Comparison of Test Setups for High Field Conductivity of HVDC Insulation Materials

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Abstract

Electrical conductivity is considered to be a key property for HVDC insulation. For cable insulation the conductivity level has to be sufficiently low in order to avoid a large leakage current that could cause heat generation in the insulation and contribute to additional transmission losses. The distribution of conductivity in the radial direction of the cable insulation dictates the distribution of electric field and space charge at steady state. It is therefore of interest to know the conductivity characteristics of insulation materials intended for HVDC cables.

This paper presents a test method and procedure for evaluating the high field electrical conductivity of HVDC insulating materials and crosslinked polyethylene in particular. The results presented in this paper are generated from two nearly identical measurement setups using the same sample geometry, but installed in two different test facilities (ABB and Borealis). The results reveal that differences in conductivity can be seen; even between test setups with only minor differences and that the influence of sample preparation is crucial to obtain reproducibility. However, the decay of the measured current was observed to be relatively different between the measurement set-ups.

1. Introduction

The conductivity characteristics of polymer insulation materials can be evaluated using a variety of test samples such as flat plates, molded cups, model cables and full-scale cables. The smaller samples are often favored due to lower cost and shorter time to obtain results. At the early stage of material development it can also be difficult to manufacture the quantities of materials that would be needed for cables. Furthermore, for quality check of insulation materials it can also be advantageous to use small samples to measure e.g. electrical conductivity at well-defined test conditions.

In order to obtain reliable and reproducible measurement data of the electrical conductivity of polymeric materials used for HVDC insulation, several important requirements have to be fulfilled. The data presented in the literature are often generated using different test conditions. This makes a direct comparison of published data difficult and unreliable [1] even though the present standards are followed [2, 3]. There are several parameters affecting the measured leakage current through a test sample that is related to both the measuring system and the sample preparation. The ASTM standard points out that results obtained with different electrode materials will be different, and the choice of electrode materials has shown to be important in numerous of different publications [4-6]. In [7] the authors measured the conductivity with a three terminal electrode system and varied the area of the measuring electrode. They found that a 10 fold reduction of measurement area did not reduce the measured current with the same amount. This was explained by an inhomogeneous current density distribution. However, the presented method could still be used to determine the temperature and electric field dependence of materials, but without knowing the absolute value of the conductivity. The hydrostatic pressure applied on the test sample has also been observed to influence the current in samples made of LDPE [8]. Moreover, the sample preparation and handling is of paramount importance to get reproducible results. In published literature, samples are often either compression moulded directly from pellets or from pre-extruded films with different press parameters, which also can influence the conductivity. Even the choice of backing film has shown to influence when measuring space charges at high electric fields [9].

In this study we will stress the importance and difficulties to achieve similar results on plaque samples prepared and measured using nearly identical preparation steps and measuring system at two different test-laboratories.

2. Experimental set-up and sample preparation

The first measurement set-up is located at ABB corporate research in Västerås, Sweden and the second set-up is installed at Borealis Innovation Centre, Stenungsund, Sweden. The measuring set-ups consist of a three terminal electrode system made of brass and has earlier been described in [10]. The brass electrodes are Rogowski shaped and have diameter of 200 mm and the measuring electrode diameter is 100 mm. To prevent partial discharges and increase the flashover voltage the electrodes are partly surrounded by a transparent silicone rubber (see Fig. 1). The current is recorded with an electrometer or picoammeter from Keithly. The most significant difference between the two different set-ups is the way by which they are heated. The set-up at ABB is heated by pipes attached to the electrodes, circulated with heated oil, whereas the set-up at Borealis is heated in an oven ventilated with dried air to keep the environment around the samples as constant as possible. Since the brass electrodes have a long thermal time constant during heating both set-ups have a temperature sensor attached to the lower electrode to measure the actual electrode/sample temperature. At Borealis two identical set-ups have been installed and these are connected in parallel to the same HVDC-generator, which allow two samples to be measured simultaneously. During mounting of a new test sample on the Borealis set-up at for example a test temperature of 70°C, the electrode temperature drop is usually ~5°C due to handling and opening of the oven. Therefore the electrode system needs to be heated for at least 1 h before the measurement starts. This is typically not needed for the set-up at ABB since the sample can be mounted without switching off the circulation of heated oil. The current and sample temperature is recorded every second. The plaque samples used in this study have been compression moulded at 180°C and 200 bar with similar procedures used at both ABB and Borealis. Three different materials have been used in this study based on their differences in conductivity range. Materials from the same batches were used at both locations for the experiments to be able to compare the same materials. The current measured in this study is presented as conductivity (S/m) and the measurements are made at 70°C and 30 kV/mm during approximately 24 hours.

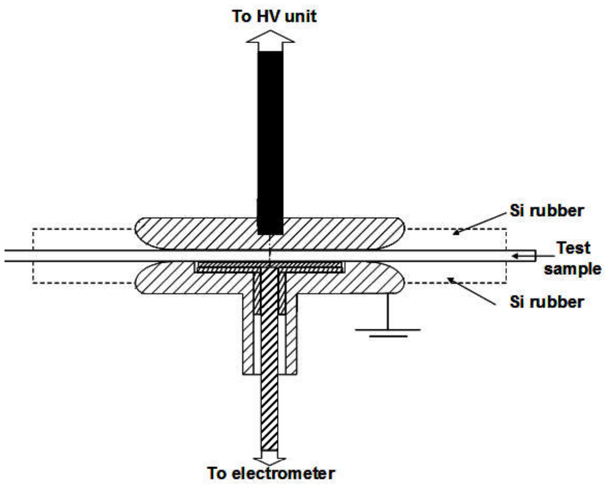

Fig. 1. Schematic of experimental setup with a three terminal cell for conductivity measurements.

3. Experimental results and discussion

Experimental results of the first material is summarized in Fig. 2, where six samples were measured at Borealis (black curves) to study the scatter in the measurement data and one sample was measured at ABB (grey curve). For the measurements performed at Borealis all data followed the same trend except for one measurement that stabilized on a higher level after approximately 40000 s compared to all the other samples. The reason for this behavior could not be identified since no discrepancies could be observed during visual inspection of the plaque sample or the temperature logging. The average conductivity was calculated between 22-23 h (79200-82800) to $(7.7\pm4.4)\cdot10^{-14}$ S/m for the Borealis samples excluding the sample with high conductivity and $7.6\cdot10^{-14}$ S/m for the sample measured at ABB. Even though the final conductivity measured at the two different locations was very similar, the curve shape was different by a lower absolute value of the recorded current measured at ABB (grey curve) throughout most of the measuring time.

Fig. 3 presents the average conductivity for each hour with standard deviation for each 5000 s for the Borealis measurements presented in Fig. 2, excluding the data from the sample with highest conductivity. The standard deviation is decreasing with test time, which indicates that measurements after a longer period of test time are more reliable when comparing measurement results.

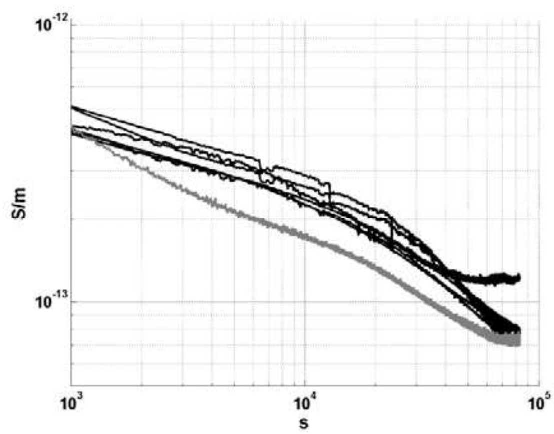

Fig. 2. Conductivity measurements of the first material. Black curves are measurements performed at Borealis and grey curve present the measurements done at ABB.

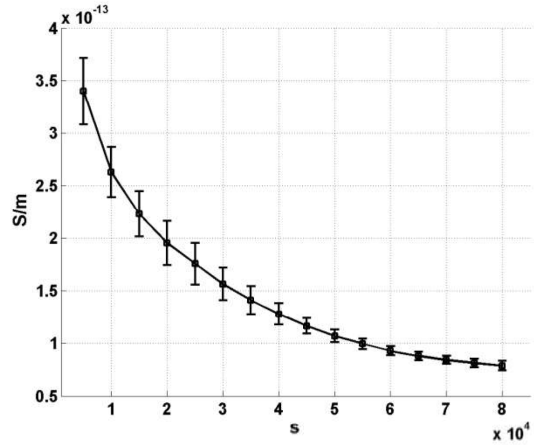

Fig. 3. Average conductivity for each hour of the measurements performed at Borealis in Fig. 2 (without the sample with highest conductivity).

In Fig. 4 the temperature data from the Borealis measurements in Fig. 2 are presented. Due to the large solid brass electrodes the time to reach a stable temperature is ~10000 s plus the extra conditioning time before measurements start. It can also be observed that the temperature reached 69.4°C and 69.8°C in oven 1 and oven 2 respectively. In order to minimise the time between measurements an oven where the temperature regulation is controlled by a temperature sensor in the electrode have been installed, together with a computer controlled regulation that can significantly decrease the time to reach a stable test temperature. The system at ABB that heats the electrodes with oil is faster to reach a stable temperature. The main advantage of this heating system is that it allows higher voltage during measurements since no bushing is needed through an oven wall. The maximum voltage is limited by the air insulation distances that in principle could be made very large. A disadvantage of the heating system is that the heating is applied to the high voltage electrode and to the guard electrode but not directly to the measurement electrode. A small temperature gradient will therefore be formed across the test sample above the measurement electrode and the gradient can be further decreased by appropriate thermal insulation below the measurement electrode.

The conductivity measurements of the second material are summarized in Fig. 5, where two measurements were measured at Borealis (black curves) and one at ABB (grey curve). The two measurements performed at Borealis show almost an identical curve form and the final conductivity at 22-23 h was $3.9 \cdot 10^{-13}$ and $3.7 \cdot 10^{-13}$ S/m respectively and the measurement at ABB showed a conductivity of $2.0 \cdot 10^{-13}$ S/m. The lower value is only about half of the higher value. This despite care was taken to handle the test samples in a similar way at the two laboratories, it is likely that a small difference in the pre-treatment conditions would results in a change in conductivity.

The measurement result from the third material is presented in Fig. 6, and similar to the first and second materials Borealis measured a higher conductivity ($1.2 \cdot 10^{-14}$ S/m and $1.0 \cdot 10^{-14}$ S/m compared to $6.0 \cdot 10^{-15}$ S/m that was measured at ABB). Even though the absolute difference of the conductivity is small, the lowest value is still only about half of the highest value, and this could be an indication of the uncertainty of the method.

In this study similar compression moulding parameters were used and the backing film used was made of the same type of material. The steel plates used during moulding could have caused minor differences on the surface roughness of the samples prepared at ABB compared to Borealis. To reduce the influence of surface roughness the steel plates at Borealis were covered with a smooth sheet of aluminum. Another parameter that needs further investigation is the influence from small temperature variations between the two set-ups. Furthermore, an aligned cleaning procedure of the electrodes or samples between ABB and Borealis was not clearly established prior to testing.

The conductivity is calculated as

$$\sigma = \frac{j}{E} = \frac{I/A}{U/d} \qquad (1)$$

where j is current density, E electric field, I current, A area of the measurement electrode, U voltage and d the thickness of the sample. An uncertainty in d of 5% would then translate into the same uncertainty in the conductivity. However, due to the exponential dependence of the field the actual uncertainty would be larger. It is often assumed that the conductivity depends on temperature and electric field as

$$\sigma = \sigma_{293} e^{-\frac{E_A}{k_B}\left(\frac{1}{T} - \frac{1}{293}\right)} e^{\gamma|E|} \qquad (2)$$

E_A is the activation energy, k_B the Boltzmann constant, T is the temperature in K, and γ is the field exponent. Setting γ to 5×10^{-8} m/V, the 5 % uncertainty in sample thickness translates into approximately 8% uncertainty in conductivity.

The influence of uncertainty in temperature on the measured conductivity can also be evaluated from Eq. (2). For materials having activation energies E_A equal to e.g. 0.5 and 1.5 eV, a variation of 1 K would translate into variations in conductivity of 5 % and 16 % respectively. Based on these estimates it is concluded that the large differences seen for some of the data included in this paper cannot simply be related to uncertainties in the control of temperature or sample thickness. Instead, the differences reflect the sensitivity of the tested materials to variations in preparation and pre-treatment of the samples, and this cannot easily be avoided by the choice of testing method. Thus, this does not only emphasise the need for a standardisation of measuring conductivity, but also a standardised method of preparation and pre-treatment of samples.

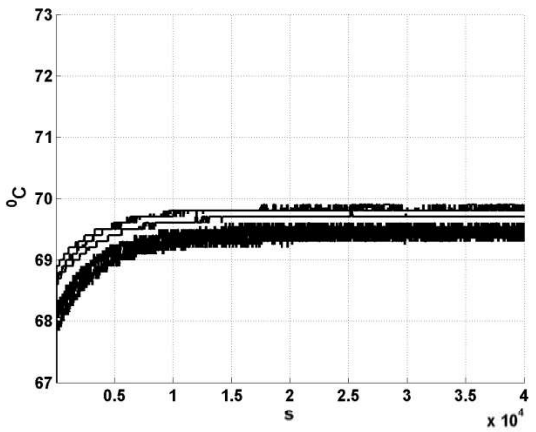

Fig. 4. Temperature data obtained from the sensor in the lower electrode on the Borealis set-up from the measurement data on the material in Fig. 2.

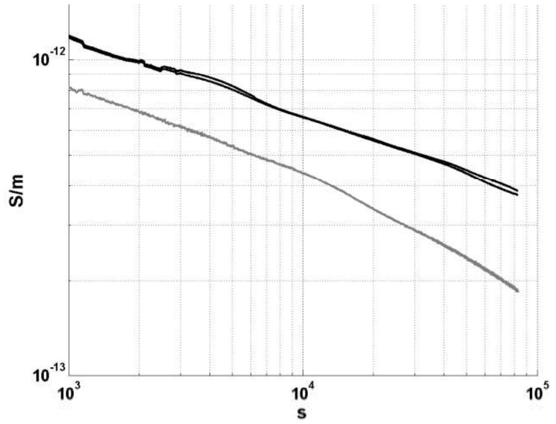

Fig. 5. Conductivity measurements of the second material. The two black curves were measured at Borealis and the grey curve at ABB.

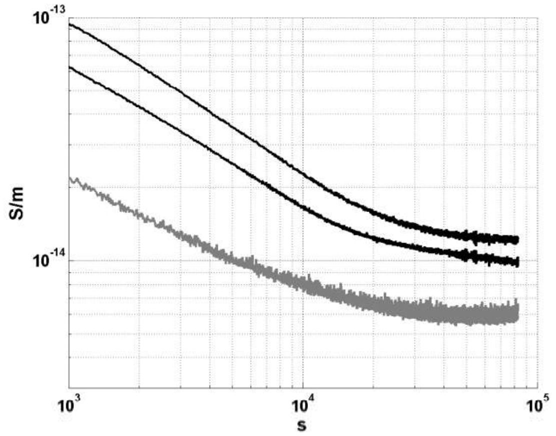

Fig. 6. Conductivity measurements of the third material, black curves are measurements performed at Borealis and grey curve represents the measurements done at ABB.

4. Conclusions

From the data generated within this work it can be concluded that there are differences in conductivity, even between test setups with only minor differences. However, it is also seen that it is possible to have reproducibility between two different test cells as long as parameters, such as sample preparation, electrode set-up and measurement protocols are kept constant.
The differences in conductivity between the different test set-ups further emphasise the significance of a standardised test arrangement and methodology in order to achieve reliable conductivity measurements of insulating materials.

5. References

[1] Ildstad E, Nysveen A, Sletbak J, Nyberg BR, "Factors affecting the choice of insulation system for extruded HVDC power cables", CIGRÉ, D1-203, 2004.

[2] ASTM D257-07. *Standard test methods for DC resistance or conductance of insulating materials*, 2007.

[3] IEC 60093. *Methods of test for volume resistivity and surface resistivity of solid electrical insulating materials*, 1980.

[4] Sanden B. *XLPE cable insulation subjected to HVDC stress, space charge, conduction and breakdown strength*, PhD- Thesis, NTNU, 1996.

[5] Suh KS, Lee CR, Noh JS, Tanaka J, Damon DH. "Electrical conduction in polyethylene with semiconductive electrodes". IEEE Transactions on Dielectrics and Electrical Insulation, vol 1, no 2, 1994, pp 224-230.

[6] Crine JP. "On the interpretation of some electrical aging and relaxation phenomena in solid dielectrics", IEEE Transactions on Dielectrics and Electrical Insulation, vol 12, no 6, 2005, pp 1089-1107.

[7] Aladenize B, Coelho R, Assier JC, Janah H, Mirebeau P. "Field distribution in HVDC cables: dependence on insulating materials". 4th international conference on insulated power cables (Jicable 1999), Paris, 1999.

[8] Malec D, Truong VH, Essolbi R, Hoang TG. "Carrier mobility in LDPE at high temperature and pressure", IEEE Transactions on Dielectrics and Electrical Insulation, vol 5, no 2, 1998, pp 301-303.

[9] Suh KS, Jung Hoe K, Seung Hyung L, Jung Ki P, Takada T. "Effects of sample preparation conditions and short chains on space charge formation in LDPE", IEEE Transactions on Dielectrics and Electrical Insulation, vol 3, no 2, 1996, pp 153-160.

[10] Olsson CO, Källstrand B, Ritums J, Jeroense M, "Experimental determination of DC conductivity for XLPE insulation". 21st Nordic insulation symposium (Nord-Is 09), June 15-17, Gothenburg, Sweden, 2009.