

Studies Concerning the Fast Ageing by Thermal Cycling of Power Cables

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Abstract: In the present paper the results concerning the structural modifications and dielectric properties of polyethylene insulations taken from a medium voltage cable (20 kV) subjected to 120 thermal cycles between $-35\text{ }^{\circ}\text{C}$ and $+100\text{ }^{\circ}\text{C}$ are presented. The structural modifications were investigated by thermal analysis methods (TG, DTG and DTA), showing that during the thermal cycling the degree of cross-linking of polyethylene increases and the degree of crystallinity decreases. Dielectric modifications of polyethylene due to thermal cycling were determined by using the dielectric spectroscopy method in range $10^{-2} \div 10^6$ Hz, for $30\text{ }^{\circ}\text{C}$ but also for $100\text{ }^{\circ}\text{C}$. After 120 thermal cycles the results obtained show that $\text{tg}\delta$ for $30\text{ }^{\circ}\text{C}$ increases slowly for frequencies higher than 100 Hz and substantial for frequencies lower than 100 Hz. This increase is more pronounced for $100\text{ }^{\circ}\text{C}$ (up to 100 %) especially for frequencies between $10^{-2} \div 2 \cdot 10^3$ Hz.

I. INTRODUCTION

In sustainable development perspective, the continuous and safety supply of urban utilities, especially of electrical energy, represents a permanent preoccupation. The electricity supply security is determined by the durability and safety of power cables during operation. In this context, the study of degradation processes mechanisms of power cables is a current problem and has an important economical importance.

Durability and safety of power cables during operation is determined, first, by the lasting behavior of the polymer during exploitation, from the cables insulation was realized – respectively of polyethylene, usually used for power cables insulation.

Depending on the obtaining method and ingredients used during manufacturing, but also by the future thermal treatments, during electrical and thermal stresses, the polyethylene used as insulator for power cables suffers structural smaller or larger degradations, leading to the decrease of breakdown strength of insulation (“ageing of insulation”).

During operation, on the cable conductor a heat quantity P_d is released (which leads to the conductor heating) proportional with the square of current strength I , respectively:

$$P_d = r_c \cdot I^2 \quad (1)$$

where r_c represents the ohmic resistance of conductor. In these conditions the polymeric insulation of cable is subjected to thermal gradient determined by the room temperature T_a

(of soil, where the cable is installed) and by the operation temperature of conductor T_{ex} – determined by the charge current strength.

In practice, in most of cases, the charge current presents semnificative variations determined by the charge variations of the consumers (the charge curve). In these conditions the polymeric insulations of cables are subjected to cycling thermal stress $\Delta T_{(t)} = T_a - T_{ex}$.

Thermal degradation of organic dielectrics may be put into evidence by physical-chemical methods such as: infrared spectroscopy [1, 2], emission spectroscopy, chromatography and thermal analysis [1 – 3].

The aim of the present paper is the experimental study of parameters evolution (structurals and electrics) of polyethylene insulation of power cables, due to cycling thermal stresses.

II. EXPERIMENTS

A medium voltage cable sample type A2XS2Y of 250 mm^2 was subjected to thermal cycling in a thermoclimatic room (type VÖTSCH-Industrietechnik), according with the temperature diagramme from Figure 1.

From polyethylene insulation of cable sample probes were taken (before, during and at the end of thermal stresses) in order to their characterisation by the thermal analysis method [4 – 7].

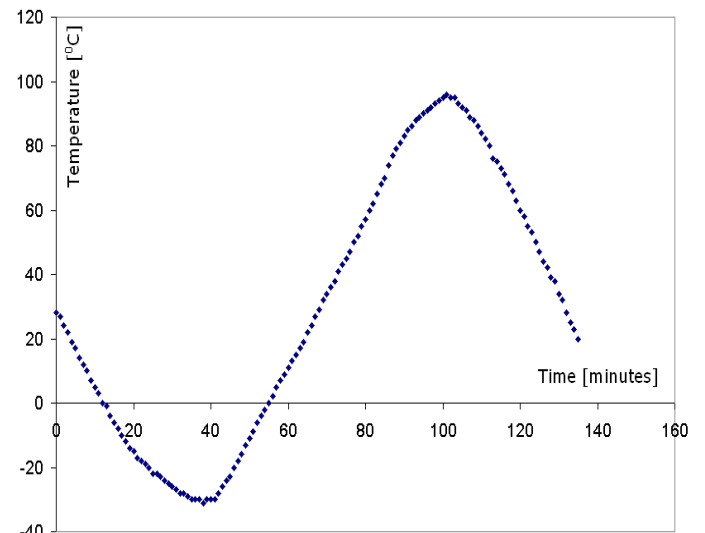


Fig. 1. Thermal treatment profile of cycles (thermocycles) applied.

The experiments by thermal analysis were realized by using an equipment type STA 409 PC (Netzsch – Germany) and its software, in the following conditions:

- Temperature range: 25 °C → 650 °C;
- Temperature ramp: 10 K/min;
- Atmosphere: static air;
- The sample mass between 0.1 and 0.55 g.

Before thermal treatment and after 120 complete thermal cycles (Fig. 1), from polyethylene insulation of cable sample 5 crown circular shape samples were taken (17 mm inner diameter and 25 mm outer diameter). By using the dielectric spectroscopy method the complex permittivity (the real component ϵ_r' and the imaginary one ϵ_r'') but also the loss factor ($\text{tg } \delta$) were determined. The experiments were done in the frequency range $10^{-2} \div 10^6$ Hz, at 30 °C but also at 100 °C by using a SOLARTRON ANALYTICAL AMETEK analyzer type 1260 A.

III. RESULTS

The Nyquist diagrams obtained by dielectric spectroscopy at 30 °C before and after thermal cycling (120 complete thermal cycles) are presented in Figure 2.

The complex impedance $Z^*(\omega)$ can be written as follows:

$$Z^*(\omega) = R + j\omega[\epsilon_0(\epsilon_r' - j\epsilon_r'')(A/g) - jC''] \quad (2)$$

where: R represents the resistance [Ω], ϵ_0 – electrical permittivity of vacuum [F/m], ϵ_r' – the real component of complex permittivity, ϵ_r'' – the imaginary component of complex permittivity, A – the electrodes surface [mm^2], g – the sample thickness [mm], C'' – the imaginary component of complex capacity [F].

In Figures 3 and 4 the variations of real component complex permittivity and imaginary component complex permittivity with the frequency f are presented.

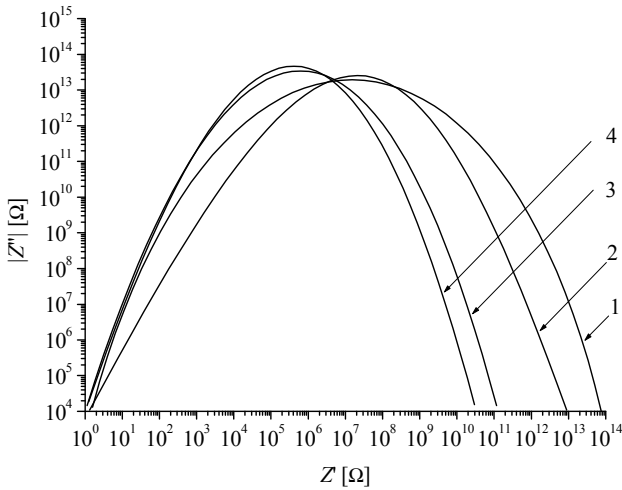


Fig.2. Nyquist diagrams obtained on polyethylene samples: (1) – uncycled at 30 °C ; (2) – thermal cycled at 30 °C; (3) uncycled at 100 °C and (4) thermal cycled at 100 °C.

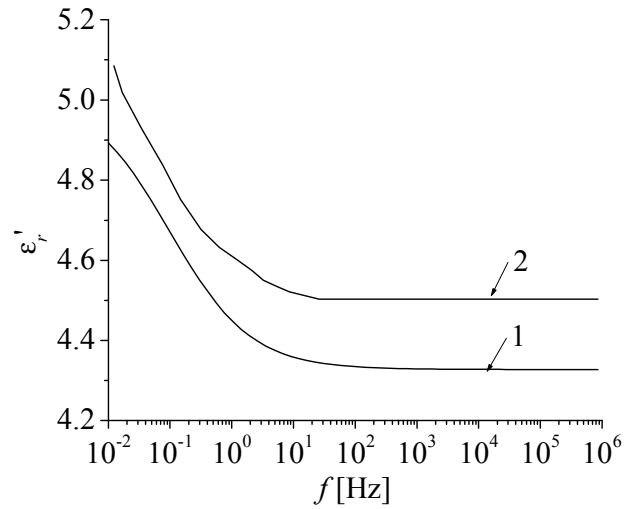


Fig. 3. Variation of real component complex permittivity ϵ_r' with frequency f at 30 °C: (1) – uncycled, (2) – thermal cycled (applied voltage 3 V_{RMS}).

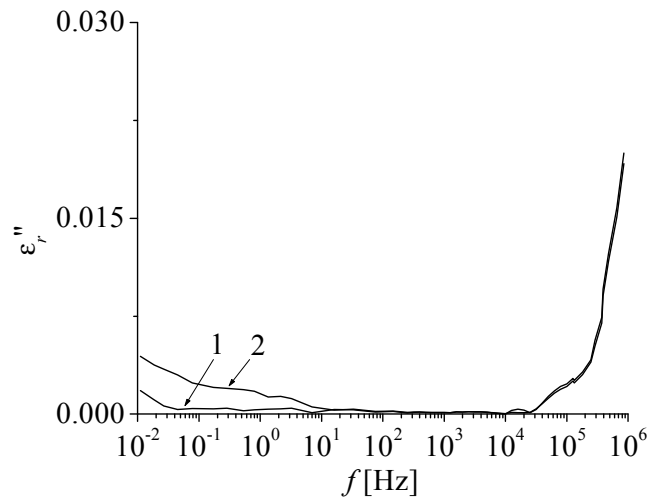


Fig. 4. Variation of imaginary component complex permittivity ϵ_r'' with frequency f at 30 °C: (1) – uncycled, (2) – thermal cycled (applied voltage 3 V_{RMS}).

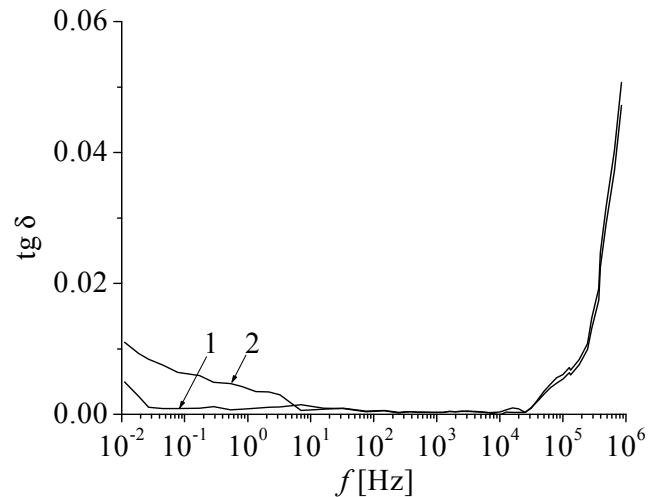


Fig.5. Variation of loss factor $\text{tg } \delta$ with frequency f at 30 °C: (1) – uncycled, (2) – thermal cycled (applied voltage 3 V_{RMS}).

Considering the loss factor $\text{tg } \delta$ as follows:

$$\text{tg } \delta = \epsilon_r'' / \epsilon_r' \quad (3)$$

its variation with the frequency is obtained (Fig. 5).

Similar, the results obtained at 100 °C of parameters ϵ_r' , ϵ_r'' and $\text{tg } \delta$ are presented in Figures 6, 7 and 8.

Analyzing the Figures 3 – 8 it can be seen that due to applied thermal cycles (120 thermal cycles according to Figure 1), dielectric performance of polyethylene insulation decreases, respectively $\text{tg } \delta$ increases. The increase of losses at 30 °C are remarkable for frequencies below 1 Hz and substantial at 100 °C in the range 0.5 Hz ÷ 2 kHz. These results show that the thermal stress of insulation by cyclic variations leads to the „ageing of insulation” characterized by the decrease of the insulation resistance and increase of losses, modifications more pronounced at higher temperatures.

Thermogram of polyethylene insulation, before the first cycle is presented in Figure 9.

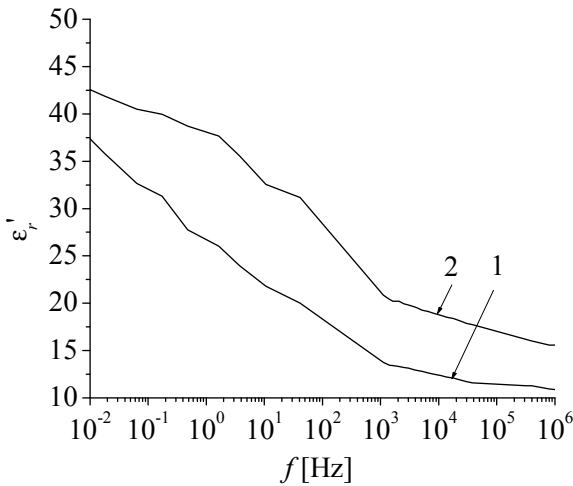


Fig. 6. Variation of real component complex permittivity ϵ_r' with frequency f at 100 °C: (1) – uncycled, (2) – thermal cycled. (applied voltage 3 V_{RMS}).

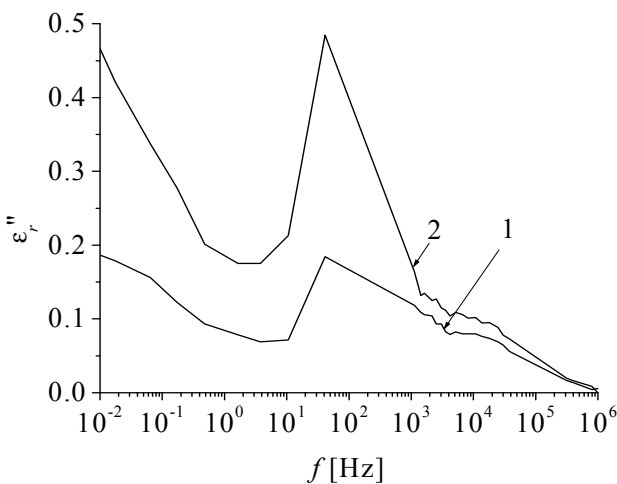


Fig. 7. Variation of imaginary component complex permittivity ϵ_r'' with frequency f at 100 °C: (1) – uncycled, (2) – thermal cycled. (applied voltage 3 V_{RMS}).

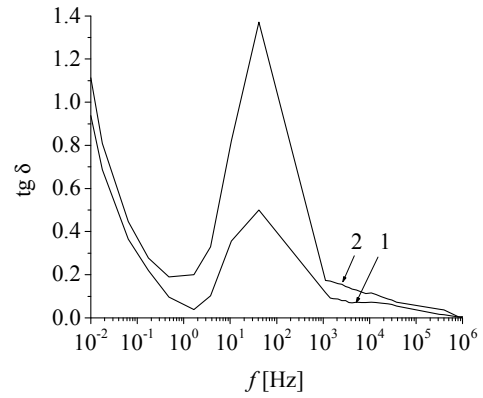


Fig. 8. Variation of loss factor $\text{tg } \delta$ with frequency f at 100 °C: (1) – uncycled, (2) – thermal cycled (applied voltage 3 V_{RMS}).

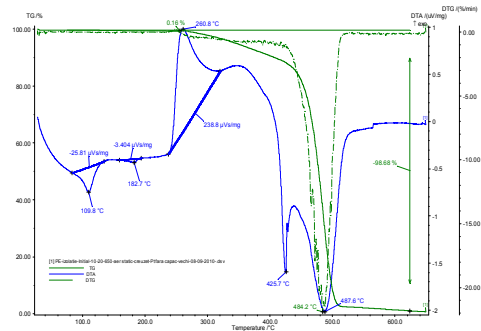


Fig. 9. Thermogram obtained on polyethylene sample, before the first thermal cycling.

Analyzing the Figure 9 it can be seen that the followings processes are produced:

- Melting of crystalline component of polyethylene, characterized by an endotherm minimum in the DTA curve. Two minimum are identified, first at 109.8 °C and the other one at 182.7 °C, showing that there are two different material fractions with different molecular mass.
- Thermo-oxidation with generation of solids products, characterized by an exotherm maximum in DTA curve at temperature 260.8 °C
- Thermo-oxidation with generation of volatile products, characterized by a mass loss put into evidence in TG curve, one or more minima in DTG curve and exotherm maximum and endotherm minimum in DTA curve.

Allure of thermograms on the samples taken during the thermal cycles has a similar allure with the one presented in the Figure 9 but are different by the temperatures values and the enthalpies characteristics of each process. As example in the Figure 10 the thermogram obtained after 23 complete thermal cycles (Fig. 1) is presented.

Comparing the Figures 9 and 10, it can be seen that the fraction of polyethylene, initially with the melting point of 182.7 °C disappears after 23 thermal cycles a new endotherm process appears at 191.8 °C with mass increase (oxidation solids products).

Considering that the electrical performance of polyethylene are determined by the majority fraction, in Figure 11 the melting temperatures evolution during the thermal cycling is

presented. Similar, the melting enthalpies evolution of majority fraction is presented in Figure 11.

Analyzing the Figure 11 it can be seen an increase of the melting point (due to the cross-linking degree) and a decrease of melting enthalpy (due to the decrease of polyethylene crystallinity degree) during the thermal cycling. This remark suggests that due to ageing the sample cross-link (the number of tertiary carbon-carbon chains increase, according with the schematic representation from Figure 12) but in the same time become more amorphous.

From recorded thermogram on the polyethylene samples taken during the thermal cycling two thermo-oxidative processes forming solid products, characterized by exotherm peaks in the DTA curves. First in the temperature range $182 \pm 15 \text{ }^\circ\text{C}$ and the second one in $257 \div 268 \text{ }^\circ\text{C}$ range.

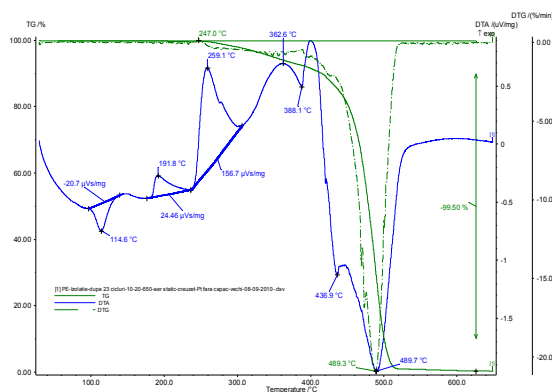


Fig. 10. Thermogram obtained on polyethylene insulation sample subjected at 23 complete thermal cycles.

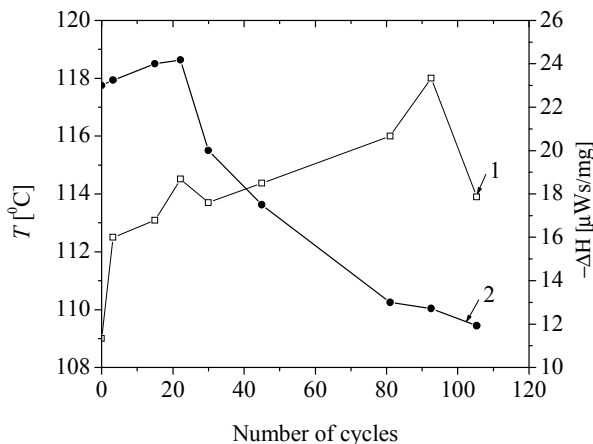


Fig. 11. Temperatures (1) and enthalpy (2) evolution corresponding to the melting process during thermal cycling.

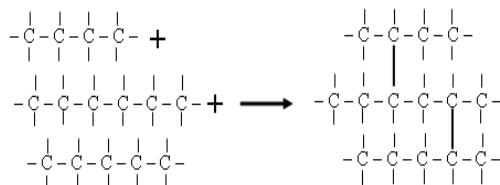


Fig. 12. Schematic representation of polyethylene cross-linking - 3 molecules with different polymerization degree form a single macromolecule with two carbon-carbon tertiary chain.

This is probably due, according to [8, 9] to the atoms oxidation of tertiary carbon (more reactive) after cross-linking and the second one due to the oxygen attack on the methylene groups and the hydroperoxides formation. Comparing the results obtained by dielectric spectroscopy and thermal analysis methods the decrease of insulation resistance and the increase of loss factor during thermal cycling is due to the decrease of polyethylene crystallinity degree and formation of solids peroxide products (polar groups, charge carrier whose mobility increases with the temperature).

IV. CONCLUSIONS

In the present paper the thermal fast ageing by applying successively thermal cycles (between -35 and $+100 \text{ }^\circ\text{C}$) on polyethylene insulation taken from a medium voltage cable (20 kV) was studied. Analyzing the results obtained by dielectric spectroscopy and thermal analysis was found that:

- By thermal cycling the dielectric performances of studied polyethylene insulation decrease, respectively $\text{tg } \delta$ increase;
- Increase of $\text{tg } \delta$ is more pronounced at higher temperatures ($100 \text{ }^\circ\text{C}$), especially in the frequency range $0.5 \text{ Hz} \div 2 \text{ kHz}$;
- By thermal fast ageing the polyethylene insulation cross-link (increase the number of tertiary carbon-carbon chains) but in the same time becomes more amorphous.

ACKNOWLEDGMENTS

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