Influence of Semicon Shields on the Dielectric Loss of XLPE Cables

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Abstract- **Dielectric response measurement techniques in both time and frequency domains are studied in order to measure the dielectric loss of XLPE cables, which have very low losses. A high sensitivity transformer ratio bridge system, which can measure loss tangents as low as 10^{-5}, has been developed with the ability to measure these cables. A tuned amplifier was designed to help to extend the frequency range from 200Hz to 20kHz. Different model cables from Borealis AB with different semiconducting materials have been measured in the temperature range 15^{o}C to 120^{o}C. It is found that the semiconducting layers dominate the dielectric loss in the insulation system of the XLPE cables, when the outer semicon is treated as measuring electrode. In this case, steadily increasing dielectric loss has been measured at higher frequencies. The resistivity of the semiconducting materials was measured, which confirmed that the increasing slope is due to the semiconducting layers. After using conductive tapes to wrap the cable samples, monotonically decreasing losses were measured, corresponding to the actual dielectric frequency response of the XLPE cables. It is concluded that the axial resistance of semiconducting shields have a substantial influence on the dielectric loss of XLPE cables, especially for dielectric response in high frequency range. A device on measuring the loss of such cables is presented.**

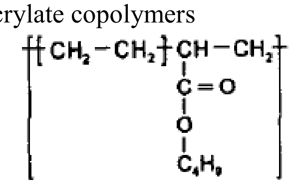
I. INTRODUCTION

Because of the intrinsic breakdown strength of up to 800kV/mm and increased maximum operating temperature from 70°C to 90°C after cross linking [2], XLPE cables are the best choice and dominating in power industry nowadays. Since the XLPE cables were introduced in the 1960s, numerous tests on cables at all voltages have clearly shown that the semiconductive screening layers play a very important role in the successful operation of a power cable. The semiconductive compounds have been the subject of tremendous development over the last two decades and have kept pace with the advances in cable technology. [1]

Research on semicon cable shields has been playing an important role in the development of electric power cables. Semiconducting materials are essential components of the power cable, because they are used for:

a. preventing partial discharge at the interfaces between the insulation and conductor and between the insulation and external shielding layer;
b. moderating the electrical stress in the insulation layer by providing a uniform electric field around the cable insulation with reduced potential gradient;
c. providing protection during short-circuit against damages caused by the heating of the conductor.

In power cables, conducting carbon black (CB)-filled ethylene copolymers, such as ethylene-butyl acrylate, ethylene vinyl acetate and ethylene ethyl acrylate, are commonly used as a semiconducting layer [2]. Different kinds of cables should have different suitable shields. Shields that are designed for use with XLPE dielectric are often not suitable for use with EPR dielectric, and vice versa. Likewise, the appropriate shield also depends on the configuration of the extrusion line on which the cable is manufactured [3]. In this research project specifically the semiconductinve materials used are ethylene-butyl acrylate copolymers



Factors such as CB content, mixing quality and temperature that affects CB network development, affect the properties of CB filled semiconductors. Based on previous research studies, increasing CB loading and process temperature can decrease the volume resistivity, which usually vary between 10 and 100 Ω cm and should not exceed 10^4 Ωcm [5][6].

It is known that the semiconductive layers can influence the loss tangent of power cables. This is surely related to the electric conductivity of the semicon in the radial direction; if the conductivity is too low, there will be losses not only in the insulation but also in the semicons, especially at higher frequencies [7]. The axial resistance of semicon layer will dominate the dielectric loss if it is not well grounded, as we found in this paper. Recently there is more awareness of the influence of semicon shields on the dielectric loss of power cables [8]. Therefore, the study of electrical properties on XLPE cables must include the influence of semicon shields, because they are essential part of the insulation system for power cables.

In this study, the XLPE homopolymer cables with two types of semicon layers, standard and supersmooth semicon materials, were measured with dielectric spectroscopy technique in order to find the loss origins of power cables. Conductivity measurement of the semicon materials was also carried out for explaining the loss tangent measurement. The influence of semicon layers on the dielectric loss of the cables was investigated with equivalent circuit modelling.

II. Experiment Setup

Transformer ratio bridge technique was utilized in this study, as it has two main advantages over Schering bridge technique for low-loss dielectric measurement: 1, impedances between the unknown and earth do not affect the bridge balance so that long screened leads and guarded electrodes can be used; 2, the voltage transformer can be tapped accurately to obtain decade ratios so that only a few standards are required. The measurement system is shown in Figure 1. Wayne Kerr universal bridge B221 was used together with signal generator as external source for the inductive bridge. The oscilloscope was used to monitor the bridge balance. A tuned amplifier was designed to extend the accuracy range down to 300Hz. DC battery was used to replace the mains power supply to drive the bridge with further improvement against noises. The system frequency range was maximized to 300Hz~10kHz and it has sensitivity of 10^{-5} for loss tangent measurement.

The XLPE model cables were produced by Borealis. They all have the same homopolymer insulation layer of 1.5mm and two different semicon materials, which are called standard semicon (cable AAA) and supersmooth semicon (cable BAB). The cable samples were prepared with 5m length. They are degassed at 80C for 5 days and put in an oven for measurement under different temperatures. Before measurement, the system was calibrated to cancel out the lead effect and background noises. The capacitance and conductance were measured on the cable samples.

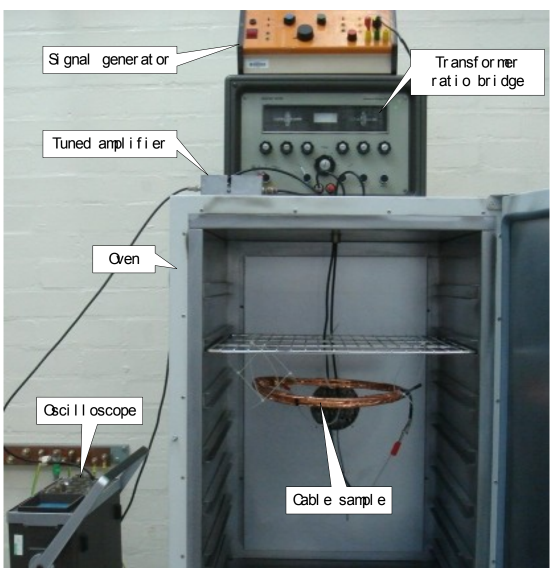


Figure 1 Transformer ratio bridge system setup

The measuring electrode was prepared in two different ways. As a traditional method, the outer semicon layer was treated as measuring electrode [9][10]. The current was measured at a random point of the outer semicon shield along the cable, neglecting its axial resistance. After it was found that the axial resistance of outer semicon layer dominated in dielectric loss at higher frequencies, the cable samples were prepared in a better way. They were fully wrapped with copper tapes eliminate the influence of semicon shield's axial resistance. The resistivity of different semicon materials were also measured in order to explain and confirm the loss origin of semicon shield.

III. Results and Discussion

The measurement results on standard semicon cable sample (AAA) are shown in Figure 2 and Figure 3. From Figure 2, the dielectric loss tangent has increased at higher frequencies for all temperatures. Under lower temperatures up to 60C, the spectra have decreasing slopes below 3kHz. This implies two dielectric loss behaviour are present, while the second one became dominant when the temperature was higher. The dielectric loss of the cable AAA is about 10^{-3} at 300Hz and rose to 3×10^{-2} at maximum. The temperature spectra in Figure 3 shows that there is a peak at 90C for all frequencies.

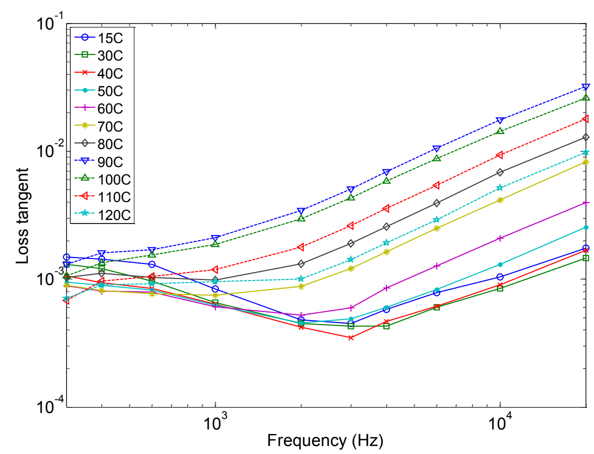


Figure 2 Frequency spectra of cable AAA

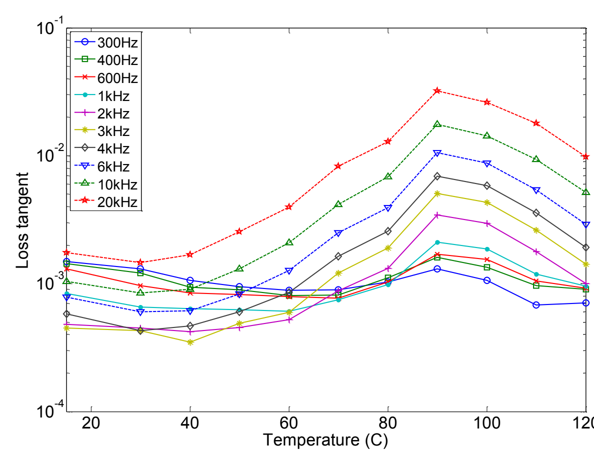


Figure 3 Temperature spectra of cable AAA

The measurement results on supersmooth semicon cable sample (BAB) are shown in Figure 4 and Figure 5. The frequency spectra are very similar with those of cable AAA. The shapes of temperature spectra are also similar, except that the temperature of maximum loss tangent is at 100C.

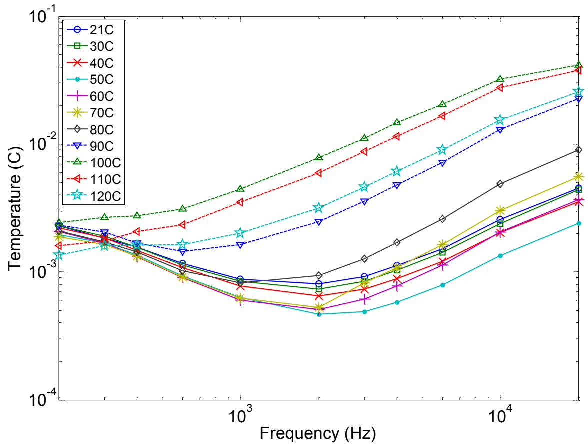


Figure 4 Frequency spectra of cable BAB

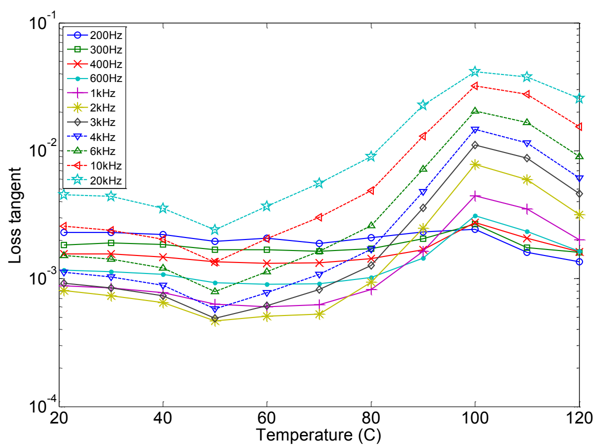


Figure 5 Temperature spectra of cable BAB

In order to find the reasons for the increasing dielectric loss and the difference of loss peak temperatures, the DC resistivity measurement was carried out on these two different semicon materials under various temperatures. In Figure 6, in comparison with the temperature spectra in Figure 3 and Figure 5, the resistivities of semicon materials are plotted in solid lines, together with loss tangent spectra of the cable samples in dotted lines. Both semicon materials have resistivity peaks at 90C and 100C respectively. Their resistivities are from 1Ωm and 100Ωm. From the curves, the dielectric loss peaks for both cables have the same shapes as the resistivity peaks for both semicon materials. This implies that the axial resistance is the main contribution of the loss tangent for both types of cables.

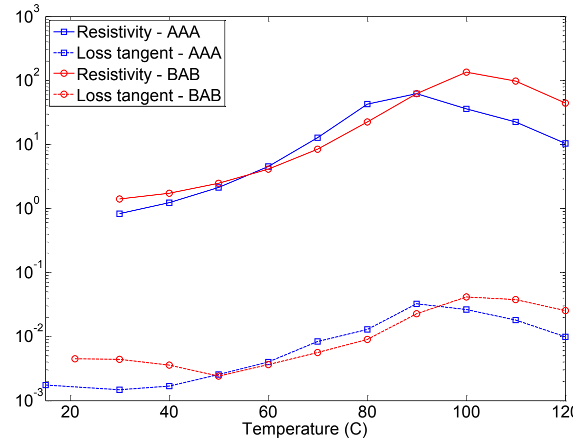


Figure 6 Comparison between resistivity measurement and loss tangent measurement

Equivalent circuit modelling was used to study the effects of semicon layers on the dielectric loss of power cables. Instead complicated circuit networks to describe the power cables, Figure 7 shows the simplified equivalent circuits with semicon layers, with only inner semicon layer and without the semicon layers. In the case with semicon layers, the loss tangent and complex permittivity can be calculated from the impedance by equations

$$Z^* = \frac{R_p + R_0(1+\omega^2 C_p^2 R_p^2)}{1+\omega^2 C_p^2 R_p^2} - j\frac{\omega C_p R_p^2}{1+\omega^2 C_p^2 R_p^2}$$

$$\varepsilon^* = \frac{C_p R_p^2}{C_0[\omega^2 C_p^2 R_p^2 R_0^2 + (R_p + R_0)^2]} - j\frac{R_p + R_0 + \omega^2 C_p^2 R_p^2 R_0}{\omega C_0[\omega^2 C_p^2 R_p^2 R_0^2 + (R_p + R_0)^2]}$$

$$\tan\delta = \frac{R_p + R_0(1+\omega^2 C_p^2 R_p^2)}{\omega C_p R_p^2} = \frac{\varepsilon''}{\varepsilon'}$$

Assuming the resistivity of 1Ωm and cable length of 5m, the inner and outer semicon radial resistance were calculated as 0.0223Ω and 0.0016Ω by equation

$$R = \frac{\rho}{2\pi L}\ln\left({}^{r_2}\!/_{r_1}\right)$$

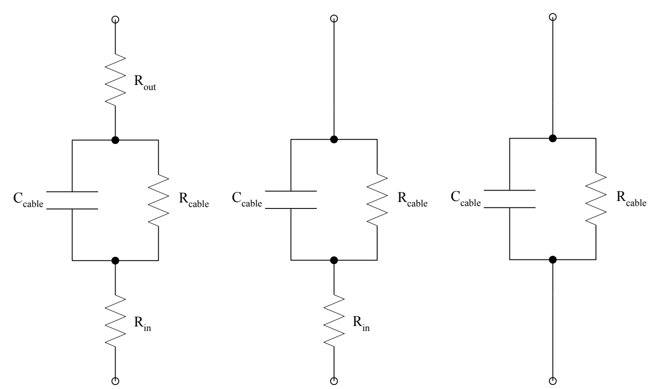


Figure 7 Equivalent circuits of power cables

The modelling results are shown in Figure 8. The pure conduction loss of the insulation layer without any semicon layers has monotonic decreasing slope of -1. This DC conduction loss is not measurable at higher frequencies. It can only be measured at very low frequencies due to instrument measuring limit. The radial resistance of both semicon layers can cause the dielectric loss to increase at 200Hz, but it is beyond the measurement limit. There is not much difference when the outer semicon is removed. However, the loss tangent becomes much higher if there is series resistance due to the contribution of the axial resistance of outer semicon layer. Because the axial resistance is much bigger than the radial resistance for the outer semicon layer, the dielectric loss contribution of the axial resistance is bigger and detectable at lower frequencies. This modelling results agree with the measurement data shown in Figure 2.

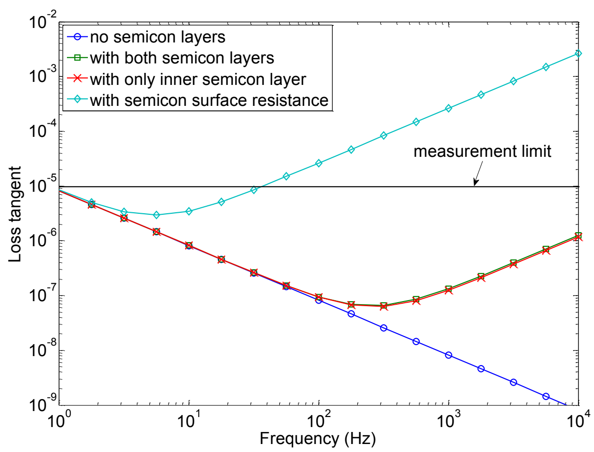


Figure 8 Modelling results on the effect of semicon shields

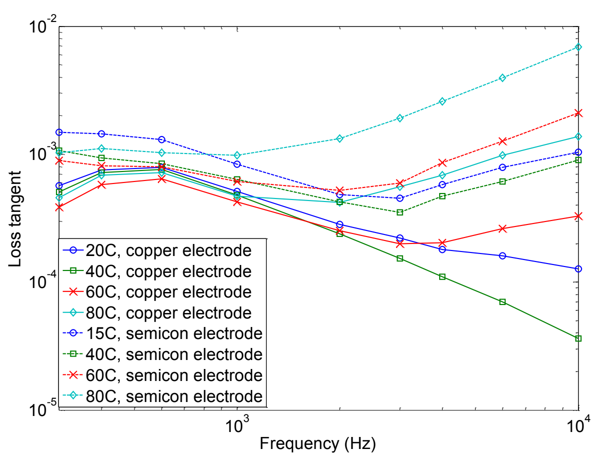


Figure 9 Comparison of the results from different sample preparation methods. (copper electrode: solid lines, semicon electrodes: dotted lines)

The influence of semicon shields was diminished by using conductive adhesive copper tapes to fully wrap the cable sample AAA. From Figure 9, the loss tangent is smaller with copper tape electrode. There is a loss peak in the beginning and this is probably due to relaxation process, because the DC conduction loss is beyond the measurement limit, according to modelling results in Figure 8.

IV. Conclusion

Experiments of triple extruded XLPE model cables have demonstrated the importance of semicon layers in loss tangent measurements. The semicon layers of the XLPE cables have been found dominant in the dielectric loss in the frequency range of 200Hz~20kHz when the outer semicon layer was not in good contact with measuring electrode. Resistivity measurement and equivalent circuit modelling provided the explanations for the influence of outer semicon axial resistance. With totally wrapped electrode, the true loss of the cable insulation can be measured and the radial resistance of semicon layers gave rise to loss tangent only at higher frequencies under higher temperatures. The results imply that the AC power cables have extra dielectric loss origin from semicon layers, compare with DC power cables, especially if the outer semicon layers are not well earthed.

Acknowledgment

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References

[1] C Broman, L Lindbom & U Nilsson, The continuing evolution of semiconductive screening materials for power cable applications, 6th International Conference on Insulated Power Cables, Paris, 2003.

[2] Vahdat Vahedy, "Polymer Insulated High Voltage Cables", IEEE Electrical Insulation Magazine, Vol. 22, No. 3, 2006.

[3] W. R. Kegerise, "Feature article - Manufacturing and Performance Criteria for Medium Voltage Power Cable Semiconducting Shields", IEEE Electrical Insulation Magazine, Vol. 24, No. 2, 2008.

[4] Henryk Herman, Janet Thomas and Gary Stevens, "Exploring relationships between chemical species and electrical properties in cross-linked polyethylene", IEEE Annual Report Conference on Electrical Insulation and Dielectric Phenomena, CEIDP 2005.

[5] Y.Miyashita, Y.Makishi and H.Kato, "New approach to elucidate the properties of carbon black-filledsemiconducting materials for high voltage power cables", IEEE Annual Report Conference on Electrical Insulation and Dielectric Phenomena, CEIDP 1993.

[6] E. J Kim, D. H. Park, H. S. Kim, and G.J. Lee, "An investigation of the influence of semiconductive electrodematerials in the ac breakdown and the charge accumulation in XLPE", IEEE Annual Report Conference on Electrical Insulation and Dielectric Phenomena, CEIDP 1998.

[7] Hongoke et al, "The dielectric loss tangent of extruded polyethylene cables at cryogenic temperature", Trans IEE of Japan, Vol 105, No3/4, 1985.

[8] T.J.Person, P.J.Caronia, S.J.Han, "The Influence of the Semicon on Cable Dielectric Losses", ICC Spring Meeting, 2006.

[8] Peter Werelius, *Development and Application of High Voltage Dielectric Spectroscopy for Diagnosis of Medium Voltage XLPE Cables*. PhD thesis, Stockholm: KTH, Electrical Engineering, 2001.

[10] P. Werelius, P. Tharning, R. Eriksson, B. Holmgren, and U. Gafvert, "Dielectric spectroscopy for diagnosis of water tree deterioration in XLPE cables", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 8, No. 1, pp. 27–42, 2001.