Study on dimensions of void in GRP rod of composite insulator

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Abstract. As an important part of composite insulator, glass fiber reinforced polymer (GRP) rod needs to bear the main mechanical and keep certain insulation performance. The void in the material is key factor to the performance of GRP rod. The void with larger size could affect the electric field distribution significantly and lead to the “Lantern-like” heating. In this paper, the structure of void in GRP rod is studied by 3D X-ray microscope. It is found that the void dimensions in the GRP rod is generally less than 300μm, but the interconnection of linear hole makes the length of the void increase significantly. For the GRP rod with high porosity, the length of connection hole is hard to be detected directly by the existing technology, but it could be calculated based on the diameter of the hole. Based on the calculation method, the dimensions of void in GRP rod could be inspected by the observation of section using optical microscope.

1. Introduction

Compared with traditional insulation equipment such as ceramic and glass insulators, composite insulator composed of high-temperature vulcanised silicone rubber (HTVSR) and glass fibre reinforced polymers (GRP) have the advantages of anti-pollution flashover, high strength, and low density [1-3]. The rod in the composite insulator is the main carrier of axial tension load, and GRP has always been considered the most suitable rod material since the birth of the composite insulator [4]. However, void defects are inevitable for the production process of GRP material are inevitable [5-6]. The axial channels composed by void defects in GRP rod could affect the electric field distribution significantly and lead to the “Lantern-like” composite insulator heating defects at the early stage of operation [7]. It is necessary to propose an effective methods to inspect the void dimensions in the GRP rod.

The existing detection tests for dimensions of void in composite insulator GRP rods include the dye penetration test [8-9], transparency test [10], ultrasonic test [11], and X-ray transmission test [12]. Although each evaluation method has its own basis, their effectiveness is limited to the analysis on the void structure. For the material of GRP rod, the diameter of glass fiber is 14~20 μm and the distance between the fiber usually does not exceed the glass fiber diameter, so that the dimensions of void should be less than 15 μm [13]. In order to accurately describe the void structure and calculate the void size, the 3D scanning is necessary and the pixel unit of the scanning device need to be less than 2 μm.

In this paper, an analysis method of void structure was proposed based on X-ray microscope and the interconnection of void has been proved to be the main reason for the formation of large-size holes.
Furthermore, the calculation method of the length of connection hole was proposed based on the relationship between diameter and length. Finally, it is demonstrated that the dimensions of connection hole in GRP rod could be inspected by the observation of section using optical microscope.

2. Analysis method of void structure
X-ray computed tomography is the basis of three-dimensional imaging. For this method, the material properties of each pixel unit could be distinguished by the difference of X-ray absorptivity. For a single material with small volume, its X-ray absorption coefficient expression is shown in equation (1). \( a \) is a parameter with weak energy dependence and \( b \) is a constant. \( E \) is the energy of X-ray, which is depended on the wavelength of the electromagnetic wave. \( \rho \) and \( z \) are the density and atomic number of the material respectively.

\[
\mu(E) = \rho \left( a + b \frac{z^{3.8}}{E^{3.2}} \right)
\]

As X-ray with determined radiation intensity \( I_0 \) penetrates a substance through a path \( L \), the X-ray intensity detected by the detector without scattering is shown in equation (2). By multi-dimensional scanning of the object and solving the multivariate equations, the three-dimensional model of the sample could be constructed based on absorption coefficient of each pixel unit. However, the imaging resolution of Micro-CT system with geometric magnification only reach 2~3 μm, which could not meet the analysis requirements of the void structure in GRP rod.

\[
I_0(L) = I_0 \exp \left(-\int \mu(x,E) \, dL \right)
\]

In order to get higher magnification, the optical principle is proposed for secondary amplification, known as X-ray microscope. The image formed on the X-ray detector is observed with an optical microscope and recorded with a high-resolution camera (as shown in figure 1). Under 20-fold optical magnification, the theoretical resolution can reach up to 500 nm and the spatial resolution can reach up to 2-3μm when a CCD camera with 10 μm pixels is used for recording [14].

![Figure 1. Schematic diagram of X-ray microscope.](image1)

![Figure 2. Grayscale image of X-ray microscope.](image2)

Although the principle of optical microscope improves the resolution significantly, the three-dimensional model of the sample could not be constructed based on absorption coefficient of each pixel unit anymore. Moreover, the imaging from X-ray detector is different from that of scanning electron microscope (SEM). When X-ray penetrates the sample, it scatters at the boundary of different materials, thus forming a transition region in the projection (as shown in figure 2). Due to there are large number of interfaces in the GRP rod, it is difficult to form characteristic peaks based on the gray value of pixels. In order to get the actual volume ratio of fiber to epoxy resin, we made thermos-gravimetric analysis (TGA) of GRP rod material and obtained corresponding gray value range of glass fiber and epoxy resin. In equation (3), \( m_f \) is the gray value range of the glass fiber pixel, \( M_f \) is threshold of glass fiber and epoxy pixel unit, \( M_{\text{max}} \) and \( M_{\text{min}} \) are the maximum and minimum gray value of the solid material.
\[ m_f \in \left[ M_f, M_{\text{max}} \right] \quad M_f = (M_{\text{max}} - M_{\text{min}}) \times 23.7\% + M_{\text{min}} \quad (3) \]

The void in the GRP rod is composed of gas molecules, so that its X-ray absorption coefficient as well as gray value is close to 0. Although the X-ray will scatter at the boundary between the void and the solid material, making the gray value of some void pixels increase, the gray value is still far less than the solid material itself. Because of this, the pixel unit with gray value of \((0, M_{\text{min}} + 3)\) are used as the model building of the void.

3. Void structure and dimensions

According to void structure, the hole in GRP rod can be divided into linear hole and spherical hole. As shown in figure 3, the number of linear hole far exceeds that of spherical hole. The length and section diameter of spherical hole are about 70 μm and 115 μm, while the length and section diameter of linear hole are about 10 μm and 260 μm.

![Figure 3. Linear hole and spherical hole in GRP rod.](image)

The interaction of these two type of void is totally different. For spherical hole (as shown in figure 4), even if some voids are very close to each other, the voids are not interconnected. For linear hole (as shown in figure 5), its extension direction is consistent with that of glass fiber, but there is a certain deviation from the rod axial direction. Therefore, as the porosity of GRP rod increase, there will be a large number of voids connected with each other.

![Figure 4. The interaction of spherical hole in GRP rod.](image)  
![Figure 5. The interaction of linear hole in GRP rod.](image)

The number of linear holes (include independent and connection hole) in samples with different porosity is shown in figure 6 and figure 7. As the porosity lower than 0.1%, the number of independent holes with 10 μm will less than 50 and the connection hole will not form. As the porosity over 0.5%, the number of independent holes with 2 μm and 10 μm exceeds 500000 and 25000 respectively.
Figure 6. The number of independent holes in samples with different porosity.

Figure 7. The number of connection holes in samples with different porosity.

For the axial positions of the linear holes are generally different, the axial length of the whole structure will increase significantly as the linear holes are connected with each other. The dimensions of connection holes are shown in figure 8.

Figure 8. The dimensions of connection hole.

The section diameter and length of connection hole is generally more than 20 μm and 200 μm. For the largest connection hole intersects the entire scanning area, its length could not be inspected directly. However, due to the connection hole is formed by the random connection of adjacent linear holes, the relationship between the diameter and the length satisfies the statistical law. It can be seen from the Figure 8, the upper limit value $L_{\text{max}}$ and the lower limit value $L_{\text{min}}$ of the length of connection hole meet the equation (4) and equation (5) respectively. The proportion of voids whose length exceeds the upper and lower limits shall not exceed 5.3%. For the diameter of the largest connection hole in Sample I is 351 μm, the length of the void shall be 1702~6318 μm.

\[
L_{\text{max}} = 18d
\]  
\[
L_{\text{min}} = 4.85d
\]

4. Inspection method of connection hole

Due to the length of connection hole satisfies the statistical law and always over the scanning area of X-ray microscope, the observation of section by optical microscope should be a better method for GRP rod inspection. In this paper, the Sample I was processed to 1 mm and the position of the connection hole was determined by dye penetration test. The section of connection hole taken by optical microscope is shown in Figure 9. Since the diameter of the void is about 200 μm, the length of the void should be 970~3600 μm. This calculation result was demonstrated by dye penetration test of adjacent slice sample.
5. Conclusion

- The void in GRP rod can be divided into linear hole and spherical hole. The void dimensions in the GRP rod is generally less than 300μm, but the interconnection of linear hole makes the length of the void increase significantly.
- Due to the connection hole is formed by the random connection of adjacent linear holes, the relationship between the diameter and the length satisfies the statistical law.
- The largest connection hole will intersect the entire scanning area as the porosity increase. Based on the relationship between the diameter and the length, the dimensions of connection hole in GRP rod could be inspected by the observation of section using optical microscope.

Acknowledgments

The authors thank Economic and Technological Research Institute of State Grid Hubei Electric Power Co.

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