Lightning impulse (LI) breakdown testing of a rubber-epoxy interface

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Abstract

The lightning impulse (LI) breakdown strength of a rubber-epoxy interface was measured using a test cell developed earlier for AC breakdown testing. The electrically active length of the rubber-epoxy interface in the test cell was about 10 mm. The rubber was compressed and the pressure in the rubber-epoxy interface was controlled and measured. It was shown that the test cell performed well under LI breakdown testing with the majority of the breakdowns located at the rubber-epoxy interface as desired and not in the bulk insulation. A higher LI breakdown strength was obtained for smoother epoxy surfaces.

1. Introduction

Electrically stressed interfaces between solid insulating materials are critical in high voltage apparatus like e.g. cable terminations and connectors. The dielectric strength of these solid-solid interfaces is influenced by among other things the electric field distribution, the interfacial pressure, roughness of the involved surfaces, and the possible presence of lubricants. To secure sufficient margins in product designs it is necessary to study the dielectric strength of solid-solid interfaces and how it is influenced by different parameters.

When measuring dielectric strength of solid-solid interfaces, care must be taken to create a relevant electric field distribution at the interface and to prevent undesirable influence from the electrodes on the discharge activity. A CIGRE working group (WG15-10 1996 [1]) made the recommendations that the electric field component tangential to the interface should be as uniform as possible and should contribute more to breakdown than the normal field component. In addition no metal electrodes should be in contact with the interface.

A number of different types of test cells for dielectric strength of solid-solid interfaces have been presented in the literature, see e.g. [2]. Especially for interfaces with insulating rubber there has been a common problem with breakdowns occurring in the bulk rubber instead of at the interface [1][3][4][5]. One example where this problem was prevented is [6] where the electrodes were cast in the epoxy instead of in the rubber material which however results in rather complicated sample manufacturing. Another example is [7] where plane parallel electrodes and a plastic cylinder with a surrounding rubber ring was used which however results in that the interface is in direct contact with the electrodes. Also in [8], where two rectangular shaped samples were placed on top of each other between two Rogowski-shaped electrodes, the interface is in contact with the electrodes.

In the present work the lightning impulse (LI) breakdown strength of a rubber-epoxy interface was measured by use of a test cell developed earlier by the authors [9]. The test cell comprised a rubber plug that was fitted into a hole in an epoxy disc. The epoxy disc was pressed between two disc-shaped electrodes. The test cell was designed for AC breakdown testing of interfaces with compressed rubber and the pressure at the interface could be controlled and measured. The electrically active part of the interface was about 10 mm long and the interface end-points were screened. The test cell performed well in AC testing with a majority of the breakdowns located at the interface and not in the bulk insulation [9]. The purpose of the work presented here was to check the performance of the test cell in LI testing and to study the influence of epoxy surface roughness on the LI breakdown strength.

Lightning impulse breakdown strength of solid-solid interfaces with rubber has been studied earlier in [7] and [10]. In both these studies a higher LI breakdown strength was measured for smoother surfaces and for higher interfacial pressure. This behavior is similar to that for AC breakdown strength of solid-solid interfaces as reported earlier by many authors.

2. Test cell design

The test cell was designed for AC breakdown testing of rubber-epoxy interfaces with compressed rubber.

2.1. Geometry

A schematic picture of the test cell is shown in Figure 1. It comprised a rubber plug that was fitted into a hole in an epoxy disc thus creating a rubber-epoxy interface. The epoxy disc with the rubber plug inside was pressed between two disc-shaped metal electrodes. High voltage was applied to the upper electrode and ground to the lower electrode. The electrodes were pressed together by a mechanical support. In the upper electrode there was a centered whole with a movable metal plunger. The plunger was pressed into the rubber body and the pressure was controlled by a spring system. The whole test cell was cast in insulating gel to avoid flashover. Gel was used instead of oil to prevent oil penetration into the rubber-epoxy interface which would otherwise influence the dielectric strength of the interface. In addition the gel box was partly immersed in a container with insulating transformer oil to further prevent flashover.

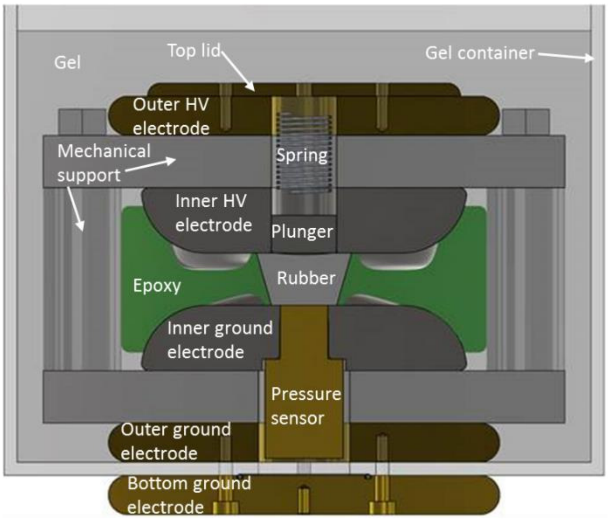

Figure 1 Schematic picture of test cell. During testing the gel container was partly immersed in insulating oil to prevent flashover.

Figure 2 shows a drawing of the inner part of the test cell. The rubber plug had height 20 mm and small diameter 25 mm. The mechanical support was made of POM (Polyoxymethylene) and the radial distance between the epoxy disc and the vertical POM supporting rod was 20 mm. The gel container was made of transparent PC (polycarbonate) and had width 240 mm and height 125 mm. The insulating gel was a two-component silicone gel. In Figure 3 a photo is shown of the mounted inner part of the test cell prior to gel filling.

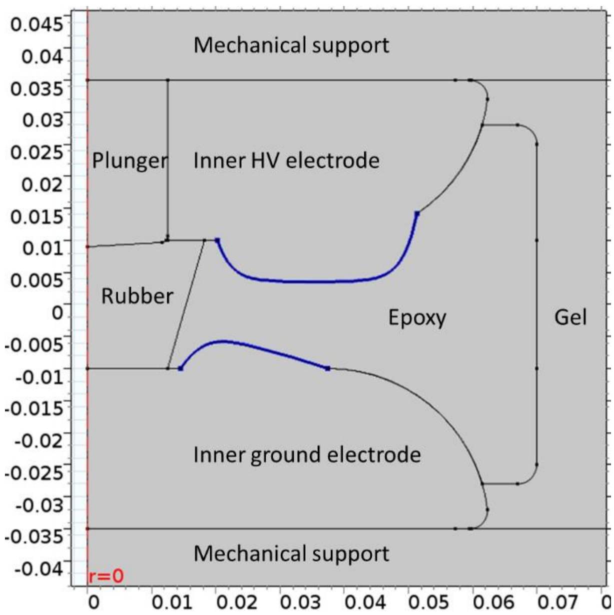

Figure 2 Drawing of inner part of test cell. Cylindrically symmetric around r = 0. Measures in meter. Protruding Rogowski-shaped parts of electrodes marked in blue.

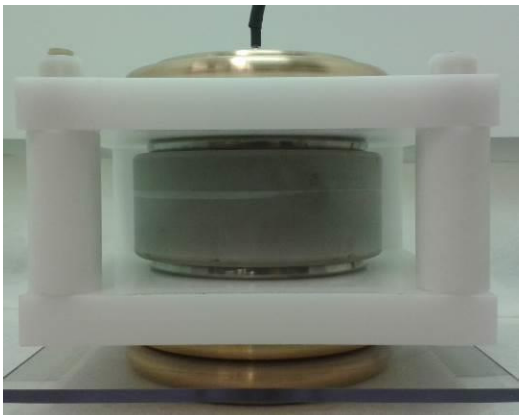

Figure 3 Photo of mounted inner part of test cell prior to gel filling.

2.2. Electrodes

The inner metal electrodes were made of stainless steel and were Rogowski-shaped to avoid local field enhancements at their edges. In addition part of the electrode edge was covered by the epoxy body to avoid too high electric field in the silicone gel.
To obtain a suitable electric field distribution at the rubber-epoxy interface, the inner electrodes were complemented with protrusions extending into the epoxy as shown in Figure 1 and Figure 2 (protruding parts marked in blue in Figure 2). The protrusions were not part of the metal electrode but were created by painting part of the surface of the shaped epoxy body with conductive silver paint. A schematic picture of the shaped epoxy body is shown in Figure 4. The protruding parts were Rogowski-shaped to avoid local field enhancements at their edges. The protrusions were shifted apart radially to have the same radial distance to the interface and the lower protrusion was rotated clockwise to relax the field in the bulk epoxy. The main purpose of the protruding parts of the inner electrodes was to screen the end-points of the rubber-epoxy interface were the interface is in contact with the electrodes. This is important to prevent influence from the electrodes on the discharge activity at the interface. In addition the protruding parts of the inner electrodes secured that the electric field in the rubber body was highest at the rubber-epoxy interface and lower inside the bulk rubber. This reduced the risk of having breakdowns inside the bulk rubber instead of at the interface.

The upper inner electrode had a centered whole (diameter 25 mm) with the movable spring-loaded metal plunger fitted inside. The lower inner electrode also had a centered whole were a pressure sensor could be placed.

To avoid too high electric field along the horizontal POM-gel interface at the edge of the inner electrodes, this area was electrically screened by introducing the outer electrodes. The outer electrodes were made of brass and had diameter 150 mm, height 15 mm and corner radius 7.5 mm.

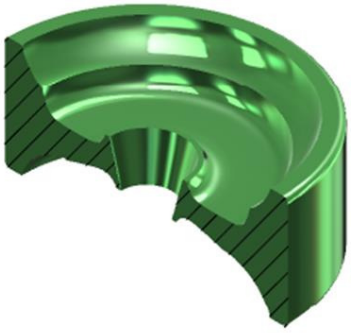

Figure 4 Schematic picture of epoxy body.

2.3. Pressure at interface

Since the dielectric strength of solid-solid interfaces depends on the interfacial pressure, it was important to control the pressure at the rubber-epoxy interface in the test cell. Pressure was applied to the rubber body using the stainless steel plunger. The plunger had diameter 25 mm and a domed surface with diameter of 100 mm to prevent air trapping between plunger and rubber. The pressure was controlled by use of a spring and a top lid as shown in Figure 1 and could be varied by using different spacers between the spring and plunger. The pressure in the rubber body was hydrostatic and therefore a pressure sensor at the bottom surface of the rubber body could be used to determine the pressure at the rubber-epoxy interface. The pressure sensor was place in a centered whole in the bottom inner electrode and was replaced with a dummy during breakdown testing.

2.4. Electric field distribution

The simulated electric field distribution in the inner part of the test cell is shown in Figure 5. The field was highest in the epoxy between the protruding parts of the inner electrodes. This was advantageous since the bulk epoxy was expected to have higher breakdown strength than the bulk rubber and also higher than the rubber-epoxy interface. There were no significant local field enhancements at the edges of the protrusions thanks to the Rogowski-shape. As intended, the end-points of the rubber-epoxy interface were screened and the field in the rubber body was highest at the rubber-epoxy interface.

The simulated electric field distribution at the rubber-epoxy interface is shown in Figure 6. The field was mainly tangential, as desired, and was high over a relatively large part of the interface. The maximum field was obtained at the interface midpoint (z = 0). At a distance of 5 mm from the midpoint along the interface the field was only reduced by 20%. Therefore it was considered that at least a distance of 10 mm of the interface centered at the midpoint was electrically active. At the interface end-points the field dropped by more than 50%. Hence the interface end-points were practically screened.

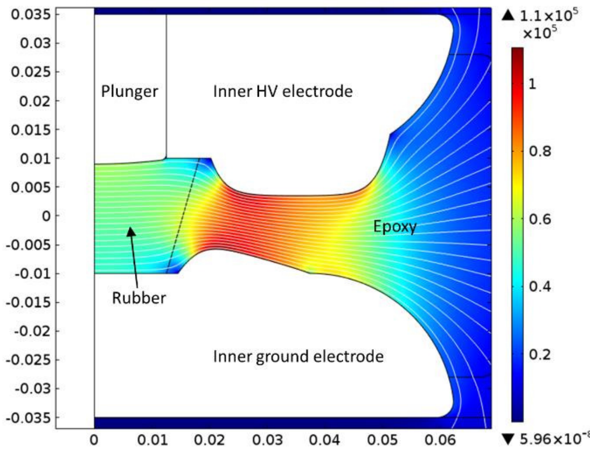

Figure 5 Simulated electric field distribution (color) and equipotential lines in inner part of test cell. Applied voltage 1 kV peak. Plunger extending 1 mm into rubber plug.

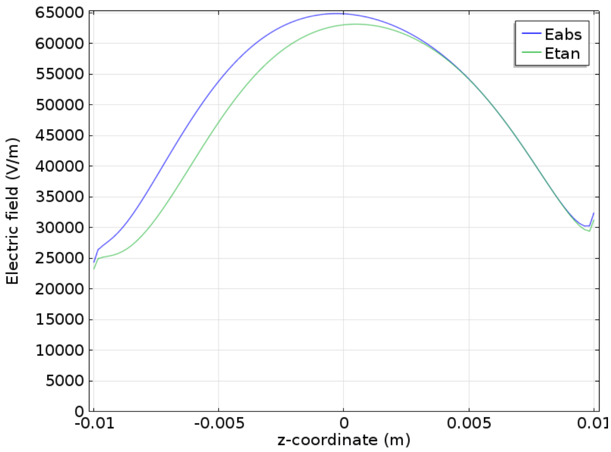

Figure 6 Simulated electric field in rubber-epoxy interface at applied voltage 1 kV peak. Absolute field (Eabs) and tangential field (Etan).

3. Experimental

3.1. Mounting of test cell

During mounting of the test cell, care was taken to keep all interfaces of the test cell inner parts clean and free of dust and particles. All inner parts were cleaned with ethanol prior to mounting. No lubricants were used at the rubber-epoxy interface. The protruding parts of the inner electrodes were created by painting the corresponding parts of the shaped epoxy body with conductive silver paint as shown in Figure 7. Contacting strips of copper foil were placed in the silver paint to secure electrical contact with the metal inner electrodes. During mounting it was important to avoid air trapping at interfaces, e.g. between the rubber body and the plunger, and to secure that the metal inner electrodes were in mechanical contact with the epoxy body in all regions intended. The inner metal electrodes were well polished for each test. The silicone gel was prepared by first degassing the two components separately for 30 min at 0.1 bar. Then the degassed components were mixed and the mixture was degassed again for another 30 min at 0.1 bar. Thanks to the degassing any small air bubbles that were introduced in the gel during gel-filling of the test cell dissolved in the gel during curing. The gel was cured in room atmosphere.

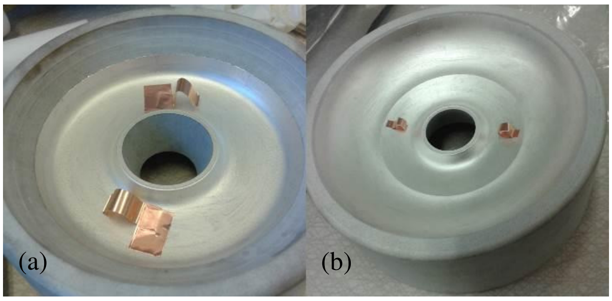

Figure 7 Shaped epoxy body painted with conductive silver paint (a) top surface, (b) bottom surface. Contacting strips of copper foil placed in silver paint to secure contact to metal inner electrodes.

3.2. Breakdown testing

As mentioned before, the gel container was partly immersed in transformer oil during breakdown testing to avoid flashover. Lightning impulse (LI) step tests were performed and the test procedure was set according to IEC 60243-3 [11]. The starting voltage was 100 kV and the polarity was positive. The peak voltage was successively increased by 10 kV, with three impulses applied on each voltage level. The waiting time between impulses was set to 30 seconds.

4. Results and discussion

The test cell was used for LI breakdown testing of in total 30 samples as shown in Table 1. Out of these, 24 samples had the breakdown located at the rubber-epoxy interface as desired. For three samples there was flashover and one sample had breakdown in the bulk epoxy. Two samples had breakdown inside the rubber body and for both of these there was an air bubble inside the rubber at the breakdown location. The air bubbles were discovered during sample dissection after the breakdown testing and it was believed that the air bubbles caused the breakdown in these cases. The air bubbles were probably trapped inside the rubber during molding of the rubber body.

Table 1 Breakdown location for tested samples.

Breakdown location	**Number of samples**
Rubber-epoxy interface	24
Flashover	3
Air bubble in bulk rubber	2
Bulk epoxy	1
Total number of samples tested	**30**

In summary, the test cell performed well in LI breakdown testing with the majority of breakdowns located at the rubber-epoxy interface. Hence this test cell can be used for studies of LI breakdown strength of rubber-epoxy interfaces without having a large amount of breakdowns undesirably occurring in the bulk insulation.

In order to study the influence of the epoxy surface roughness on the LI breakdown strength, samples with similar surface roughness were selected and grouped together. This resulted in two groups: one group of 6 samples with a rougher epoxy surface, and one group of 8 samples with a smoother epoxy surface. The rubber material and the interfacial pressure was the same for both groups. In Figure 8 the normalized measured breakdown strength for the two groups are compared in a Weibull plot. A higher LI breakdown strength was obtained for the samples with smoother epoxy surface. This is in accordance with results presented by other authors for LI breakdown strength of solid-solid interfaces with rubber [7][10]. The scatter in the data was somewhat smaller for the rougher epoxy surface than for the smoother epoxy surface. A similar trend was observed earlier in [9] for AC breakdown testing with the same test cell.

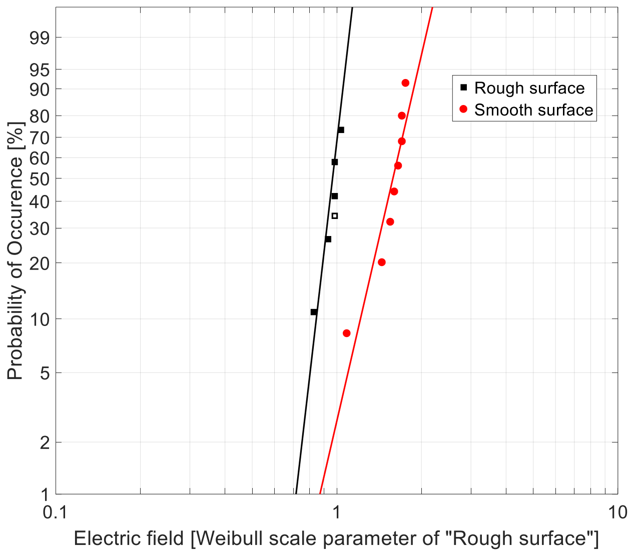

Figure 8 Weibull plot of breakdown measurement results normalized by Weibull scale parameter (α) of curve “Rough surface”.

5. Conclusion

The LI (lightning impulse) breakdown strength of a rubber-epoxy interface was measured using a test cell developed earlier for AC breakdown testing. The electrically active part of the rubber-epoxy interface was about 10 mm long and the interface end-points were screened. The rubber in the test cell was compressed and the pressure at the rubber-epoxy interface was controlled. The test results showed that the test cell performed well also under LI testing with 24 out of 30 samples tested having the breakdown located at the rubber-epoxy interface as desired and not in the bulk insulation. A higher LI breakdown strength was obtained for smoother epoxy surfaces.

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