Optimization Study of New Type High-Capacity Synchronous Condenser based on Coupling of Electromagnetic and Temperature Field

Xi Zhang [1], Weiqing Wang [1,2], Shan He*[1,2], Jing Cheng [1,2], Zhi Yuan[1,2]

[1] School of Electrical Engineering, Xinjiang University, Urumqi, Xinjiang Uygur Autonomous Region 830049, China
[2] Engineering Research Center of Ministry of Education for Renewable Energy Power Generation and Grid Connection Technology, Urumqi, Xinjiang Uygur Autonomous Region 830049, China

Abstract. In order to optimize electromagnetic structure of new type high-capacity synchronous condenser, increase reactive capacity, and improve the speed of dynamic response, the theoretical derivation of the effects on the main performance parameters of the synchronous condenser is carried out, also the influence of the structure size of the synchronous condenser on the transient characteristics is clarified. Changing the air gap length and improving the size of stator structure are proposed to optimize the performance of synchronous condenser. The electromagnetic calculation of the optimized synchronous condenser is carried out by using finite element analysis method, the mathematical relationship between length of air gap and reactive capacity is clarified and the relationship between size of stator slot and fast response characteristics is explicited too. The temperature field of the synchronous condenser under multiple working conditions is simulated. The simulation results show that the temperature distribution of the optimized synchronous condenser is reasonable, and it possess good effect of cooling. Also the overload capacity of the synchronous condenser is verified with the temperature field.

1 Introduction

The 300 Mvar new type high-capacity synchronous condenser developed by China, is the largest condenser in the world. Related research shows that the new type condenser could stabilize the voltage fluctuation, compensate the reactive power loss of converter station caused by short circuit and restrain the short circuit current[1-3]. In order to meet the demand of power grid, the research on the performance optimization of new type condenser is carried out gradually. It is pointed out in the literature[4] that the electromagnetic structure of the condenser is similar to the large synchronous generator. The optimization and design of its electromagnetic structure could refer to the synchronous motor, however, further investigation of the operation region of new type condenser shows that it could operate stably under negative excitation, which could better meet the demand of voltage regulation flexibility of power grid, but it brings a further challenge to optimization of the condenser[5]. In order to solve the problem of eddy current loss and local overheat caused by magnetic leakage at the leading end of new condenser, a new type of copper shield structure is proposed, which lays a foundation for stator end optimization[6-8]. The results show that the improvement of the cooling structure is an effective measure to reduce the vibration of new type condenser[9]. In order to optimize the capacity of condenser, a comparative study on the slot distribution of the excitation windings has been carried out in the literature[10]. In this paper, the temperature of new type of condenser is calculated by means of formula deduction and field test, which provides experience for the optimization of new type condenser[11]. At present, there is not much experience in the optimization of new type condenser, and the optimization method of its structure still needs to be further explored.

Based on the design theory of synchronous condenser, the influence of the structure parameters of synchronous condenser to the electromagnetic characteristics is deduced, the optimization method is verified from the aspects of capacity, response characteristics and temperature field distribution, which provides theoretical support for the structure optimization of a new type high-capacity condenser.

2 The optimization design of synchronous condenser

The optimization of new type synchronous condenser mainly considers the improvement of response rapidity and the increase of reactive power capacity, and the main factor affecting the dynamic response characteristic is that the smaller the direct axis supertransient reactance x''_d[12], the better its rapidity, it can not only output more reactive

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*Corresponding author's e-mail: 2513041660@qq.com

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power to the power network at the moment of fault, but also restrain commutation failure effectively. In addition, the length of the air gap is an important factor that affects the reactive power capacity, and from the multi-angle analysis of the air gap, the structure of the stator and the rotor, the concrete influence of the structural parameters on the x''_d and the capacity is determined, the key factors are analyzed qualitatively and the optimization scheme of the structure of the condenser is put forward.

2.1 The influence of structure parameter to electromagnetic character

2.1.1 The influence aboutto x''_d about stator structure

According to the law of flux conservation, the aperiodic eddy current in the rotor is obvious in the early stage of transient, and the damping effect is strong, and then decreases until the straight axis synchronous reactance equal to the synchronous reactance[13]. Combined with above theoretical process, the equivalent straight-axis operation circuit model of the condenser is obtained as shown in Figure 1.

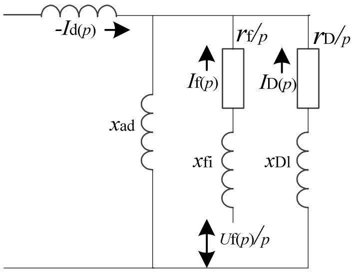

Figure.1 Direct axis operation circuit model of synchronous condenser

Direct axis synchronous reactance x_d is:

$$x_d(p) = x_l + \cfrac{1}{\cfrac{1}{x_{ad}} + \cfrac{1}{x_{fl} + \cfrac{r_f}{p}} + \cfrac{1}{x_{Dl} + \cfrac{r_D}{p}}} \qquad (1)$$

Respectively, x_l、x_{ad}、x_{fl}、x_{Dl}、r_f and r_D represent stator winding leakage reactance, direct axis armature reaction reactance, excitation leakage reactance, armature leakage reactance, excitation reluctance and armature reluctance. According to above process, the direct axis supertransient reactance x''_d is the direct axis reactance in the initial phase under the damping condition, when the resistance is equivalent to the short circuit, so the direct axis supertransient reactance x''_d is:

$$x''_d = x_d(p)\Big|_{\text{damped},\, p=\infty} = x_l + \cfrac{1}{\cfrac{1}{x_{ad}} + \cfrac{1}{x_{fl}} + \cfrac{1}{x_{Dl}}} \qquad (2)$$

Because under unsaturated state, $x_{ad} >> x_{fl}$， $x_{fl} >> x_{Dl}$

$$x''_d \approx x_l + x_{Dl} \approx x_l \qquad (3)$$

According to the generator electromagnetic calculation equation handbook[14], synchronous condenser stator winding leakage reactance x_l is:

$$x_l = K_x \frac{2pl_x}{Z_1} \times \frac{3\beta + 1}{4} \times \frac{h_{11} + 3h_{31}}{3b_{n1}} + K_x \frac{1}{3p} K_{\omega 1}^2 D_{i1} \qquad (4)$$

Among them, k_x is the stator winding leakage impedance coefficient, p is the polar logarithm, l_x is the stator core length, Z_1 is the stator slot number, β is short distance ratio of winding, h_{31} is length of stator notch to slot wedge end , b_{n1} is slot width of stator, $K_{\omega 1}$ is fundamental winding factor, D_{i1} is stator core inner diameter

In summary, the vertical axis supertransient reactance x''_d mainly determined by the leakage reactance of stator windings, which is affected by the structure of the stator slots and the length of the air gap, and its size mainly affected by the structure of the stator slots, inversely proportional to the width of the stator slots and directly proportional to the depth of the stator slots, it has little to do with the rotor structure.

2.1.2 The influence to reactive power about air gap length

In the ideal state, the sine current and the sine air-gap magnetic field are produced by condenser, but in fact, the air-gap magnetic field is a sine wave with harmonic component[15]. The magnitude of excitation current directly determines the reactive power of the condenser. Under the same excitation condition, the magnetization current can be expressed as:

$$I_m = \frac{2pF_0}{0.9mNK_{dp}} \qquad (5)$$

In the formula, m is the phase number, N is the number of turns per phase, and K_{dp} is the winding coefficient. From Formula 5, it can be seen that each pole magnetic potential F_0 is mainly used to overcome the air gap magnetic pressure drop, that is, the magnetization current of the condenser is mainly affected by the air gap magnetic density. In order to get better reactive power output performance, the length of air gap should be as small as possible to reduce no-load current and increase the synthetic flux. At the same time, because the air gap harmonic component is the source of the additional vibration and noise, it will affect the operating efficiency and lead to the decrease of the mechanical reliability, the increase of total loss and temperature, so the air gap length unfit for too small[16].

2.2 The optimization scheme of condenser structure

Take an existing 300 Mvar condenser as an example, rated voltage 20 kV, rated current 8660 A, temperature rise Class B, double water internal cooling, its basic structure parameter is as Table 1.

Based on above research, the length of air gap is kept constant, the width of stator slot is increased, the depth of stator slot is decreased, the area of stator slot is kept constant during the optimization process, the optimization scheme of stator slot is 142.6 mm; stator slot width 37.2 mm.

By finite element calculation, before optimization condenser x''_d is 0.1082, and after the optimized condenser x''_d is 0.1015.

Table.1 The basic structure schemes of synchronous condenser

Name	Value
Stator out-dimater /mm	2500
Stator inner-dimater /mm	1240
Air gap/mm	70
Stator slot number	48
Stator slot parameter $b_s\times h_s$/mm	35.2×150.6
Rotor slot number/slot number of division	32/45
Rotor slot parameter $b_r\times h_r$/mm	39.9×156.7

3 Optimization method of synchronous condenser structure simulation

The finite element software is used to model and analyze the new type condenser, and the simulation calculation is carried out from the saturation degree of magnetic flux density, fast response characteristic and reactive power capacity to verify the rationality of optimization.

3.1 The analysis and contrast of flux density

The magnetic flux density of stator core will verify when the structure of stator sheet is changed. As shown in Figure 2, the characteristic points A, B, C and D represent the stator tooth root, the stator tooth end, the rotor tooth end and the rotor tooth root, respectively, the distribution of flux density before and after optimization is shown in Table 2.

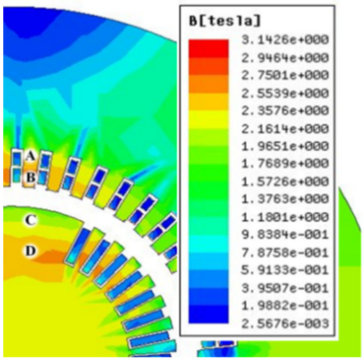

Figure.2 The flux density distribution of synchronous condenser

Table.2 The optimized flux density distribution of synchronous condenser

Position	Before optimized /T	After optimized /T
A	2.21	2.29
B	2.45	2.54
C	1.91	1.89
D	2.33	2.31

It can be seen from Table 2, after optimization, the flux density distribution of condenser is reasonable, the deviation maximum of flux density is only 3.7%, the flux density of the rotor root and the end of the stator tooth is larger, the flux density of the stator root is smaller, and the saturation degree of the iron core is lower, there is a certain margin for deep over-excitation operation.

3.2 The character of repaid response

The simulation calculation of the optimized condenser is carried out, and the model is shown in Figure 3. The finite element simulation of the operation process is as follows:

3.2.1 t<5s

The condenser keeps no-load operation, and the excitation current on the rotor side is no-load excitation current.

3.2.2 t>5s

The condenser starts to enter the rated operation, the rotor side excitation current increases to the rated excitation current.

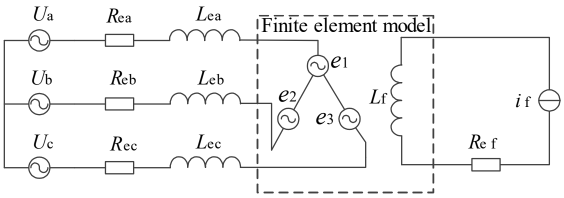

Figure.3 The calculation model of synchronous condenser

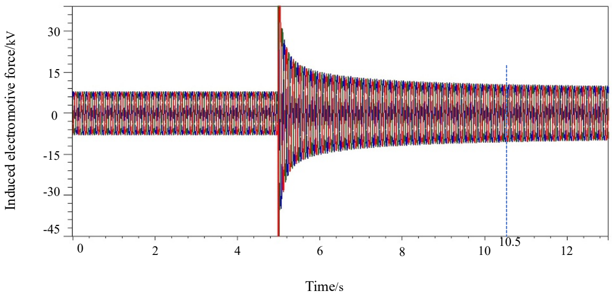

Figure.4 The three-phase induction electromotive force of synchronous condenser

It can be seen from Figure 4, since the 5s moment, the condenser enters rated operation, the three-phase induction voltage increases rapidly, and enters the stable state gradually. It is due to the large excitation inrush current caused by the sudden rise of excitation current, any load changes will produce inrush current, which requires the condenser as soon as possible through the transient process into a stable operating state. The simulation results show that the condenser could respond rapidly to the sudden increase of load, and the response time of the excitation system voltage rise of the phase modulator is less than 0.02 s, it takes approximately 5.5 s from initial response to steady-state operation.

3.3 Capacity check

When stator structure changed, the magnetic flux of the iron core is verified. The simulation results show that the electromotive force is 13.41 kV and the induction current is 12.45 kA, the optimized condenser rating capacity is 288.6 Mvar. The results show that increase the width of stator slot and decrease the depth of stator slot could reduce the x''_d and enhance the fast response, but reduce the reactive power capacity to a certain extent.

Therefore, in order to compensate the loss of reactive power capacity, the air gap synthesis flux is increased by changing the length of air gap in order to increase the reactive power capacity. The length of air gap is 65mm-75mm, step length is 0.5mm, and the total number of 20 points is simulated to investigate the relationship between the air gap length and reactive power. The results are shown in Figure 5.

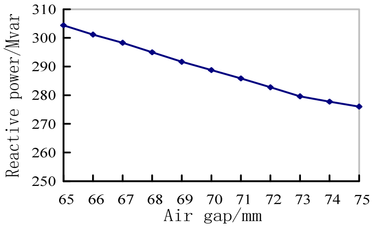

Figure.5 The relationship between size of air-gap and reactive power

It can be seen from Figure. 5, the output reactive power of condenser decreases with the increase of the air gap length. It can be proved that reducing the air gap could properly effectively increase the output reactive power and increase the condenser capacity.

4 Simulation and calculation of condenser temperature rise

The loss in operation is the main factor that affects the temperature distribution of the condenser. Accurate calculation and analysis of each part of the loss is helpful to control the temperature rise, increase the electrical reliability and verify the rationality of the optimal design. In this paper, the one-way coupling method is used for the finite element analysis of the temperature field because of the time-consuming and the high performance of the computer.

4.1 The loss calculation of synchronous condenser

Based on Bertotti's iron loss calculation model, the core loss caused by rotating magnetic field is calculated by hysteresis loss, eddy current loss and additional loss. The iron consumption of the condenser is simulated, and DW315-50 silicon steel sheet is used in the iron core of the condenser. After setting the reduced loss coefficient in the physical model, the finite element calculation results are obtained. The loss of the condenser core under rated working condition is shown in Figure 6.

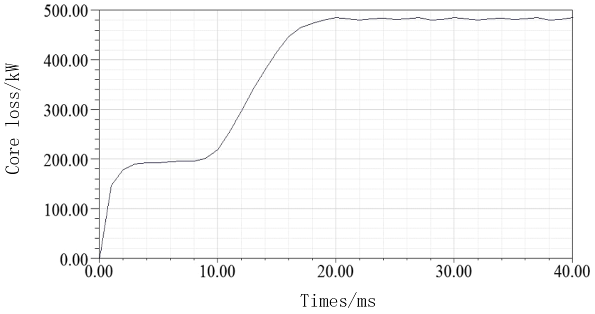

Figure.6 The core loss of synchronous condenser

With the increase of time, the core loss of the condenser increases firstly and then reaches the stable value gradually. The simulation results show that the core loss is 481.8 kW after 20 ms and go into the stable region.

The winding resistance calculated by finite element method is $1.5\times10^{-3}\Omega$ for stator winding and $1.09\times10^{-1}\Omega$ for rotor winding. The copper consumption of stator winding and rotor winding is 337.5 kW and 460.2 kW respectively.

4.2 The calculation result of temperature field

4.2.1 Rated temperature field distribution

The steady-state temperature field of the model was simulated under rated conditions, and the axial temperature distribution was obtained as shown in Figure 7.

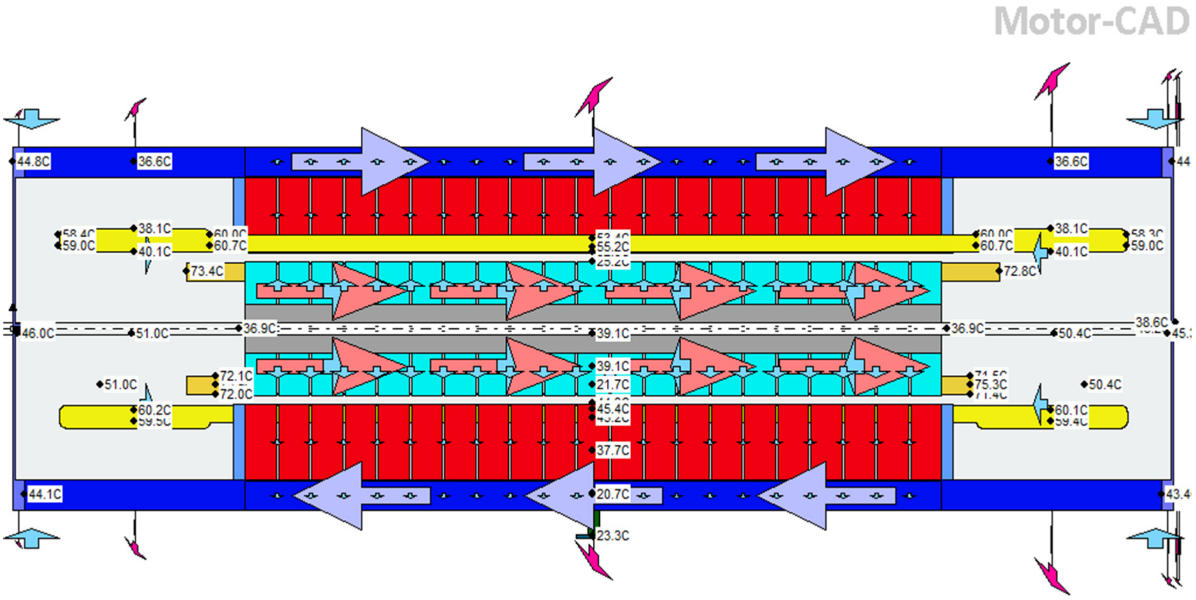

Figure.7 The 3D axial temperature distribution of synchronous condenser

It can be seen from Figure 7, the highest temperature of the stator terminal and the rotor terminal is 60.2 °C and 72.1 °C respectively, due to the air cooling at the end of the condenser in rated operation. Water and air cooling coexist in the fuselage, with a minimum temperature of 21.7 °C. Taking the stator part as an example, the highest temperature is located at the end of the stator winding, because the loss of stator winding is relatively large, the thermal conductivity of insulation material is poor, and the winding is in the interior of condenser, the heat dissipation condition is poor, the heat can't escape from the casing in any significant way. Similarly, the highest rotor temperature is located at the end of the rotor winding.

4.2.2 The simulation and verification about overload ability

According to GB / T1029-2005"Experimental method of three-phase Synchronous Motor", the overload capacity of the new type condenser is verified, and the temperature rise of the condenser under the working conditions of 3.5 times rated current of stator and 2.5 times rated current of rotor are simulated and analyzed respectively. The simulation results are as follows: Figure 8, when the stator coil is 3.5I_N in strong excitation, the temperature of the stator coil is 127.5 °C, and the temperature of the outlet is 98.2 °C. Under 2.5 I_N in forced excitation, the outlet temperature of the rotor coil is 128.6 °C, and the outlet temperature is 98.8 °C. Under both overload operating conditions, the outlet joint temperature is lower than 100 °C and the temperature rise of the motor does not exceed 130 °C, the results show that the optimized condenser possess a good overload capacity [17].

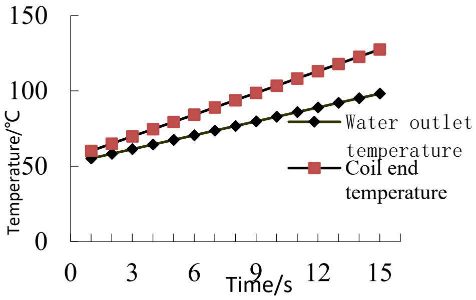

Figure.8 The over-load temperature diagram of synchronous condenser

5 Conclusion

The transient performance and reactive power reserve are the key to the optimization of new type high-capacity condenser. Based on the equivalent model of the phase modulator, the main parameters affecting the key transient performance of the phase modulator are analyzed and the optimization scheme is proposed, the conclusions are as follows:

(1) The key factor of the direct axis supertransient reactance of the condenser is the structure size of the stator slot, which is derived from the electromagnetic design manual of steam turbine, the results show that the vertical axis supertransient reactance is proportional to the depth of the stator slot and inversely proportional to the width of the stator slot. The optimization scheme of reducing the depth of stator slot and increasing the width of stator slot is put forward.

(2) Through finite element modeling and analysis, the rationality of structure optimization is verified from magnetic density, reactive power capacity and fast response characteristics. The loss of reactive power capacity can be compensated by properly reducing the length of air gap.

(3) The three-dimensional model of the condenser is established and the distribution of temperature field is

analyzed. The temperature field distribution of the condenser is reasonable and the cooling effect is good. The regulation of excitation current verifies its short-term overload capability.

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