Temperature field simulation of medium and low voltage composite cable

Yiyong Xiong\textsuperscript{a}, Jinghong Zhao\textsuperscript{b}, Guoqiang Guo\textsuperscript{*}

School of Electrical Engineering, Naval University of Engineering, Wuhan, China

*Corresponding author e-mail: 449829699@qq.com, xiongyiyong1989@163.com, zhaojinghong@163.com

Abstract. This paper introduces the basic principle of calculating the temperature field of composite cable based on finite element method, and simulates the rated, short-circuit and overload conditions of the cable, and explains the situation of the temperature rise of the cable. The cable resistance is analyzed and calculated. In this paper, the temperature field of the composite cable is systematically studied by means of simulation, and the design conformity of the cable is verified.

1. Introduction
The cable is the link between the dock and the ship, the key link to ensure the power supply and information communication between the ship and the ship, and the main support to realize the stable power supply of the shore power system to the ship and the wired communication between the command post and the ship. With the development trend of ship integration technology, it is urgent to carry out the work applicable to the current shore-ship cable integration technology. In this paper, a type of cable is selected and its performance parameters are calculated and studied.

2. Basic principle of calculating temperature field of composite cable based on finite element method
The basic principle of cable temperature field simulation based on finite element method is presented in reference [1]. The basic idea of finite element numerical calculation is to simplify complex problems. The distinct advantage of the finite element method over other numerical methods is that the Mesh can be arbitrarily divided. In the process of Mesh Generation, considering that the size and size of triangular element can be changed flexibly, the Mesh can be denser in the region with large temperature gradient and complex shape, and the Mesh can be denser in the region with small temperature gradient, the region with simple shape divides the grid into a few sparse parts, which not only improves the computing speed, but also improves the computing precision. The result is an approximate value, but the approximate result is very close to the real one, which can meet the engineering requirement. Finite element method is an effective method for engineering problem analysis. The heat transfer process of the cable is simplified to two dimensions, and the axial heat transfer of the cable is ignored.

For the element in Figure 1, it is considered that there is a linear interpolation relationship between the temperature at any point in the element and the coordinates:

\[ T^e(x, y) = \alpha_1 + \alpha_2 x + \alpha_3 y \] (1)
In the middle of the ceremony, \( \alpha_1, \alpha_2, \alpha_3 \) is a constant.

![Figure 1. Triangular Element](image)

So, I'm going to plug in the coordinates of the three points

\[
\begin{align*}
T_i &= \alpha_1 + \alpha_2 x_i + \alpha_3 y_i \\
T_j &= \alpha_1 + \alpha_2 x_j + \alpha_3 y_j \\
T_m &= \alpha_1 + \alpha_2 x_m + \alpha_3 y_m
\end{align*}
\]

Solve for:

\[
\begin{align*}
\alpha_1 &= \frac{1}{2\Delta} (a_i T_i + a_j T_j + a_m T_m) \\
\alpha_2 &= \frac{1}{2\Delta} (b_i T_i + b_j T_j + b_m T_m) \\
\alpha_3 &= \frac{1}{2\Delta} (c_i T_i + c_j T_j + c_m T_m)
\end{align*}
\]

In the middle of the ceremony:

\[
\begin{align*}
a_i &= x_j y_m - x_m y_j \\
b_i &= y_j - y_m \\
c_i &= x_m - x_j \\
a_j &= x_m y_i - x_i y_m \\
b_j &= y_m - y_i \\
c_j &= x_i - x_m \\
a_m &= x_i y_j - x_j y_i \\
b_m &= y_i - y_j \\
c_m &= x_j - x_i
\end{align*}
\]

So, you can get the temperature at any point in the cell.

\[
T^e(x, y) = \frac{1}{2\Delta} \left[ (a_i + b_i x + c_i y)T_i + (a_j + b_j x + c_j y)T_j + (a_m + b_m x + c_m y)T_m \right]
\]

In the middle of the ceremony, \( \Delta \) is the area of the triangular element. Shape function:

\[
\begin{align*}
N_i &= \frac{1}{2\Delta} (a_i + a_j x + a_m y) \\
N_j &= \frac{1}{2\Delta} (a_i + a_j x + a_m y) \\
N_m &= \frac{1}{2\Delta} (a_i + a_j x + a_m y)
\end{align*}
\]
Then Formula 7 is converted to:

$$T^e(x, y) = \sum_{i=1}^{N_e} N_i T_i = N_e T_e$$  \tag{7}$$

The temperature at any point on the space domain can be expressed by node temperature:

$$T^e(x, y) = \sum_{i=1}^{N_e} N_i T_i$$  \tag{8}$$

3. Calculation of main line core resistance of cable

IEC 60287-1-1 (2006) gives the following formula for calculating the ac resistance of stranded conductors commonly used in power cables when the skin effect and proximity effect are taken into account [3]:

$$y_s = \frac{x_s^4}{192 + 0.8x_s^4} \quad 0 < x_s \leq 2.8$$  \tag{9}$$

$$y_p = \frac{x_p^4}{192 + 0.8x_p^4} \left[ 0.312 \left( \frac{d_c}{s} \right)^2 + \frac{1.18}{\left( \frac{x_p^2}{192 + 0.8x_p^4} + 0.27 \right)} \right] \quad x_p \leq 2.8$$  \tag{10}$$

$y_s$ is skin effect coefficient; $y_p$ is the proximity effect coefficient; $f$ is the current frequency, Hz; $d_c$ is the outer diameter of the conductor, is the distance between the central axis of the conductor.

$$x_s^2 = \frac{8\pi f}{R'} 10^{-7} k_s$$  \tag{11}$$

$$x_p^2 = \frac{8\pi f}{R'} 10^{-7} k_p$$  \tag{12}$$

The unit length ac resistance at the operating temperature of the conductor is:

$$R' = R_0 \left[ 1 + \alpha_{20}(\varphi_c - 20) \right]$$  \tag{13}$$

$$R_0 = \frac{\rho}{\pi r^2}$$  \tag{14}$$

$R'$, the DC resistance of working for the unit length of the conductor temperature: per unit length of the cable core DC resistance at 20 °C, $\Omega$/m, calculated, $R_0 = 1.853 \times 10^{-4} \Omega/m$; $\varphi_c$ is the core temperature, °C; $R'$ for the unit length of wire core in the DC resistance (cables running the rated conditions, temperature $\varphi_0 = 67$ °C), $\Omega$/m; $y_s$ is skin effect coefficient; $y_p$ Is the proximity effect coefficient; $\alpha_{20}$ is the resistance temperature coefficient of core conductor material at 20°C, copper conductor, 1 / °C. $\alpha_{20} = 0.00393$; $\rho$ is the conductivity of copper conductor at 20°C. $\rho = 0.01760 \Omega \cdot mm^2$, Can be calculated according to the corresponding conductor resistance temperature coefficient.

4. Cable type and specification

The cable model parameters are shown in Table 1.
Table 1. The cable model parameters

| model                        | JZREGFP - KG |
|------------------------------|--------------|
| KV voltage                   | 6/10         |
| The outer diameter of the power conductor is mm | 11.0         |
| Conductor shielding semi-conducting extrusion pack thickness calculated mm | 0.7          |
| Nominal insulation thickness mm | 2.5          |
| Insulation shielding semi-conductive extrusion pack thickness calculated mm | 0.7          |
| External guard nominal thickness mm | 5.0          |
| Outer diameter after outer protection mm | 64           |

5. **Simplified modeling and simulation analysis of temperature field**

Linear Composite cable temperature design requirements:

(1) the maximum allowable temperature of the cable conductor: 90°C, and the maximum allowable temperature of the conductor short-circuit (short circuit is no more than 5s) is 250°C;

(2) normal ambient temperature of the cable: -10°C to +55°C;

![Figure 2. Construction of cable](image)

1 - power core conductor; 2 - conductor shielding; 3 - insulation; 4 - insulating shield; 5 - metal shield; 6 - ground core conductor; 7 - ground core semi-conductive layer; 8 - control line core conductor; 9 - insulation of control wire core; 10 - control line metal shield; 11 - control line internal protection; 12 - optical fiber; 13 - fiber sheath; 14 - fill in the core; 15 - inner sheath; 16 - reinforcement of fiber braiding; 17 - outer sheath
Table 2. Equivalent structure parameters and materials table

| Model       | JZREGFP - KG | Material               |
|-------------|--------------|------------------------|
| KV voltage  | 6/10         |                        |
| Specifications in mm² | 3 + 1 x 50 + 7 x 1.5 x 95 + 6 fo (62.5/125) |                        |
| Core power lines | Outer diameter of power conductor mm | 11.0 | copper |
|              | Nominal insulation thickness mm | 3.5 | Polyvinyl chloride (PVC) |
| Cable sheath | Sheath outside diameter | 5 | Polyvinyl chloride (PVC) |
| Refer to outer diameter mm for cabling | 64 |                        |
| Reference weight kg/km | 6500 |                        |

Table 3. Thermal conductivity of the cable materials

| Material            | Thermal conductivity [W/(m·k)] | The density of   | Atmospheric heat capacity [J/(kg·K)] |
|---------------------|---------------------------------|-----------------|-------------------------------------|
| Polyvinyl chloride  | 0.2                             | 1380            | 1800                                |
| Copper              | 400                             | 8700            | 385                                 |

In order to facilitate the simulation calculation, on the premise of meeting the actual requirements of the project, the cable parameters are simplified as shown in table 2. The simplified structure diagram is shown in figure 3 and the following assumptions are made:

1. Ignore the influence of control wire core, optical fiber and ground wire on temperature;
2. In order to simplify modeling, conductor shielding, insulation, insulation shielding and metal shielding are equivalent to PVC protective layer;
3. The three-dimensional electrostatic field calculation is equivalent to the two-dimensional electric field calculation.

![Figure 3. Simplified cable structure](image_url)
5.1. Temperature field distribution during rated operation of the cable
The jzregfp-kg cable works at an external temperature of 20 ℃. Under rated conditions, the temperature of the copper conductor is stable at 58 ℃ after a period of operation because the copper conductor of the cable is heating during operation. In the simulation, the rated current is set as 320 A, so that the cable in the model can reach the temperature condition of stable operation, so as to obtain the temperature field distribution diagram under the rated working condition 3 as figure 4.

![Figure 4. distribution of temperature field in rated conditions](image)

5.2. Temperature field analysis of short-circuit fault
In the short-circuit condition, the conductor temperature in the rated condition of the cable is 67 ℃, which is determined by the material of the cable. However, in the long-term operation of the cable, short-circuit fault may occur, which may lead to power interruption and may cause fiber optic communication. In the event of a short circuit fault of the cable, the short circuit current may reach tens of times the rated current. Cause the cable temperature to rise instantly. In the simulation, the maximum temperature shall not exceed 250 ℃ within 5 seconds of the short circuit time. In the case of two-phase short-circuit, set the short-circuit current to 6000 A. Simulation time figure 4 is as follows: The temperature at 5 s is as shown in the figure above, about 110 ℃. Temperature of 90 ℃. During the normal operation of the cable, when a phase cable suddenly shorted, the temperature in 5 s could reach 157 ℃, far lower than the design requirement of 250 ℃. The cable meets the design requirements.

![Figure 5. Temperature change diagram in case of short circuit](image)
5.3. Temperature field analysis under overload condition
In case of overload failure of the cable, the short-circuit current may reach several times the rated current. Cause the cable temperature to rise instantly. In the simulation, the overload current is set as 1024A, and the maximum temperature shall not exceed 250°C within 5 seconds. Simulation time figure 6 is as follows:

![Figure 6. temperature change diagram in case of short circuit](image)

According to the simulation results, the temperature is about 24°C for 5s overload. The temperature rise was 4°C, the normal operating temperature of the cable was 67°C, and the 5s temperature reached about 71°C when the cable was suddenly overloaded, far lower than 250°C. The cables meet the technical requirements.

6. The conclusion
Above, the simulation of this type of cable is carried out under different working conditions, and the design of the cable is verified to meet the requirements of the cable.

References
[1] Wu Wenke. Finite element numerical calculation of ampacity of direct Buried Power Cable D. Northeast Electric University, 2017.
[2] Ye lingling, you minghua, shen xiaoqing, et al. Measurement method of frequency stability based on phase noise testing system [J]. China science and technology information,2011, (12): 150.
[3] Xie yinzhong, zhang baozhou. Virtual instrument application research under VC++ platform [J]. Computer measurement and control,2010, (1): 237-239.
[4] Sommelier. PN9000 phase noise measurement system and its application [C] // national academic exchange on time and frequency, 2003:295-299.
[5] Chen mengxi. Simulation study on temperature field of 10kV three-core cable joint [D]. Xi’an university of science and technology,2019.
[6] Niu jing. Simulation study on temperature field of mine fiber optic composite high-voltage cable [D]. China university of mining and technology,2019.
[7] Tang ke, wen wu, ruan jiangjun, zhan qinghua, xiao wei, liu chao. Simulation study on temperature field of single-core cable based on finite element method [J]. Journal of wuhan university (engineering),2018,51(09):811-816.