Scale Modeling on the Overheat Failure of Bus Contacts in Gas-Insulated Switchgears

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***Abstract*—In this paper, scale model is proposed to investigate the overheat failure mechanism and processes of bus contacts in Gas-Insulated Switchgears (GIS). Similarity of the overheat phenomenon is analyzed and the scaling relationships of the coupled eddy current-fluid-heat field are derived. Considering the availability and feasibility of the model, the scaling relationships are simplified and a partial scale model is further designed with all the geometric dimensions, physical parameters and boundary conditions presented. The current densities and temperature distributions of the scale model and the prototype are compared to verify the effectiveness of the scale model by 3-D finite element method (FEM).**

***Index Terms*—Equipment failure, contact resistance, solid modeling, thermal analysis, finite element methods.**

I. INTRODUCTION

Gas-Insulated Switchgears (GIS) are widely applied in substations for many advantages. In their operations, the overheat failure of bus electrical contact caused by poor contact defect threatens the security and stability of power grid. Temperature detection is the most straightforward way to reveal the poor contact defect on-site. In order to put forward the implementation method for temperature detection, failure mechanism and failure process, which is the theoretical basis for the overheat failure detection, should be studied with the help of destructive simulation tests.

It is well known that destructive tests can hardly be achieved by prototypes because of the high cost and many other reasons. However, scale models, which have shown good economical and practical significance, have been extensively employed in simulation tests. Incomplete contact phenomena and detection method of disconnecting switch and detachable bus in GIS were studied in [1]-[2], while the poor contact defect of bus contacts was not mentioned. Temperature field distribution of GIS bus bars was calculated in [3], but the bus contacts were excluded and the overheat failure was not considered. Scaling relationships for electrical contact resistance joining two current channels were discussed in [4] and scaling rules for the thermal time constants and the maximum current were analyzed in [5], while the overheat phenomenon was not studied and the scaling relationships of the multi-physical field were not derived.

In this paper, a reduced scale model of the GIS bus is designed for the destructive simulation tests. The coupled field scaling relationships of the overheat failure are analyzed in detail. The finite element model of the scale model is established and the calculated current density and temperature are compared with that of the prototype to validate the correctness of the scale modeling.

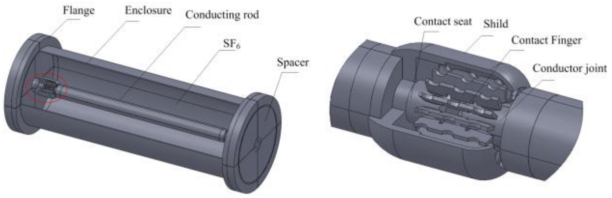


Fig. 1. Schematic diagram of plum blossom contact

II. SCALE MODELING METHOD

This paper focuses on the plum blossom contacts which have been widely applied in GIS bus joints. The full model of GIS is shown to the left with an enlargement of the bus contact region to the right in Fig. 1. The scale model on overheating failure of bus contact is summarized briefly as follows:

1) Build the mathematical models of the overheat phenomenon based on electrical contact, electromagnetic field and heat transfer theories. 2) Derive the coupled field scaling relationships by analyzing the mathematical models of the overheat phenomenon theoretically. 3) Simplify and modify the scaling relationships of the convective heat transfer and the eddy current power loss for better practicability of the scale model. 4) Assess the effectiveness and robustness of the scale model by comparing the current density and thermal characteristics of the prototype and the scale model under different load currents and contact resistances.

III. MATHEMATICAL MODEL OF THE OVERHEAT FAILURE

A. Contact Resistance

Because the cleanliness inside the enclosure is highly required, film resistance is neglected and the contact resistance mainly depends on the applied pressure and the hardness of the material [6]. Taking plastic deformation into account [6]-[7], the static contact resistance can be expressed as

$$R_{\mathrm{c}} = \frac{\rho_1 + \rho_2}{4}\sqrt{\frac{8NC^3 nH}{\pi i G d \Delta l}} \tag{1}$$

where ρ_1 and ρ_2 are the resistivity of the two contact materials, N and i are, respectively, the number of contact fingers and springs, C is the spring index, G, n and d are, respectively, the shear modulus, active coils and wire diameter of spring, H is the hardness of the softer material and Δl is the radical deformation of the spring.

B. Power Loss

Using the $\boldsymbol{A}$, $\phi - \boldsymbol{A}$ method, joule heat loss P_{c} caused by source current flowing in conductor and eddy current loss P_{t} caused by induced eddy current in enclosure are expressed as

$$\begin{cases} P_{\mathrm{t}} = \dfrac{1}{\sigma}\int_{\mathrm{v}} (-\sigma \dfrac{\partial \boldsymbol{A}}{\partial t} - \sigma \nabla \phi)^2 dv \\ P_{\mathrm{c}} = \dfrac{1}{\sigma}\int_{\mathrm{v}} \boldsymbol{J}_{\mathrm{s}}{}^2 dv \end{cases} \tag{2}$$

where σ is the conductivity, $\boldsymbol{A}$ is the magnetic vector potential, t is the circle, ϕ is electric scalar potential, $\boldsymbol{J}_{\mathrm{s}}$ the current density.

C. Heat Transfer

All the power losses generated in conductor and enclosure are converted into heat which is dissipated to the surrounding air via conduction, convection and radiation due to the temperature difference at the boundaries of the components. Heat transferred by convection Q_{c} and by radiation Q_{r} between conductor and enclosure are calculated respectively:

$$\begin{cases} Q_{\mathrm{c}} = Sh\Delta T \\ Q_{\mathrm{r}} = S\delta\varepsilon X \left(T_1^4 - T_2^4\right) \end{cases} \tag{3}$$

where S is the external surface area of the conductor, h is the convective heat transfer coefficient, ΔT is the temperature difference of the SF_6 gas, δ is Stefan-Boltzmann constant, ε is the emissivity of the conductor, X is the angle factor, T_1 and T_2 the Kelvin temperatures of the conductor and the enclosure.

Heat transfer follows the thermal equilibrium equation：

$$P_{\mathrm{c}} = Q_{\mathrm{r}} + Q_{\mathrm{c}} \tag{4}$$

IV. Model Formation and Numerical Validation

Equation analysis and dimensional analysis are both employed to derive the coupled field scaling relationships theoretical. The simplification and modification which makes the scale model physically realizable are described as:

1. The enclosure of GIS is made of aluminum alloy and its thermal effect on bus contacts is small, therefore, the scaling relationship of current frequency is neglected.

2. In order to fulfill the similarity of the natural convection under the premise of the same fluid material, the scaling of the fluid density, which is unrealizable in simulation tests, can be avoided as long as the characteristic length of the scale model equals to that of the prototype. The characteristic length of the SF_6 gas channel is approximated by the equivalent diameter.

3. Systematic error of temperature may be founded because the flow sectional of the SF_6 channel is not a constant along the axial direction, strictly speaking. According to the scaling relationships, the density of SF_6 gas is the other parameter that could be modified within an acceptable range to reduce the temperature discrepancy between prototype and scale model.

Similarity criterions of overheat failure are summarized as

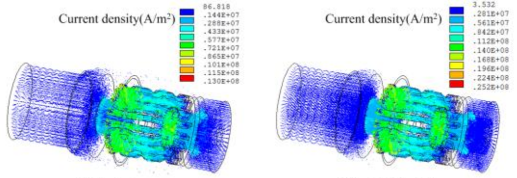
$$\begin{cases} R_{\mathrm{c}} i^{1/2} G^{1/2} d^{1/2} l^{1/2} / (\rho H^{1/2} n^{1/2} N^{1/2} C^{3/2}) = \prod_1, \\ \mu\sigma l\phi / A = \prod_2, \ \ \mu J_{\mathrm{s}} l^2 / A = \prod_3, \ \ J_{\mathrm{s}}^2 l^3 / (\sigma P_{\mathrm{c}}) = \prod_4, \\ Q_{\mathrm{c}} / l^2 hT = \prod_5, \ \ Q_{\mathrm{r}} / l^2 \varepsilon X T^4 = \prod_6, \\ P_{\mathrm{c}} / Q_{\mathrm{r}} = \prod_7, \ \ P_{\mathrm{c}} / Q_{\mathrm{c}} = \prod_8, \end{cases} \tag{5}$$

where μ is the permeability and l is the dimension parameter.

TABLE I
SIMULATION PARAMETERS

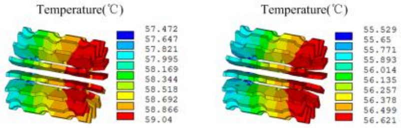
	Prototype	Scale model
Inner Diameter of Enclosure(mm)	508	404.25
Outer Diameter of Enclosure(mm)	492	420.25
Length of GIS(mm)	1600	400
Contact Resistance(μΩ)	160	1280
Current Magnitude(A)	2000	250
Current Frequency(Hz)	50	50
Pressure of SF_6 gas(MPa)	0.4	0.37

The dimension of the current carrying part is scaled to 1/4 and the rest of the simulation parameters are given in Table I. Current densities and temperature distributions in bus contacts of the prototype and the scale model are shown in Fig. 2 and Fig. 3. Steady state thermal analysis under different load currents is presented. Contact temperature of the prototype and the scale model are given in Fig. 4.



1)Prototype 2)Scale Model

Fig. 2. Current density comparison



1)Prototype 2)Scale Model

Fig. 3. Temperature distribution comparison

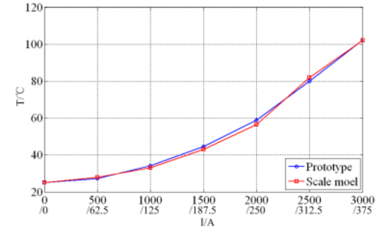


Fig. 4. Temperature of the contact under different current

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