Infrared Detection and Thermoelectric Coupling Simulation Analysis of 220 kV Insulator Abnormal Heating

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Abstract. Heat and pollution flash caused by surface contamination are one of the common defects of insulators. If not discovered and eliminated in time, it will cause the deterioration of the insulator and seriously affect the service life of the insulator. If we can grasp the temperature distribution characteristics of the insulator in the state of contamination, the infrared temperature measurement can be used to quickly find and eliminate defects in a timely manner. This paper introduces a large area heating defect of porcelain post insulator and composite suspension insulator in 220kV equipment area, whose temperature distribution showed the rule of overheating at the high-voltage end and the temperature gradually decreasing toward the low-pressure end. Based on the field infrared temperature measurement and thermal image characteristics, it preliminarily analyzed that the heating was caused by insulator contamination and damp. Then, combined with pollution sampling, three-dimensional model establishment and thermoelectric coupling simulation calculation, the correctness of the above conclusions was verified, and preventive measures and suggestions were put forward.

1. Introduction
Due to the influence of strong electric field, mechanical stress and environmental factors during the long-term operation of the insulator, the structure strength and insulation performance are prone to decline, which is a major hidden danger for the safe operation of the power system. Among them, heat and pollution flash caused by surface contamination are one of the common defects of insulators. If not discovered and eliminated in time, it will cause the deterioration of the insulator and seriously affect the service life of the insulator. Infrared temperature measurement is an efficient, convenient, and highly accurate live detection method, which can quickly and efficiently diagnose and identify insulator defects without power outages [1-5]. If we can grasp the temperature distribution characteristics of the insulator in the state of contamination, the infrared temperature measurement can be used to quickly find and eliminate defects in a timely manner.

In this paper, the 220kV porcelain post insulators and composite suspension insulators actually operated on site were used as research objects. The finite element simulation software was used to establish a three-dimensional thermoelectric coupling simulation model in the contamination state, and the temperature distribution characteristics of the insulator in the contamination state were studied. Analysis and comparison with the results of on-site infrared temperature measurement verified the correctness of the conclusion.

2. Simulation model of insulator
According to the actual structural dimensions of the 220kV disconnector porcelain post insulator and
the bus suspension insulator operating on site, the three-dimensional thermoelectric coupling simulation model of the insulator was established using finite element analysis software, as shown in figure 1. To facilitate the calculation process, the following simplified thermoelectric coupling model,

1). Ignore the influence of small parts such as connecting bolts between insulators and conductors on the temperature distribution;

2). The electrical conductivity, dielectric constant, and thermal conductivity of porcelain, mandrel, umbrella skirt, flange, etc. were constant and isotropic;

3). Under the operating voltage, the amount of heat generated per unit time and volume within the insulator was constant, and the heat transfer and temperature distribution at various positions were in a steady state.

At the same time, considering the influence of high-voltage conductors such as lead wires, conductive arms and tube bus on the electric field distribution of the insulator, a metal conductor with a length of about 1m was retained at the high-voltage end of the insulator and an operating phase voltage of 127 kV was applied. A contamination layer with a thickness of 1mm was added on the surface of the umbrella skirt to simulate the state of contamination accumulation, and the resistivity of the contamination layer was measured by a spot pollution sampling test.

![Diagram](image1)

**Figure 1.** Temperature distribution of arrester surface under different wind speeds.

For the salt density measurement of the replaced insulator, wash the surface of the insulator with 300mL deionized water, and use the equivalent salt density meter to test the conductivity of the contaminated liquid after cleaning, and then calculate the salt density value. Take three measuring points on the upper, middle and lower sides of each insulator, a total of 9 measuring points for one phase and three insulators of the disconnector, and a total of 6 measuring points for the pair of bus suspension insulators, as shown in table 1.

| Measuring points | Upper | Middle | Lower | Average value |
|------------------|-------|--------|-------|---------------|
| Disconnector      |       |        |       |               |
| Post insulator 1  | 0.13  | 0.11   | 0.13  |               |
| Operating insulator | 0.15  | 0.13   | 0.12  | 0.13          |
| Post insulator 2  | 0.13  | 0.13   | 0.14  |               |
| Bus               |       |        |       |               |
| Suspension insulator 1 | 0.08  | 0.12   | 0.14  | 0.11          |
| Suspension insulator 2 | 0.10  | 0.10   | 0.12  |               |
For a wet contamination layer with a thickness of 1mm (0.1cm), the relationship between the salt concentration $S_a$ and the salt density $r_{ESSD}$ can be approximated as

$$S_a = \frac{r_{ESSD}}{0.1\text{cm}}$$  \(1\)

According to literature [6-8], the conductivity $\sigma_{20}$ of a solution with a salt concentration of $S_a$ at 20°C can be expressed as

$$\sigma_{20} = (1754\mu\text{S/cm}) \cdot \left(\frac{S_a}{1\text{g/L}}\right)^{0.97}$$  \(2\)

Take the reciprocal to get the resistivity of the contamination layer on the porcelain post insulator and the suspension insulator of the bus is 4.42\,\Omega\cdot\text{m} and 5.19\,\Omega\cdot\text{m} respectively.

The electrical material properties of the remaining components in the thermoelectric coupling model are shown in table 2.

| Component                                      | Relative permittivity | Resistivity (\Omega\cdot\text{m}) |
|------------------------------------------------|-----------------------|-----------------------------------|
| Air                                            | 1                     | 1014                              |
| Insulation materials such as porcelain and mandrel | 4.3                   | 2.5\times10^{12}                 |
| Metal                                          | 5000                  | 10^{-7}                           |

3. Insulator heating and heat dissipation

According to literature [9-12], The heat generated under the condition of insulator contamination mainly includes penetrating leakage current heating, surface contamination leakage current heating and dielectric loss heating, whose expressions are

$$P_l = U_I l_l$$  \(3\)

$$P_w = U_I l_w$$  \(4\)

$$P_j = U_I^2 \omega C_0 \tan \delta$$  \(5\)

In the formula, $P_l$, $P_w$, and $P_j$ are respectively the penetrating leakage current heating power, surface contamination leakage current heating power, and dielectric loss heating power of the insulator, $U_I$ is the distributed voltage, $I_l$ is the penetrating leakage current, and $I_w$ is the surface contamination leakage Current, $\omega=100\text{prad/s}$ is the angular frequency of the power frequency voltage, $C_0$ is the equivalent capacitance between stages, and $\delta$ is the dielectric loss angle of the porcelain material.

The heat dissipation of the insulator includes three parts: heat dissipation with solid conduction, heat convection with air, and radiation heat dissipation. The expressions are,

$$q_c = -\lambda \text{grad}T$$  \(6\)

$$q_d = h(T-T_0)$$  \(7\)

$$q_f = \varepsilon \sigma (T^4-T_0^4)$$  \(8\)

In the formula, $q_c$, $q_d$, and $q_f$ are the heat flux density of conduction heat dissipation, convection heat dissipation, and radiation heat dissipation, $l$ is the thermal conductivity of the solid, $h$ is the air convection heat dissipation coefficient, $\varepsilon$ is the radiation coefficient, and $s$ is the Boltzmann constant, $T$ and $T_0$ are the insulator temperature and the ambient temperature, respectively. The values of each parameter are shown in table 3.
Table 3. Value of thermal characteristic parameters

| Parameters | Values         | Parameters | Values         |
|-----------|----------------|------------|----------------|
| $l_{\text{porcelain}}$ | 1.163 W/(m·℃) | $s$        | 5.67×10^{-8} W/(m²·℃⁴) |
| $l_{\text{metal}}$       | 49.8 W/(m·℃)  | $e_{\text{porcelain}}$ | 0.9          |
| $l_{\text{silastic}}$    | 2 W/(m·℃)     | $e_{\text{silastic}}$ | 0.95         |
| $h$          | 5 W/(m²·℃)    | $T_0$      | 27℃          |

4. Simulation results and analysis

First, the electric field simulation calculation of the three-dimensional thermoelectric coupling model of the insulator is carried out, and the distributed voltage, leakage current and other parameters are extracted from the results. And the heating power of each part is calculated using equations (3)-(5), which is used as the heat source combination equation (6)-(8) to simulate the temperature field of the model, so as to calculate the temperature distribution of each part of the disconnector porcelain post insulator and the bus suspension insulator, as shown in figure 2.

![Figure 2. Temperature distribution of insulator (unit: ℃).](image)

It can be seen that the temperature at the upper end (high voltage end) of the porcelain post insulator is too high, and the temperature gradually decreases toward the low voltage end. The hot spot temperature is 30.3℃, the normal point temperature is about 27.8℃, and the temperature rise is 2.5K.

The hot spot of the composite suspension insulator is centered on the lower side (high voltage end) of the insulator with the mandrel as the center. The hot spot temperature is 31.8℃, the normal point temperature is 27.9℃, and the temperature rise is 3.9K.

On-site infrared temperature measurement was carried out on the actual 220kV disconnector porcelain post insulator and the bus suspension insulator. The test results are shown in the figure 3. It can be seen that the infrared spectrum and simulation results of the insulator show the law of overheating at the high voltage end and the temperature gradually decreasing toward the low voltage end, which verified the correctness of the simulation results.
The temperature rise values of the infrared test porcelain post insulators and the bus suspension insulators are 1.9K and 3.7K, respectively, which are slightly lower than the temperature rise values in the simulation results. The main reasons for analyzing the error are as follows:

1). The parameters such as the resistivity and thermal conductivity of each material in the simulation model are set as constants, and in practice, each parameter may change with temperature changes;

2). During the field test, the wind speed and ambient temperature may fluctuate slightly, and the other surrounding equipment and buildings may have impact on the electric field and temperature field;

3). Infrared camera's reflectivity, test distance and other parameter settings will also bring some errors.

In order to further analyze the cause of the heating of the insulators, the axial current density distribution diagram was taken from the simulation results, and the direction was from the high-voltage end to the low-voltage end, as shown in Figure 4.

It can be seen that the penetrating leakage current density inside the porcelain column and the mandrel is very small, and the surface contamination increases the leakage current of the umbrella skirt surface. These leakage currents flow into the flange at the high voltage end of the porcelain column and the mandrel. The axial leakage current density at the high-voltage end increased significantly. At the same time, the voltage distribution of the insulator string is a "saddle-shaped"
distribution, and the high-voltage end bears a larger distributed voltage. The simultaneous increase of the distribution voltage and the leakage current causes the heating power to increase, thereby causing the phenomenon of overheating at the high-voltage end.

5. Conclusion
In this paper, the 220kV porcelain post insulator and composite suspension insulators actually operated on site were used as research objects. The finite element simulation software was used to establish a three-dimensional thermolectric coupling simulation model in the state of contamination, and the simulation parameters of the contamination layer was calculated through on-site pollution sampling to simulate the actual situation, so as to analyze the temperature distribution characteristics of the insulator under the condition of contamination. The results showed that the temperature distribution of the insulator that had been fouled for a long time showed the rule of overheating at the high-voltage end and the temperature gradually decreasing toward the low-pressure end. This was caused by a large amount of leakage current converging at the high-voltage end and withstanding a high distributed voltage, resulting in increased heating power. By comparing with the on-site infrared temperature measurement results, the correctness of the conclusion was verified.

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