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Research Paper

Hot spot temperature inversion for the single-core power cable joint

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HIGHLIGHTS

- The authors propose a novel approach to invert temperature of cable joint.
- Indirect temperature measurement of conductor of the cable joint is realized.
- The verification experiment was carried out.
- Inversed results match with measured ones, and the relative errors do not exceed 6%.

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ABSTRACT

Monitoring temperature inside the power cable joint is of great meaning to the safety of power distribution, while measuring it directly is infeasible. In this paper, the authors propose a new method to invert real-time hot spot temperature of conductor in the single-core power cable joint. This method consists of two parts, the radial-direction temperature inversion (RDTI) in the cable and axial-direction temperature inversion (ADTI) in the conductor. With this method, hot spot temperature of conductor in the cable joint could be figured out with the surface temperatures of the cable nearby the cable joint and load current, both of which are measurable. Then, the authors carry it out on an actual power cable joint in the laboratory, and the inversed temperatures are compared with experiment data, which come from the indoor experiment platform, to validate the availability of this method. The maximum error of this method is 6%, and it shows that this method for temperature inversion is feasible in laboratory scale.

1. Introduction

The power cables have been widely used for decades in power system and industrial circle. Being different with overhead transmission lines, the power cable lines are characterized in smaller covering area and less affected by environment. Due to manufacturing technology, installation processing and site condition, the cable joint, which is an important part of power cable line, is likely to be the weak point. Meanwhile, the structure of cable joint is more complex than the cable, which makes the overheating much more severe. Partial discharge and insulation aging contribute extra temperature rise in the cable joint, which would in turn accelerate the partial discharge and insulation aging. Finally, this may lead to explode of the cable joint in breakdown condition, causing great damage to the safety of power grid. Since the existence of contact resistance in the cable joint, the hot spot usually locates in the contact surface of the cable conductor. So, study on temperature rise of hot spot in the cable joint is of great meaning.

In the area of cable and cable joint temperature rise, the related research had begun in the 1980s, and IEC standards on calculating cyclic and short-term transient rating of power cables were set up [1–9]. At present, there are mainly two kinds of widely used methods to investigate temperature rise in the cable and cable joint, known as the thermal circuit model and numerical calculation method. The former one is based on the method introduced in the standard of IEC-60287 and IEC-60853, in which the equivalent thermal resistance and thermal capacity are calculated to build up thermal circuit model. In the IEC standard method, heat flow in the axial direction is ignored, and it is not suitable for analysis of temperature rise in the cable joint [10–14]. The latter one include heat charge simulation method, finite element method (FEM) and field-circuit coupling method [15–19,5], in which the FEM could be used to carry out analysis of temperature rise in the cable joint. In the recent years, BP neural network has also found its application in estimating temperature rise of cable conductor [20].

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Just as partial discharge is a feature of defect in the cable joint, temperature rise of the hot spot can also reflect defect in it. While the conductor of cable joint is of high voltage, which makes directly measuring temperature of the conductor is infeasible.

The structure of cable is symmetry both in the axial and radial direction, and the transient temperature rise of cable conductor could be calculated through 1-D thermal circuit model introduced in the IEC-60853, which makes conductor temperature rise inversion feasible through surface temperature and load current. As for the cable joint, the structure is more complex and not symmetry in the axial direction, so the method of 1-D thermal circuit model is no more suitable for calculation of temperature rise in the cable joint. Compared with cable, thermal resistivity of the whole cable joint is so large that surface temperatures of the cable joint could hardly be influenced by the heat source inside, which makes it less efficient to measure surface temperature of the cable joint. To solve this problem, this new method is brought up. By measuring the surface temperature of cable close to the cable joint and load current, hot spot temperature of conductor in cable joint is figured out with numerical algorithm.

2. Temperature inversion method

Supposing the current of cable circuit is 1000 A and ambient temperature is 30 °C, the static thermal field of directly buried single-phase cable joint is calculated. The surface temperature and conductor temperature along the cable direction are shown in Fig. 1.

Comparing surface and conductor temperature of cable joint, it is obviously that the surface temperature is quite close to the ambient temperature and hardly influenced by the inner conductor temperature. For the nearby cable, the surface temperatures are relatively close to the inner conductor temperatures, and it means the temperature inversion is feasible in the cable. Since temperature difference exists in the conductor of the cable joint and cable, it is possible to invert hot spot temperature from the conductor temperatures of the nearby cable.

What mentioned above is the main idea of this new method. It consists of two parts, radial-direction temperature inversion (RDTI) in the cable and axial-direction temperature inversion (ADTI) in the conductor. The schematic diagram of the method is shown in Fig. 2. The RDTI method is to calculate conductor temperatures of some spots in the cable with surface temperatures of the cable and load current, and the ADTI method is to estimate hot spot temperature in cable joint according to the conductor temperatures of the cable mentioned in RDTI. Since the hot spot of the cable joint locate in the middle of the conductor and around the contact surface region, the "conductor temperature in cable joint" mentioned below would refer to temperature of the specific spot.

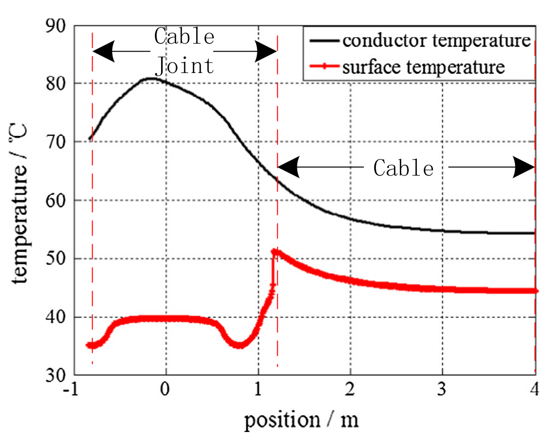

Fig. 1. Temperature distribution along the cable direction.

2.1. Radial-direction temperature inversion

For RDTI, it could be realized through thermal circuit method, which utilizes the resemblance between heat flow in a thermal system and electric current in an electric circuit to calculate the transient thermal response to heat flow. For a directly buried single-core cable, the structure of surrounding soil hardly affect the temperature distribution of the cable, and the semi-infinite surrounding soil could be approximated to cylindrical region [21–23]. According to the IEC-60853, the transient thermal circuit model could be set up, as shown in Fig. 3. In this model, the cable consists of 7 layers, which are conductor, XLPE, waterproof layer, Aluminum sheath, cable jacket, backfill and native soil. The dielectric loss and sheath loss take only a very small part of total losses in the cross-bonding cables [24–26], so the heat source from these two losses are ignored in this model.

Here W_c is the heat flow of the conductor; T_i is the thermal resistance of each layer; C_i is the thermal capacity divided to each layer; θ_i is the temperature on outside boundary of each layer; θ_o is the ambient temperature; and θ_{i-} is the initial temperature on outside boundary of each layer. According to the theory of dynamic circuit transient response, the step response of the above transient circuit is unsolvable in time domain, but it is solvable in complex frequency domain. With Laplace transforms, the equations of this circuit could be listed according to nodal method of analysis, as shown in Eq. (1).

$$\begin{cases} \theta_1*(s*C_1+1/T_1)-\theta_2*(1/T_1)=W_c/s+C_1*\theta_{1-} \\ -\theta_1*(1/T_1)+\theta_2*(1/T_1+1/T_2+s*C_2)-\theta_3*(1/T_2)=C_2*\theta_{2-} \\ -\theta_2*(1/T_2)+\theta_3*(1/T_2+1/T_3+s*C_3)-\theta_4*(1/T_3)=C_3*\theta_{3-} \\ -\theta_3*(1/T_3)+\theta_4*(1/T_3+1/T_4+s*C_4)-\theta_5*(1/T_4)=C_4*\theta_{4-} \\ -\theta_4*(1/T_4)+\theta_5*(1/T_4+1/T_5+s*C_5)-\theta_6*(1/T_5)=C_5*\theta_{5-} \\ -\theta_5*(1/T_5)+\theta_6*(1/T_5+1/T_6+s*C_6)=\theta_o/(s*T_6)+C_6*\theta_{6-} \end{cases} \tag{1}$$

In order to solve the equations above, both thermal resistance T_i and thermal capacity C_i should be figured out. These lumped parameters are determined by the material and structure of each layer, and they can be calculated through some formulas [8,9]. The heat flow W_c changes with load current, which is measurable. For the parameter θ_{i-}, it is the final temperature of each layer in the previous step response. Solving Eq. (1) in the complex frequency domain with Gaussian elimination algorithm, the temperature expression of each layer $\theta_i(s)$ could be obtained. Doing inverse Laplace transformation, the step response of each layer in time domain is figured out, as shown below. $\theta_1(t)$ is the transient temperature in the conductor, and the RDTI in single-step input is realized.

$$\theta_i(t)=a_i+\sum_{j=1}^{6}(b_{i_j}*e^{-\tau_j*t}) \tag{2}$$

where a_i and b_{ij} are complex expressions of T_i, C_i, W_c, θ_{i-}, and θ_o; τ_j is time constant. For transient thermal circuit of six orders, the step response is a superposition of six step responses of one order circuit with different time constant. For each node of the thermal circuit, they share the same time constant.

Under single step response, the load current and ambient temperature is constant. But actually they both change with time, and it is a multi-step problem. To realize multi-step response, the actual load current should be approximated to combination of many step currents one after another, as shown in Fig. 4. Since time constant of the cable is relatively large, the temperatures change