical applications that can be realized. Literature [5] preliminarily explored the technical route of health status assessment based on digital twin technology, and made a virtual deduction of the system trend. Literature [6] establishes a digital twin model on the low-voltage side of distribution transformer, which can capture all harmonic contents and identify system faults. Literature [7] established a simplified model of digital twin transformer based on LabView environment, which can simulate electrical, thermal, chemical and other processes, and can also consider current overload and other operating modes. Reference [8] has studied the relationship between the life of transformer insulation materials and hot spot temperature. In conclusion, the analysis theory of transformer thermal life loss is relatively mature, and the scheme and application of digital twin technology are still preliminarily explored. How to build a digital twin assessment system for transformer thermal life loss based on digital twin technology, integrating the transformer numerical simulation results and physical entity status monitoring results, is the difficulty in the implementation of this technology.

Based on the actual demand of the power grid, this paper takes an oil immersed power transformer model as an example to conduct simulation calculation and analysis on magnetic leakage, loss, velocity distribution, temperature and aging, etc., monitor and analyze the multi state characteristic parameters of the transformer during operation through sensors, and build a transformer thermal life loss evaluation system based on digital twin technology, Real time analysis and evaluation of the operation state of the transformer.

2. Theoretical analysis of multi field coupling and thermal life assessment

2.1 Electromagnetic analysis

The principle of electromagnetic induction is the basis of transformer operation. This paper calculates the three-dimensional magnetic field of transformer based on T - Ω method [9].

$$\nabla^2 \boldsymbol{T} - \mu\sigma \frac{\partial \boldsymbol{T}}{\partial \boldsymbol{t}} = -\nabla \times \boldsymbol{J_S} \quad \text{Current carrying area} \tag{1}$$

$$\nabla \cdot \mu \nabla \Omega - \mu\sigma \frac{\partial \Omega}{\partial t} = 0 \quad \text{Global} \tag{2}$$

$$\nabla \cdot \mu \nabla \Omega = \nabla \cdot \boldsymbol{T} \quad \text{Conductor area} \tag{3}$$

$$\nabla^2 \boldsymbol{T} - \mu\sigma \frac{\partial \boldsymbol{T}}{\partial \boldsymbol{t}} = -\mu\sigma \frac{\partial \nabla \Omega}{\partial \boldsymbol{t}} \quad \text{Eddy current region} \tag{4}$$

When a metal conductor is in a magnetic field, it will induce potential and generate eddy current inside the conductor, which will cause eddy current loss.

$$P_e = \int_v \frac{\overline{J \cdot J}}{\sigma} \mathrm{d}v = \int_v \frac{J_{0rms} \cdot J^*_{0rms}}{\sigma} \mathrm{d}v \tag{5}$$

Where, Pe is the periodic average eddy current loss; J0rms is the average value of J_0 in the period; J_0 is the relevant quantity of J.

When the metal magnet is magnetized repeatedly in the magnetic field, hysteresis loss will be produced in the magnetic conductor.

$$P_h = \sum_{i=0}^{N} P_h^{(i)} \left(B_m^{(i)} \right) \sigma V^{(i)} \tag{6}$$

Wherein, P_h is the hysteresis loss; N is the number of discrete elements; P_h (i) is the hysteresis loss in unit i; B_m (i) is the amplitude of magnetic flux density in unit i; V (i) is the volume of i unit.

The total loss P is:

$$P = P_e + P_h \tag{7}$$

2.2 Flow thermal analysis

The transformer cooling system has complex structure and numerous branches. The equations for solving the flow state of transformer oil are composed of mass, momentum, energy conservation equations and turbulent viscosity equations. The general expression of conservation equation is:

$$\begin{aligned} &\frac{\partial(\rho\phi)}{\partial t} + \frac{\partial}{\partial x}(\rho u \phi) + \frac{\partial}{\partial y}(\rho v \phi) + \frac{\partial}{\partial z}(\rho w \phi) = \\ &\frac{\partial}{\partial x}(\Gamma_\phi \frac{\partial \phi}{\partial x}) + \frac{\partial}{\partial y}(\Gamma_\phi \frac{\partial \phi}{\partial y}) + \frac{\partial}{\partial z}(\Gamma_\phi \frac{\partial \phi}{\partial z}) + S_\phi \end{aligned} \tag{8}$$

Among them, ϕ Is each equation variable; Γϕ Is the diffusion coefficient; S ϕ Is the source item.

Turbulence dissipation rate ε Equation:

$$\varepsilon = \frac{\mu}{\rho} \overline{\left(\frac{\partial u_i^{'}}{\partial x_k} \right) \left(\frac{\partial u_j^{'}}{\partial x_k} \right)} \tag{9}$$

turbulent viscosity μ T can be expressed as k and ε Function of, that is:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{10}$$

Where, C μ Is an empirical constant.

The heat transfer modes include conduction, radiation and convection, and conduction and convection are mainly considered in the calculation of transformer temperature.

The heat conduction control equation is:

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)=-q \tag{11}$$

Convection is controlled by the energy transport equation:

$$\begin{aligned}&\frac{\partial(\rho h)}{\partial t}+\frac{\partial(\rho uh)}{\partial x}+\frac{\partial(\rho vh)}{\partial y}+\frac{\partial(\rho wh)}{\partial z}\\&=\nabla\cdot(\lambda\cdot\nabla T)-p\cdot\nabla U+\Phi+S_h\end{aligned} \tag{12}$$

Among them, λ Is the thermal conductivity of transformer oil, Sh is the heat source, Φ Is a dissipation function.

$$\Phi=\mu\begin{Bmatrix}2\left[\left(\frac{\partial u}{\partial x}\right)^2+\left(\frac{\partial v}{\partial y}\right)^2+\left(\frac{\partial w}{\partial z}\right)^2\right]\\+\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2+\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)^2\\+\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)^2\end{Bmatrix}+\lambda\left(\nabla\cdot U\right)^2 \tag{13}$$

2.3 Thermal life assessment analysis

The thermal life of the transformer is closely related to the aging degree of the insulation part. The aging degree of the insulating paper directly affects the thermal life of the transformer. According to the 6 ℃ rule, the relative aging rate of the insulating paper [8]:

$$V = 2^{(T_h-98)/6} \tag{14}$$

Where Th is the hot spot temperature in the transformer.

The thermal life loss of transformer can be written as:

$$L=\int_{t_1}^{t_2} V dt=\sum_{n=1}^{N} V_n \times \Delta t_n \tag{15}$$

Where, Vn is the relative aging rate in the nth time interval; Δ Tn is the time of the nth interval.

The thermal life equation of transformer established in this paper is:

$$T = S - L \tag{16}$$

Where, T is the thermal life of the transformer; S is the service life of the transformer.

3. Physical and mathematical models

This paper takes a 1000kVA power transformer as an example, and the three-dimensional mathematical model of transformer magnetic field calculation is shown in Figure 1.

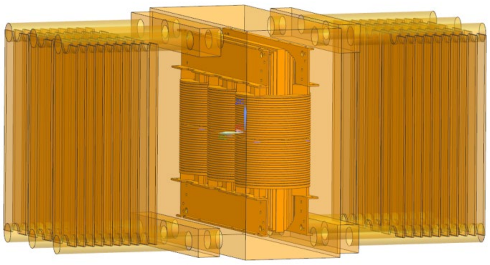

Figure 1: Transformer simulation calculation model

Based on the digital twin technology, the digital model of transformer is established. Through monitoring the multi state characteristic parameters during the operation of transformer, the operation state of transformer is simulated and its thermal life is predicted.

4. Analysis of calculation results

The magnetic density distribution of the main air duct is shown in Figure 2. From the distribution curve, it can be seen that the magnetic density distribution of the main air duct is small at the end of the winding, the maximum in the middle, and the magnetic density amplitude is about 0.0905T.

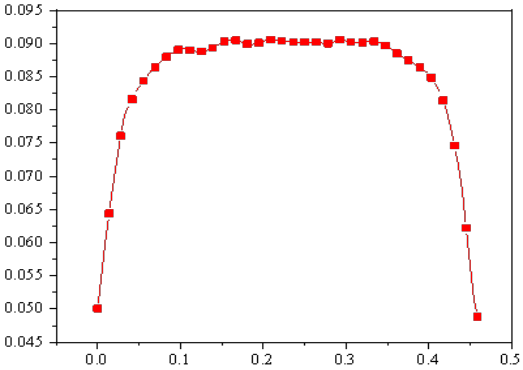

Figure 2: Magnetic density curve of main empty channel

The winding is the current flow path of the transformer, and the magnetic density distribution is shown in Figure 3. It can be seen from the figure that the magnetic leakage density at the end of the winding is greater than that in the middle.

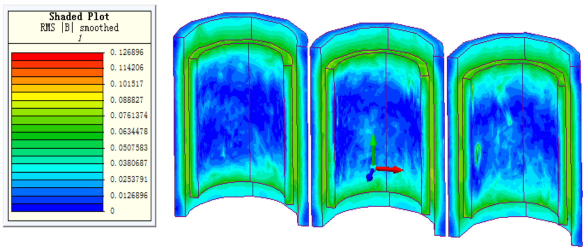

Figure 3: Winding magnetic density distribution

The temperature curve of the wire cake in the upper, middle and lower areas of the high-voltage winding is shown in Figure 4. The temperature distribution in the winding area shows a nonlinear upward trend along the axial height. The hot spots are mainly located at the upper end. The hot spot temperature is 55.99 °C, the test value is 53.94 °C, and the error is about 3.8%.

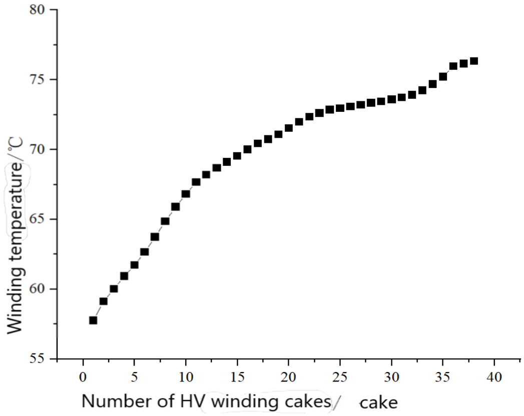

Figure 4: Temperature curve of high voltage winding

The temperature distribution of low-voltage winding is shown in Figure 5. The temperature of LV winding is higher than that of HV winding, mainly because it is located between HV winding and iron core, close to two heat sources, and has poor heat dissipation effect. The hot spot position in the upper middle section is 59.50 ℃, the test value is 57.78 ℃, and the error is about 3%.

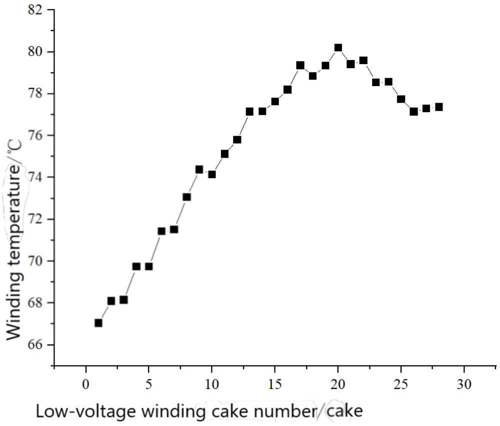

Figure 5: Temperature curve of low voltage winding

The heat generated by each component of the transformer is transferred to the transformer oil in the form of heat conduction. Due to the non-linear property of the transformer oil, the density of the hot oil decreases, flows upward, passes through the radiator, transfers some heat, and returns to the bottom of the oil tank, forming the transformer oil circulating cooling system. The oil temperature distribution diagram is shown in Fig. 6, and the temperature decreases vertically from top to bottom.

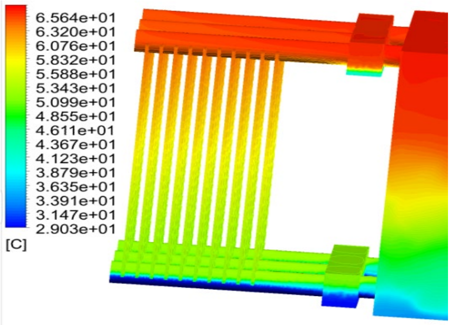

Figure 6: Radiator part transformer oil temperature field

This paper analyzes the thermal life of the transformer based on the hot spot temperature. The thermal life loss corresponding to the hot spot temperature can be determined from the data in the table.

5. Conclusion

This paper takes 1000kVA oil immersed power transformer as the research object, and analyzes the thermal life loss of transformer based on digital twin technology. The conclusions are as follows:

(1) By reasonably simplifying the numerical simulation analysis model of the transformer, the hot spot temperature is simulated and calculated, and the transformer operation parameters obtained from the monitoring are fused to achieve the thermal life loss analysis of the transformer, which shows that the digital twin established in this paper is effective;

(2) The hot spot temperature of the digital twin is calculated based on the magnetic, current and thermal multi field coupling method, and the error is controlled within 5%. The numerical calculation model of thermal life loss is established through the simulation results, which not only ensures the analysis speed, but also improves the analysis accuracy of the transformer thermal life loss evaluation system;

(3) The thermal life loss of an actual product is evaluated, which proves the feasibility of the method proposed in this paper, and also provides a reference for transformer maintenance.

To sum up, this paper establishes the digital twin model of transformer, and analyzes the thermal life loss of transformer by monitoring multiple characteristics. This method can provide reference for power companies to formulate governance measures.

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