Edge effect and its influence on the adjacent cavities in a composite insulator

Salakjit Nilboworn[1*], Kuntapon Mahamad[1], Weerachai Sangchay[1], Paisan Kongrueang[1]

[1]Faculty of Industrial Technology, Songkhla Rajabhat University, Thailand
[*]Corresponding author. E-mail: s.nilboworn@ieee.org

ABSTRACT

In high voltage measurement systems, fringing field effect is related to the degradation mechanism in insulators. The densely field stress can lead to insulator failure faster and cause further deterioration. Another reason for the localized degradation is the existence of a defect in the insulator. Therefore, the fringing field at edge electrodes and the field stress around the cavities, which are adjacent near the electrode, are important factors when investigating the degradation. This work showed the effect of the fringing field on a composite insulator specimen. Moreover, the 2D model was built in the COMSOL multiphysics program based on the experimental insulation test. The effect of cavity shapes were also conditions in the modeling. The experiment was performed using operation voltage 20 kV according to ASTM D149. The test structure consisted of two brass electrodes with a radius of 37.5 mm as a parallel plate with the composite insulator in between. Then, the failure possibility at the edge electrode from two methods were compared. The results revealed that the edge electric field was higher than in other areas. This field stress accelerated the pre-discharge within the cavities, significantly increasing the electric field intensity.

Keywords: Composite insulators, Edge electric field, COMSOL multiphysics program, Partial discharge

1. INTRODUCTION

Electrical insulation is widely used in various high voltage equipment. The most commonly used and well-known insulator in high voltage is the composite insulator [1]. It is due to their better electrical, chemical, and physical characteristics when compared with glass and porcelain insulators [2]. Their characteristics are provided according to the specific standards from organizations such as IEC, IEEE or ASTM to ensure the safe operation of the insulator. Therefore, it comes with many requirements and procedures to follow [3]. The test conditions are also optimized to get the required output which saves time and money during manufacturing [4].

One of the prospects that cause insulation failure is the existence of a defect in the insulator [5]. The defect can be initiated during manufacturing, installing or operating process [5,6]. These are reasons for many researchers to investigate the size, shape, gas-filled cavity and position of the defect [7]. The noticeable effect of these defects is to make different characteristics in the area and cause a distortion in the insulator. Although, the modeling method is important to better understand the phenomena of the insulator. The modeling is always used to establish the problems [8,9].

Also, modeling has been proposed to analyze electric field (EF) distribution

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around the material. To understand and explore the EF information in the insulation system, the numerical computation methods have been developed [10, 11]. The development and design of HV devices with electromagnetic computational tools such as the finite element method (FEM) and the boundary element method (BEM) have been widely adopted [12,13]. Several aspects make computational tools essential for the insulation system. For instance, the E-field in the parallel plate electrodes is evaluated as a capacitor. Therefore, the behavior of the field near the edges (Fringing fields) is considerable and must be accounted for the modeling of the electrostatic forces [14].

For E-field distortion at the edge electrodes, the fringing fields are an initial reason for studying. The E-field between the two electrodes is a uniform field, except the edge field effect. The insulation degradation is enhanced from this non-uniform field by influencing the partial discharge in this area [15,16]. If there is a defect nearby this area, the internal ionization will occur because of the lower dielectric constant inside it.

In this paper, the design and simulation of edge effect in the high voltage insulator are emphasized. The composite insulation is adopted with the formation of cavities. For this consumption, the high electric field stress at the edge electrode influences the degradation of the insulator and also leads to partial discharge in the cavities irresistibly. Firstly, the simulation model in COMSOL multiphysics software and the influence of these cavities were analyzed. Then, the experimental test was performed to illustrate the deterioration from the edge electric field. The simulation and experimental results are compared and discussed. Finally, the simulation of edge effect can be beneficially explained with the dielectric breakdown.

2. MATERIALS AND METHODS

The composite insulator was procured from natural rubber and nano-composite fillers. The fillers have significant effect to enhance the mechanical or electrical properties of the base material. But during the vulcanization process, the cavity percolation can be filled unexpectedly. However, both effects of edge E-field and cavity are also investigated by modeling prolate and oblate cavities inclusions. Assuming that the electrostatic field between the two electrodes are parallel, the capacitance (C) between neglecting electrode thickness is

$$C = \varepsilon \frac{w}{d}. \tag{1}$$

Where w is the width and d is the gap between the electrodes. The fringing field effect is derived by the approximate analytical formula [17]

$$C = \varepsilon \frac{w}{d}\left[1 + \frac{d}{\pi w}\ln\left(\frac{\pi w}{d}\right)\right]. \tag{2}$$

The COMSOL multiphysics program was provided and used to simulate the electrical phenomena in this insulator. The 2D simulation presented the edge E-field and voltage stress level nearby the edge. The distribution of both electric potential and field strength across the model are computed with electrostatics (es) under the AC/DC branch.

The test structure consists of two brass plates, radius 37.5 mm, as parallel plate electrodes with the composite insulator in between. Many ellipse shapes of the cavity were adjacent near the ground as illustrated in Figure 1. The radius of the semi-major and semi-minor axes of an ellipse were randomly set. After that, the materials and the electrical properties were set as listed in Table 1. The 20-kV terminal voltage was set at the electrode (+) and another electrode was the ground terminal. The model includes only the test object and the applied voltage while the other components are omitted. The mesh sequence in the model was assigned as extra fine.

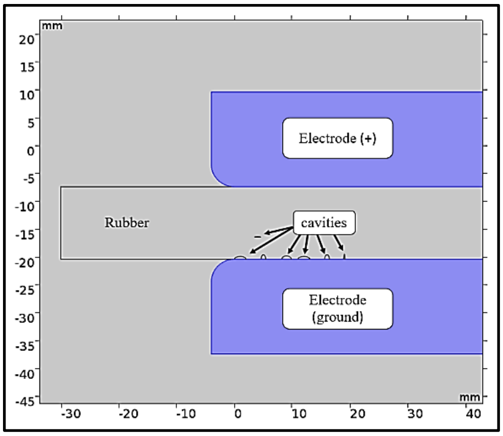

Figure 1. Simulation geometry of the cavities when adjacent near the electrode (Dimensions in millimeters).

Table 1. Parameters setup for the simulation

Materials	Brass	SF6	Rubber composite
Relative permittivity	1	1.02	4
Electrode (+)	20 kV		
Electrode (ground)	Ground		

3. RESULTS AND DISCUSSION

The 2D model was created to follow the insulation test approach. Then, the cavities were created near the high electric field stress area. From this model, the electrical phenomena from the top electrode was set at operation voltage. (20kV). And, the voltage level at the bottom electrode was the ground terminal, whereas the medium insulator used SF6 gas.

The electric field distribution and electric equipotential lines (grey lines) across the insulator and the field near the edges were plotted. The electrical potential (y-axis) along the insulator (x-axis), length in millimeters, is plotted as in Figure 2. And also, the electric field strength along the insulator length was simulated and plotted. The intensity in all Figures are defined by the color bar, as shown in Figure 2 and 3.

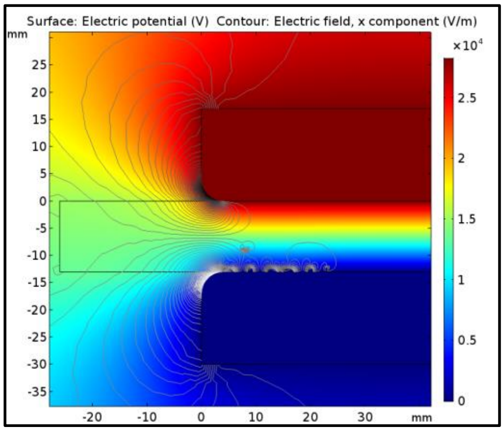

Figure 2. A 2D potential profile at the edge electrode and around the cavities along the insulator (x-axis), length in millimeters.

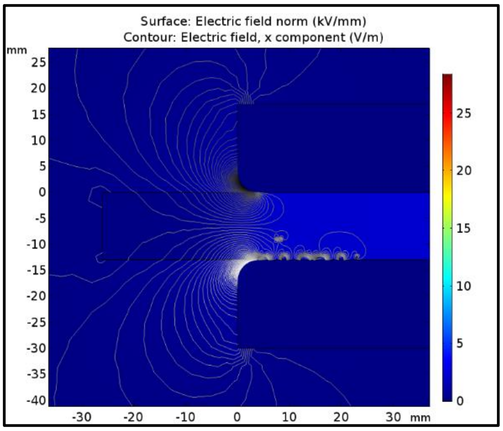

Figure 3. Electric field strength (y-axis) in kV/mm at the edge electrode along the insulator (x-axis), length in millimeters.

Due to the edge effect, the equipotential lines are densely covered at the re-entrant angle and decrease with the distance. The E-field in the cavity in this area is sharply increasing and exposed to higher distortion, especially at the cavity wall. In Figure 4, the line plot of the electric field norm (kV/mm) has been illustrated. The line plot throughout all cavities was set. From the result, the electric field norm at the edge electrode along the x-coordinate (mm) was higher than the inside. This E-field norm quickly increased, especially at the cavity walls.

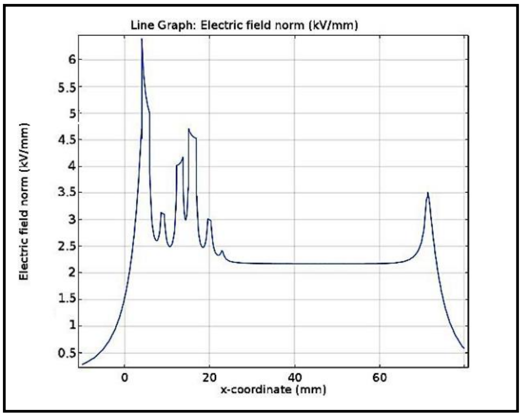

Figure 4. Line plot of the electric field norm (kV) along the insulator (Dimensions in millimeters) with the cavities present.

Figure 5 shows the comparison of E-fields between the upper (Red line) and lower (Blue line) boundaries of the composite insulator. From this result, it has been emphasized that the lower permit-tivity in the cavity leads to the higher electric field stress. Besides the cavities, the E-field stress has a uniform field. Because of the potential values, positions, and morphology, shapes of the cavity were affected by the E-field stress value at the edge.

Table 2. Summary of the permittivity and electric field strength of composite insulator.

Permittivity	4	1.0204
EF strength (kV/mm)	6.4 @cavities	28 @edge

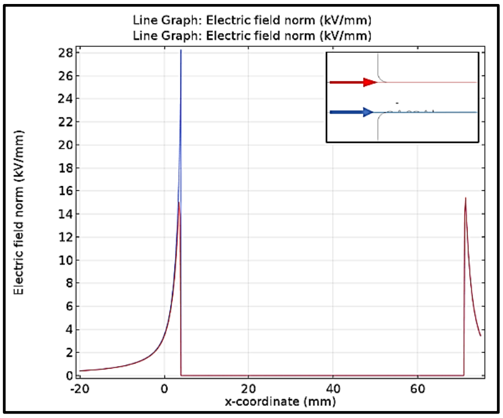

Figure 5. The electric field magnitudes (kV) along the boundary of the insulator (mm.) between the active 20 kV contact (red line) and ground contact (blue line).

Table 2 shows the simulation electric field strength at the edge electrode and the cavities. From the simulation result, it indicates that a high electric field at the edge electrode can cause insulation damage. The edge electric field without a cavity is 3.5 kV/mm, and the presence of cavities increases the electric field intensity by 54.6%. Therefore, the cavity gave more failure possibilities for materials at those points. This phenomenon is clearly explained by the experimental results which imitate the conditions found in high voltage insulation test. To obtain the dielectric breakdown spot, the brass electrodes and the insulator were placed into the bucket which was SF6 contained. The insulation test circuit was energized with a high voltage transformer according to the ASTM D149 standard test method as shown in Figure 6.

The measurement circuit consists of applied voltage 110 Vac 60 Hz, a 40 kV HV transformer, a coupling capacitor, a measuring impedance, and the test object. In Figure 7, it shows the parallel plate electrodes and the composite insulator. The voltage was applied from zero and increased until the breakdown occurred. The experiment was carefully tested three

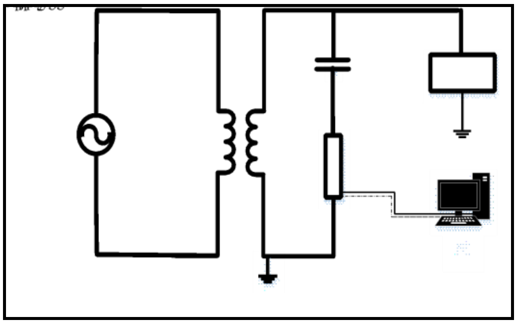

Figure 6. Schematic picture of the measurement circuit.

times in each sample to validate the burnt spot. The experimental results have shown good agreement and represented the accuracy of the model. The position of the burnt spot was mostly punctured near the edge electrode if it has a cavity in it. Figure 8 shows the puncture spot after the test. However, if there was an insulator failure in this condition, it originated from edge effect and cavities in this area.

Figure 7. The experiment HV test structure consists of brass electrodes, radius 37.5 mm and the composite insulator.

4. CONCLUSIONS

In this paper, the edge effect was reviewed and considered. Investigations were carried out to reveal the edge effect via FE simulation and experiment. The voltage and electric field at edge effect showed the highest risk for breakdown. In this study, the cavities were assumed adjacent near the edge electrode to exceed the failure.

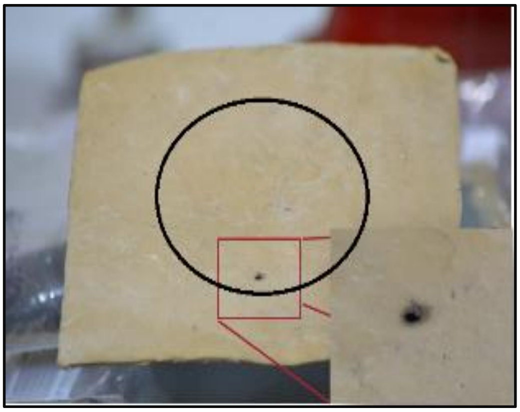

Figure 8. The puncture spot near the edge electrode in composite insulator

The potential distribution and E-field strength was calculated numerically. It was found that the edge E-field is normally higher than the uniform field area. And, this stress can accelerate the insulation failure, by causing the cavities to quickly extinguish or degrade itself under the HV test. The simulation edge electric field without cavities was 3.5 kV/mm, and the presence of cavities increased the electric field intensity by 54.6%. With 1.7 mm thickness of the sample, the PD inception voltage under 20 kV has been generated.

From the hypothesis, the edge effect influences the insulator distortion and also initiates the PD in cavities which are adjacent in this area. However, the experimental insulation test was set up and illustrated good agreements between both methods. The edge effect influences the breakdown point in this area first if the cavities exist. There are many methods for reducing the edge effect such as curving the electrode edge or utilizing the removal function compen-sation. Therefore, the edge effect could not be avoided in most measuring methods.

5. ACKNOWLEDGMENTS

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