Temperature field analysis and calculation of augmented capacity conductor

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Abstract. Augmented capacity conductors (ACC) are emerged with the increase of electricity demand and the improvement of materials science and technology. Transient current-carrying capability (CCC) of ACC has an important effect on the reliability service of the power grid, and it has a closely relationship with the temperature distribution of the ACC, while few academic are conducting. In view of this problem, the fine calculation of the temperature field of the ACC by the Finite element analysis is conducted, aiming to analysis the temperature distribution of ACC and increase the reliability service of the power grid. In this paper, based on the calculation of heat source and thermal convection coefficient of ACC, the thermal model of one type of the ACC is established, and the calculation results are verified by the experiment.

Keywords: Augmented capacity conductors, thermal field, Finite element analysis, load capacity.

1. Introduction

With the sustained and rapid development of China’s national economy, the demand for power electricity is growing dramatically. Therefore, various projects, for example, the transmission of electricity from the west to the east, the mutual supply from the north to the south, and the nationwide interconnection are started. These new transmission lines will be able to transport more electricity, but with the increase of the new transmission lines, more land and investment are needed. At present, the usage of land is shortage, especially for the eastern coastal area and large and medium-sized cities, so more land for new lines is difficult. On the other hand, the transmission capacity of electric energy of the original lines can be increased by increasing the cross-sectional area of wires. However, the height and strength of support tower and even the steel tower need to be replaced due to the increase of cross-sectional area of wires. So, in order to avoid the above two cases, new types of wires are need to be adopted, which have the similar types or parameters with the original wires. For this reason, a variety of ACC for changing the old lines are produced [1]–[3].

ACC is a special wore used in overhead transmission lines. It is a general name of several kinds of wires that can transmit more electric energy compared with the traditional steel-cored aluminum stranded wire [1], [2], [4], [5]. Up to now, there have been a variety of new wire species in the world,
which can be summarized into two categories. One is to increase the transmission capacity of the wire, and the temperature limit of this wire is higher, while the strength of the conductive part is not reduced, it is still maintain close to the total tensile force at room temperature, such as the series of heat resistant aluminum alloy conductor wires. The other kind focuses on the energy saving of the conductive part, the conductive part usually has a high conductivity, while the overall mechanical properties of the conductor are borne by the load-bearing core. Even if the current carrying capacity and temperature of the conductor are increased, these wires can also be operated safely, such as the series of wires with organic composite material as the reinforcing core [2], [6], [7].

Based on the development demand above, the new technology of ACC is developing rapidly, which provide a sufficient option for power construction and design departments. Up to 2008, a variety of ACC, including steel core heat-resistant aluminum alloy strand, gap type heat-resistant aluminum alloy strand, Yin steel core super-heat-resistant aluminum alloy strand, synthetic core heat-resistant aluminum strand et al. have been used in construction in Jiangsu province. The research of ACC will have a great significance for saving project investment, improving the transmission capacity, extending the life, ensuring the safety operation of line and reducing the operation cost of power grid.

CCC and temperature are the two important parameters for designing and operation of ACC. At present, the CCC of ACC is usually calculated at steady state, where the ACC can operate for a long time. However, the disturbance and fault are need to be considered when designing for the ACC. Since disturbance and fault usually bring the short-time overload, which will increase requirements on the transmission line, and then the short-time overload capacity of the line becomes very important. The transient CCC of transmission lines is the main factor that restricts the transmission capacity. However, temperature of conductor usually changes with the current of the conductor asynchronously, and the temperature of the conductor will lag behind the change of the current. Therefore, increasing the CCC of the conductor in the excessive time of the temperature change of the conductor will cause an electric accident, which will lead to unnecessary power failure. In addition, the surface temperature of the wire is usually as the working temperature of the wire when calculating the CCC of the conductor, which is due to the heat exchange between the surface of the wire and the air, but the core temperature inside the wire determines the size of the sag of the wire. Therefore, it is necessary to calculate the temperature field and study the temperature distribution of ACC carefully.

The object of this paper is to study the temperature distribution of ACC from the angle of improving the safe operation. By taking aluminum augmented capacity conductor (ACCR) as an example, the temperature field model of ACCR is established in section two. In the third section, the relevant thermal parameters, such as heat source and convection coefficient are calculated. In the fourth section, the finite element simulation results are verified by the experimental data.

2. Thermal field model of ACCR
ACC is composed of different conductor materials and reinforcing materials, and there are different materials in the radial distribution of the conductor. In the finite element calculation of the ACC, in order to correspond to the actual situation and compare with the existing experimental data, the modeling calculation is carried out based on the meteorological conditions of Jiangsu province and the ACCR-150/25 is used in this paper. Its actual structure of ACCR is shown in Fig.1.

![Figure 1. Real model of the ACCR](image)
In terms of appearance and structure, ACCR as shown in Fig. 1(a) is basically same as aluminum cable steel reinforced (ACSR). And the different is that the steel core is replaced by the ceramic fiber composite core, and the outer aluminum wire is replaced by the aluminum zirconium alloy. The material of the load-bearing core of ACCR wire is a composite material made of alumina ceramic fiber implanted in pure aluminum. This composite is also called metal-matrix reinforced fibers, which consists of a polymer of naphthenic oil and a plastic material, but the basic material is metallic aluminum, each of which is reinforced with thousands of ultra-strong, high-purity alumina fibers. Although the structure of the metal matrix is changed by this composite material changes, but the rigidity is enhanced and the mass is still the same as aluminum. Compared with the steel, the linear expansion coefficient is smaller, and the tensile strength at high temperatures is greater. Therefore, the ACCR have the merit of low creep property, high conductivity and strong corrosion resistance similar to aluminum [3], [10], [11].

2.1. Mathematical model of ACCR
The 2-D temperature field mathematical model of ACCR is shown in formula (1), and the following assumptions are made in the calculation process [12]-[14],

1) Only the heat conduction in the direction of the cross section of ACCR is considered, and the heat conduction along the axial direction is 0;
2) The initial temperature of the environment is 40°C;

\[
\begin{align*}
\frac{\partial}{\partial x}(k_x \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k_y \frac{\partial T}{\partial y}) + q_v &= c \rho \frac{\partial T}{\partial t} \\
k_x \frac{\partial T}{\partial n} l_x &= 0 \\
k_m \frac{\partial T}{\partial n} l_x + \alpha (T - T_f) &= 0
\end{align*}
\]

(1)

Where, \(k_x\) and \(k_y\) are the thermal conductivity along the x and y directions of various material in the ACCR. \(k_a\) and \(k_m\) are the heat transfer coefficients on the first and third boundary conditions respectively. \(q_v\) is the heat source density, \(C\) is the specific heat capacity of the material, \(\rho\) is the density of the material, and \(T\) and \(T_f\) are the real-time temperature and the ambient temperature respectively.

2.2. FEA model of ACCR
The finite element analysis (FEA) model of ACCR is established according to the actual model of ACCR, as shown in Fig.2. In the model, the outer diameter of the wire is 17.2mm, in the wire, two layers of the aluminum wire are arranged, and the number of aluminum wires is 26. The diameter of the single aluminum wire is 2.7 mm, and the conductor area of the aluminum wire is 150 mm². The ACCR contains 7 composite core, and the diameter of single wire is 2.1mm, the area is 25mm². At 20°C, the thermal conductivity of aluminum zirconium alloy is about 235 W/(m·K), the thermal conductivity of air is 0.025 W/(m·K), and the thermal conductivity of ceramic fiber is 5 W/(m·K).
2.3. Calculation of the thermal parameters of ACCR

CCC of ACC at the operating temperature, especially at high temperature load flow is the key parameter for extending the capacity of the conductor, it is also the main basis for extending the capacity of the line. CCC is the maximum steady-state current that causes an acceptable temperature rise on the conductor under given environmental conditions. The CCC depends on the structure size of the conductor, the resistance of the conductor (which is related to the resistivity of the conductor material), the maximum allowable operating temperature and environmental conditions [15]-[16].

The CCC of ACC at steady-state can be calculated by equation (2),

$$I_{\text{max}} = \left( P_{\text{rad}} + P_{\text{conv}} + P_{\text{sol}} \right) / R_T^{1/2} \tag{2}$$

Where $P_{\text{sol}}$, $P_{\text{rad}}$ and $P_{\text{conv}}$ are the heat exchange loss from sunlight, radiation, and heat convection with environment, respectively, and $R_T$ is the resistance of conductor at temperature $T$.

In the conductor, the temperature difference between conductors is very small, so the convection and radiation of air between conductors are ignored. The heat conduction in the conductor is mainly carried out by air gap and the contact between conductors. The heat loss caused by radiation can be calculated by equation (3),

$$P_{\text{rad}} = S\pi D K_e (T_2^4 - T_1^4) \tag{3}$$

Where, $S$ is the Stefan-Boltzmann number ($5.67 \times 10^{-8}$ W/(m²·K⁴)); $D$ is the diameter of conductor (m); $K_e$ is the emissivity coefficient of black body. $T_2$ is the steady-state temperature (K); $T_1$ is the temperature of the environment (K).

The heat source absorbed from the sun light can be calculated by equation (4),

$$P_{\text{sol}} = \gamma DS_i \tag{4}$$

Where $\gamma$ is the solar radiation heat absorption coefficient, $D$ is the conductor diameter (m), $S_i$ is the solar radiation intensity (W/m²).

The heat convection loss $P_{\text{conv}}$ can be calculated by equation (5),

$$P_{\text{conv}} = \lambda N_u (T_2 - T_1) \pi \tag{5}$$

Where $\lambda$ is the heat conduction coefficient of air, and $N_u$ is the Nusselt number, which can be calculate by

$$N_u = 0.65 Re^{0.2} + 0.23 Re^{-0.61} \tag{6}$$

Where $Re$ is the Reynolds number.
3. Simulation of ACCR

3.1. Thermal parameters of ACCR

Since the resistivity of aluminum zirconium alloy is much higher than that of ceramic fiber composite core, and the wire material does not contain the iron material which can produce hysteresis loss and eddy current loss, so for the ACC, only the effect of skin effect is considered. With the influence of skin effect, it is considered that during normal operation, the current only flows through the aluminum zirconium alloy wire, not through the ceramic fiber core.

The heat source density in aluminum zirconium alloy can be calculated by equation (7),

\[ \rho_i = \frac{I_{\text{max}}}{\sqrt{2} N R V_{\text{con}}} \]  

Where, \( I_{\text{max}} \) is the current-carrying capacity of ACCR, \( N \) is the number of Aluminum zirconium alloy wire, \( R \) is the resistance of al zirconium alloy wire, \( V_{\text{con}} \) is the volume of al zirconium alloy wire.

Through the calculation, the corresponding heat source density of ACCR-150/25 under different CCC is shown in Table 1.

| CCC (A) | Heat source density (A/mm²) |
|--------|-----------------------------|
| 341    | 1.1×10⁵                     |
| 417    | 1.6×10⁵                     |
| 478    | 2.2×10⁵                     |
| 651    | 4.1×10⁵                     |
| 800    | 6.1×10⁵                     |

According to equation (3)-(6), the convective heat transfer coefficient 55.23W/(m²·℃) between the wire and the environment is obtained when the current-carrying capacity is 341A, the ambient temperature is 40℃, and the steady-state temperature is 70℃. Similarly, the convective coefficient between ACCR and the environment can be calculated under other CCCs.

3.2. Simulation results analysis

Based on the actual meteorological conditions of Jiangsu province, the CCC of ACCR at high temperature is calculated, as shown in Table 2, which provides a reference for the capacity increasing of the modified line.

Through the simulation calculation, the steady-state temperature distribution diagram of ACCR is shown in Fig. 3 (a) and Fig. 3 (b) respectively when the CCC is 341A and 417A respectively. From the Fig. 3, it can be seen that,

(1) the temperature distribution in ACCR is not uniform, the highest temperature lies in the center of the cross surface, the temperature decreases radially from the center, and the surface temperature is the lowest,

(2) the temperature of the internal ceramic fiber core is basically the same, and the temperature is the highest,

(3) there is a temperature gradient in the aluminum zirconium alloy conductor, and the temperature of the outer conductor is lower;

The allowable temperature and the simulation calculated temperature of ACCR under different current-carrying capacities are shown in Table 2, and the comparison curve is shown in Fig. 4.

From Table 2 and Fig. 4, it can be concluded that the temperature of the simulated ACCR is slightly higher than the allowable temperature, and the error value is within 9%, which is within the error range of the current temperature field.
Figure 3. Temperature distribution of ACCR in different load capacities (a) the load capacity is 341A; (b) the load capacity is 417A

Table 2. Allowable and calculation temperature of ACCR in different load capacities

| CCC (A) | Allowable temperature (°C) | Calculated temperature (°C) |
|---------|----------------------------|-----------------------------|
| 341     | 70                         | 64.16                       |
| 417     | 80                         | 80.97                       |
| 478     | 90                         | 91.83                       |
| 651     | 130                        | 135.857                     |
| 800     | 180                        | 184.8                       |

Figure 4. Comparison between allowable temperature and simulation temperature of ACCR in different load capacities

4. Summary

Based on the analysis of the application of ACCR, it finds that when fault or disturbance occurred, the current-carrying capacity will exceed the value calculated at steady-state. And in order to avoid the troubles caused by the limited CCC at steady-state, it is necessary to calculate the CCC at transient-state, and study the temperature change. In this paper, based on the real structure and the thermal parameters calculation of ACCR-150/25, the thermal model of ACCR-150/25 is established and the temperature distribution of ACCR-150/25 under different CCC are researched. In the end, the simulation results are
verified by the existing experimental results. Temperature of the simulated ACCR is slightly higher than the allowable temperature, and the error value is within 9%, which is within the error range of the current temperature field.

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