Three Dimensional Study of Eddy Current Field and Temperature Field of 126kV three-phase enclosure-type GIS Bus

Yahui Li*
Xuzhou Power Supply Company of State Grid, China

*Corresponding author e-mail: 815497680@qq.com

Abstract. Heat is one of the most obvious characteristics of gas insulated switchgear (GIS) bus. This paper established three-dimensional eddy current field mathematical model for 126kV three-phase enclosure-type GIS bus. Magnetic field finite element method (FEM) was employed to calculate power loss in the conductors and the tank, and the result was the input data for the solution of temperature field. According to the theory of computational fluid dynamics (CFD), SF6 gas movement differential equations was given as well as solved region and boundary conditions of three dimensional fluid field. Nussle number was utilized to figure out nature convection coefficients of different segments of the bus. Solving the differential equations, fluid and temperature field distribution of the bus was calculated, which theoretically supported temperature on-line monitoring system of GIS bus.

1. Introduction

With the increasing demand for electric energy and reliability of power supply, Gas Insulated Switchgear (GIS) has been widely used [1, 2]. However, in the long-time running of GIS, busbar contact overheating may cause contact creep or melting, then partial discharge and short circuit fault to ground are caused which seriously threatens the safe operation of GIS equipment, therefore, it is necessary to study the temperature field distribution of GIS bus bar.

At present, research on temperature field of power equipment at home and abroad mainly focuses on bus layout and parameter design [3], analysis of Temperature Field of Power Cable [4, 5], and Parameter Design of Generator Rotor and Stator [6,7], there are few reports on the distribution of bus temperature field in GIS. The traditional bus temperature field distribution mainly uses two-dimensional FEM method to calculate the electromagnetic field, only heat conduction model is considered in solving temperature field [8] or the calculation results of temperature field of bus housing show isothermal distribution [9]. The three-phase common-box GIS bus usually does not satisfy the spatial symmetry structure, and the gas convection effect along the extension direction of the bus has an important impact on the distribution of bus temperature field. For three-phase common-box bus, it is obvious that two-dimensional field calculation cannot be satisfied.

On the basis of finite element method, heat transfer theory and fluid mechanics theory, a three-dimensional model of 126 kV three-phase common box GIS bus is established, which includes heat conduction, natural convection and heat radiation. Considering the factors of environment temperature, model size and material characteristics, the convection heat transfer coefficient of fluid-solid interface
is calculated by Nussle number, and the eddy current field and temperature are calculated by eddy current field and temperature. The method of field indirect coupling to determine the temperature field distribution of GIS bus has certain reference significance for the study of GIS temperature field and online temperature monitoring.

2. Mathematical Model of Bus Eddy Current Field and Temperature Field

2.1. Governing equations and boundary conditions of three-dimensional eddy current field

The bus structure of three-phase common-box GIS is composed of three-phase conductor and metal shell. A and C phase conductors are located above B phase conductor. SF6 gas is filled with certain pressure inside the conductor and between the conductor and the outer shell.

When the main body flows through the time-varying current, there is induced current in the shell. Bus loss is mainly composed of Joule heat loss in the conductor and eddy current loss in the shell. The contact part of the conductor is modeled as a conductor with larger resistivity. Before establishing the mathematical model of eddy current field, the first assumption is that:

1) The three-phase current is 50 Hz sinusoidal current, and the phase difference is 120 degrees in turn.
2) The conductivity and permeability of conductors and enclosures are constant.
3) For quasi-stable electromagnetic field, the influence of displacement current is neglected.

Using magnetic vector potential and scalar potential as unknown functions, a complex three-dimensional eddy current field control equation is derived from Maxwell equation [10-13]:

\[
\nabla \times (i\nabla \times A) - \nabla \left( i\nabla \cdot A \right) + j\omega \sigma A + \sigma \nabla \phi = 0 \quad \text{in } V_1 \\
\n\nabla \cdot \left( -j\omega \sigma A - \sigma \nabla \phi \right) = 0 \\
\n\nabla \times (i\nabla \times A) - \nabla \left( i\nabla \cdot A \right) = J_s \quad \text{in } V_2
\]

Among them, A is the magnetic vector potential, \( \psi \) is the scalar potential, \( \gamma \) is the magneto resistance, \( \sigma \) is the conductivity, \( J_s \) is the source current density, \( V_1 \) and \( V_2 \) are the eddy current region containing the conductive medium (shell region) and the non-eddy current region of the given source current (three-phase conductor region).

The model loads and boundary conditions are as follows:
1) The parallel boundary condition \( AZ=0 \) is applied to the left and right sides and the upper ends of the bus, the vertical boundary condition of the magnetic line naturally satisfies;
2) Coupled conductor and shell voltage freedom VOLT at the right and upper end of bus;
3) The upper end conductor is defined as 0 potential;
4) A current load is applied to the conductor at the right end.

The Galleria finite element method is used to solve the mathematical model of eddy current field. The average Joule heat loss per unit length of each part of the model is obtained:

\[
P_{rms} = \int_{S} \frac{J_{t}^2}{\sigma} \, ds
\]

In the formula, \( J_t \) is the total current density, including the source current density and eddy current density.
2.2. Mathematical Model of Bus Temperature Field and Flow Field

2.2.1. Analysis of Heat Transfer Mechanism. The GIS studied in this paper is in the indoor environment, so the heat exchange between the shell and the outside air is mainly carried out by natural convection and radiation. The heat transfer mode in the shell is more complex. Because of the influence of gravity and uneven local heat density, the flow mode of SF6 gas is laminar flow, and the heat transfer mode between SF6 and the inner wall of conductor and shell is natural convection heat transfer. The heat transfer mode between the shell and the conductor is considered as radiation, while the heat transfer mode inside the unit is heat conduction.

The principle of energy conservation is one of the basic bases for establishing mathematical models of heat transfer problems. In a steady state, the energy flowing in and out of a surface is equal. According to the principle of conservation of energy:

\[ Q_{CA} + Q_{CB} + Q_{CC} = Q_C + Q_R \]
\[ Q_{CA} + Q_{CB} + Q_{CC} + Q_T = Q_{TC} + Q_{TR} \]  
(4)

In formula, \( Q_{CA}, Q_{CB}, Q_{CC} \) are Joule heat losses of three-phase conductors respectively. \( Q_T \) is shell eddy current loss. \( Q_C \) and \( Q_R \) represent convective heat transfer between conductor and SF6 gas and radioactive heat transfer between conductor and shell. \( Q_{TC} \) denotes heat transfer by convection between shell and air, \( Q_{TR} \) represents the radiation heat from the outer shell to the outer air.

2.2.2. Governing equations of flow and heat transfer. In the model, SF6 gas is an incompressible fluid. Its heat conduction and convection heat transfer can be described by the governing equations of flow and heat transfer, including mass, momentum and energy conservation equations, which are expressed as follows:

\[ \nabla \cdot \mathbf{U} = 0 \]  
(5)

\[ \nabla \cdot \left( \mu \mathbf{U} \right) = \nabla \cdot \left( \nu \nabla \mathbf{U} \right) - \frac{1}{\rho} \frac{\partial p}{\partial x} \]  
(6)

\[ \nabla \cdot \left( \nu \mathbf{U} \right) = \nabla \cdot \left( \nu \nabla \nu \right) - \frac{1}{\rho} \frac{\partial p}{\partial y} + g_y \]  
(7)

\[ \nabla \cdot \left( \omega \mathbf{U} \right) = \nabla \cdot \left( \nu \nabla \omega \right) - \frac{1}{\rho} \frac{\partial p}{\partial z} \]  
(8)

\[ \nabla \cdot \left( \mathbf{UT} \right) = \nabla \cdot \left( \frac{\lambda}{\rho c_p} \nabla T \right) + \frac{S}{\rho} \]  
(9)

In the formula, \( \mathbf{U} \) is the velocity vector of SF6 gas, \( \mu, \nu, \omega \) are the components of \( \mathbf{U} \) on three coordinate axes. \( P \) is pressure, \( \rho \) is SF6 gas density, \( \nu \) is the kinematic viscosity of SF6, \( g_y \) is gravitational acceleration, \( \lambda \) denotes the thermal conductivity, \( c_p \) denotes the constant pressure heat capacity, and \( S \) denotes the generalized source term.
2.2.3. Radiant heat transfer. According to Stefan-Boltzmann law, radiation heat transfer between conductor and shell:

\[ Q = \varepsilon \sigma A_M \left[ (T_1 + 273)^4 - (T_0 + 273)^4 \right] \varphi \]  

(10)

In the formula, \( \varepsilon \) is the emissivity, \( \sigma \) is the Stefan-Boltzmann constant, \( T_1 \) is the shell or conductor temperature, \( T_0 \) is the ambient air or shell temperature, \( A_M \) is the surface area of radiation surface, and \( \varphi \) is the average angle coefficient, which is only used in the calculation of radiation between the conductor and the shell.

2.2.4. Differential governing equation of thermal conductivity

Bus conductor and shell unit transfer heat mainly by means of heat conduction, heat conduction satisfies differential governing heat conduction equation:

\[
\frac{d}{dx} \left( \lambda \frac{dT}{dx} \right) + \frac{d}{dy} \left( \lambda \frac{dT}{dy} \right) + \frac{d}{dz} \left( \lambda \frac{dT}{dz} \right) + \Phi_V = 0
\]

(11)

In the formula, \( \Phi_V \) is the heating rate per unit volume.

2.2.5. Convective heat transfer coefficient. Although there are other objects around GIS, they generally do not affect the flow of the thermal boundary layer around it. Therefore, the convective heat transfer between the shell and the surrounding air can be regarded as natural convective heat transfer in large space. The convective heat transfer coefficient is usually calculated by Nussle number. For different shapes and orientations of the fluid-solid interface, the solution of Nussle number is as follows:

Horizontal position housing and conductor,

\[ N_u = C(G_r P_r)^n \]  

(12)

Vertical housing and conductor,

\[ N_u = \left\{ 0.825 + \frac{0.387 R_a^{1/6}}{1 + (0.492/P_r)^{9/16}} \right\}^2 \]  

(13)

Among them, \( G_r = g \alpha \Delta T d^{1/2} \) is Crashaw number, \( P_r = v/a \) is Planet number.
Convective heat transfer coefficient

\[ h = \frac{N_u \lambda}{l} \]  

(14)

In the formula, \( l \) is the characteristic length.

2.2.6. Analytical Load and Boundary Conditions of Temperature Field and Flow Field. In the solution region, the temperature field and flow field loads and boundary conditions include:
1) The convective heat transfer coefficients of transverse and vertical shell surfaces are 3.59W/(m²·K), 12.2W/(m²·K).
2) The thermal conductivity of conductors and enclosures.
3) Emissivity of Conductors and Shells, here is 0.85.
4) The heat generation load of conductor and shell is mapped from eddy current calculation unit to temperature field.
5) Applying Non-slip Boundary Conditions to the Solid Region Contacting with SF6 Gas: Bus conductor and shell unit transfer heat mainly by means of heat conduction, heat conduction satisfies differential governing heat conduction equation: \( u = v = \omega = 0 \).

3. Numerical calculation and analysis of eddy current field and temperature field

3.1. 3-D eddy current field calculation and analysis

In this paper, a 126 kV GIS bus is taken as the object of analysis, and the model is established for simulation analysis, the results of mesh generation are shown in Figure 1. The total number of elements in the model is 306206, with a total of 461238 nodes. Specific bus size and physical parameters are shown in TABLE 1.

| Parameter | Conductor | Shell | Basin insulator |
|-----------|-----------|-------|-----------------|
| Material  | Al 6063-T6 | Al 6005A-H112 | Ceramics |
| I.D (mm)  | 50        | 492   | -               |
| O.D (mm)  | 86        | 508   | -               |
| Relative permeability | 1 | 1 | 1 |
| Resistivity (Ω·m) | 2.78E-8 | 2.78E-8 | - |
| Conductivity (W·m⁻¹·K⁻¹) | 201 | 237 | 1.1 |

When the current is 2 kA, the current density distribution of GIS bus conductor is shown in figure 2. It can be seen from the figure that the current of phase A and B mainly concentrates on the outer surface of the conductor, while that of phase C mainly concentrates on the inner surface of the conductor; the current direction of phase A and C is opposite to that of phase B; the current density of the welding position of phase B conductor contacts is much higher than that of phase A and C, and the rest is close to that of phase A and C. The main reasons for this phenomenon lie in the phase of three-phase current and the difference of conductor structure and space position.

![Figure 1. Finite element mesh of GIS bus](image-url)
Fig. 3 shows the three-dimensional eddy current density distribution of bus housing. From the graph, it can be seen that the distribution of induced eddy current in the shell is symmetrical because of the symmetry of the three-phase conductor along its elongation direction; the maximum induced current is in the position closest to the conductor; the eddy current induced by the B-phase conductor is larger than that induced by the A-phase and C-phase in the shell; the eddy current direction of the A-phase and C-phase in the shell is opposite to that of the conductor. The maximum eddy current density is 629615 A/m², and the left-most eddy current of the shell tends to zero.
The results of Joule heat loss calculation for bus housing and conductor of GIS are shown in TABLE. The average heat loss of conductor B Joule is the largest, and that of shell is the smallest. The heat loss of conductor A and C Joule is basically the same. The conclusion is consistent with the analysis of Fig. 2.

Table 2. Joule heat loss in the tank and conductors of GIS bus

| Parameter | Shell | Conductor A | Conductor B | Conductor C |
|-----------|-------|-------------|-------------|-------------|
| Loss (Watt) | 24.419 | 43.837 | 59.987 | 43.023 |

3.2. Calculation and Analysis of Temperature Field and Flow Field

When solving the temperature field and flow field, it is necessary to fully consider the relationship between the physical parameters of SF6 gas and pressure and temperature. In the actual operation of the GIS bus, the pressure of SF6 gas is about 0.4MPa, and the pressure increases with the increase of temperature, which satisfies the ideal gas state equation. The thermal conductivity and viscosity of gases increase with the increase of temperature, but in a considerable range, the thermal conductivity and viscosity of gases change little with pressure, which can be neglected in general engineering calculation. Therefore, in practical calculation, only the relationship between thermal conductivity, viscosity and temperature is considered, and the specific heat is a fixed value. The required density values are found by referring to Mollie diagram according to the corresponding pressure and temperature. The physical properties of SF6 gas are shown in TABLE 3.

The calculation results of eddy current field are indirectly coupled to the temperature field and flow field. The temperature field distribution of GIS bus conductor is shown in Fig. 4 under the ambient temperature of 27°C.

Table 3. Parameters of SF6 Gas

| Parameter | Thermal conductivity (W·m⁻¹·K⁻¹) | Viscosity (m²·s⁻¹) | Specific heat (J·kg⁻¹·K⁻¹) | Density (kg·m⁻³) | Pressure (MPa) |
|-----------|---------------------------------|-------------------|-----------------------------|-----------------|--------------|
| Value     | 0.014                           | 1.7E-5            | 665.18                      | 24              | 0.4          |
The figure shows that the highest temperature of the conductor is 56.375°C, which appears at the top of the vertical direction of the B and C phase conductors, and the lowest temperature is at the bottom of the B phase conductor, which is 20.494°C higher than the ambient temperature.

Figure 5. Temperature distribution in the tank of GIS bus

Figure 6. Flow field distribution inside the bus

Figure 5 shows the temperature field distribution of bus housing. As can be seen from the figure, the highest temperature of the shell is 35.718°C, the lowest temperature is 31.229°C, which is higher than the ambient temperature of 4.229°C. The highest temperature is located at the top of the vertical shell, not the nearest position between the transverse shell surface and the contact, and the lowest temperature is located at the left end of the shell. The above distribution results show that the shell temperature has no direct relationship with the distance between the shell and the contacts. The location of temperature detection point should be located at the top of the vertical part of the shell when the bus state detection is carried out in GIS, where the temperature change is most obvious and the best temperature measurement effect can be achieved.

The temperature distribution of conductor and shell is determined by bus structure and SF6 gas flow. The distribution of gas flow in bus is shown in Fig. 6. Most of the high-temperature gas flows to the top of the bus and gathers here. Because of the relatively narrow space and the restriction of gas flow, the temperature of the conductor and the shell is higher than that of other places. There is no heat source at the left end of the bus, and the gas flow velocity below the bus is the smallest, only a few hot gases pass
through, so the heat transfer in this area is hindered and the temperature at the bottom of the shell is the lowest.

4. Conclusion

(1) The current distribution of bus conductor and enclosure of three-phase common-box GIS is calculated. The direction of source current is opposite to induction current. The Joule heat loss of phase B conductor is the highest, the eddy current loss of enclosure is the lowest, and the power loss of phase A and C conductor is approximately equal.

(2) The heat transfer mechanism in three-dimensional GIS bus is analysed. The convective heat transfer coefficients at different locations of bus are calculated by Nussle number. The differential control equations and boundary conditions of temperature field and flow field are established.

(3) Three-dimensional temperature field distribution of three-phase common-box GIS bus is calculated by eddy current field, temperature field and multi-field coupling of flow field. The results show that the temperature distribution of bus housing of three-phase common-box GIS has particularity. The transverse shell surface is closest to the contact, but the highest temperature of the shell is located at the top of the vertical shell. Therefore, the convection characteristics of gas should be fully considered in the detection of bus heating state.

(4) In view of the limitation of two-dimensional temperature field and flow field analysis, the numerical calculation of three-phase common-box GIS bus three-dimensional eddy current field and temperature field provides a reference for the determination of sensor installation position of the GIS bus temperature online monitoring system, and has certain engineering application value.

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