Influence of Field Grading in Setup for Electric Breakdown Testing of Polyethylene Films

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Abstract

High dielectric strength of solid electrical insulation materials for high voltage applications is essential for high reliability and long-term performance.

The IEC 60243 and ASTM D149 both describe very similar test methods to determine the short-term electric strength of solid insulation materials. A test sample, usually thin plaque, is placed in an electrode system with surrounding insulating oil. The voltage is then steadily increased until an electric breakdown occurs. Despite the relatively simple test setup, testing materials with high electric strength can be difficult. The breakdown channel is often located outside the active testing area of the electrodes and found at the electrode edge at the triple point between the electrode, test object, and surrounding oil.

In this study, we have investigated different possibilities to control the electrical field enhancement in the vicinity of the electrode edges using silicone rubber, field grading silicone rubber, and a high permittivity oil. The testing was performed with semi-spherical electrodes and electrodes as recommended in IEC 60243 on polyethylene films. Electrodes covered with the field grading rubber increased the short-term breakdown strength compared to standard testing without modification. The high permittivity oil and silicone rubber seemed to have limited effect on the breakdown strength.

1. Introduction

Electric breakdown strength is an important property of insulation material for high voltage applications and test procedures to determine the short-term electric strength, as described in ASTM D149 and IEC 60243 [1, 2]. In spite of the standards, reliable and meaningful conclusions can be very difficult to draw from the test results [3, 4]. Test results are to a great extent dependent on a variety of different test conditions, but one of the main challenges is still to reduce the influence at the triple point between electrodes, test object, and the immersion fluid [4-6]. Often the breakdowns are triggered by surface discharges at this triple point giving breakdown channels located close to the electrode edges or outside the active electrode area. This implies that the results are dependent on how the electrical field distribution at the triple point is controlled not only by the rounded electrode edges, but also by the matching of permittivity between test object and the immersion fluid. Therefore, even if the same immersion fluid is used for ranking or selection of materials, drawing conclusions will be difficult especially if some materials have lower, while other materials have higher permittivity compared to the oil. In ASTM [7], recommendations how to choose immersion fluid in order to suppress discharges and control the electric field are presented, but this is sometimes of limited use since standard transformer mineral oil or silicone oil is most commonly used. The use of a high permittivity fluid is presented in [4], where a significant increase was detected in electric breakdown strength of a solid material. For XLPE cables it is common to use terminations circulated with deionized water having a permittivity close to 80 or other field grading materials to control the electrical field at the triple point. Another approach to minimize the impact from the triple point is to use recessed test objects or electrodes molded into the test objects [3]. However, preparation of such test objects can be very time consuming and require several preparation steps. Therefore it is still desirable to use the procedure described in the IEC and ASTM standards with flat test objects since they are easy to produce in large quantities and in a repeatable way that allows testing on multiple test objects for statistical evaluation.

2. Experimental

2.1 Test objects

The breakdown tests were performed on extruded cast film from low density polyethylene (LDPE). The cast films had uniform thickness, an important feature in the present study since the AC breakdown strength will depend on the thickness of the test objects. Two thicknesses of films were used with a nominal thickness of 0.30 mm with measured values in the interval 0.28 – 0.31 mm, and a nominal thickness of 0.50 mm with variation 0.49 – 0.51 mm.

2.2 Electrode system and test parameters

Two different electrode systems have been used in this study. The electrode system with phased edges that is recommended in the IEC standard [2] and a truncated spherical (semi-spherical) electrode system as shown in Figure 1. The semi-spherical system was manufactured by cutting stainless steel spheres (Ø 40 mm) in a way that the electrode area became identical with the IEC electrode (Ø 25 mm). An advantage with the semi-spherical electrodes compared to the IEC electrodes was the simplicity to prepare and mold silicone rubbers around the electrodes to control the electric field at the triple point, see Figure 2. The first silicone rubber is developed for cable accessory applications and has a high permittivity in order to achieve good electric field grading properties. However, it contained black fillers that easily contaminated the immersion fluid during testing. The two other silicone rubbers are both commonly used high voltage insulation materials; one being transparent, which made it easier for inspection of air pockets during testing. The testing was performed with two different silicone oils as immersion fluid, a standard silicone oil based on polydimethylsiloxane (PDMS) with a viscosity of 50 cSt and a fluorosilicone oil with viscosity of 1000 cSt higher permittivity compared to standard silicone oil, see Table 1. The fairly high viscosity of the fluorosilicone oil made it difficult to remove air bubbles during testing.

All measurements were performed at room temperature under ambient conditions. The AC voltage was first raised to 15 kV and thereafter increased 100 V/s until breakdown occurred. A constant pressure of 1.7 kg was applied on the electrodes, and the electrode pairs were changed when the surface were visibly damaged from breakdowns. Table 2 summarize the different test series A-G with different combinations of electrode shape, immersion fluids and silicone rubber.

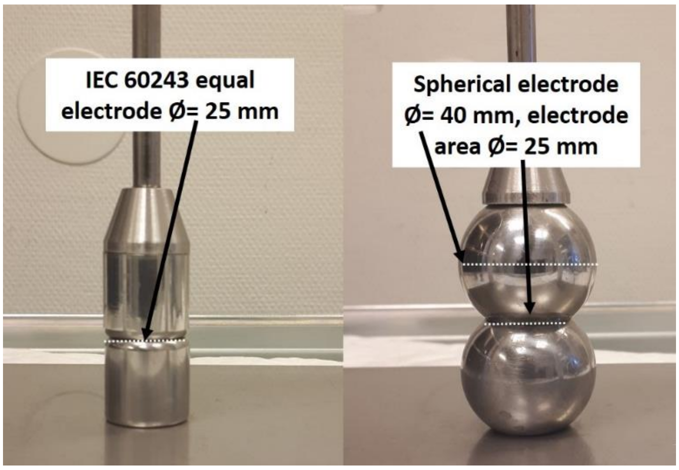

Figure 1. Electrode system according to IEC 60243 to left and partially-spherical electrodes to right.

Figure 2. Spherical electrode system molded with silicone rubber.

Table 1. Relative permittivity of immersion fluids and silicone rubbers used to mould on the electrodes.

Component	Relative permittivity (50 Hz)
Immersion fluid:	
Silicone oil (oil 1)	2.6
Fluorosilicone oil (oil 2)	~7
Silicone rubber:	
Silicone 1	2.9
Silicone 2	~15
Silicone 3	2.7

Table 2. Test series and test configuration of electrode system, oil and silicone rubber for breakdown testing.

Series	Electrode	Oil type	Silicone
A	IEC	Oil 1	-
B	IEC	Oil 2	-
C	Spherical	Oil 2	-
D	Spherical	Oil 2	Silicone 1
E	Spherical	Oil 2	Silicone 2
F	Spherical	Oil 2	Silicone 3
G	Spherical	Oil 1	Silicone 2

3. Results and discussion

The breakdown strength of series A-G are summarized in Figure 3 to Figure 8 and Table 3 to Table 4, where the 2-parameter Weibull scale parameter is the 63.2% value and the shape parameter β describing the scatter of the data. A high value of the shape parameter is equivalent to low scatter.

3.1 Impact from immersion fluid

Figure 3 show the difference between series A and B for both 0.3 mm and 0.5 mm test objects. In both series the IEC standard electrodes were used, but in series A the standard silicone oil was used as immersion fluid whereas the fluorosilicone with higher permittivity was used in series B. The 63.2% value was very similar between the test series, but the shape parameter was significantly improved by testing in oil 2 due to some low breakdown values occurring when testing in oil 1. It was expected that oil 2 would have a positive effect on the breakdown strength value due to better electrical field grading by the higher permittivity. During testing with oil 1 discharges around the electrode could sometimes be observed before breakdown occurred in the test object, but such discharges disappeared when testing with oil 2. However, still the majority of the breakdowns in both series A and B occurred close to the electrode edges. This could indicate that the high permittivity oil 2 both reduced the electrical field in the triple point close to the electrode edges as well as increased the inception voltage of discharges prior to breakdown. This effect was however not sufficient to significantly affect the scale parameter, but the breakdown population was made more homogenous.

3.2 Impact from electrode shape

In Figure 4 the comparison between IEC and semi-spherical electrodes on both 0.3 mm and 0.5 mm test objects is presented. Only a few kV/mm in breakdown strength differ between the two electrode configurations but the scatter is lower for the IEC electrodes for the 0.3 mm test objects and vice versa for the 0.5 mm test objects. The comparison in Figure 4 revealed that the semi-spherical electrode system was good enough in order to evaluate the impact from molded silicone rubber. Even though oil 2 improved the shape parameter β, the high viscosity made the test vulnerable to air bubbles that required long time to disappear, making it likely that some air bubbles were present during some of the breakdown tests.

3.3 Impact from silicone rubber

For the tested 0.3 mm test objects in Figure 5 silicone 2 (Series E) increased the breakdown strength with about 30 kV/mm or 30% compared to unclad electrodes (Series C) while silicone 1 (Series D) had no or insignificant impact. However, the use of silicone 2 drastically increased the scatter as shown in reduced shape parameter. When the semi-spherical electrodes were embedded in the different silicones the series F with the transparent silicone 3 was only tested with the 0.5 mm samples.

For the 0.5 mm samples an increase with 14 kV/mm (17%) was observed with silicone 2, but for silicone 1 and silicone 3 the breakdown strength was reduced compared to series C. The silicone 3 (series F) reduced the breakdown strength with 12 kV/mm. Also the shape parameter was reduced for the 0.5 mm samples with embedded electrodes, but not very much for silicone 3.

It could also be observed that the shape parameter for silicone 2 was only 5.7 for the 0.3 mm test objects, but 20.8 for the 0.5 mm test objects. The low shape parameter could to some extent be explained by a few breakdowns that occurred at low voltage levels during testing of the 0.3 mm test objects. The higher scatter could be due to the molding quality of the electrodes or non-evaporated air bubbles in the oil. Silicone 2 contained a filler which made it difficult to mould why it had to be additionally kneaded onto the electrode. This could influence the surface smoothness towards the test object surface and triple point. Another reason could be that the filler steadily contaminated the oil during testing.

3.4 Impact from the combination oil and silicone rubber

In Figure 7 and Figure 8 series C and E is compared with series G, where silicone 2 embedded electrodes were used with oil 1 (standard silicone oil). The results show that when tested, the embedded electrodes with silicone 2 in oil 1 had no effect on the breakdown strength compared to series C without rubber molding. This effect was observed for both 0.3 and 0.5 mm test objects. On the other hand, as seen earlier in Figure 5 and Figure **6**, the combination of silicone 2 and oil 2 increased the breakdown strength. In common for all test series, even series F, the majority of breakdowns occurred close to the triple point at the electrode edges. It was earlier mentioned that oil 2 had a higher inception voltage for discharges occurring in the oil compared to oil 1. This in combination with the ability of silicone 2 to grade the electrical field resulted in an increase of breakdown strength of the test objects, but due to imperfection in the molding the breakdowns still mainly occurred close to the electrode edges. At the same time, oil 1 could not suppress pre-breakdown discharges occurring due to the non-homogenous smoothness of the embedded electrodes, which could explain similar breakdown strength results as without silicone 2 molded on the electrodes.

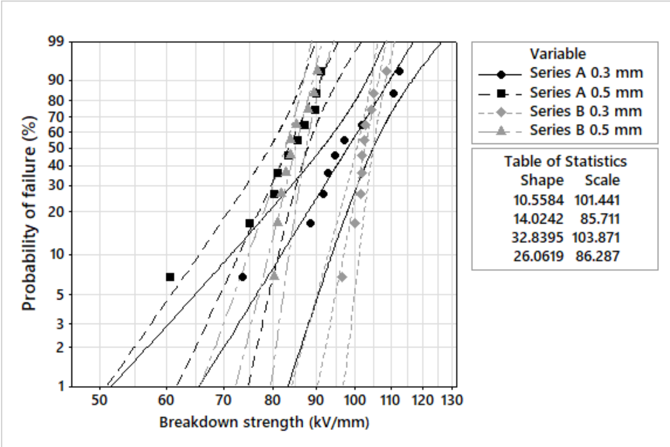

Figure 3. Comparison of breakdown strength between oil 1 (Series A) and oil 2 (Series B) using IEC electrodes.

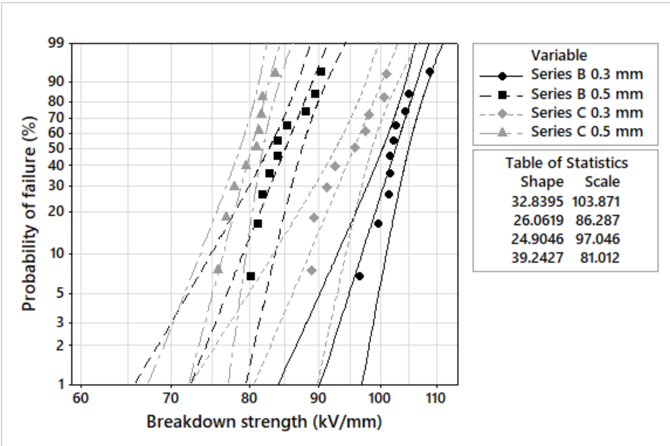

Figure 4. Comparison of breakdown strength between IEC (Series B) and semi spherical electrodes (Series C) performed in oil 2.

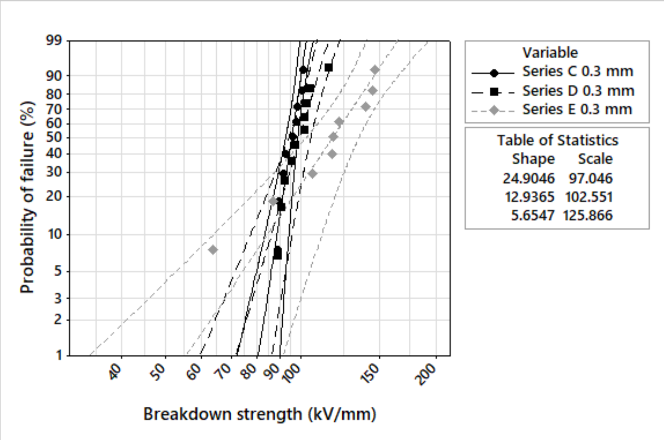

Figure 5. Breakdown strength on 0.3 mm test objects using semi-spherical electrodes an in oil 2 with (Series D and E) and without (Series C) silicone embedded electrodes.

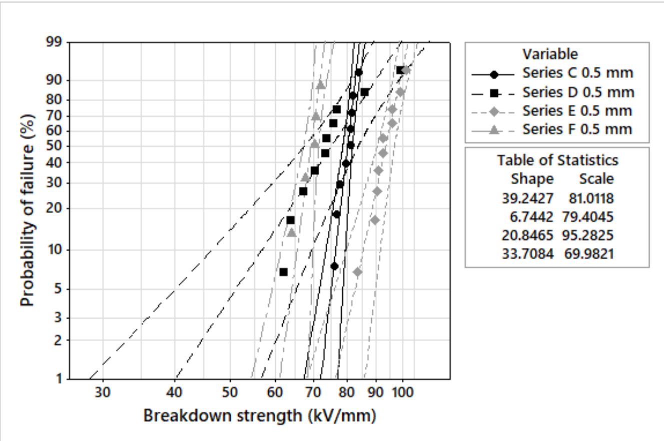

Figure 6. Breakdown strength on 0.5 mm test objects using semi-spherical electrodes an in oil 2 with (Series D, E, and F) and without (Series C) silicone embedded electrodes.

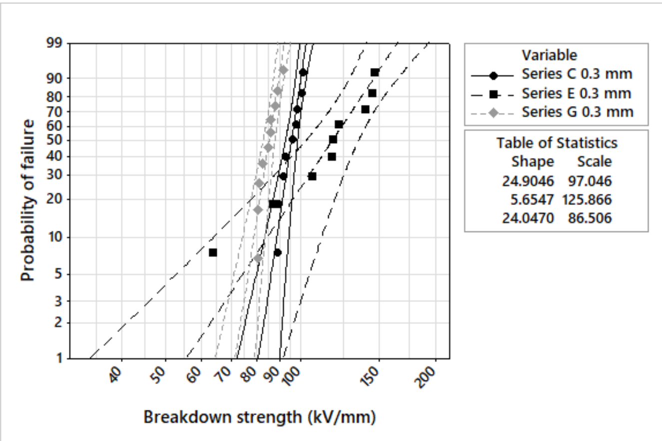

Figure 7. Breakdown strength on 0.3 mm test objects using semi-spherical electrodes in oil 1 and 2 with and without silicone 2, where the combination of oil 2 and silicone 2 (Series E) has combined effect on the breakdown strength compared oil 1 and silicone 2 (Series G).

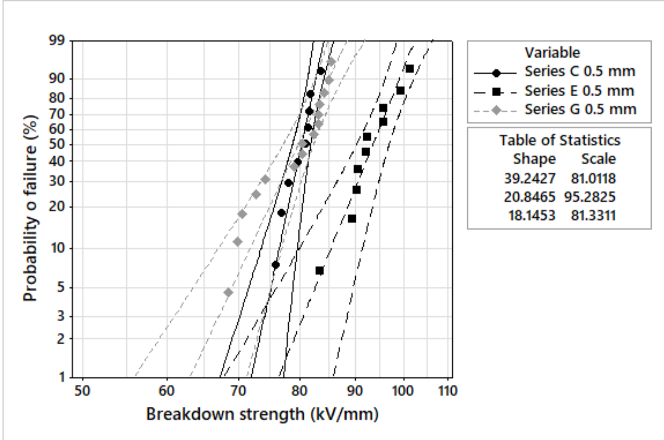

Figure 8. Breakdown strength on 0.5 mm test objects using semi spherical electrodes an in oil 1 and oil 2 with and without silicone 2, where the combination of oil 2 and silicone 2 (Series E) has a combined effect on the breakdown strength compared oil 1 and silicone 2 (Series G).

4. Conclusions

In this study the behavior of electrical breakdown on LDPE films with two different thicknesses has been tested with focus on experimental conditions of electrodes and immersion fluid. It was found that the breakdown strength increased with the combination of the fluorosilicone oil and electrodes embedded in the type of silicone rubber designed for stress grading in cable accessories. This effect was not observed when testing in standard silicone oil with electrodes embedded in the stress grading silicone rubber

In earlier test series it was found that testing with IEC electrodes with the two types of oil gave similar electric breakdowns strength value, but the scatter in the data was reduced with the high permittivity fluorosilicone oil. The fluorosilicone oil also reduced the inception voltage of discharges occurring in the oil before breakdown occurred compared to the standard silicone oil. It is believed that this effect together with the ability of silicone 2 to grade the electric field was the reason of increased breakdown strength of the tested test objects. Due to non-ideal molding procedure the surface homogeneity and smoothness probably also influenced the results. It is important that such preparation results in better interfaces between the embedding material and test object. This work point on the complexity of performing electrical breakdown testing. More work is needed in order to find the best combination of immersion fluid and embedded electrodes in order to increase the reliability of test procedure and reduce the influence of experimental conditions.

Table 3. AC breakdown strength of 0.3 mm test objects.

Series	Electrode	Oil type	Silicone rubber. Permittivity in parenthesis.	Scale (kV/mm)	Shape
A	IEC	Oil 1	-	101	10.6
B	IEC	Oil 2	-	104	32.8
C	Spherical	Oil 2	-	97	24.9
D	Spherical	Oil 2	Silicone 1 (2.9)	103	12.9
E	Spherical	Oil 2	Silicone 2 (15)	126	5.7
F	Spherical	Oil 2	Silicone 3 (2.7)	-	-
G	Spherical	Oil 1	Silicone 2 (15)	86	24.0

Table 4. AC breakdown strength of 0.5 mm test objects.

Series	Electrode	Oil type	Silicone rubber. Permittivity in parenthesis.	Scale (kV/mm)	Shape
A	IEC	Oil 1	-	86	14.0
B	IEC	Oil 2	-	86	26.1
C	Spherical	Oil 2	-	81	39.2
D	Spherical	Oil 2	Silicone 1 (2.9)	79	6.7
E	Spherical	Oil 2	Silicone 2 (15)	95	20.8
F	Spherical	Oil 2	Silicone 3 (2.7)	70	33.7
G	Spherical	Oil 1	Silicone 2 (15)	81	18.1

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