

# Study on the Calculation of Cable Emergency Current Capacity Based on Real-time Measurement Data

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**Abstract.** In actual operation, the cable may bear extra load due to other line faults within a certain time. This load is called the emergency Current Capacity, and this time period is called the emergency time. There are two main ways to solve the emergency Current Capacity using the thermal circuit. One is to take the surface temperature of the cable outer sheath as the boundary of the transient thermal circuit, without considering the influence of laying environment. The other is to use the environmental thermal parameters recommended by IEC standard. Since the actual environment along the cable is complex and changeable, and the environmental thermal parameters are time-varying, both methods will cause errors. In this paper, the environmental thermal parameters are calculated by using the data obtained from the real-time measurement, which is then substituted into the derived formula to obtain the emergency Current Capacity algorithm. The correctness of the algorithm is verified by comparing the results with the ones of FEA simulation and IEC. The results show that: the algorithm proposed in this paper is safe and more accurate. The effects of initial load and emergency time are also be analysed at the same time.

## 1. Introduction

The temperature of cable conductor is affected by environmental conditions and load during operation [1-2]. To ensure the enough insulation strength and expected service life, the normal operating temperature of cables shall not exceed the long-term tolerance temperature of insulation materials[3-4]. However, in the actual operation of the cable circuit, the “N-1” operation mode may be applied because of the line faults or repair condition. It will cause load increase in a certain time so that the temperature of cable conductor rises, reaching to even more than 90 °C. Therefore, when the load of cable line needs to be increased in a short term, under the conditions when taking the “N-1” mode, it is practical and significant to study how to accurately calculate the emergency cable current capacity. It will ensure the temperature rise of cable conductor within a certain amount of time does not exceed 90 °C and the safe operation of cable line.

IEC-60853 is the most widely used method for calculating cable emergency current capacity at present; however, it is based on varies of assumptions in the literature [5] which limit the transmission capacity of cables. In recent years, many researchers have studied how to improve the calculation accuracy of cable emergency current capacity. In reference [6], a distributed optical fiber temperature



measurement is adopted to analyze the current temperature of cable, and then the current temperature is substituted into the transient thermal circuit to realize the calculation for the transient current capacity of cable in a short time. Based on IEC method, literature [7] proposed an improved calculation method for the thermal parameters of cable insulation, which improved the calculation accuracy of conductor temperature. Literature [8] used finite difference method and finite element method to calculate the transient temperature field and short-term current capacity of underground laying cable group and improved the calculation accuracy of emergency current capacity under complex laying conditions.

Based on the IEC standard algorithm, most of the existing methods for calculating cable emergency current capacity are to reduce the differential equations representing the cable transient thermal circuit to algebraic equations and simplify them by substituting the solution of algebraic sum for the integral solution. However, this simplification is only applicable to the calculation in the case of short time interval of data points, and it will bring great error when applied to the calculation of emergency current capacity with a large time length. Moreover, the existing research focuses on the optimization solution of the bulk thermal parameters in the cable transient thermal circuit, and there are few studies on the calculation of the thermal parameters of the external environment.

In this paper, the equivalent thermal circuit model of the external environment of cable is built, and the environmental data obtained through real-time monitoring is used to calculate the environmental thermal parameters. After substituting the parameters into the derived formula for the emergency current capacity, the algorithm reflecting the changes of environmental parameters is obtained. To verify the correctness of the algorithm, the cable finite element simulation model is established. The calculation results of the algorithm are compared with the finite element simulation results and the IEC standard calculation results. Meanwhile, the influence of initial load and emergency time on the error of the algorithm is analyzed.

## 2. Review of IEC method

According to IEC-60853, the transient temperature rise of the cable line is determined by the cable body and the medium around the cable surface. Therefore, the transient temperature rise caused by sudden load in the cable line is composed of two parts, one is the transient temperature rise of the cable body, and the other is the transient temperature rise of environment.

Based on the calculation formula of cable transient temperature rise, IEC-60853 further provides the calculation formula of cable emergency current capacity. An emergency load  $I_2 (I_2 > I_1)$  is applied to the cable with initial load of  $I_1$  at time 0. It is assumed that the cable conductor temperature reaches the insulation long-term tolerance temperature at time  $t$ , which means the cable emergency response time is  $t$ , then the calculation formula of cable emergency current capacity  $I_2$  is shown in formula (1).

$$I_2 = I_R \times \left[ \frac{h_1^2 R}{R_{max}} + \frac{R_R / R_{max} (r - h_1^2 \times \frac{R_1}{R_R})}{T(t) / T_{R(\infty)}} \right]^{1/2} \quad (1)$$

$$h_1 = I_1 / R_1 \quad (2)$$

$$r = T_{max} / T_{R(\infty)} \quad (3)$$

In formula (1):  $I_R$  is the rated current capacity of cable, A;  $I_1$  is the steady-state current of the cable line before the emergency load is applied, A;  $R_1$  is the ac resistance value of the conductor when the cable load is  $I_1$ ,  $\Omega$ ;  $R_R$  is the ac resistance value of conductor when the cable load is the rated current capacity in operation,  $\Omega$ ;  $R_{max}$  is the corresponding ac resistance value of conductor when the emergency current capacity is applied at the highest temperature of conductor,  $\Omega$ ;  $T_{max}$  is the temperature rise caused by conductor joule loss after applying emergency load to cable,  $^{\circ}\text{C}$ ;  $T(t)$  is the temperature rise caused by conductor joule loss after applying emergency load to cable in the time period  $t$ ,  $^{\circ}\text{C}$ ;  $T_{R(\infty)}$  is the steady temperature rise of conductor caused by joule loss when the cable is operated at steady rated current capacity,  $^{\circ}\text{C}$ .

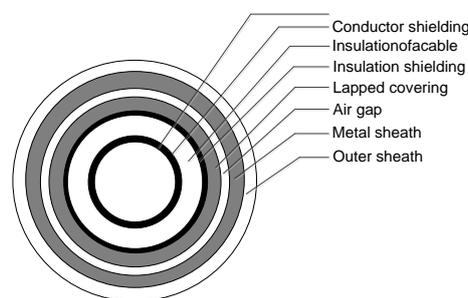
It can be seen from formula (1) that the calculation formula of IEC standard for emergency current capacity is based on the calculation of cable transient temperature rise. The corresponding errors will occur in the conditions when in the process of solving the transient thermal circuit, the surface temperature of the cable outer sheath is taken as the boundary of the thermal circuit; or when the value of cable temperature rise is obtained by using the simplified algebraic equation instead of the differential equation and is substituted into the calculation of emergency current capacity formula.

### 3. Cable emergency current capacity based on real-time measurement data

#### 3.1 Construct transient thermal circuit model

This paper takes high voltage single-core cable as the research object, and its structure is shown in Fig. 1. Considering that the temperature of the cable outer sheath is time-varying and unknowable when predicting the cable emergency current capacity, this paper sets the external environment as the starting point of the calculation for the cable emergency current capacity of thermal circuit model. The location where the external environment of the cable is not significantly changed is selected as the boundary of the laying environment. The environmental parameters within the boundary are equivalent by using the first-order thermal resist-heat capacity of T-type thermal circuit. The influence of the cable on the internal heat transfer of the environment outside the boundary can be ignored. According to the structural characteristics of each layer of the cable and the principle of heat transfer, the thermal circuit model for calculating the emergency current capacity of single-core cable including the external environment is built, as shown in Fig. 2. During the establishment of the thermal circuit model for the calculation of cable emergency current capacity, the cable body model is simplified as follows:

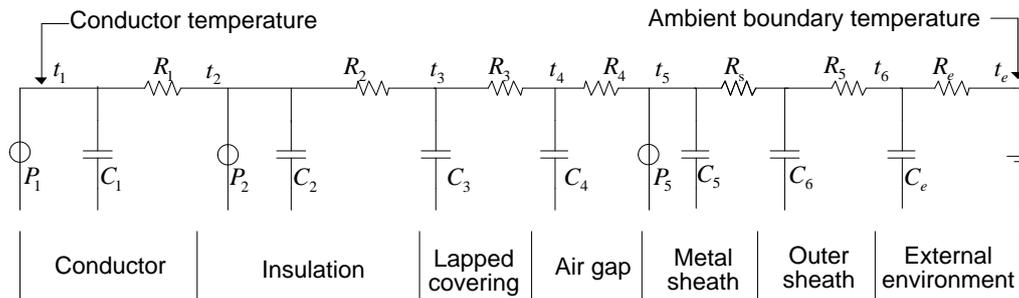
- 1) The thickness of conductor shielding layer and insulation shielding layer is much less than that of insulation layer, so the conductor shielding, the insulation shielding, and the insulation layer can be considered as one layer.
- 2) Due to the long length of cable, the thermal and physical parameters of the external environment around the cable will not change abruptly under normal circumstances. In addition, the axial consideration range of the external environment is much larger than its radial consideration range. The surrounding environment of the cable is symmetric with the axis of the cable, so the axial heat transfer can be ignored.



**Fig. 1** Single-core cable structure studied in this paper

- 3) Due to the good thermal conductivity of metal, the thermal resistance of copper conductor and aluminum sheath are ignored, corresponding to  $R_I$  and  $R_s$  in Fig. 2, respectively.

### 3.2 Parameters solution

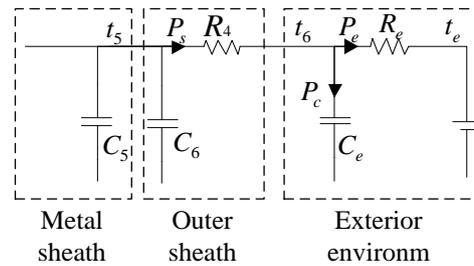


**Fig. 2** Single-core cable transient heat circuit including laying environment

where,  $t_1$  is the temperature of cable conductor, °C;  $t_2$  is the temperature of insulation layer, °C;  $t_3$  is the temperature of lapping layer, °C;  $t_4$  is the temperature of air-gap layer, °C;  $t_5$  is the temperature of metal conductor cable, °C;  $t_6$  is the outer surface temperature of cable, °C;  $C_1$  represents the thermal capacity of cable conductor, J/K;  $C_2$  represents the thermal capacity of the main insulation of cable, J/K;  $C_3$  represents the thermal capacity of lapping layer, J/K;  $C_4$  represents the thermal capacity of the air-gap layer, J/K;  $C_5$  represents the thermal capacity of the metal sheath of cable, J/K;  $C_6$  represents the thermal capacity of cable outer sheath, J/K;  $C_e$  represents the equivalent thermal capacity of the external laying environment of cable, J/K.  $R_1$  is the thermal resistance of conductor, K/W;  $R_2$  is the thermal resistance of the main insulation of cable, K/W;  $R_3$  is the thermal resistance of the lapping layer, K/W;  $R_4$  is the thermal resistance of the air-gap layer, K/W;  $R_5$  is the thermal resistance of the outer sheath layer, K/W;  $R_e$  is the equivalent thermal resistance of the external laying environment of cable, K/W;  $P_1$  represents the loss of cable conductor, W;  $P_2$  represents the loss of insulation and also internal and external shielding media of each layer, W;  $P_5$  represents the loss of cable metal sheath, W. The calculation of thermal parameters of the cable structure can refer to the literature [9], which will not be repeated here. The calculation of environmental thermal parameters is emphatically introduced below. The thermal parameters of cable laying environment are affected by many factors. The environment of in-ground laying cable, for example, the thermo-physical parameters of soil are related to the depth of soil, season, and the proportion of its gas, liquid and solid components.

Meanwhile, the thermal resistance of soil is affected by soil moisture, density, temperature, particle size distribution, and porosity [10]. However, when IEC standard is adopted to calculate the environmental thermal resistance and heat capacity [11][12][13][14], the uncertainty of medium parameters in external laying environment makes the calculation of emergency load complicated and inaccurate, and its applicability and accuracy are greatly limited.

To solve the problem of difficulty in analytic calculation for the thermal parameters of cable external environment, based on the principles of heat transfer, the heat transfer process is equivalent to the thermal circuit model with lumped parameters of first-order thermal resistance and thermal capacity. The method of cable temperature on-line monitoring is adopted in this paper. That is, the external environment temperature of the cable and the surface temperature of the outer sheath of the cable can be obtained by real-time monitoring, while the temperature of the aluminum sheath can be obtained by substituting the above-mentioned two real-time monitoring values into the cable transient thermal circuit. Taking the external temperature of the cable, the surface temperature of the outer sheath of the cable and the temperature of the aluminum sheath as known values, the environmental equivalent heat capacity and thermal resistance parameters were solved by substituting them into the first-order thermal circuit. The first-order thermal resistance-thermal capacity of t-type thermal circuit model of the cable external environment is established, shown in Fig. 3.



**Fig. 3** Transient thermal circuit of external laying environment

where,  $t_5$  is the temperature of cable metal sheath, °C;  $t_6$  is the temperature of cable outer sheath layer, °C;  $t_e$  is the temperature of outside the boundary of external laying environment, °C;  $C_5$  represents the thermal capacity of cable metal sheath, J/K;  $C_6$  represents the thermal capacity of cable outer sheath layer, J/K;  $C_e$  represents the thermal capacity of the external laying environment, J/K;  $R_5$  is the thermal resistance of outer sheath, K/W;  $R_e$  represents the equivalent thermal resistance of the external laying environment of cable, K/W;  $P_s$  is the heat flowing through  $R_5$ ;  $P_e$  is the heat flowing through  $R_e$ ;  $P_c$  stands for the heat flowing through  $C_e$ .

It can be obtained from the thermal circuit in Fig. 3,

$$\begin{cases} t_6 - t_e = P_e R_e \\ t_5 - t_6 = P_s R_5 \\ P_c = C_e dt_6 / d\tau \\ P_e = P_s - P_c \end{cases} \quad (4)$$

According to equation (4), the equivalent thermal parameters of environment have the following relations:

$$\frac{dt_6}{d\tau} = \frac{t_5 - t_6}{R_4 C_e} + \frac{t_e - t_6}{R_e C_e} \quad (5)$$

In equation (5),  $R_e$  and  $C_e$  are both parameters to be solved, so actually two different equations are needed to be solved. The finite difference method is used in this paper to set the outer surface temperature of cable are  $t_6^n$ ,  $t_6^{n+1}$ , and  $t_6^{n+2}$  at three time points of  $n$ ,  $n+1$ , and  $n+2$  respectively when the time interval is  $h$ . Then the Equation (5) can be converted into the following equations:

$$\begin{cases} \frac{t_6^{n+1} - t_6^n}{h} = \frac{t_e - t_6^n}{R_e C_e} + \frac{t_5^n - t_6^n}{R_5 C_e} \\ \frac{t_6^{n+2} - t_6^{n+1}}{h} = \frac{t_e - t_6^{n+1}}{R_e C_e} + \frac{t_5^{n+1} - t_6^{n+1}}{R_5 C_e} \end{cases} \quad (6)$$

The environment thermal resistance and environment thermal capacity at real-time can be obtained by the finite difference method, shown as follows:

$$R_e = -R_5 \cdot \frac{(t_6^{n+1})^2 - t_6^n t_6^{n+2} - t_e^n t_6^{n+1} + t_e^n t_6^{n+2} + t_6^n t_e^{n+1} - t_6^{n+1} t_e^{n+1}}{(t_6^{n+1})^2 - t_6^n t_6^{n+2} - t_5^n t_6^{n+1} + t_5^n t_6^{n+2} + t_6^n t_5^{n+1} - t_6^{n+1} t_5^{n+1}} \quad (7)$$

$$C_e = -\frac{h}{R_5} \cdot \frac{t_6^n t_5^{n+1} - t_5^n t_6^{n+1} + t_e^n t_6^{n+1} - t_6^n t_e^{n+1} + t_5^n t_e^{n+1} - t_e^n t_5^{n+1}}{(t_6^{n+1})^2 - t_6^n t_6^{n+2} + t_6^n t_e^{n+1} - t_e^n t_6^{n+1} + t_e^n t_6^{n+2} - t_6^{n+1} t_e^{n+1}} \quad (8)$$

In the process of cable transient temperature rise, abnormal values may appear in the calculation results of environment thermal resistance and thermal capacity obtained by the above calculation method due to the measurement error of the temperature measuring devices. The obtained data can be

filtered using the Pauta criterion, and the total parameter values of the equivalent thermal capacity and thermal resistance set can be obtained by taking the average value of the processed results.

### 3.3 Formula derivation of cable capacity

According to the transient thermal circuit model of single-core cable established in Fig. 2, the following differential equation of thermal equilibrium can be found:

$$\dot{\mathbf{t}} = \mathbf{A}\mathbf{t} + \mathbf{B}\mathbf{P} \quad (9)$$

Where,

$$\mathbf{A} = \begin{bmatrix} \frac{1}{(C_1 + C_2)R_2} & \frac{1}{(C_1 + C_2)R_2} & 0 & 0 & 0 \\ \frac{1}{R_2C_3} & -\frac{1}{C_3} \left( \frac{1}{R_2} + \frac{1}{R_3} \right) & \frac{1}{R_3C_3} & 0 & 0 \\ 0 & \frac{1}{R_3C_4} & -\frac{1}{C_4} \left( \frac{1}{R_3} + \frac{1}{R_4} \right) & \frac{1}{R_4C_4} & 0 \\ 0 & 0 & \frac{1}{R_4(C_5 + C_6)} & -\frac{1}{(C_5 + C_6)} \left( \frac{1}{R_4} + \frac{1}{R_5} \right) & \frac{1}{(C_5 + C_6)R_5} \\ 0 & 0 & 0 & \frac{1}{C_e R_5} & -\frac{1}{C_e} \left( \frac{1}{R_5} + \frac{1}{R_e} \right) \end{bmatrix} \quad (10)$$

$$\mathbf{B} = \begin{bmatrix} (C_1 + C_2)^{-1} & 0 & 0 & 0 & 0 \\ 0 & C_3^{-1} & 0 & 0 & 0 \\ 0 & 0 & C_4^{-1} & 0 & 0 \\ 0 & 0 & 0 & (C_5 + C_6)^{-1} & 0 \\ 0 & 0 & 0 & 0 & C_e^{-1} \end{bmatrix} \quad (11)$$

$$\mathbf{t} = [t_2 \quad t_3 \quad \dots \quad t_6]^T \quad (12)$$

$$\dot{\mathbf{t}} = \left[ \frac{dt_2}{d\tau} \quad \frac{dt_3}{d\tau} \quad \dots \quad \frac{dt_6}{d\tau} \right]^T \quad (13)$$

$$\mathbf{P} = \left[ P_1 \quad P_2 \quad 0 \quad 0 \quad P_5 \quad \frac{t_e}{R_e} \right]^T \quad (14)$$

Observe the matrix  $\mathbf{A}$ , in the actual cable calculation, the matrix  $\mathbf{A}$  can prove diagonalizability, so let

$$\mathbf{A} = \mathbf{H}\mathbf{\Lambda}\mathbf{H}^{-1} \quad (15)$$

where,  $\mathbf{\Lambda}$  is a diagonal matrix, matrix  $\mathbf{H}$  is the 5th order square matrix, and the elements in the matrix  $\mathbf{H}$  are  $h_{ij}$  ( $i=1,2,3,\dots, j=1,2,3,\dots$ ).

Let  $\mathbf{t} = \mathbf{H}\mathbf{Y}$ ,  $\mathbf{Y}$  is a  $n \times l$  order matrix, the element is  $y_{ij}$  ( $i=1,2,3,\dots, j=1,2,3,\dots$ ), then formula (9) can be converted to

$$\mathbf{H}\dot{\mathbf{Y}} = \mathbf{A}\mathbf{H}\mathbf{Y} + \mathbf{B}\mathbf{P} \quad (16)$$

Multiply both sides by  $\mathbf{H}^{-1}$ , get,

$$\dot{\mathbf{Y}} = \mathbf{H}^{-1}\mathbf{A}\mathbf{H}\mathbf{Y} + \mathbf{H}^{-1}\mathbf{B}\mathbf{P} = \mathbf{\Lambda}\mathbf{Y} + \mathbf{H}^{-1}\mathbf{B}\mathbf{P} \quad (17)$$

then

$$\dot{\mathbf{Y}} = \begin{bmatrix} \frac{dy_1}{d\tau} & \frac{dy_2}{d\tau} & \frac{dy_3}{d\tau} & \frac{dy_4}{d\tau} & \frac{dy_5}{d\tau} \end{bmatrix}^T \quad (18)$$

Let  $L=H^{-1}B$ ,  $K=H^{-1}BP$ , it can be given by the initial conditions:

$$\mathbf{T}_0 = \mathbf{HY}_0 \quad (19)$$

Where  $T_0$  is the matrix for initial temperature of each layer.

Solve the equation can get,

$$t_1 = t_2 = (P_1 + P_2) \cdot \sum_{i=1}^5 \frac{h_i l_{i1} (e^{\lambda_i \tau} - 1)}{\lambda_i} + P_5 \cdot \sum_{i=1}^5 \frac{h_i l_{i4} (e^{\lambda_i \tau} - 1)}{\lambda_i} + \sum_{i=1}^5 h_i \left( \frac{l_{i5} t_e (e^{\lambda_i \tau} - 1)}{\lambda_i R_e} + y_{i+1,0} e^{\lambda_i \tau} \right) \quad (20)$$

Due to  $P_i = I^2 R$ , the variable separation can be conducted for the current capacity  $I$ , and the formula for the emergency time  $\tau$  and the emergency current capacity  $I$  is obtained from:

$$I = \sqrt{\frac{t_1 - P_2 \cdot \sum_{i=1}^5 \frac{h_i l_{i1} (e^{\lambda_i \tau} - 1)}{\lambda_i} - P_5 \cdot \sum_{i=1}^5 \frac{h_i l_{i4} (e^{\lambda_i \tau} - 1)}{\lambda_i} - \sum_{i=1}^5 h_i \left( \frac{l_{i5} t_e (e^{\lambda_i \tau} - 1)}{\lambda_i R_e} + y_{i+1,0} e^{\lambda_i \tau} \right)}{R \cdot \sum_{i=1}^5 \frac{h_i l_{i1} (e^{\lambda_i \tau} - 1)}{\lambda_i}}} \quad (21)$$

Where,  $\lambda_i$  is the elements in the  $A$  matrix,  $i_{ij}$  ( $i = 1, 2, 3, \dots, j = 1, 2, 3, \dots$ ) is the element of matrix  $L$ ,  $y_{ij}$  ( $i = 1, 2, 3, \dots, j = 1, 2, 3, \dots$ ) is the element of the matrix  $Y$ .

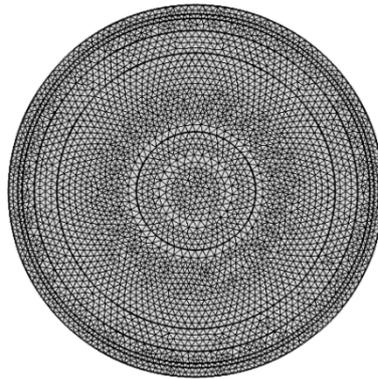
#### 4. Simulation model of finite element

In order to verify the correctness of the integral algorithm for cable emergency current capacity, based on environmental parameter optimization proposed in this paper, the finite element simulation model of single-core cable is constructed. The transient temperature rise after the cable is loaded with emergency load is simulated and the curve of emergency load and emergency time is obtained. At the same time, in order to further verify the superiority of the improved algorithm, this paper also compares the calculation results of IEC standard with the improved algorithm results.

##### 4.1 Simulation model

The 110kV XLPE insulated cable in air is taken as an example for analysis. The structural parameters and thermal conductivity of each layer of the cable are shown in table 1. Based on the previous assumption, if the cable length is long enough, its axial heat transfer can be neglected, and the cable body can be considered as an axisymmetric structure with isotropic homogeneous medium materials. If a complex three-dimensional simulation model is adopted to solve the problem, the calculation speed will be greatly reduced. Therefore, a two-dimensional simulation model can be adopted to calculate the temperature field of a single-core cable.

A triangle element method is used to divide mesh. Since the temperature field only changes violently around the cable area, in order to improve the calculation accuracy and save the calculation time, the grid is divided into dense sections at the junction of each layer of the cable and the contact between the cable and the environment. The mesh subdivision effect is shown in Fig. 4.



**Fig. 4** COMSOL finite element simulation model for single-core cable

**Table 1** Relevant parameters of cable studied in this paper

Structure	material	diameter/mm	Conductive index/(W/(m·K))
conductor	Copper	32.5	407
Insulator	XLPE	75.7	0.4
Lapping layer	PET	88	0.2
Air gap	Air	94.6	0.02
Metal sheath	aluminium	97	238
outer sheath	MDPE	102	0.4

#### 4.2 Temperature field control equation and boundary condition setting

According to the principle of heat transfer, the control equation of the temperature field inside cable is as follows:

$$\lambda \left( \frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2} \right) + q_v = \rho c \frac{\partial T}{\partial \tau} \quad (22)$$

Where,  $T$  is the temperature at point  $(x,y)$ ,  $K$ ;  $\lambda$  is the thermal conductivity coefficient,  $W/(m \cdot K)$ ;  $q_v$  is the volume heat generation rate,  $W/m^3$ .

There are three main ways of cable heat transfer: heat conduction, heat convection and heat radiation. The numerical algorithm of heat transfer provides the boundary conditions of three kinds of thermal fields. The first boundary condition is the known boundary temperature. The second boundary condition is the known boundary normal heat flux density. The third type of boundary condition is the convection boundary condition, that is, the convection heat transfer coefficient and the fluid temperature are known. The control equations corresponding to the three boundary conditions in turn are shown in equation (23)-(25).

$$T(x, y)|_{\tau} = f(x, y)|_{\tau} \quad (23)$$

$$\lambda \frac{\partial T}{\partial n} |_{\tau} + q_2 = 0 \quad (24)$$

$$-\lambda \frac{\partial T}{\partial n} |_{\tau} = \alpha (T - T_f) |_{\tau} \quad (25)$$

Where:  $\lambda$  is the thermal conductivity coefficient,  $W/(m \cdot K)$ ;  $q_2$  is the heat flux density,  $J/(m^2 \cdot s)$ ;  $\alpha$  is the convection heat transfer coefficient,  $W/(m \cdot K)$ ;  $T$  is the fluid temperature,  $^{\circ}C$ ;  $\tau$  is the integral boundary. It is difficult to determine the ambient boundary temperature and boundary heat flow density around the cables laid in the air, so the boundary conditions of category 1 and category 2 are not applicable.

Considering the natural convection, the external air velocity is less than  $0.15\text{m/s}$ , so the boundary of the cable transient temperature field model can be set with the third boundary condition.

#### 4.3 Excitation setting

The heat sources of cables are mainly divided into three categories: joule loss in cable conductors, dielectric loss in insulation, and metal sheath loss. The calculation of the above three types of heat sources can be carried out in reference [11] and will not be described here.

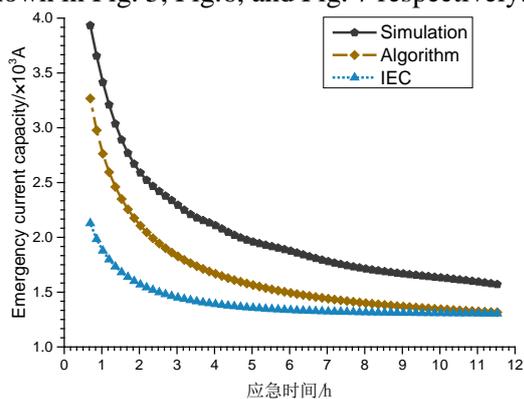
Under the physical field setting conditions mentioned above, the steady-state current capacity of this type of cable in the air laying mode is obtained through finite element simulation as  $1438\text{A}$ . According to the N-1 criterion for safe operation of power grid, the most severe working condition is studied, that is, when  $N=2$ , if the primary cable fails, at this time, the intact cable of the other primary needs to bear a load twice of normal load. Therefore, 1-2 times steady-state current capacity is set as the range of emergency overload, and the change curves of emergency current capacity and emergency time in this range is studied.

During simulation, step load is applied. First, the initial load is added long enough to make the cable reach steady state. Emergency loads are applied on a steady-state basis. With a temperature limit of  $90\text{ }^\circ\text{C}$  of cable conductor, get emergency load time curve.

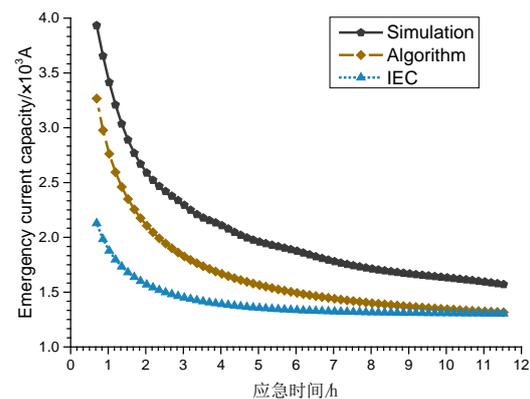
### 5. Analysis of algorithm and finite element simulation results

To study the impact of initial load on emergency response time and emergency current capacity, three initial loads of  $800\text{A}$ ,  $1000\text{A}$  and  $1200\text{A}$  are set respectively.

The simulation results are compared with the results of the improved algorithm for emergency current capacity proposed in this paper and the calculation results of IEC standard. The emergency current capacity and emergency time curves calculated by different algorithms under the three initial loads are shown in Fig. 5, Fig.6, and Fig. 7 respectively.

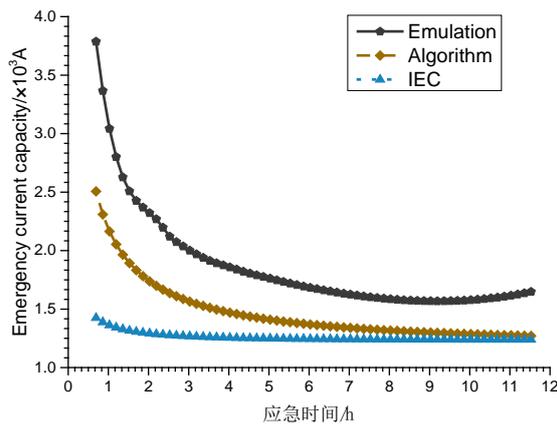


**Fig. 5** Calculation result curves from three methods under initial load of  $800\text{A}$

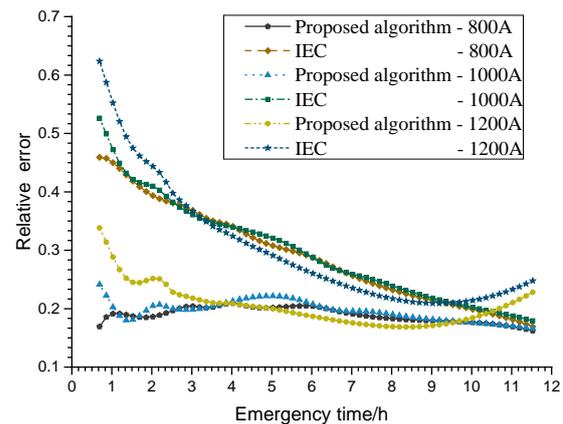


**Fig. 6** Calculation result curves from three methods under initial load of  $1000\text{A}$

In order to compare the error between the improved algorithm proposed in this paper and the calculation result of IEC standard with that of the finite element simulation result, the relative error curve is drawn as shown in Fig. 8.



**Fig. 7** Calculation result curves from three methods under initial load of 1200A



**Fig.8** Error curves of emergency current capacity calculated by three methods under different initial loads

- 1) In the range of 1-2 times of overload studied in this paper, the emergency current capacity curve of the algorithm in this paper and IEC standard are both lower than the simulation calculation curve in the 8-hour emergency time, and also there is a certain margin, indicating that the predicted load of the algorithm and IEC curve is safe and will not damage the cable.
- 2) Under three initial loads of 800A, 1000A and 1200A, the emergency current curve calculated by the algorithm proposed in this paper is closer to the simulation curve than the IEC standard. Therefore, the emergency current algorithm based on real-time measurement data is adopted to calculate the emergency current capacity with higher accuracy and better utilization for the potential transmission capacity of the line.
- 3) The impact of initial load on the result curve of emergency current capacity is more obvious in the case of short emergency time, while the impact of initial load is very small in the case of long emergency time.
- 4) Taking the emergency current curve obtained by finite element simulation as reference, in the case of short emergency time, the relative error of emergency current capacity calculated by IEC standard is much greater than that of the emergency current capacity algorithm based on real-time measurement data. And the shorter the emergency time, the better the correction effect of the algorithm for IEC calculation results. Under the initial load of 800A, the relative error of IEC algorithm's emergency current capacity within 1h is 0.45, while the algorithm proposed in this paper is only 0.15. Under the initial load of 1200A, the maximum relative error of IEC algorithm within 1h reaches 0.63, while the algorithm proposed in this paper is 0.35.

## 6. Conclusion

- 1) Taking the finite element simulation results as a reference, the calculation results curves of IEC standard and the emergency current capacity algorithm based on real-time measurement data are both under the curve of the finite element simulation results, and have a certain degree of margin, indicating that the algorithm results are safe and reliable. Compared with the calculation result of IEC standard, the calculation curve proposed in this paper is closer to the finite element simulation result curve, with higher accuracy and higher utilization rate of potential transmission capacity of the line.
- 2) The length of the emergency response time and the size of the initial load have an impact on the calculation results of the emergency current capacity algorithm based on real-time measurement data proposed in this paper. The impact of initial load on the result curve of emergency current capacity is more obvious in the case of short emergency time. As the emergency time increases, the error of the algorithm under different initial loads tends to be consistent.

3) In the power grid dispatching, according to the N-1 safety criterion, it is the emergency load of 1 to 2 times the steady-state carrying capacity that needs to be considered in practice. At the same time, for the safety of line operation, the emergency time for the line to carry a large load is generally short. When the emergency time is short, the error of the algorithm proposed in this paper is far less than the error from the calculation result of IEC standard, and the shorter the emergency time, the better the correction effect of the algorithm for IEC calculation results. For the practical application, the shorter the emergency time, the more obvious the superiority of using the algorithm proposed to calculate the emergency capacity is, and the stronger the guiding significance will be.

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