Influence of sheath thickness and core rod diameter on fault temperature rise of composite insulator

Hui Liu¹,², Hao Shen¹, Zhao Qi¹, Xiaobin Sun¹, Dandan Li², Ran Jia¹, Rong Liu¹ and Yang Zhang¹

¹ State Grid Shandong Electric Power Research Institute, Jinan 250003, China
² State Grid Shandong Electric Power Company, Jinan 250003, China
³ E-mail: 441018631@qq.com

Abstract. Infrared temperature measurement is an effective means for insulator health monitoring, and the theoretical basis and the subsequent diagnosis methods have been widely studied. However, in practical applications, the influence of insulator itself on fault temperature rise is rarely considered. In this paper, the temperature rise experiment of composite insulator was conducted to study the influence of sheath thickness and core rod diameter on fault temperature rise. According to the experimental results, the evolution law of fault temperature rise with the change of sheath thickness and core rod diameter was obtained. On this basis, the design strategy for composite insulators was proposed.

1. Introduction

An insulator is the main insulating component in the power grid, especially in transmission line, whose basic function is to connect the conductor to the tower mechanically and insulate them electrically [1]. According to the difference of materials, insulators can be divided into three major types, including porcelain insulator, tempered glass insulator, and composite insulator [2, 3]. Due to the special working environment, insulators are generally required to have properties of excellent high and low temperature resistance, UV aging resistance, biological and chemical corrosion resistance, high strength and high hydrophobicity [4, 5]. Among the above three types of insulators, composite insulator shows the optimal comprehensive properties. It is thus that composite insulators began to dominate in electrical insulation in power grid, especially in heavily polluted areas. In China, the usage number of composite insulators has exceeded 9 million so far. As the key equipment of transmission system, the operation safety of composite insulator is of great significance for the stable operation of transmission system.

Though composite insulators have excellent electrical and mechanical properties, they will inevitably suffer performance degradation with the increase of working time [6]. The interface between the core and sheath will age after a long-term operation, which is characterized by debonding, micropore and other defects in the interface area. The defect will increase the field strength, resulting in interface breakdown and partial discharge, which will accelerate the aging of insulators, eventually develop fault states. The defect usually leads to abnormal temperature rise of insulators [7]. Therefore, the state of the insulator can be evaluated by measuring the temperature of the insulator. Numerous studies have been devoted to establishing the criterion of temperature and insulator aging degree. Through experiments, Reference [8] gives the interval range for judging each aging grade of insulator. Reference [9] constructs the interface thermal wave model of composite post insulator and puts
forward the nondestructive detection method of interface defects of composite insulator. The detection method realizes the detection of defects of composite insulator at millimeter size. Reference [10] studies the correlation between the measured temperature of composite insulator and ambient relative humidity and gives the measurement strategy of infrared temperature measurement when considering ambient humidity. By analyzing the influence of different humidity on insulator temperature rise, the temperature rise model of insulator is established in Reference [11], which provides a theoretical basis for insulator fault discrimination.

However, it should be pointed out that although some insulator temperature rise models have been established, they more consider the influence of external factors and rarely consider the influence of insulator itself. In this paper, the influence of sheath thickness and core rod diameter on the fault temperature rise was studied. Through experiment of temperature rise of insulators, the evolution law of fault temperature rise under different sheath thickness and core rod was given.

2. The principle of infrared temperature measurement
When an object is at absolute zero temperature (-273 °C), the microscopic particles including atoms and molecules of the object are in a stable motion state. When the temperature of the object is higher than absolute zero temperature, the stable motion state of particles will be destroyed, resulting in irregular motion. The irregular motion of particles will enable the object to radiate infrared energy. Therefore, the surface temperature of the object can be determined accurately by measuring the infrared energy, which is the theoretical basis of infrared temperature measurement. The radiation measurement is shown in Figure 1.

![Radiation measurement diagram.](image)

Planck's law can describe the relationship between infrared radiation energy and object surface temperature, which is expressed as:

\[
M(\lambda, T) = \frac{c_1\lambda^{-5}}{e^{c_2/\lambda T} - 1}
\]

where \(M(\lambda, T)\) denotes spectral radiant emittance of blackbody, \(c_1\) denotes the first radiant constant, \(c_1 = 3.741 \times 10^{-16} \text{W}\cdot\text{cm}^2\), \(c_2\) denotes the second radiant constant, \(c_2 = 1.4388 \times 10^{-2} \text{W}\cdot\text{K}\), \(\lambda\) denotes wavelength, \(T\) denotes the absolute temperature of the blackbody. It should be noted that the so-called blackbody refers to the body that has the maximum radiant power among all bodies under ideal conditions.

When \(\exp(c_2/\lambda T) \geq 1\), Planck's law can be replaced by Wien displacement equation, which is expressed as:

\[
M(\lambda, T) = c_1\lambda^{-5}e^{-c_2/\lambda T}
\]

Wien displacement law indicates that the higher the temperature of an object, the shorter the wavelength of its radiation spectrum, and the central peak wavelength will shift to the short wave...
direction. During temperature measurement, radiant energy identified by infrared thermometer comes from three aspects, including the radiant energy of the object, radiant energy of surrounding environment reflected by the object and radiant energy of atmosphere. The surface spectral radiance of the object to be measured is:

\[ L_\lambda = \varepsilon_\lambda M(\lambda, T_o) + \rho M(\lambda, T_o) = \varepsilon_\lambda M(\lambda, T_o) + (1-\alpha_\lambda)M(\lambda, T_o) \] (3)

where \( \varepsilon_\lambda M(\lambda, T_o) \) denotes the spectral radiance of the object surface, \((1-\alpha_\lambda)M(\lambda, T_o)\) denotes the spectral radiance of surrounding environment reflected by the object, \( T_o \) denotes the temperature of the object surface, \( T_a \) denotes the environment temperature, \( \varepsilon_\lambda \) denotes surface emissivity, \( \rho \) denotes the surface reflectance, \( \alpha_\lambda \) denotes the surface absorptivity.

The irradiance acting on the infrared thermometer is:

\[ E_\lambda = A_d d^{-2} [\tau_{a\lambda} \varepsilon_\lambda M(\lambda, T_o) + \tau_{\lambda\lambda} (1-\alpha_\lambda)M(\lambda, T_o) + \varepsilon_{a\lambda} M(\lambda, T_o)] \] (4)

where \( A_d \) denotes the visible area of the object corresponding to the minimum spatial opening angle of the infrared thermometer, \( d \) denotes the distance between the infrared thermometer and the object, \( \tau_{a\lambda} \) denotes the spectral transmittance of atmosphere, \( \varepsilon_{a\lambda} \) denotes atmospheric emissivity, \( T_a \) denotes the atmosphere temperature.

The principle of infrared thermometer is to integrate the radiant energy that belongs to the wave with the wavelength of 2–5 \( \mu \)m or 8–13 \( \mu \)m, and further convert the integral into an electrical signal proportional to energy. The voltage of the electrical signal is:

\[ V_s = A_R \int_{\lambda_d} E_\lambda R_\lambda d\lambda \] (5)

where \( A_R \) denotes the area of the lens of the infrared thermometer, \( R_\lambda \) denotes the spectral responsivity, which denotes the ability that infrared thermometer to convert radiant energy into electrical signal.

Since infrared thermometer work in a narrow band, namely 2–5 \( \mu \)m or 8–13 \( \mu \)m, \( \varepsilon_\lambda \), \( \alpha_\lambda \), and \( \tau_{\lambda\lambda} \) are generally considered to have no relevance with \( \lambda \). Given this, Equation (5) can be rewritten as:

\[ V_s = A_R A_d d^{-2} \left\{ \tau_{a\lambda} \int_{\lambda_d} R_\lambda M(\lambda, T_o) d\lambda + (1-\alpha_\lambda) \int_{\lambda_d} R_\lambda M(\lambda, T_o) d\lambda \right\} + \varepsilon_{a\lambda} \int_{\lambda_d} R_\lambda M(\lambda, T_o) d\lambda \] (6)

It can be concluded from Equation (6) that the main factors affecting the accuracy of infrared temperature measurement are ambient temperature and temperature measurement distance when the aiming angle and blackbody emissivity of the infrared thermometer are certain.

Let \( K=A_R A_d d^{-2} \int_{\lambda_d} R_\lambda M(\lambda, T_o) d\lambda = f( T_o ) \), Equation (6) is rewritten as:

\[ V_s = K \left\{ \tau_{a\lambda} \left[ \int_{\lambda_d} R_\lambda M(\lambda, T_o) d\lambda + (1-\alpha_\lambda) \int_{\lambda_d} R_\lambda M(\lambda, T_o) d\lambda \right] + \varepsilon_{a\lambda} \int_{\lambda_d} R_\lambda M(\lambda, T_o) d\lambda \right\} \] (7)

For some non-metal surfaces, if they meet the principle of grey body approximation, \( \varepsilon=\alpha \). For the atmosphere, it is generally considered that \( \varepsilon_{a\lambda}=\alpha_{a\lambda}=1-\tau_{a\lambda} \). Given this, Equation (7) can be converted to:

\[ V_s = K \left\{ \tau_{a\lambda} \left[ \int_{\lambda_d} R_\lambda M(\lambda, T_o) d\lambda + (1-\alpha_\lambda) \int_{\lambda_d} R_\lambda M(\lambda, T_o) d\lambda + (1-\tau_{a\lambda}) \int_{\lambda_d} R_\lambda M(\lambda, T_o) d\lambda \right] \right\} \] (8)

Equation (6) and Equation (7) are the general equation for the infrared temperature measurement.

3. Experimental setup
The influence of sheath thickness and core rod diameter on fault temperature rise are studied in this paper. The heating film with the dimension of 12 mm×39 mm was made of polyimide and used to heat the insulator core rod to simulate fault of insulators. Different heating voltages were set to simulate different insulator fault degrees. The voltage set in this paper is shown in Table 1.

| Core rod diameter (mm) | Heating voltage (V) |
|------------------------|---------------------|
| Φ 18                   | 3.017(minor fault)/3.532 (severe fault) |
| Φ 24                   | 3.017(minor fault)/3.539(severe fault) |
| Φ 30                   | 3.009(minor fault)/3.486(severe fault) |
Table 2. Parameters of insulators.

| No. | Core rod diameter (mm) | Sheath thickness (mm) |
|-----|------------------------|-----------------------|
| 1,2 | Φ18                    | 3(thin)/5(thick)      |
| 3,4 | Φ24                    | 3.5(thin)/5(thick)    |
| 5,6 | Φ30                    | 5(thin)/6(thick)      |

All experiments were completed in the laboratory. The laboratory environment had an ambient temperature of 30°C and a humidity of 56%. Test samples used in this paper is the composite insulator of 110 kV transmission line in Shandong. In order to ensure the preciseness of the experiment, the test samples were from the same manufacturer, and a total of 6 insulators with different sizes of sheath thickness and core rod diameter were selected for measurement. The specific parameters of each insulator are shown in Table 2. The infrared thermometer was adopted to measure temperature of insulator surface. During the measurement, the medium voltage end was selected as the measuring point, and the temperature at the measuring point was measured at a distance of 3m, 6m, 9m, 12m and 15m from the insulator, respectively. The experiment is mainly divided into two aspects. One was to fix the core rod diameter unchanged to measure fault temperature rise of insulators and further evaluate the influence of different sheath thicknesses on the fault temperature rise. The other was to fix the sheath thickness unchanged to measure fault temperature rise of insulators and further the influence of different core rod diameters on the fault temperature rise. The measured values are the average of the five measurements. In addition, when the measurement distance exceeds 6m, the high-power lens was also used to measure the heating temperature of the insulator.

![Graphs of temperature measurement results for different insulators under different fault conditions.](image)

**Figure 2.** Temperature measurement results of Φ18mm insulator under the case of minor fault.

**Figure 3.** Temperature measurement results of Φ18mm insulator under the case of severe fault.

**Figure 4.** Temperature measurement results of Φ24mm insulator under the case of minor fault.

**Figure 5.** Temperature measurement results of Φ24mm insulator under the case of severe fault.

**Figure 6.** Temperature measurement results of Φ30mm insulator under the case of minor fault.

**Figure 7.** Temperature measurement results of Φ30mm insulator under the case of severe fault.

4. **Analysis of the experiment results**

Figure 2 to Figure 7 show the temperature measurement results of insulators with core rod diameters of 18mm, 24mm and 30mm respectively. Take Figure 3 as an example to illustrate the meaning of the curve in the figures: the curves all are temperature measurement results of insulators with core rod
diameters of 18mm; The two solid lines in the figure represent the temperature measurement results of insulators with sheath thicknesses of 3mm and 5mm using an ordinary lens, respectively; The two dashed lines in the figure represent the temperature measurement results of insulators with sheath thicknesses of 3mm and 5mm using an enlarging lens.

It can be seen intuitively concluded from Figure 3 to Figure 7 that with the increase of measurement distance, the temperature measured by the thermometer shows a downward trend, and the use of enlarging lens plays no role in the improvement of measurement accuracy. Comparing the temperature measurement results of insulators with different sheath thicknesses, it can be seen that the surface temperature of thick sheath insulators is lower than that of thin sheath insulators under the same fault degree. The average surface temperature difference of thick sheath insulators and thin sheath insulators over different degree faults is shown in Figure 8. It can be seen that the average surface temperature difference between the thin sheath insulator and the thick sheath insulator measured by the infrared thermometer is higher than 0.4 °C when using ordinary lens. As mentioned earlier, when studying the influence of different sheath thicknesses on fault temperature rise, the heating power of heating film is set to the same to simulate the same degree of fault. Therefore, it can be concluded from the above results that the thick sheath will hinder the internal heat dissipation of the insulator. When the sheath thickness difference is only about 1mm, the average temperature difference is higher than 0.4 °C, which will definitely accelerate the aging of insulators and cause more severe faults over time. It is generally known that the local temperature rise of insulator will further aggravate the fault degree of insulator, and even lead to fracture accident. Through the experimental results of this study, it can be concluded that the sheath thickness should be decreased as much as possible on the premise of meeting the mechanical and electrical properties of insulators. In addition, it should be noted that enlarging the lens seems to increase the error of the result, which may be related to the inaccurate focusing after enlarging the lens.

Further, the temperature rise of insulators with different core rod diameters and the same sheath thickness under the same fault conditions is compared. The experimental results are shown in Table 3. It can be seen that under the same fault degree (the same heating power of heating film), the larger the core rod diameter, the lower the measured insulator surface temperature. In order to evaluate the effect of core rod diameter on local temperature rise, an evaluation index, namely temperature difference rate (100*the average temperature difference/diameter difference), is formulated to evaluate this effect. The temperature difference rate is shown in Figure 9.

As can be seen, with the increase of diameter, the temperature difference rate increases. Therefore, it can be concluded from the above results that the diameter of the core rod should be increased as much as possible on the premise of meeting the mechanical and electrical properties of insulators. However, it should be noted that the increase of the volume and quality of the insulator caused by the increase of the core rod diameter will bring new challenges to the installation of the insulator and the corresponding support structure. The specific balance requires a lot of effort to be invested in the future research.
Table 3. Temperature measurement results.

| Distance (m) | Φ18   | Φ24   | Φ30   |
|-------------|-------|-------|-------|
| 3           | 39.3  | /     | 39.0  |
| 6           | 39.1  | /     | 38.7  |
| 9           | 38.6  | 38.3  | 38.2  |
| 12          | 38.1  | 37.9  | 37.9  |
| 15          | 38.1  | 37.9  | 37.5  |

5. Conclusions

Through the fault temperature rise experiment of composite insulator, this paper discussed the influence of sheath thickness and core rod diameter on the local temperature rise of insulator, and obtained the evolution law of local temperature rise of composite insulator with the change of sheath thickness and core rod diameter. The evolution law shows that the local temperature rise caused by insulator faults is positively correlated with sheath thickness while negatively correlated with core rod diameter. In view of this, when designing the insulator, the thickness of the sheath should be decreased while the diameter of the core rod should be increased as much as possible on the premise of meeting the mechanical and electrical properties.

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