Electrical Ageing of Polyethylene Power Cables Insulation Subjected to an Electric Field in the Presence of Water

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***Abstract*-Under the action of an electric field and in the presence of water, water trees develop inside power cables insulations. Regardless of their type, shape or dimension, water trees contribute to the worsening of electrical properties, especially lowering the inception voltages of partial discharges and electrical trees leading to breakdown [1].**

In this paper an experimental study regarding the variation of permittivity and loss factor of the polyethylene with the frequency (f_a) and the duration (τ) of applied electrical field is presented. The experiments were made on flat XLPE samples sliced from a power cables insulation. The samples were subjected to an electrical field with the intensity E = 4 kV/mm and frequencies f_a = 3 and 5 kHz for τ = 48, 72 and 96 hours. After ageing the water trees dimensions (length l_{wt} and diameter D) and concentration c_{wt} were measured.

The permittivity (ε_r) and the loss factor (tgδ) were measured (using a NOVOCONTROL dielectric spectrometer) at the temperature T = 30 ^{o}C and frequency f_m =10^{-3} – 10^{6} Hz. The results show that with the increase of ageing time or the ageing frequency all the quantities c_{wt}, l_{wt}, D, ε_r and tgδ increase, too.

I. INTRODUCTION

During service polyethylene insulated power cables are subjected to electrical, thermal, mechanical and environmental stresses. Electric field in the presence of water and salts, contributes at the initiation and development of water filled tree-like structures called water trees [1-3].

Water trees leads to a local intensification of the electric field, the increase of the electric conductivity, permittivity and dielectric losses in insulations, a decrease of the partial discharges and electrical trees inception voltages and, finally, to decrease of the breakdown voltage (respectively, to a premature breakdown of the insulations) [4-9].

In the papers [5], [10-11] the influence of water trees length on the electric field repartition in polyethylene samples with different shapes was analyzed. In this paper a study concerning the water trees dimensions and concentrations evolution in electrical accelerated aged XLPE samples (E = 4 kV/mm and f_a = 3-5 kHz) is presented. The complex permittivity parts (ε_r', ε_r”) and loss factor (tgδ) variations with measure frequency f_m, ageing time τ and frequency f_a are presented. Also, the average dimensions (length L_{wt} and diameter D_{wt}), volumes V_{wt} and densities c_{wt} of water trees are analyzed.

II. SAMPLES AND SETUPS

The experiments were made on circular crown shaped samples (0.5 mm thick), sliced from the polyethylene insulation of a 110 kV cable (Fig. 1).

On one of the samples surface, superficial defects were made with an abrasive paper P240 (for 2 minutes), using a Carver press (at 2 MPa). After pressing, on the surface with defects, two polyethylene cylinders with different diameters were fixed, and the gap between them was filled with a NaCl solution (0.1 mole/l) (Fig. 2). On the surface without defects a semi-conductive layer was laid down (to avoid partial discharges).

For the growth of water trees the setup presented in Figure 3 was used. To reduce the ageing time and to accelerate water trees development, electric fields with frequencies 3 and 5 kHz (higher than the standard operating frequency 50 Hz) were applied.

Fig. 1. Samples taken from a HV cable insulation.

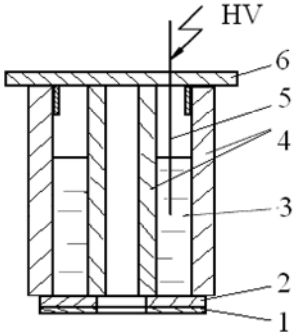

Fig. 2. Water tree development cell: 1 - Semiconducting layer, 2- Sample, 3 – NaCl solution, 4 – Polyethylene tubes, 5 –Platinum electrode, 6- Cap.

After ageing, 200 μm thick slices were cut from each sample and placed in a rhodamine solution. Afterwards this container was maintained in an oven at 60 ^{0} C for 72h. For measuring water trees dimensions (L_{wt} and D_{wt}) the setup presented in Figure 4 was used.

The modality of the trees dimensions measurement and average densities computation is presented in [12].

The real (ε_r') and imaginary (ε_r") parts of complex relative permittivity and loss factor (tgδ) were measured using a NOVOCONTROL Alfa-A High Performance Analyzer dielectric spectrometer (for frequencies between 10^{-3} and 10^4 Hz at 30 °C) [13].

The cell used to measure ε_r', ε_r" and tg δ on circular crown shaped samples is presented in Figure 5.

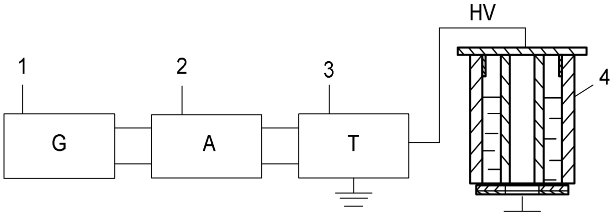

Fig. 3. Setup used for the accelerated growth of water trees: 1- Signal generator, 2- Amplifier, 3- Transformer, 4 – Ageing cell.

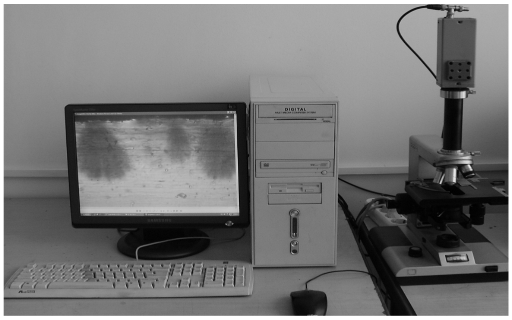

Fig. 4. Setup for water trees dimensions measurement.

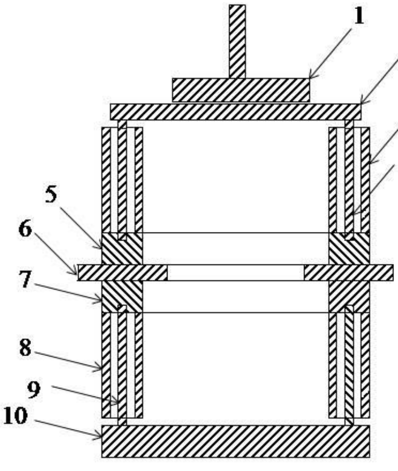

Fig. 5. Cell for the measurement on circular crown shaped samples: 1 – Upper spectrometer electrode; 2 - Flat electrode; 3,8 – Insulator Cylinders; 4,9 – Conductors; 5,7 – Circular crown electrodes; 6 – Sample, 10 – Lower spectrometer electrode.

III. RESULTS

Groups of 5 samples were subjected to accelerated electrical ageing using sinusoidal voltage with the effective value U = 2 kV and frequency f_a = 3 … 5 kHz, for three values of ageing time τ (48, 72 and 96 hours). After ageing, the samples were introduced in the spectrometer cell to measure the complex permittivity parts and the loss factor. Afterwards, the values of water trees dimensions (L_{wt} and D_{wt}) and concentrations c_{wt}, surface A_{wt} and volume V_{wt} were measured.

Variations with the ageing time τ, for L_{wt}, D_{wt}, c_{wt}, A_{wt}, V_{wt} and c_{wt} are presented in Figures 6…9. It can be observed that all water trees characteristics increase with τ as well as with the ageing frequency f_a.

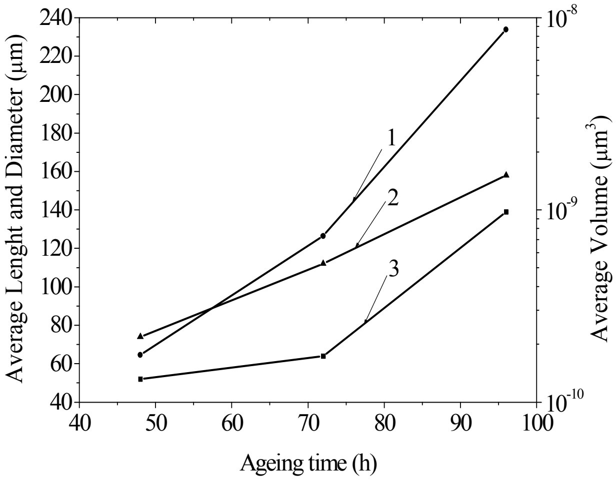

Fig. 6. Water trees average volume (1), length (2), and diameter (3) versus ageing time for f_a = 3 kHz (U = 2 kV).

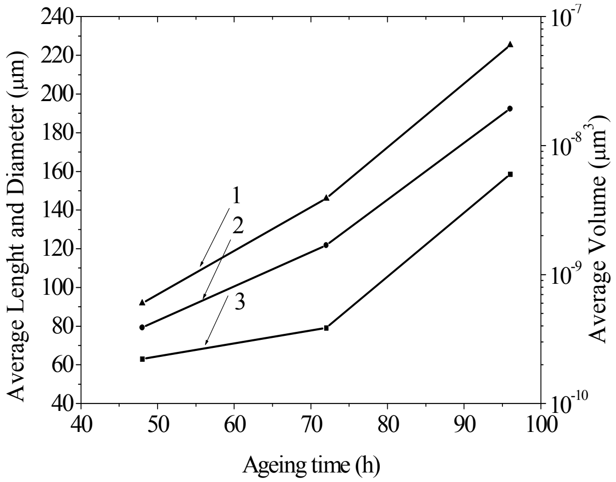

Fig. 7. Water trees average volume (1), length (2), and diameter (3) versus ageing time for f_a = 5 kHz (U = 2 kV).

Furthermore, with the increase of the ageing time results an important increase of the water trees growth rate v_{wt} and a smaller increase of the trees density (concentration) (Figs. 8 and 9).

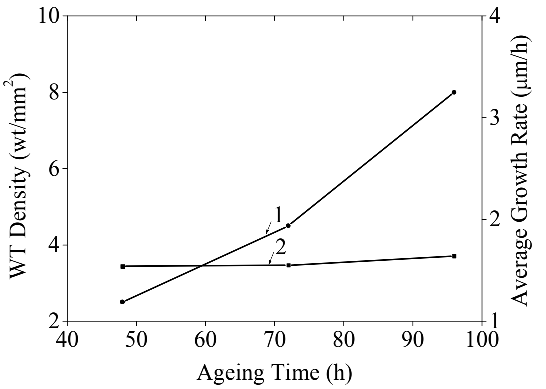

Fig. 8. Water trees average growth rate (2) and density (1) versus ageing time for $f_a = 3$ kHz ($U = 2$ kV).

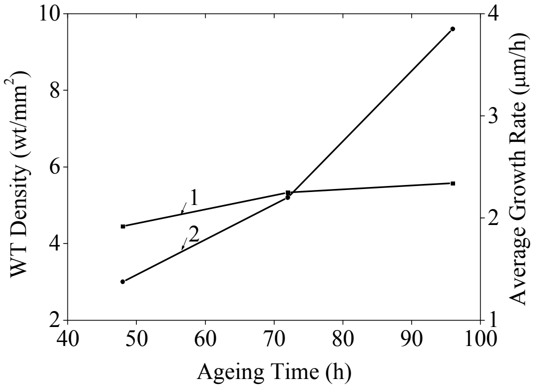

Fig. 9. Water trees average growth rate (1) and density (2) versus ageing time for $f_a = 5$ kHz ($U = 2$ kV).

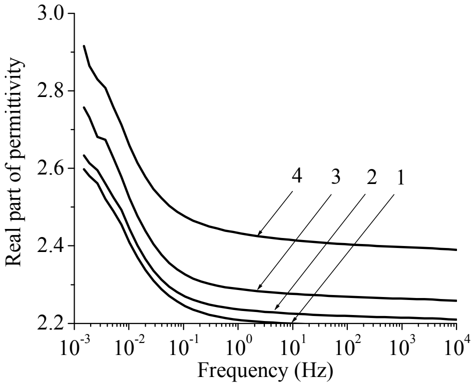

Fig. 10. The real permittivity part variation with measurement frequency for different ageing times τ: 1 – τ = 0, 2 – τ = 48 h, 3 - τ = 72 h, 4 – τ = 96 h (U = 2 kV, $f_a = 3$ kHz).

In Figure 10 the real and imaginary complex relative permittivity parts ε_r' variations with measure frequency f_m for different values of ageing time τ, are presented. It can be seen that ε_r' increase with the ageing time and that these increases are significant for low values of measure frequency f_m. The increase of permittivity can be explained by the growth of water concentration [9] and of polyethylene-water interface area and the interfacial polarization intensification [14].

The increase of the ageing time τ leads to the enhancement of dielectric losses, respectively of ε_r" and tgδ amounts (Figs. 11 and 12). This phenomenon can be explained by the increase of the water trees volume inside the samples (Figs. 6 and 7, curves 1), and by the intensification of the electric field in the areas outside of the water trees. It must also be highlighted that although for ε_r' the variations are small, for ε_r" and tgδ variations are quite significant at low frequencies.

The electric field frequency f_a used for electrical ageing plays an important role in the development of the water trees. For example, an increase of f_a from 3 kHz to 5 kHz determines an increase in water trees average growth rate v_{da} with 45 % and of the water trees total volume V_a with 129 %.

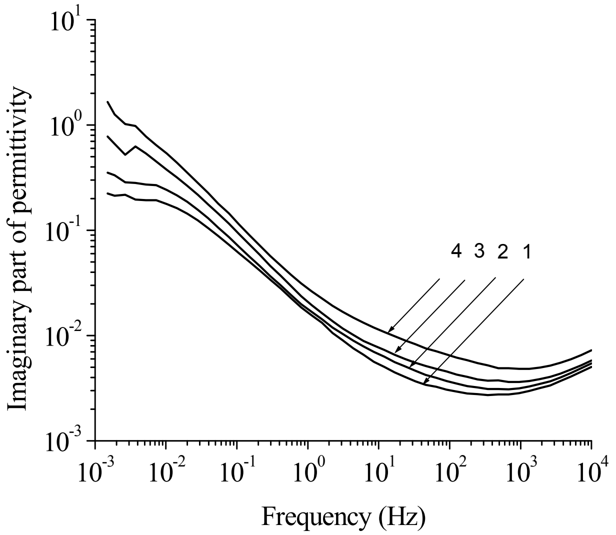

Fig. 11. The imaginary permittivity part variation with measurement frequency for different ageing times τ: 1 – τ = 0, 2 – τ = 48 h, 3 - τ = 72 h, 4 – τ = 96 h (U = 2 kV, $f_a = 3$ kHz).

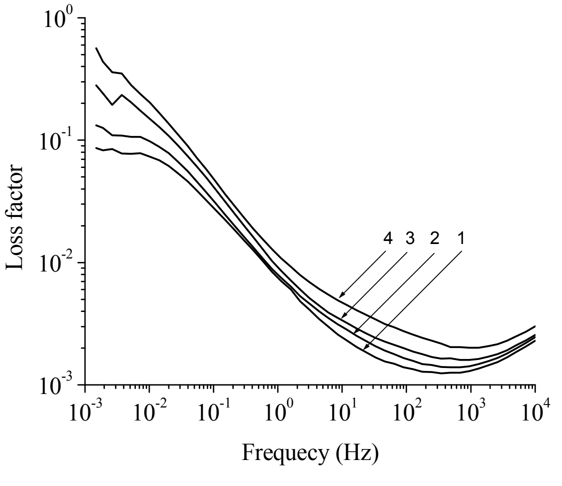

Fig. 12. Loss factor dependence on measurement frequency for different ageing times τ: 1 – τ = 0, 2 – τ = 48 h, 3 - τ = 72 h, 4 – τ = 96 h (U = 2 kV, $f_a = 3$ kHz).

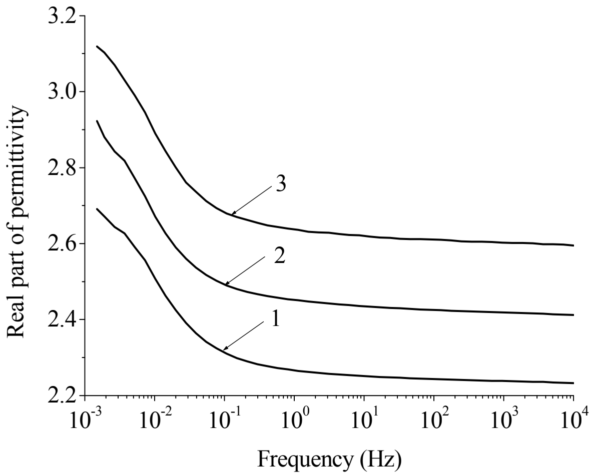

Fig. 13. The real permittivity part dependence on measurement frequency for different ageing frequencies f_a: 1 – $f_a = 0$, 2 – $f_a = 3$ kHz, 3 - $f_a = 5$ kHz ($U = 2$ kV, $\tau = 72$ h).

IV. CONCLUSIONS

The increase of ageing time τ determines an important growth of the water trees areas and volumes values, as well as of the permittivity and loss factor.

The increase of the electric field frequency (from 3 to 5 kHz) leads to an important increase of all quantities related to water trees development.

The use of a new type of cells for the accelerated electrical ageing setup as well as for the NOVOCONTROL spectrometer allows testing on small samples sliced from cable insulations still in service. Therefore, information regarding the condition of the insulation of a cable still in service can be obtained (especially, by slicing samples from the vicinity of breakdown areas, couplings, end cases etc.)

The influence of the electric fields frequency on the shape and dimensions of water trees will be attended to in a future paper.

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