Postprint of Design Analysis on Expansion Capacity of Thermal Compensation Bellows for GIS Busbar

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Abstract

Owing to design deficiencies in thermal compensation bellows employed in GIS busbars, deformation of the enclosure induced by temperature variations cannot be compensated during substation operation and maintenance, leading to cracking or fracture of fixed supports. To address these issues, the primary factors and design principles governing bellows deformation in GIS busbars are analyzed. Through coupled electromagnetic-thermal field simulation, the temperature rise of GIS enclosures under rated current is determined, furnishing critical parameters for bellows expansion-contraction design, with experimental verification conducted subsequently. Experimental results demonstrate that the simulation outcomes align with temperature rise test data, thereby providing a reliable theoretical foundation for bellows design.

Full Text

The Analysis of Expansion Amount Calculation of Thermal Compensation Bellows for GIS Busbar

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Abstract

Due to design deficiencies in thermal compensation bellows for GIS busbars, deformation caused by temperature variations cannot be adequately compensated during substation operation, leading to cracks or fractures in fixed supports. To address these issues, this paper analyzes the primary factors influencing bellows deformation and establishes design principles. Through coupled electromagnetic and temperature field simulations, the temperature rise of GIS enclosures under rated current is determined, providing critical parameters for bellows expansion design, which are subsequently validated through experimental testing. The results demonstrate strong agreement between simulation and temperature rise test data, offering a reliable theoretical basis for bellows design.

Keywords: GIS busbar, bellows, expansion amount, electromagnetic field, temperature field

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1 Introduction

Gas-insulated switchgear (GIS) has become increasingly prevalent in power grid construction due to its compact footprint, high reliability, and low maintenance requirements [1-2]. However, GIS equipment experiences thermal strain and stress in its enclosures and support structures due to ambient temperature fluctuations. This problem is particularly severe in regions with large temperature variations, where cracking of GIS support structures frequently occurs in substations, potentially leading to SF gas leakage and serious grid incidents.

To mitigate thermally induced stresses, GIS equipment typically incorporates thermal compensation bellows that accommodate temperature-induced deformation. The design of bellows expansion capacity critically affects the structural integrity of GIS installations, especially in high-altitude regions with extreme temperature differentials where substantial thermal stresses can cause support structure cracking.

This study investigates the design principles for bellows expansion capacity. By analyzing the electromagnetic field distribution in GIS busbars under rated current, the temperature rise of enclosures due to current flow is determined. Combined with regional temperature variations, this enables the design of appropriate expansion capacity for thermal compensation bellows, ensuring safe and reliable GIS operation.

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2 Design Principles for Thermal Compensation Bellows Expansion Capacity

The expansion capacity design of thermal compensation bellows directly impacts GIS operational safety. In high-altitude, large-temperature-difference substations, support cracking caused by improper bellows design and installation is a common issue. Table 1 presents detection data for support cracking in 110 kV equipment at Taoyuan Substation in Qinghai Province during 2013, while

Figure 1 [Figure 1: see original paper] illustrates the cracking observed in 126 kV GIS busbar supports at the same substation.

As shown in Figure 1 [Figure 1: see original paper], environmental temperature-induced deformation and stress significantly affect GIS equipment. Progressive cracking at fixed support locations may lead to SF gas leakage and even grid accidents [3]. Therefore, proper bellows installation and design are essential for GIS switchgear.

The required expansion capacity of GIS thermal compensation bellows is determined by the maximum deformation between two fixed supports. A simplified installation model is shown in Figure 2 [Figure 2: see original paper]. Based on substation operational experience, GIS deformation is primarily caused by temperature changes, though foundation settlement affects some regions. This study focuses on thermal effects, with the main influencing factors being: the temperature range of the installation region, the temperature range during on-site installation, the temperature rise under rated current, the maximum temperature rise due to solar radiation, and the distance between fixed supports [4].

The axial length change of a GIS enclosure due to temperature variation is given by:

$$\Delta l = \alpha l \Delta T \tag{1}$$

where l is the original length of the enclosure, α is the linear expansion coefficient of the enclosure material, and ΔT is the temperature change.

From equation (1), the bellows expansion capacity can be calculated as:

$$\Delta L = [\alpha_1 (K_{1\max} - K_{2\min} + K_{m1} + K_{m2}) - \alpha_2 (K_{2\max} - K_{2\min})] L \tag{3}$$

where α_1 and α_2 are the linear expansion coefficients of the enclosure and foundation, respectively; $K_{1\max}$ and $K_{1\min}$ are the maximum and minimum temperatures of the installation region; $K_{2\max}$ and $K_{2\min}$ are the maximum and minimum temperatures during installation; K_{m1} is the temperature rise due to rated current; and K_{m2} is the temperature rise due to solar radiation. Regional temperature ranges, installation temperature ranges, and solar-induced temperature rise are objective data. The distance between fixed supports is determined by equipment strength requirements and deflection control, while the temperature rise under rated current must be determined through testing or calculation. The following section presents coupled electromagnetic and temperature field simulations to determine this critical parameter.

3 Electromagnetic Field Analysis of GIS Busbar

Due to skin effect, both the impedance and current density distribution in tubular conductors change when carrying rated current. A GIS single-phase busbar model was established based on GIS busbar parameters, as shown in Figure 3 [Figure 3: see original paper]. Simulation results are summarized in Table 2 .

The electromagnetic field calculation equation [10] is:

$$P_e = I_e^2 R_e = J_e^2 \rho L_e \tag{4}$$

where I_e is the current in a finite element cell, J_e is the current density in a finite element cell, and L_e is the axial length of the busbar.

Considering eddy current losses in the enclosure, the electromagnetic field equation yields the current density distribution. Using the electromagnetic module in Workbench, a small section of busbar was modeled with a rated current of 4000 A at 50 Hz. The resulting GIS busbar current density distribution is shown in Figure 4 [Figure 4: see original paper].

4.1 Coupled Electromagnetic-Temperature Field Calculation

The electromagnetic field calculation provides current density distributions for both conductor and enclosure, which generate loss-based heat sources. For simplified analysis, a two-dimensional temperature field calculation is performed. The cross-sectional power loss equations [11-13] are established, and heat transfer occurs through conduction and convection between the conductor and SF gas, and between the enclosure and ambient air:

$$q_1 = h \Delta t \tag{5}$$

where h is the convective heat transfer coefficient and Δt is the temperature difference between the two media.

Heat transfer in SF gas occurs through radiation and natural convection. The radiation heat transfer is calculated as:

$$q_2 = \varepsilon \sigma T^4 \tag{6}$$

where ε is the surface emissivity, σ is the Stefan-Boltzmann constant, and T is the thermodynamic temperature.

Natural convection in gases follows the continuity, momentum, and energy conservation equations:

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \tag{7}$$

$$\rho c \left(u \frac{\partial T_g}{\partial x} + v \frac{\partial T_g}{\partial y} \right) = \nabla \cdot (k \nabla T_g) + q_v \tag{8}$$

where ρ is SF density, u and v are gas velocity components in the x and y directions, c is specific heat capacity, T_g is gas temperature, q_v is heat generation per unit volume, k is thermal conductivity, η is kinematic viscosity, p is pressure, g is gravitational acceleration, and β is the thermal expansion coefficient.

Using electromagnetic-temperature field coupling in Workbench, electromagnetic losses are imported as heat sources into the fluid temperature field. Appropriate radiation coefficients are assigned to conductor surfaces, and convective heat transfer coefficients are applied to enclosure surfaces based on experimental correlations. The surrounding air boundary is treated as isothermal. To enable subsequent experimental validation, the initial and far-field temperatures are set to the ambient temperature of 14°C (286 K). The resulting GIS busbar temperature distribution under rated current is shown in Figure 5 [Figure 5: see original paper].

The calculated enclosure temperature is 307.7 K, corresponding to a temperature rise of 21.7 K due to rated current.

4.2 Temperature Rise Test Verification

To validate the calculated temperature rise of GIS busbar enclosures under rated current, a temperature rise test was conducted according to the schematic shown in Figure 6 [Figure 6: see original paper]. In the test setup, a voltage regulator supplies power, a current booster provides the required test current, and sensors monitor the current magnitude. The test is considered stable when the temperature rise variation does not exceed 1 K within one hour [16].

Based on this principle, a temperature rise test was performed on a GIS busbar of identical dimensions. The test apparatus and temperature measurement points are shown in Figure 7 [Figure 7: see original paper] and Figure 8 [Figure 8: see original paper]. According to GB/T 11022–2011, the ambient air temperature during testing should be between +10°C and +40°C [17]. The test was conducted at an ambient temperature of approximately 14°C, meeting the standard requirements. Following the GB/T 11022–2011 procedure, the final enclosure temperatures are recorded in Table 3 .

The test yields an average temperature rise of 20.86 K for the GIS busbar enclosure, which closely matches the simulated value of 21.7 K. This validation confirms the reliability of the simulation methodology for bellows design applications.

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5 Example Calculation of Bellows Expansion Capacity

With the temperature rise under rated current determined, the required expansion capacity of GIS thermal compensation bellows can be calculated. Consider the following conditions: 1. Ambient temperature: -40°C to 40°C 2. Installation temperature: 5°C to 32°C 3. Solar-induced temperature rise: 10 K 4. Rated current temperature rise: 21.7 K 5. Distance between fixed supports: 10 m

Substituting these parameters into equations (1) and (3) yields a maximum enclosure elongation of 11.85 mm and maximum contraction of 8.78 mm. Incorporating a safety factor and considering the GIS operating environment, the bellows expansion capacity is typically designed as ±15 mm.

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6 Conclusion

This study investigates the expansion capacity design of thermal compensation bellows for GIS busbars, leading to the following conclusions:

1. The significance of proper expansion capacity design for GIS thermal compensation bellows is analyzed, and fundamental design principles are established.
2. Through coupled electromagnetic, fluid, and temperature field simulations, critical parameters for bellows design are obtained, providing essential data for reliable design.
3. Temperature rise testing under rated current validates the simulation methodology, providing strong experimental support for bellows design.

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