Postprint: Current-Carrying Temperature Rise Model for High-Voltage Overhead ACCC Conductors Based on Particle Swarm Identification

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Abstract

The current-carrying temperature rise model of overhead conductors constitutes the theoretical foundation for dynamic line rating decisions, safe operation condition monitoring, and current-carrying capacity assessment. However, due to disparities in materials, structure, and operating temperature between carbon fiber composite core conductors (ACCC conductors) and conventional overhead conductors, existing current-carrying temperature rise calculation models cannot be directly applied to ACCC conductors, thereby constraining the development of dynamic line rating for ACCC conductors and the exploitation of their transmission potential. To this end, this paper establishes a current-carrying temperature rise model for ACCC conductors based on the heat balance principle and thermoelectric analogy theory, and utilizes particle swarm optimization algorithm to identify and solve for the model parameters. An experimental platform for ACCC conductor current-carrying temperature rise was designed, and its thermal dynamic process was measured and simulated under natural convection conditions. The results demonstrate that the particle swarm identification method can effectively identify model parameters, and the model exhibits high accuracy in calculating the conductor temperature rise process.

Full Text

Preamble

Current-Temperature Model of ACCC Conductors Based on PSO Identification Method

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Abstract

The current-temperature model of overhead conductors serves as the theoretical foundation for dynamic capacity-increasing decisions, safe operation monitoring, and ampacity evaluation. However, due to differences in material, structure, and operating temperature between Aluminum Conductor Composite Core (ACCC) conductors and traditional overhead conductors, existing current-temperature calculation models cannot be directly applied to ACCC conductors, limiting the development of dynamic capacity-increasing technology and the exploitation of transmission potential for ACCC conductors. This paper establishes a current-temperature model for ACCC conductors based on thermal equilibrium principles and thermoelectric analogy theory, and employs particle swarm optimization (PSO) to identify the model parameters. An experimental platform for ACCC conductor current-temperature rise was designed to measure and simulate the thermal dynamic process under natural convection conditions. Results demonstrate that the PSO identification method can effectively determine model parameters, and the proposed model achieves high accuracy in calculating conductor temperature rise processes.

Keywords: ACCC conductors, current-temperature model, parameter identification

2. Current-Temperature Model for High-Voltage ACCC Conductors

The operating temperature of overhead conductors is a critical indicator for transmission line condition monitoring, serving as the primary basis for line ampacity determination, dynamic capacity-increasing decisions, and safe operation [1,2]. The current-temperature calculation model, which establishes the relationship between conductor operating temperature and current carrying capacity, can accurately predict conductor temperature rise processes and holds significant guiding importance for power system transmission lines. This model is commonly applied in monitoring line safe operation status and evaluating current-carrying capacity, as well as in correcting line equivalent parameters, improving power flow calculation accuracy, enabling electro-thermal coordinated dispatching, and optimal power flow calculations [3,4], thereby exerting substantial influence on theoretical research into traditional power system safety analysis and dispatching, with important theoretical significance and practical engineering value.

Currently, research on current-temperature models for overhead conductors has reached a mature stage, primarily encompassing standard models, numerical simulation models, and thermal circuit models. Standard models mainly refer to the IEC 61597-1995 standard model [4] and the IEEE 738-2006 standard model [5], which can calculate conductor operating temperature under various meteorological and current conditions to determine line ampacity. The IEEE model can also calculate conductor temperature dynamics in real-time, offering greater practical value than the IEC model [6], and continues to be refined for practical application in dynamic capacity-increasing technology. Numerical models based on heat transfer theory discretize the partial differential equations describing conductor thermal dynamics in space and time to simulate the conductor temperature field [7-9]. However, these models involve enormous computational loads that hinder practical implementation. The thermal circuit model introduces thermoelectric analogy theory into the IEEE model, effectively simplifying complex heat transfer calculations through circuit analysis [10-12]. Compared with the IEEE model, the thermal circuit model can characterize conductor thermal dynamics with fewer parameters, making it suitable for dynamic line rating applications.

For new Aluminum Conductor Composite Core (ACCC) conductors, despite their advantages of light weight, high strength, large ampacity, low sag, and corrosion resistance—offering clear benefits and broad application prospects for line capacity-increasing upgrades [13-18]—differences in material, structure, and operating temperature from traditional overhead conductors result in distinct electrical and thermal parameters. Consequently, the aforementioned current-temperature models cannot be applied to ACCC conductors. Unfortunately, ACCC conductors remain in the development and research stage, with limited studies on their parameters, which constrains the establishment of current-temperature models for ACCC conductors.

Therefore, this paper focuses on ACCC conductors, establishing a current-temperature model based on thermal equilibrium principles and thermoelectric analogy theory, and proposes a parameter identification method using particle swarm optimization algorithm to provide necessary support for dynamic capacity-increasing and safe operation of ACCC transmission lines.

The cross-section and physical model of ACCC conductors are shown in [Figure 1: see original paper]. During operation, conductors exchange heat with the environment due to solar radiation, ambient temperature, and wind speed. According to the thermal equilibrium principle, the thermal dynamic process of ACCC conductors can be expressed as:

$$C\frac{dT_c}{dt} = q_I + q_s - q_c - q_r$$

where t is time; T_c is conductor temperature; C is conductor heat capacity; $q_I = I^2R(T_c)$ is the conductor’ s self-heating power; $R(T_c)$ is the AC resistance at temperature T_c; q_s is solar heat gain; q_c is convective heat loss; and q_r is radiative heat loss.

Based on thermoelectric analogy theory, the thermal circuit model of ACCC conductors can be represented as the circuit model shown in [Figure 2: see original paper], which can be rewritten as:

$$C\frac{dT_c}{dt} = q_I + q_s - \frac{T_c - T_e}{R_e}$$

The line ampacity can be expressed as:

$$I_{\max} = \sqrt{\frac{T_{\max} - T_e - q_s + q_r}{R(T_{\max})}}$$

where R_e is the equivalent environmental thermal resistance between the conductor surface and environment; $T_{\max}$ is the maximum allowable operating temperature. Studies have shown that ACCC conductors can operate continuously at temperatures up to 160°C, with short-term operating temperatures exceeding 200°C [19].

Parameters in the thermal circuit model are calculated as follows:

$$q_s = \gamma D S_i$$

$$q_r = \varepsilon \sigma D k_e (T_c^4 - T_e^4)$$

$$R(T_c) = R_{\text{ref}}[1 + \alpha(T_c - T_{\text{ref}})]$$

where α is the resistance temperature coefficient; R_{ref} is the AC resistance at reference temperature T_{ref} (generally 20°C); D is conductor outer diameter; S_i is solar radiation intensity; σ is the Stefan-Boltzmann constant; γ and k_e are the absorptivity and emissivity of the conductor surface material, typically taken as 0.5 in engineering practice.

3. PSO Identification of Thermal Circuit Model Parameters

In the proposed thermal circuit model, theoretical determination of parameters C, R_{ref}, and α remains challenging for two primary reasons. First, the ACCC conductor core consists of cylindrical carbon fiber composite material, making its heat capacity difficult to calculate directly from theory. Second, due to insulation resin encapsulation, the core exhibits non-conductive and non-magnetic properties, eliminating eddy current and magnetic losses in the conductor. Therefore, unlike traditional overhead conductors, the resistance increment caused by eddy currents and magnetic hysteresis in ACCC conductor AC resistance can be neglected, making R_{ref} and α in Eq. (6) difficult to reference from traditional conductor calculations.

Literature [20] indicates that environmental thermal resistance R_e is essentially related to the temperature difference between conductor and environment. Considering that exponential functions can describe both linear and nonlinear variable variations, this paper expresses environmental thermal resistance as:

$$R_e = a(T_c - T_e)^b$$

where a is a proportionality factor related to conductor diameter and air density; b is an exponential factor. Both a and b are unknown and must be determined through identification methods.

To obtain these model parameters, an objective function must first be established. At time $k+1$, the conductor temperature is $T_c(k+1)$. From the differential form of the thermal circuit model, $T_c(k+1)$ can be derived from input quantities before time $k+1$ and initial boundary conditions. Substituting Eqs. (4)-(7) into the thermal circuit model and discretizing in time yields the conductor temperature function at time $k+1$:

$$T_c(k+1) = f_{k+1}(T_c(0), I(0), I(1), \dots, I(k), R_e(k), T_e(0), T_e(1), \dots, T_e(k), \mathbf{x}, \Delta t)$$

where $\mathbf{x} = [C, \alpha, R_{\text{ref}}, a, b]^T$.

The objective function for thermal circuit model parameter identification is:

$$J(\mathbf{x}) = \min \sum_k \|\hat{T}_c(k+1) - T_c(k+1)\|^2$$

subject to $\mathbf{x} \geq 0$, where $\hat{T}_c(k+1)$ is the measured conductor temperature at time $k+1$.

Since the proposed thermal circuit model involves numerous parameters to be identified and represents a nonlinear optimization problem requiring strong global optimization capability, this paper employs particle swarm optimization (PSO) to solve the objective function.

First, define the search population:

$$G = \{P_u \in \mathbb{R}^5, n \in \mathbb{N}, 1 \leq u \leq n\}$$

where $\mathbb{R}^5$ is the five-dimensional search space formed by the parameters to be identified, and P_u represents search particles.

After population initialization, each particle's position vector is substituted into the objective function to calculate fitness values, and the optimal particle and optimal fitness value are selected. Subsequently, particle positions and velocity vectors are updated for the next optimization round. The update equations for the s-th search iteration are:

$$\mathbf{v}_u^s = w_s \mathbf{v}_u^{s-1} + c_1(\mathbf{p}_{\mathrm{ub}} - \mathbf{l}_u^{s-1}) + c_2(\mathbf{g}_b - \mathbf{l}_u^{s-1})$$

$$\mathbf{l}_u^s = \mathbf{v}_u^s + \mathbf{l}_u^{s-1}$$

where $\mathbf{p}_{\mathrm{ub}}$ is the particle’ s best solution; $\mathbf{g}_b$ is the population’ s best solution; c_1 and c_2 are learning factors representing the particle’ s ability to learn from itself and others; w_s is the weight coefficient; $\mathbf{l}_u = [l_u^1, l_u^2, l_u^3, l_u^4, l_u^5]^T$ is the particle’ s position vector representing identified parameter values; and $\mathbf{v}_u = [v_u^1, v_u^2, v_u^3, v_u^4, v_u^5]^T$ is the particle’ s velocity vector indicating the search direction toward the next position.

Using the PSO algorithm, the objective function can be solved after several optimization iterations, completing the establishment of the ACCC conductor thermal circuit model.

4. Experimental Verification

4.1 Experimental Platform

To identify thermal circuit model parameters and verify their correctness and accuracy, an ACCC conductor current-temperature rise experimental platform was designed as shown in [Figure 3: see original paper]. The platform primarily consists of a steel frame, test conductor, high-current generator, temperature probes, differential voltage probes, Hall-effect current transducers, data acquisition devices, and a PC. The steel frame comprises two side supports and a crossbeam from which fiberglass ropes suspend the test conductor. Fiberglass ropes offer high temperature resistance and low thermal conductivity, minimizing the influence of support materials on conductor heat transfer. Silicon Valley Chemical-produced ACCC conductors were used as test specimens, with parameters listed in .

The experimental platform was placed in a sealed indoor environment with air velocity less than 0.1 m/s, constituting natural convection conditions with approximately constant temperature and humidity during testing. During experiments, the high-current generator coupled current into the ACCC conductor while temperature probes and Hall-effect current transducers continuously measured conductor temperature, ambient temperature, and current. Data were collected by the acquisition device and uploaded to a backend PC database at 0.5-second intervals.

4.2 Results and Analysis

To capture comprehensive conductor temperature rise processes including overload conditions, experimental currents ranging from 400 A to 1000 A in 100 A increments were applied.

The identified parameters obtained using the PSO algorithm are presented in . First, the validity of AC resistance parameters was verified by comparing calculated values from Eq. (5) with measured AC resistance values obtained through the vector current-voltage method, as shown in [Figure 4: see original paper]. The maximum error is only 1.2%, indicating high accuracy in the identified parameters for R_{ref} and α.

Subsequently, all identified parameters were substituted into the thermal circuit model to simulate the conductor temperature dynamic process under various current loads, with results shown in [Figure 5: see original paper]. [Figure 6: see original paper] presents the relative simulation errors, which do not exceed 2.8%, demonstrating the effectiveness of the PSO identification method.

To further validate model accuracy, additional current levels of 450 A to 850 A in 100 A increments (not used in identification) were applied as loading currents. The measured and simulated temperature rise results are compared in [Figure 7: see original paper], with relative errors shown in [Figure 8: see original paper]. The maximum error does not exceed 2.2%, confirming that the model achieves high accuracy and can reliably describe the conductor temperature rise dynamic process, providing necessary basis for calculating conductor thermal dynamics.

5. Conclusions

This paper proposes a high-voltage ACCC conductor current-temperature model based on PSO parameter identification. Experimental verification demonstrates the feasibility of the identification method and the accuracy of the model, establishing specific calculation methods for all model parameters. The conclusions are as follows:

1. The proposed PSO-based parameter identification method can effectively determine both electrical and thermal parameters in the ACCC conductor current-temperature model, providing necessary support for calculating conductor thermal dynamic processes.
2. Comparison between experimental and calculated results indicates that under natural convection conditions, the ACCC conductor current-temperature model achieves high accuracy in reflecting conductor temperature rise processes, establishing a theoretical foundation for conductor current-temperature models under complex meteorological conditions.

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