Effects of the distance and test angle on the precision of infrared temperature measurement

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Abstract. The target distance and test angle are the main factors that affect the accuracy of infrared temperature measurement. To study the infrared temperature measurement precision of different heat source intensities at different distances and test angles, a temperature measurement test with built-in heat source within the rod of the insulator was designed. By setting four different heat source temperatures on the heating film, the temperature data were collected by infrared camera at the distances of 3, 6, 9, 12 m and 15 m and three test angles of 0°, 90° and 180°, respectively, and the variation law of the measurement results was analysed. The main conclusions are as follows. As the distance increases, the measured values basically show a downward trend. When the distance reaches 12 m, the temperature fluctuates significantly. When the angle between the observation direction and the heat source is 0°, the measurement value is the highest, followed by the 90° direction, and the lowest is the 180° direction, which indicates that the test angle has an obvious influence on the measurement results. With the increase of heat source temperature, the infrared temperature measurement value increases gradually and tends to be saturated. When an infrared device is adopted to measure the temperature of the insulators in service, it is necessary to pay attention to the influence of the distance and angle on the value in engineering practice.

1. Introduction

The research on composite insulators in China began in the early 1980s. Tsinghua University, Wuhan University, East China Electric Power Test & Research Institute and Xian Electric Porcelain Research Institute and other entities developed 110 - 500 kV composite rod insulators after arduous efforts to tackle key problems during the Seventh Five Year Plan period, which passed all the test items of the IEC1109 standard [1-4]. Since the first batch of domestic composite insulators was put into operation in the Shijiazhuang-Taiyuan Railway and Baoji-Chengdu Railway in 1983, the development of composite insulator in China has been more than 30 years. In the late 1980s, the development, achievement transfer and industrial production of silicone rubber composite insulator were completed successively. In the early 1990s, to control large-scale pollution flashover accidents in pollution areas such as East China, North China and Northeast China, a large number of composite insulators were introduced into power system. According to statistic, the current consumption of composite insulators in China has been nearly 9 million [5]. China has become the first country in the world to use organic external insulation in UHV AC and DC transmission systems.

With the extensive use of composite insulators across the country, there are more and more reports about the flashover and damage of composite insulator after a period of operation in the power grid. It
is reported that only from the end of 2018 to July 2019, there were no less than 6 failures of 500 kV composite insulator strings in State Grid Corporation of China, and abnormal heating occurred frequently. By analyzing the faults, it is found that the interface defects between the rod and silicone rubber sheath are one of the main causes for the heating. Due to the defects of processing technology and moisture intrusion caused by sealing failure, the hidden defects appear at the interface between the rod and the sheath, resulting in partial discharge, accelerating the aging of the material, and finally inducing the faults such as interface breakdown and brittle fracture of the rod. When composite insulators are sampled at home and abroad, the commonly used detection method is steep-front impulse breakdown test. However, the internal defects of the insulators are rarely found. Yuan C et al. believe that the steepness of 1000 ~ 1500 kV/μs specified in the standard GB/T 19519-2004 is relatively low, which leads to a decrease in the effective of steep-front impulse test for detecting the defects within the composite insulator [6].

Compared with traditional temperature measurement technology, infrared measurement has the advantages of non-contact, long measurement distance, high sensitivity and fast speed [7-8]. It is widely used in the defect detection of composite insulator. Meanwhile, it is one of the means to prevent insulator failure. Moreover, there is no special research on insulator heating resulting from the interface defects between the rod and the sheath. Therefore, the principle of infrared temperature measurement and its reasons for misjudgment were analyzed in the current study. Then, the temperature measurement test of the rod with built-in heat source was designed and the heating film with different temperature was set at the interface between the rod and the sheath to simulate the influence of different degree of defects on the heating. Finally, the effects of target distance and test angle on the measured values were investigated. The present research is expected to provide a useful reference for infrared temperature measurement of composite insulator in the engineering practice.

2. Principle and application of infrared temperature measurement

Infrared measurement technology can accurately measure the temperature of a specific target, which has been widely used in many industries such as electric power, medicine, and biology. The principle of infrared temperature measurement is introduced in the following.

2.1. Principle of infrared temperature measurement

Any object with an absolute temperature higher than zero will radiate energy to the outside in nature. According to the distribution of wavelengths, the radiated energy has a close relationship with the surface temperature of the object, which can be describe by the Plank radiation law [9-10]:

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

where $M(\lambda, T)$ is the emissivity of blackbody radiation. $c_1$ and $c_2$ are the first and second radiation constants, respectively. $\lambda$ is the wavelength of the radiation and $T$ is the absolute temperature of blackbody. When $\exp(c_2/\lambda T)>>1$, the Plank formula can be replaced by the following Wien displacement formula:

$$ M_b(\lambda, T) = c_1 \lambda^{-5} e^{-c_2/\lambda T} $$

Wien displacement law points out that the higher the temperature of an object is, the shorter the wavelength of its radiation spectrum is, and the central peak moves toward short wavelength. However, the radiant energy entering the detector is not only the radiant energy of the target, but also that of the surroundings and the atmosphere in actual measurement. Therefore, the spectral radiance of the target surface can be expressed as the following:

$$ L_\lambda = \varepsilon_\lambda M_b(\lambda, T_{\text{obj}}) + (1 - \alpha_\lambda) M_b(\lambda, T_{\text{sur}}) $$

where $\varepsilon_\lambda$ and $T_{\text{obj}}$ are the emissivity and temperature of the target, respectively; $\varepsilon_\lambda M_b(\lambda, T_{\text{obj}})$ and $M_b(\lambda, T_{\text{sur}})$ are the spectral radiances of the target and surrounding environment. $\alpha_\lambda$ is the absorptivity of the surface of the target. $T_{\text{sur}}$ is the ambient temperature.
The first term on the right side in Equation (3) is the spectral radiance of the target surface, and another term is the spectral radiance of the surrounding environment reflected by the target. The irradiance acting on the infrared temperature measurement system is shown in Figure 1, whose main sources are the surrounding environment, the object and the atmosphere. It can be expressed as:

$$E_\lambda = A_{obj} d^2 \left[ \tau_{\alpha\lambda} \varepsilon_\lambda M_b (\lambda, T_{obj}) + \tau_{\alpha\lambda} (1 - \alpha_\lambda) \cdot M_b (\lambda, T_{sur}) + \varepsilon_{\alpha\lambda} M_b (\lambda, T_{atm}) \right]$$  \hspace{1cm} (4)

**Figure 1.** Schematic diagram of received energy for infrared temperature measurement system.

where $A_{obj}$ is the visible area of the target corresponding to the minimum tensor angle of the infrared thermometer, and $d$ is the distance from the target to the infrared thermometer. In general, $A_{obj} d^2$ is a constant. $\tau_{\alpha\lambda}$, $\varepsilon_{\alpha\lambda}$, $M_b (\lambda, T_{atm})$, $\varepsilon_\lambda$, and $T_{atm}$ are the spectral transmittance, radiance, emissivity and temperature of the atmosphere, respectively.

The received infrared radiant energy is converted into a current signal by the detector, that is, the incident infrared radiant energy is integrated along the response band $\Delta \lambda$. Hence, the conversion relationship between the radiant energy and the current can be expressed as follows:

$$I_o = \int_{\Delta \lambda} A_k R_k \tau_\lambda E_\lambda d\lambda$$ \hspace{1cm} (5)

where $I_o$ is the current signal output from the detector. $E_\lambda$ is the radiation illumination received by the infrared measurement system. $A_k$ is the area of the infrared focusing lens. $R_k$ is the spectral responsivity of the infrared detector. $\tau_\lambda$ is the transmittance of the optical system. The output current can be converted into a voltage signal through the I/V conversion circuit, which can be expressed as:

$$V_{out} = \int_{\Delta \lambda} R A_{obj} d^2 A_k \tau_\lambda R \left[ \tau_{\alpha\lambda} \varepsilon_\lambda M_b (\lambda, T_{obj}) + \tau_{\alpha\lambda} (1 - \alpha_\lambda) M_b (\lambda, T_{sur}) + \varepsilon_{\alpha\lambda} M_b (\lambda, T_{atm}) \right] d\lambda$$ \hspace{1cm} (6)

where $R$ is the load.

Equation (6) indicates that there are many factors affecting infrared temperature measurement. In fact, the effective area of the lens, the transmittance of the optical system and the load are determined after the hardware of the temperature measurement system is specified. When $K = R A_k \tau_\lambda$, Equation (6) can be simplified as:

$$V_{out} = KA_{obj} d^2 \int_{\Delta \lambda} R \left[ \tau_{\alpha\lambda} \varepsilon_\lambda M_b (\lambda, T_{obj}) + \tau_{\alpha\lambda} (1 - \alpha_\lambda) M_b (\lambda, T_{sur}) + \varepsilon_{\alpha\lambda} M_b (\lambda, T_{atm}) \right] d\lambda$$ \hspace{1cm} (7)

It can be seen from Equation (7) that the measured accuracy is influenced by the ambient temperature, distance and test angle when the blackbody emissivity is defined.

2.2. Application of infrared temperature measurement

Infrared temperature diagnosis technology can detect different types of faults of high-voltage power equipment, including external and internal thermal faults of the equipment [11].

The heat-generating parts of external thermal fault of the equipment are, in general, overexposed in the environment, at which time the infrared measurement technology can be used to observe the equipment surface to analyze its actual heat distribution and clarify the location of the fault. The main reason for this fault is a sudden increase in the contact resistance. Uneven contact surface, rough equipment surface and connection problems can lead to external thermal failure of the equipment.
Thermal faults within the equipment mainly occur inside the high-voltage power equipment. As the heat generating parts are inside the equipment, it is difficult to be detected by an ordinary thermal imaging camera. Hence, a thermal imaging of the interior of the equipment by the infrared temperature diagnosis technology is adopted to analyze the temperature distribution. Usually, if there is a poor contact problem in the internal electrical connection of the device, it will cause the current heating effect. A lot of dielectrics inside the equipment are in the state of excessive loss, thereby leading to the heating problem.

3. Misjudgement of infrared temperature measurement
In practical application, there are many factors affecting infrared temperature measurement, including emissivity, ambient temperature, illumination, distance, dust, electromagnetic interference and so on.

The research in [12] shows that when the measured equipment operates in an outdoor environment, the wind speed has an impact on the ambient temperature and target temperature. Under the condition of strong wind, the thermal energy of the heating equipment dissipates quickly, causing the temperature of the defective equipment decreasing because of the influence of convective cooling by wind speed. Therefore, the measured value is lower than the actual temperature.

The vibration of many molecules in the composition of the atmosphere overlaps with the infrared spectral frequency, so these molecules absorb the infrared, thereby influencing the measured results. Among them, water vapor and carbon dioxide have strong absorption capacity of infrared radiation due to their wide spectral absorption band [13].

The research demonstrates in [14] that when the temperature of the surrounding object is higher or lower than that of the measured object, its measurement results may be affected by the thermal radiation of the adjacent objects. The lower the temperature of the object is, the greater the impact of the radiation from adjacent objects is. Therefore, to eliminate the effect of reflection interference on the measured target, the shielding measures should be adopted in the infrared measurement.

Generally, the greater the load rate of the equipment, the more heat it generates. Ideally, the conductor flows through the rated load current to detect the heating defects of the equipment. In this way, the current passes for a period of time and a stable temperature rise obtains, then the measurement is performed. By comparing the temperature of equipment under different loads to establish a unified standard, the temperature rise of the defective equipment is converted to that at rated load, which is compared with the standard value and the accurate judgment of defect degree has been completed.

The defects at the interface between the rod and the sheath of the insulator in service causing the heating. With the further development of the defects, the heating problem becomes more serious. When applying infrared camera to measure the temperature of the insulators in engineering practice, it is necessary to consider not only the distance, but also the influence of the test angle on the measured value to avoid the misjudgment problems.

4. Influence of the distance and test angle on the infrared temperature measurement value
Usually, the value measured by infrared thermometer is not the real temperature of the target, but the result affected by many factors. Therefore, it is necessary to study and analyze many factors that affect infrared temperature measurement. In the present research, a temperature measurement test with built-in heat source within the rod of the insulator was designed, and the influence of the distance and test angle on the measurement results was studied.

4.1. Experiment
In this paper, a heating film was placed at the interface between the rod and the sheath to simulate the internal defects of the insulator. The rod diameter was 18 mm and the thickness of the sheath was 3 mm. The dimension of the heating film was 12 mm×39 mm. Different voltages were applied to the heating film to simulate the influence of the defect degrees on the heating. The voltages applied to the heating film were 1.97, 2.53, 3.017 V and 3.532 V, respectively. To analyze the influence of test angle
on the infrared temperature measurement, this paper defined the direction of the infrared camera MAG 160 Core facing the heating film as 0°. The heating film on the side of the camera was defined as 90°, and the heating film on the opposite side of the camera was defined as 180°, as shown in Figure 2. Environmental factors have an obvious influence on infrared temperature measurement. The standard stipulates that for accurate temperature measurement, the wind speed should not exceed 0.5 m/s and the humidity should not be greater than 85%. In the current study, the test was carried out in a windless environment with a humidity of about 60%. The specific test process was as follows.

1) According to the requirements, the predetermined voltage was applied to the heating film.
2) After preheating the sample, the infrared camera was turned on.
3) The focal length of the camera was adjusted.
4) The measured target was moved to fill the field of view, and the target temperature at the distances of 3 m, 6 m, 9 m, 12 m and 15 m was recorded, respectively. When the distance is greater than 6 m, ordinary lens and magnifying lens are used to measure the target temperature simultaneously.

**Figure 2. Schematic diagram of test angle.**

### 4.2. Analysis of influencing factors

The measured data under different voltages and different angles are shown in Table 1 and Figures 3-6.

**Table 1.** Measured values under different distances and different angles.

| Angle (°) | Distance (m) | U=1.97 V Ordinary | U=1.97 V Enlarging | U=2.53 V Ordinary | U=2.53 V Enlarging | U=3.017 V Ordinary | U=3.017 V Enlarging | U=3.532 V Ordinary | U=3.532 V Enlarging |
|-----------|--------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| 0°        | 3            | 34.4              | /                 | 36.2              | /                 | 36.6              | /                 | 37.7              | /                 |
|           | 6            | 34.2              | /                 | 35.7              | /                 | 36.0              | /                 | 37.0              | /                 |
|           | 9            | 33.7              | 34.0              | 35.6              | 35.0              | 35.7              | 35.8              | 36.5              | 36.1              |
|           | 12           | 33.9              | 34.0              | 35.3              | 34.8              | 35.4              | 35.2              | 35.9              | 36.0              |
|           | 15           | 33.9              | 33.5              | 35.4              | 34.8              | 35.0              | 34.9              | 36.0              | 36.1              |
| 90°       | 3            | 33.8              | /                 | 34.7              | /                 | 35.2              | /                 | 35.9              | /                 |
|           | 6            | 33.8              | /                 | 34.6              | /                 | 35.0              | /                 | 35.6              | /                 |
|           | 9            | 33.5              | 33.4              | 34.5              | 34.3              | 34.9              | 34.4              | 35.4              | 35.6              |
|           | 12           | 33.7              | 33.7              | 34.5              | 34.1              | 34.8              | 34.1              | 35.1              | 35.0              |
|           | 15           | 33.5              | 33.2              | 34.4              | 33.9              | 34.6              | 34.1              | 35.1              | 34.7              |
Figure 3. Measured values under the voltage of 1.97 V applied to the heating film.

Figure 4. Measured values under the voltage of 2.53 V applied to the heating film.

Figure 5. Measured values under the voltage of 3.017 V applied to the heating film.

Figure 6. Measured values under the voltage of 3.532 V applied to the heating film.

The following conclusions can be obtained from Table 1 and Figures 3-6.

1) When different voltages are applied to the heating film, the results have a similar trend at different angles. It proves that the measured values are valid and there is a certain variation law, that is, whether using a normal lens or a magnifying lens, the measured temperature basically tends to decrease with increasing distance. The fluctuation of the measured temperature is obvious at a measuring distance of 12 m.

2) The test angle has a significant effect on the results. The Lambert law of cosines states that the radiation intensity of an object in any direction is proportional to the cosine of the angle of the observation direction with respect to the normal to the radiation surface, that is, the blackbody has the strongest radiation in the normal direction of the radiation surface. Therefore, when the angle between the observation direction and the heating position is 0°, the value is the highest, while the result for 180° is the lowest. The measurement at 90° is in between. Taking the voltage of 1.97 V and the distance of 3 m as an example, the measured temperatures in the three cases are 35.5 °C, 34.4 °C and 33.8 °C, respectively. Therefore, if the test angle is selected improperly, it will cause large measurement errors. As for the actual situation, it is difficult to capture the maximum temperature in most cases because the inspector is often under the equipment and the test angle is prone to be obscured. Therefore, the inspector must be familiar with the structure of the equipment and find the best test point possible. When the maximum temperature cannot be measured and may affect the...
judgment of the defect level, appropriate corrections should be made based on the equipment structure and test angle.

(3) When the measurement distance exceeds 9 m, the effect of ordinary lens and magnifying lens on the results was compared. The results show that the results measured by magnifying lens are slightly lower than those by ordinary lens. The reason for this can be explained by the fact that the magnifying lens is mainly aimed at the object to be measured at a long distance. After installing a magnifying lens, the infrared image is clear, but the viewing range is greatly reduced. In this case, if the overall image of the equipment is to be taken, the detection distance needs to be increased, resulting in the overall attenuation of the temperature, but the equipment defects can still be identified by the temperature rise.

Figure 7 shows relationship between the measured value and the voltage applied to the heating film at different distances.

![Figure 7. Relationship between the measured values and the voltage applied to the heating film.](image)

As can be seen from Figure 7, the values increase with the increase of the applied voltage at different measurement distances and has a saturation trend. For a certain applied voltage, the larger the distance is, the smaller the temperature is, which is consistent with the actual situation. The reason can be explained by the fact once there is a defect in the interface between the rod and the sheath of the insulator in service, the field strength at the defect increases with the further development of the defect, resulting in the increase of the heating.

5. Conclusions
In the present research, the defects are simulated by a built-in heat source at the interface between the rod and the sheath. The influence of the distance and test angle on the infrared temperature measurement values is analysed. Main conclusions are summarized as follows. For the different degree of defects simulated by the heating film, the infrared temperature measurement value basically shows a decreasing trend with increasing distance, and the test angle has no effect on the variation law of measurement results. Test angle has a significant effect on the results of infrared temperature measurement. When the angle between the camera and the heating position is 0°, the measured value is the highest, followed by the 90° direction. When the heating film is at the opposite side of the camera, the value is the lowest. In actual measurement, the surveyors find the best test point as much as possible. Although the magnifying lens can capture a clear infrared image, but increases the detection distance, thereby resulting in attenuation of measurement temperature. Therefore, the appropriate lens should be selected according to the actual situation.
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