Simulation study on ±320kV DC power cable steady-state temperature field distribution and its influencing factors

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Abstract. Temperature distribution is an important parameter in the operation of DC cables, while there are few studies at present. In this paper, the steady-state temperature field distribution of DC cable was calculated by simulation, and the factors including conductor current and outer surface temperature were discussed and analyzed. The results showed that there is a temperature gradient in the radial direction of the cable; Both the conductor current and the outer surface temperature have a significant effect on the overall temperature of the cable; The increase in the conductor current and the outer surface temperature will significantly increase the conductor temperature. However, the insulation temperature difference changes little.

1. Introduction

High Voltage Direct Current (HVDC) transmission plays an increasingly important role in the power system with the advantages of long transmission distance, large transmission capacity and flexible operation style [1]. In recent years, with the Nan’ao ±160kV multi-terminal flexible DC transmission project, Zhoushan ±200kV five-terminal flexible DC transmission project and Xiamen ±320kV flexible DC transmission project been put into operation, HVDC crosslinked polyethylene (XLPE) cable has been rapidly developed and application [2-5]. A large number of studies have shown that the AC cable temperature distribution is an important parameter reflecting its operating state and an important basis for determining the current carrying capacity [6-8]. Although the DC cable is similar in structure to the AC cable, some scholars have proposed that the DC cable current carrying capacity calculation should consider the temperature distribution of the insulation in addition to the maximum allowable operating temperature of the conductor, even if the specific constraints have not been determined [9].
At present, Yan Youxiang, Yang Yuexi, et al have studied the cable selection and laying, control mode and operation performance, switching method and system control strategy of Xiamen ±320kV flexible DC transmission project [10]. However, the steady-state temperature field distribution and current carrying capacity of the cable have not been specifically studied. Therefore, it is necessary to study ±320kV power cable steady-state temperature field distribution and its influencing factors. This paper took Xiamen ±320kV DC cable as an example, used COMSOL Multiphysics finite element simulation software to establish a two-dimensional axisymmetric model and calculated its steady-state temperature field distribution. On this basis, the effects of different conductor currents and different outer surface temperatures on the temperature of the cable conductor and the temperature difference of the insulation were studied.

2. Simulation model

2.1. Finite element method and governing equation
The finite element method is an approximate mathematical simulation for real physical systems and is a commonly used numerical calculation tool for solving practical engineering problems. The basic idea is to divide a continuously solved region into a finite number of interconnected elements, and then combine the relations of each unit into a system of equations, and finally obtain an approximate solution of the entire solution domain.

COMSOL Multiphysics is a simulation calculation software based on finite element method. The software integrates various physical modules such as AC/DC and heat transfer in advance, and has strong computing performance. This article uses the solid heat transfer module in COMSOL Multiphysics to study the steady-state temperature field distribution of the DC cable.

The governing equation for solid heat transfer is:

$$\rho C_v \nabla T = \nabla (\lambda \nabla T) + Q$$  \hspace{1cm} (1)

where: $\rho$ is the density of the solid material, kg/m$^3$; $C$ is the constant pressure heat capacity of the solid material, J/(kg·K); $v$ is the velocity vector, m/s; $\nabla$ is the vector differential operator; $T$ is the temperature of the solid material, K; $\lambda$ is the thermal conductivity of the solid material, W/(m·K); $Q$ is the heat source in the solid material, W/m$^3$.

2.2. Geometrical model and material parameters
The structure of ±320kV DC cable is mainly composed of conductor, conductor screen, XLPE insulation, insulation screen, water-blocking tape, aluminum sheath and outer sheath, as shown in Figure 2. The structural parameters and material parameters of the cable were given in table 1.

![Figure 1. The structure of ±320kV DC cable.](image)
Table 1. The structural parameters and material parameters of ±320kV DC cable.

| NO. | Structures             | Outside radius / mm | Thermal Conductivity / [W/(m·k)] | Constant pressure heat capacity / [J/kg·K] | Density / [kg/m³] |
|-----|------------------------|---------------------|---------------------------------|-------------------------------------------|------------------|
| 1   | Copper conductor       | 25                  | 400                             | 385                                       | 8700             |
| 2   | Conductor screen       | 27                  | 0.2857                          | 2603                                      | 922              |
| 3   | XLPE insulation        | 53                  | 0.2857                          | 2603                                      | 922              |
| 4   | Insulation screen      | 54                  | 0.2857                          | 2603                                      | 922              |
| 5   | Water-blocking tape    | 56                  | 0.4                             | 2182                                      | 1100             |
| 6   | Aluminum sheath        | 58.8                | 238                             | 900                                       | 2700             |
| 7   | Outer sheath           | 63.8                | 0.2857                          | 2532                                      | 948              |

When studying the temperature distribution of a cable, the cable structure is usually simplified to a two-dimensional radial plane or a two-dimensional axisymmetric model, as shown in Figure 1. Studies have shown that the two-dimensional axisymmetric model can reflect the change of the DC resistance of the conductor with temperature, which is more in line with the actual situation. Therefore, a two-dimensional axisymmetric model of ±320kV DC cable was established.

Figure 2. Two-dimensional axisymmetric model of ±320kV DC cable.

In addition, the calculations are properly assumed from an engineering perspective:

- The thermal conductivity of each layer of the cable is constant;
- The thermal conductivity of the cable is the same in all directions;
- The outer surface of the cable is an isothermal surface.

2.3. Boundary conditions and meshing

The temperature of the outer surface of the cable is set to 30°C, the heat flux density at the upper and lower ends of the cable model is set to 0, and the Joule heat generated by the current in the conductor is equivalent to a heat source[11]. They are used as the first, second and third types of boundary conditions in heat transfer calculation. The triangle mesh adaptive segmentation of the model effectively avoids the shortage of manual processing, greatly improves the calculation efficiency, and ensures that the minimum mesh is smaller than the thinnest layer.

3. Simulation results

3.1. Steady-state temperature field distribution

At present, the current carrying capacity of the DC cable is mainly determined according to the constraint that the maximum operating temperature of the conductor does not exceed the maximum allowable temperature of the insulation. In this paper, the maximum operating temperature of the conductor is 70°C as a constraint to determine the current carrying capacity. In the case where the
outer surface temperature of the cable is 30°C, the conductor temperature reaches 70°C when the current flowing through the conductor is equal to 1479A. Figure 3 shows the steady-state temperature field distribution of the cable in this case. As can be seen from the figure, there is a temperature gradient in the radial direction of the cable—a downward trend from the inside out. The conductor temperature is the highest and the outer surface temperature is the lowest; The temperature is mainly borne by the insulation layer, and the temperature difference of the layer reaches 30.74°C.

**Figure 3.** Steady-state temperature field distribution of ±320kV DC cable.

### 3.2. Conductor current

Different Joule heats produced by different currents will cause differences in the radial temperature distribution of the cable, especially the insulation temperature distribution. Set the temperature of the outer surface of the cable to 30°C. The temperature field distribution under low load (conductor current \( I_C = 600A/800A/1000A \)), normal load (\( I_C = 1200A/1400A/1479A \)) and excessive load (\( I_C = 1600A/1800A/2000A \)) was studied. As can be seen from figure 4:

- Under the same current, the temperature of the copper conductor and the aluminum sheath remain unchanged in the radial direction, while the temperature of the other structures shows a downward trend and the insulation temperature drops the fastest.
- As the conductor current \( I_C \) increases, the overall temperature \( T \) of the cable increases. The larger \( I_C \) is, the more significant the temperature increase trend is. When the current \( I_C = 600A \), the curve changes gently; when the current \( I_C = 2000A \), the curve becomes very steep. The thermal conductivity of the cable is the same in all directions;

**Figure 4.** The relationship between temperature and radial distance.
The conductor temperature and insulation temperature difference are the influencing factors of the two constraints on the current carrying capacity. Further analysis is carried out to obtain the results as shown in figure 5. As the conductor current $I_c$ increases, the conductor temperature $T_c$ and insulation temperature difference $\Delta T$ both increase exponentially. When $I_c=600$ A, $T_c=35.85°C$, $\Delta T=4.49°C$; When $I_c=2000$ A, $T_c=113.68°C$, $\Delta T=64.27°C$.

Figure 5. The relationship between conductor temperature/insulation temperature difference and conductor current.

3.3. Outer surface temperature
The cable laying environment will cause the temperature of the outer surface of the cable to be different. Different outer surface temperatures can affect the heat dissipation of the cable, which in turn affects the cable temperature distribution. Set the cable conductor current $I_c=1479$ A, study the temperature distribution of the outer surface temperature of the cable $T_S=10°C/20°C/30°C/40°C/50°C$, and get the results as shown in figure 6. When the temperature of the outer surface of the cable increases, the overall temperature $T$ curve of the cable is basically upwardly inclined.

Figure 6. The relationship between temperature and radial distance.

It can be seen from figure 7 that as the outer surface temperature increases, both the conductor temperature and the insulation temperature difference increase in a positive proportion. When the temperature of the outer surface increases, the temperature of the conductor rises more obviously while the temperature difference of the insulation changes less. When $T_S=10°C$, $T_c=47.00°C$,
$\Delta T = 28.42^\circ C$; When $T_S = 50^\circ C$, $T_C = 93.05^\circ C$, $\Delta T = 33.07^\circ C$. It can be considered that the influence of the outer surface temperature on the overall temperature distribution of the cable is small compared to the conductor current.

![Graph showing the relationship between conductor temperature, insulation temperature difference, and outer surface temperature.](image)

**Figure 7.** The relationship between conductor temperature/insulation temperature difference and outer surface temperature.

### 4. Conclusions

In this paper, ±320kV DC cable steady-state temperature field distribution and its influencing factors were simulated and the following conclusions were drawn:

- There is a temperature gradient in the radial direction, that is the temperature gradually decreases from the conductor to the outer sheath.
- The conductor current has a significant influence on the conductor temperature. As the conductor current increases, the insulation temperature difference increases.
- The external surface temperature also has a significant effect on the conductor temperature, but the effect on the insulation temperature difference is negligible.
- The influence of the conductor current on the overall temperature distribution of the cable is greater than the influence of the external surface temperature.

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Acknowledgements
This work was supported by the Science and Technology Research Foundation of State Grid Corporation of China (2019202).