The Effect of DC Electro-thermal Ageing on Electrical Treeing in Polyethylene

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Abstract

Electrical treeing is among the main mechanisms responsible for electric breakdown in polymeric high voltage cables. In this paper, electrical treeing in electro-thermally aged low density polyethylene (LDPE) was evaluated by means of a real-time microscopic detection system. A wire – plane electrode test object with semiconducting tab was used in the study. The ageing was performed at a constant temperature of 80°C and an applied DC voltage of 10 kV of both polarities and lasted from 100 up to 800 hours. For testing the resistances to electrical treeing, tests were performed by applying 50 Hz AC voltage at a ramping speed of 0.5 kV/s. The obtained experimental results showed that mainly the thermal component of the ageing had an influence on electrical treeing parameters, namely on the initiation voltage as well as the shape and occurrence frequency of the trees. With an increase of the ageing time, the tree inception voltage gradually decreased.

1. Introduction

Since the second half of the 20th century polymeric insulating materials have been widely used in high voltage insulation systems. For future long distance transmission, the high voltage direct current (HVDC) technology is considered as the most feasible technical and economic solution and especially extruded polymeric cables are to be used as a mean for electric energy transportation.

Electrical treeing is one of the main mechanisms of the degradation of polymeric insulation. There are three stages describing the formation of trees: initiation, propagation and finally breakdown. In the initiation stage, it is implied that microscopic voids are formed in highly stressed regions of the insulation bulk without any detectable PD activity. In the propagation stage, thin channels in the insulation material are being eroded and developed by partial discharges. During this phase the distribution of the electric field varies significantly within the forming tree. Breakdown will occur when a conducting tree channel appears or the electric tree's breakdown strength falls below the applied stress [1 - 4].

To evaluate the degradation of the materials a needle-plane electrode configuration has been widely used [5], but this arrangement has a number of disadvantages. Due to the thickness and opacity of the sample, a visual analysis of the electrical treeing phenomenon is difficult. There are also concerns regarding the possible fracturing of the needle tip as well as the creation of micro-voids that may give rise to partial discharges inside them, forcing the treeing process to start at a much lower stress compared to void-free specimens and underestimating this way the real properties of the analyzed material. To solve some of the problems generated by the use of needle-plane configurations, a new more robust test set-up based on wire plane geometry has been developed at Chalmers in conjunction to examining the effectiveness of various voltage stabilizers [6 - 8].

In this paper the influence of thermal and electrical stresses on the electrical treeing characteristics of low density polyethylene was studied. The thermo-electrical ageing was performed on tree test objects at a DC voltage of 10 kV and a temperature of 80°C, lasting from 100 to 800 hours. Electrical treeing was thereafter tested under a ramping AC voltage with a real-time microscope detection system coupled to a CCD camera. The obtained results are analyzed by means of a two-parameter Weibull distribution.

2. Method

2.1. Test objects

The test objects were manufactured following the wire plane geometry, comprised of a semiconducting tab, a tungsten wire electrode of 10 μm diameter and LDPE insulation material to be tested, manufactured by Borealis and supplied by ABB Corporate Research in Västerås. The tungsten wire was hand sewn into the semiconducting tab leaving a half-circle loop to act as the high field electrode. The semiconducting tab with the sewn wire was pressed between two strips of LDPE and the joining took place at a temperature of 130°C and a pressure of 200 kN. After finalizing the pressing procedure the samples were degassed for 7 days in a vacuum oven at 60°C to remove any eventual byproduct formed during the pressing stages. Finally, all samples were cut at the bottom edge at a distance of 3 mm from the wire loop to create the plane electrode. A general view of the complete test object with dimensions is shown in Fig. 1.

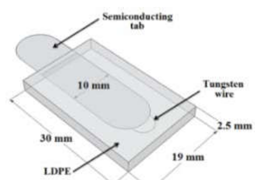

Fig. 1 – General view of the wire – plane test object with dimensions

As a side-effect of the manufacturing process, kinks were observed in most of the test samples. In addition, the final shape of the high field wire electrode varied because of the heating and slow cooling steps during the pressing process.

2.2. Experimental set-up

A set-up used for applying the various aging conditions with carefully controlled parameters (voltage, temperature and polarity) was built, as illustrated in Fig. 2. Its components include an oven, a variable AC transformer for controlling the aging temperature and a high voltage DC supply for applying the test voltage to the samples. The set-up was also equipped with a protection system designed to shut it down in case of smoke detection.

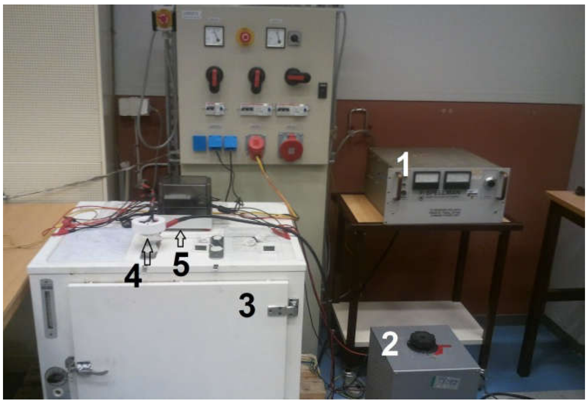

Fig. 2 – DC thermo-electrical ageing set-up: (1) HVDC supply; (2) variable AC transformer; (3) oven; (4) smoke detector; (5) fire safety control box

In order to gather knowledge on potential influence of high DC electric stress on the properties of polyethylene used in high voltage direct current applications, the test-objects were thermo-electrically aged at 80°C and a DC voltage of 10 kV of both polarities, up to 800 hrs.
Electrical treeing tests were performed in a set-up, shown in Fig. 3, equipped with a custom made sample holder, under a 50 Hz ramping AC voltage (provided by a 75 kV transformer) with a ramping speed of 0.5 kV/s.

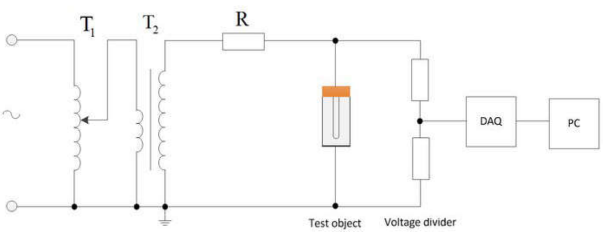

Fig. 3 – AC electrical treeing experimental set-up

2.3. Weibull statistics

The most common statistical tool for characterizing solid insulating materials is the Weibull analysis. It is widely used for studying the electrical treeing phenomena. As described by the IEEE Guide for the Statistical Analysis of Electrical Insulation Breakdown Data [9], the two-parameter Weibull distribution is expressed by a cumulative density function as follows:

$$F(t;\alpha,\beta)=1-\exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \quad (1)$$

where t represents the measured parameter (time to breakdown or breakdown voltage), $F(t)$ is the failure probability at a time or voltage lower or equal to t, α is the scale parameter, always positive, and β is the shape parameter, also always positive.
To avoid the influence of kinks on the treeing conditions only trees grown further away from these defects should be considered for analyses.

3. Results and discussion

Electrical treeing tests were performed by applying a ramping AC voltage on an initial number of 20 unaged samples, considered to be a reference data set. By comparison with XLPE data from previous works the behavior of the reference batch was satisfactory, the only deviations in the distribution parameters being due to material differences. It was revealed that the presence of the semiconducting tab influence the value of the tree inception voltage. As seen in Fig. 4, the inception voltages for trees growing on wires with a shorter loop height were significantly larger. This can be explained by a screening of the wire electrode (electric field strength reduction) by the semiconducting tab and this way determining an increase of the tree inception voltage.

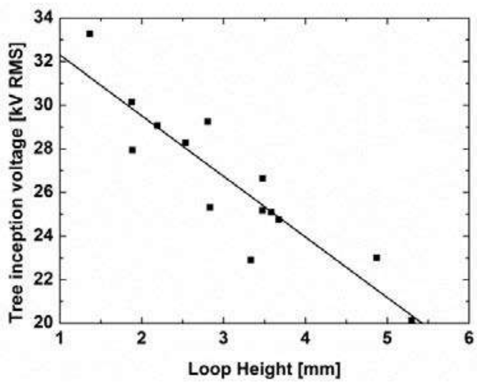

Fig. 4 – Dependence of tree inception voltage on the wire electrode loop height

To further study the behavior shown above, the sample configuration was simulated by means of Comsol Multiphysics software, taking into account the presence of the semiconducting tab, for properly explaining the higher tree inception voltage observed for shorter loop heights. The simulation resulted in a simple expression illustrating the variation of the electric field on the wire surface as follows:

$$E_{max}=K\cdot U \quad (2)$$

where E is the electric field strength on the wire (kV/mm), U represents the applied voltage (kV) and K is a field enhancement coefficient (mm^{-1}). It was observed that the electric field strength as well as the field enhancement coefficient increases with increasing loop height (Fig. 5) due to the screening of the electric field at the surface of the high voltage electrode by the semiconducting tab.

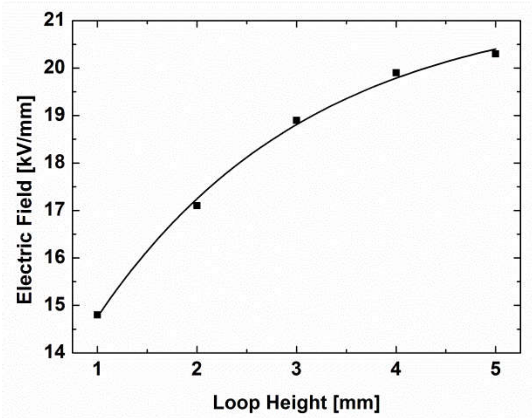

Fig. 5 – The simulated electric field strength at the tip of the wire loop with increasing loop height

For investigating the effect of ageing, the test objects have been exposed to thermal and electrical ageing from 100 to 800 hours. Fig. 6 illustrates the two-parameter Weibull distribution of the tree inception voltage for the samples aged under -10 kV. The results show that the plots are consistently shifted to the left with increasing ageing time. The tree inception voltage suffers a 25% reduction in the objects aged for 800 hours compared to the reference batch. The Weibull distributions for the other ageing cycles, thermal and +10 kv electro-thermal, follow a similar trend to that shown below.

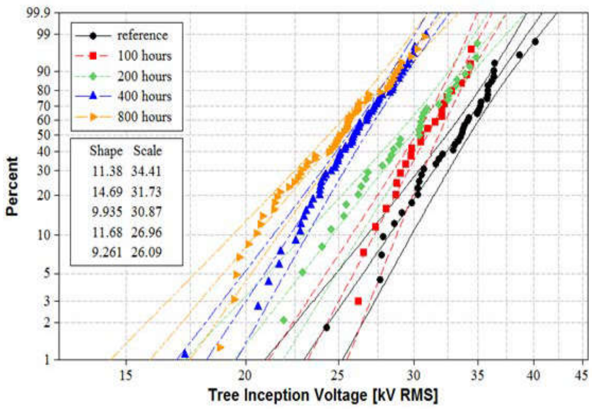

Fig. 6 – Plot of two-parameter Weibull distribution for LDPE samples aged at 80°C and -10kV DC for various times

Due to thermal and electro-thermal ageing, the tree inception voltage rapidly decreases within the first 200 hours of ageing, gradually reaching a more stable level. Nevertheless, there are no significant differences in the results for both thermal and electro-thermal ageing cycles, the tree inception voltage under all tested ageing conditions being located within a 5% error range. Fig. 7 presents the varying Weibull scale parameter with ageing time.

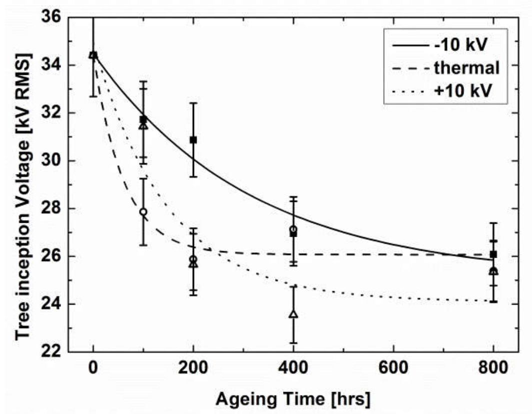

Fig. 7 – Variation in the Weibull scale parameter with increasing time for LDPE samples aged at 80°C and -10 kV

Besides the decreasing tree inception voltage, the effect of thermal stress on LDPE was also evident in FTIR and DSC analysis.

The FT-IR spectra acquired for thermally aged wire-plane test objects reveal a linear increase in the carbonyl group content (1710 – 1730 cm^{-1}) with increasing ageing time, as shown in Fig. 8.

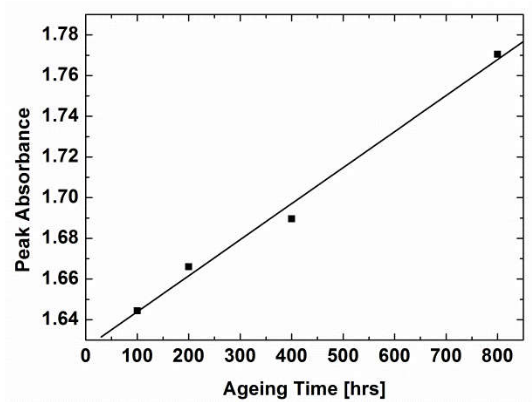

Fig. 8 – Variation in the carbonyl absorbance peak with ageing time

The antioxidant was observed to migrate during the ageing cycle and initial heating treatments. As a consequence of this consumption, the increase in the carbonyl groups suggests the occurrence of a thermo-oxidative process. This illustrates that free radicals, which are known to have a very important role in the treeing initiation stage by causing repeated polymer chain scissions [10, 11], are being formed during the thermal ageing process. By accumulation in the polymer matrix, the free radicals will trigger an auto-oxidation process, thus forming a micro-cavity which leads to the appearance of a rapidly growing tree channel.

Fig. 9 shows the typical DSC curves for the tested samples with increasing ageing time. Two distinct melting peaks can be observed: a main melting peak in at 115°C – 119°C range, attributed to the melting of the insulating material and an additional smaller peak which varies with the thermal ageing time from 70°C up to 100°C.

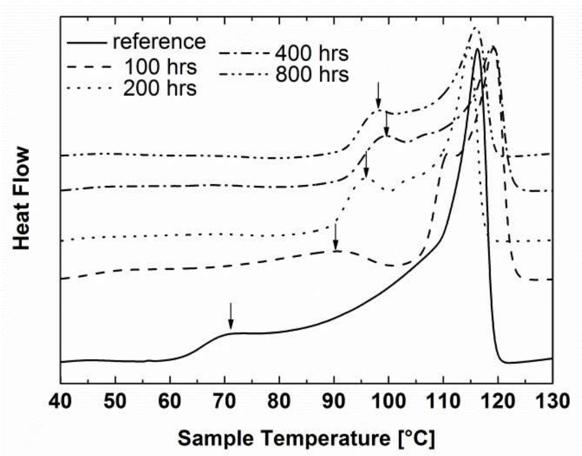

Fig. 9 – DSC melting curves for of test objects with increasing ageing time

By comparing the DSC curves it was noticed that the small melting peak shifts to higher temperatures with the thermal ageing time. This peak is most likely attributed to a recrystallization of the polymer matrix during the thermal treatments. The process will cause a growth of the free volume thus increasing the mobility of the charge carriers and facilitating tree initiation.

4. Conclusions

The semiconducting tabs caused a screening of the electric field strength at the wire electrode. Thus, for samples in which the wire electrode lies closer to the semiconducting tab electrical trees develop at higher voltage levels.

The electrical tree inception voltage consistently decreased with increasing ageing time, whereas the applied DC electric stress had negligible effect and the observed change was mainly due to the thermal stress.

The dominant influence of thermal stress on the treeing process in LDPE was confirmed by DSC and FTIR analyses. It was seen that the DSC small melting peak moved to higher temperature with prolonged ageing time. FTIR analysis demonstrated that a thermo-oxidation accompanied by a loss of antioxidant occurred in the ageing process with a growing content of carbonyl groups.

5. Acknowledgements

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6. References

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