Steady-state temperature field of stator bar of double water internal cooling synchronous condenser

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Abstract. Synchronous condenser is a key part of ensuring stable operation of the extra-high voltage AC and DC transmission grid. In order to optimize and ensure the reliable operation of the synchronous condenser cooling system, it is necessary to master the temperature distribution in the synchronous condenser. In the double water internal cooling synchronous condenser, the fluid flow and heat transfer are quite complicated in the water-cooling system of the stator and the rotor. In this paper, the steady-state temperature field of stator coil of TTS-300-2 300MVar double water internal cooling synchronous condenser is calculated by using the finite volume method. The influence of empirical parameters on the calculation results is reduced. The calculation results show that the water temperature and copper temperature increase linearly along the direction of water flow.

1. Introduction
As China’s Direct current ultra-high voltage (DC UHV) transmission continues to deepen, the capacity required for reactive power compensation continues to increase, and the static var compensator can no longer meet its capacity requirements. In order to meet the requirements of reactive power compensation, China has invested in a batch of 300Mvar synchronous condenser. The problem of heat generation and cooling of synchronous condensers has become one of the major concerns of the design, manufacturing and operation departments. Therefore, monitoring the temperature and temperature rise during its operation is an important part of ensuring its normal operation. For large steam turbine generators, the main cooling methods are air cooling [1], hydrogen cooling [2], water cooling [3], and evaporative cooling [4]. Large capacity synchronous condenser is improved on the basis of turbine synchronous generators. As one of the key indicators of generator design, temperature rise is directly related to the life and operational reliability of synchronous condenser. An excellent cooling system plays a vital role in controlling the temperature rise of the unit. At present, the large capacity synchronous condenser has mainly two cooling modes including in total-air-cooling and double-water internal cooling systems. All of components are cooled by air in the total-air-cooling synchronous condenser. The stator coil and rotor winding are seperately cooled by water and the iron core is cooled by air in the dual-water internal cooling synchronous condenser. The large-scale synchronous condensers have only emerged in recent years, however, the current researches are mainly directed to the stator winding temperature field of large generator sets[5].In order to make the synchronous condenser run stably, it is very necessary to study the temperature field of the synchronous condenser stator winding.
The scholars have studied the calculation of the stator temperature field of large steam turbines. The calculation method of temperature field in large capacity generators includes mainly finite element method\[6\], finite volume method\[7\] and heat net method\[8\], all of these methods obtained the precise result in partly. The finite volume method has good conservativeness, could solve complex engineering problems well, and has good adaptability to the grid. It has good adaptability to the grid. In the fluid-solid coupling analysis, it can be perfectly integrated with the finite element method. For example, the QFSN-220-2 turbo generator is used as an example to compare the calculation results with the experimental data and the two are in good agreement, which verified the reliability of the finite element method [9]. As far as the temperature field calculation of large generators is concerned, it can be found that the research on the the stator coil is mainly carried out by the method of finite element, and only local analysis can be performed due to the limitation of model size and meshing [10]. The synchronous condenser is optimization designed on the basis of turbine generator, so the finite element method is also suitable for the temperature field analysis of the synchronous condenser.

The paper studied the steady state temperature field of stator bar in the dual-water internal cooling synchronous condenser. Since 97 percent of the heat loss generated by the stator coil is taken away by water [11,12], it is assumed that the losses generated by the stator coil are all carried away by water, and the conjugate transfer between copper and water over a water path length is performed by the finite volume method. The temperature field is directly analyzed and calculated to improve the accuracy of the calculation results.

2. Stator bar physical model and meshing

2.1. Physical model of stator bars
The TTS-300-2 synchronous condenser is taken as an example for analysis and calculation of temperature field. The cooling method of TTS-300-2 synchronous condenser is double-water internal cooling, that is, the stator and the rotor windings are cooled by passing cooling water into the hollow strands. This paper mainly studies the cooling system of its stator windings. The synchronous condenser stator bar consists of 30 strands, in which there are 24 solid strands and 6 hollow strands, cooling water is passed through the hollow strands to achieve cooling of the bars. A temperature sensor is installed at the outlet end of each bar to detect the temperature of the cooling water there. The stator bar has an effective length of 12,000 mm, a height of 58.75 mm, and a width of 33.9 mm. The wire rod structure is shown in figure 1.

![Figure 1. Cross-sectional view of the stator bar.](image_url)

2.2. Meshing of stator bars
The ICM CFD software is used for calculating the temperature field of synchronous condenser, the fluid control equations are discrete in the spatial domain [13]. Since the axial length of stator bar is much larger than its equivalent diameter and the stator bar belongs to the elongated pipe fluid model,
the hexahedral meshing strategy is most suitable when dividing the Solution domain. Because the length of stator bar is large, its grid partition sketch is divided into two visual angles: radial and axial. The partition results are shown in figure 2 and figure 3.

![Figure 2. Radial meshing of stator bars.](image)

![Figure 3. Axial meshing of the part of stator bars.](image)

3. Mathematical model of three-dimensional fluid field and temperature field of stator bars

In order to simplify the model, the fluid field and temperature field in the stator bar are analyzed and calculated under the following preconditions according to the structure of the stator bar, fluid flow and heat transfer characteristics [12].

- Since the Mach number of the cooling water in the stator bar is small, the fluid is considered as an incompressible fluid.
- The Reynolds number of the cooling water in the stator bar is much larger than 2300, so it is in the turbulent state, and the turbulence model is used for calculation and analysis of internal cooling water.
- Ignore the effects of buoyancy and gravity.
- The fluid flow and fluid solid heat transfer in steady state are studied only.

The cooling water in the stator bar is incompressible and in a stable state. The mass conservation equation and the momentum conservation equation are as following [9][13]:

\[ \nabla (\rho \vec{V}) = 0 \]  \hspace{1cm} (1)

\[ \nabla (\rho \vec{V} \vec{V}) = -\nabla p + \nabla \tau + F \]  \hspace{1cm} (2)

Where, \( \rho \) is the density; \( p \) is the static pressure on the fluid micro-body; \( \tau \) is the viscous stress generated by the viscous action; \( F \) is the volume force on the micro-body; \( \nabla \) is the divergence, ie \( \nabla = \text{div} \). 

\[ \nabla (\rho \vec{V}) = \text{div} (\rho \vec{V}) \]

For the fluid in the stator bar body and the cooling channel, the general energy conservation equation is [5]:

\[ \frac{\partial (\rho T)}{\partial \tau} + \nabla \cdot (\rho \vec{V} T) = \nabla^2 \left( \frac{\lambda}{C} T \right) + S_T \]  \hspace{1cm} (3)

Where, \( \vec{V} \) is the velocity vector; \( T \) is the temperature; \( \lambda \) is the thermal conductivity; \( C \) is the constant pressure specific heat capacity; \( \lambda / C \) is the diffusion coefficient; \( S_T \) is the ratio of the sum of the heat source per unit volume and the mechanical energy converted to thermal energy due to viscous action to \( C \), for the fluid in the cooling channel, \( S_T = 0 \).
The heat generated by the stator winding is mainly taken away by cooling water in the hollow wire with convection heat transfer, and satisfies the third type of boundary condition at the fluid-solid coupling boundary. Which is:

\[-\lambda\left(\frac{\partial T}{\partial n}\right)_\omega = h(T_\omega - T_f)\] (4)

Where, \(n\) is the outer normal of the heat exchange surface; \(h\) is the surface heat transfer coefficient; \(T_\omega\) and \(T_f\) are the temperature of the interface and the fluid around it, respectively. For the conjugate heat transfer problem, the solid domain and the fluid domain need to be defined first, and the subdomain loading heat source is set in the solid domain, the heat source is given in the form of heat generation rate\([14][15]\). The boundary conditions of the stator bar solution domain are as following:

- The outer side of the stator bar is an adiabatic boundary;
- The cooling water inlet is a mass flow inlet, and the cooling water outlet is a pressure outlet;
- The wall surface is smooth and has no slippage;
- The water channel of the hollow copper wire is the coupling heat exchange boundary.

4. Results and analysis
The basic parameters of TTS-300-2 synchronous condenser are: \(Q_N=300\) MVar, \(U_N=20kV\), \(I_N=8660A\). The coupling calculation of the stator winding fluid field and temperature field was completed on the FLUENT software platform using the above conditions.

The boundary condition setting values are shown in table 1.

| Waterway entrance flow (kg/s) | Inlet water temperature (°C) | Water outlet pressure (MPa) |
|-----------------------------|-----------------------------|---------------------------|
| 0.02652                     | 45                          | 1.01                      |

4.1. Determination of heat source of material
The main heat source of the stator is the copper loss caused by the stator winding and the iron core loss caused by the stator core. In the stator winding solution domain, the copper loss constitutes a part of the main heat source in the stator winding temperature field. The stator copper loss includes basic copper loss and additional eddy current loss, and the additional eddy current loss is calculated by the classic formula of skin effect\([16]\). Below is the copper consumption formula:

\[q = q_{Cu} + q_{ps} = I^2 r_0[1 + 0.004(T - 15)] + I^2 k_f r_f[1 + 0.004(T - 15)]\] (5)

Where \(I\) is the strand current and \(T\) is the strand temperature, \(r_0\) is DC resistance of strand wire at 15°C; \(k_f\) is the fielder coefficient that accounts for the increase in resistance caused by eddy current effect.

When the current phase of the upper and lower bars is the same, the average field coefficient \(k_{f1}\) of the upper bars is 7 times of the average field coefficient \(k_{f2}\) of the lower bars, that is, \(k_{f1} = 7k_{f2}\). When the upper and lower bars are in different phase, the average field coefficient of the upper bars is 5.5 times of that of the lower bars, that is, \(k_{f1} = 5.5k_{f2}\). The field coefficient of the lower stator bar is derived from document\([17]\). This paper considered the case when the current phase of upper and lower rods is the same. After calculation, the upper bar copper loss is 953886W/m3, and the lower bar copper loss is 820349W/m3.
4.2. Analysis of the fluid field and temperature field of stator bars

When the synchronous condenser is operated under the rated load, the velocity distribution of the fluid in the hollow tube is as shown in figure 4.

![Figure 4. Velocity profile.](image)

It can be seen from the velocity profile in figure 4 that the velocity distribution in the hollow tube is low at the inlet and outlet, and the velocity near the inlet of the hollow tube is slightly higher. From the axial section of the pipe, because of the viscosity of the fluid, the intermediate speed of the section is the highest, the peripheral speed is gradually reduced and the fluid is evenly distributed near the wall.

Figure 5 and figure 6 show the temperature distribution of the upper and lower stator bars respectively:

![Figure 5. Upper stator bar temperature distribution cloud map.](image) ![Figure 6. Lower stator bar temperature distribution cloud map.](image)

It can be seen from figure 5 and figure 6 that the outlet temperature of the upper stator bar is 329.8K, and the outlet temperature of the lower stator bar is 328.2K, so that the average temperature of the outlet is 329K, and the experimental data is 328.1K. The calculation value is compared with the experimental one by 0.9K, which can explain that the model meets the requirements of the condenser state simulation system. The cooling water flows at a relatively stable speed in the hollow strand, the temperature distribution inside the strand is relatively uniform, and the cooling effect is sufficient to meet the temperature requirements for stable operation of synchronous condenser.

The axial distribution of the cooling water temperature and the temperature of the copper wire portion in the hollow strand in the stator bar is shown in figure 7.
Figure 7. Axial temperature distribution of cooling water and copper wire.

It can be seen from Fig. 7 that the variation of the temperature of the cooling water and the copper wire in the stator bar in the axial direction is approximately linear. The temperature of the cooling water in the upper strand hollow strand is higher than the temperature of the cooling water in the lower strand hollow strand by an average of nearly 0.99K. The temperature of the upper copper wire corresponding to each portion of the cooling water in the axial direction is 0.72 K higher than the cooling water; the temperature of the lower copper wire corresponding to each portion of the cooling water in the axial direction is 0.73 k higher than the cooling water.

5. Conclusion
In this paper, FLUENT is used to calculate the water cooling conjugate heat transfer of stator bars. By directly solving the coupled heat transfer between water and copper, the influence of empirical parameters on the calculation is reduced. Through calculation and analysis, the following conclusions can be drawn:

- The flow velocity of water is larger in the middle of the strand than on both sides of the strand, and the water temperature and copper wire temperature in the hollow copper strand increase gradually along the flow direction.
- The water temperature of each section in the hollow strand is approximately linear with the water inlet temperature corresponding to the section.
- Due to the skin effect, the additional loss of the upper layer stator bar is higher than that of the lower layer stator bar, so the average temperature of the upper bar is higher than the lower bar, but the difference is small, which indicates that the cooling effect of the cooling water in the hollow copper wire is better. It can meet the temperature control requirements of the normal operation of the unit.

The new-type synchronous condenser with large capacity is put into operation for a short time, and research on its condition monitoring and fault diagnosis has not been carried out in depth. This paper could provide the early basis of the health fault research in synchronous condenser. In the next work, the heat fault characteristic of synchronous condenser will be studied using finite element method.

6. References
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