Research on Temperature Rise Calculation of the Large Synchronous Compensator in UHVDC System

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Abstract. In order to study the temperature distribution characteristics of stator and stator winding of large dual-water internal cooling synchronous compensator. According to the fluid-solid multi-physical field coupling method, a three-dimensional calculation model of large-scale dual-water internal cooling synchronous compensator is established. Considering the complexity of the stator slot structure and the high requirement for computer performance, the simplified equivalent treatment of the stator slot structure is made. Then, based on the fluid-temperature coupled heat transfer theory, the temperature distribution is solved by finite element method with the loss of stator core and stator coil as heat source. Finally, the accuracy of temperature distribution and simplified equivalent model is verified by steady-state temperature field analysis method.

1. Introduction

Large synchronous compensator is the preferred reactive power compensation equipment in UHVDC transmission network [1]. However, the temperature rise of large capacity phase modulator is high, and there is a large temperature difference between the various components, which will threaten the insulation and affect the safe and stable operation of the equipment. Therefore, it is of great significance to study the internal loss, fluid flow characteristics and heat transfer characteristics among the components of a large synchronous compensator.

At present, domestic and foreign scholars mainly focus on simplified formula method, equivalent thermal circuit method, equivalent thermal grid method, finite element simulation method parameter identification method [2]. Based on the finite element method, XIE Ying simulated the temperature field of a cage induction motor[3]. LI Wei-li established the equivalent model of winding air gap. The temperature field of the motor is analysed by finite element method, and the effectiveness of the equivalent model method is further verified by experiments [4]. LI Liyi presents the layered equivalence of the end windings in the three-dimensional temperature field calculation model of the motor. The calculation and experimental results show that the layered equivalence model can improve the accuracy of the calculation of the winding temperature rise [5]. LIU Ping equivalent stator winding to copper rod thermal conductor and insulation thermal conductor, introduced the concept of effective thermal conductivity coefficient, solved the mutual coupling problem of fluid field and temperature field in air gap, simplified the complex heat exchange process between stator and rotor [6].
In this paper, a TTS-300-2 dual-water internal cooling synchronous compensator is taken as the research object of temperature field. The stator simulation model is established with the loss of stator core and stator coil as heat source. The temperature distribution characteristics of stator teeth are solved by finite element method. Firstly, a real scale three-dimensional simulation model of stator is built in SolidWorks. Then, it is imported into Fluent to solve the temperature distribution by setting parameters. Considering the complexity of the stator coil, the accuracy of the equivalent model is verified by the steady-state thermal analysis method after the stator coil is equivalent, which provides a basis for the complete simulation of the stator temperature field and fluid field.

2. Theoretical analysis

2.1. Heat source calculation

According to the hypothesis, only copper and iron consumption of synchronous phase modulator are considered in the calculation of temperature field in this paper. The calculation method is as follows [7] − [9]:

\[ P_{C} = mI^{2}R \]  \hspace{1cm} (1)

\[ P_{F} = K_{m}f_{m}^{2}B_{m}^{2} + 2K_{c}f^{2}B_{c}^{2} \]  \hspace{1cm} (2)

Where \( m \) is the number of winding phases, \( B_{m} \) is the maximum magnetic induction intensity, \( \alpha \) is the index determined by experiments, \( K_{m} \) is the calculation coefficient of different materials, \( K_{c} \) is the eddy current loss coefficient and the additional loss coefficient.

2.2. Coupled Fluid-Temperature Calculation

For a rotating motor, the thermal conductivity differential equation and boundary conditions are as follows:

\[
\begin{align*}
\frac{\partial^{2}T}{\partial x^{2}} + \frac{\partial^{2}T}{\partial y^{2}} + \frac{\partial^{2}T}{\partial z^{2}} + \frac{q_{t}}{\lambda} &= 0 \\
\lambda \frac{\partial T}{\partial n} \bigg|_{\gamma} &= 0 \\
\lambda \frac{\partial T}{\partial n} \bigg|_{\delta} &= -\alpha \left( T - T_{r} \right)
\end{align*}
\]  \hspace{1cm} (3)

The cooling water is regarded as an incompressible fluid, which satisfies the mass conservation equation, momentum conservation equation and energy conservation equation in the flow process.

2.3. Boundary conditions and parameter calculations

Accurate solution of convective heat dissipation coefficient is the premise of temperature field calculation. Forced convection heat transfer between stator clearance and stator yoke and air, and the calculation method of convection heat dissipation coefficient is as follows:

\[ \alpha_{\delta} = 28 \left( 1 + \omega_{\delta}^{0.5} \right) \]  \hspace{1cm} (4)

Where \( \alpha_{\delta} \) is heat transfer coefficient of air gap surface; \( \omega_{\delta} \) is the average air gap wind speed.

Forced convection heat transfer occurs between the cooling water and the motor. The calculation method of convection heat transfer coefficient is as follows:

\[ \alpha_{b} = \frac{0.023 \Re^{0.8} \Pr^{0.4}}{d} \]  \hspace{1cm} (5)

Where \( \alpha_{b} \) is the convective heat transfer coefficient between cooling water and motor; \( \Re \) is Reynolds number; \( \Pr \) is the Prandtl number; \( d \) is the diameter of pipeline; \( P_{r} \) is the Prandtl number.
In order to simplify the calculation and improve the accuracy of calculation, in this paper, the complex hollow conductor, solid conductor and turn-to-turn insulation are equivalent to the equivalent copper wire layer with uniform thermal conductivity [10], as shown in figure 2. Basic heat parameters such as thermal conductivity, density and specific heat capacity of the equivalent heat conductor can be calculated according to the following equation [11]:

\[
\lambda = \frac{d_1 + d_2 + \cdots + d}{\frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} + \cdots + \frac{d}{\lambda_n}}
\]

(6)

\[
\rho = \frac{\rho_1 \nu_1 + \rho_2 \nu_2 + \cdots \rho_n \nu_n}{\nu}
\]

(7)

\[
c = \frac{c_1 \rho_1 \nu_1 + c_2 \rho_2 \nu_2 + \cdots c_n \rho_n \nu_n}{\rho \nu}
\]

(8)

3. Model Assumes
The stator core of the adjustable camera is made of cold-rolled non-oriented silicon steel sheet with fan-shaped high permeability and low loss. The windings of the cold-rolled stator in water are three-phase and double-layer windings. The stator windings are laminated windings, and the insulation of the stator windings to ground is F grade epoxy mica tape continuous insulation. The upper and lower coils are designed with equal sections. The wire rods are composed of two rows of solid and hollow flat copper wires spaced at intervals. The ratio of each row of hollow copper wires to solid copper wires is 1:4.

The following assumptions are made between the establishment of motor calculation models:
1) The surface heat dissipation coefficient of synchronous compensator is constant.
2) The loss of synchronous phase modulator is used to generate heat.
3) Loss does not change with time.
4) The temperature rise caused by iron consumption is applied to the stator core.

4. Calculation of Temperature Rise
Figure 1 shows the stator temperature distribution by simulation

![Figure 1. Stator Temperature Cloud](image-url)
Figure 2. Fluid-solid Coupling Method for Radial Temperature Distribution of Molecules

From figure 1 and figure 2, it can be seen that the highest temperature of stator is on the core, and the highest temperature is 65.13°C. Because of the relative staggered arrangement of cooling water, the temperature rise of conductor and insulation in the slot is low, and the temperature rise of stator core affected by slot wedge and insulator can hardly be cooled by cooling water.

The accuracy of the above model is high, but for the complete stator, if the coil and insulation are not treated equally, the simulation will consume a lot of memory and require a high performance of the computer. In order to solve this problem, the coil and insulation are treated equivalently. Due to the short circulation path of cooling water in the model, Fluent simulation shows that its temperature remains around 35°C. The simplified equivalent model is shown in figure 3 below.

Figure 3. Model comparison before and after equivalent simplification

According to formula (9) (10) (11), the calculated parameters of the equivalent stator core are shown in Table 1.

| Quantity/Unit                  | Insulating layer | Coil and insulation equivalent |
|-------------------------------|------------------|--------------------------------|
| Thermal conductivity / (W/m·k) | 0.16             | 0.46                           |
| Density / (kg/m³)              | 1250             | 5594                           |
| Specific heat capacity / (J/(kg·k)) | 1750       | 141                            |

Table 1. Calculating parameters of stator heat

In order to verify the accuracy of the stator fluid-solid coupling model and the calculation results and the equivalent model, the steady-state thermal analysis method was used to compare the results. The heat source of stator coil is equivalent to that of coil and insulation, and is used as heat source together with stator iron consumption. The ambient temperature is set to 27 °C. The radial surface of stator core and the back surface of stator are set to convection surface with air. The calculation results are shown in figure 5.
From figure 4 and figure 5, it can be seen that the temperature field calculated by the simulation method based on fluid-solid coupling has the same distribution rule as that of the simplified model, and the maximum temperature of the stator is not much different, which verifies the accuracy of the simplified model and the non-simplified model of the stator.

5. Conclusion
In this paper, the stator model of a large-scale dual-water internal cooling synchronous compensator is established. The temperature distribution characteristics are obtained by fluid-solid coupling finite element calculation with copper conductor and iron loss as heat sources. The following conclusions are drawn:

1) The overall temperature distribution of the stator shows that the lower region is lower than the upper region, the yoke of the stator is larger than the teeth of the stator, and the highest temperature point appears on the stator core.

2) Summarize and analyse the distribution law of stator axial temperature. In the axial direction, the distribution law of temperature is high-low-high. The temperature of stator core is about 30% higher than that of coil part.

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