

Accurate Simulations of Thermal Field of Operational Conductors

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Abstract. It is of significant importance to compute the exact thermal field of operational conductors so as to increase loading ampacity of operational transmission line in a safe manner. This paper performs an accurate thermal analysis for operational transmission conductors based on the two-dimensional steady-state heat transfer control functions. A refined finite element model for the section of conductor is used, which considers the main sources of heat gains, heat loss and studies the key factors affecting the radial temperature distribution. A typical aluminum conductor steel reinforced (ACSR) conductor is studied using the model presented herein, and the thermal distribution in its section is obtained. This paper discusses the effects of loading ampacity and convection condition on thermal field of conductors.

1. Introduction

The domestic and industrial electric consumption increase rapidly along with the economic development. The inadequate power supply becomes a more and more critical problem. Several methods are adopted to solve the shortage of current-carrying capacity of operational transmission conductor [1]. Using these methods, the determination of operational conductor temperature is one of the most critical but very difficult task. Firstly, several factors influence the thermal field of conductor, such as loading ampacity, solar radiation, air convection, radiation, etc [2]. Furthermore, the existence of radial temperature distribution within a conductor, which is proved by indoor and outdoor measurements on tensioned stranded conductors carrying current loading [3], makes thermal field analysis more complicated.

In this paper, a new method is proposed to simulate the radial thermal field of a conductor in the operational conditions. Firstly, a numerical method is established based on 2-D steady-state heat transfer control functions to exactly solve radial thermal field of conductor by taking main heat gain and heat loss of conductors into account. Subsequently, the influence of loading ampacities and convective conditions to radial thermal field are studied through the case studies of ACSR conductor.

2. Thermal field solution of operational conductor

2.1 Establishment of Steady Thermal Transfer Equation

In the solution of thermal field of conductor, factors such as conductor current, surrounding environment,



and so on, are assumed to remain unchanged in the limited length of transmission line, and thus the temperature of conductor along its longitudinal direction can be regarded as the same. Heat transfer through strands and voids within a conductor accords with the 2D steady thermal transfer control equation, and thus heat equilibrium equation in the whole sectional area Ω is established as follows[4]:

$$k(T_{,xx} + T_{,yy}) + s = 0, \quad (x, y) \in \Omega \quad (1)$$

and the equilibrium equation of heat dissipation at the boundary of conductor Γ is [4]:

$$q_n = -k(T_{,x}n_x + T_{,y}n_y) = \alpha(T - T_a), \quad (x, y) \in \Gamma \quad (2)$$

where T is the two-dimensional temperature field in the conductor; $T_{,xx}$, $T_{,yy}$, $T_{,x}$ and $T_{,y}$ are the second and first derivative of coordinates x and y , respectively; k is the thermal conductivity of the metal or air; s is the heat gain rate per unit volume and its value varies in different areas of a conductor; q_n is the heat loss rate in the outward normal direction of conductor surface; n_x , n_y are the x and y component of the normal direction n , respectively; α is the composite coefficient of heat dissipation; T and T_a are the surface temperature of conductor and the ambient temperature, respectively.

2.2 Computation of Heat Gain and Heat Loss

Aluminum cable steel reinforced (ACSR) conductors, widely used in the existing overhead transmission lines, are chosen for discussion of heat gain and loss, and radial heat transfer. A typical cross section of ACSR conductors consists of outer-layer aluminum strands and inner-layer steel strands. The heat gain rate of steel core per unit volume is:

$$s_s = \frac{P\lambda / (\lambda + 1)}{A_s} \quad (3)$$

where A_s is the sectional area of steel core; P is the total heat gain rate; λ is the current ratio of steel core I_s to aluminum strands. For the outer-layer aluminum strands, solar heating should be taken into consideration, and thus the heat gain rate per unit volume is:

$$s_a = \frac{P/(\lambda + 1)}{A_a} + \frac{\gamma_s SD}{A_a} \quad (4)$$

A_a is the sectional area of aluminum strand; S is the solar radiation intensity; γ_s is the solar radiation absorptivity of conductor; D is the external diameter of conductor.

Based on the principle that heat loss rate remains constant, the composite thermal dissipation coefficient of conductor surface in Eq. (2) can be determined as follows[5]:

$$\alpha = \frac{P_c + P_r}{(T_{sur} - T_a)A} \quad (5)$$

where convective cooling P_c and radiative cooling P_r are two major ways of heat loss for ACSR conductors. T_{sur} is the average surface temperature of conductor, A is the side superficial area per length.

2.3 Numerical Iterative of Thermal Field Solution

Several critical parameters in the basic formulas of radial temperature field (see Eq.(1-2)), are the function of mean temperature or surface temperature of conductor, such as thermal conductivity of air, heat gain rate of steel core and aluminum strands per unit volume, and composite coefficient of heat dissipation. Hence, an initial conductor temperature is given before hand, and then a series of numerical iterations are used to obtain a stable solution of radial thermal field of conductor.

3. Parameter analysis of conductor radial temperature

3.1 FE Model of ACSR Conductor

Taken as an example, the FE model of type-LHA2/LB1A-227/10 ACSR conductor is established according to geometrical parameters of the conductor. The conductor consists of 1 steel-core strand and

18 aluminum strands, and its standard cross section is shown in Figure 1(a). The FE model of type-LHA2/LB1A-227/10 ACSR conductor is established and shown in Figure 1(b).

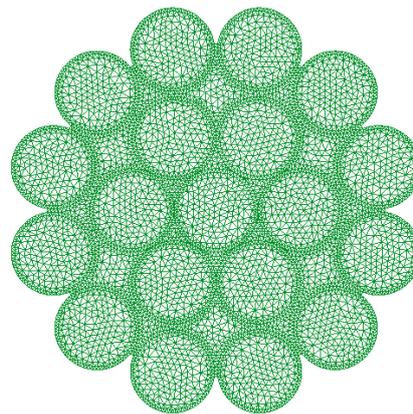
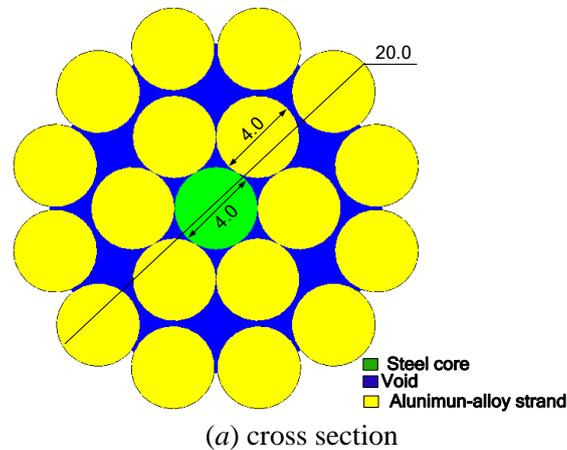


Figure 1. Type-LHA2/LB1A-227/10 ACSR conductor

3.2 Effects of Ampacity on Radial Temperature of Conductor

To analyze the ampacity effect on radial temperature of operational conductor, the radial temperature field of type-LHA2/LB1A-227/10 ACSR conductor under different current loadings are simulated, and all of them remain in the nature convection condition (wind speed = 0). The alternating current gradually increases from 160 to 660A at an interval of 100A. To perform this calculation, some fundamental computational parameters are required and input as follows: resistivity of steel core and aluminum strand are $\rho_s = 20 \times 10^{-8} \Omega \cdot m$ and $\rho_a = 3.253 \times 10^{-8} \Omega \cdot m$; thermal conductivity of steel core and aluminum strand are $k_s = 80 W / (m \cdot C^\circ)$ and $k_a = 237 W / (m \cdot C^\circ)$; solar radiation is $S = 300 W / m^2$. Then, the thermal field of the conductors is determined by the aforementioned iterative solution method. Fig.2 shows the radial temperature field of the typical type of ACSR conductor under the current of 360 A in nature convection condition. The results indicate that the highest temperature exists in the inner layer of aluminum strands and the innermost layer of steel core; the lowest temperature is in the outmost layer of aluminum strands, and the maximum temperature difference within the conductor is around $4^\circ C$.

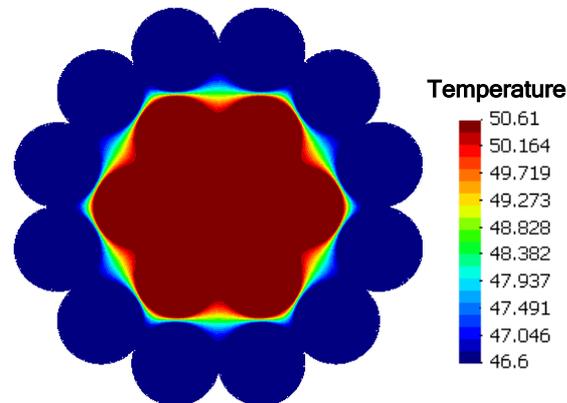


Figure 2. Radial temperature field of type-LHA2/LB1A-227/10 ACSR conductor

To study the relationship between ampacity and radial temperature distribution in the natural convection condition, the current loading gradually increases from 160 A to 660 A. Parameters to be analyzed include heat gains rate of steel core and aluminum strand per unit volume, composite coefficient of heat dissipation, the highest and the lowest temperature, and the temperature difference. All results are listed in Table 1 for comparisons. Some major conclusions can be drawn from the table that: (1) the heat gain rate per unit volume of aluminum strand is significantly larger than that of steel core; (2) the overall temperature increase along with the increase of current loading; (3) the temperature difference within the cross section of conductor significantly increases with the current loading, and it can reach 13.38°C at the 660 A. Because heat insulators in a conductor, such as air encapsulated between the strands, leads to low efficiency and inhomogeneous of heat transmission

Table 1 Relationship of radial temperature distribution parameters and current loading in the natural convection condition

Ampacity	Heat gain rate per unit volume of SC ($\text{W}/\text{m}^2\cdot^{\circ}\text{C}$)	Heat gain rate per unit volume of AS ($\text{W}/\text{m}^2\cdot^{\circ}\text{C}$)	Composite coefficient of heat dissipation	Highest temp. ($^{\circ}\text{C}$)	Lowest temp. ($^{\circ}\text{C}$)	Maximum Temperature difference ($^{\circ}\text{C}$)
160A	2.73E+03	3.00E+04	8.71	30.53	29.35	1.18
260A	7.43E+03	5.89E+04	9.75	38.75	36.45	2.30
360A	1.47E+04	1.03E+05	10.65	50.61	46.60	4.01
460A	2.52E+04	1.68E+05	11.62	65.86	59.48	6.38
560A	3.91E+04	2.54E+05	12.44	85.05	75.59	9.46
660A	5.77E+04	3.68E+05	13.45	108.00	94.62	13.38

Notes: SC-steel core; AS: aluminum strand

3.3 Effects of Convection Condition on Radial Temperature of Conductor

Convective heat loss of conductor can be mainly divided into two types: natural convection and forced convection. Natural convection (wind velocity $V_w = 0$) occurs in the still air conditions, where, in a continuous process, cool air surrounding the hot conductor is heated and rises, and then replaced by cool air. Forced convection (wind velocity $V_w \neq 0$) occurs when blowing air passes through conductor and takes away the heated air. In this section, the influence of convection conditions on radial temperature distribution of a conductor is studied, and other parameters are assumed to remain constant. The wind velocity is assumed to $V_w = 0.6$ m/s and wind direction is $\delta = 30^{\circ}$. Based on the aforementioned numerical solution procedure, the thermal field of conductor in the forced convection condition are simulated, and the results of different cases are listed in Table 2. Comparing with those in the natural convection condition (see Table 1), some phenomena can be found that (1) regardless of convection condition, the highest, the lowest temperature and the maximum temperature difference all nonlinearly

increase with the current loading; (2) forced convection can lower the overall temperature; (3) convection condition has little influence on the maximum temperature difference.

Table 2. Relationship of radial temperature distribution parameters in forced convection and ampacity

Ampacity	Heat gain of SC (W/m ³)	Heat gain Of AS (W/m ² ·°C)	Composite coefficient of heat dissipation	Highest temperature (°C)	Lowest temperature (°C)	Maximum Temperature difference (°C)
160A	2.69E+03	3.00E+04	15.42	26.42	25.25	1.17
260A	7.26E+03	5.89E+04	15.50	32.45	30.17	2.28
360A	1.43E+04	1.01E+05	15.60	41.60	37.66	3.94
460A	2.44E+04	1.63E+05	15.81	54.46	48.17	6.29
560A	5.38E+04	3.44E+05	16.16	70.80	61.55	9.25
660A	5.49E+04	3.51E+05	16.29	91.79	78.75	13.04

Notes: SC-steel core; AS: aluminum strand

4. Conclusions

This paper performs an accurate thermal analysis for operational transmission conductors based on the two-dimensional steady-state heat transfer control functions. By using a refined finite element model for the conductor section, the main sources of heat gains and heat loss are considered and the key factors affecting radial temperature distribution are studied. The thermal distribution in the section of a typical aluminum conductor steel reinforced (ACSR) conductor is calculated, and the influences of loading ampacity and convective conditions to thermal field of conductor are discussed.

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