Simulation Analysis of Current in Metal Sheath of Power Cable Considering Temperature Characteristics

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Abstract—This paper proposes a cable broadband circuit model considering the temperature characteristics. This paper establishes the equivalent circuit model of the cross-bonded power cable and proposes the broadband parameter calculation method considering the temperature. The cable parameters are calculated by the vector fitting method. Based on the operating current and cable temperature data of the cable on a certain day, the simulation analysis of the cable sheath current considering the temperature is carried out using Simulink. Finally, the simulation results show that the cable sheath current is significantly affected by temperature.

1. Introduction

The widespread use of power cables has brought severe challenges to cable operation, maintenance and overhaul. As the service life increases, power cables continue to age, and cable defects will occur during operation, which will eventually cause operation failures [1]. The cable metal sheath current is one of the important indicators to judge the operating status of cables. Therefore, simulating and analyzing the characteristics of the cable sheath current is important.

To limit the sheath-induced voltage and sheath current, the cable generally adopts the grounding method of metal sheath cross-bonding. Literature [2] proposed a cross-bonded cable model under normal operation but did not consider the leakage current. Literature [3,4] further considered the induced current part and the leakage current part and proposed a power frequency lumped parameter model for calculating the induced current and the leakage current respectively. Based on the commonly used cable frequency domain simulation model, the cable joints and along the cable impedance change are strengthened, which can be used to accurately calculate the transmission line parameters and cable resonance analysis.

Cable parameters are also affected by the temperature of the cable. The temperature of the cable will change during operation, which will affect the resistivity of the cable conductor and the dielectric constant of the insulating material [5]. However, few cable modeling studies consider both the broadband characteristics and temperature characteristics of the cable. Therefore, based on the study of the broadband circuit model of the cross-bonded cable and the cable temperature characteristics, this paper establishes a cable broadband equivalent model and analyzes the cable sheath current by simulation.
2. Cable Broadband Circuit Model Considering Temperature Characteristics

2.1. Equivalent circuit model of the cross-bonded cable
To suppress the current in the metal sheath of the cable, the metal sheath of the single-core cable generally adopts a three-section cross-bonded grounding method. The major section of a typical cross-bonded cable is shown in Fig 1.

![Fig 1 Major section of the cross-bonded cable](image)

The connection mode of the metal sheath inside the cross-bonded box J1 is: the cable section A1 is connected with section B2, the cable section B1 is connected with section C2, and the cable section C1 is connected with the cable section A2. In the same way, in the cross-bonded box J2, the metal sheath connection mode is: the cable section A2 is connected with section B3, the cable section B2 is connected with section C3, and the cable section C2 is connected with the cable section A3. Therefore, the sheath current of the cross-bonded cable flows through three loops, A1-B2-C3, B1-C2-A3, and C1-A2-B3.

The I-shaped lumped parameter model is used to establish the equivalent circuit of the cross-bonded cable, as shown in Figure 2.

![Fig 2 Equivalent circuit model of cross-bonded cable](image)
cable, \(Z_{sa1}(j\omega)\sim Z_{sa3}(j\omega)\), \(Z_{sb1}(j\omega)\sim Z_{sb3}(j\omega)\), \(Z_{sc1}(j\omega)\sim Z_{sc3}(j\omega)\) are the metal sheath impedances of each phase in each section; \(I_{sa1}(j\omega)\sim I_{sa6}(j\omega)\), \(I_{sb1}(j\omega)\sim I_{sb6}(j\omega)\), \(I_{sc1}(j\omega)\sim I_{sc6}(j\omega)\) are the currents flowing through the metal sheath of each phase, \(I_{A1}(j\omega)\sim I_{C1}(j\omega)\) are the currents flowing into each phase core of the cross-bonded cable, and \(I_{A2}(j\omega)\sim I_{C2}(j\omega)\) are the currents flowing out of each phase core of the cross-bonded cable.

2.2. Calculation of cable broadband equivalent circuit parameters considering temperature characteristics

To improve the accuracy of the metal sheath current simulation analysis, this paper considers the broadband characteristics of power cables. The calculation formulas of cable unit conductor frequency-dependent impedance \(z_c(j\omega)\), unit metal sheath frequency-dependent impedance \(z_s(j\omega)\) and unit insulation frequency-dependent admittance \(y_d(j\omega)\) are as follows:

\[
\begin{align*}
z_c(j\omega) &= \frac{1}{2\pi r_c} \sqrt{j\omega \mu_0 \rho_c} + \frac{1}{2\pi r_c} \frac{j\omega \mu_0}{\ln \frac{r}{r_c}} \\
&+ \frac{1}{2\pi r_c} \sqrt{j\omega \mu_0 \rho_c} \\
z_s(j\omega) &= \frac{\rho_s}{\pi (r_s^2 - r_d^2)} + j\omega \left[ \frac{\mu_0}{8\pi} - \frac{\mu_0}{2\pi} \left( \frac{r_s^2}{(r_s^2 - r_d^2)^2} \right) \ln \frac{r}{r_s} \\
&+ \frac{r_d^2}{(r_s^2 - r_d^2)^2} \ln \frac{r_d}{r_s} + \frac{r_s^2}{2(r_s^2 - r_d^2)} \right] \\
y_d(j\omega) &= j\omega \frac{2\pi \varepsilon_r \varepsilon_s}{\ln \frac{r}{r_s}} \\
\end{align*}
\]

Where \(\mu_0\) is the vacuum permeability, \(\varepsilon_0\) is the vacuum dielectric constant, \(r_c\) is the radius of the cable conductor, \(r_d\) is the outer diameter of the cable insulation layer, \(r_s\) is the outer diameter of the cable metal sheath, and \(\varepsilon_r\) is the relative permittivity of the cable insulation material, which is expressed by plural \(\varepsilon_s = \varepsilon_r - j\varepsilon_r^\prime\).

For the XLPE cable, the influence of temperature on the dielectric constant can be ignored, only the influences on the resistivity of the conductor and the metal sheath are considered. The calculation formulas of cable unit conductor frequency-dependent impedance \(z_c(j\omega, \theta_c, \theta_s)\) and unit metal sheath frequency-dependent impedance \(z_s(j\omega, \theta_c)\) considered the temperature characteristics are shown in (4) and (5).

\[
\begin{align*}
z_c(j\omega, \theta_c, \theta_s) &= \frac{1}{2\pi r_c} \sqrt{j\omega \mu_0 \rho_c(\theta_c)} + \frac{1}{2\pi r_c} \frac{j\omega \mu_0}{\ln \frac{r}{r_c}} \\
&+ \frac{1}{2\pi r_c} \sqrt{j\omega \mu_0 \rho_c(\theta_c)} \\
z_s(j\omega, \theta_c) &= \frac{\rho_s(\theta_c)}{\pi (r_s^2 - r_d^2)} + j\omega \left[ \frac{\mu_0}{8\pi} - \frac{\mu_0}{2\pi} \left( \frac{r_s^2}{(r_s^2 - r_d^2)^2} \right) \ln \frac{r}{r_s} \\
&+ \frac{r_d^2}{(r_s^2 - r_d^2)^2} \ln \frac{r_d}{r_s} + \frac{r_s^2}{2(r_s^2 - r_d^2)} \right] \\
\end{align*}
\]

Where \(\theta_c\) is the cable conductor temperature, \(\theta_s\) is the cable sheath temperature, \(\rho_c(\theta_c)\) is the temperature-corrected cable conductor resistivity, and \(\rho_s(\theta_c)\) is the temperature-corrected cable metal sheath resistivity. The calculation formula of the temperature-corrected resistivity \(\rho(\theta)\) is shown as:

\[
\rho(\theta) = \rho_{c0} \left[ 1 + \alpha_{c0} (\theta - 20) \right]
\]
Where \( \rho_{20} \) is the resistivity of the material at 20°C, \( \alpha_{20} \) is the temperature coefficient of resistance of the material, and \( \theta \) is the temperature of the material.

### 3. Parameter Fitting of Power Cable Broadband Circuit Model

In this paper, the vector fitting method is used to calculate the cable frequency variation model parameters. The principle of the vector fitting method is: suppose the frequency domain response function of a certain system is \( F(j\omega) \), the frequency domain response function after fitting is \( F_{\text{fit}}(j\omega) \), which is expressed as:

\[
F_{\text{fit}}(j\omega) = j\omega \sum_{i=1}^{n} \frac{c_i}{j\omega - a_i} + h + d
\]

(7)

Where \( c_i \) is the residue, \( a_i \) is the pole, \( h \) and \( d \) are real numbers, and \( n \) is the number of poles.

The low-order rational function expression of the approximate cable frequency parameters is obtained by the vector fitting method, and the vector fitting result can be equivalent to the series-parallel circuit of passive components. The cable frequency-dependent impedance can be equivalent with an R-L series circuit, and the cable frequency-dependent admittance can be equivalent with a G-C parallel circuit, as shown in Fig 3.

![Fig 3 Equivalent circuits of cable frequency-dependent parameters](image)

The corresponding relationship between the vector fitting results and the parameter values of the components in the equivalent circuits of Figure 3 is as follows: for the frequency-dependent impedance, DC resistance \( R_0 = d \), inductance \( L_0 = h \), resistance \( R_i = c_i \), inductance \( L_i = -c_i/a_i \), \( i = 1, \cdots, N \); for the frequency-dependent admittance, DC conductance \( G_0 = d \), capacitance \( C_0 = h \), conductance \( G_i = c_i \), capacitance \( C_i = -c_i/a_i \), \( i = 1, \cdots, N \).

The cable parameters of a certain 110 kV XLPE cable per unit length are shown in Table 1. In the process of vector fitting, it is considered that the cable conductor temperature \( \theta_c \) and the sheath temperature \( \theta_s \) are both 20°C.

| Tab 1. Main parameters of the 110kV XLPE cable | Value |
|-----------------------------------------------|-------|
| Voltage rating (kV)                           | 110   |
| Conductor cross-sectional area (mm²)          | 1000  |
| Length of each cable section (m)              | 480   |
| Diameter of cable conductor \( d_c \) (mm)     | 38.4  |
| Outer diameter of insulation layer \( d_i \) (mm) | 74.4  |
| Outer diameter of metal sheath \( d_s \) (mm) | 80.4  |
| Outer diameter of outer sheath \( d_e \) (mm) | 87.6  |
| Resistivity of cable core at 20°C \( \rho_{c20} \) (Ω·m) | \(1.75 \times 10^{-8}\) |
| Resistivity of metal sheath at 20°C \( \rho_{s20} \) (Ω·m) | \(21.4 \times 10^{-8}\) |
| two-phase space between AB and BC \( s \) (m) | 0.27  |
| Distance between cable and temperature measuring point \( L \) (m) | 0.5   |
According to the results obtained by vector fitting $d$, $h$, $c_i$ and $a_i$, the resistance, the inductance, conductance, and the capacitance of each level in Fig 3 are calculated. The fitting parameters are shown in Tab 2-Tab 4.

**Tab 2** Fitting parameters of the $R$-$L$ equivalent circuit for conductor frequency-dependent impedance

| Resistance | Value ($\Omega$/m) | Inductance | Value (H/m) |
|------------|--------------------|------------|-------------|
| $R_0$      | $3.3842 \times 10^{-5}$ | $R_0$      | $1.5129 \times 10^{-7}$ |
| $R_1$      | $1.8112 \times 10^{3}$  | $R_1$      | $2.0119 \times 10^{-3}$ |
| $R_2$      | $1.3598 \times 10^{3}$  | $R_2$      | $6.9649 \times 10^{-4}$ |
| $R_3$      | $1.6632 \times 10^{2}$  | $R_3$      | $3.8737 \times 10^{-4}$ |
| $R_4$      | $1.2127 \times 10^{1}$  | $R_4$      | $1.9587 \times 10^{-4}$ |
| $R_5$      | $3.5548 \times 10^{-3}$ | $R_5$      | $6.8873 \times 10^{-5}$ |
| $R_6$      | $4.3656 \times 10^{-4}$ | $R_6$      | $2.0681 \times 10^{-5}$ |

**Tab 3** Fitting parameters of the $R$-$L$ equivalent circuit for sheath frequency-dependent impedance

| Resistance | Value ($\Omega$/m) | Inductance | Value (H/m) |
|------------|--------------------|------------|-------------|
| $R_0$      | $2.5727 \times 10^{-4}$ | $R_0$      | $5.2695 \times 10^{-7}$ |
| $R_1$      | $1.2655 \times 10^{-5}$ | $R_1$      | $1.7925 \times 10^{-7}$ |
| $R_2$      | $1.8530 \times 10^{-5}$ | $R_2$      | $7.0997 \times 10^{-7}$ |
| $R_3$      | $1.0937 \times 10^{-6}$ | $R_3$      | $1.4781 \times 10^{-6}$ |
| $R_4$      | $5.5284 \times 10^{-7}$ | $R_4$      | $3.07138 \times 10^{-5}$ |
| $R_5$      | $6.8012 \times 10^{-8}$ | $R_5$      | $2.2521 \times 10^{-5}$ |
| $R_6$      | $2.9605 \times 10^{-8}$ | $R_6$      | $5.8589 \times 10^{-5}$ |

**Tab 4** Fitting parameters of the $G$-$C$ equivalent circuit for insulation frequency-dependent admittance

| Conductance | Value ($S$/m) | capacitance | Value (F/m) |
|-------------|---------------|-------------|-------------|
| $G_0$       | $1.2719 \times 10^{-7}$ | $C_0$     | $1.8128 \times 10^{-10}$ |
| $G_1$       | $2.6302 \times 10^{1}$  | $C_1$     | $4.6655 \times 10^{-4}$  |
| $G_2$       | $2.6285 \times 10^{1}$  | $C_2$     | $3.6654 \times 10^{-4}$  |
| $G_3$       | $1.4252 \times 10^{-3}$ | $C_3$     | $3.6978 \times 10^{-5}$  |
| $G_4$       | $1.4178 \times 10^{-3}$ | $C_4$     | $3.6989 \times 10^{-5}$  |
| $G_5$       | $3.7055 \times 10^{-8}$ | $C_5$     | $2.0586 \times 10^{-7}$  |
| $G_6$       | $1.7480 \times 10^{-9}$ | $C_6$     | $3.2981 \times 10^{-7}$  |

Substituting the data in Tab 2-Tab 4, the equivalent circuit of the conductor frequency-dependent impedance, the sheath frequency-dependent impedance, and the insulation frequency-dependent admittance can be obtained.
4. Case Study
Simulink is used to simulate the cable model, and the main parameters of the model are shown in Tab 1. Based on the cable broadband equivalent model, the current of the metal sheath is simulated. The simulation results are as shown in Fig 4.

![Fig 4 Simulation results of cable sheath current](image)

As can be seen from Fig 4, the magnitude of the sheath current simulation value is related to the cable operating current, and the changing trend of the sheath current is consistent with the changing trend of the cable operating current. The cable temperature has a significant impact on the sheath current, but it has little effect on the changing trend of the sheath current, and the simulation value of the sheath current when the temperature is not considered is higher than cable sheath current considering the temperature. Comparing the two cable sheath current curves, we can see that the maximum difference between the two current curves appeared at the 9th hour, with an absolute value of 3.67 A and a relative error of 4.2%.

The requirement for the live test results of the cable sheath ground current is: the ground current should be less than or equal to 100 A, and the ratio of the ground current to the load current should be less than 20%. When the cable operating current increases, the temperature of the cable will increase accordingly and will affect the current value of the cable sheath. According to the current simulation results of the cable metal sheath considering the influence of temperature, it can be seen that the influence of temperature will increase the resistance of the cable metal sheath and cause the current value of the metal sheath to decrease. Therefore, when judging the operating state of the metal sheath, the influence of temperature should be considered. This article suggests improving the criterion of the ground current of the metal sheath and reduces the threshold of the normal value of the metal sheath current by 5% to exclude the impact of temperature on the judgment of the operating state of the cable metal sheath.

5. Conclusion
This paper proposes a cable broadband circuit model that takes into account the temperature characteristics. Taking the major section of the cross-bonded cable as the research object, the equivalent circuit model is established, and the cable broadband parameter calculation method considering the...
temperature characteristics is proposed. The cable parameters are calculated by the vector fitting method. Based on the operating current and cable temperature data on a certain day, a simulation analysis of the cable sheath current is carried out. The simulation results show that the cable sheath current is significantly affected by temperature. The simulation value of the cable sheath current considering the temperature is lower than the simulation value of the cable sheath current not considering the temperature, and the maximum difference reaches 4.2%. In summary, the cable broadband circuit model considering the temperature characteristics proposed can improve the accuracy of the cable metal sheath current calculation, and then provide guidance for the monitoring and identification of the cable operating state.

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