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A method for measuring surface electric field intensity of insulators based on electroluminescent effect

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Abstract

The measurement for the surface electric field intensity of insulators based on electroluminescent effect is a non-contact measurement. By spraying a coating of epoxy paint mixed with ZnS:Cu electroluminescence powder on the surface of insulators, the part with high surface electric field intensity would be the first to glow. As the applied voltage increases, the area of luminous and the brightness increase. Therefore, the surface electric field distribution can be deduced by photographing and analyzing the luminescence of insulator surface coating. This method has successfully measured the surface electric field intensity distribution of disc insulators in GIL. Without the use of electric field probe, this method eliminates the electric field distortion caused by the probe completely. Besides, the permittivity of the coating can be decided according to the permittivity of the insulator material, and so eliminate the electric field distortion caused by the coating. The measure results of this method are in good agreement with reality.

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Keywords: Electroluminescent effect; Insulator; Surface electric field intensity measurement; Non-contact measurement

1. Introduction

The measurement of surface electric field intensity plays a crucial role in insulator design [1,2]. At present, the design of insulator mainly depends on simulation to check its surface electric field intensity [3]. However, it is also important to verify by experiment whether the actual surface electric field intensity distribution of insulator is consistent with the simulation results, so as to realize the optimal design of insulator structure.

Recently, using electric field probe is the most common way to measure the surface electric field intensity of insulator [4–6]. Rong Zeng et al. designed and used an integrated electro-optic sensor to measure impulse electric

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Nomenclature

Gray	Gray value
R, G, B	The red, green and blue levels of color image
E	Electric field intensity (kV/mm)
U	Voltage (kV)
x, y	Coordinates (mm)

field intensity [7]. Xu Kong et al. developed a one-dimensional norm detector for nanosecond-level transient electric field measurement based on digital measurement technology [8]. Binxian Lu et al. proposed a measurement method for the electric field intensity on the metal surface of high-voltage equipment [9]. However, the electric field probe would distort the original surface electric field distribution of the insulator, resulting in a large measurement error. A. Kumada et al. mentioned auto-compensated induction probes of electrostatic voltmeters to improve the performance [10] Nevertheless, there is an urgent need for a method to obtain the surface electric field intensity distribution of insulators accurately [11].

Electroluminescent effect is a kind of solid material luminescence in which electrons and holes compound and then emit light under the excitation of high DC or AC electric fields [12,13]. It can convert electricity directly into light energy. This effect has been mainly used in photoelectric display field since discovered [14]. By adding different doping material, ZnS electroluminescent device would glow with different colors [15–17]. Winscom et al. introduced a review on ACPEL devices and introduction to different approaches of introducing CCM for tuning of emitted light color [18]. With high efficiency and short response time, electroluminescence devices have great application prospects in full-color display.

The electroluminescent effect has been applied to voltage measurement since 1970s. F. Baudoin et al. took polyethylene as an example to build a bipolar charge transport model and explained the mechanism of electroluminescence from the microscopic view [19]. Tadeusz Pustelny and Barbara Pustelny mentioned the applications of electroluminescent effect in measuring power frequency electric field [20]. C. S. Li et al. introduced a voltage sensor based on electroluminescent effect and the way to eliminate the influence of temperature [21].

In this paper, we discuss an experimental method for measuring the surface field intensity distribution of insulators by electroluminescent effect, and verify the accuracy and efficiency of this method by measuring the surface electric field intensity distribution of disc insulator between coaxial cylindrical electrodes. This method is of vital importance to the measurement of surface electric field intensity distribution and even the design of insulator structure.

2. Method

This chapter introduces the experimental platform for measuring surface electric field intensity of insulators, and provides the experimental methods to measure surface electric field intensity distribution basing on electroluminescent effect.

2.1. Experimental platform

The disc insulator is placed between coaxial cylindrical electrodes to simulate its actual working condition in GIL. The radius of the intermediate high voltage electrode is 20 mm and the inner radius of the grounding shell is 60 mm. Since ZnS:Cu electroluminescent powder has an luminescence threshold electric field intensity of about 1 kV/mm, we need to apply a higher voltage to make the electroluminescence more obvious. Therefore, an inflatable high voltage gas chamber as shown in Fig. 1 is designed to avoid insulators flashover. The outside of the cylindrical gas chamber is grounded, and the top of which is connected with bushing to apply high voltage to middle electrode, while at the bottom there is a transparent observation window to observe the electroluminescence of insulator surface coating.

Fig. 1 shows the connection of the experimental platform. One output end of the test transformer is grounded, and the other one applies high voltage to gas chamber through a protective resistance. Using a voltage regulator to

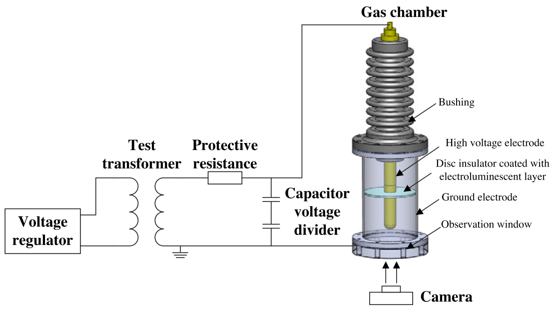

Fig. 1. The connection of the experimental platform.

control the voltage amplitude of test transformer. A capacitor voltage divider is connected with the gas chamber in parallel, and a camera is fixed directly under the chamber to photograph the electroluminescence on the insulator surface through the observation window. The aperture of the camera is f4.0, with an ISO of 400 and 30-second exposure.

2.2. Experimental methods

This part introduces the experimental methods to measure surface electric field intensity distribution basing on electroluminescent effect.

Firstly, it needs to spray a coating of epoxy paint mixed with ZnS:Cu electroluminescence powder in the surface of insulators. ZnS:Cu electroluminescent powder also glows under ultraviolet radiation, so spraying can be done under ultraviolet light to monitor the effects of spraying in real time and ensure it is uniform. Besides, the coating should be thin enough to reduce the surface electric field distortion, and its permittivity should be the same as the insulator as far as possible. The material of both the coating and the insulator is epoxy in this paper, whose relative permittivity is 4.5.

Then apply voltage to the insulator to make its surface coating glow, and photograph the luminescence phenomena of the insulator under different voltages.

According to those pictures about the luminescence phenomena of the insulator, the surface electric field intensity distribution of the insulators could be deduced finally.

The algorithm of deducing electric field distribution from images is introduced as below:

In the process of voltage increasing, the part of insulator that has high surface electric field intensity will glow first, and the brightness area would increase. In order to deduce the surface electric field distribution of insulator, we firstly convert the color image to grayscale image and use gray scale to represent luminance:

$$Gray\left(x,y,U\right)=\frac{\left(R\left(x,y,U\right)+G\left(x,y,U\right)+B\left(x,y,U\right)\right)}{3} \tag{1}$$

Then select the calibration point (x_0, y_0), assuming that the electric field intensity is proportional to the applied voltage at the same position, which is:

$$E\left(x_0,y_0\right)=kU \tag{2}$$

Where k is a coefficient whose value would only affect the inversion results.

The grayscale depends on electric field intensity:

$$E\left(x_0,y_0\right)=f\left(Gray\left(x_0,y_0,U\right)\right) \tag{3}$$

By combining Eqs. (2), (3) and the gray value of the calibration point under different voltage, we can get the relation function f between electric field intensity and gray scale.

The solution of the relation function between electric field intensity and gray scale mentioned above is solved by simulation. But the relation function f also can be solved by making insulator blocks for calibration, spraying the same electroluminescence coating as the insulator sample on its surface and using plate electrode to apply voltage to it.

According to the relationship between electric field intensity and the gray scale, taking the gray data under a certain voltage U_1 and then can obtain the surface electric field distribution of the insulator under U_1:

$$E(x, y, U_1) = f(Gray(x, y, U_1)) \tag{4}$$

3. Results

After building an experimental platform as shown in Fig. 1, apply voltage to the chamber whose value increase gradually from 0 kV to 48 kV at intervals of 1 kV. Fig. 2 shows some of the results. The part near the intermediate electrode has a higher electric field density, which would start to glow when the applied voltage is 20 kV. With the increase of voltage, the area of luminous and the brightness for the same place increase. There is a bright ring on the outermost part of images, which is caused by the reflection of the cylinder wall but not the electroluminescence of insulator. This phenomenon is the most obvious in Fig. 2(h).

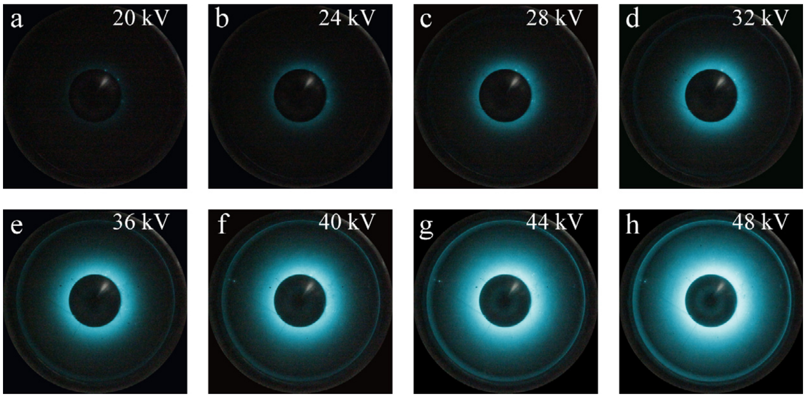

Fig. 2. The electroluminescence under different voltage (a) 20 kV; (b) 24 kV; (c) 28 kV; (d) 32 kV; (e) 36 kV; (f) 40 kV; (g) 44 kV; (h) 48 kV.

According to Eq. (1), convert the color image Fig. 2(h) into grayscale image Fig. 3. Since the structure of the disc insulator is axisymmetric, only one line of the radius is taken for analysis here. The locations of the sampling points have been indicated in Fig. 3 and the point with relatively high brightness is chosen as the calibration point, which is the red point in the figure.

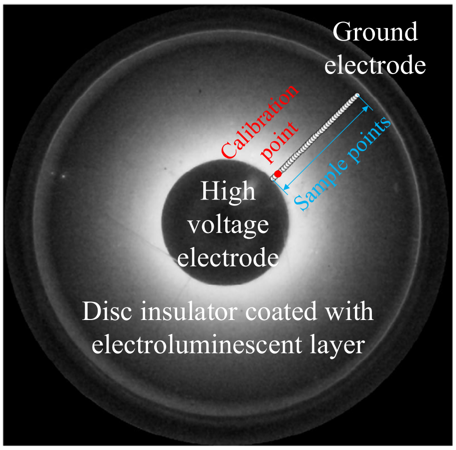

Fig. 3. Grayscale image (U = 48 kV).

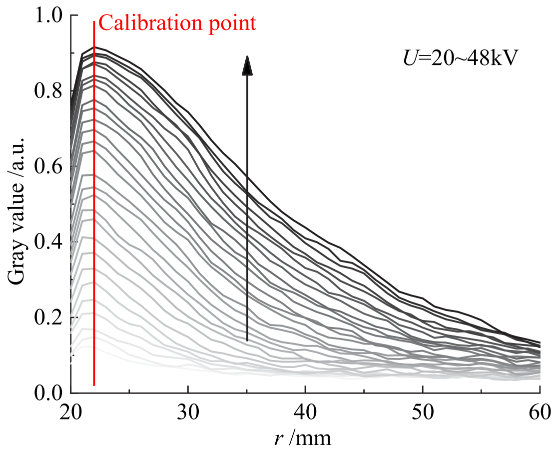

Fig. 4. The gray value of sampling points (U = 20∼48 kV).

Fig. 4 shows the gray value of sample points at 20∼48 kV. In order to avoid the interference of camera noise, the gray value of one sample point is obtained by averaging the value of several surrounding pixels. As Fig. 4 shows, the gray value of each point increases when the voltage increases. The gray value of points that near the high voltage electrode is higher, indicating that the electric field intensity here is higher. In Fig. 4, the points on the red line are the gray scale of calibration point (x_0, y_0) at different voltages.

The disc insulator has a simple structure, and its surface electric field intensity has an analytical solution:

$$E\left(r, U\right) = \frac{U}{r \ln \frac{R_2}{R_1}} \tag{5}$$

So we can get the electric field intensity at the calibration point is 0.827 kV/mm when the voltage is 20 kV. On the basic of the gray value of the calibration point at different voltages, the relationship between gray scale and electric field intensity can be obtained and shown in Fig. 5.

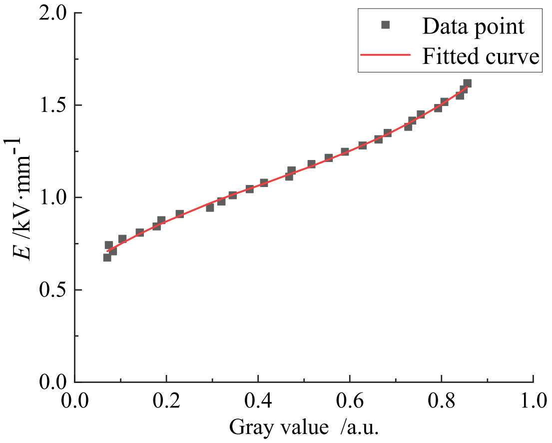

Fig. 5. The calibration results of gray scale and electric field intensity.

Put the gray value of 48 kV into the relationship of grayscale and electric field intensity showed in Fig. 5, the electric field intensity distribution can be deduced and the results is shown in Fig. 6.

As shown in Fig. 6, the surface electric field intensity of the disc insulator is measured with an error within 6% when the radius at the range of 25 mm to 55 mm.

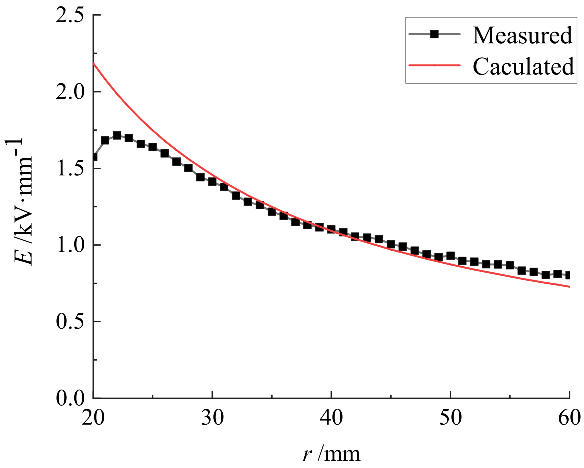

Fig. 6. The measurement results of electric field intensity (U = 48 kV) .

Within the radius of 20 mm to 25 mm, the measurement error is relatively large. It is probable that this part is near the high voltage electrode, so its electric field intensity and the brightness are higher, leading to a larger gray value. While the relationship between gray scale and electric field intensity is more sensitive to high gray level, which is shown at the right terminal of the curve in Fig. 5. So the slope of the curve would be high when the gray value is large, which leads to the relatively large error of the calculation of electric field intensity here.

The measurement error is also relatively large within the radius of 55 mm to 60 mm, which might because that this part is near the ground electrode and the inside wall of the chamber is smooth so it would reflect the glow of the insulator surface coating. The reflection makes the brightness near the ground electrode higher so the results of electric field intensity deduction would be higher and causes a larger error.

With the relationship of grayscale and electric field intensity showed in Fig. 5, convert Fig. 2(h) into electric field intensity map, the comparison with the calculated results is shown in Fig. 7.

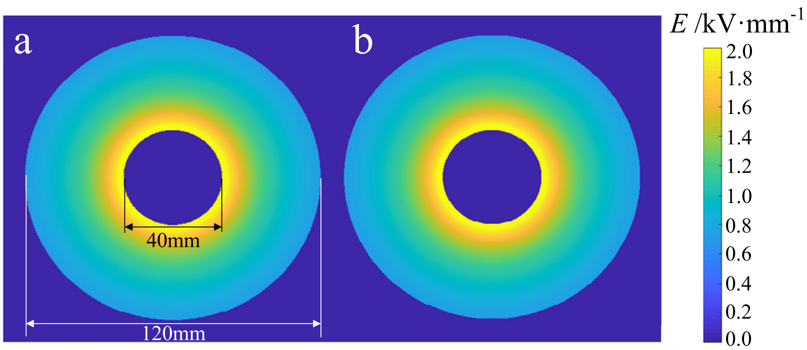

Fig. 7. The deduction results of insulator surface electric field intensity (a) measurement; (b) calculation.

Fig. 7 also shows that the measurement error near the high voltage electrode is larger, but the whole result is in good agreement with the calculated result.

4. Conclusion

This paper proposed a method for measuring surface electric field intensity of insulators by electroluminescent effect and deducing the electric field intensity from images. Depending on this way, we measured the surface electric field intensity distribution of disc insulator between coaxial cylindrical electrodes successfully, and the error is less than 6% within the radius range of 25 mm to 55 mm. However, because of some reasons like the brightness is too large or the electrode would reflect light and so on, the measurement of the electric field intensity near the electrode has a relatively large error, which should be solved in the follow-up works.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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