Theoretical Analysis of Electric Heating Field and Insulation Accident of High Voltage AC Basin Insulator

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Abstract. Basin insulator is widely used in GIS equipment. It is an important insulating part to realize electrical isolation between central conductor and grounding flange. In this paper, the insulation properties of the materials used for the basin insulator are analyzed experimentally, and the distribution of the electric field of the basin insulator is obtained through the electro-thermal coupling analysis process, and the relationship between the hottest spot temperature and the current carrying capacity is calculated. The heating curve of the basin insulator is obtained by using the theoretical model, and the basin insulation accident is analyzed by using the curve. Considering that the basin insulator is in the SF6 gas atmosphere for a long time, the local temperature rise caused by overheating fault of the basin insulator, and then the variation law of SF6 gas pressure and density caused by the overheating fault of the basin insulator are theoretically analyzed in this paper. Research shows: there is significant non-linear relationship between the insulation performance parameters of the basin body and the temperature. The eddy current field and harmonic field analysis method based on the finite element method can effectively calculate the heating of the center guide rod and the basin body under the power frequency condition. The maximum electric field intensity appears at the interface between the basin and the center conductor, with the value of 6.033kV/mm. The maximum temperature is near center conductor side of the basin, with value of 0.033kV/mm. When the current carrying capacity is higher than 1.5 times of the rated value, the thermal breakdown phenomenon of sudden temperature rise occurs. The calculation process of thermal electric coupling proposed in this paper provides way for verification of thermal electric performance of basin insulator design scheme, and also provides theoretical guidance for its on-site maintenance and accident analysis.

1. Introduction
High voltage basin insulator is widely used in substation GIS equipment. Its main function is to realize the electrical isolation between central conductor and grounding pipe, and to provide mechanical support for the central conductor. The majority of GIS pipelines are filled with SF6 gas with a certain pressure, which has good insulation performance, so GIS pipelines can achieve compact design. In the narrow space, there are SF6 gas, organic insulating material of basin insulator body, central conductor and other media at the same time. Under the action of high voltage and large current for a long time, basin flash-over or even explosion and other insulation accidents are prone to occur. Therefore, the long-term combined effect of electro-thermal effect is the direct cause of basin insulator accidents [1].

Under the actual operating conditions, the heat source of the basin insulator mainly includes two parts: one part comes from the eddy current heating under the current carrying condition of the central
conductor, and the other part comes from the Joule heating under the voltage bearing condition of the basin insulator body. The eddy current field analysis model of GIS pipeline bus was established in reference [2], and the bus temperature field distribution was calculated. In reference [3], the electric field distortion of GIS basin insulator with air gap, free metal particles and other defects was simulated and analyzed. In reference [4], the fracture process of the basin insulator in hydrostatic test was quantitatively analyzed by measuring stress and strain. However, there are few literatures on how the insulation performance of basin insulator body affects the distribution of electric field under long-term rated operation condition, how the electric field of basin insulator will change under short-term overload, and how the relationship between the insulation failure of basin insulator and its electric field distribution.

In view of this, this paper first tests insulation performance of the body material of the basin insulator, obtains the relationship between the performance parameters of the body material of the AC basin and the temperature, and uses the display function for the nonlinear fitting. Combined with the formula derivation, the theoretical calculation model of the electric field of the basin insulator is established, and the heating characteristic curve in the actual operation is obtained. Furthermore, based on the finite element analysis, the decoupling calculation method for the thermal field of basin insulator is developed, which takes into account the nonlinear relationship between the insulation performance parameters and temperature. The steady-state distribution of the electric field of the high-voltage AC basin insulator under the long-term rated operation condition and the variation law of the electric field under the short-term overload condition are obtained by iterative calculation. According to the heating characteristic curve and the finite element calculation results, an accident of the basin insulator is analyzed. The calculation process of electro-thermal coupling proposed in this paper provides a way to check the electro-thermal performance of basin insulator design scheme, and also provides theoretical guidance for its field maintenance and accident analysis.

2. Insulation performance test of basin insulator body material
The macroscopic dielectric properties and thermal conductivity of basin insulator body material are related to its micro-structure, and the electrical performance parameters of basin determine its global electric heating field distribution under the current carrying and voltage carrying conditions, and the electric heating field distribution also provides the basis for the structural design and optimization of basin insulator [5-7].

![The relationship between dielectric property parameters and temperature](image)

The temperature spectrum curve of the insulator material in the range of -50-150 ℃ is measured. The high voltage AC basin insulator operates under the power frequency voltage, so the frequency is set to 50Hz in the measurement. The relationship between the relative dielectric constant, the tangent value of loss angle and the temperature is shown in Figure 1. The temperature range of -50-20℃ is
defined as low temperature zone, 20-100°C temperature range is defined as rated operation area, and 100-150 °C temperature range is defined as high temperature zone. Figure 1 shows that in the low temperature region, the relative dielectric constant increases with the increase of temperature, but the tangent value of the loss angle decreases with the rise of temperature. In the rated operation area, the relative dielectric constant increases slightly, while the tangent value of the loss angle decreases first and then rises. In the high temperature region, the relative dielectric constant and the loss angle tangent value rise sharply, and the tangent value of the loss angle is displayed later.

Fig. 2 The relationship between thermal conduction parameters and temperature

The thermal performance parameters of the basin insulator body material are measured, including the changes of the thermal conductivity, the thermal capacity and the thermal expansion coefficient in the temperature range of 25~150 °C, as shown in Figure 2. The results show that the thermal conductivity of the pot body material is about 1.02W/(m*K) at 25°C, and the addition of fillers in the epoxy material is conducive to heat conduction. The maximum value is 1.2W/(m*K) near 50°C, and then gradually decreases to 1.05W/(m*K), which indicates that the temperature of basin insulator should be controlled near 50°C in actual operation. The results show that the heat capacity increases with the increase of temperature, and the heat capacity keeps between 1~1.4J/(g*K).

3. Theoretical analysis of influence factors on calorific value of basin insulator

When calculating the load capacity of the high-voltage basin insulator, it is considered that the tangent value of the loss angle \( \tan \delta \) is a constant value independent of temperature, generally the maximum value within the allowable working temperature range is taken[8-10]. For the insulation material of the pot body, the dielectric performance parameters test results shown in Fig. 1 are fitted and analyzed. The specific expression of the double exponential function (1) shows that one part corresponds to the ion conductivity loss and the other part corresponds to the dipole relaxation loss [11]:

\[
\tan \delta = \sigma_1 e^{\alpha_1 T} + \sigma_2 e^{\alpha_2 T} \quad (1)
\]

Fig. 3 The fitting effect by double exponential function
In the above formula, $\sigma_1$, $\alpha_1$, $\sigma_2$, $\alpha_2$ are the constants to be fitted, $T$ is the temperature value, and the unit is K. Constant fitting results are $\sigma_1 = 0.09278$, $\alpha_1 = -0.007719$, $\sigma_2 = 7.686e-12$, $\alpha_2 = 0.05604$, and the fitting effect is shown in Figure 3. Considering the feasibility of the subsequent theoretical formula derivation, the following assumptions are made: 1) the dielectric constant $\varepsilon$ and the thermal resistance $\rho_t$ of the basin body material are temperature independent constants; 2) the basin topology is simplified as a cylindrical model; 3) the relationship between the loss tangent and temperature is fitted by using the exponential function $\tan \delta = \tan \delta_0 e^{\alpha(\theta - \theta_0)}$, where $\tan \delta_0$ is the value when the insulation temperature is $\theta_0$, $\alpha$ is a constant. Therefore, the calorific value per unit volume per unit time of the insulating layer is the equivalent conductivity of the insulating material:

$$\gamma = \omega \varepsilon_0 \varepsilon \tan \delta_0 [\alpha (\theta - \theta_0)]$$  

(2)

The pot is equivalent to a cylindrical model, so:

$$W_i = \gamma E^2 = \omega \varepsilon_0 \varepsilon_1 \tan \delta_0 e^{\alpha(\theta - \theta_0)} \left( \frac{U_0}{R} \right)^2$$

$$= \frac{\omega C^2 U_0^2}{4\pi^2 \varepsilon_0 \varepsilon_1} \tan \delta_0 e^{\alpha(\theta - \theta_0)}$$

(3)

In formula (3), $x$—the distance between the insulati ng layer and the central conductor. $C$—the capacitance of the basin insulator. $R$—the radius of the central guide rod. $R$—the radius of the basin insulator. $U_0$—the bearing voltage of the basin. The equation (3) is substituted into the steady heat transfer equation of the cylinder model:

$$x^2 \frac{d^2 \theta}{dx^2} + x \frac{d\theta}{dx} + \frac{\omega C^2 U_0^2 \rho_t}{4\pi^2 \varepsilon_0 \varepsilon_1} \tan \delta_0 e^{\alpha(\theta - \theta_0)} = 0$$

(4)

Order:

$$n = \frac{\omega C^2 U_0^2 \tan \delta_0 \rho_t}{4\pi^2 \varepsilon_0 \varepsilon_1}$$

Then the solution of the above formula is as follows:

$$f = -2\ln \left[ \frac{1}{d^2} \left( \frac{x}{r_c} \right)^k + \frac{1}{g^2} \left( \frac{x}{r_c} \right)^k \right] = \alpha \theta$$

(5)

Among them:

$$k = dg \sqrt{\frac{na}{8}}$$

(6)

Where $d$ and $g$ are integral constants, and their values can be obtained according to the boundary conditions:

$$A = \frac{\alpha W_c^2 \rho_t^2}{4\pi^2 n} e^{-\alpha \theta_0}, \quad B = 2 + A + \sqrt{A^2 + 4A}$$

(7) and $\theta_c - \theta = \frac{2}{\alpha} \ln \left( \frac{x}{r_c} \right)^k + \frac{B - 1}{B} \left( \frac{x}{r_c} \right)^k$

W_c is the heating power of the central conductor of the basin, and it is the temperature value at the interface between the basin and the central conductor. Given $W_c$ and $\theta_c$, the values of $K$, $a$ and $B$ can be calculated, and the temperature distribution in the insulating layer of the basin can be determined.
by the above formula. In order to obtain the heating curve of basin insulator under rated load current, a series of constant values of $K$, $a$ and $B$ can be determined according to the load current $I$ and $W_c$:

$$\theta_s = \theta_c - \frac{2}{\alpha} \ln \left[ \frac{r_c}{B} \right]$$  (9)

The calorific value of the pot was $W_R$:

$$W_R = \frac{2\pi x d\theta}{\rho_t} \bigg|_{x=R}$$

$$= \frac{4\pi k}{\alpha \rho_t} \left( \frac{R}{r_c} \right)^4 - \frac{R}{r_c}$$  (10)

So get the heating curve of the basin. When the thermal resistance of the medium around the basin does not change with the temperature and heat flux, the heat dissipation curve will be a straight line. According to the equivalent thermal circuit, there are:

$$\frac{\theta_s - \theta_a}{T} = W_R$$  (11)

In the above formula, $\theta_s$ - temperature of surrounding medium. $T$-thermal resistance of surrounding medium. $W_R$-heat emitted to surrounding medium. The thermal stability of the basin insulator can be judged after the heating and heat dissipation curves of the basin insulator are obtained by the above method. The theoretical parameter setting is shown in Table 1.

| Theoretical parameters | $r_c$(mm) | $R$(mm) | $\varepsilon_c$ | $\rho_t$ | $U_0$(kV) | $I$(A) |
|------------------------|-----------|---------|-----------------|--------|-----------|--------|
| Numerical value        | 115       | 537     | 6.5             | 1.1    | 1000      | 6150   |

Fig.4 The heating curve of spacer

Figure 4 shows the relationship between the basin heating curve and the heat dissipation curve of the basin insulator in the process of changing the three influence factors of $\tan \delta_0$, $\alpha$ and the external environment temperature $\theta_a$. The figure shows that the higher the ambient temperature $\theta_a$ and $\tan \delta_0$ is, the higher the calorific value $P$ is. In the process of change, the change trend of basin
heating characteristic curve will also change, and there are two intersections between heating curve and heat dissipation curve. The above theoretical calculation results will be used for the subsequent basin insulator accident analysis.

4. Analysis of electric heating field of basin insulator based on finite element method

In the actual operation environment, the center guide bar of GIS equipment carries a power frequency current of 50 Hz, which will produce eddy current heating due to skin effect. On the other hand, the basin insulator will generate joule heating when it bears high voltage. Under the combined action of two kinds of heat sources, the basin insulator will bear greater thermal stress [12]. Under AC condition, the electric field distribution of the basin insulator is determined by the dielectric constant of the material, while the thermal field is determined by the loss tangent and thermal conductivity of the body material [13]. The results show that the relative permittivity of the basin body material changes little with the temperature in the rated operating range, so the electric field distribution of the basin is less affected by the temperature in this range. When the temperature reaches the high temperature region, the relative permittivity, loss tangent and thermal conductivity change significantly with the temperature. At this time, the distribution of the electric field is distorted. Therefore, the nonlinear relationship between the material parameters of the basin and the temperature should be considered.

In the simulation environment, the calculation process of electric field coupling for AC basin insulator is proposed. The eddy current field and harmonic field calculation methods are adopted respectively for the heating of central guide rod and basin insulator body [14]. Input the current carrying capacity \( I \), current frequency \( f \) and initial resistivity \( R_0 \) of the center guide rod to establish the eddy current field physical calculation environment. Input the bearing voltage \( U \), relative permittivity and loss tangent of the basin insulator to establish harmonic field calculation environment. The calorific value calculated by the eddy current field and harmonic field is applied to the finite element calculation model of basin insulator to calculate the thermal field distribution, and temperature value \( T \) of each unit is obtained. Then \( \varepsilon_r(T) \), \( \tan\delta(T) \), \( \lambda(T) \) values are corrected according to insulation performance test curve of basin insulator body material, and the thermal field distribution is calculated repeatedly until the two adjacent calculation results are less than the control accuracy. Finite element calculation model of basin insulator is shown in Fig. 5.

![Fig.5 The FEM model of the GIS spacer](image)

(a) FEM of current carrying structure         (b) Finite element model of basin body

Figure 5 shows that the key components such as central conductor, shield cover, insert, pot body and other key parts are considered in the finite element model of basin insulator. According to the actual modeling, accuracy of subsequent finite element calculation results is ensured [15,16]. In the electric field calculation, high potential of 1000kV is applied to the central conductor and zero potential is applied to the grounding flange. The electric field distribution of basin insulator body is shown in Figure 6. It can be seen from Figure 6 (a) that the maximum electric field in the basin body is near the insert, which is about 6.033kV/mm. Figure 6 (b) shows that the electric field distribution on the surface of the basin body is uneven. The electric field intensity near the center guide rod is higher, while the
electric field intensity near the flange side is lower. Therefore, it is necessary to add a pressure equalizing cover near the center guide rod to reduce the electric field intensity.

Figure 6 shows the distribution of electric field on the surface of the central guide rod and the insert. The maximum electric field strength values are 9.344kV/mm and 6.033kV/mm respectively. Because the medium around the central guide rod is SF6 gas, it has a large safety margin. However, if the insert is in direct contact with the basin body, if there is an air gap defect between the contact surfaces, it is easy to produce high field strength and partial discharge.

Applying voltage of 1000kV and rated operating current of 6150A to the center guide rod of basin insulator finite element calculation model, taking into account eddy current heating and Joule heating, the electric and thermal stress distribution and change trend of basin insulator body under rated current...
carrying capacity of 6150A and 1.5 times overload current of 9225A are analyzed. Based on the above calculation process of basin insulator thermal electric field coupling, the analysis is carried out under the condition of current carrying capacity of 6150A. After about three iterations, the temperature distribution tends to converge. The surface temperature distribution of basin is shown in Figure 7.

Figure 7 shows that when the ambient temperature is set at 20 °C, the temperature distribution around the grounding flange is close to the ambient temperature, the central conductor is basically isothermal, and the hottest spot is near the insert, about 82 °C. According to the path shown in Fig. 7, the temperature and electric field distribution curves on the path are intercepted and shown in Fig. 8. It can be seen from the figure that the maximum electric field intensity on the surface of the basin is about 3.5kV/mm, which is basically consistent with the location of the hottest spot. The low electric field intensity near the central guide rod is mainly due to the shielding effect of the pressure equalizing cover. The insulation medium at the place about 100mm away from the center guide rod bears high electric and thermal stress at the same time, which is the weak part of the basin insulation. The insulation strength at this position should be strengthened in the basin structure design. Under the overload current of 1.5 times 9225A, the variation of surface temperature distribution of basin insulator during three iterations is listed, as shown in Figure 9.

5. Fault analysis of basin insulator based on numerical simulation

Figure 10 shows the core insulation failure of the basin insulator in operation. It can be seen that the basin body is cracked and there are obvious arc ablation traces. The initial discharge trace appears between the central conductor and the grounding flange of the basin insulator. With the extension of the operation time of the basin, the discharge channel between the two becomes more and more significant, which eventually leads to a large area flash-over of the basin and the final insulation failure.
The surface of the basin insulator is seriously ablated, and the traces of arc development can be observed on the basin body. Due to the gradual development of arc between the high potential central conductor and the grounding flange, a through discharge channel is formed. The short-circuit current releases a lot of heat in a short time, resulting in a sudden rise in temperature, which leads to irreversible insulation damage of the basin insulator. In order to further verify the existence of thermal collapse site with sharp temperature rise, field emission scanning electron microscope was used to analyze the morphology of arc ablation products on the surface of the basin, as shown in Figure 11. The figure shows that there are filler particles with different sizes and shapes in the ablation section of the basin, which are evenly dispersed in the epoxy material of the basin body. Both of them peel off at the interface, and there are a lot of ablation holes, so a lot of heat is released during the accident.

The actual minimum temperature of basin insulator can reach \(-40^\circ C\). If the external environment temperature of basin insulator is in the range of \([-40^\circ C, T_a]\), the body calorific value is greater than the heat dissipation, then the loss of basin insulator can heat the core body, which is the heating area. When the external environment temperature is in the range of \([T_a, T_b]\), the body calorific value is lower than the heat dissipation, and the basin can operate stably; the external environment temperature reaches \(T_b\), if the current carrying capacity increases slightly, it will enter the instability region, resulting in the continuous increase of temperature and the final thermal breakdown, and the calorific value of the loss characteristic curve is the lowest when the ambient temperature is \(T_C\).

6. Conclusion
1) The dielectric constant, tangent value of loss angle and thermal conductivity of basin insulator body material are all functions of temperature and have nonlinear relationship with them. The above nonlinear relationship should be considered in the calculation of electric heating field. The eddy current...
field method is used to calculate the heat of the center guide rod, and the harmonic field method is used to calculate the heat of the basin body. The proposed algorithm can take into account the eddy current heat and Joule heat, and the nonlinear relationship between the insulation performance parameters of the basin body and the temperature is also considered.

2) The establishment of temperature field of basin insulator comes from eddy current heating of center guide rod and Joule heating of body material. Under the action of rated current and voltage, the hottest spot temperature of basin is 82 ℃, which is located near the high voltage side of basin. The maximum electric field intensity is 6kV / mm, which is located at the interface between the basin and the central conductor. Under the rated condition of 1.5 times, the temperature value diverges in the thermal field iteration process, which proves that the temperature characteristic of loss tangent has a significant effect on the thermal performance of the basin.

3) The theoretical model of temperature distribution and current carrying capacity of basin is established, which proves the simulation results in theory. At the same time, combined with a basin insulator accident, the development reason of basin from local arc near the central conductor to overall flashover of basin is analyzed. In the process of basin current carrying capacity design, the temperature should be controlled in the stable region to reduce the risk of basin insulator thermal breakdown accident possibility.

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