Temperature distribution characteristics and heat defect judgment method based on temperature gradient of suspended composite insulator in operation

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Abstract
In order to solve the problem of determining the heating suspended composite insulators in transmission lines, infrared tests for composite insulators newly put into operation and with heat defect were conducted. The insulator surface temperature distribution characteristics were obtained. Furthermore, the characteristic parameters based on temperature gradient were revealed and the judgment method of heating defect was established. The results indicate that considerable proportion of the composite insulators in operation have a temperature difference more than 5 K, thus false judgment could occurred when judging heating defect only by temperature difference. Normal composite insulator temperature curve was composed of high-frequency and low-frequency components. The influence of the low-frequency component on the temperature difference is greater than that of the high-frequency component. Obvious temperature gradient exists at the heating region boundary. The standard deviation of temperature gradient and the maximum absolute value of temperature low-frequency component gradient are effective characteristic parameters to distinguish whether heating defects exist. The heating defect judgment method was established based on the characteristic parameters, and was verified by field data with an accuracy rate of 94.31%. The method satisfied the heating defect judgement under UAV infrared lens with spatial resolution value not larger than 0.895 mrad.

1 | INTRODUCTION

Composite insulators have been widely used in overhead transmission lines due to excellent contamination flashover resistance and light weight. Defects such as rod corrosion and sealing failure of suspended composite insulators exists in operation [1], which could develop to fracture or internal breakdown. In recent years many incidents of decay-like composite insulator fracture occurred in China [2]. The establishment of early warning method for composite insulator internal defects is of great significance to ensure the safety of overhead lines [3]. The gradual development of internal defects of composite insulator, partial discharges occurs in core [4] leading to heating. In addition, in areas with high humidity, several batches of composite insulators in operation were with heating phenomenon, part of these insulators were found to have internal defects through anatomy [5]. Many researchers have researched the heating mechanism, heating characteristics and infrared detection methods of composite insulators.

In terms of heating mechanism, literature [6] found that the temperature rise of insulator core with initial electrical corrosion was caused by the dielectric loss and leakage current of core. Literature [7, 8] held that for composite insulators without internal defects, the dielectric loss of aged sheath was the main reason for end-heating. Literature [9] analysed the influences of pollution and sheath aging on the end heating of composite insulators, and held that the end heating of composite insulator was closely related to the sheath aging under the same surface state.

In terms of heating characteristics, the literature [10] studied the heating generation law of conductivity defects through simulation and experiment. For internal continuity defects
or large-area core rods exposed to moisture, the temperature difference between sheath surface and core rod is limited. Thus infrared is an effective means to find defects. Literature [11] studied the temperature rise of internal air gap defects of insulator core and found that the temperature rise inside the sheath reached 207 K when the temperature rise of sheath surface reached 1.4 K, which could cause the decomposition of silicone rubber and bring challenges to infrared testing. Also based on the heating character, literature [11] gave a composite insulator renew strategy considering heating position, which is instructive to field test analysis.

In terms of infrared testing methods, literature [12, 13] studied the influence of humidity on the temperature rise of composite insulators in the laboratory. The results showed that with the increase of humidity, the amount of composite insulators with heat defect and the value of temperature rise increased significantly. Therefore, it was recommended to carry out field infrared test at low humidity. Literature [14] suggested that the test should be conducted at night based on the tracking detection of a field heat defect. Based on the summary of field infrared testing, literature [15] suggested that infrared testing should be conducted in sunny days or after sunset, and at least one day after rain to ensure that the insulator surface is dry. When the handheld infrared is used for testing on the ground, it is suggested that the testing distance should be 50–100 m to avoid the occlusion of the core by shed, and infrared instrument with long focal lens is recommended. The temperature rise value used for defect judgment is derived from the difference between the highest and lowest surface temperature of an insulator, which is the same as that in literature [11].

From the existing research results, the heating mechanism and temperature rise value of composite insulator have been revealed in details and the influence of humidity on infrared test has also been clear. However, the current research achievements are still not enough to satisfy the demand of large-area transmission line infrared monitoring. First, false judgment that normal insulator determined to be heating, or misjudgement that heating insulator determined to be normal, could occur frequently when judging heating defect only by temperature difference regardless the test parameters. The transmission towers are widely distributed and the terrain is complex, making it difficult to carry out large-scale infrared testing at night. When the infrared test is carried out on a cloudy day, visible light will still affect the surface temperature of the composite insulator, resulting in a false temperature rise. In addition, improper parameters of the equipment used can also produce false temperature rise [15]. Nevertheless, there is no in-depth analysis on the surface temperature distribution of the normal composite insulator on site, and there is no basis for eliminating the false temperature rise. Second, currently the analysis of the infrared spectrum of composite insulators mainly depends on humans, and the judgment method involves the composite insulator temperature difference and its infrared spectrum characteristics, which could be influenced by subjective effect, thus the test efficiency and accuracy are limited. Literature [16] proposed the development direction of on-site composite insulator heating defect automatic identification technology based on unmanned aerial vehicle (UAV) and expert system. With the development of line UAV patrol technology, infrared test technology of composite insulator using UAV is matured. However there are very few reports on the technology for automatic determination of the composite insulator heating defects.

Temperature gradient is a common method of thermal analysis, which has been widely used in fatigue analysis [17] and thermal defect analysis [18]. Based on field UAV infrared test and laboratory infrared test, a large number of infrared spectra of normal and heating composite insulators were obtained in this paper. Through analysing the composite insulator temperature curve, the surface temperature distribution characteristics and temperature gradient characteristics of normal and heating composite insulator were obtained, and a method for judging heating composite insulator based on temperature gradient was established. The method aims to identify heating insulators. The diagnosis of the heating cause will be the next step of research. The method is based on silicone rubber (SIR) composite insulator because in China most of the composite insulator is made by SIR. Combining the achievements of this article with composite insulator object identification technology gradually matured currently, it is expected to realise automatic analysis of large-area composite insulator infrared spectra on site and early warning of defects, which could greatly improve the safety and intelligence level of transmission line operation and maintenance.

### 2 RESEARCH METHOD

#### 2.1 Test samples and method

##### 2.1.1 Composite insulator newly put into operation

| Tested lines         | Structural height/mm | Arcing distance/mm | Leakage distance | Material type   |
|----------------------|-----------------------|--------------------|------------------|-----------------|
| 500 kV line A/B      | 4900                  | 4550               | 16,000           | Silicon rubber  |
| 220 kV line C/D      | 2240                  | 1900               | 6300             | Silicon rubber  |

Double circuit transmission line 500 kV A/B and 220 kV C/D were selected for infrared test. The composite insulators tested on the above lines were put into service in 2019, which have been inspected by sampling test. The results showed that the insulators were in well condition. The parameters of insulators are listed in Table 1.

Field infrared test of composite insulators was carried out by UAV with infrared equipment. One infrared image of each insulator was recorded. The parameters of infrared equipment and the tested insulator numbers are shown in Table 2, in which the infrared parameters of UAV are the most commonly used equipment parameters in transmission line inspection.
TABLE 2  Parameters of UAV infrared equipment and number of insulators newly put into operation tested

| Tested lines | Insulator number | Infrared image number | Focal length, mm | Pixel pitch, µm | Spatial resolution, mrad |
|--------------|------------------|-----------------------|-----------------|----------------|------------------------|
| 500 kV line A/B | 139              | 139                   | 25              | 17             | 0.68                   |
| 220 kV line C/D | 88               | 88                    | 19              | 17             | 0.895                  |

FIGURE 1  Typical infrared images of composite insulators in operation. (a) 500 kV insulator, (b) 220 kV insulator

All tests were conducted in sunny and dry weather. The ambient humidity is between 50–80%, and the ambient temperature is between 25–30 °C. The day before test is not rainy, thus no liquid water exist in the surface of composite insulators. The sky was selected as test background to increase the contrast between tested insulator and background, which is conducive to test object identification. The test reflectivity was 0.95 and the test distance was 10 m. In order to assure these insulators is without heating, all the infrared images were checked that no abnormal heating exist on these insulators [15].

The key point of infrared test of composite insulator is the heating state of core. The shed occlusion will affect the detect sensitivity of insulator heating defect [19], which was avoided as much as possible during the test. Typical infrared images of 500 and 220 kV composite insulators are shown in Figure 1(a) and Figure 1(b) respectively.

2.1.2  Heating composite insulators

500 kV heating composite insulators

500 kV heating composite insulators were from 500kV line G. The thermal infrared spectrum were obtained by laboratory test. The laboratory test layout is shown in Figure 2(a). \( T_1 \) stands for the voltage regulator with capability of 4800 kVA, \( T_2 \) is the test transformer with rated voltage and current of 800 kV/6 A. The \( R_1 \) is the protective resistance. \( V_d \) stands for the voltage divider. \( T_c \) is the tested insulator. \( C \) is the climate chamber with diameter of 22 m and height of 25 m, where the test is conducted. \( I_d \) stands for infrared imaging device. The temperature sensitivity of the infrared test equipment was <50 mK, the test focal length was 49 mm, the pixel pitch was 17 µm, the spatial resolution was 0.347 mrad, the reflection coefficient was set at 0.95, the test distance was 10 m. The relative humidity is controlled at 50%.

The test equipment outside the climate chamber such as test transformer, voltage divider and climate chamber is shown in Figure 2(b), the arrangement of tested insulators inside the climate chamber is shown in Figure 2(c). The infrared equipment is shown in Figure 2(d).

Voltages of 1.0 \( U_0 \) and 0.5 \( U_0 \) were applied to two insulators with internal defects. Total of 31 infrared images under different test duration were recorded to obtain infrared images with different heating degrees. In addition, 11 composite insulators that have been in operation for 10 years was tested under 1.0 \( U_0 \) with corona ring removed, which causes high-voltage end heating due to the distorted electric field [5]. One infrared image of each insulator with corona ring removed was recorded. Thus the number of 500 kV heating insulator infrared images is 42.

The decay phenomenon of the two insulators with internal defect and its infrared images are shown in Figure 3(a–d). In subsequent analysis, the infrared data of 500 kV heating composite insulators were all from laboratory test data.

220 kV heating composite insulators

In February 2020, 61 heating composite insulators at the 220 kV double circuit line E/F were found. The existence of heating is confirmed by laboratory retest. One of the insulators is with internal defect, the other 60 insulators is with heating from surface sheath aged, which would disappear when the surface aged sheath is removed similar to the case in literature [7]. The insulators is package appropriate in transmission thus the pollution is
kept well. The test is conducted as soon as possible when insulator is transmitted to the laboratory thus the surface sheath still keep moisture. Typical field infrared spectra of heating insulator are shown in Figure 4(a), and laboratory retest infrared spectra are shown in Figure 4(b,c).

The laboratory retest layout was the same as the 500 kV insulators mentioned above. In subsequent analysis, the infrared data of the 220 kV heating composite insulator was from the field test. The field infrared test was conducted by UAV. The infrared lens parameters, field test location and test parameter were the same as those in Section 2.1.1 of the 220 kV C/D line. A total of 61 infrared images of heating 220 kV composite insulators were obtained with one image corresponds to one insulator.

The parameters of all heating insulators are listed in Table 3.

### Data analysis method

After test images obtained, the temperature curve data of composite insulator core axis was exported by analysis software of infrared equipment, and the temperature span, temperature gradient and other parameters were calculated.

The temperature curve is a series of discrete temperature data points along the insulator core, as shown in Equation (1).

$$ f_T = \left[ T_1, T_2, T_3, \ldots, T_i, \ldots, T_m \right] $$

Where, $f_T$ is the temperature curve of the insulator core, $m$ is the data number of the temperature curve, and $T_i$ is the $i$th data in the temperature curve with the unit of °C.

The temperature rise was described by the temperature span $T_{\Delta}$ of the temperature curve, which was calculated according to Equation (2) [18].

$$ T_{\Delta} = T_{\text{max}} - T_{\text{min}} $$

Where $T_{\text{max}}$ is the maximum value of the temperature curve and $T_{\text{min}}$ is the minimum value of the temperature curve.

By calculating the temperature gradient in Equation (1) through Equation (3), the temperature gradient curve $k_1$ of composite insulator is obtained.

$$ \begin{cases} k_1(i) = \frac{f_T(i+1) - f_T(i)}{l} = \frac{T_{i+1} - T_i}{l} \\ l = H/(m-1) \end{cases} $$

Where, $H$ is the insulation height of a composite insulator, $m$ is the point number of composite insulator temperature curve, and $l$ is the distance between the adjacent data points of the temperature curve. Equation (3) provide the mean value of the temperature gradient in the small section between two temperature data points.

The standard deviation of temperature gradient $S_{kd}$ is calculated according to Equation (4) [18]. Where, $\bar{k}_1$ stands for the average temperature gradient value of composite insulator temperature curve.

$$ S_{kd} = \sqrt{\frac{\sum_{i=1}^{m-1} (k_1(i) - \bar{k}_1)^2}{m-1}} $$

The temperature curve along composite insulator consists of high-frequency component $f_{HT}$ and low-frequency component $f_{LT}$, which are attained through wavelet decomposition and reconstruction. The decomposition and reconstruction is conducted through multiresolution analysis [20]. The wavelet base is dmey, which could maintain the smooth character of the $f_{LT}$.

### Table 3: Parameters of heating insulators

| Tested lines | Structural height/mm | Arcing distance/mm | Leakage distance/mm | Material type |
|--------------|----------------------|--------------------|---------------------|---------------|
| 500kV line G| 4900                 | 4520               | 16,940              | Silicone rubber |
| 220kV line E/F| 2240               | 1900               | 6300               | Silicone rubber |
The temperature curve \( f_T \) could be decomposed as shown in Figure 5.

In Figure 5 the \( f_T \) is decomposed to approximate component \( f_{1AT} \) and detailed component \( f_{1DT} \). The approximate component \( f_{1AT} \) is further decomposed to \( f_{2AT} \) and \( f_{2DT} \), while the detailed component \( f_{1DT} \) could not be further decomposed. The whole decomposition layer is 4.

In the decomposition process, the \( j \)th layer of approximate component \( f_{jAT} \) is as Equation (5) [21].

\[
\begin{align*}
    f_{jAT} &= f_{(j+1)AT} + f_{(j+1)DT} \\
    f_{jAT} &= \sum_{\alpha \in Z} a_{j\alpha} \psi (\alpha) \\
    f_{(j+1)AT} &= \sum_{\alpha \in Z} a_{(j+1)\alpha} \psi (\alpha) \\
    f_{(j+1)DT} &= \sum_{\alpha \in Z} d_{(j+1)\alpha} \phi (\alpha)
\end{align*}
\]

In Equation (5) the \( \psi(\alpha) \) is the wavelet function and the \( \Phi(\alpha) \) is scale function according to the selected wavelet [21]. The relationship between \( a_{j\alpha} \) and \( a_{(j+1)\alpha} \), and between \( d_{j\alpha} \) and \( d_{(j+1)\alpha} \), are expressed as Equation (6).

\[
\begin{align*}
    a_{(j+1)\alpha} &= \sum_{n \in Z} \bar{b}_{n-2\alpha} \cdot a_{j\alpha} \\
    d_{(j+1)\alpha} &= \sum_{n \in Z} \bar{\phi}_{n-2\alpha} \cdot a_{j\alpha}
\end{align*}
\]

In Equation (6) the parameters \( \bar{b}_{n-2\alpha} \) and \( \bar{\phi}_{n-2\alpha} \) are determined by scale function \( \Phi(\alpha) \) and wavelet function \( \psi(\alpha) \) [21]. Based on Equations (5) and (6), the 4th layer of approximate component \( f_{4AT} \) is attained as the low-frequency component \( f_{4LT} \), and \( f_{4HT} \) is acquired through Equation (7).

\[
f_{4HT} = f_T - f_{4LT}
\]

Based on the temperature low-frequency component \( f_{4LT} \), the temperature low-frequency component gradient \( k_{4,max} \) can be obtained through replace \( f_T \) into \( f_{4LT} \) Equation (3). Furthermore the maximum absolute value of temperature low-frequency component gradient \( k_{4,max} \) can be obtained according to Equation (8).

\[
\begin{align*}
    k_{4,max} &= \max \left( |k_2(j)| \right) \\
    k_2(j) &= \frac{x_{j(i+1)} - x_{j(i)}}{f}
\end{align*}
\]

Where, \( k_2(i) \) stands for the gradient value of the \( i \)th data in the temperature curve low-frequency component \( f_{4LT} \).

The kurtosis of temperature gradient \( p_1 \) is calculated according to Equation (9).

\[
    p_1 = \frac{\frac{1}{(n-1)} \sum_{i=1}^{n} (k_1(i) - \bar{k}_1)^4}{\left[ \frac{1}{(n-1)} \sum_{i=1}^{n} (k_1(i) - \bar{k}_1)^2 \right]^2}
\]

The kurtosis of the temperature low-frequency component gradient \( p_2 \) is calculated according to Equation (10).

\[
    p_2 = \frac{\frac{1}{(n-1)} \sum_{i=1}^{n} (k_2(i) - \bar{k}_2)^4}{\left[ \frac{1}{(n-1)} \sum_{i=1}^{n} (k_2(i) - \bar{k}_2)^2 \right]^2}
\]

Divide \( p_1 \) by \( p_2 \) to obtain \( p_i \), as Equation (11). The value \( p_i \) describes the change in the steepness of the temperature gradient distribution before and after wavelet treatment.

\[
p_i = \frac{p_1}{p_2}
\]

3 | TEMPERATURE CHARACTERISTICS OF COMPOSITE INSULATOR

3.1 | Temperature characteristics of normal composite insulator

3.1.1 | Temperature difference

The temperature span \( T_i \) of 500 kV A/B line and 220 kV C/D line insulators were calculated from the temperature curves. The temperature span distribution of the lines are shown in Figure 6.

As shown in Figure 6, the proportions of composite insulators with \( T_i \) over 5 K for 500 and 220 kV insulators reached 25.9% and 42.0% respectively. According to literature [11], the composite insulator with temperature difference exceeding 5 K is suggested to be replaced in time. However, the insulators tested in line A/B of 500 kV and line C/D of 220 kV are newly put into operation without defects. Therefore, new method is needed to judge heating defect besides the method based on temperature rise. Although heating defect judgment only by temperature rise might cause false-judgement, temperature rise value is still critical parameters because it can be used for judging the severity of the defect [6,11].
3.1.2 Typical temperature curve

The temperature curve of insulators was analysed in order to excavate the characteristics of normal insulator temperature distribution. Take a typical 500 kV insulator as an example. The infrared image and temperature curve are shown in Figure 7. The temperature data sequence stand for the serial number of the temperature data in the temperature curve, which starts from high voltage end. Figure 7(c) and Figure 7(d) correspond to the 4 shed units near high voltage end.

It is indicated from Figure 7 that fluctuation exist on temperature curve. Through wavelet decomposition and reconstruction, the fluctuation and baseline of the temperature curve were separated in Figure 8. The wavelet type was db4 and the decomposition layer number was 4.

In Figure 8, the base line and the fluctuation of the temperature curve is defined as the low-frequency component and high-frequency component respectively.

3.1.3 Source of temperature difference

Based on the wavelet analysis method in Section 3.1.2, all of the 500 kV composite insulator temperature curve is separated into high-frequency component and low-frequency component. The temperature span $T_f$ values of the high-frequency and low-frequency components from normal composite insulator temperature curves are shown in Figure 9(a,b) respectively. In Figure 9, the insulator sequence stand for the serial number of the temperature span data, which is determined by the infrared test sequence.

Based on Figure 9, the proportion of the 500 and 220 kV composite insulators whose high-frequency component temperature span exceeds 3 K reaches 0% and 1.12%, respectively. The proportion of the 500 and 220 kV composite insulators with low-frequency components temperature span exceeds 3 K reaches 21.7% and 30.0% respectively. The conclusion could be drawn that the temperature curve low-frequency component makes greater contribution to the insulator temperature rise than the high-frequency component.

3.2 Temperature characteristics of heating composite insulator

500 kV heating composite insulator consists of insulators with internal defect and insulators with corona ring removed. Two 500 kV composite insulators with internal defects were tested under 0.5 $U_0$ and 1.0 $U_0$. The temperature span is calculated from insulator temperature curve under different test time. For the 500 kV composite insulator with the corona ring removed, the infrared images were recorded under 1.0 $U_0$ applied for 30 min. The temperature span distribution of the two kinds of
heating insulators are shown in Figure 10. The heating samples sequence stand for the serial number of the temperature span data, which is determined by the infrared test sequence.

The typical infrared spectrum and temperature curve of insulator with internal defect near high voltage is shown in Figure 11(a,b), and the typical infrared spectrum and temperature curve of insulator with corona ring removed is shown in Figure 12(a,b).

The field infrared test spectrum and the temperature curve of 220 kV heating composite insulator is similar to the 500 kV insulator with corona ring removed.

By comparing the heating image and temperature curve of the composite insulator in Figures 11 and 12 with that of the normal composite insulator in Section 3.1, Figure 7, it can be seen that the heating image and temperature curve of the composite insulator have the following two characteristics:

1. The high temperature section length of heating composite insulator is longer than that of normal composite insulator.

2. Significant temperature gradient exists in the high temperature region edge of composite insulator.

In Figures 11(a) and 12(a), the number of shed units covered by the high temperature area of the heating insulator is up to 3 and 1, respectively. The high temperature pulse in Figures 7 and 8 of Section 3.1 is more cramped than the high temperature area of the heating insulator.

**4 | TEMPERATURE GRADIENT CHARACTERISTICS OF COMPOSITE INSULATOR**

**4.1 | Maximum absolute value of temperature low-frequency component gradient**

Based on the high temperature section length difference of the heating and normal composite insulators, wavelet analysis was utilised to expand the gradient difference between them. Taking a 500 kV normal composite insulator and a 500 kV
heating composite insulator as examples, the low-frequency components are decomposed and reconstructed by 4-layer decomposition of db4 wavelet. The original temperature curve of the normal insulator and its low-frequency components are shown in Figure 13(a), and the original temperature curve and its low-frequency components of the heating insulator are shown in Figure 13(b).

In Figure 13, it is shown that the high-frequency components on the normal composite insulator temperature curve were removed by wavelet decomposition and reconstruction, while the high temperature region and its temperature gradient of the heating composite insulator temperature curve can still be retained to a certain extent. Thus the temperature gradient differences between the heating and the normal insulator are amplified.

The temperature gradient of the 500 kV normal and heating insulators was calculated. The maximum absolute values of the gradient of the original temperature curve $k_{\text{max}}$ is shown in Figure 14(a). The maximum absolute value of temperature low-frequency component gradient $k_{L\text{max}}$ is given in Figure 14(b).

It can be seen from Figure 14(a) that for the maximum absolute gradient of the composite insulator original temperature curve, the values of normal insulators distribute between 0.031–0.478 K/mm, with a large overlap range compared to the values of heating insulators distribute between 0.030–0.726 K/mm. The low-frequency component of temperature curve was obtained by wavelet decomposition. Significantly difference of temperature low-frequency component gradient between the normal and the heating insulator exist. The values of normal insulators distribute between 0.001–0.013 K/mm, and the values of heating insulators distribute between 0.002–0.115 K/mm. The high temperature section of heating insulator is longer than the temperature fluctuation of the normal insulator, being key point assuring difference between heating and normal insulators. In the study, the test distance is 10 m and spatial resolution is not larger than 0.895 mrad, which assure recording the heating section area correctly.

### 4.2 Temperature gradient characteristic parameters

A large number of high temperature pulses exist in the temperature curve of normal insulator, which is the main source of the temperature gradient standard deviation of normal insulators. The heating insulator temperature gradient standard deviation is mainly derived from the temperature gradient at the edge of high temperature region. Assuming that the maximum temperature gradient of a heating insulator is close to that of a normal insulator, the standard deviation of the heating insulator temperature gradient is likely to be smaller than that of the normal insulator.

A two-dimensional characteristic parameter space was constructed based on the standard deviation of temperature gradient $S_{k\text{d}}$ and the maximum absolute value of temperature low-frequency component gradient $k_{L\text{max}}$. The overall distribution of normal insulators and heating insulators of 500 kV composite insulator is shown in Figure 15(a). Figure 15(b) focus on the coordinate origin area to clearly show the overlap of normal insulators and heating insulators.

In figures of this article, the standard deviation of temperature gradient is represented by $S_{k\text{d}}$, and the maximum absolute
value of temperature low-frequency component gradient is represented by $k_{\text{Lmax}}$.

It can be indicated from Figure 15 that, in the characteristic parameter space composed of $S_{\text{kd}}$ and $k_{\text{Lmax}}$, there are significant differences between 500 kV normal insulators and 500 kV heating insulators. The total number of heating insulators is 42. Only three heating insulator data overlap with the normal insulators. The test condition and the temperature rise corresponding to the three overlapped data is listed in Table 4.

It is shown in Table 4 that the temperature rise amplitude of the three heating insulators overlapping with normal insulators is less than 1 K, which is quite weak. The heating of #2 insulator is weak with temperature span within 0.7 to 3.7 K, which is utilised to show the relationship between the temperature span and the characteristic parameters. The change trend of $k_{\text{Lmax}}$ and $S_{\text{kd}}$ is shown in Figure 16.

From Figure 16 it is shown that the $k_{\text{Lmax}}$ value of #2 insulator increase from 0.006 to 0.03 K/mm with the temperature span rise from 0.7 to 3.7 K. The $S_{\text{kd}}$ value is stable when temperature span is within 0.7 to 2.0 K, while when the temperature span exceed 2 K, the $S_{\text{kd}}$ value shows a upward trend when temperature span enlarging. Owning to the increasing trend of $k_{\text{Lmax}}$, it is possible to distinguish heating insulators from normal insulators when temperature span is within 2 K. When temperature span become larger than 2 K, the increasing trend of $k_{\text{Lmax}}$ and $S_{\text{kd}}$ makes the heating defect identification more easily. In conclusion, the standard deviation of temperature gradient $S_{\text{kd}}$ and the maximum absolute value of temperature low-frequency component gradient $k_{\text{Lmax}}$ are effective characteristic parameters to distinguish whether composite insulator heating defects exist.

### 4.3 Influence of spatial resolution on characteristic parameters

The infrared measurement accuracy of UAV is closely related to the spatial resolution of the infrared equipment. The relationship between the spatial resolution $S_r$, focal length $L_{en}$ and pixel distance $A_p$ is shown in Equation (12).

\[
S_r = A_p / L_{en} \tag{12}
\]

The unit of spatial resolution $S_r$ is mrad, the unit of focal length $L_{en}$ is mm, and the unit of pixel distance $A_p$ is $\mu$m.

For a fixed size detection target, the number of data points on the target infrared image is inversely proportional to the value of spatial resolution. Along the radial direction of the insulator, the increase of the spatial resolution would enhance the influence of background. When the background is sky, the temperature of the whole insulator would be reduced. Along the length of the insulator, the increase of the spatial resolution is equivalent to the reduction of the spatial sampling rate of the temperature curve, which is discussed below.
The spatial resolution of original 500 kV normal composite insulator infrared images is 0.68 mrad. The normal insulator temperature curve was sampled at equal intervals so that the spatial resolutions are equivalent to 1.36 and 2.04 mrad respectively. The spatial resolution of original 500 kV heating composite insulator infrared images is 0.347 mrad. The heating insulator temperature curve was sampled at equal intervals so that the spatial resolutions are equivalent to 0.695 mrad and 1.041 mrad respectively. The changes of characteristic parameters $S_{kd}$ and $k_{Lmax}$ under different spatial resolutions are shown in Figure 17.

It is shown in Figure 17 that the value of $S_{kd}$ and $k_{Lmax}$ both decrease with the spatial resolution value increasing, which lead to the rise of the overlap section of $S_{kd}$ and $k_{Lmax}$ between normal and heating insulators. The values of $S_{kd}$ and $k_{Lmax}$ of normal and heating insulators with space resolution of 1.36 and 1.041 are shown in Figure 18, in which the overlapped heating insulator number increases to 9.

5.1 Wavelet decomposition layer number optimisation

In order to obtain the best judge accuracy of composite insulator heating defects, the $S_{kd}$ and $k_{Lmax}$ values of 500 kV normal insulators and the heating insulators were calculated with wavelet decomposition layers of 2–5. The wavelet type is dmey. The results of the decomposition layers of 2 are shown in Figure 19. The overlap insulator numbers of normal insulators and heating insulators in the space of $S_{kd}$ and $k_{Lmax}$ under each wavelet analysis layer are listed in Table 5.

It can be seen from Table 5 that the best accuracy of heating defect judgment can be obtained through four-layer dmey wavelet decomposition and reconstruction. If the number of wavelet analysis layer number is too small or too large, the overlapping area of the heating insulator and the normal insulators in the characteristic parameter spaces of $S_{kd}$ and $k_{Lmax}$ will increase. When the decomposition layer number is too small, the high-frequency components of the normal insulator
temperature curve are not completely suppressed. If the decomposition layer number is too large, the heating area of the heating insulator temperature curve is excessively smoothed, which will affect the judgment of heating defects.

5.2 Judgement method of heating defects

It is indicated from Figure 19 and Table 4 that the three points in the overlap section is with weak temperature rise. According to literature [22], the temperature rise judge threshold for heating composite insulators in ideal infrared test condition is 0.5 K -1 K. Thus the 3 results points in the overlap section in Figure 19 is near the boundary. In order to ensuring that heating insulator is not judged to be a normal insulator, and the number of false judgments is minimised as much as possible, the boundary distinguish normal and heating insulators should be as close as possible to the normal points. By fitting the data points of normal insulators closest to the heating insulator data, the criterion for determining composite insulator heating defect is constructed as Formula (10). The units of \( S_{kd} \) and \( k_{L_{max}} \) are both K/mm. The boundary between the normal insulators and the heating insulators formed by the criterion is shown in Figure 20.

\[
\begin{align*}
S_{kd} - 1.7153k_{L_{max}} - 0.0144 &\geq 0 \\
k_{L_{max}} &\geq 0.006
\end{align*}
\]

The process of heating defect judgement is concluded in Figure 21.

5.3 Validation of heating defects judge method

The data of 220 kV field composite insulator was used for verification. The values of \( S_{kd} \) and \( k_{L_{max}} \) of normal and heating composite insulators are obtained. Formula (7) is applied as the criterion for judging heating defects. Results are shown in Figure 22.

It is shown in Figure 22 that five insulators of 220 kV heating composite insulator have been judged to be normal, with a misjudgment rate of 8.19%. 3 insulators of 220kV normal composite insulator have been judged to be heating, with a false judgment rate of 3.41%. The integrate judge accurate is 94.31%. The spatial resolution in 220 kV composite insulator test is 0.895 mrad, which is lower than that of 500 kV composite insulator test. From the analysis in Section 4.3 above, it can be seen that the rise of spatial resolution value will increase the difficulty of determining thermal defects. Therefore, the verification of the 220 kV insulators shows that the heating defect method proposed in this paper is reliable for composite insulator infrared test with spatial resolution not less than 0.895 mrad and test distance not larger than 10 m.

The temperature span of the internal defects and sheath aging heating distributes in 0.7–13.8 K and 2.0–9.1 K respectively, covering most of the weak heating condition in transmission lines. Thus the method is adaptable to the internal defect and sheath aging heating composite insulators.
5.4 Discussion on distinguishing heating reason

Researches has found that internal discharge and fracture could occur on the composite insulators with internal heating defect, while the insulators with sheath aging heating are still with well operating performance [6,7–9]. Thus distinguishing the heating reason is useful for further maintenance decisions.

The heating mechanism of 500 kV insulators with corona removed is similar with the sheath aging heating. As is to the 500 kV internal heating insulators, 500 kV insulators with corona removed, and 220 kV sheath aging heating insulators, the distribution of temperature span $T_f$ and kurtosis parameters $p_i$ are shown in Figure 23. The 500 kV data is from the laboratory test in Section 2.1.2 (1), the 220 kV data is from the laboratory test in Section 2.1.2 (2) except one internal heating sample, thus the data is acquired with the same infrared equipment.

Based on Figure 23, it is shown that the distribution of $T_f$ and $p_i$ is different between composite insulators with internal heating and insulators with sheath aging or corona ring removed. Thus it is feasible to determine the heating reason based on the distribution of $T_f$ and $p_i$, which could help to make maintenance decision.

6 CONCLUSION

In this paper, based on the infrared test data of 500 and 220 kV composite insulator in field and laboratory, the temperature curve characteristics of normal and heating composite insulator are compared and analysed. Furthermore, a method for judging heating defects of composite insulators based on temperature gradient characteristics is established. The main conclusions are as follows:

1. Temperature curve of normal composite insulator is consisted of high-frequency and low-frequency components.
2. Considerable proportion of the composite insulators in operation has a temperature difference more than 5 K. False judgment could occur when judging heat defects only by temperature difference. The influence of the low-frequency component on temperature difference is greater than that of the high-frequency component.
3. There is a significant temperature gradient at the edge of the heating region of the heating composite insulator. The heating region length of heating insulator is generally larger than that of the normal insulator high temperature pulses.
4. The standard deviation of temperature gradient $S_{kd}$ and the maximum absolute value of temperature low-frequency component gradient $k_{Lmax}$ are effective characteristic parameters to distinguish whether composite insulator heating defects exist.
5. A method for judging composite insulator heating defects is established based on the standard deviation of temperature gradient $S_{kd}$ and the maximum absolute value of temperature low-frequency component gradient $k_{Lmax}$. The accuracy of judgment was 94.31% of field 220 kV composite insulators.
6. The rise of spatial resolution value will increase the difficulty of determining heating defects. The method established in this article satisfied the heating defect judgement under UAV infrared lens with spatial resolution of 0.895 mrad, which is the most commonly used equipment in transmission line.

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