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Research Paper

Heat analysis of the power transformer bushings using the finite element method

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HIGHLIGHTS

- Heat analysis of the bushing is performed in two-dimensional space using the differential equations.
- The Finite Element Method is employed to determine a bushing's temperature distribution.
- Bushing's hottest spot temperature is specified.
- Effects of increasing the temperature on the bushing's conductor are compared in different currents.

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ABSTRACT

Reliability of power transformers significantly depends on the performance of their bushings and bushing lifetime is mainly dependent on its hottest spot temperature, which is caused by the power dissipation in the bushing's conductor. In this paper, the thermal analysis of the bushing is firstly performed in two-dimensional space using the differential equations. Then, the Finite Element Method (FEM) is employed to determine a bushing's temperature distribution and specify its hottest spot. The effects of increasing the temperature on the bushing's conductor are also investigated and the results are compared in different currents. The proposed method calculates the temperature distribution in all parts of bushing including conductor surface, paper, porcelain and oil. It is useful for manufacturer and utilities to evaluate the insulation design, temperature distribution and loss of insulation life.

1. Introduction

Bushings are major components in the power transmission networks. Indeed, the reliability of power transformers, as the most crucial part of the power networks, strongly depends on their bushings performance. As a bushing is operating, a portion of the flowing electricity through the bushing's conductor dissipates and converts to heat. Although, comparing to the transmitted power, the resulting heat is negligible, it increases the bushing's temperature. If the bushing is overheated or its exposure to the high temperatures is elongated, the chemical nature of the insulator can alter, which in turn leads to changes in the physical characteristics of the bushing and intensifies its wearing rate. The bushing lifetime is inversely related to its Hottest Spot Temperature (HST). Therefore, calculating the HST and the bushing's temperature distribution is particularly useful in optimal design of the bushing and determining its optimum performance.

Researchers adopt various ways to determine the HST and the temperature distribution for bushings. McNutt and Easley [1] employed a simple mathematical model, namely the analog thermal modeling, to obtain the HST in the steady-state. Their approach required three parameters: the current in the unit length of the conductor, the ambient temperature, and the highest temperature of the oil in the tank. Then, obtaining the three thermal constants ($k1$, $k2$ and n), the HST could be determined. These thermal constants could be experimentally determined using four distinct load currents. The authors of Ref. 1 expressed that the bushing's lifetime has an inverse relationship with the HST. Zeng [2] presented an accurate, but simple, method to estimate the temperature increments of the bushing's conductor under any load conditions. Zeng in fact employs the McNutt equation [1], but he assumes that the thermal constant, n, always constitutes 2. Also, instead of $k1$ and $k2$, he used $F1(z)$ and $F2(z)$, which are the temperature increments at a specific current and zero current, respectively. Using this approach, it is possible to determine the HST and the temperature distribution of the conductor under any load current. In Refs. 3 and 4, a coded program is developed to analyze the steady-state temperature distribution of the conductor of power transformer bushings. The equivalent thermal circuit for the conductor's element of length dx is investigated and a thermal differential equation is

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then derived. Next, the locations of the hot spots under various currents are determined on the conductor. In addition, the conductor's temperature distribution is evaluated under the evaporative cooling condition. In Ref. 5, Hebert and Steed introduced the finite difference model as an economical way to specify the bushing performance and discussed its calculations. The accuracy of the proposed model is evaluated via comparing its predicted temperatures with the measured temperatures. Indeed, the authors of Ref. 5 elaborate on the model proposed in Ref. 1. Craghead et al. [6] conducted some thermal experiments to determine the temperature distribution under normal currents. In addition to tabulation and assessment of the experimental results and conducting the lifetime tests on the bushing, they evaluated the physical conditions of the insulator so that the effects of the high temperatures on the bushing performance could be studied. Zhang [7] obtained the transient temperature distribution of the bushing using the ATP, electrical equivalent circuit, and the heat capacity (as a key indicator of the transient thermal capabilities). He discusses thermal modeling of the bushing, heat sources and cooling methods in his research. The authors of Ref. 8 report their findings on the temperature distribution of the bushing body based on the Alternative–Current (ac) conductivity of the Resin Impregnated Paper (RIP) insulation. They present a theoretical model to calculate the temperature distribution of the insulator body as a function of the ac conductivity of the RIP insulation. Their model is based on the solution of the Partial Differential Equation (PDE) of the Joule Heating problem using the methods of nonlinear second-order differential equation and the Bessel function. They also propose an approach to obtain the maximum thermal voltage.

Finite Element Method (FEM) is an approach to the approximate solution of the PDEs. To do this, FEM eliminates a differential equation or simplifies it to obtain the Ordinary Differential Equation (ODE). Some researchers have solved the Joule Heating problem by the FEM and have found it effective in solving the PDEs. The authors of Ref. 9 studied the bushing of a positive displacement motor. They adopt the FEM to calculate the bushing's temperature distribution and the thermal stresses resulted from the viscoelastic residuals. The sensitivity of the results to the Poisson's ratio, and the pressure and rotational speed of the rotor is also investigated. The authors of Ref. 10studied the effects of the aluminum shield on the temperature rise and the set up of transformer dissipations. They adopt five different lead arrangements for a 220 MVA transformer with a phase current of 4.4 kA.

In Ref. 11, a general solution for the nonlinear, steady-state heat-conductivity equation of the metal heated by the electricity dissipation is presented. In fact, the author of Ref. 11 has solved a one-dimensional Joule Heating equation. In Ref. 12, the fundamentals of the thorough analytical solution for the time-variant Joule Heating problem using the FEM are discussed.

HST is a key factor in the performance of the power equipment such as bushings and transformers. The authors of Ref. 13 firstly formulated the heat conductivity equation of the transformers. Then, using the FEM and COMSOL software, they obtained the temperature distribution of the transformer body and the HST. They claimed that the PDE approach together with the FEM provide an accurate estimation of the temperature distribution to obtain the HST. In Ref. 14, the FEM is adopted to solve a three-dimensional Joule Heating problem. These authors derived the temperature distribution of the vivo gene electrotransfer, which is a Biomedical Engineering apparatus, using the FEM. Zhang et al. [15] discusses optimal design of bushings. Its proposed method is based on the electro-thermal analysis of the bushing, which is, in fact, a solution to the Joule Heating problem.

In the present work, the analog thermal modeling is briefly introduced. Then, two-dimensional thermal analysis of the bushing is conducted via PDE formulation. Next, using the FEM, the temperature distribution and the HST of a bushing body is determined and the results are presented taking account bushing materials' thermal specifications and dimensions. Finally, the effect of current on the conductor's temperature and the HST distribution is investigated.

2. Thermal model

The electrical equivalent circuit is usually employed in analyzing the heat transfer problems since it provides a clear physical understanding. In this approach, the heat flux is assumed analogous to the electric current. The heat flux, generated by the temperature gradient, is controlled by the thermal resistance R_T. The equations of this analogous model are as follows

$$I = \Delta V/R \tag{1}$$

$$Q = \Delta\theta/R_T \tag{2}$$

where Q denotes the heat flux. In heat conduction, the thermal resistance is

$$R_T = L/kA \tag{3}$$

where L and A represent the length and cross-sectional area of the conductor, respectively; and k denotes the heat conductivity, which is determined by the conductor material. In heat convection, however, the thermal resistance will be

$$R_T = 1/hA \tag{4}$$

where A is the convection area and h is the heat transfer coefficient (convection coefficient) determined by the Newton's law of cooling. Conduction is the dominant heat transfer mechanism in loaded bushings. So, the electrical equivalent circuit analysis suits it. Heat conduction occurs in the inner copper or aluminum conductor and also the oil, porcelain, and the metal flange. The heat transfer meshing can be constructed such that the temperature of various spots of the bushing could be determined accurately [1].

Adding the heat capacity as the main component of the transient electrical behavior of the system, one can obtain the HST in the transient state. Fig. 1 shows the transient-state model of the bushing and Fig. 2 illustrates the steady-state model of the bushing.

3. Partial differential equations

According to the heat conduction principles, the divergence of the heat flux should constitute the produced heat in the unit volume of the system [14].

$$\nabla.[-k\nabla T] = P(r) \tag{5}$$

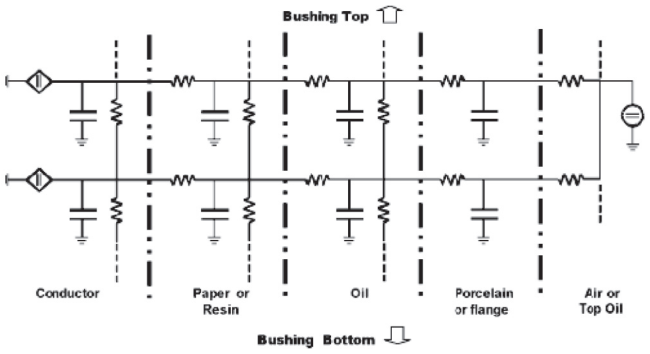

Fig. 1. Electrical equivalent circuit of the bushing in the transient state [7].