Study on influence factors and restraining measures of composite insulator end heating caused by housing microstructure defects

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Abstract
In recent years, the quantity and proportion of heating defects have increased significantly with more composite insulators used in transmission lines and deterioration of early composite insulators. End heating is the main characteristic of this kind of defect in high-temperature and high-humidity areas. In this paper, microstructures of the housing material were observed through scanning electron microscopy and the key factors leading to temperature rise were studied through water absorption and power loss experiments. The results show that polarisation loss is the main cause of temperature rise and power loss increases exponentially with higher electric field intensity. The microporous structures of the housing material not only enhance the moisture absorption effect, but also affect the uniform distribution of the electric field. Due to the concentration of the local electric fields at high-voltage end, the effect of porosity on temperature rise is more significant. By adjusting the shielding depth (i.e. installation height) of grading ring or adding a race-track ring to restrain electric field intensity at high-voltage end of composite insulator, the temperature rise in high-humidity areas can be effectively reduced.

1 INTRODUCTION

The composite insulator has been widely used on transmission lines for its excellent anti-pollution flashover performance, high intensity and easy installation and maintenance [1–4]. With the rapid growth of its number and proportion in transmission lines, the composite insulator has become one of the most important insulation equipment in power transmission, so that the problems caused by the operation faults of the composite insulator have been gradually concerned by power grid companies and research departments [5–8]. At present, brittle fractures of the insulator rarely happen with the use of the ECR acid-resistant rod [9–11], but the decay-like fracture still threatens the safe operation of transmission line seriously [12, 13]. The abnormal temperature rise on the surface of the composite insulator is considered the precursor of the decay-like fracture [14], so maintainers check each composite insulator using infrared thermal imagers and replace the insulators with standard-exceeding temperature rises.

In many subtropical areas with high temperature and humidity, such as, the coastal areas of southern China, the proportion of the composite insulators with abnormal temperature rises is relatively high, especially the composite insulators on 500 kV transmission lines [15, 16]. What’s more, abnormal temperature rises of the composite insulator are found on some transmission lines with an operation time less than half a year. On the one hand, partial discharge caused by moisture penetration due to the defect of the interface bonding between the rod and the housing was once considered to be the main cause of surface temperature rise [17, 18], but a large number of dissection results show that only a small number of the heating insulators have interface defects. On the other hand, aging of the housing surface was once considered to be a necessary condition for end heating [19, 20]. However, in recent years, some new products also have showed end heating in spot-check and the possibility of heating caused by partial discharge has been ruled out based on dissections. Although polarisation loss of housing material has been proved to be the main cause of temperature rise in some areas, the factors that further determine the temperature rise have not been sufficiently studied.

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respects, the reason of polarisation loss difference between the samples and the restraining measures has never been explained and proposed [15, 16]. Therefore, it is necessary to study the key factors that cause the temperature rise and find out the specific causes of end heating from the perspective of individual differences. Then effective methods could be proposed to avoid more heating products from being used and restrain the temperature rise of the insulators on transmission lines.

In this paper, a large number of heating composite insulators replaced from the lines passed the water diffusion test, the dye penetration test and the end sealing test, while the infrared temperature measurement results under different conditions showed that the damp of the housing material is the main cause of the end heating of most samples. Then, the microstructure difference of the housing materials among the samples was analysed with a scanning electron microscope and the influence of the microstructure difference on heating power was analysed through the water absorption and the power loss experiments. Based on modelling and simulation calculation, the temperature rise at the end of the composite insulator can be effectively reduced by judging new product housing based on its moisture absorption and adjusting the shielding depth of the grading ring or adding a racetrack grading ring to restrain electric field intensity at the high-voltage end of the insulator.

2 | INVESTIGATION OF HEATING SAMPLES

In June 2019, it was discovered that there were 131 heating composite insulators whose temperature rose by over 5 K on a 500 kV transmission line in the coastal areas of southern China. The infrared temperature measurement result of a double composite insulator string is shown in Figure 1(a). The heating composite insulators have been in operation for 13 years. In order to ensure safe operation of the transmission line, the power grid company carried out emergency replacement of the heating insulators.

However, the temperature of new composite insulators was still significantly higher than that of other composite insulators. The infrared temperature measurement result of new composite insulators is shown in Figure 1(b). In order to avoid the influence of sunlight, infrared temperature measurement is usually carried out in the evening and the ambient temperature is about 25°C. The ambient temperature difference between the two measurements is less than 2°C and the relative humidity is more than 80%. Therefore, it can be considered that the ambient conditions of infrared temperature measurement are the same.

In order to find out the main cause of composite insulator end heating, 30 samples from before and after the composite insulator replacement were selected in this paper. The operation time and the states of these samples were investigated and the water diffusion, the dye penetration and the sealing test on the samples were done according to the existing national standards [21–23]. In addition, the infrared temperature measurement was carried out again under the dry and wet conditions.

The results of the investigation and the tests showed that the interface bonding performance, water penetration resistance of the rod and end sealing of fittings meet the national standards, which eliminates the possibility of partial discharge in most heating samples. The infrared temperature measurement results under the dry and wet conditions of three typical insulators are shown in Figure 2. For the dry condition, the samples were firstly dried at 40°C for 24 h, and then the infrared temperature measurement was carried out at 28 ± 2°C and 46% ± 2% humidity. For the wet condition, the samples were firstly exposed at 30°C and 90% humidity for 24 h, and then the infrared temperature measurement was carried out at 28 ± 2°C and 89% ± 2% humidity. The voltage applied to the composite insulator was 318 kV and the surface temperature of composite insulators was measured 2 h after the voltage was applied. The temperature rises at high-voltage ends of all the samples in the dry state were below 3 K, while the temperature rises in the wet condition were consistent with the results of the transmission line temperature measurement. The heating at high-voltage end not only existed in the aging samples that had been in operation for more than 10 years, but also existed in the new samples that had been in operation for less than 1 month. The temperature rises of the aging samples were more than 15 K, while the maximum temperature rises of new samples were less than 8 K. For the normal samples without heating, the temperature rises were less than 1 K in the dry state and less than 2.5 K in the wet condition. In addition, the temperature rise distribution at different angles was analysed. The temperature rises of the insulator samples at different angles were basically the same, but were significantly affected by surface contamination for the aging insulators. The surface contamination of insulator is shown in Figure 3. Because the moisture in the air is the necessary condition of heating, the microstructures of the housing material and contamination exposed to air are the key factors that influence heating. The cause of the end heating could be reasonably explained through the microscopic observation and the analysis of the influence of the microstructure difference on the moisture absorption and the heating power.

3 | EXPERIMENTAL DESIGN

For the composite insulator samples used in the experiment, the surface states of the housing were the main study object so the samples were classified according to the aging states of
FIGURE 2  Infrared temperature measurement results under the dry and wet conditions. (a) Dry condition, (b) wet condition and (c) infrared picture

The samples used in the experiment are shown in Table 1. For the aging composite insulators, they had been in operation for more than 10 years and therefore were serious powdered on the housing surface but the contamination degrees varied significantly. Therefore, comparative study was conducted on the areas with serious contamination and the areas with only aging, and some areas were cleaned with ethanol as reference. The replacement composite insulators were also cleaned with ethanol to make the housing microstructures the only variable in the experiments.

The scanning electron microscope used has a magnification of more than 2000 times. Therefore, the micro-pores and contamination distribution on the surfaces and inside the housing could be studied and the microstructures were recorded in the form of micrographs.

In this paper, the difference in moisture absorption of the samples was studied through a 96 h water absorption experiment. The water absorption device is shown in Figure 4. The size of the water absorption device is $155 \text{ mm} \times 105 \text{ mm} \times 85 \text{ mm}$. During the water absorption experiment, the samples were placed on a plastic grid and a certain amount of deionised water was injected into the device. The sample is about 40 mm away from the water surface. A plastic sealing bag was used to prevent air exchange between the tank and the outside during the experiment. In order to avoid condensation on the sample surfaces due to the temperature changes during the experiment and the sampling process, the temperature in the device was kept consistent with the room temperature.

In order to keep the error at a low level, three samples were made for each type of housing. The water absorption samples were collected from first and second sheds of the high-voltage ends. The water absorption samples were processed into rounds...
with a diameter of 30 mm ± 0.5 mm. Because the water absorption samples contained surface of the shed, the thickness of the samples is different. But the mass of the samples was about 4 g and the weight difference of such three samples was not more than 20%. Before the experiment, each housing sample was dried at a temperature of 60°C and the weight of the housing samples did not drop any more after 24 h. The average weight of such three samples was recorded as the initial value $m_0$. During the experiment, all samples were put into the same experiment device and the relative humidity in the tank was above 90%. The samples were weighed at the set time and the average value $m(t)$ of such three samples was calculated. The percentage of absorbed moisture can be expressed by Equation (1).

$$w(t) = \frac{m(t) - m_0}{m_0} \times 100\%.$$  

The housing power loss under different electric field intensity is the key parameter that reflects the degree of heating and can be calculated by measuring the leakage current and the dielectric loss angle. The experiment samples were collected from the high-voltage ends of the composite insulators I, II and III. After removing the internal rod, the samples were processed into rings with a length of $L$ (300 mm ± 1 mm) and each sample was placed between flat electrodes shown in Figure 5 during the measurement.

A DC generator was used to supply a constant voltage $U_d$ to the electrodes and a DC microammeter was used to measure the leakage current $I_c$. Under a constant electric field, the equivalent circuit model is shown in Figure 6(a). Since there was no polarisation loss under the constant electric field, the conductivity power loss $P_d$ of unit-length housing can be calculated by Equation (2).

$$P_d = \frac{U_d I_c}{L}.$$  

A test transformer was used to supply an alternating voltage to the electrodes. An AC microammeter was used to measure the leakage current $I_a$ and the Schering bridge was used to measure the dielectric loss angle $\delta$. Under an alternating electric field, the equivalent circuit model is shown in Figure 6(b). The leakage current is composed of a reactive current, a conductive current and a polarisation current. The power loss (i.e. the heating power $P$) of a unit-length sample can be calculated by Equation (3) with the phase relationship between the voltage and the current.

$$P = \frac{U_a I_a \sin \delta}{L}.$$  

$U_d$ is the constant voltage; $U_a$ is the alternating voltage; $I_c$ is the conductive current; $I_{pa}$ is the polarisation current; $I_{pa}$ is the reactive current; $R_c$ is the conductive loss; $R_p$ is the dielectric loss and $C$ is lossless polarisation.

Since the heating power $P$ is composed of the conductivity power loss $P_d$ and the polarisation power loss $P_p$, the conductivity power loss $P_d$ can be obtained under the DC and the polarisation power loss $P_p$ can be calculated by Equation (4).

$$P_p = P - P_d.$$  

### TABLE 1  Samples used in the experiment

| Sample | Pollution status | Aging | Treatment | Insulator | Operation year | Temperature rise (RH < 40%) | Temperature rise (RH > 80%) |
|--------|------------------|-------|-----------|-----------|----------------|----------------------------|----------------------------|
| A      | Contaminated     | Powdered | None      | I         | 2006          | 2.2 K                     | 15.2 K                     |
| B      | Not contaminated | Powdered | None      |           |               |                           |                           |
| C      | Contaminated     | Powdered | Cleaned   | II        | 2019          | 2.8 K                     | 7.8 K                      |
| D      | Not contaminated | Not powdered | Cleaned | II        | 2019          | 1.1 K                     | 2.3 K                      |
| E      | Not contaminated | Not powdered | Cleaned | III       |               |                           |                           |
FIGURE 7 Microstructures of the housing samples from a new heating composite insulator. (a) Surface microstructure and (b) internal microstructure

FIGURE 8 Microstructures of the housing samples from a new normal composite insulator. (a) Surface microstructure and (b) internal microstructure

4 RESULTS AND DISCUSSION

4.1 Analysis of housing microstructure

Firstly, the microstructures of the new composite insulator housing were compared. The grey value of pore area is less than 5, while the grey value of normal area is between 130 and 255. Taking the grey value of 100 as the threshold value to count the number of pixels, the porosity of the surface layer can be analysed quantitatively.

For the new composite insulator with heating at high-voltage end (i.e. insulator II), its micro-pore structures on the surface and inside the housing are shown in Figure 7. It can be seen that there are some pores on the surface of the housing and some of them are more than 10 μm in diameter and the pores are dispersed. The porosity of the surface material is about 5%. However, due to the incomplete vulcanising process inside the material, the pores were connected through cracks, which made the air diffuse more widely and the porosity is twice of that for surface material.

For the normal composite insulator without a heating phenomenon (i.e. insulator III), its microstructures are shown in Figure 8. No pore was found on the surface of the housing through 2200-time microscopic observation and the cracks caused by shrinkage and expansion did not exceed 1 μm, while there were some pores inside the material due to vulcanisation difference, but the pores were not more than 5 μm in diameter and independent of each other, so that continuous air gaps were not formed and the porosity is less than 1%.

For the heating insulator which had been in operation for more than 10 years (i.e. insulator I), the aging of the housing of different areas was significantly different. Compared with the internal material, the housing surface was seriously powdered and some areas were completely covered by contaminants. The microstructures of the contaminated, powdered, cleaned and internal areas under the 2200-time microscope are shown in Figure 9. Compared with the new sample, the aging sample had loose surface microstructures with significant cracking and the porosity is more than 6.5%. In some areas, the cracking widths were more than 10μm and the powder condition of the material on both sides of the cracks was more serious. In the contaminated areas, the housing surfaces were covered by particles and the particles were denser at the cracks, even filled part of the cracks and were transferred into the housing. The particles on the housing surfaces were significantly reduced and some pores were exposed after cleaning. The internal housing material was not powdered, but some areas were cracked under mechanical force, while the pore structure was not significant compared with that of the new heating composite insulator housing.

Through the study of the microstructures, it could be seen that the housing samples from the heating composite insulators had significant pore structures. Unlike the samples from the new insulators, the cracks on the surfaces of the aging housing and the accumulation of the contaminants on its powdered layers could further enhance the moisture absorption of the surface structures. Compared with the pore structure, the moisture on the aging surfaces was continuous and the effect on composite insulator heating was more serious under high electric field intensity. However, the aging layers were only located at the outermost areas of the housing. If the ambient humidity drops, the moisture will dissipate quickly under convection.

4.2 Analysis of moisture absorption

The percentage of absorbed moisture within 96 h of the five sample groups are shown in Figure 10.

It can be discovered that the moisture content increased rapidly within 24 h and remained relatively stable after 72 h although it still showed an increasing trend which conformed to the diffusion process described by Fick’s law. The effect of the microstructure on moisture absorption was verified and the pore structure and the aging surface layer were the key factors that enhance moisture absorption. Due to the pore structure, the absorbed moisture of the housing samples from the heating insulator was more than 0.5%, while that of the normal insulator was less than 0.15%. The aging surface layers further enhanced the moisture absorption of the housing. The absorbed moisture of the powdered housing samples was 0.7%, while the absorbed moisture of the contaminated housing sample was more than 1%.
In the high temperature and humidity environment, the moisture content of air is high. The moisture content of air at 35°C and 90% humidity is 35.56 g m\(^{-3}\). When the environment temperature decreases, the air in the pores reaches the dew point and the water condenses in the pores. The pore structure makes the surface layer contain more moist air, so that the moisture absorption enhanced significantly. The moisture absorption and greyscale of micrographs of 10 aging and new composite insulators were analysed. The experimental results and fitting curve are shown in Figure 11. As the coefficient of determination of porosity-moisture absorption closes to 1, the fitting results show that porosity from the greyscale is strong positive correlated to the moisture absorption. Therefore, the pores and cracks more than 10 μm on the surface of the housing is the main factor leading to the increase of moisture absorption. For some contaminated areas with moisture absorption more than 1%, porosity cannot be obtained through greyscale analysis because the pores and cracks were denser by particles. Compared with pores and cracking, loose structure of contaminants is more conducive to moisture absorption.

4.3 Analysis of heating power

The heating power of the housing samples before and after the 96 h moisture absorption is shown in Figure 12. The heating power increased exponentially with higher electric field intensity and became almost 10 times that of the dry state after moisture absorption. In the dry state, the heating power was generally low, but the pore structure inside the housing affected the uniform distribution of the electric fields, which made the heating power of the housing samples reach 5 mW cm\(^{-1}\) under electric field intensity of 4 kV cm\(^{-1}\) while the heating power of the samples without pore structures was less than 2 mW cm\(^{-1}\). The moisture penetration significantly increased the heating power of all samples. When the electric field intensity exceeded 4 kV cm\(^{-1}\) the heating power of the normal sample reached 25 mW cm\(^{-1}\) while the maximum heating power of the heating samples was more than 75 mW cm\(^{-1}\). Therefore, the humid environment and the concentrated electric field distribution at the high-voltage end of the insulator are the necessary conditions for the temperature rise.
Polarisation and conductivity power loss are the main components of the active power loss of the housing samples. Table 2 shows the polarisation and conductivity power loss of the three samples under electric field intensity of 4 kV cm\(^{-1}\). The experiment results showed that the polarisation power loss was far greater than the conductivity power loss, so the polarisation power loss was the key factor leading to the heating. Besides, the polarisation power loss of the housing samples from the aging insulator was similar to that of the new heating insulator after water absorption, while the conductivity power loss of the housing samples from aging insulator was greater than that of the new heating insulator due to the powdered and contaminated surface layers. However, the conductivity power loss decreased rapidly with the moisture dissipation in the aging layers, so that the heating power of the two samples reached the same level 10 min after sampling from the tank.

### 4.4 Analysis of heating mechanism

Based on the analysis of the power loss results of the housing samples with different microstructures, the heating mechanism of the composite insulator can be obtained. The dielectric constant of housing material is 3.5 and that of moisture is 78.3 at 25°C. Due to the great difference of dielectric properties between the housing material and moisture, the local field distribution will change and the maximum field strength will increase significantly as moisture in the pore. The polarisation loss of the housing material is the main source of heating energy and the electric field intensity is the main factor affecting the power loss. Because the relationship between electric field intensity and heating power is non-linear, the concentrated distribution of the electric fields at the high-voltage end and the micro local parts of the insulator housing will lead to a significant increase of the polarisation loss. When the energy lost for heat production exceeds the heat loss under the current environment, the local temperature of the composite insulator will gradually rise. Figure 13

### Table 2  Polarisation and conductivity power loss of the three samples

| Insulator | Before water absorption | After water absorption |
|-----------|-------------------------|-----------------------|
|           | Polarisation loss        | Conductivity loss      | Polarisation loss | Conductivity loss |
| I         | 0.7048 mW cm\(^{-1}\)    | <0.1 mW cm\(^{-1}\)    | 51.752 mW cm\(^{-1}\) | 22.797 mW cm\(^{-1}\) |
| II        | 4.93 mW cm\(^{-1}\)     | 24.09 mW cm\(^{-1}\)  | 48.82 mW cm\(^{-1}\) | 2.039 mW cm\(^{-1}\) |
| III       | 1.599 mW cm\(^{-1}\)    | 1.364 mW cm\(^{-1}\)  | 28.09 mW cm\(^{-1}\) | 1.364 mW cm\(^{-1}\) |
TABLE 3 Simulation results of different voltage-level composite insulators in transmission lines

| Voltage level (kV) | Grading ring size (mm) ring diameter/pipe diameter | Maximum electric field intensity (kV cm\(^{-1}\)) |
|-------------------|----------------------------------------------------|-----------------------------------------------|
|                   | Large ring (high-voltage) | Small ring (high-voltage) | Low-voltage end | String type | Shielding depth(mm) | Normal | 10 µm pore in dry state | 10 µm pore in wet state |
| 1000              | 920/120                  | 232/32                      | 500/60          | Single string | 240/32/100          | 1.653 | 2.57                      | 3.18                      |
| 1000              | 920/120                  | 400/50                      | 400/50          | Double string racetrack ring | 600/250/250 | 2.293 | 3.57                      | 4.41                      |
| 750               | 800/80                   | 160/25                      | 440/60          | Single string | 100/25/90          | 2.9   | 4.52                      | 5.37                      |
| 500               | —                        | 400/50                      | 400/50          | Single string | 50/50              | 3.891 | 6.06                      | 7.48                      |
| 500               | —                        | 400/50                      | 400/50          | Double string | 50/50              | 4.361 | 6.79                      | 8.39                      |

Based on the transmission line and the composite insulator high-voltage end model with micro-pores, the electric field intensity of the insulator end in operation is calculated with simulation software. The parameters of composite insulators of China and local electric field intensity simulation results are shown in Table 3. For 1000 and 750 kV composite insulators, the maximum electric field intensity is limited to below 3 kV cm\(^{-1}\) as the grading ring at the high voltage-end is required to be in the form of racetrack or large and small rings. However, for single 500 kV composite insulator string, its maximum electric field intensity at the high-voltage end exceeds 3.5 kV cm\(^{-1}\) and the double string reconstruction project for protecting the insulator from fractures further increases the local maximum electric field intensity. Therefore, compared with that of the composite insulators on higher-voltage-level transmission lines, the heating defect proportion of 500 kV composite insulators is significantly higher.

Besides, because the relative dielectric constants of the housing material and the air are 3.5 and 1, respectively, and the appearance of the pore changes the uniform distribution of the electric field, so that the maximum electric field intensity at the end of the composite insulator increases significantly. After the moisture occupies the pore, local electric field intensity further increases as the relative dielectric constant of moisture at 25°C is 78.3, which is much higher than those of solid materials. The moisture penetration also reduced the internal electric field intensity of the pore to less than 0.5 kV cm\(^{-1}\) so that the voltage on the housing material increased significantly. Therefore, the heating defect often occurs as humidity increases and the temperature rises of different samples are quite different. The simulation analysis in this paper only considered the influence of individual pore structures on the maximum electric field intensity, while the key factors affecting the heating power in the actual situation are more dependent on the distribution of concentrated electric field areas, which is closely related to the density of pore structures.

### 4.5 Solution to heating defect

As the pore structure inside the housing and high electric field intensity at the high-voltage end of the composite insulator are both key factors affecting heating power, the heating defect of the composite insulator can be avoided to some extent through access inspection of new products and grading ring reform projects.

For access inspection of new composite insulator products, if the micro graphs of pore structures are used as the standard, the result will not only be random due to the difference in scanning areas, but also difficult to be analysed quantitatively. The experimental results show that, the new composite insulator with absorbed moisture of the housing of less than of 0.15% has lower heating power in humid environment. Even if the grading ring has fallen off, the temperature rise at the end of the 500 kV composite insulator is less than 3 K. Therefore, the heating defect of the composite insulator of the new transmission line in humid areas can be effectively prevented through the water absorption test of the housing material.

The simulation results of electric field distribution at the high-voltage end of the 500 kV composite insulator under operating conditions are shown in Table 4. After the shielding depth of the single string was increased to 110 mm or the racetrack ring was

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**TABLE 4 Simulation results of the electric field distribution of the 500 kV composite insulators under operating condition**

| String type | Shielding depth (mm) | Racetrack ring | Electric field intensity (kV cm\(^{-1}\)) | Potential integral in 10 cm (kV) |
|-------------|----------------------|----------------|----------------------------------------|---------------------------------|
| Single string | 50                   | —              | 3.891                                  | 40.52                           |
| Single string | 90                   | —              | 3.165                                  | 34.22                           |
| Single string | 110                  | —              | 2.947                                  | 32.13                           |
| Double string | 50                   | Without        | 2.75                                   | 21.99                           |
| Double string | 50                   | With           | 4.361                                  | 34.49                           |
added to the double string, the maximum electric field intensity was not more than 3 kV cm\(^{-1}\) which is the same level as that of 750 and 1000 kV transmission lines. Through these measures, the abnormal temperature rise at the high-voltage end of the composite insulator can be effectively suppressed.

5 | CONCLUSION

The polarisation loss of the housing material is the main source of heating energy and the electric field intensity is the main factor affecting the heating power. Because the relationship between electric field intensity and heating power is non-linear, the heating power will increase significantly if the electric field distribution at the end of the composite insulator changes with the moisture penetration. When the energy lost for heat production exceeds the heat loss in the current environment, the local temperature of the composite insulator will gradually rise.

The microstructure of the housing and the form of the high-voltage end grading ring are both the main causes of the difference in temperature rises of composite insulators. The pore structure appearance not only affects electric field distribution, but also enhances the moisture absorption of the housing material, which is the cause of most new composite insulators’ heating defect. Compared with that of the composite insulators on higher-voltage-level transmission lines, the restraining effect of the grading ring of 500 kV composite insulators on higher-voltage-level transmission lines, the restraining effect of the grading ring of 500 kV composite insulators on end electric field intensity is insufficient, so the heating defect occurs frequently.

Reducing the porosity of new composite insulator housing based on moisture absorption and adjusting the form and shielding depth of the 500 kV composite insulator grading ring can solve the problem of composite insulator end heating in humid areas to a certain extent.

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