Dielectric spectroscopy study of thermally-aged extruded model power cables

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Abstract—**"Model" extruded power cables, having a much reduced geometry but using the same extrusion techniques and materials as full-sized cables, have been examined using dielectric spectroscopy techniques to study their thermal ageing effects. Cables insulated with homo-polymer XLPE and co-polymer of XLPE with micron-sized ethylene-butyl-acrylate (EBA) islands were studied by both frequency-domain and time-domain dielectric spectroscopy techniques after accelerated thermal ageing under 135°C for 60 days. In the frequency domain, a frequency response analyzer (FRA) was used to measure the frequency range from 10^{-4}Hz to 1Hz at temperatures from 20°C to 80°C. In the time domain, a special charging/discharging current measurement system was developed to measure the frequencies from 10^{-1}Hz to 10^{2}Hz. These techniques were chosen to cope with the extremely low dielectric losses of the model cables. The results are compared with those from new model power cables that were degassed at 80°C for 5 days. Thermal ageing was found to increase the low-frequency conductivity, permittivity and the discharging current. Both homo- and co-polymer cables have substantial increase of dielectric loss after ageing.**

Keywords- dielectric spectroscopy; model power cables; XLPE; thermal ageing

I. INTRODUCTION

Power cables are critical components of power systems, and nowadays their insulation system needs to withstand high voltages up to 500kV with reliable long-term operation and insulation thickness as thin as possible. Therefore, the study of the ageing effect upon the insulation system of power cables is of interest to the cable manufacturing industry and the utilities.

Dielectric spectroscopy is a powerful tool in both ageing and fault detection for insulation systems including power cables [1-3]. Dielectric loss mechanisms which lead to energy dissipation and ageing of the insulation material can be studied by this means. Despite various spectroscopy techniques in both frequency and time domain, the dielectric loss measurement of XLPE cables is beyond the abilities of many commercial instruments because: 1) XLPE homo-polymer theoretically contains only very weak polar molecular groups and is without a net permanent dipole, thus has a very low dielectric constant and energy dissipation factor; 2) commercial XLPE after subsequent thermal conditioning results in a material with low levels of added substances such as can contribute to electrical conductivity and dielectric loss; 3) XLPE cables have much thicker insulation than typical film samples used for dielectric spectroscopy.

It is not possible to study the loss mechanisms of power cables with measurements on thin film samples because of the following reasons: 1) the morphological characteristics (crystalline lamella) of thin films are different from the bulk insulation layer of XLPE cables; 2) unlike film samples, the carbon black filled polymer semiconducting layers have unique dielectric properties and may contribute to the dielectric loss of power cables; 3) the concentration and distribution of insulation defects (by-products and impurities) inside power cables produced by the triple extrusion manufacturing process is different from film samples.

In order to study the dielectric properties of power cables more accurately, model cables with triple extrusion comprising a conductor, semiconducting layers and XLPE insulation were prepared. Their dielectric characteristics were studied by means of both frequency and time domain dielectric spectroscopy, in order to determine the loss mechanisms of the XLPE power cables. Thermal ageing effects were investigated in this paper for different types of model power cables with dielectric spectroscopy systems from 10^{-4}Hz to 10^{2}Hz.

II. EXPERIMENTAL SETUP

A. Cable sample preparation

The model power cables have three insulation materials. Two of them (coded as A and B) have homo-polymer insulation but different base resins. The other (coded as C) is a co-polymer with micron-size ethylene-butyl-acrylate (EBA) islands. Inner and outer semicon materials comprising of carbon loaded EBA resins (coded A) were combined with the three insulating materials. The cables were therefore described by a three letter code including the inner semicon, insulation and outer semicon materials respectively, e.g. "ABA" means cable insulation with semicon A and insulation B. The solid central copper conductor is 1.4 mm in diameter. The inner semicon layer is 0.7 mm thick and the outer semicon layer is 0.15 mm thick. The insulation layer is 1.5mm thick. The model power cables with different insulation were cut into 5 meter lengths and thermally aged in an oven at 135°C for 60 days.

The thermal ageing is an accelerated ageing process and imitates the long term actual thermal ageing condition of power cables. As shown in Figure 1, the colour of the XLPE insulation layer changed from grey to dark brown, which indicated chemical reactions have occurred inside the insulation material. Unaged cables that were measured for comparison were degassed at 80°C for 5 days.

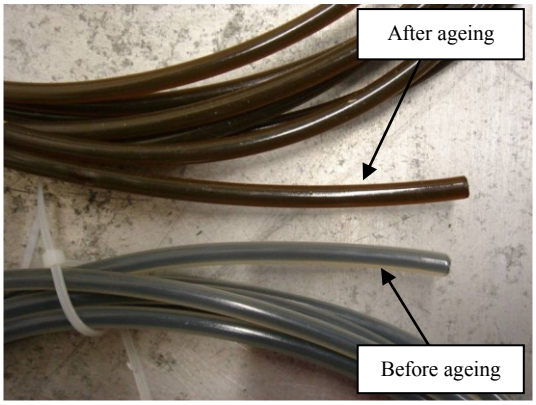

Figure 1 Cable insulation before and after thermal ageing. Model cables without outer semicon layer were used in the photograph

B. Measurement techniques

Measurement techniques have been carefully chosen for accurate low loss measurement of the model cables. A Frequency Response Analyzer (FRA) was used to measure low frequencies from 10^{-4}Hz to 1Hz, above which the dielectric loss is below the noise floor of the FRA technique, as detailed in [4]. The time domain charging/discharging current was measured from 1ms to 10s, and Fourier Transformation was used to obtain the frequency spectra from 0.1Hz and 250Hz [5]. Electrical conductivity of the cable insulation was measured by measurement of the steady state current using the time domain system. For every cable sample, measurements were carried out at temperatures from 20°C to 80°C.

III. MEASUREMENT RESULTS

A. FRA measurement results

The real permittivity ε' and imaginary permittivity ε" of homo-polymer cable AAA are plotted together in Figure 2, in order to judge the types of dielectric loss. It was found that unaged homo-polymer cable AAA has the lowest dielectric loss, with ε" only measurable at 80°C. After cable AAA was aged, the ε" was found to have increased considerably. The ε" at 60°C was about the same (ε"≈0.15) as that of unaged cable at 80°C for f=10^{-4}Hz. The ε" of aged homo-polymer cables has a slope of very close to -1 in the log(ε") - log(f) plot. Since the ε' has a very small increment at lower frequencies, the dielectric loss can be taken to be mainly due to DC conductivity.

The results for co-polymer cable ACA before and after ageing process are shown in Figure 3 and Figure 4. The co-polymer cable was found to have higher dielectric loss than the homo-polymer cables. The ε" increased significantly after thermal ageing and by a greater amount at higher temperatures. An additional loss peak in the unaged cable sample can be seen for 60°C and 80°C in addition to the DC conduction loss. These loss peaks are related to the increment in the real permittivity ε' at lower frequencies, as shown in Figure 4. However, this loss peak is overwhelmed by conduction loss especially after ageing.

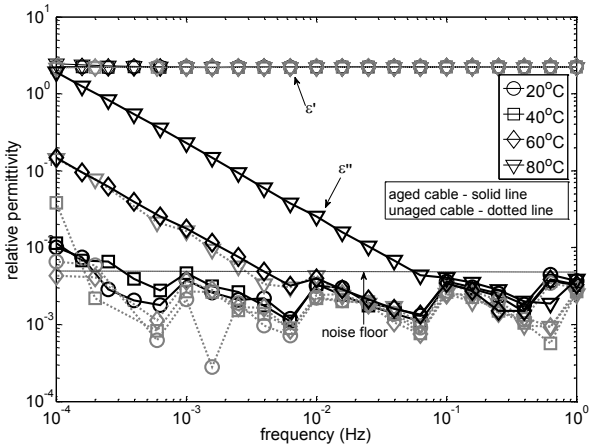

Figure 2 Comparison of ε' and ε" between aged and unaged cable AAA

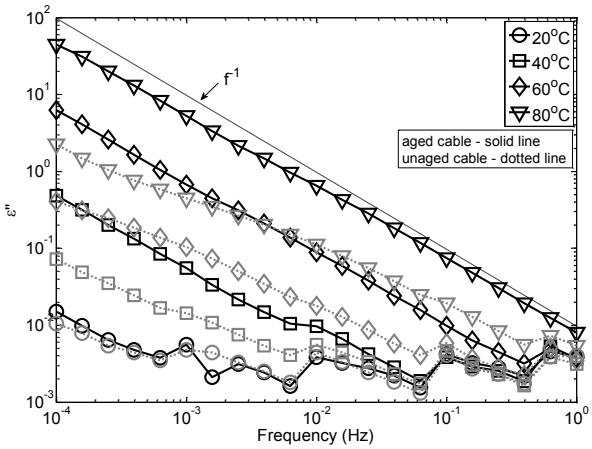

Figure 3 Comparison of ε" between aged and unaged cable ACA

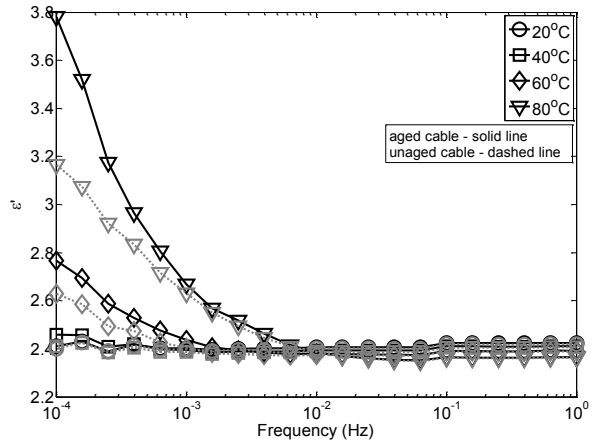

Figure 4 Comparison of ε' between aged and unaged cable ACA

B. Time domain measurement results

For all types of model power cables tested, the discharging currents from 1ms to 10s substantially increased after the

thermal ageing process, and more strongly at higher temperatures and longer times. A comparison between aged and unaged cable at 20°C and 80°C can be seen in Figure 5. It can be seen that the magnitude of discharging current has increased after ageing. The discharging current at 20°C decayed towards 10^{-11}A for both aged and unaged cables with similar decaying trend, but at 80°C the discharging current had bigger curvature in the end.

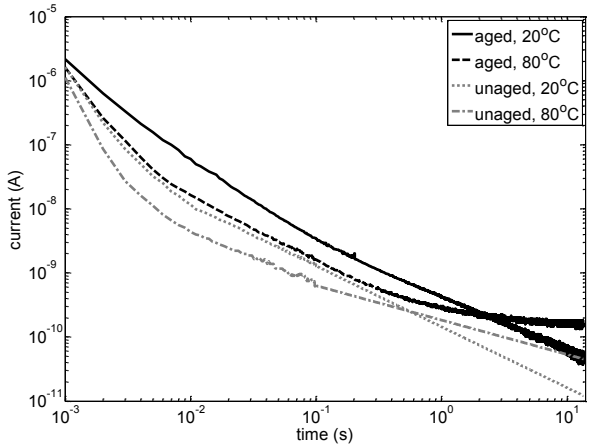

Figure 5 Comparison of discharging current between aged and unaged homo-polymer cable AAA at 20°C and 80°C

Fourier transformation was used to convert the time domain discharging current data into a frequency domain dielectric spectrum. The equation for calculating the complex permittivity ε^* is [6]

$$\varepsilon^* = \varepsilon_\infty + \frac{1}{C_0 U}\int_0^\infty I(t)e^{-j\omega t}dt - j\frac{G}{\omega C_0}$$

where ε_∞ is the high frequency permittivity, C_0 is the geometric capacitance (i.e. with ε' = ε$_0$) of the measured sample and U is the applied step voltage. $\int_0^\infty I(t)e^{-j\omega t}dt$ is the Fourier transform for the measured time dependent current $I(t)$. Without the DC conduction term $jG/\omega C_0$ in the discharging current, discrete Fourier transform (DFT) can be used to digitize the above equation as

$$\varepsilon^*(k) = \varepsilon_\infty + \frac{1}{NC_0 U}\sum_{n=1}^{N} x(n)e^{\frac{-2\pi i}{N}jk} \qquad \text{k} = 1,2,3...\text{N}$$

where $x(n)$ is the time domain series. The real part ε' and imaginary part ε'' of the complex permittivity ε* were calculated. With ε_∞ measured at higher frequencies and DC conduction contribution measured at long times, the loss tangent can therefore be calculated using $\varepsilon''(k)$ estimated from the above equation in the following

$$\tan\delta = \frac{\varepsilon''(k) + \sigma_{DC}/\omega}{\varepsilon'(k)}$$

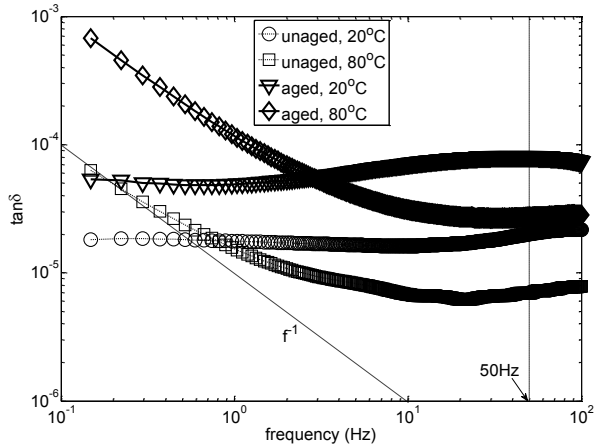

Figure 6 Loss tangent spectra transformed from time domain discharging currents in Figure 5 for cable AAA

Figure 6 shows the transformed loss tangent spectra from Figure 5. The spectra obtained at 20°C show evidence for a broad dielectric dispersion in the case of aged cable, while for the unaged cable at 20°C the spectra is relatively flat. A bulk conduction loss is evident when the cable sample was measured at 80°C. The aged cable shows an increase in tanδ over the whole frequency range compared with the unaged cable, and the increase became greater at 80°C. For practical consideration at 50Hz, the loss tangent is always higher at 20°C than at 80°C before and after ageing.

C. DC conductivity measurement resutls

The conductivity of the aged model power cables has been measured with a 1kV battery voltage supply and Keithley 617 electrometer. Four hours were determined as a charging delay before taking a measurement. The measurement setup and conditions were the same for both aged and unaged cables. The DC conductivity σ for the cylindrical cable insulation is shown in Figure 7. It was calculated using

$$\sigma = \frac{\ln(r_0/r_i)I}{2\pi LU},$$

where r_0 and r_i are outer and inner radius of the cable insulation and L is the length of the cable sample.

The DC conductivity of the model power cables has been found to follow well the Arrhenius equation with activation energies given in Table 1. It can be seen that the activation energy has increased after ageing for both homo- and co-polymer cables. A similar result was found for the same kind of XLPE measured as thin films [7] where the activation energy for unaged films was 0.89 eV and 1.06 eV for aged samples.

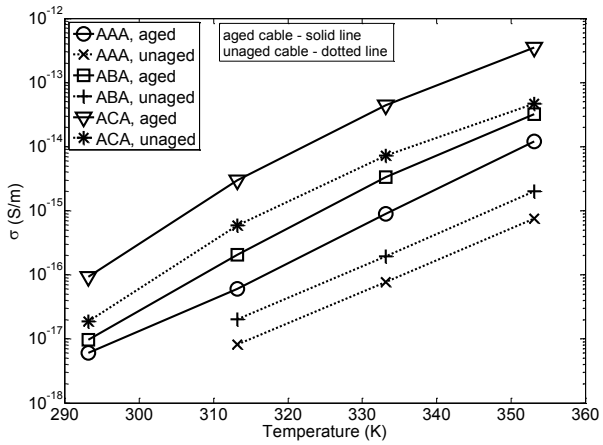

Figure 7 Temperature dependent conductivity of both aged and unaged cables

Table 1 activation energy of the model power cables

Cable	AAA		ABA		ACA	
E_a (eV)	aged	unaged	aged	unaged	aged	unaged
	1.13	1.08	1.21	1.10	1.23	1.17

IV. DISCUSSION

The results on aged cables of the spectroscopic measurements using FRA and time domain measurements can be merged together to obtain the spectra over a wider frequency range. Figure 8 shows the merged results for aged homo-polymer cables (dashed lines in Figure 8) and the original data points using FRA and time domain system.

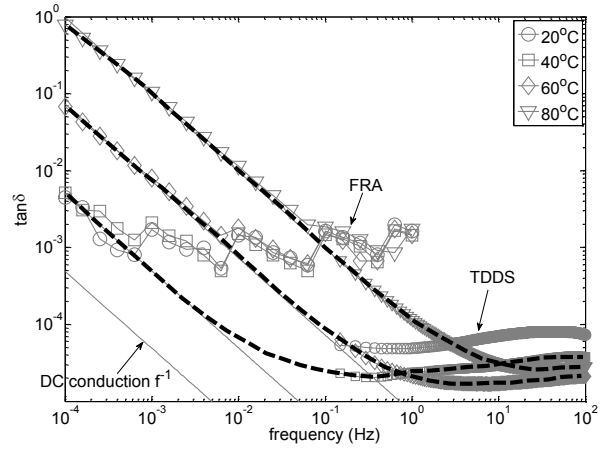

Figure 8 Merged curves of aged homo-polymer cable at 40°C, 60°C and 80°C

The FRA can measure the lower frequencies when the loss tangent of the aged cables is above the noise floor ($\tan\delta > 10^{-3}$). It can be seen that the DC conduction loss measured in time domain has very good correlation with the FRA results that were measured in the frequency domain. It was found that the DC conduction loss increased about 10 times after the thermal ageing by comparing with results of unaged cable. Oxidation of the semi-crystalline XLPE may be responsible for the increased electrical conductivity, since the amorphous region may increase when the oxidation occurs and electron hopping and ionic conduction should have an enhanced contribution to the DC conduction loss.

At higher frequencies, the time domain dielectric spectroscopy (TDDS) has better sensitivity with the ability to measure down to a tanδ of 10^{-5}. Since the DC conduction loss has little contribution in this frequency range, the dielectric loss may be intrinsic to the cable insulation. This intrinsic loss has different temperature dependence to that of the DC conduction loss. The temperature dependence shows a minimum value for tanδ at 60°C and increase as the measurement temperature is decreased or increased from this temperature. This has been found before, e.g. on 12kV full-size XLPE cable samples [8]. In rubbery XLPE the relaxation behavior of the interconnecting polyethylene branch chains in the amorphous region may be the main contributor to the intrinsic loss.

V. CONCLUSION

High sensitivity dielectric spectroscopy measurements have been carried out on aged and unaged model power cables. Based on the experimental results, three conclusions can be obtained:

1. The dielectric loss in the frequency range from 10^{-4} to 10^{2}Hz and DC conductivity both increased after thermal ageing.
2. The thermal activation energy of DC conductivity increased after thermal ageing with co-polymer cables having the highest activation energy.
3. The DC conduction loss has Arrhenius temperature dependence and the higher frequency intrinsic loss at $1\sim10^{2}$Hz has not.

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