Dynamic Temperature Calculation of Gas Insulated Bus Bars

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Abstract. As the key link of different voltage levels of power system, gas insulated bus bars have the important function of power transmission in large capacity. Temperature at the conductor is the highest when the bus bar gets overheat. As the conductor locates inside the metal shell, the usual thermal detection method can only measure the outer surface temperature and cannot obtain the temperature rise of the conductor inside. In this paper, a dynamic thermal analysis model of bus is proposed based on Thermal-electric analogy method. The thermal constant is calculated as the key parameter for conductor temperature prediction. An exponential function is obtained to model the temperature rise process of the conductor. The comparison between the temperature prediction results calculated by finite element model and dynamic model shows in good agreement. The research results provide theoretical basis and reference for the conductor temperature monitoring of gas insulated bus bars.

1. Introduction
As a key link between power transmission and distribution, gas insulated bus bar (GIB) plays an important role in the transmission of power in large capacity. The voltage level of gas insulated bus bar in China has developed to a milestone of 1100 kV. Thus, its operational reliability is of great significance for the safe operation of the entire power grid [1].

The temperature rise of the GIB is caused by the Joule heat loss in the conductor and the eddy current loss in the shell which are relative with the load condition and the ambient temperature. In order to obtain the distribution characteristics of the temperature field distribution inside the GIB and accurately calculate the temperature rise of the conductor and the conductor, domestic and foreign scholars have done a lot of experiments and researches including conductor and shell temperature monitoring, temperature field calculation model, influencing factors analysis of temperature rise and dynamic temperature rise calculation method [2, 3].

Accurate calculation of temperature rise is the premise for monitoring and fault diagnosis of GIBs. This paper establishes the equivalent thermal circuit model of GIB under normal conditions by thermal-electric analogy method. The temperature rise progress of the bus bar under step load currents is calculated with the finite element method (FEM). According to the definition, the thermal time constant of the conductor is calculated. By dividing the actual load curve into segments, the dynamic temperature rise response of the bus bar is predicted with an exponential function. The comparison to the two-dimensional FEM temperature rise calculation results verifies the proposed dynamic thermal model.
2. Thermal-Electric Analogy
Heat is an invisible energy that is transmitted between different temperature systems that are in contact with each other. In general, the heat flux can be quantitatively described according to thermodynamic and fluid dynamic theory. According to Fourier's law \[4\]:

\[
q = \frac{\lambda A \Delta \theta}{\delta} = \Delta \theta \frac{A}{R_{th}} \tag{1}
\]

Where \( q \) is the heat flux, \( A \) is the heat transfer area, \( \delta \) is the thickness, \( R_{th} \) is the heat resistance, and \( \Delta \theta \) is the temperature difference.

For the thermal circuit, the following equation with energy balance relationship is given:

\[
q = C_{th} \frac{d\theta}{dt} + \frac{\theta - \theta_a}{R_{th}} \tag{2}
\]

Where \( C_{th} \) is the heat capacity, \( \theta_a \) is the ambient temperature.

3. Dynamic Thermal Analysis Model of GIB
3.1. Equivalent Heat Path of Gas Insulated Bus Bar
The internal and external heat transfer process of the GIB is shown in Fig. 1. The Joule heat loss \( q_c \) in the conductor is transmitted to the inner surface of the shell by means of heat convection and radiation of SF\(_6\) gas. On the outer surface of the shell, the Joule heat loss in the conductor and eddy current loss \( q_t \) in the shell are transmitted to the surrounding air by large-space natural convection and radiation.

The equivalent thermal circuit model of the GIB is shown in Fig. 2. In the figure, \( C_c \), \( C_g \) and \( C_t \) are the heat capacity of the conductor, SF\(_6\) gas and the shell, respectively. \( R_g \) and \( R_a \) are the thermal resistance of SF\(_6\) gas between the conductor and the shell and the thermal resistance between the shell and the air, respectively. \( \theta_c \) and \( \theta_t \) are the conductor temperature and the shell temperature, respectively.

![Figure 1. Simplified process of heat transfer in GIB](image)

![Figure 2. Equivalent thermal model of the GIB](image)
According to the circuit theory, the differential equations used to describe the conductor-shell and the shell-air thermal circuits in Fig. 2 are [4]

\[ q_c = \left( C_c + C_g \right) \frac{d\theta_c}{dt} + \frac{1}{R_g} (\theta_c - \theta_t) \]

\[ q_c + q_t = C_i \frac{d\theta_t}{dt} + \frac{1}{R_a} (\theta_t - \theta_a) \]

When the thermal circuit reaches steady state, the temperature difference \( \Delta \theta_c \) between the conductor and the shell and the temperature difference \( \Delta \theta_t \) between the shell and the surrounding air can be, respectively, written as [5]

\[ \Delta \theta_c = \Delta \theta_{sc} + (\Delta \theta_{s0} - \Delta \theta_{sc}) e^{-t/\tau_c} \]

\[ \Delta \theta_t = \Delta \theta_{st} + (\Delta \theta_{t0} - \Delta \theta_{st}) e^{-t/\tau_t} \]

Where \( \Delta \theta_{sc} \) and \( \Delta \theta_{st} \) are the steady-state temperature difference between the conductor and the shell and that between the shell and the surrounding air, respectively. \( \tau_c \) and \( \tau_t \) are the temperature rise time constants of the conductor and the shell, respectively. \( \Delta \theta_{s0} \) and \( \Delta \theta_{t0} \) are the initial temperature difference between the bus conductor and the shell and that between the shell and the surrounding air, respectively.

### 3.2. Calculation of Thermal Time Constant of the GIB

In the actual operation process, when the load current of the GIB changes, the temperature cannot be immediately changed due to the heat capacity of the GIB. It gradually changes with time and reaches a stable state after some period. According to the principle of heat transfer, in the case of unsteady thermal analysis, the thermal time constant is generally used to reflect the degree of change in bus temperature. The thermal time constant represents the time required for the temperature rise from zero to the maximum temperature change of 63.2% during non-steady-state heat conduction

\[ \tau = R_{th} C_{th} \]

Where the thermal time constant, \( R_{th} \) and \( C_{th} \) is are the thermal resistance and heat capacity of each component of the GIB.

In the thermal analysis of GIBs by lumped parameter method, the heat capacity and the nonlinear thermal resistance are often difficult to solve because of the complicated internal heat transfer process. The thermal time constant is obtained by fitting the temperature rise data calculated with FEM model.

### 3.3. Dynamic Simulation of Temperature Rise Process of the GIB

When the ambient temperature changes, the steady-state temperature rise of the bus bar remains basically unchanged. At this time, the steady-state temperature rise of the GIB is only related to the load current. The finite element method is used to establish a two-dimensional thermal analysis model to calculate the temperature rise of the GIB, and a quadratic polynomial fit is applied to the temperature rise-load relationship, as shown in Fig. 3. The mathematical relationship between the steady-state temperature rise of the bus bar and the load current can be expressed as
\[ \Delta \theta = \theta_s - \theta_a = aI^2 + bI + c \]  

(8)

Where \( I \) is the load current, \( a, b, \) and \( c \) are polynomial coefficients, \( \Delta_s \) and \( \Delta_a \) are the steady-state and initial temperature, respectively.

During the actual operation of the GIB, the load current is continuously changed. The mathematical relationship between the bus thermal equilibrium temperature and the bus operating conditions must be constructed. A series of step curves are used to simulate the continuous change process of the load. The method is shown in Fig. 4. The temperature value corresponding to each discrete point will be used as the initial value for the next temperature calculation.

It is assumed that the load current change process is equally divided into \( n \) time periods as shown in Fig. 4. Each time period has a length of \( \Delta t = t_i - t_{i-1} \). At time \( t_i \), the temperature of each conductor of the gas insulated bus bar can be expressed as [6]

\[ \theta(t) = \theta_s(t_{i-1}) + [\theta(t_{i-1}) - \theta_s(t_{i-1})] \cdot \exp[-(t - t_{i-1}) / \tau], \quad t_{i-1} \leq t \leq t_i \]  

(9)

where \( \theta_s(t_{i-1}) \) is the steady-state temperature at which the bus bar corresponds to the load current \( I \) at time \( t_{i-1} \).
Figure 5. Temperature rise process of the GIB under step load current 1.5 kA

4. Application Results and Analysis

The ambient temperature is assumed to be 25 °C. Under the action of 1.5 kA step load current, the temperature rise process of the GIB is shown in Fig. 5. The thermal time constants of the bus bar A/C phase conductor, B phase conductor, SF₆ gas and shell were calculated according to the thermal time constant, which were 1.25 h, 1.21 h, 1.47 h and 1.77 h, respectively. In order to verify the feasibility of simulating the temperature rise process of GIB by exponential relationship, the temperature rise response process of GIB is calculated by using (5) and (6). The comparison between the calculation results and the results of finite element analysis is shown in Fig. 6. The maximum calculation error of the conductor temperature is 0.3 °C, and the maximum calculation error of the shell temperature is 0.8 °C. The relative error of both is less than 5%, which meets the requirements of engineering applications.

Figure 6. Step response of temperature rise in the GIB under different load currents

Since the thermal time constant of the GIB is related to the heat capacity of the bus bar and the thermal resistance of the gas, it does not change with the load current. Therefore, the obtained thermal time constant can also be used for the analysis of the bus bar temperature rise process under different load current conditions.
5. Conclusion
In this paper, the equivalent thermal circuit model of the GIB under normal operating conditions is established. The thermal time constant of the bus conductor and the shell is calculated by the finite element method, and the temperature rise process of the bus bar is simulated by a single exponential function. The comparison with the finite element transient temperature rise analysis shows that the single exponential function can track the bus temperature change process more accurately under the step load condition. It can provide as reference for the judgment of the overheated state of the GIB.

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