Magnetic Eddy-Current, Fluid and Thermal Coupled Models for the Finite Element Behavior Analysis of Gas-Insulated Bus Bars

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This paper describes a coupled magnetic eddy-current, fluid and thermal finite-element model to analyze the steady and transient thermal behavior of a three-phase gas-insulated bus bar (GIB). The magnetic eddy-current field is indirectly coupled into the fluid and thermal fields through the power loss density while considering the temperature dependent electrical conductivity. As a new methodology, multiple species transport technique is introduced into the thermal model using computational fluid dynamics (CFD), circumventing the difficulty of applying temperature and geometry dependent heat transfer coefficient on the model boundaries. Good agreement is found between the CFD and experimental results. The proposed methodology is further used to predict the steady and transient thermal behaviors of the GIB under the effects of various gas pressures, gas types, electrical loads, and ambient temperatures, which provides useful sensitivity information for GIB designers in the product development process.

***Index Terms*—Finite element method, eddy current, thermal analysis, fluid dynamics, sensitivity analysis, product development.**

I. Introduction

KNOWLEDGE of the thermal behavior plays an important role in understanding the improvement of the design and manufacture processes of gas-insulated bus bars (GIBs). In currently available thermal models [1], [2], the heat transfer problem is less understood for the difficulty in applying the convective heat transfer coefficient on the enclosure surface. Moreover, the sensitivity analysis, which provides useful information identifying the important parameters affecting the steady and transient temperature rise of the GIB, is never mentioned. In this paper, the surrounding air of the GIB is introduced into the solution region, and the multiple species transport technique is proposed to calculate the material properties of the gas mixture of the air and the insulation gas. The convective heat transfer occurred both inside and outside the GIB is calculated with computational fluid dynamics (CFD). The model is further used to analyze the thermal behaviors of the GIB affected by the parameters of gas pressure, gas type, electrical loading, and ambient temperature.

II. Finite Element Model

A. Eddy Current Field Model

The solution region of the GIB is shown in Fig. 1. The 2-D eddy current diffusion problem in a time-harmonic regime can be stated as follows [1]:

$$\begin{cases} \Omega: \nu\nabla^2 A + j\omega\sigma(T)(-A + \dfrac{J_s}{j\omega\sigma(T)}) = 0 \\ \Gamma_1 : A = 0 \end{cases} \tag{1}$$

where A is the magnetic vector potential, σ(T) is the electric conductivity dependent on temperature T, ν is the reluctivity, J_s is the source current density, Ω is the solution region, Γ_1 is the Dirichlet boundary condition.

The total current density J is decomposed into source and eddy current densities, the total current I for the conductor of

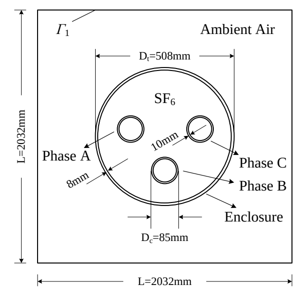


Fig. 1. Solution region of the three-phase gas insulated bus bars

the cross-section area S_c can be expressed as

$$\iint_{S_c} j\omega\sigma(T)(-A + \frac{J_s}{j\omega\sigma(T)})ds = \iint_{S_c} Jds = I \tag{2}$$

Applying the Galerkin method to discrete (1) and (2), the power loss Q in the conductor per unit length can be calculated by

$$Q = \frac{1}{2}\sum_{i=1}^{n}\frac{\tilde{J}_i \cdot \tilde{J}_i^*}{\sigma_i(T)} s_i \tag{3}$$

where s_i is the element area, n is the total element number of the conductor, $\tilde{J}_i$ is the complex total current density for element i, $\tilde{J}_i^*$ is the complex conjugate of $\tilde{J}_i$.

B. Thermal model

For multiple species transport problem in GIB, the bulk properties of the gas mixture of the ambient air and insulation gas can be calculated as a linear combination of the properties of these species, which can be written as follows [3]:

$$\alpha = \sum_{i=1}^{2}\alpha_i Y_i \tag{4}$$

$$\sum_{i=1}^{2} Y_i = 1 \tag{5}$$

where α is the density, thermal conductivity, dynamic viscosity, or specific heat of the gas mixture, α_i and Y_i are the material property and mass fraction of the insulation gas or ambient air corresponding to α, respectively.

According to the theory of CFD, the natural convection inside and outside the GIB satisfying the following governing equations [4]:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}=0 \tag{6}$$

$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho uu)}{\partial x}+\frac{\partial(\rho vu)}{\partial y}=-\frac{\partial p}{\partial x}+\mu\nabla^2 u+S_x \tag{7}$$

$$\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho uv)}{\partial x}+\frac{\partial(\rho vv)}{\partial y}=\rho g-\frac{\partial p}{\partial y}+\mu\nabla^2 v+S_y \tag{8}$$

$$\frac{\partial}{\partial t}(\rho CT)+\frac{\partial}{\partial x}(\rho uCT)+\frac{\partial}{\partial y}(\rho vCT)=\lambda\nabla^2 T+Q_{\mathrm{v}} \tag{9}$$

where ρ is the density, λ is the thermal conductivity, μ is the dynamic viscosity, p is the gas pressure, u and v are the fluid velocity in x and y direction and are zero for solid domains, respectively, S_x and S_y are the source terms, g is the gravitational acceleration, C is the specific heat, Q_{v} is the heat source.

The radiation boundary condition at the solid surfaces, the constant temperature and no-slip boundary conditions on Γ_1 are applied in the model. It can be observed that the need of convective boundary condition is eliminated.

III. Results and Discussions

A. Power Losses

As the power losses are temperature dependent, an iterative method between magnetic eddy current and thermal fields has been used. The total current density distribution along the enclosure surface is shown in Fig. 2. The induced eddy current at the position adjacent to the conductors is much higher than that of the other locations on the enclosure surface. The power losses of the components in the GIB are calculated and used as heat source input for the thermal analysis.

B. Stead- and Transient-State Thermal Behaviors

Fig. 3 gives the symmetrical temperature and fluid velocity distribution of the whole solution region of the GIB at 1500 A. The convective heat transfer coefficient distribution on the enclosure surface is shown in Fig. 4. The result is deemed to be the actual distribution, as the coefficient is found to be continuously changing along the enclosure surface and also to be temperature dependent. The proposed model is validated by experimental results obtained from a 126 kV three-phase GIB prototype, as shown in Table I. The calculated and tested temperatures are found to be in good agreement. Several calculations are carried out to investigate the temperature variation with load current, ambient temperature, gas pressure and insulation gas. It is found that there is a nonlinear relationship between the temperature and the load current and that the temperature rise of GIB is nearly not influenced by the variation of ambient temperature. The GIB insulated with pressurized SF_6 has lower operation temperature than that insulated with SF_6/N_2 (20/80%), and the temperature decreases as the gas pressure increases. Time variation of the GIB temperature with changing load currents in 12 hours is shown in Fig. 5. The GIB temperature changes rapidly with the variation of load currents. With transient thermal analysis, the time constant of the conductor and enclosure can be obtained, which is useful for the dynamic prediction of the temperature rise process in GIB.

TABLE I
Comparison of the Calculated and Tested Temperatures (℃)

Load Current (A)	Phase A/C		Phase B		Enclosure	
	FEM	Tested	FEM	Tested	FEM	Tested
600	43.7	45.3	43.2	43.9	40.1	40.8
1 000	44.7	47.3	43.3	45.3	35.2	35.4
1 500	63.0	63.4	60.6	60.1	43.2	43.3
1 980	87.2	85.8	83.2	80.2	54.5	52.5

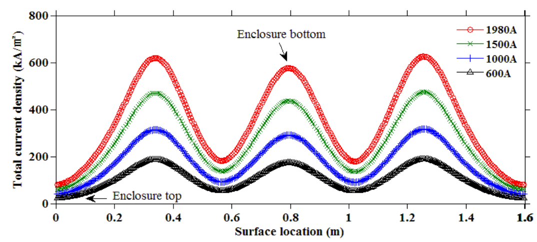
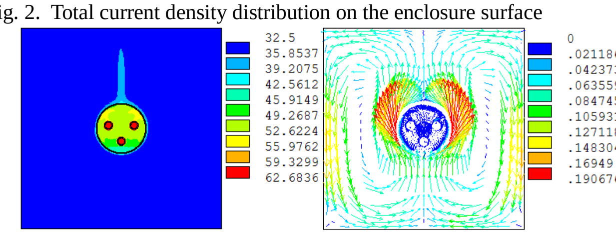


Fig. 2. Total current density distribution on the enclosure surface



(a) (b)

Fig. 3. Temperature and fluid velocity distribution of the whole solution region at 1 500 A. (a) Temperature distribution. (b) fluid velocity distribution.

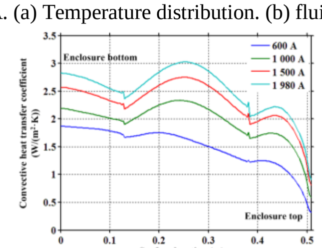


Fig. 4. Convective heat transfer coefficient on the enclosure surface

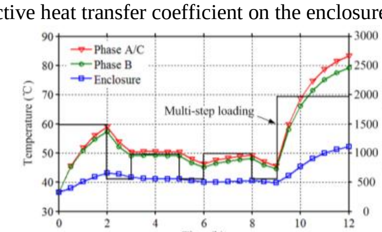


Fig. 5. Time variation of the GIB temperature with changing load current

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