Analysis of Cable Temperature Field Based on Finite Element Method

Li-kai LIANG, Xiao-feng ZHOU, Zi-dan SUN, Jian-ping QI, Han WANG and Wen-bin LI
School of Mechanical, Electrical and Information Engineering, Shandong University,
Weihai 264209, China
*Corresponding author

Keywords: Cable temperature field, Finite element method, Grounding mode, Loss.

Abstract. The analytical method of ampacity and temperature based on the IEC (International Electrotechnical Commission)-60287 standard has been widely used for its simplicity. However, the density of cable group and the complicated laying conditions reduce the accuracy of the analytical method which simplifies or ignores the actual situation. In this paper, the loss of the conductor temperature is taken as the internal heat source of cables. The finite element model is established to analyze the distribution of cable temperature field under two grounding modes by COMSOL to further improve the accuracy of cable ampacity.

Introduction

In the power cables, performance of insulation material determines the life of cables [1]. The cable conductor temperature which has correlation with the transmission capacity is an important parameter for the safe operation [2]. However, excessive worrying about the condition of low load may cause the cable cannot reach the maximum allowable temperature in stable state and power resources are wasted. When the power grid accident increases the load to an overload state and the dispatcher doesn’t receive effective information in time, overheating conductor can damage the insulation performance. The insulation aging will be accelerated, and the operation safety of cables will be threatened. Therefore, it is necessary to obtain the accurate distribution of cable temperature field in steady state and the temperature change in transient state. It is also essential to control the real-time current carrying to increase the cable transmission capacity and ensure a safe operation.

In recent years, the development of computer technology has led to the rise of finite element software. The numerical analysis method has been widely concerned and studied, especially in the simulation of cable temperature field and current carrying [3]. Due to the advantages of solving complex boundaries, analyzing nonlinear problems and no limitation of node partition [4], the finite element method takes the leading position in the field of numerical calculation [5]. The finite element analysis method is of great significance for the calculation of cable ampacity and the simulation of temperature field under complicated conditions [6]. A systematic comparison of the thermal path model method under IEC-60287 standard and the finite element method for various cables is presented in [7,8]. The ampacity of buried cables with external heat source and land skin temperature variation is obtained by the finite element method [9]. Based on the principle of heat transfer and the finite element method, a new numerical method to calculate the ampacity of underground cables is proposed in [10]. The factors that affect the cable ampacity and the temperature field are analyzed by the finite element method in [11]. The electromagnetic coupling model is proposed in [12]. Electromagnetic field and thermal field are combined in the same model, and the finite element analysis is achieved by COMSOL Multiphysics. In [13], the axial and radial heat transfer of cables is considered. A three-dimensional heat transfer model of single-core cables is established to improve the calculation accuracy of the cable core temperature. The conductor temperature is a key factor to determine the ampacity. In this paper, the loss of the conductor temperature is taken as the internal
heat source of cables. The finite element model is established to analyze the temperature field under

two grounding modes by COMSOL software to further improve the accuracy of cable ampacity.

The rest of this paper is organized as follows. Section 2 establishes the cable temperature field

model. In Section 3, the cable temperature distribution under two sheath grounding modes is

analyzed. Conclusions are given in Section 4.

Establishment of Cable Temperature Field Model

The conductor loss, the metal sheath loss and the insulation loss are the internal heat sources of the
cable, which are the main causes of the cable temperature field. The accurate calculation and analysis

of various losses is an important prerequisite for studying the cable temperature field. In this paper,
the type of the cable is YJLW02-66/110-1*1000 and the temperature field of single circuit cable is

studied. The parameters of the cable are shown in Table 1.

Table 1. Material parameters of the cable.

<table>
<thead>
<tr>
<th>Conductor diameter</th>
<th>Outside diameter of insulation layer</th>
<th>Outside diameter of buffer layer</th>
<th>Outside diameter of metal sheath</th>
<th>Outside diameter of outer sheath</th>
</tr>
</thead>
<tbody>
<tr>
<td>38.5 [mm]</td>
<td>70 [mm]</td>
<td>74 [mm]</td>
<td>80 [mm]</td>
<td>90 [mm]</td>
</tr>
</tbody>
</table>

The core loss of cable is affected by the load and the resistance. When the load is constant, the AC

resistance becomes the main factor affecting the core loss. The AC resistance per unit length $R$ is

shown in Eq. 1 and Eq. 2.

$$R = R_{20} [1+\alpha(T_0-20)]$$

$$R = R_t (1+Y_s+Y_p)$$

where $R_{20}$ is the DC resistance per unit length at the temperature of 20°C; $\alpha$ is the temperature

coefficient of material, and the temperature coefficients of copper and aluminum are 0.00393 and

0.00403 respectively; $T_0$ is the maximum allowable operation temperature; $Y_s$ and $Y_p$ are the skin
effect factor and the proximity effect factor, respectively. The core loss $W_c$ is shown in Eq. 3.

$$W_c = I^2 R$$

where $I$ is the current through the conductor. AC resistance is mainly affected by skin effect factor and

proximity effect factor after the type of cable is determined. The proximity effect factor is affected by

the axis distance and the number of cables. The proximity effect factor of three-phase cable $Y_p$ is

shown in Eq. 4.

$$Y_p = \frac{x_p^4}{192 + 0.8x_p^4 + \left[0.312 \left(\frac{d_c}{s}\right)^2 + \frac{1.18}{192 + 0.8x_p^4 + 0.27}\right]} \left[0.312 \left(\frac{d_c}{s}\right)^2 + \frac{1.18}{192 + 0.8x_p^4 + 0.27}\right]$$

where $x_p^2 = \frac{8\pi f}{R'} \times 10^{-7} k_p$, $d_c$ is the diameter of conductor; $s$ is the axis distance between adjacent
cables. If three cables are arranged in parallel, $s = \sqrt{s_1 \cdot s_2}$, where $s_1$ and $s_2$ are the axis distances

between one cable and the other two cables. If three cables are arranged in a triangle, $s$ is the axis
distance of adjacent cables.

Ignoring the longitudinal heat transfer of the cable, the cable can be simplified to a
two-dimensional model. The temperature field of three-phase single-core buried cables is established.
The physical parameters are set as follows. Three single-core cables are arranged in a single loop. The
axis distance is 0.2m. The laying depth is 1m. The distance between the cables is 20m. The physical
model is shown in Figure 1.
Figure 1. Physical model of cable temperature field.

The boundary conditions of the model are set as follows. The temperature of the deep soil is 25°C. The heat flux of the left and right boundaries is 0 W/m². The temperature of the soil surface is 40°C. The convection heat transfer coefficient is 12.5 W/m²°C.

The cable model is a circular boundary in the two-dimensional cable temperature field model. Therefore, triangular elements are used for mesh division. Not only the junction of the inner layers, but also the junction of the outer layer and the soil are divided finely. The other areas are divided sparsely. The thermal physical parameters of each layer materials and the soil medium around the cable are shown in Table 2.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Thermal conductivity [W/(m·K)]</th>
<th>Density [kg/m³]</th>
<th>Specific heat capacity [J/(kg·K)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper conductor layer</td>
<td>400</td>
<td>8900</td>
<td>380</td>
</tr>
<tr>
<td>XLPE insulation layer</td>
<td>0.2857</td>
<td>1200</td>
<td>1000</td>
</tr>
<tr>
<td>Semi conductive nonwoven fabric layer</td>
<td>0.2857</td>
<td>550</td>
<td>1900</td>
</tr>
<tr>
<td>Metal aluminum sheath layer</td>
<td>160</td>
<td>2700</td>
<td>900</td>
</tr>
<tr>
<td>PVC outer sheath layer</td>
<td>0.1667</td>
<td>1380</td>
<td>800</td>
</tr>
<tr>
<td>Soil</td>
<td>1</td>
<td>1350</td>
<td>2400</td>
</tr>
</tbody>
</table>

Cable Temperature Distribution under Two Sheath Grounding Modes

Three single-core cables are arranged horizontally in a single loop. The axis distance is 0.2 m. When the frequency of three cables is 50 Hz and the three-phase alternating current is 700 A, the middle cable is zero phase, the left cable is 120-degree leading phase and the right cable is 120-degree lagging phase. According to the equations of loss, the core loss and the sheath loss can be obtained under two grounding modes. The ratio between the loss and the area of loss is the volume generation heat of loss layer. The loss is taken as a heat source in the finite element model. The loss results are shown in Table 3.

<table>
<thead>
<tr>
<th>Cable position</th>
<th>Core loss [W/m]</th>
<th>Volume generation heat [W/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left cable</td>
<td>12.65</td>
<td>10869</td>
</tr>
<tr>
<td>Middle cable</td>
<td>12.71</td>
<td>10924</td>
</tr>
<tr>
<td>Right cable</td>
<td>12.65</td>
<td>10869</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cable position</th>
<th>Sheath loss (single-end grounded) [W/m]</th>
<th>Volume generation heat [W/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left cable</td>
<td>0.39</td>
<td>798</td>
</tr>
<tr>
<td>Middle cable</td>
<td>1.42</td>
<td>2890</td>
</tr>
<tr>
<td>Right cable</td>
<td>0.35</td>
<td>711</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cable position</th>
<th>Sheath loss (two-end grounded) [W/m]</th>
<th>Volume generation heat [W/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left cable</td>
<td>11.79</td>
<td>24060</td>
</tr>
<tr>
<td>Middle cable</td>
<td>13.16</td>
<td>26870</td>
</tr>
<tr>
<td>Right cable</td>
<td>16.94</td>
<td>34578</td>
</tr>
</tbody>
</table>
As the heat sources, the calculated losses of two grounding modes are loaded into the finite element model of the temperature field. The temperature field distribution is shown in Figure 2.

Figure 2. Cable temperature field under two kinds of grounding modes. (a) Single-end grounded; (b) Two-end grounded.

The simulation results of the temperature field under single-end and two-end grounding modes are shown in Fig. 2 (a) and (b), respectively. It can be seen that the maximum temperature of the cable reaches 57.2°C and 83.9°C respectively when 700A is applied to the cable. Increasing the load and changing the loss until the maximum temperature reaches 90°C, the load at this time is the cable ampacity, which is 1076A and 745A respectively. Therefore, the ampacity of single-end grounding mode is larger than that of two-end grounding mode. Two-end grounding mode is a way based on security considerations, the circuit will generate large circulation losses, which will lead to the increases of sheath loss and conductor temperature. Therefore, the actual situation should be considered comprehensively in actual laying. The middle cable core is taken as the midpoint, and the axis with a length of 4m parallel to the horizontal ground is defined as the radial path. The temperature distributions of the radial path under two grounding modes are shown in Fig. 3.

Figure 3. Radial distribution of cable temperature. (a) Single-end grounded; (b) Two-end grounded.

It can be seen that the temperature of the middle cable is higher than that of the cables on both sides. The two sides of the cable can be considered as the external heat sources of the middle cable, which affects the heat dissipation of the middle one. The external heat sources make the temperature of the soil around the middle cable rise, and the temperature gradient is so small that the heat flux decreases. The temperature difference between the two sides of the conductor is very small, because the circulation losses of the sheath are zero and the eddy current losses are approximately equal under the condition of single-end grounding. It can be seen from Fig. 3 (a), the temperature of the middle cable is 3.1°C higher than that of both sides. As the heat dissipation of the cable decreases, the temperature drops gradually from the cable center to the both sides. At a certain length, the temperature of the soil is equal to the temperature of stable deep soil. The temperature of the middle cable is 5.9°C and 1.2°C higher than that of the left and right cable respectively. The temperature of the right cable is about 4.8°C higher than that of the left cable, which is caused by the eddy current loss of the lagging-phase cable is higher than that of the leading-phase cable.
Conclusions

In this paper, the cable temperature field model is established. The temperature field distribution is analyzed under two grounding modes by COMSOL software to further improve the accuracy of cable ampacity. The results of finite element analysis show that the ampacity under single-end grounding mode is larger. It can also be seen that the temperature of the middle cable is higher than that of the cables on both sides. The proposed method can be used to analyze the steady state temperature field of cable effectively. In the future, the distributed temperature measurement system and the finite element method can be combined to reduce the error and determine the temperature more accurately, which will provide more information for increasing the capacity of cables.

References