Calculation of Temperature Rise in Gas Insulated Busbar by Coupled Magneto-Thermal-Fluid Analysis

Hong-Kyu Kim†, Yeon-Ho Oh and Se-Hee Lee*****

Abstract – This paper presents the coupled analysis method to calculate the temperature rise in a gas insulated busbar (GIB). Harmonic eddy current analysis is carried out and the power losses are calculated in the conductor and enclosure tank. Two methods are presented to analyze the temperature distribution in the conductor and tank. One is to solve the thermal conduction problem with the equivalent natural convection coefficient and is applied to a single phase GIB. The other is to employ the computational fluid dynamics (CFD) tool which directly solves the thermal-fluid equations and is applied to a three-phase GIB. The accuracy of both methods is verified by the comparison of the measured and calculated temperature in a single phase and three-phase GIB.

Keywords: Gas insulated busbar, Temperature rise, Magneto-thermal-fluid analysis, Computational fluid dynamics

1. Introduction

The calculation of the temperature rise in a high voltage apparatus requires solving the coupled problem of the electromagnetic (EM) and thermal fields [1]. To analyze the temperature distribution, the sequential approach, one-way and one-time solving technique between the EM and thermal fields has been widely adopted in engineering fields. In this study, however, the fully coupled approach (two-way and iterative solving technique) is presented to predict the temperature rise in a gas insulated busbar (GIB).

In the EM field analysis, the power losses are calculated and are transferred to the thermal field analysis as a heat source. In a GIB system, the natural convection effect is treated as equivalent heat conduction. In the outer region of a GIB tank, the natural convection and radiative heat transfer are considered using an effective natural convection heat transfer coefficient. The developed technique is applied to the analysis of the temperature rise in a single phase GIB. The simulation results are quite accurate compared to the measured temperature rise.

To predict the temperature rise in a three-phase GIB, we employed the coupled solving scheme which solves the EM field and thermal-fluid problem iteratively. Thermal-fluid analyses include the conduction, convection, and radiation arising in a GIB. To reduce the solving time of thermal-fluid analysis, we adopted the effective natural convection heat transfer coefficient on a tank surface as a function of temperature. To verify the numerical technique, the predicted temperature rise is compared to the measured one for the three-phase 25.8kV 2000A 25kA GIB.

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2. Calculation of Power Loss

In the main conductor of a GIB, steady state AC current flows and the total current density (the sum of the source current density and eddy current density) is different with respect to its position. For quasi-stationary harmonic eddy current problems [2]-[3], the current distribution can be computed by:

$$\nabla \times \frac{1}{\mu} \nabla \times \mathbf{A} = \mathbf{J}_{total} = \mathbf{J}_s + \mathbf{J}_e = -\sigma \nabla \phi - j\varpi\sigma \mathbf{A} \quad (1)$$

where $\mathbf{J}_{total}$ is the total current density, $\mathbf{J}_s$ the source current density, and $\mathbf{J}_e$ the eddy current density.

In a GIB, the power loss is generated in the main conductor and enclosure tank. Using the current distribution from (1), the power loss density is calculated by:

$$P = \frac{J_{total}^2}{\sigma} \ [\mathrm{W/m^3}]\cdot \quad (2)$$

where σ is the electric conductivity and a function of temperature.

3. Coupled Analysis Combined with EM and Thermal Field Analysis

The main heat transfer mechanisms in a GIB system are conduction, convection and radiation, as shown in Fig. 1. Inside a GIB, the radiative heat transfer effect can be neglected because temperature variation is small. On the shield tank surface, both radiation and natural convection are important. From the thermal analysis, the temperature distribution is calculated, and this is used to evaluate the temperature-dependent resistance of conducting materials in the EM field analysis.

3.1 Natural Convection inside Tank

Inside a GIB tank, SF_6 gas is generally filled and the natural convection is the dominant heat transfer mechanism. The Rayleigh number for a concentric enclosure can be expressed as [4]:

$$R_a = \frac{g\beta(T_s - T_\infty)L_c^3}{\nu^2}\ \mathrm{Pr}, \tag{3}$$

where g is the gravitational acceleration, $\beta = 1/T_a$, $T_a = (T_s + T_\infty)/2$, T_s the temperature of surface, T_∞ the temperature of fluid sufficiently far from the surface, $L_c = (D_o - D_i)/2$, D_i and D_o the diameters of the inner and outer cylinders of tank, respectively, ν is the kinematic viscosity, and Pr is the Prandtl number.

The Nusselt number for two concentric cylinders is expressed as:

$$Nu = 0.386\left(\frac{\mathrm{Pr}}{0.861+\mathrm{Pr}}\right)^{1/4}(F_c\ R_a)^{1/4}, \tag{4}$$

where the shape factor $F_c = \frac{[\ln(D_o/D_i)]^4}{L_c^3(D_i^{-3/5}+D_0^{-3/5})^5}$.

Then, the effective thermal conductivity κ_{eff} is:

$$\kappa_{eff} = \kappa\ Nu, \tag{5}$$

where κ is the thermal conductivity of a filling gas.

The gas properties, such as ν, κ and Pr, are evaluated at the average temperature T_a. Using the effective thermal conductivity of (5), the natural convection inside an enclosure can be treated as an equivalent thermal conduction problem [4].

3.2 Heat Transfer on Tank Surface

The Heat flow rate by natural convection is expressed as:

$$Q_{conv} = h_{conv}A_s(T_s - T_\infty)\ \ [\mathrm{W}], \tag{6}$$

where A_s is the surface area, T_s the surface temperature, and T_∞ the ambient temperature.

The heat transfer coefficient h_{conv} for natural convection in a cylindrical shape is calculated by:

$$h_{conv} = \frac{\kappa}{D}Nu = \frac{\kappa}{D}\left\{0.6 + \frac{0.387\ R_a^{1/6}}{[1+(0.559/\mathrm{Pr})^{9/16}]^{8/27}}\right\}^2. \tag{7}$$

The radiative heat flow rate between the tank surface and ambient air can be calculated by:

$$Q_{rad} = \varepsilon A_s\sigma_s(T_s^4 - T_\infty^4) = h_{rad}A_s(T_s - T_\infty)\ \ [\mathrm{W}], \tag{8}$$

where ε is the emissivity, σ_s is the Stefan-Boltzman constant and $h_{rad} = \varepsilon\sigma_s(T_s + T_\infty)(T_s^2 + T_\infty^2)$.

From (6) and (8), the total heat flow rate through the tank surface can be expressed as:

$$Q_{total} = h_{eff}A_s(T_s - T_\infty), \tag{9}$$

where h_{eff} is the effective heat transfer coefficient and $h_{eff} = h_{conv} + h_{rad}$.

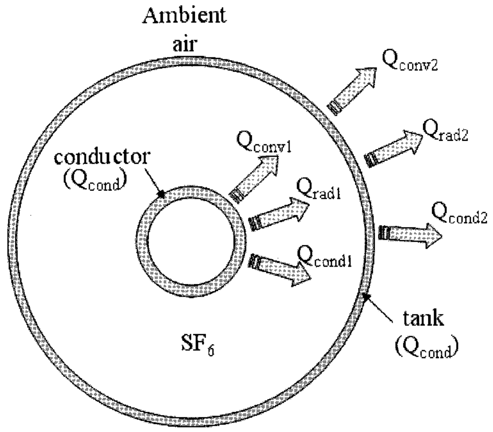

Fig. 1. Heat transfer mechanism in GIB(cond : conduction, conv : convection, rad : radiation)

3.3 Coupled Analysis Procedure and Simulation Results

Fig. 2 shows the coupled analysis procedure in which EM field and thermal field analysis are carried out with the transfer of power loss and temperature between each field. In the thermal analysis, the gas properties such as κ_{eff} and h_{eff} are temperature-dependent and, therefore, nonlinear thermal analysis should be performed.

The transferred quantity at (n+1) step is calculated by using the previous and current step's values as follows:

$$f^{(n+1)} = \alpha f^{(n+1)} + (1-\alpha)f^{(n)} \tag{10}$$

where f is the transferred load such as power loss or temperature, and α is a relaxation factor.

The meshes between the EM field and thermal analysis are different. Therefore, the interpolation scheme is used during the load transfer. The analyzed model is a 362kV 63kA 4000A GIB. The main conductor material is aluminum and the tank material is stainless steel. Fig. 3 shows the temperature distribution in a GIB and Table 1 shows the comparison of the measured and analyzed temperatures on the conductor and tank surface. The predicted temperature shows good agreement with the measured one.

To investigate the convergence characteristics with respect to the relaxation factor, the total iteration number and final temperature are compared in Table 2. Here, the convergence criterion is the relative difference between previous and current temperature all over the finite elements and set as 10^{-3}. From the Table 2, it can be said that the relaxation factor 1.0, in which one expects no relaxation effect, shows the best result in terms of the total iteration number for this kind of coupled problem.

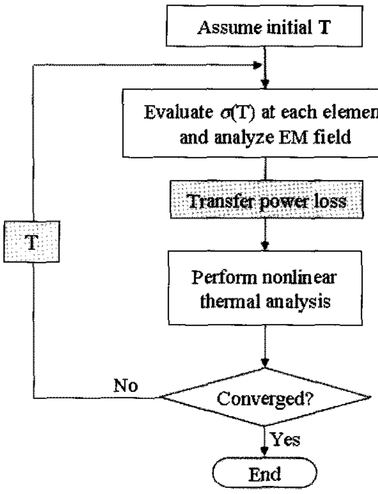

Fig. 2. Coupled analysis procedure of EM and thermal field

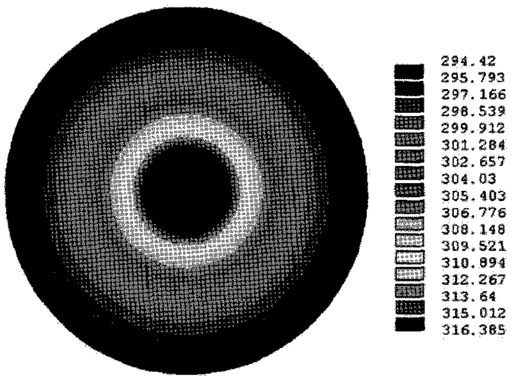

Fig. 3. Temperature distribution of 362kV single phase GIB

Table 1. Comparison of measured and calculated temperature for 362kV GIB

Temperature [K]	Measured	Calculated
Conductor	315.6	316.3
Tank surface	293.3	294.4

Table 2. Comparison of total iteration number with respect to relaxation factor

Relaxation factor	Total iteration number	Temperature on conductor [K]
0.3	16	316.2
0.7	6	316.3
1.0	3	316.3

4. Fully Coupled Analysis Technique with EM Field and Thermal-Fluid Analysis

In order to employ the coupled analysis method presented in the previous chapter, the effective thermal conductivity of (5) should be calculated with regard to the shape of the GIB. For a three-phase GIB, however, it is difficult to derive the effective thermal conductivity due to the relatively complex arrangement of the three conductors as shown in Fig. 4. Hence, thermal-fluid analysis is performed to calculate the temperature distribution in the conductor and tank region considering the complicated flow phenomena caused by the gravitational effect and density difference of filling gas inside a tank. The thermal-fluid analysis involves the thermal conduction analysis in the conductors and tank and the gas flow analysis in the gas region. The conjugate heat transfer problem which is the mixed problem of convection and conduction phenomena is solved by the computational fluid dynamics (CFD).

4.1 Governing Equations for Thermal-Fluidic Analysis

The governing equations for thermal-fluidic analysis can be expressed as the continuity, momentum, and energy equations. The main concern here is the steady state analysis of thermal-fluidic behavior, so the steady state basic governing equations are employed as follows:

$$\nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) = \nabla \cdot [-p\ddot{\mathbf{I}} + \eta(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] + \mathbf{S}_M \tag{11}$$

$$\nabla \cdot (\rho \mathbf{u}) = 0 \tag{12}$$

$$\nabla \cdot (\rho \mathbf{u} h_{tot}) = \nabla \cdot (\lambda \nabla T) + S_E \tag{13}$$

where ρ is the density, $\mathbf{u}$ the velocity, $\otimes$ the tensor product, p the pressure, $\ddot{\mathbf{I}}$ the identity tensor, η the dynamic viscosity, the superscript ^{T} the transpose of a matrix, $\mathbf{S}_M$ the momentum source, h_{tot} the specific total enthalpy, λ the thermal conductivity, T the temperature, and S_E the energy source.

For buoyancy calculations, a source term is added to the momentum equations as follows:

$$\mathbf{S}_{M,buoy} = (\rho - \rho_{ref})\mathbf{g} \tag{14}$$

where $\mathbf{S}_{M,buoy}$ denotes the momentum source for buoyancy, ρ_{ref} the reference mass density and $\mathbf{g}$ the gravity vector. Here, we simplified Eq. (14) and adopted the Boussinesq model as follows:

$$\rho - \rho_{ref} = -\rho_{ref}\beta(T - T_{ref}) \tag{15}$$

where β is the thermal expansivity and T_{ref} the buoyancy reference temperature.

4.2 Numerical Results with Three-Phase GIB

Fig. 5 shows the schematic procedure of the fully coupled analysis of EM field and thermal-fluid dynamics. The finite volume method (FVM) is employed for obtaining the distributions of temperature, velocity, and pressure [5]. To save the computational time in the process of CFD routine, we also employ the effective heat transfer coefficient at the tank surface as a function of temperature as shown in Fig. 6.

To validate the proposed method, we measured the temperature at several points with a 25.8kV 2000A 25kA GIB model composed of tank and hollow conductors as shown in Fig. 4. Inside the tank and hollow conductors, SF_6 gas is filled at a pressure of 1.2 [bar], and the material of the tank is silicon-steel, and that of the conductors is aluminum. Temperature was recorded using the thermocouple sensors. In the test, the measured currents for A, B, and C phase are 2018 A, 1977 A, and 1908 A, respectively. The currents are determined by the applied voltage and the impedance of each phase. In this test, currents are not balanced due to the different impedance for each phase.

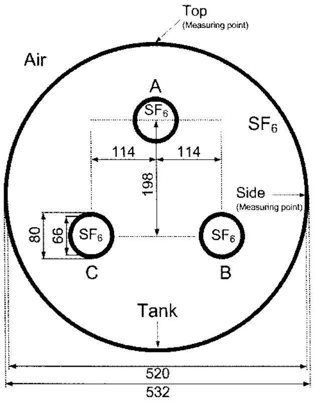

Fig. 4. 25.8kV 2000A 25kA GIB analysis model for numerical and experimental tests (Unit: [mm])

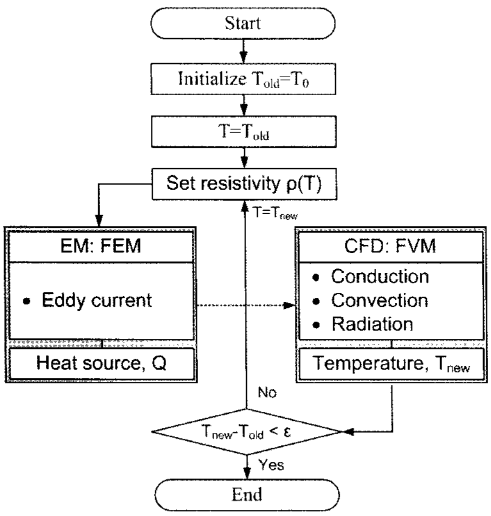

Fig. 5. Schematic procedure of coupled analysis combining EM field and thermal-fluid dynamics

To consider the radiation effect on solid surfaces, the emissivity for the conductors and tank is set as 0.1 and 0.3, respectively. The temperature distribution in steady state is depicted in Fig. 7. The highest temperature was obtained at phase A in which the flowing current is maximum. The warmed SF_6 gas flows upward and circulates inside a tank as shown in Fig. 8, which shows the typical flow pattern for a natural convection. Table 3 shows the comparison of temperature between measured and simulated results. They agree well with each other within 10% of the maximum relative error.

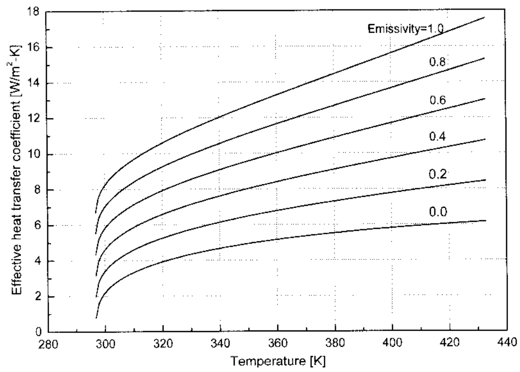

Fig. 6. Effective heat transfer coefficient heff, as a function of emissivity and temperature

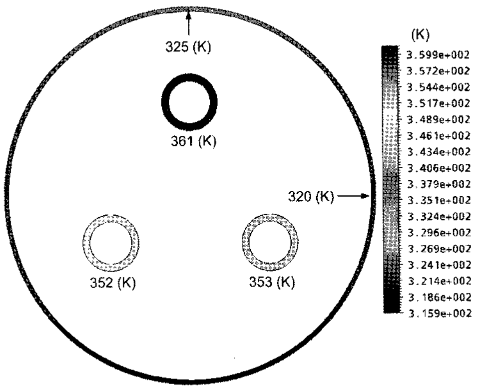

Fig. 7. Temperature distribution of three-phase GIB

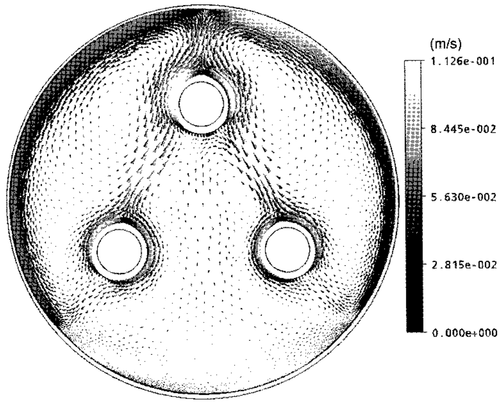

Fig. 8. Flow velocity distribution.

Table 3. Comparison of temperature between measured and calculated results.

Temperature [K]		Measured	Calculated
Conductor	A	362.4	361.3
	B	359.1	353.1
	C	358.4	352.2
Tank	Top	322.9	325.4
	Side	318.5	320.4

5. CONCLUSION

In this paper, the two-way coupling technique between the EM field and thermal field is presented to calculate the temperature rise in a GIB. The thermal conduction problem is solved for a single phase GIB using the effective natural convection coefficient inside a GIB tank. For a three-phase GIB, the coupled analysis method of EM field analysis and CFD technique is employed. The CFD analysis can give the detailed flow velocity field and temperature distribution in gas region and solid parts with a considerable accuracy. The radiative heat transfer on a tank surface is considered as an equivalent convective heat transfer. The effective heat transfer coefficient h_{eff} is computed as a function of emissivity and temperature. By measuring the temperature rise for single phase and three-phase GIB, we can get quite good agreement between simulated and measured results. It should be noted that one of the most important things for the solution of a coupled problem is the temperature-dependant material properties such as electric and thermal conductivity, emissivity and so on.

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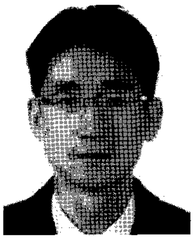

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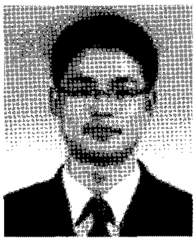

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