Study on the detection method of holes in composite insulator rods

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Abstract
The holes in composite insulator rods are a type of quality defects. However, not all holes can be identified by the dye penetration test according to existing standards and some holes can cause abnormal heating of the composite insulator during operation. Micro-computed tomography is used to study the structure of these holes. Based on the pore structure, the holes are classified as dependent or independent. The dependent hole is formed by several interconnected adjacent pores and the overlong equivalent penetration path makes it cannot be effectively identified by the standard dye penetration test. Considering the structure of the dependent hole, ethanol gas was used to increase the effectiveness of the dye penetration test. The experimental results show that the detection rate of dependent holes is approximately 80% as the ethanol concentration is close to saturation, and the porosity can be inferred based on the number of penetration points.

1 | INTRODUCTION

Composite insulation equipments are made from various high-grade insulating materials whose combined properties result in an improved performance. Unlike traditional insulating materials such as ceramics and glass, high temperature vulcanised silicone rubber features good antipollution flashover capability and glass reinforced polymer (GRP) has high strength and low density. The composite insulators composed of these two materials have been widely used on transmission lines [1–3]. The rod in the composite insulator is load bearing component and GRP has always been considered the most suitable material for the rod since the inception of composite insulators [4,5]. However, quality defects during the production process are inevitable. To avoid the occurrence of fracture accidents in composite insulators [6–8], the International Electrotechnical Commission (IEC) has proposed standard requirements for GRP rods [9,10]. The GRP rods used in composite insulators need to be evaluated by a sampling test before putting the products into operation [11,12].

The holes with certain axial length are a type of quality defects in GRP rod, and the existing detection tests include dye penetration tests [9,10], transparency tests [13], ultrasonic tests [14], and X-ray transmission tests [15]. Although each evaluation method has its own basis, the effectiveness evaluation requires pore structure analysis. When the difference in the X-ray absorptivity is discriminated for each pixel, the pore structure can be distinguished by computed tomography [16,17] and detection effectiveness for different kinds of holes can be discussed individually. The overall detection effectiveness can also be improved by overcoming the limitation of one certain type of hole.

The IEC has prescribed the dye penetration test as a detection method in sampling test. In this study, the inadequate effectiveness of the standard dye penetration method is demonstrated by considering an abnormal heating fault of the composite insulators. The GRP rods from three composite insulator suppliers were chosen as samples for this study based on a survey of abnormal heating faults in southern China. The rod samples sourced from different suppliers and prepared by different processes were subjected to the standard dye
penetration test and the pore structure of the samples was studied by the micro-computed tomography (micro-CT) technology. Based on the pore structure, the holes in the samples were classified as dependent or independent. The dependent holes are abundant in composite insulator with high abnormal heating fault rates. These holes are hardly detectable effectively by the standard dye penetration method owing to their winding pore structure. Finally, attempts were made to improve the existing dye penetration test by prolonging the test duration and increasing the ethanol concentration of the detection environment. The dye penetration test with an ethanol concentration close to saturation is considered to be effective for the detection of dependent holes. Further, an effective method is proposed to infer the porosity of the GRP rod based on the relationship between the porosity and the number of dye penetration points.

2 | ABNORMAL HEATING FAULT AND STANDARD DYE PENETRATION TEST

Although composite insulator products have been able to meet the IEC standard, abnormal heating faults and decay-like fracture events are still widespread [18–22]. In July 2019, a maintenance department in southern China replaced some composite insulators; however, it was observed that the replaced composite insulators seriously heated during operation. Compared to other heating composite insulators, these samples are peculiar. First, these samples are new products, thus the influence of aging on operation can be eliminated. Furthermore, the heating extends from the high-voltage end to the middle of the insulator. Previous studies [22–24] reported that the heating fault is caused by polarisation loss and the high intensity of the local electric field primarily contributes to the temperature rise. Under normal conditions, the field strength at the middle of the composite insulator is sufficiently low, and the electric field is concentrated at the high voltage end. However, if internal paths exist inside the rod, the electric field intensity at the corresponding region increases significantly, which causes the section heating of the composite insulators. Finally, the dissection results show that the interface of the heating area is well bonded; therefore, the internal paths connecting the end and middle of the insulator should be located in the rod. However, the standard dye penetration test reveals no dye penetration in the rods of these two composite insulators (shown in Figure 1). Tests on the heating insulators show that the effectiveness of the existing dye penetration test is inadequate. In order to avoid the heating faults caused by holes in composite insulator products, it is necessary to propose a more effective test method.

3 | EXPERIMENTAL DESIGN

3.1 | Experimental sample

The rod samples used in this study are shown in Table 1. In order to evaluate the effectiveness of the standard dye penetration test, the rods used by suppliers A, B, and C were selected as the samples I, II, and III. Further, to study the influence of production processes on the structure of holes, samples IV, V, and VI were prepared with the injection and dipping method.

Reports from the maintenance department show that some 500 kV transmission lines in southern China, which have an operating service life of less than four years, exhibited abnormal heating faults. The suppliers of the composite insulators in these transmission lines are A, B, and C. Among the 408 composite insulators that were examined through the infrared temperature measurement, 131 insulators were identified as possessing emergency defects (Delta-T > 5°C), 80 insulators were identified as possessing major defects (3°C < Delta-T < 5°C), and 173 insulators were identified as possessing general defects (1°C < Delta-T < 3°C). The heating rate was more than 90%. The temperature threshold of the different defect grades is based on the field experience. In southern China, the heating grade is used to implement maintenance measures. Additionally, there are also four cases of composite insulator decay-like fracture events in the 500 kV transmission lines in this area; the shortest operation time among these fractured composite insulators is only one year. This type of fracture is usually associated with abnormal heating and the hydrolysis of the epoxy resin of GRP rods [19–21]. The number of faulty composite insulators from suppliers A, B, and C is shown in Table 2 according to the heating grades and decay-like fracture events. The composite insulator products from suppliers A and B present more abnormal heating faults and experience decay-like fracture accidents during operation, while those from supplier C present less abnormal heating faults, with no incidences of decay-like fracture.

Injection and dipping are the main production processes for preparing composite insulator GRP rods. Sample IV was fabricated by injection. In the injection process, liquid epoxy resin is directly injected into the mould under a negative pressure so that minimal gas remains in the rod products. Samples V and VI were fabricated by dipping. In the dipping process, the glass fibre is dipped into liquid epoxy resin, and both are pulled into the mould together to form the rod. Owing to the inherent form of the insulator rod, its performance depends on two key factors. One is the increase in the viscosity of the epoxy resin. The other is that some glass fibres may not be fully dipped. To study the influence of these two factors on the pore structure of the rod, the last batch of the rods was selected as sample V before the replacement of liquid epoxy resin, following which sample VI represented rods whose glass fibre was not fully dipped.

Referring to the requirements of the IEC-62217 standard, the rod used in the dye penetration test was processed to 10 mm, and the number of each kind of sample was 10. Due to the limited penetrability of X-rays, the samples for dye penetration cannot be directly tested by the micro-CT. After determining the sampling position, the rod material was extracted using a hollow drill of 1.5 mm diameter. The length for a single extraction was approximately 3.3 mm, so that the rod material in each position was extracted thrice. The scanning results were processed by software to restore the overall structure.

3.2 | Dye penetration test

The detailed procedure of the dye penetration test is provided in the IEC-62217 standard. In line with the requirements of
the standard, the specimens were placed (long axis of the insulator vertical) on a layer of steel balls of diameter 1 mm. A solution of 1% (by weight) fuchsin in ethanol was poured into the vessel, and its level was 2 to 3 mm higher than that of the steel balls.

Prolonged test duration and a higher condensation of ethanol in air were used to promote dye penetration. While the IEC standard does not stipulate an ethanol concentration for the test environment, the tray is recommended to be used in the test (shown in Figure 2a). The relative concentration of ethanol was measured by gas chromatography analysis, and the air 2 cm above the tray was collected to analyse the ethanol concentration. In the flowing air condition, the concentration of ethanol is close to 0, in the static air condition, the concentration of ethanol is approximately 0.5% of the saturation value. A sealed transparent box was used as the vessel to increase the ethanol concentration in the test environment (shown in Figure 2b). Due to the volatility of ethanol, the ethanol concentration in the box reached close to saturation after 5 min. The dye penetration tests were conducted using a sealed transparent box and tray under a flowing air condition to study the effect of ethanol concentration on dye penetration. The standard penetration time prescribed in IEC-62217 is 15 min. To improve the effectiveness of the test, the penetration time was set to 120 min and the dye penetration test was carried out with a tray under a flowing air condition.
To compare the detection effectiveness, the rod samples need to be repeatedly used under different penetration conditions. To this end, the existing dye penetration traces on the upper end of the surface were removed by polishing and the samples were dried for 24 h before the next dye penetration test.

3.3 | Analysis method of pore structure

The surface microstructure of the GRP rod is typically observed with a scanning electron microscope [21] and metallographic microscopy [25,26]. Because the fragility of the glass fibre makes it impossible to make slices, using the same techniques to analyse the holes inside the rod is difficult.

Although three-dimensional imaging is a better solution, the pixel size should be much smaller than the pore diameter, and the pixel extraction method must be effective for different substances.

It is known that the diameter of the glass fibre used in GRP rods is 16 μm. The glass fibre and epoxy resin are distributed alternatively in the rod, increasing the requirement of resolution to beyond 10 μm. The imaging of traditional industrial CT is based on the geometric projection principle (shown in Figure 3a). The resolution of this method is in the range of 10–100 μm, which cannot meet the detection requirements of the rod. A novel micro-CT system uses an additional high-resolution lens-coupled detector based on geometric projection (shown in Figure 3b). Under 20-fold optical magnification, the theoretical resolution can reach up to 500 nm and the spatial resolution can reach up to 2 μm when a CCD camera with 10 μm pixels is used for recording [27,28].

The X-ray absorption capacity of glass fibre is the highest, while those of epoxy resin and pores are low. During the pixel extraction process of different substances, there is a clear boundary between the glass fibre and epoxy resin; however, the threshold value of the epoxy resin and pore needs to be determined based on the ratio of grey value. A threshold of 2.5% of the maximum grey value of the epoxy resin was used to determine the pore boundary in the analysis. Although the boundary described by the threshold is not sufficiently accurate, it provides a reference to study the porosity. The scanning results of three samples in the same sampling position were processed using a software, to restore the overall structure. The entire structure composed of adjacent air pixels was defined as a pore and extracted. The pores contacting both the upper- and lower-end pixels were considered as holes.

4 | RESULT AND DISCUSSION

4.1 | Standard dye penetration test

The results of the standard dye penetration test are shown in Figure 4. No dye penetration point was found on the upper end surface of rod samples I–V in 15 min, while 6 out of 10 rods in sample VI showed severe dye penetration.

Among rod samples I–III, which passed the standard dye penetration test, one rod sample was randomly selected, and its end surface was divided into four areas according to the quadrant method. The samples with a diameter of 1.5 mm were randomly selected for micro-CT analysis in each quadrant area; the experimental results are shown in Table 3. For rod sample I, the test samples of each quadrant area contain a hole. For rod sample II, only the test sample of the third quadrant contains a hole. For rod sample III, no test sample contains a hole.

The results show that only the not fully dipped rod samples of type VI can be identified by the standard dye penetration test; however, such defect seldom occurs in existing composite insulator products. Most of the holes cannot be identified by standard dye penetration test, whereas the micro-CT technique is an effective method for identifying the hole in the local area of the rod. The micro-CT results show that the rods sourced from composite insulator suppliers whose products with high heating fault rates have more holes. By improving the effectiveness of hole detection, the heating fault rates of composite insulators in southern China can be reduced to certain extent.
4.2 | Pore structure analysis

The X-ray tomography area of the third quadrant of rod sample I was used to analyse the pore structure in the rod. The section and three-dimensional images of the hole in the scanning area are shown in Figure 5. It is observed that the hole is composed of pore structures with a certain aperture and axial length in the rod. The pores are randomly distributed, and the aperture and axial length of the pores are significantly different. The section image shows that some adjacent pores are interconnected with each other. The overall structure of the hole, formed by interconnected pores, has a diameter of more than 350 μm, with a length running through the scanning area. The holes in other scanning areas are also formed by interconnected pores.

The distributions of all pore structures in the third quadrant scanning area of rod samples I–III are shown in Figure 6a–c. In the three-dimensional image, the yellow and blue pixels represent the pores with and without holes, respectively. It is observed that the porosities of rod samples I and II are significantly higher than that of rod sample III. The statistical pixel results show that the average porosities of rod samples I and II are 1.83% and 0.55%, respectively, while that of rod sample III is only 0.015%. The average numbers of pores with diameters more than 10 μm in rod samples I and II are 8694 and 3472, respectively, while that of rod sample III is only 67.

The micro-CT samples were randomly selected from rod samples IV and V and the distribution of all the pore structures is shown in Figure 6d–f. It can be seen from the figure that there are no holes in the scanning area. The porosity of the scanning area in rod sample IV is 0.055%. The pores are concentrated at the area where the epoxy resin is accumulated, and the axial length of the pores is small. The porosity of the scanning area in rod sample V is 0.078%. Although the porosity is slightly higher than that of rod sample IV, the pores are distributed throughout the scanning area and the axial length of the pores is greater.

The position of the holes in rod samples VI had been determined in the standard dye penetration test. Thus, micro-CT samples can be directly collected from the dye penetration position. The distribution of all the pore structures in rod sample VI is shown in Figure 6f. Although the porosity of the scanning area is low, it can be seen from the figure that there is structure like cracking formed by pores side by side. Compared to scanning areas of I and II, there were more than 30 holes in the scanning area of rod sample VI. Although some holes are formed by interconnected pores, more pores run throughout the scanning area independently.

By analysing the pore structure in the different rod samples, the holes are classified as dependent or independent. The dependent hole is formed by several interconnected adjacent holes. On the premise that the positions of the head and end of the hole are different, the more the interconnected pores that exist, the longer the overall structure is. Therefore, porosity is a key factor in the formation of a dependent hole. The independent hole is formed by a pore that can run through the upper- and lower-end surfaces independently. Its formation mode is related to the not fully damped defect of the glass fibre.

Considering the structural difference of holes, the effectiveness of the standard dye penetration test can be analysed. Based on the capillary effect, the general trend of dye penetration is bottom-up. The appearance of dye permeation depends on the establishment time of the liquid channel in the hole. For independent holes, as shown in Figure 7a, the dye solution can run through the sample directly in a single pore,
which implies that the equivalent penetration path is the length of the sample and the liquid channel can establish in a short time. On the other hand, because there are many holes located in the same area, dye penetration is prominent. For dependent hole, as shown in Figure 7b, the dye solution has to run through several connecting holes. The equivalent penetration path is the sum of the length of all holes, whereas the effective liquid channel is only one. Assuming that the penetration rate is the same, the dye permeation in dependent holes requires more time and is difficult to observe.

The production process has a major influence on the formation of holes. Compared to the dipping process, the rod produced by the injection process does not have independent hole formed by the not fully dipping of glass fibre, and the porosity is generally low. Even if pores exist due to the accumulation of epoxy resin, the occurrence of dependent through holes is rare due to the limitation of the length of the pore. For the dipping process, if the viscosity of the epoxy resin and the dipping of the glass fibre are not controlled effectively, it is impossible to avoid the formation of the two types of holes in the rod.

4.3 Improved dye penetration test

Based on the existing standard, the dye penetration time was prolonged to 120 min, and rod samples I–III were used for the test. The test results are shown in Figure 8. Because the equivalent penetration path of dependent hole is longer than the length of the sample, the edge permeation begins before internal penetration. It can be seen that edge penetration occurs in all rod samples. Although some samples exhibit the internal penetration, more areas of the samples are covered by the dye solution via edge penetration. Only prolonging the duration is not an effective measure to improve the detection effectiveness of dependent holes.

The results of dye penetration, in a saturated ethanol environment, are shown in Figure 9. Penetration of the dye solution was apparent after 5 min, and the number of penetration points did not increase after 10 min. Therefore, the penetration time not needs to be prolonged, and no edge penetration occurs during the dye penetration test. The number of dye penetration points was calculated after 15 min, to be 42–53 in rod I, 5–10 in rod II, and none in rod III. The statistical results of dye penetration points in rod samples from different suppliers are consistent with the micro-CT results shown in Table 2. To verify the effectiveness of the dye penetration test in saturated ethanol environment, 10 areas without dye penetration were rechecked with the micro-CT. The results show holes only in two areas. It can be inferred that the detection rate of dependent hole is approximately 80%.

To confirm that the dyeing areas on the test samples are formed by penetration in the rod, rather than condensation of ethanol with the dye, another experiment was carried out. Theoretically, the penetration is related to the position of the hole, while condensation is related to the surface state. If the upper-end surface of the sample is polished, the position of the hole remains the same, and only the surface state of the upper end changes. Therefore, the source of the dye can be traced by observing whether the position of the dyeing area is consistent before and after surface polishing. A rod sample with dyeing area was selected, and the letter “B” was written on its upper-end surface as a reference position. All dyeing areas around the letter “B” were removed by polishing, and the dye penetration test was conducted again in the same condition. The results of the two dye penetration tests are shown in Figure 10. As the position of dyeing areas is the same, the dye on the test samples is confirmed to originate from the holes.

The ethanol gas increases the effectiveness of dye penetration and the schematic of dye permeation process is shown in Figure 11. The ethanol gas in the detection environment could diffuse into the hole rapidly, without being limited by the pore.
structure. Further, the condensation of ethanol gas accelerated the formation of liquid channels. Although the liquid channel formed by condensed alcohol does not contain fuchsin, the diffusion of the solvent in the liquid can be realized in a short time. The absolute and relative saturation values of ethanol concentration in air are important and affect the condensation process. On the one hand, the formation of liquid channels requires sufficient ethanol such that a high absolute value is required. On the other hand, a temperature lower than the dew point is the trigger condition for condensation. When the concentration of ethanol is close to the saturation value, the dew point temperature is close to the ambient temperature; thus, ethanol gas can condense under the influence of ambient temperature fluctuation.

In addition to the hole structure, the other pores in the rod could affect the water absorption, breakdown strength, and electric field distribution. Moreover, with the decomposition of epoxy resin, new holes could be formed during the operation of the composite insulator. Although the micro-CT can be used to detect the porosity of the local area in the rod, it is hard to apply in the overall assessment, as the cost of sampling inspection will increase significantly. Therefore, a more efficient detection method for porosity is needed in the sampling test.

Based on the formation mechanism of holes, the porosity is dependent on the number of penetration points. If one assumes that the position of the pores is random, the higher porosity can lead to the higher probability of the formation of dependent holes. The relationship between the porosity and the number of penetration points of rod samples I–III is shown in Figure 12. As the scatter distribution for the same rod sample is concentrated, the relationship between the porosity and the number of holes can be analyzed. When the number of dye penetration points is more than 40, the porosity of the mandrel is greater than 1.5%. When the number of dye penetration points lies between 15 and 40, the porosity of the mandrel ranges between 1% and 1.5%. When the number of dye penetration points is not more than 15, the porosity of the mandrel ranges between 0.25% and 1%. If there is no dye penetration, the porosity of the mandrel is less than 0.25%.

5 | CONCLUSION

Rods from composite insulator suppliers whose products have higher heating fault rates have more dependent holes and higher porosity. However, the standard dye penetration test is not sufficiently effective to identify dependent holes.

The holes in the rod can be classified as dependent or independent according to the formation mode. The dependent hole is formed by several interconnected adjacent pores. Because the number of the effective liquid channel is less and
its equivalent penetration path is the sum of the lengths of all structural holes, which is much greater than the length of the sample, the dye permeation of the dependent hole requires more time and is difficult to observe. However, because of the influence of edge penetration, prolonging the test duration cannot adequately meet the test requirements.

The ethanol gas can increase the efficiency of the dye penetration test. The detection rate of dependent holes is approximately 80% under a saturated ethanol environment, and the porosity can be inferred based on the number of penetration points.

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