Calculation of Stator Temperature Field in Water Cooled Synchronous Condenser

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Abstract. When the Synchronous condenser adjusts the reactive power of the grid, it will generate a lot of internal losses. Most of these losses will eventually be converted into heat, which will increase the temperature of each part of the motor, which will hinder the safe operation of the Synchronous condenser. At present, the hollow strands in the stator windings of the water-cooled motor have a structure in which the upper and lower sections are equal. In order to reduce the loss of the inner winding of the Synchronous condenser, this paper proposes a new type of winding structure, that is, the structure of the upper section of the hollow strand is larger than the lower section. Taking a 300Mvar large-scale Synchronous condenser as an example, a two-dimensional electromagnetic field finite element simulation model of stator bars under two structures is established, and the resistance increase coefficient of each strand is calculated. Based on this, a large-scale Synchronous condenser is established. a three-dimensional mathematical model of the stator temperature field, The results show that when the hollow strands adopt different structures with upper and lower sections, the temperature rise at the highest point around the hollow strands is reduced.

Introduction

As the preferred reactive power compensation equipment in power grid, with the continuous expansion and complexity of the power system, the capacity of synchronous phase modulator has been expanded from less than 30 Mvar to 300 Mvar. With the increase of the capacity, the internal heat of the motor has been increasing. In order to maintain the good operation of the Synchronous condenser, you need to choose the appropriate cooling medium and cooling structure. At present, many motor cooling systems use water as the cooling medium, and the hollow strands have the same cross-section structure. Accidents caused by blockage of stator strands in water-cooled systems account for more than half of total motor failures [2]. Hollow strand wire blockage will destroy the stator winding, and seriously affect the stator core, so it is necessary to study the distribution of stator temperature field under different blockage conditions, in order to timely discover hidden dangers and improve the safe operation of the motor.

In [3-13], the distribution law of stator temperature field of turbo generator stator strands under different clogging degrees is studied. In [14], the finite volume method is used to calculate the fluid field and temperature field of high-altitude wind turbines, which provides a theoretical basis for the safe operation and design of generators in high altitude areas. The literature [15] studied the three-dimensional temperature field of the stator of an air-cooled turbo generator with special winding structure; In [16], the influence of transposition on the local hot spot of stator bars of turbo generators is studied, which provides a theoretical basis for the distribution of stator bar temperature in the future.
Model for Adjusting the Stator Temperature Field of the Synchronous Condenser

Physical Model

The stator winding of the 300Mvar Synchronous condenser adopts a mixed arrangement of solid strands and hollow strands. The stator hollow strands are internally cooled by water, and the stator radial ventilation grooves are air-cooled. The 300Mvar Synchronous condenser has a pole number of 2 poles, a rated capacity of 300Mvar, a rated voltage of 20Kv, and a stator slot number of 48. Considering the symmetry of the motor structure, and in order to save calculation time and ensure the accuracy of calculation, the solution area is limited to a core segment on both sides of a ventilation groove, and a range of pitches in the circumferential direction. The specific physical solution domain model is shown in Figure 1.

Mathematical Model and Its Boundary Conditions

Mathematical Model. Combined with the physical model of the stator bar, according to the basic knowledge of heat transfer [17], when the Synchronous condenser is running stably, the solution of the temperature field in the stator bar is an in-band heat source, ambient insulation and internal type 3 boundary. The three-dimensional steady-state heat conduction problem of the condition, the mathematical model for solving the three-dimensional temperature field of the stator bar is:

\[
\begin{align*}
\frac{\partial T}{\partial \tau} &= \lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{Q}{\rho c} \\
[T]_n &= T_o \\
-\lambda \left( \frac{\partial T}{\partial n} \right)_n &= f(x, y, z, \tau) \\
-\lambda \left( \frac{\partial T}{\partial n} \right)_n &= h(T_o - T_f)
\end{align*}
\]

(1)

Where: \( T \) - stator bar temperature; \( \lambda \) - The thermal conductivity of different materials; \( \Phi \) — Heat source strength on the copper core strand; \( \partial T/\partial n \) — The rate of temperature change along the normal to the boundary.

Boundary Conditions.

1) The inner and outer circular surfaces of the stator core are heat dissipating surfaces, and the other is a heat insulating surface;

2) The stator hollow strand water inlet is set as the speed inlet, the radial venting wind inlet is also the speed inlet, and the temperature of the water and wind at the inlet is given by the manufacturer;
3) The stator core and the bar and the fluid inner contact surface are set to have no slip boundary conditions;
4) The outlet of the hollow strand water is set as the pressure outlet, and the pressure is 1 standard atmospheric pressure; the outlet of the ventilation trench wind is also set as the pressure outlet, and the pressure is 5000 Pa.

**Determination of Boundary Parameters**

**Determination of Water Speed.** The stator cooling water enters the converging tube of the Synchronous condenser excitation end from the water system, and flows to the stator coil through the insulated water conduit. The upper and lower coils of each stator bar are connected to the busbar through a separate insulated water conduit, that is, each half of the coil can be regarded as a waterway. According to the characteristics of the parallel waterway, the horizontal level of the manifold can be approximated. All are assigned to each waterway [18-19], and the flow rate of cooling water in each hollow strand can be calculated by formula (2).

\[
V_{wi} = \frac{V_w}{n_w}
\]  

(2)

Where: \(V_w\) is the total flow of cooling water in the manifold; \(n_w\) the number of hollow strands; \(V_{wi}\) the flow of cooling water in each hollow strand.

When a part of the water path in the winding is completely blocked, the flow rate of water in the unblocked hollow strand can be calculated by the formula (3).

\[
V_{wi} = \frac{V_w}{n_w - m_w}
\]  

(3)

Where: \(m_w\) is the number of hollow strands that are blocked.

According to the above two formulas (2) and (3), the flow rate of water in the waterway when the hollow strand is not blocked and blocked can be obtained. With some parameters of the given Synchronous condenser, the area of the waterway inlet can be obtained. According to the formula (4), the flow rate of the water at the water inlet can be obtained.

\[
v = \frac{V_{wi}}{S}
\]  

(4)

**Calculation of Heat Dissipation Coefficient.** The motor itself is a heat transfer body with a heat source. In the process of heat transfer, it is actually a comprehensive process of heat conduction and convection heat transfer. These two processes are directly related to the heat dissipation coefficient of the medium surface. In order to accurately calculate the temperature rise in the motor, It is necessary to determine the heat dissipation coefficient of some surfaces. In the study of motor temperature field, the heat dissipation coefficient of many parts is calculated by empirical formula based on experimental data [20]:

1) The heat dissipation coefficient of the inner circle of the stator core

\[
\alpha_v = \frac{1 + 0.125v_v}{0.045}
\]  

(5)

Where \(v_v\) is the circumferential speed of the rotor; \(v_v = \pi df\), \(d\) is the diameter of the rotor.

2) Heat dissipation coefficient of the outer circumference of the stator core

\[
\alpha_v = \frac{1 + 0.24v_v}{0.045}
\]  

(6)

Where \(v_v\) is the axial wind speed of the stator core yoke, generally taking an empirical value of 5 m/s.
Calculation of Synchronous Condenser Resistance Increase Factor

In this paper, the eddy current field of the windings under the two structures is calculated by the finite element method. The resistance increase coefficients obtained under the two structures are compared, and the calculated loss is taken as one of the heat sources of the temperature field. The two-dimensional finite element analysis model of the bar is shown in Figure 2.

![Figure 2. Two-dimensional finite element analysis model of stator bars.](image)

The resistance increase coefficient of the two structures is calculated as shown in Fig. 3. The numbering sequence of the stator strands is: for the lower strands, the right side of the row insulation is hollow strand 2, solid strand 1-4, hollow strand 4, solid strand 5-8, from top to bottom. Hollow strand 6, solid strand 9-12, the left side of the row insulation from the top to the bottom are hollow strand 1, solid strand 21-24, hollow strand 3, solid strand 17-20, hollow strand 5. The solid strands 13-16 have the same structure of the upper and lower windings of the stator bar of the Synchronous condenser, and the number of the upper bar windings is the same as that of the lower bar.

![Graph of resistance increase factor comparison](image)

a) Comparison of upper wire rod resistance increase coefficient
The average value of the resistance increase coefficient of the upper layer bar under the new structure is 1.314, the resistance increase coefficient of the lower layer bar is 1.047, and the average resistance increase coefficient of the entire winding is 1.18. The average resistance increase coefficient of the upper layer bar under the original structure is 1.356, the resistance increase coefficient of the lower layer bar is 1.0536, and the average resistance increase coefficient of the entire winding is 1.2048. The average value of the resistance increase coefficient of the new structure of the upper layer bar or the lower layer bar is smaller than that of the original structure. It can also be seen from Fig. 3 that the resistance increase coefficient of each strand under the original structure is larger than that of the new structure, so that after the hollow strand is changed to the structure with the upper section being larger than the lower section, the generation of eddy current loss can be reduced.

Through the above calculation and analysis, the resistance increase coefficient of each strand in the stator winding is obtained, and the equation (10) is obtained according to the following formulas (7)-(9), so that the Joule heat of the strand can be obtained. The base value of the density, and then the resistance increase factor obtained above, can calculate the thermal power density of each strand in the stator winding.

\[ p = -nee \vec{E} \cdot \vec{v} \]  \hspace{1cm} (7)

\[ \vec{J} = -nev \]  \hspace{1cm} (8)

\[ \vec{J} = \sigma \vec{E} \]  \hspace{1cm} (9)

\[ p = \frac{J^2}{\sigma} \]  \hspace{1cm} (10)

Where \( p \) is the heat power density representing Joule heat in units of: w/m\(^3\); \( \sigma \) represents the resistivity in \( \Omega \cdot m \); \( J \) stands for field strength and the unit is A/m\(^2\).

**Calculation and Analysis of the Stator Temperature Field of the Synchronous Condenser**

On the Ansys software platform, the finite element method was used to simulate the overall temperature field distribution of a selected 300Mvar large-scale Synchronous condenser stator, and the hollow strands were not blocked, single root blockage and two blockages were studied. The
distribution of stator temperature field under the new structure is compared with the original structure.

**Calculation and Analysis of Stator Temperature Field under Normal Operation**

In Figure 4, a) is the distribution of the temperature field of the stator under the original structure when the hollow strand is not blocked, and b) is the distribution of the stator temperature field under the new structure.

![Figure 4. Distribution of stator temperature field under normal operating conditions.](image)

Comparing the a and b diagrams in Figure 4, it can be seen that the distribution trend of the whole stator temperature field is basically the same. For the stator core, the temperature of the tooth is higher than the yoke, the temperature of the wedge is the lowest, and the upper layer is close. The temperature of the solid strand at the notch is the highest, and the temperature of the upper rod is generally higher than that of the lower layer. The temperature of the stator core and the yoke of the new structure is basically the same as the original structure, and the maximum temperature rise of the strand in the winding is decreased. The highest temperature of the solid strand under the structure is 78.87 °C. The highest temperature of the solid strand under the original structure rises to 80.29 °C, and the maximum temperature decreases by 1.42 °C. According to experience, the highest temperature point determines the probability of motor accident and the length of life. Therefore, after the hollow strand structure is improved, the influence of the temperature rise of the winding on the insulation can be reduced to a certain extent, the probability of accidents is reduced, and the service life of the motor is improved.

**Analysis and Calculation of Stator Temperature Field When a Strand is Blocked**

![Figure 5. Stator temperature field distribution diagram when the upper hollow strand 6 is blocked.](image)
It can be seen from Fig. 5 b) that when the upper layer hollow strand 6 is blocked, the temperature of the stator core tooth portion is still higher than the yoke portion, and the temperature of the lower layer rod rod is lowered, when the upper layer hollow strand 6 is blocked. Because the heat generated by it cannot be conducted through the waterway, the temperature of the surrounding solid strands also rises, indicating that the heat generated by the surrounding solid strands is partially transmitted through the waterway. Compared with Figure a), the original The highest temperature rise of the stator winding under the structure is 122.83 °C, and the highest temperature rise of the new structure is 119.99 °C, which is reduced by 2.84 °C, which indicates that the stator strand resistance increase coefficient can be reduced to some extent after the new structure is reduced. The temperature rise of the stator.

Summary

In this paper, the steady-state three-dimensional temperature field calculation model of the stator bar of the Synchronous condenser is established. Taking a 300Mvar Synchronous condenser stator bar as the research object, the finite volume method is used to calculate and analyze the stator hollow wire under two different structures. One blockage and two temperature fields at the same time. The research shows that the hollow wire has little effect on the stator core when the blockage occurs, and the highest temperature point of the stator winding will be transferred from the original 13 solid strand to the vicinity of the blocked hollow strand; the temperature rise of the stator is not only related to the number of blocks. It is also related to the blocking position; when the hollow strands adopt different structures of upper and lower sections, the temperature rise of the highest point is reduced when the strands are blocked under normal operating conditions.

References


