Contact Temperature Prediction in Three-Phase Gas Insulated Bus Bars with the Finite-Element Method

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***Abstract*—Degradation of electric contact in gas insulated bus bars (GIB) is closely related to overheating phenomena occurring in the contacts. This paper employs the finite element method (FEM) to solve the three-dimensional (3-D) coupled eddy current, fluid and thermal problem in a three-phase GIB. The contact resistance between the conductor and contact finger is measured and considered in the calculation. The influence of different load currents and ambient temperatures on the location of hot spot in the tank of GIB is addressed. The predicted contact temperatures will be validated with prototype experimental results.**

***Index Terms*— Condition monitoring, contact resistance, finite-element method (FEM), fluid dynamics.**

I. Introduction

The load ability and usable life of gas insulated bus bars (GIB) is determined by the temperature rise of the contact. It is always the hot spot because of the current constriction effect and the contact resistance. According to the investigation, most serious failures in GIB are caused by contact degradation [1], [2]. Over the years, substantial efforts have been devoted to the thermal modeling of GIB. Models based on coupled two-dimensional (2-D) finite-element-analytic technique have been proposed to predict temperature rise in GIB [3], [4]. Three-dimensional (3-D) models based on the finite-element method (FEM) are used to study the temperature distribution of the bus duct systems, in which the contact resistances between the conductors are considered [5], [6]. However, in these papers the convective heat transfer coefficient is hard to be determined especially when the structure investigated is complex. Moreover, in order to obtain a thorough knowledge about the temperature rise characteristics in GIB, the way the hot spot on the tank of GIB shifts with the varying ambient temperature and load current also needs to be addressed.

This paper develops a 3-D FEM model for the temperature prediction of the contacts between the conductors and the insulator in three-phase GIB. The eddy current field is indirectly coupled with the fluid and thermal fields. The theory of fluid dynamics is employed to solve the convective heat transfer problem. The way the location of hot spot on the tank shifts with the varying ambient temperature and load current is investigated. Comparison between the calculated and tested results validates the proposed method.

II. Formulation

A. 3-D Eddy Current Field Equations

The investigated structure of three-phase GIB is shown in Fig. 1. The power losses in the GIB are evaluated with 3-D eddy current field analysis, which is described in the following.

Introducing the magnetic vector potential and the electric

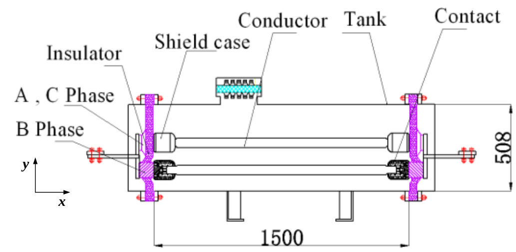

Fig. 1. Structure of the experimental prototype of GIB

scalar potential into Maxwell's equation, the 3-D eddy current field equations can be written as [5], [6]

$$\left.\begin{aligned} &\nabla\times\left(\nu\nabla\times\dot{\boldsymbol{A}}\right)-\nabla\left(\nu\nabla\cdot\dot{\boldsymbol{A}}\right)+\mathrm{j}\omega\sigma(\theta)\dot{\boldsymbol{A}}+\sigma(\theta)\nabla\dot{\phi}=\dot{\boldsymbol{J}}_{\mathrm{s}} \quad \text{in V}\\ &\nabla\cdot\left(-\mathrm{j}\omega\sigma(\theta)\dot{\boldsymbol{A}}-\sigma(\theta)\nabla\dot{\phi}\right)=0 \quad \text{in V}_1 \end{aligned}\right\} \quad (1)$$

where V is the whole solution region, V_1 is the region without source current.

The contact resistance can be described as a resistor located between the contact and conductor. It is considered to be temperature dependent and the initial value is obtained with measurement. Considering the complicated structure of the GIB, FEM is chosen in the analysis. Applying the Galerkin procedure to the equation above, the total current density and the power losses are calculated.

B. 3-D Thermal Equations

Convection and radiation are the most influential heat transfer mechanism in GIB. Unlike the traditional FEM in which the convection boundary condition is needed and the heat transfer coefficient on the tank surface is constant, the natural convection both inside and outside the GIB are solved with the theory of 3-D fluid dynamics, which satisfy the following equations [7], [8]:

$$\nabla\cdot(\rho\boldsymbol{V})=0 \tag{2}$$

$$\nabla\cdot(\rho\boldsymbol{V}\otimes\boldsymbol{V})=\nabla\cdot(-p\boldsymbol{I}+\mu(\nabla\boldsymbol{V}+(\nabla\boldsymbol{V})^{\mathrm{T}}))+\boldsymbol{S} \tag{3}$$

$$\nabla\cdot(\rho C T\boldsymbol{V})=\nabla\cdot(\lambda\nabla T)+Q_{\mathrm{v}} \tag{4}$$

where ρ, λ and μ are, respectively, the density, thermal conductivity and dynamic viscosity, $\boldsymbol{V}$ is gas velocity, $\otimes$ is the tensor product, p is the gas pressure, $\boldsymbol{I}$ is the identity matrix, $\boldsymbol{S}$ is the momentum source, C is the specific heat, Q_{v} is the volumetric heat source.

Radiation effects exist between the tank and the conductors and between the surroundings and the tank. The mathematical formulation of radiation boundary condition is given by

$$-\lambda\frac{dT}{dx}-\lambda\frac{dT}{dy}=\sigma\varepsilon F_{ij}\left(T_i^4-T_j^4\right) \tag{5}$$

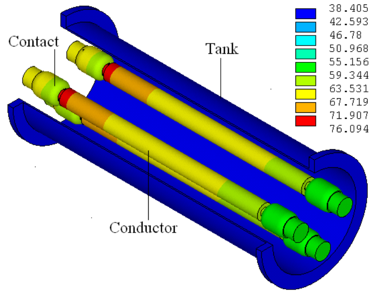

Fig. 2. Temperature distribution of the GIB

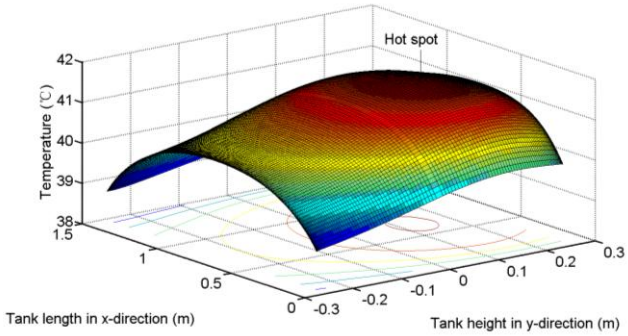

Fig. 3. Temperature distribution on the outer tank surface

TABLE I
VARIATION OF HOT SPOT LOCATION WITH DIFFERENT LOAD CURRENT

Current (A)	*x*-direction (m)	*y*-direction (m)	Temperature (℃)
500	0.70~0.77	0.25	29.4
1000	0.71~0.76	0.13~0.16	31.6
1500	0.71~0.74	0.13	35.0
2000	0.77~0.79	0.16~0.17	39.6

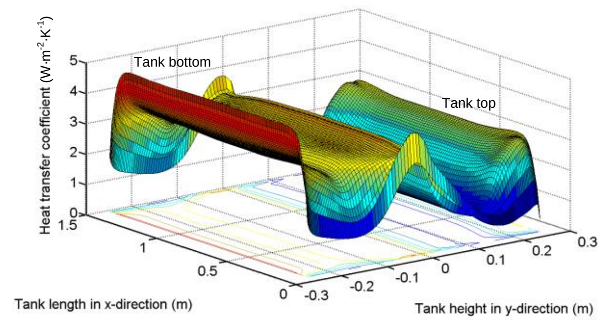

Fig. 4. Heat transfer coefficient distribution on the outer tank surface

where σ is Stefan-Boltzmann constant, ε is the emissivity of the surface, F_{ij} is the view factor.

In the model, temperature dependent thermal properties except the specific heat are considered. The gas density is calculated with ideal gas equation. The thermal conductivity and dynamic viscosity are calculated with Sutherland's law. Moreover, Radiosity method is used for the radiation analysis, and the hemicube method is used to calculate the view factors.

III. RESULTS AND DISCUSSION

The numerical simulation of the model is carried out with ANSYS 12.0. Because of the multi-scale of different parts in the GIB and the existence of ambient air in the solution region, the computation scale is increased. The solution region is meshed with 4,924,540 elements and 3,964,038 nodes. Fig. 2 gives the temperature distribution of the GIB at the ambient temperature of 25℃ and the SF_6 gas pressure of 0.4MPa. The rated load current is 2kA, and the contact resistance of each phase is 20μΩ. The maximum temperature, as expected, locates at the contact point, and the temperature rise is 51.1K.

Fig. 3 shows the temperature distribution on the outer tank surface of the GIB. The *x*- and *y*-directions are given in Fig. 1. It may be observed that the hot spot on the tank is 41.5 ℃ at the position of 0.69m in the *x*-direction and 0.13m in the *y*-direction, rather than the position over the contacts. This can be attributed to the flow characteristic of the SF_6 gas. Under the effect of buoyancy, the heated gas flows upwards at the initial stage, but the shield case changes the flow direction, thus the hot spot location shifts. The variation of hot spot location with different load current at the contact resistance of 10μΩ is given in Table I. The influence of ambient temperature has also been investigated. It is found that the hot spot location on the tank surface does not change at different ambient temperatures. This result can help to determine the installation positions of the temperature sensors for thermal condition monitoring of GIB contacts.

The heat transfer coefficient on the outer tank surface of the GIB section mentioned above is illustrated in Fig. 4. Unlike other FEM models presented before, the coefficient needs not to be calculated and is proved to be variant at different locations of the tank surface. The maximum value is 4.77 W/(m^2·K) at the bottom of the tank. It is also observed that large discrepancy exists between the maximum value and the minimum one.

The model is deemed to be accurate because the temperature dependent physical properties and heat transfer coefficient are taken into account. Admittedly, the calculation results will be more convincing when comparing with experimental findings. The experiment is scheduled and will be cooperated with XD High Voltage Electric Manufacturing co., LTD and China Electric Power Research Institute.

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