THE CHARACTERIZATION OF A LDPE AFFECTED BY DIFFERENT LEVELS OF WATER TREE DEGRADATION USING ABSORPTION CURRENT MEASUREMENTS

M. Acedo[1,3], I. Radu[2,3], F. Frutos[1], J.C. Filippini[3], A. Jiménez[1], J.A. Pérez-Gómez[1] and A. Jadraque[1]

[1) Departamento de Física Aplicada I, Fac. Informática, Univ. de Sevilla, Avda. Reina Mercedes s/n 41012, Spain.

[2) Département de Génie Physique et de Génie des Matériaux, Ecole Polytechnique de Montréal, 2900 Boul. Edouard-Montpetit, C.P. 6079, Succ. Centre-Ville, Montréal, Québec, H3C 3A7, Canada.

[3) Laboratoire d'Electrostatique et Matériaux Diélectriques de Grenoble, CNRS-UJF, 25 Avenue des Martyrs, B.P. 166, 38042 Grenoble, France.

INTRODUCTION

One of the most important applications of polymer dielectrics (EPR, HDPE, XLPE, LDPE...) is their extended use as power cable insulations. Conduction phenomena are of great interest for both users and manufacturers of cables [1]. In this work, in order to characterize the conduction process in polymer dielectrics, we will focus our interest on the absorption current through a LDPE. As our current measurements were performed on laboratory specimens, we will thoroughly describe: a) laboratory specimens, b) experimental conditions and c) results of measurements. Actually, we have experimentally considered the influence of the degree of degradation or degraded width percentage and polarization voltage on the measurements of absorption current and capacitance. From the point of view of accelerated ageing, the typical electro-chemical degradation process of service power cables known as "water treeing" was simulated at laboratory. Then we measured absorption currents for specimens with a different degree of treed degradation and finally, a correlation between the degree of ageing and the fitting parameters of current experimental data to the Curie-von Schweidler law was proposed.

EXPERIMENTAL

Plane-plane LDPE specimens were obtained from sheets prepared with a "Carver" heating press at LEMD-CNRS. A precise method for the fabrication of those sheets was developed which allowed us to cut disks of great homogeneity whose thickness/diameter were respectively $d \cong 500$ μm ($\Delta d \cong 10$ μm) and $\Phi = 35$ mm. A granulated mass of LDPE (PE1S from Borealis), m=1 g, was inserted in each of the 12 circular holes of a brass matrix and exposed to successive selected conditions of pressure, temperature and waiting periods. In this way we could attain the necessary homogeneity and quasi-uniform width in our experimental specimens for ensuring a good (i) repeatability / (ii) reproducibility in electric measurements which are defined as: (i) quality in the repetition (iteration) of a measurement on a unique specimen; (ii) quality in the repetition of a measurement on several specimens –identical specimens in principle–. From the point of view of accelerated ageing, the typical electro-chemical degradation of cable polymeric insulations known as "water treeing" was simulated at laboratory using a plane-plane electrode configuration, a 0.1 M NaCl solution and an ageing voltage of 5 kV_{rms} at 1500 Hz. Once the laboratory specimens were assembled from disks, and previously to the measurement of absorption current with a Keithley 6517, the evolution of capacitance [2] and tgδ was also controlled for the same scheduled periods of accelerated ageing. In parallel with these experiences, a destructive microscopic analysis of the water tree aged specimens was also performed, which allowed us (once the water tree kinetics for the LDPE under study was completed) to establish a continued correlation between the evolution of the above electrical variables and the actual treed thickness. Such a correlation permits the usage of the related variables as an instrument of degradation diagnosis for any specimen under test.

Growth and characterization of water trees

In order to obtain a multitude of water trees we produced a wide dispersion of tree inception points in one of the sides of the cutted disks of LDPE. We applied a pressure of 372 bar, during an interval of 2 min with an abrasive paper P400 (used and replaced after its application) and we repeated this process twice for each disk [3]. This abrasive-paper method, at least in LDPE, revealed as less aggressive and more reproducible than the method of sandblasting [4], especially because we could choose a grain width which produces a kind of defect deep enough for initiating water trees without involving a direct risk of dielectric breakdown when applying the ageing voltage. The laboratory specimens [2] (see Fig. 1) were placed on a metallic recipient which acted both as ground electrode and as a container of a small quantity of silicon oil. It

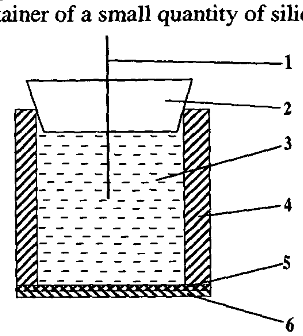

Figure 1. Specimen configuration: (1) platinum electrode, (2) silicon cap, (3) salt solution, (4) PE cylinder, (5) LDPE disk, (6) silver paint.

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helps to avoid partial discharges in the air by fulfilling the occasional small cavities that usually appear between the LDPE disk and the metallic plane of the ground electrode. As LDPE results much more affected by partial discharges than XLPE, we got several very important advantages from the usage of the oil technique.- (a) There is a drastic diminution of the risk of dielectric breakdown for short ageing periods –for thin layers of water trees–. It means not only a reduction in the number of lost test objects but the fact that the process of tree growth for the rest of specimens is much more continued and reliable, as water tree retractions attributed to periods of absence of applied electric field are mainly avoided [5]. (b) The possibility of applying a stronger ageing electric field ($E_{oiled} \cong 10$ kV/mm vs $E_{non-oiled} \cong 3$ kV/mm). Consequently, deeper and thicker degraded layers are developed for much shorter ageing periods. It permits us their detection through very significant changes for the values of electrical variables in measurements $\{C, I(t), tg\delta\}$. Once the ageing period is finished, the active part of the test object (LDPE disk with water trees) is extracted and stained with rodhamine during 48 h at a temperature of 60°C. Afterwards, five 200µm-width slices are cut from each disk with a microtome and their coloured water trees can already be visualized by using an optical microscope. Water tree average length was determined for each scheduled ageing time from equation (1),

$$l = \frac{\sum_{i=1}^{N} l_i x_i}{x_{max}} \tag{1}$$

Where l_i and x_i are respectively the length and width of each individual water tree, n is the total number of trees per slice and x_{max} is the total length of each slice.

Experimental procedures for electric measurements

Absorption current technique The LEMD experimental set-up for absorption current measurement is shown in Fig.2. Current measurement and DC stabilized voltage

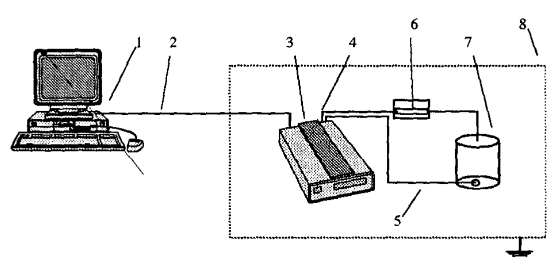


Figure 2. Experimental set-up for current measurements ((1)-(8) components described in the text).

supply were both performed by using a Keithley 6517 (3 and 4 respectively). Data acquisition was done by means of a GPIB cable (2) and a IEEE-488 card inserted in a PC586 (1) with a software developed from Keithley Testpoint packet. A special goal for this kind of very low current measurements consists in minimizing noise. Electromagnetic noise could be reduced by providing a especially designed test cell (3), triaxial connections (4,5) between Keithley and test cell, a metal box for the protection resistance (6) and an additional continuous Cu Faraday cage which confined all the previous elements). The physical components of the test cell are schematically drawn in Fig.3. A special attention must be paid to the design of its upper electrode (7), which must make contact at a very well defined area on every LDPE specimen. A first screwed version of this

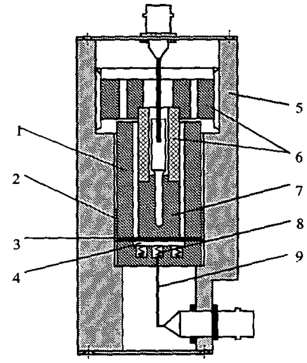


Figure 3. Test cell: (1) PE cylinder, (2) guard ring, (3) LDPE sample, (4) lower electrode, (5) protective screen, (6) PTFE insulator, (7) upper electrode, (8) contact spring, (9) Cu wire.

upper electrode was substituted by a more weighted one whose contact was simply done by its weight. In this way, repeatability and reproducibility were greatly improved because of the constant pressure at the contact and by avoiding the generation/build-up of charges by a kind of mechanical stirring on the surface of the polymer [6]. Analytical/graphical processing of experimental data was performed with Kaleidagrph 3.07 and Sigmaplot 5.0 programs.

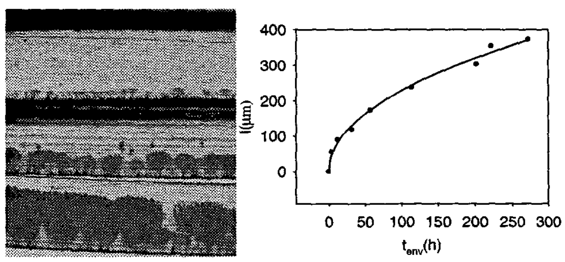
Capacitance measurements An Irlab apparatus (model LDTRP-2) and a 1621 General Radio bridge successively switched to the specially designed cell mentioned above were used to get the values of capacitance, C, and dissipation factor for every scheduled ageing period.

Parasitic effects Before each measurement, the salt solution is removed and the sample surface is dried out. Nevertheless, after this operation, a waiting period , $t_{dry} \cong 20$ min, is absolutely required for avoiding a huge variation in capacitance (and the rest of electrical variables) with the instant chosen for performing the measurement –particularly in thick treed layers–. Concerning absorption current measurements, residual currents can be measured in the absence of applied polarization voltage, V_{DC} when the ageing period is over. They can endure for periods ranging from 10 min up to 1 h depending on the LDPE volume affected by water trees. An adequate method for minimizing these residual currents was applied by short-circuiting the entire test object support –once the ageing period is finished– during a period of about, $t_{short}\cong 30$ min.

EXPERIMENTAL RESULTS

The growth kinetics and the capacitance of water trees

The evolution of water trees with the ageing time in a LDPE is shown both graphically and from the variations of the average water tree length –water tree kinetics– in Fig.4.



(a) (b)

Figure 4. Water tree evolution in LDPE: (a) three photographs taken after ageing times (from top to bottom) of 4 h, 31 h and 272 h; (b) average water tree length dependence on ageing time.

A quasi-linear dependence for the variations of the average capacitance of the samples with the ageing time is plotted in Fig.5.

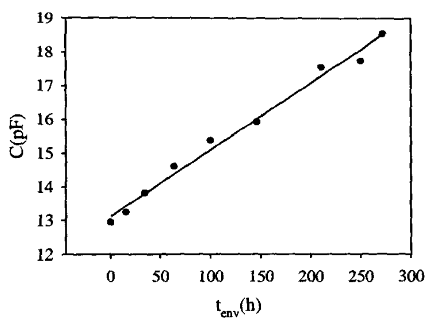


Figure 5. Electric capacitance vs ageing time.

Using an equivalent plane capacitor model for the water treed samples and taking into account the variations of capacitance, C, and water tree length, l, with the ageing time, t_{env}, the average relative permittivity of water trees, ε_1, can be derived [2] from ,

$$\varepsilon_1(t)=\frac{C(t_{env})\varepsilon_2 l(t_{env})}{l(t_{env})C(t_{env})-d\left[C(t_{env})-C_i\right]} \qquad (2)$$

where ε_2=2.3 is the relative permittivity of non-degraded PE and C_i is the non-degraded capacitance of the sample. A maximum value, ε_{1max}=4.1, was attained.

Current measurements

Evolution of $I_{abs}(t)$ with degradation Fig.6 presents the absorption current experimental data for a measuring period of 10 min, a polarization voltage V_{DC}=300 V and different periods of accelerated ageing.

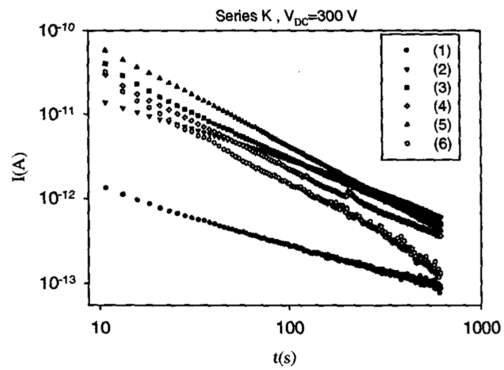


Figure 6. Absorption current measurements for different water tree ageing periods and a polarization voltage, V_{DC}=300V (averaged values from samples of Series K): (1) 0h, (2) 15h, (3) 34 h, (4) 64 h, (5) 146 h, (6) 250 h.

The experimental data were fitted to the potential Curie-von Schweidler law, $I=I_0t^{-m}$. Their corresponding parameters $\{I_0,m\}$ and degraded width percentage, g, were summarized in Table 1. We can obtain a first version of diagnostic method –estimation of the degree of degradation from a unique $I_{abs}(t)$ measurement– by simply plotting and adjusting the dependence g=g(m), which is shown in Fig.7.

Table 1. Fitting parameters $\{I_0,m\}$ for each ageing time and corresponding degraded width.

t_{env}(h)	g(%)	I_0(A)	m
0	0	$6.251\cdot10^{-12}$	0.666
15	14.8	$1.1477\cdot10^{-10}$	0.8106
34	22.3	$4.1352\cdot10^{-10}$	1.0566
64	34	$3.5889\cdot10^{-10}$	1.0893
146	56.3	$1.2905\cdot10^{-9}$	1.2491
250	70.7	$6.1215\cdot10^{-10}$	1.3001

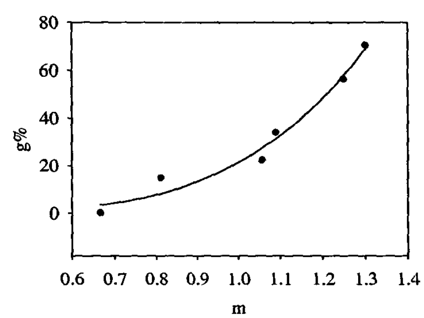


Figure 7. The dependence g=g(m) as a first version of diagnostic tool for LDPE treed samples.

Evolution of $I_{abs}(t)$ with polarization voltage Fig.8 shows the absorption current measurements in aged samples (Series J) as a function of the polarization voltage, V_{DC}. A similar study was performed for new samples (Series M) and their corresponding fitting parameters $\{I_0,m\}$ are summarized in Table 2.

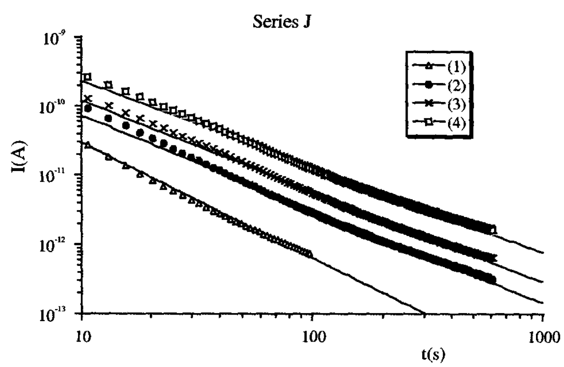


Figure 8. Absorption current measurements and their linear curve fitting for different values of the polarization voltage, V_{DC} (averaged values from aged samples of Series J, g=63%): (1) 100 V, (2) 300 V, (3) 500 V, (4) 1000V.

Table 2. Absorption current fitting parameters $\{I_0,m\}$ new samples (Series M) and aged samples (Series J) as a function of V_{DC}.

V_{DC}(V)	I_0(A)		m	
	Series M	Series J	Series M	Series J
100	$4.7826\cdot10^{-13}$	$1.3465\cdot10^{-9}$	0.42736	1.6603
300	$2.5357\cdot10^{-12}$	$1.6406\cdot10^{-9}$	0.61002	1.3546
500	$4.0321\cdot10^{-12}$	$2.4369\cdot10^{-9}$	0.63351	1.3102
1000	$1.0702\cdot10^{-11}$	$4.0661\cdot10^{-9}$	0.69758	1.2419

A prevailing trend to saturation in the evolution of exponent m with polarization voltage, V_{DC}, for both aged and new samples is observed.

DISCUSSION

The relative permittivity of water trees in LDPE continuously increased from its value for non-degraded PE, ε_2=2.3, up to a maximum value ε_{1max}=4.1, for an ageing period of 272 h and an average water tree length of 373 μm (g=74.6%); it supplies a permittivity amplification factor A=1.8, a little bit higher than the value found for XLPE in [2], A=1.6 . From absorption current measurements we could determine the evolution of coefficients $\{I_0,m\}$ from the Curie-von Schweidler law with the ageing time. A progressive increase was obtained for both coefficients: 9897% for I_0 and 95% for m, when the degraded width grew from g=0% (new sample) up to g=70.7% (sample with a high level of degradation). We could establish, as V_{DC} got from 100 V up to 1000 V: (I_0) 2137% increase in new samples and 202% increase in aged samples; (m) 63% increase in new samples, 25% decrease in aged samples and in both cases appear a remarkably trend to saturation with V_{DC}.

CONCLUSIONS

A LDPE (PE1S –base polyethylene for compounds for cable insulation with antioxidants and stabilizers– from Borealis) with different levels of water tree degradation was characterized by means of measurements of water tree kinetics, capacitance and absorption current. The consecution of an acceptable level of repeatability/reproducibility in electrical measurements depends greatly on the optimization of the experimental procedures: from the fabrication of LDPE sheets / water tree inception points and method for accelerated ageing to the techniques for minimizing the parasitic effects. Particularly, an adequate design for an optimal coupling between the test cell and the laboratory specimen should be taken into account. Combining water tree kinetics and capacitance measurements, the maximum average value for the relative permittivity of water trees in LDPE was calculated, ε_{1max}=4.1 . Absorption current measurements were fitted to the potential Curie-von Schweidler law in order to study the evolution of its parameters $\{I_0,m\}$ with ageing time and polarization voltage. Such a study is the base of two possible methods of LDPE-water tree degradation diagnosis from measurements of absorption currents.

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