WIRE-PLANE ELECTRODE SYSTEM FOR ELECTRICAL TREE INITIATION EXPOSED TO AC AND DC VOLTAGE STRESS

A. B. Johansson[1*], A. B. Sandberg[1,2], B. Sonerud[1,3], J. H. M. Blennow[1] and S. M. Gubanski[1]
[1]Chalmers University of Technology, SE-412 96 Gothenburg, Sweden
[2]presently at ABB AB, SE-771 80 Ludvika, Sweden
[3]presently at Nexans Norway AS, NO-1751 Halden, Norway
*Email: anette.johansson@chalmers.se

Abstract: Electrical treeing in XLPE exposed to DC (of both polarities) and 50 Hz AC voltages has been analysed in a wire-plane electrode geometry using real-time optical detection and microscopic observations. It has been found that treeing mechanisms differ between AC and DC stresses. For AC voltage, the tree initiation and growth is easily observable in real time during the testing. In the case of DC stress a complete breakdown of the XLPE occurs before electrical trees can be discerned with the use of CCD camera. However, in the microscopic observations of the specimens, very fine tree structures can be distinguished. The effect of voltage ramping rate was also analysed. For AC stress, the faster ramping results in a higher tree inception voltage. The opposite trend is true for DC stress, where the faster ramp results in a lower breakdown voltage level. When comparing the effect on polarity of the DC breakdown voltage, negative polarity results in higher voltage levels than positive polarity.

1 INTRODUCTION

Due to its excellent electrical, thermal and mechanical properties, cross-linked polyethylene (XLPE) is nowadays commonly used as an alternative to the oil-paper for insulation in high and medium voltage cables. These properties will however deteriorate with time as well as exposure to electric stress. Electrical treeing is one of the main causes of electric breakdown in high voltage cables. Electrical treeing is a degradation phenomenon where partial discharges cause the formation of a tree-like structure of hollow channels in the dielectric. Once initiated, the trees will continue to grow until they cross the entire insulation, thereby short-circuiting it and causing breakdown. Both experimental and theoretical research on electrical treeing has been ongoing for several decades [1]. For materials exposed to 50/60 Hz AC voltage the research has been extensive [2, 3] although it is still ongoing. With the introduction of HVDC power transmission systems the interest in electrical treeing due to DC stress has increased, though the DC treeing has not been equally extensively studied. Even so, several methods for analysing DC treeing exist; a ramped or constant DC voltage can be applied, a somewhat different approach is using grounded DC or polarity reversal of the applied voltage [4, 5]. These approaches simplifies the measurements as a rapid grounding or polarity reversal of the applied voltage will further stress the material thereby allowing a lower level of the applied voltage. Different kinds of test specimens have also been evaluated, including the ASTM standard of double needle electrode samples. Alternatives with needle-plane or short cable specimens have also been used.

The wire-plane electrode sample type, as used in this study, has recently been introduced and is more extensively described in [6]. A number of advantages have been found with this electrode arrangement. The problems of damaged and bent needle tips as well as gas-filled voids at the needle tip, which will both affect the results, are avoided. The fact that several trees are likely to initiate along the wire electrode of a single sample is also beneficial. If an electrical tree is found to be caused by a defect in a sample, there is a chance of finding another tree, not affected by the defect, for further analyses.

2 METHOD

The electrical treeing inception voltage has been measured for ramped DC voltage of both polarities as well as for AC voltage for comparison. Furthermore microscopic analyses have been made on the samples after testing to retrieve further information about differences in the treeing process depending on the type of applied electric stress.

2.1 Test object

The high voltage electrode is composed of a 10 µm tungsten wire, which provides the necessary enhancement of electric field strength inside the insulation, in turn causing the initiation of electrical treeing. This wire is manually sewn onto to a premade semiconducting tab. The tab serves as a point of connection between the wire electrode and the external high voltage circuit. The tab with the attached wire is thereafter pressed between two pieces of pre-moulded insulating material and the cross-linking process of the material takes place at a temperature of 180 ºC at high pressure. The samples are cut about 3 mm from the wire. This cut edge is pressed towards a grounded copper plate during the test procedure and acts as the second electrode. The sample design and dimensions can be been in Figure 1. After manufacturing, the samples are degassed in a vacuum oven (at 60 ºC for five days) for removing by-products left by the cross-linking process before the testing takes place.

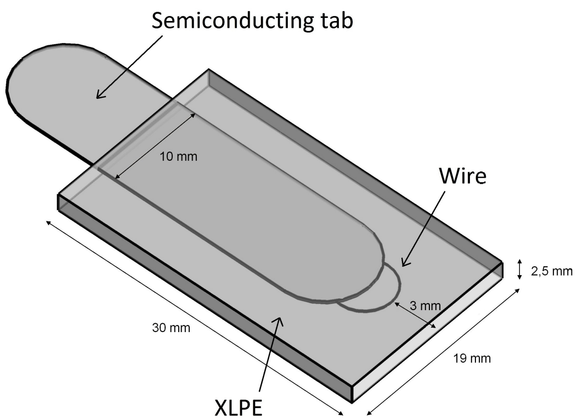

Figure 1: Dimensions of wire-plane electrode sample consisting of wire electrode, semiconducting tab and the insulation material to be tested.

2.2 Experimental set-up

A 75 kV, 50 Hz AC transformer with variable ramping rate is used as the voltage source. Two ramping rates were used in these tests, for the AC voltage tests a slower rate of 0.5 kV/s and a faster one of 3.9 kV/s. A resistor is connected in series with the test object to limit the current in case of a breakdown in the test object. The voltage across the test sample is measured with a voltage divider connected to a data acquisition card (DAQ). For the DC tests the circuit is adapted by adding a half wave rectifier, consisting of a high voltage diode and a smoothing capacitor of 0.88 μF, to the circuit. The smoothing capacitor decreases the AC ripple in the voltage to a maximum of 1.5 % of the applied voltage magnitude. The capacitor is also charged to the peak value of the AC voltage, providing a maximum DC voltage output of roughly 105 kV. The ramping rates are thus influenced by the peak value and are increased to ±0.7 kV/s and 5.3 and -5.4 kV/s respectively. The small difference in the ramp speed for the two polarities was due to a slight shift in the offset level of the AC voltage, however this is not considered as able to affect the results noticeably. A second resistor is also added to limit the capacitor in-rush current when the voltage is switched on. A schematic view showing the sample connected to the high voltage circuit is shown in Figure 2.

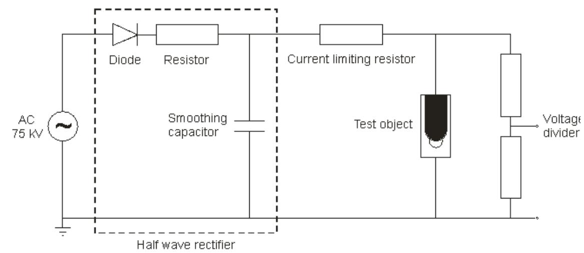

Figure 2: High voltage circuit with the test sample connected to the half wave rectifier and voltage divider.

During testing the sample was inserted into a glass tank filled with transformer oil for preventing surface flashovers. Real time detection of electrical treeing inception voltage was done optically using a CCD camera capturing 25 pictures per second. The CCD camera and the simultaneous voltage measurements were controlled and collected by a computer. In this manner real time examination of the treeing and the voltage level could be made and the voltage was switched off when the longest visible tree spanned roughly a third of the distance between the electrodes, to avoid a complete breakdown of the sample. After the experiment the video was checked to find the time and thereby the correlated voltage level for initiation of the first electrical tree. Both preceding and following testing, all samples have been studied under a microscope, to ensure that no defects were present in them. If so, these test data were not considered further.

2.3 Weibull distribution plots

The Weibull distribution is commonly chosen for describing breakdown phenomena in solid dielectrics. This is an extreme value distribution where a system fails at its weakest link. In order for data to be considered Weibull distributed, a finite threshold with a physical meaning must exist. Below this threshold no breakdown should appear. In the case of electrical treeing this would be the electrical field or voltage level below which electrical treeing will not initiate independently of the duration of applied stress. The cumulative probability function of the three-parameter Weibull distribution is as in Equation 1.

$$F(x;\alpha,\beta,\gamma) = 1 - e^{\left[\frac{x-\gamma}{\alpha}\right]^{\beta}} \quad ; x \geq \gamma \qquad (1)$$

The three parameters are; the scale parameter, $\alpha > 0$; the shape parameter, $\beta > 0$; and the threshold, $\gamma \le x$. The measured variable, x, is in this case the treeing inception voltage. The two-parametric Weibull distribution is a special case where the threshold is set to zero. This distribution is chosen when the three-parametric does not converge.

3 RESULTS AND DISCUSSION

3.1 General AC results

For the wire type electrode several trees usually initiate. The number of trees varies, from one single tree to more than twenty, in general somewhere between five and fifteen trees were distinguished for each tested object, somewhat more for the faster ramp rate. Figure 3 shows a microscopic image of three electrical trees growing from a small part of the wire. The edge connected to ground is located at the top above the trees, although outside the picture.

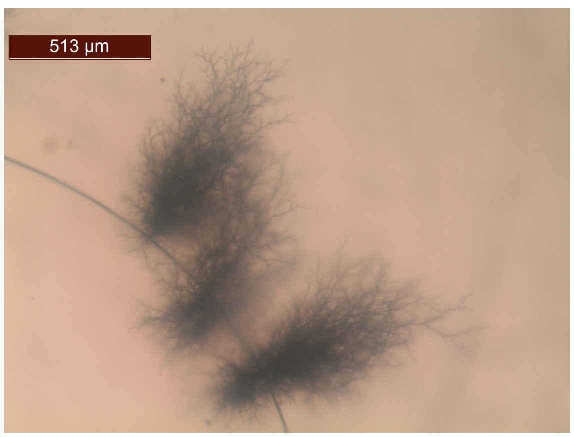

Figure 3: Electrical trees initiated at the wire electrode for the AC voltage of 0.5 kV/s.

3.2 AC treeing inception voltage

The impact of ramping rate on treeing inception voltage level has been compared for AC voltage of 0.5 kV/s and 3.9 kV/s. The three-parametric Weibull distribution of the tree inception voltage is shown in Figure 4. As can be seen treeing initiated at higher voltage levels when applying the faster voltage ramping rate. The dependence on treeing inception voltage with varying ramp rate has also been described earlier [7]. The reason behind is explained by a time delay needed for the tree initiation process, for the faster ramp the voltage will reach a higher level during this time. The probability plot shows 90 % confidence intervals and due to this, the threshold for the higher rate is lower even though the inception voltage can be seen to be higher since the values for the higher ramp rate exhibit a higher scatter.

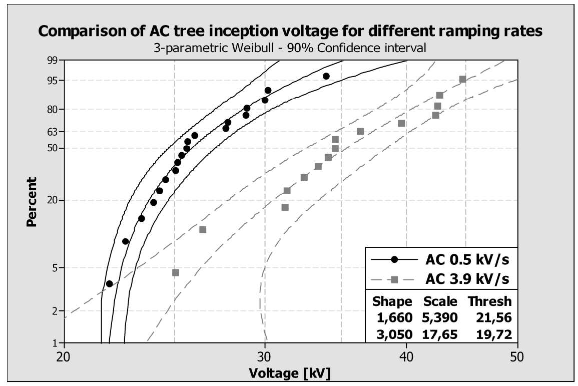

Figure 4: Three-parametric Weibull probability plot comparing AC treeing inception voltage at different ramping rates.

3.3 General DC results

During the DC tests, it was found impossible to distinguish electrical trees with the used CCD camera, as its resolution was too low. However electrical trees were distinguished in several samples later on, during microscopic examination. As a complete breakdown of the sample occurred, part of the semiconducting tab disintegrated and flowed along the wire and through the breakdown channel out into the surrounding oil. These breakdown channels, with a diameter of roughly 50 to 200 μm, completely surrounding the wire are seen in Figure 5 to 8. Obviously, these breakdown channels damaged a lot of tree structures in their vicinity, when and if such were present in the sample before the breakdown. Various kinds of electrical trees were distinguished during the microscopic observations of the DC stressed samples and they are believed to have initiated in different ways. Three distinctly different tree types are presented here; the first type, which is believed to be initiated by the ramped DC voltage; the second type, which is believed to be caused by the rapid grounding of the high voltage and the third type, only seen in samples, which have not been exposed to a breakdown through the bulk but on the other they have been exposed to flashovers in the high voltage circuit as the applied voltage reached its maximum value.

3.3.1 Trees believed to be initiated by the DC voltage ramp Examples of these trees are presented in Figure 5 and 6. This type of tree has been affected by the flow of semiconducting material as the sample broke down and therefore the tree is considered to have been present before this event. Figure 5 shows the breakdown channel to the left, as seen the channel does not cross the insulation all the way to the ground electrode, but has turned and comes out of the side of the sample. There also seems to be some remnants of tree structure remaining in the breakdown channel, indicating that a tree might have been present here before the insulation broke down. To the right of this channel an electrical tree has grown.

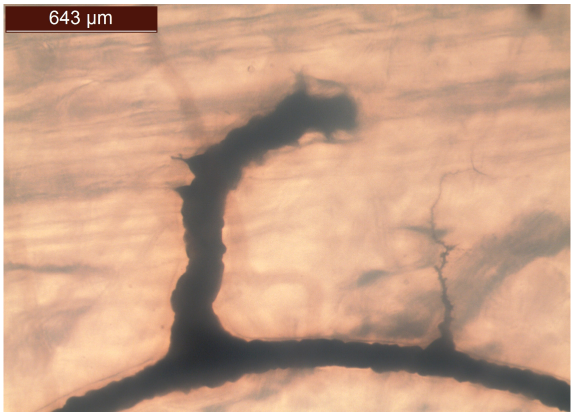

Figure 5: Breakdown channel on the left and electrical tree grown from the wire to the right side of the image. The sample was stressed by negative DC voltage of -5.4 kV/s

Figure 6 shows a close-up of another tree from the same sample. The image has been rotated and now the curvature of the wire can be seen in the right side. The tree seems to have been of a very thin branch-type, which may explain the difficulty in distinguishing it with the CCD camera. The sample illustrated in Figures 5 and 6 has been stressed with DC voltage of negative polarity with the faster ramping rate of -5.4 kV/s. This type of electrical trees, initiated by the DC voltage ramp, has also been found in samples tested with positive polarity of DC voltage.

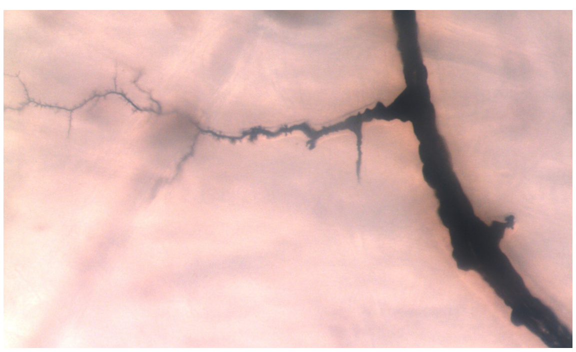

Figure 6: Electrical tree grown from the wire electrode. As seen this tree channel has been affected by the breakdown. The sample was stressed by negative DC voltage of -5.4 kV/s

3.3.2 Trees believed to be initiated by the breakdown event Electrical trees representing this second type are shown in Figures 7 and 8. Since these trees have not been affected by the flow of semiconducting material at breakdown, it is believed they were not been present at the time of breakdown. It was rather the breakdown itself causing their appearance. Similar trees have also been found for AC tested samples that experienced breakdown. This is a further implication that may indicate that the rapid voltage decrease or current surge during breakdown can be the direct cause for these trees, which are also all of very thin branch type. In Figure 7 two electrical trees can be distinguished as growing downwards, from the channel surrounding the wire electrode, in the direction towards the semiconducting tab.

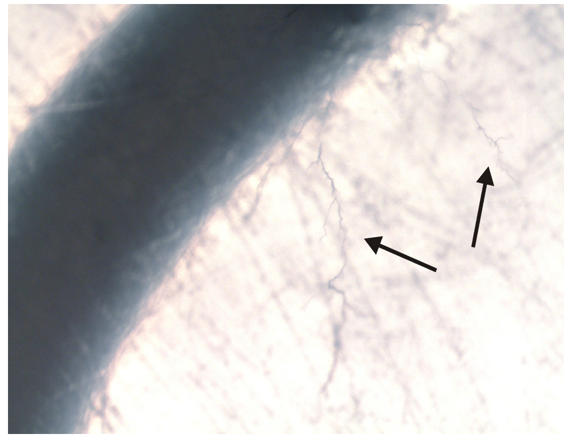

Figure 7: Electrical trees, indicated by arrows, growing from the breakdown channel around the wire shown in the right side of the image. These trees look unaffected by the breakdown. The sample was stressed by a positive DC voltage of 0.7 kV/s

Figure 8 shows a second example of such trees, initiated at the junction between the wire, seen in the far lower right corner, and the breakdown channel extending upwards on the right side of the image. The trees in the Figure 7 and 8 have been initiated by positive DC voltage with the lower ramping rate of 0.7 kV/s. This type of trees has also been found for both voltage polarities.

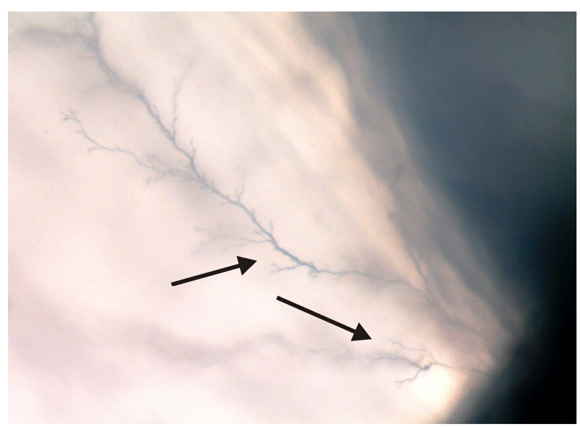

Figure 8: Electrical trees, indicated by the arrows, initiated at the junction between the wire, in the far left bottom, and the formed breakdown channel, seen as extending upwards. The sample was stressed by a positive DC voltage of 0.7 kV/s

3.3.3 Trees in samples which did not break down

The third kind of DC trees were found in two of the tested objects, stressed with negative voltage of the lower ramp rate. The sample would withstand the maximum voltage level of 105 kV before a flashover. Due to these flashover problems, the samples were tested repeatedly, as the samples did not exhibit a full breakdown nor was treeing observed by the CCD camera. After several attempts, the test was aborted, as it was uncertain whether some treeing could be distinguished by the CCD camera or not. Later on, as the samples were examined by microscopy, a large quantity of tiny tree filaments could be discovered all along the wire electrode. A small part of the wire with these filaments is shown in Figure 10. Assumptions on the cause of their initiation are difficult to make as the material has been subjected to the voltage ramp and the rapid grounding of the applied voltage caused by flashover, repeatedly. This stress is however similar to the aging procedure presented in [8]. Also worth noticing is that the trees grow both towards the grounded plane electrode as well as towards the semiconducting tab. This tendency can also be seen for the AC trees in Figure 3. The trees did not tend to extend perpendicular to the length of the sample.

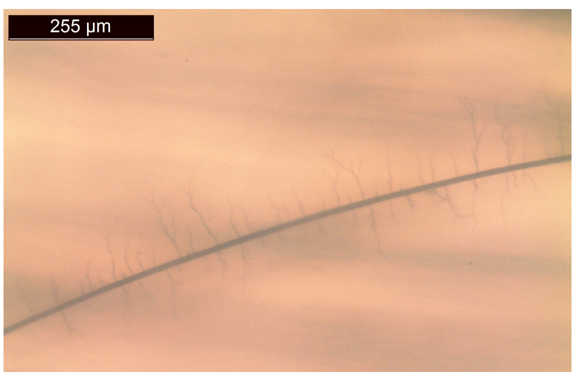

Figure 9: An abundance of tiny electrical trees along the wire of a sample stressed by negative DC voltage of -0.7 kV/s

3.4 DC breakdown voltage

Since the treeing initiation could not be detected with the CCD camera, Weibull distributions of the DC breakdown voltage were considered instead, though it is not improbable that the breakdown voltage levels might be correlated to the treeing inception. In the case of surface flashovers, these test results were not considered. Ten samples have been tested for each polarity at the faster ramp rate; for the positive only one of them had to be discarded, whereas for the negative polarity four test results could not be considered due to either no breakdown or a flashover. The probability of a flashover occurring in the external circuit before breakdown of the sample increases with the magnitude of applied voltage, making the DC experiments more difficult for negative DC polarity. Consequently the breakdown tests were only possible for positive DC voltage when applying a voltage of the lower ramp rate and three of the tested samples were discarded. For negative DC the testing had to be aborted after several attempts of testing. Only two samples completed testing and without results.

The breakdown voltage has been compared between positive and negative polarity of the applied voltage. A two-parametric Weibull probability plot comparing the breakdown voltage for the faster ramp rate with the treeing inception level of the AC test is shown in Figure 10. As seen in the figure the breakdown voltage appears significantly higher for the negative polarity. This also corresponds to the results previously presented in [9] and can be explained to be caused by a greater quantity of charge injected to the material at negative polarity, which renders a higher effective radius of the electrode and in turn lowers the electric field at it

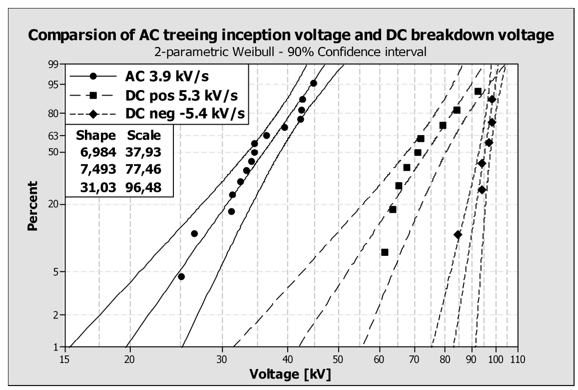

Figure 10: Two-parametric Weibull probability plot showing DC breakdown voltage for both positive and negative polarity as well as the tree inception voltage for AC voltage. The comparison is made for the faster ramp rate

A two-parametric Weibull distribution comparing the impact of ramp rate for positive DC voltage is shown in Figure 11. It can be seen that the slower rate resulted in a higher breakdown voltage. This trend has also been indicated earlier [10], where a faster voltage rate resulted in lower tree inception voltage levels for both voltage polarities. This effect seemed stronger for negative voltage. Anyhow the effect of ramping rate can be seen to be opposite for DC voltage as compared to the results of the AC testing presented earlier.

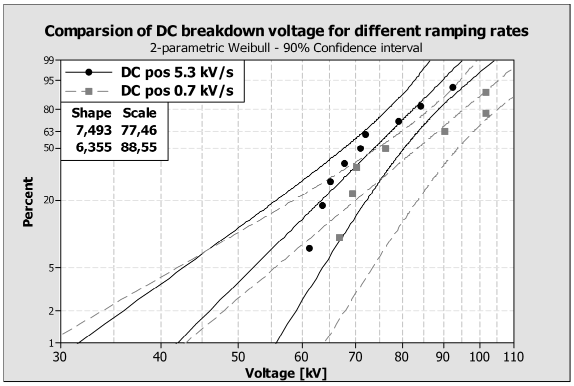

Figure 11: Two-parametric Weibull probability plot comparing the influence of ramp rate for positive DC voltage

4 CONCLUSIONS

Samples containing wire-plane electrodes have been used to analyse electrical treeing in XLPE under exposure to AC and DC voltage stress by means of real-time optical detection and post mortem microscopic observations. It has been found that the treeing mechanisms differed when applying DC stress from that observed under AC stress and the resulting electrical trees of thin branch type could now only be discerned by mean of a microscope.

When investigating the effect on voltage ramp rate, it appeared that for AC stress the treeing was initiated at a higher voltage level for the faster ramp rate. As the treeing inception could not be distinguished when applying DC stress, breakdown voltage has been analysed instead and in this case an opposite dependence on the ramping rate was found, i.e. the stressed samples could withstand higher voltage before breakdown at the lower ramp rates. It was also found that XLPE could withstand higher stress at negative polarity of DC stress.

The microscopic analysis that followed the testing revealed existence of thin branch-like trees in DC stressed samples, which have been divided into three different categories. The first kind is believed to be initiated by the voltage ramp although the thin structure made them impossible to distinguish with the CCD camera. The second type is considered to be caused by the rapid grounding of the applied voltage at the time of a complete breakdown in the sample. The third type, comprising tiny tree filaments has been discovered in samples stressed repeatedly up to the maximum voltage level, which flashed over externally in the circuit. The latter type of trees might have appeared in all the DC stressed samples, though no longer visible after a complete breakdown in the XLPE.

5 ACKNOWLEDGEMENTS

ABB AB, Karlskrona, Sweden, is gratefully acknowledged for providing the XLPE material used in the described tests as well as for providing the possibility of using microscope facilities. This project is presently continued with financial support from Chalmers Area of Advance in Materials Science.

6 REFERENCES

[1] L. A. Dissado: "Understanding Electrical Trees in Solids: From Experiment to Theory", IEEE TDEI, Vol. 9, No. 4, pp. 483-497, 2002

[2] R. J. Densley: "An Investigation into the Growth of Electrical Trees in XLPE Cable Insulation", IEEE TEI, Vol. EI-14, No. 3, pp. 148-158, 1979

[3] J. Holto, E. Ildstad: "Electrical Treeing in Extruded Polypropylene High Voltage Cable Insulation", ICHVE, pp. 373-376, 2010

[4] H. Kawamura, M. Nawata, "dc Electrical Treeing Phenomena and Space Charge", IEEE TDEI, Vol. 5, No.5, pp. 741-747, 1998

[5] G. Katsuta et al.: "DC and Impulse treeing characteristics in Insulation Material for HVDC Cable", ICPADM, pp. 422-425, 1997

[6] R. Huuva, V. Englund, S. M. Gubanski, T. Hjertberg: "A Versatile Method to Study Electrical Treeing in Polymeric Materials", IEEE TDEI, Vol. 16, No. 1, pp. 171-178, 2009

[7] L. A. Dissado: "The statistics of Electrical Tree Inception", IEEE TEI, Vol. 25, No. 4, pp. 660-666, 1990

[8] M. Selsjord, E. Ildstad: "Electrical Treeing Caused by Rapid DC-Voltage Grounding of XLPE Cable Insulation", ISEI, pp.502-505, 2006

[9] Y. Sekii et al.: "DC Tree and Grounded DC Tree in XLPE", CEIDP, pp. 523-526, 2005

[10] M. Ieda: "DC Treeing Breakdown Associated with Space Charge Formation in Polyethylene", IEEE TEI, Vol. EI-12, No. 1, pp. 19-25, 1977