Calculation Method of Cable Ampacity Based on Field-circuit Combined Mode

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Abstract. Electricity is usually transmitted through power cables in densely populated areas. It is significant to predict the ampacity and temperature field accurately to ensure safe and economical operation of cables. In this paper, a field-circuit combination algorithm is proposed. The equivalent thermal circuit method and the finite difference method are effectively combined to calculate the temperature of cable and soil area respectively. This method is more accurate than the equivalent thermal circuit method and faster than the traditional numerical method. It is proved that the new method in this paper can meet the needs of engineering by comparing with the results of equivalent thermal circuit method in homogeneous soil and coordinate combination method in inhomogeneous soil respective.

1. Introduction
Accurate calculate cable ampacity is great significance to improve the economics of cable applications with the wide application of cables in power grids construction. The equivalent thermal circuit method for calculating cable ampacity is in accordance with the IEC-60287 standard recommended by the International Electrotechnical Commission[1]. When the actual laying environment conditions are different from the standard conditions, the correction factor is usually used for correction. The selection of the correction factor is a very complicated problem due to lack of reliable correction basis. Numerical calculation method has advantages of low cost and ability to simulate complex working conditions, which has high practical value for improving the calculation accuracy of ampacity. The numerical methods commonly used to calculate temperature field include: finite element method [2-4], boundary element method [5], finite difference method [6], and simulated thermal charge method [7].

The equivalent thermal circuit method provided by IEC standard is a rapid method with high accuracy when dealing with cable ampacity in uniform soil [8], however the calculation error in non-uniform soil environment is large. The calculation accuracy of numerical method is not affected by soil environment complexity but it's slow. Combining the advantages of the two, this paper use the finite difference method to calculate the soil temperature field in the cable laying area, and combines the equivalent thermal circuit method to obtain the core temperature quickly and accurately.

2. Equivalent Thermal Circuit Method for Calculating Cable Core Temperature
The core, the insulation layer, the metal sheath, etc. will generate losses in running cables, and heat is generated to form a heat flow field. Each layer structure can be represented by an equivalent thermal resistance when heat flow is conducted outward through the various layers of cable. Take the
insulating layer shown in Figure 1 as an example. $\theta_c$ and $\theta_{sh}$ are the temperature (°C) of the inner and outer surfaces of the insulating layer respectively; $D_i$ and $D_{sh}$ are the inner and outer diameters (m) of the cable insulation layer respectively; $W_c$ is the core loss (W); $\rho_T$ is the thermal resistance of the insulating layer coefficient (K•m/W); $R_t$ is the thermal resistance of the insulation layer (K•m/W).

Assume that the cable consists of core, insulating layer, water blocking layer, metal sheath, and outer sheath. Figure 2 shows the overall equivalent thermal path of the cable. $W_w$ and $\sigma_1W_c$ are the insulation layer loss and the metal sheath loss (W) respectively. $R_2$, $R_3$, and $R_4$ respectively represent the thermal resistance of the water blocking layer, the outer sheath and the surrounding medium (the thermal resistance of the metal portion is negligible). If the total number of cables is $M$, the depth of a cable is $L$, and the thermal resistance coefficient of the cable group adjacent to the soil is $\rho_{T4}$, then the $R_t$ of the cable is [8]:

$$R_t = \frac{\rho_{T4}}{2\pi} \ln \left( \frac{4L}{D_{oa}} \frac{d_{ik}}{d_{ik}'} \frac{d_{2k}}{d_{2k}'} \cdots \frac{d_{MK}}{d_{MK}'} \right) \quad (1)$$

$d_{ik}$, $d_{2k}$, $\ldots$, $d_{MK}$ is the distance from the center of the cable 1, 2, ..., $M$ to the center $K$ of the cable; $d_{ik}'$, $d_{2k}'$, $\ldots$, $d_{MK}'$ is the distance from the mirror center of the cable 1, 2, ..., $M$ to the center $K$ of the cable, and the $D_{oa}$ is the outer diameter of the outer sheath of the cable. (m), the heat balance equation for each cable is [8]:

$$\theta_c = \theta_a + R_t(W_c + \frac{1}{2}W_w) + R_2(W_c + W_m) + (R_3 + R_t)(W_c(1 + \sigma_1) + W_m)$$

$\theta_a$ is the temperature of the medium surrounding the cable. Using the equivalent thermal circuit method to calculate the core temperature, the soil in the laying area is required to have a single thermal conductivity. If the thermal conductivity of the laying area soil is not unique, the temperature of the core cannot be accurately determined. In this case, a numerical method is needed to solve the problem.

3. The New Method- field-circuit Combination Algorithm

Calculate temperature field in cable laying area by finite difference method [6]. The calculation area including the cable is divided into right angle grids, the soil and cable layers in the area are divided into different grids. The thermal conductivity of the corresponding materials in the grid is assigned to the right grid, where the core is located as heat source. In order to improve the calculation accuracy and reduce the calculation amount, the cable area adopts an encrypted grid. The farther from the cable, the more sparse the grid is. The temperature error of the cable core obtained by this method is large, but the soil temperature error around the cable is small. At the periphery of the cable, take a few layers of soil concentric with the cable and the same thickness, the total thickness is $d$, as shown in Figure 4, the thermal resistance of the soil layer can be expressed as:
Cable thermal differential equations, initial conditions and boundary conditions can accurately describe the transient temperature field distribution of a particular cable. The heat conduction differential equation of the cable transient temperature field in the Cartesian coordinate system shown in Figure 3 is [9]:

\[ \frac{\rho C_p}{\partial t} \frac{\partial T}{\partial t} = K [\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}] + Q \]  

(4)

Where \( \rho C_p \) is the product of the medium density and the specific heat at a certain point in the field, \( T \) is the temperature, \( K \) is the thermal conductivity of the medium, and \( Q \) is the heat source. The heat transfer equation can be discrete into:

\[ a_p T_p + a_E T_E + a_W T_W + a_N T_N + a_S T_S = b + \rho C_p \frac{T^0_{i,j}}{\Delta t} \]  

(5)

In the formula: \( a_p = \frac{\rho C_p}{\Delta t} + 2K(\frac{1}{\Delta x_1 \Delta x_2} + \frac{1}{\Delta y_1 \Delta y_2}) \); \( a_E = -\frac{2K}{\Delta x_1 (\Delta x_1 + \Delta x_2)} \); \( a_W = -\frac{2K}{\Delta x_2 (\Delta x_1 + \Delta x_2)} \); \( a_N = -\frac{2K}{\Delta y_1 (\Delta y_1 + \Delta y_2)} \); \( a_S = -\frac{2K}{\Delta y_2 (\Delta y_1 + \Delta y_2)} \); \( b = Q \).

![Figure 3. Grid of rectangular coordinates](image)

Based on the temperature field of the right-angle grid, the quadratic interpolation is used to obtain the temperature of the outermost layer of the soil layer. The average temperature of the soil layer is:

\[ \theta_a = \frac{1}{12} \sum_{i=1}^{12} \theta_{a_i} \]  

(6)

Substituting this result into equation (2) in combination, the core temperature can quickly and accurately determine by the equivalent thermal circuit method. This method can not only solve the problem of uneven soil which cannot be solved by the equivalent heat path method, but also the calculation efficiency of the numerical method is significantly improved.

Since the insulation loss and metal sheath loss are much less than the core loss, the former two can be equivalent to the core loss. In addition, in order to improve the calculation speed more effectively under the premise of ensuring the calculation accuracy, the layer structure other than the cable core can be processed by the harmonic averaging method [10]:

The thickness of each layer is equivalent to a medium, and its thermal conductivity \( \lambda_T \) can be expressed as:

\[ \lambda_T = \frac{\ln(r_n / r_i)}{2\pi} \]  

(7)
\( \lambda \) is the equivalent thermal conductivity obtained by the harmonic averaging method; \( i = 1 \) is the insulating layer, \( i = n \) is the outer sheath; \( \lambda_i \) is the thermal conductivity of the layer \( i \); \( r_i \) is the radius of the layer \( i \).

**Figure 4. Temperature of the soil around the cable**

4. Ampacity Calculation and Method Verification

The load current of each cable is the same. The heat dissipation of each cable is affected by the embedding mode and other cables. The ampacity should be based on the cable with the worst heat dissipation condition. In order to effectively reduce the number of iterations, the following steps can be used to calculate the ampacity:

1. First set \( t_m \) and \( \Delta t \) to the maximum allowable steady-state temperature of the cable core and the allowable error respectively, then obtain the initial value of the load current \( I_O \) by the image method[7];

2. Input \( I_O \) into the program to find the steady-state temperature \( t \) of the cable core. If \( t > t_m \), recalculate \( I_O - \Delta I \) as a new \( I_O \), otherwise reverse \( I_O + \Delta I \) as a new \( I_O \);

3. When iteratively calculates to \( t_m - \Delta t < t < t_m \), \( I_O \) is the ampacity of the cable group.

In order to verify the correctness of the method, the ampacity of 66kV direct buried cables with single-circuit and double-circuits is calculated, and the calculation results are compared with the IEC standard and coordinate combination method [6]. The calculation object is XLPE insulated cable. The nominal cross section of the copper cable core is 630mm\(^2\). The metal sheath is grounded by three-section cross-connection. The soil temperature in the laying area is 25°C, the thermal conductivity is 0.83 W/m•K, and the thermally conductive coefficient of back-filled sand is 0.3W/m•K. The laying method is shown in Figure 5.

Table 1 shows the calculation results of the three methods, in which \( I_1 \) and \( I_2 \) are the ampacity of single and double circuits respectively, and \( t_1 \) and \( t_2 \) are the calculation time of single and double circuits, respectively.

**Figure 5. Laying method of 66kV single circuit cable**
Table 1. Ampacity comparison of different methods

| Calculation method               | Uniform soil | Backfill sand |
|----------------------------------|--------------|---------------|
|                                 | $I_1$ (A)    | $I_2$ (A)     | $t_1$ (min) | $t_2$ (min) | $I_1$ (A) | $I_2$ (A) | $t_1$ (min) | $t_2$ (min) |
| IEC standard                     | 954          | 802           | —           | —           |            |            | —           | —           |
| Field-circuit combination        | 963          | 817           | 8.8         | 27.5        | 715        | 579        | 5.8         | 30.0        |
| Coordinate combination           | 970          | 826           | 36.5        | 77.0        | 706        | 565        | 51.3        | 200.0       |

As shown in Table 1, it can be seen that when the soil of laying area is uniform, the calculation results of the field-circuit combination method and the coordinate combination method are in good agreement with the IEC standard; when the sand is backfilled, the field-circuit combination method and the coordinate combination method are in good agreement. It is worth noting that the calculation time of the field-circuit combination method is significantly lower than the coordinate combination method.

5. Conclusion

Compared with the IEC standard method and the coordinate combination method, the field combination method proposed in this paper has the advantages of high numerical calculation accuracy and high analytical calculation efficiency. It can solve the ampacity of cable group in complex soil condition, and the calculation efficiency is obviously higher than the simple numerical calculation. The calculation of the field-field combination method for the current-carrying cable carrying capacity of clustered soil has important practical significance and high engineering application value.

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