DEGRADATION OF POWER CABLES POLYETHYLENE INSULATION DUE TO THERMAL CYCLING

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Abstract: In the present paper the results concerning the modifications of structural and dielectric properties of polyethylene insulation of medium voltage cables (20 kV) subjected to ageing by thermal cycling (between –35 and +100°C) are presented. The structural modifications of polyethylene were investigated by thermal analysis methods (TG, DTG and DTA). Dielectric properties modifications of polyethylene due to thermal cycling were investigated by dielectric spectroscopy method (in range $10^{-2} \div 10^{6}$Hz) and by the insulation resistance measurement (at 5kV)

Key words: polyethylene insulation, thermal ageing, thermal cycling, thermal analysis, spectroscopy.

1. 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.

Polyethylene is a thermoplastic polymer whose structure consists of ethylene monomer chain (Figure 1).
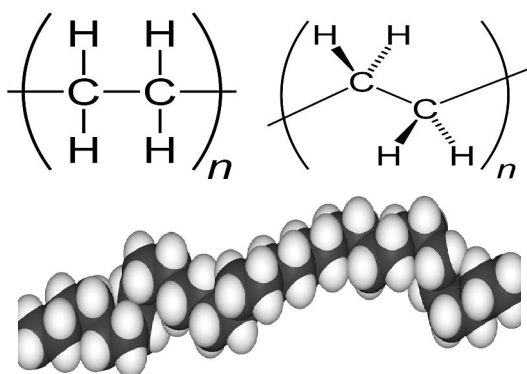
Fig. 1. Different structural representations of polymeric chain.

Polyethylene is obtained by polymerization process of ethylene. Ethylene molecule, known also as ethylene may me described by the molecular formulas, C_2H_4, or by the structural one $CH_2=CH_2$ (Figure 2).
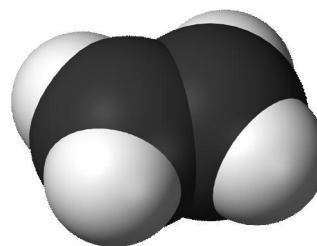
Fig. 2. Spatial model of ethylene molecule.

Over time, several methods have been developed for obtaining polyethylene, such as radical polymerization, addition polymerization reactions, anionic and cationic polymerization of metal ion coordination (polymerization in the presence of catalysts). Each of these methods produces a different type of polyethylene.

The melting and glass transition of polyethylene depends of its crystallinity and molecular weight. Thus, for commercial types of polyethylene with medium and high density, the melting point is in the range 120÷130°C, while for low density polyethylene the melting occurs between 105÷115°C.

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:

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

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 significant 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 (structural and electrics) of polyethylene insulation of power cables, due to cycling thermal stresses.

2. EXPERIMENTS

A medium voltage cable sample type A2XS2Y of 250 mm^2 was subjected to thermal cycling in a thermo climatic room (type VÖTSCH-Industrietechnik), according with the temperature diagram from Figure 3.
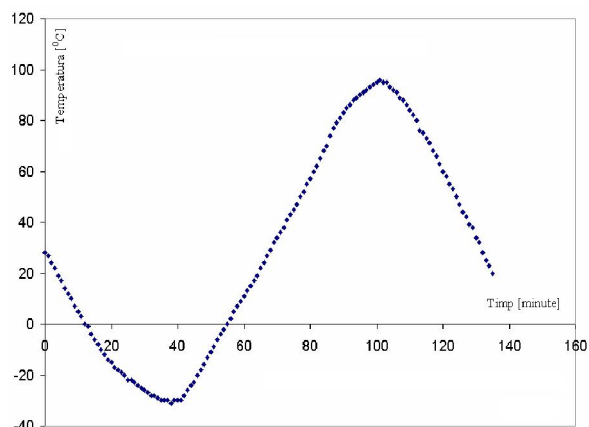
Fig. 3. Thermal treatment profile of cycles (thermo cycles) applied.

Before, during and after the thermal treatment from polyethylene insulation of cable the insulation resistance was determined (at 5kV by using a gigaohmeter type FLUKE 1550 B).

From polyethylene insulation of cable sample probes were taken (before, during and at the end of thermal stresses) in order to their characterization by the thermal analysis method [4, 5].

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

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

Before thermal treatment and after 120 complete thermal cycles (Figure 3), from polyethylene insulation of cable sample 5 crown circular shape samples were taken (17 mm inner diameter and 25mm 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 (tg δ) 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.

3. RESULTS

a) Results obtained by thermal analysis

Thermogram of polyethylene insulation, before the first cycle, is presented in Figure 4.

Analyzing the Figure 4 it can be seen that by progressive heating of polyethylene insulation the followings processes are produced:

- melting of crystalline component of polyethylene, characterized by an endothermic 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. One of them is majority which melts at 109.8°C and the other one is minority (which higher molecular mass) which melts at 182.7°C;
- thermo-oxidation with solids products generation, characterized by a maximum exothermic in DTA curve at 260.8°C;
- thermo-oxidation with volatiles products generation, characterized by a mass loss put into evidence in the TG curve, one or more minimum in DTG curve and exothermic maximum and endothermic 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 4 but are different by the temperatures values and the enthalpies characteristics of each process. As example in the Figure 5 the thermogram obtained after the subjection of polyethylene at 23 complete thermal cycles is presented.

Comparing the Figures 4 and 5, it can be seen that the fraction of polyethylene, initially with the melting point of 182.7°C disappears after 23 thermal cycles are a new endothermic process appears at 191.8°C with mass increase (oxidation solids products).

Considering that the electrical performances of polyethylene are determined by the majority fraction, in Figure 6 the melting temperatures evolution during the thermal cycling is presented. Similar, the melting enthalpies evolution of majority fraction is presented in Figure 7.

Analyzing the Figures 6 and 7 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 cristallinity 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 8) but in the same time become more amorphous.
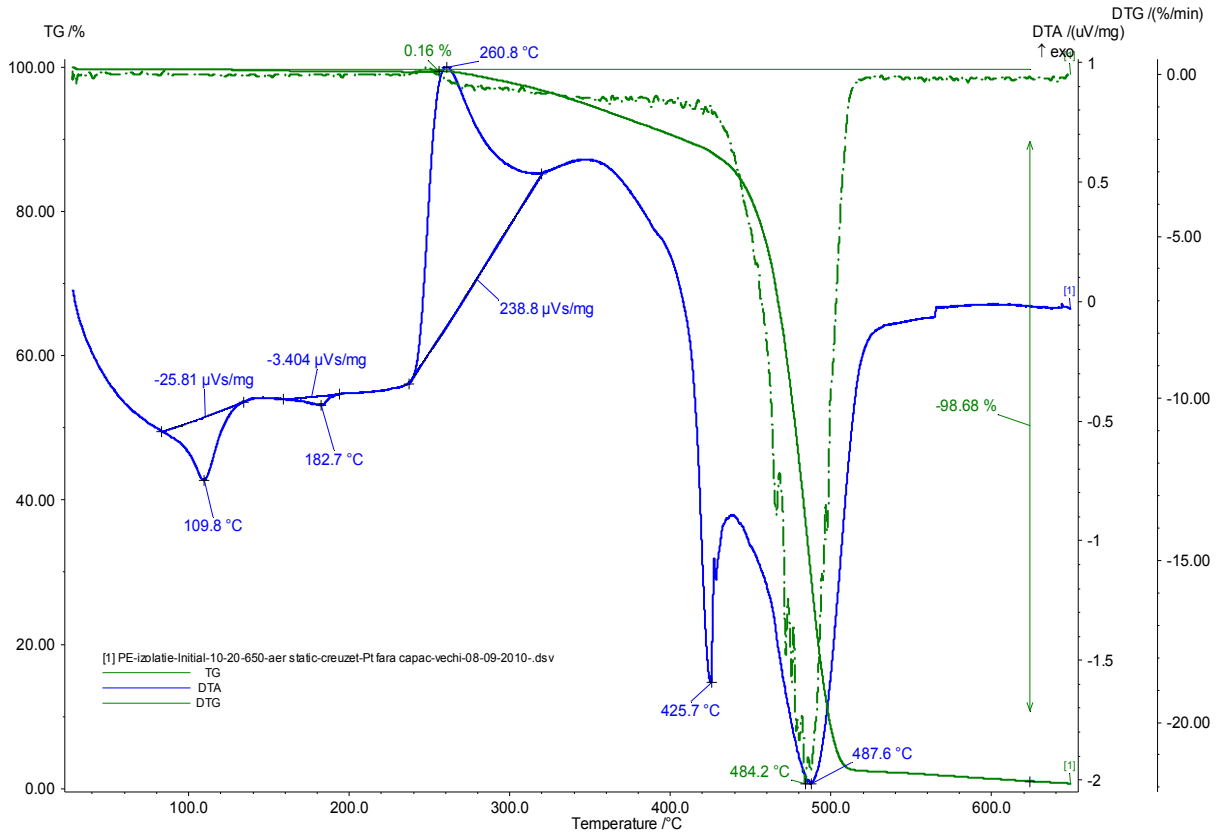
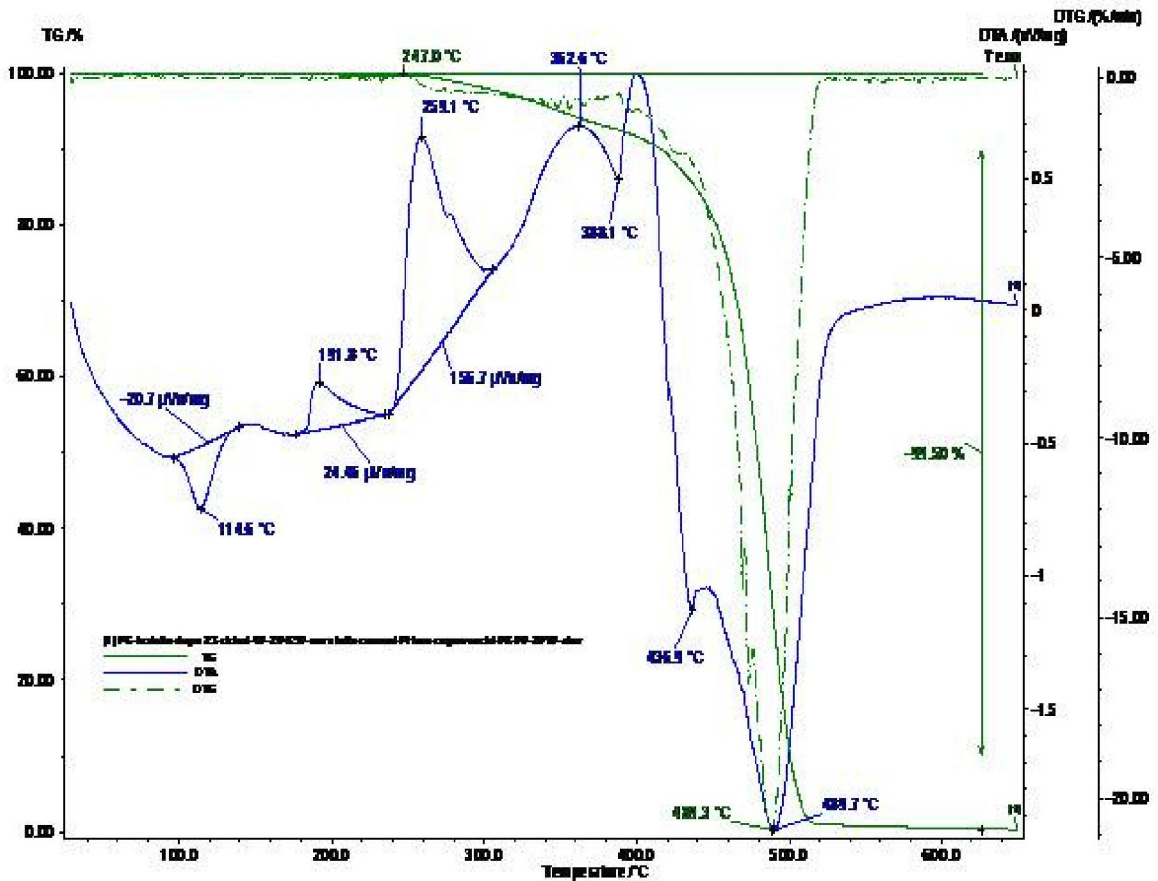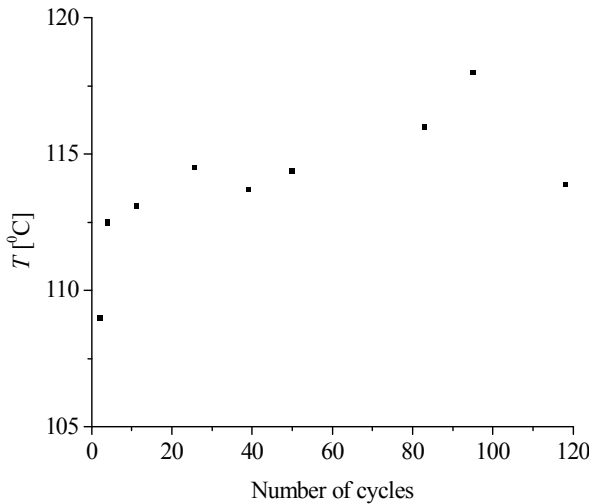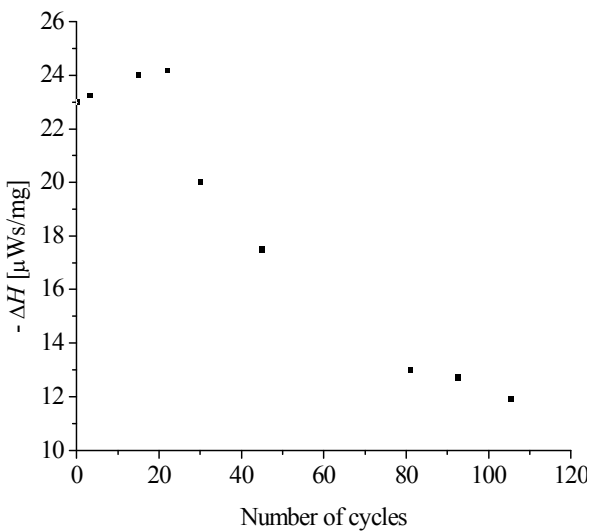**Fig. 4. Thermogram obtained on polyethylene sample, before the first thermal cycling.**
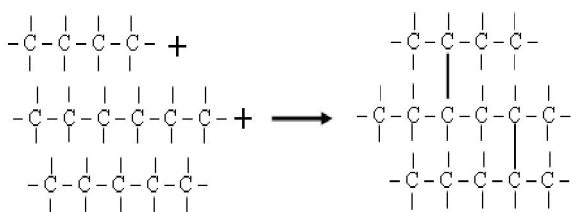

Fig. 5. Thermogram obtained on polyethylene insulation sample subjected at 23 complete thermal cycles.

Fig. 6. Temperatures evolution corresponding to the melting process during thermal cycling.

Fig. 7. Enthalpy evolution, corresponding to the melting process during thermal cycling.


Fig. 8. Schematic representation of polyethylene cross-linking - 3 molecules with different polymerization degree form a single macromolecule with two carbon-carbon tertiary chain.

From recorded thermogram on the polyethylene samples, taken during the thermal cycling two thermo-oxidative processes forming solid products, characterized by exothermal peaks in the DTA curves. First in the temperature range 182±15°C and the second one in 257÷268°C range. This is probably due, according to [6÷9] to the atoms oxidation of tertiary carbon (more reactive) after cross-linking and the second one due to the oxygen attack on the methyl groups and the hydro peroxides formation.

b) Insulation resistance evolution

Evolution of the insulation resistance during the thermal cycling of the cable sample measured at 100±2°C and 5kV is presented in Figure 9.
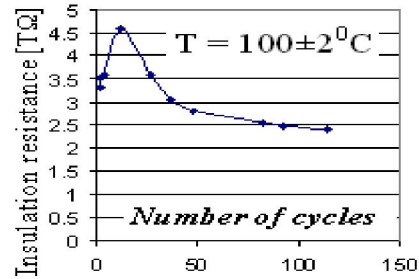

Fig. 9. Evolution of insulation resistance of cable sample.

Analyzing the results presented in Figures 7 and 9 a good correlation between the evolution of insulation resistance of cable sample and the melting specific heat of polyethylene, respectively its cristallinity degree can be seen.

c) Results obtained by dielectric spectroscopy

The Nyquist diagrams, obtained by dielectric spectroscopy at 30°C before and after thermal cycling (120 complete thermal cycles) are presented in Figure 10.
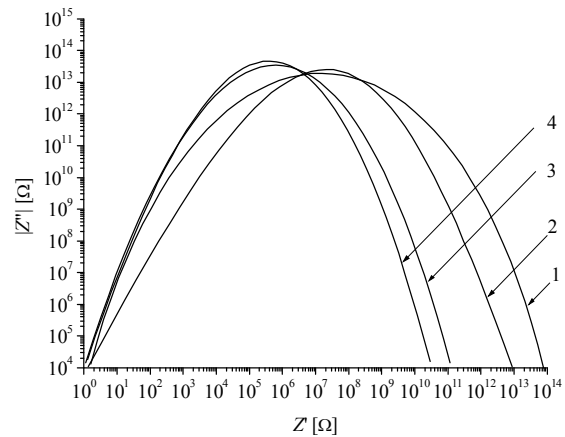
**Fig. 10. Nyquist diagrams obtained on polyethylene samples:** (1) uncycled at 30°C ; (2) thermal cycled at 30°C; (3) uncycled at 100°C and (4) thermal cycled at 100°C.

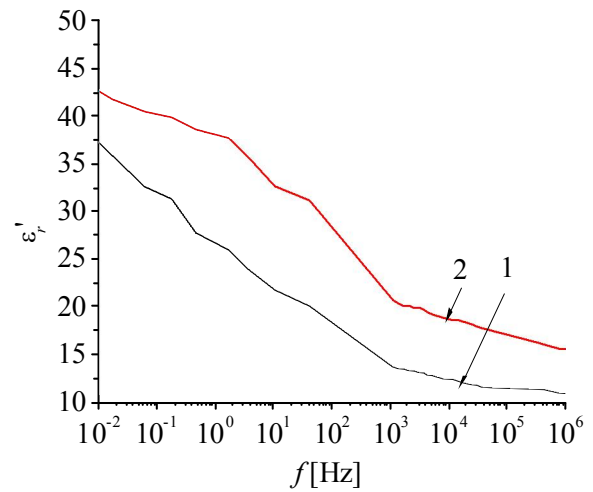The complex impedance $Z^*(\omega)$ can be written as follows:

$$Z^*(\omega) = R + j\omega[\varepsilon_0(\varepsilon_r{}' - j\varepsilon_r{}'')(A/g) - jC''] \qquad (2)$$

where: R represents the resistance [Ω], ε_0 - electrical permittivity of vacuum [F/m], $\varepsilon_r{}'$ - the real component of complex permittivity, $\varepsilon_r{}''$- the imaginary component of complex permittivity, A - the electrodes surface [mm²], g - the sample thickness [mm], C'' - the imaginary component of complex capacity [F].
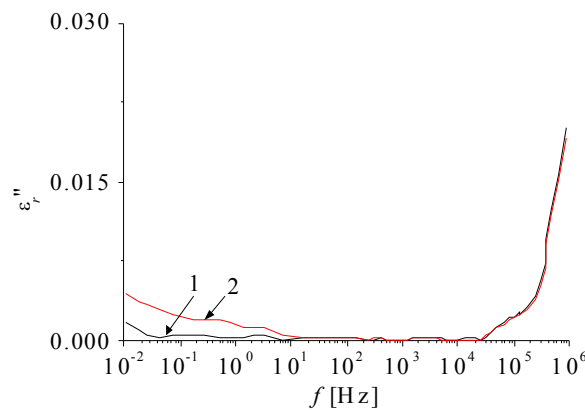
In Figures 11 and 12 the variations of real component complex permittivity and imaginary component complex permittivity with the frequency f are presented.
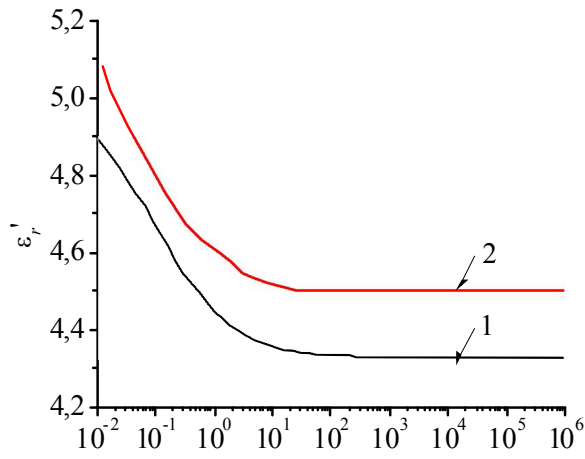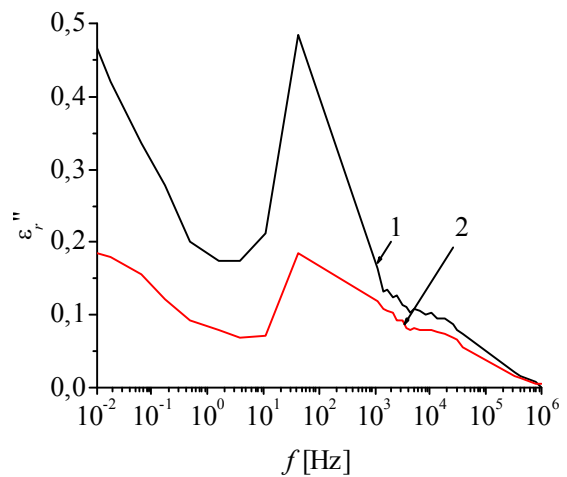
Fig. 11. Variation of real component complex permittivity ε_r' with frequency f, at 30°C, 3V$_{RMS}$: (1) uncycled, (2) thermal cycled.

Fig. 12. Variation of imaginary component complex permittivity ε_r" with frequency f, at 30°C, 3V$_{RMS}$: (1) uncycled, (2) thermal cycled.

Considering the loss factor tg δ as follows:

$$tg\ \delta = \varepsilon_r^{"}/\varepsilon_r^{'} \qquad (3)$$

it variation with the frequency is obtained (Figure 13).

Fig. 13. Variation of loss factor tg δ with frequency f, at 30°C, 3V$_{RMS}$:
(1) uncycled, (2) thermal cycled.

Similar, the results obtained at 100°C of parameters ε_r', ε_r" and tg δ are presented in Figures 14, 15 and 16.

Fig. 14. Variation of real component complex permittivity ε_r' with frequency f at 100°C, 3V$_{RMS}$: (1) uncycled, (2) thermal cycled.
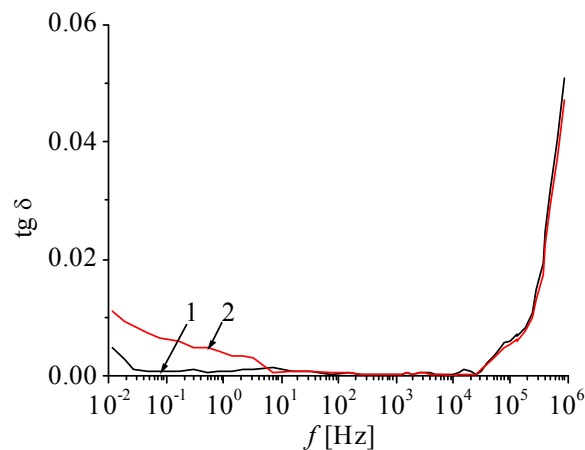

Fig. 15. Variation of imaginary component complex permittivity ε_r" with frequency, at 100°C, 3V$_{RMS}$: (1) thermal cycled, (2) uncycled.
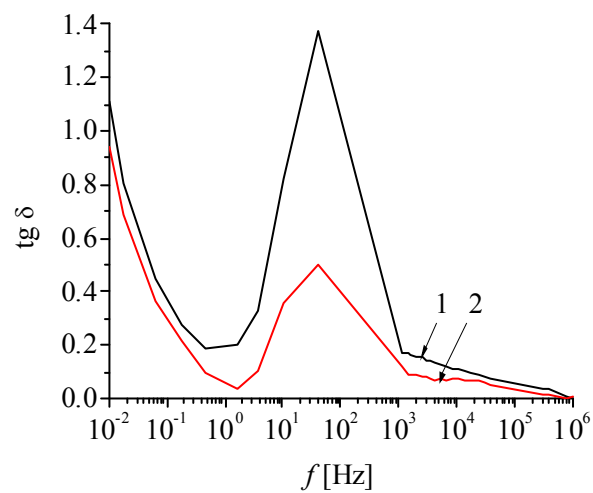

Fig. 16. Variation of loss factor tg δ with frequency f, at 100°C, 3V$_{RMS}$:
(1) thermal cycled, (2) uncycled.

Analyzing the Figures 11÷16 it can be seen that due to applied thermal cycles (120 thermal cycles according to Figure 3), dielectric performance of polyethylene

insulation decreases, respectively tg δ increases. The increase of losses at 30°C is remarkable for frequencies below 1Hz and substantial at 100°C in the range 0.5Hz÷2kHz. 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.

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 cristallinity degree and formation of solids peroxides products (polar groups, charge carrier whose mobility increases with the temperature).

4. CONCLUSIONS

In the present paper the thermal fast ageing by thermal cycles (between –35°C and + 100°C) of polyethylene cable insulation taken from a medium voltage cable (20kV) was studied.

From experimental data obtained by dielectric spectroscopy, electric determinations and thermal analysis was found that:

- by thermal cycling (120 cycles between –35 and +100°C) the dielectric performances of studied polyethylene insulation decrease, respectively tg δ increase;
- increase of tg δ are more pronounced at higher temperatures (100°C), especially in the frequency range 0.5Hz ÷ 2kHz;
- 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.

A good correlation during thermal cycling between the insulation resistance of cable sample (inclusive the loss factor - tg δ) and melting specific heat of polyethylene, respectively its cristallinity degree – which leads to the conclusion that electrical properties of polyethylene are determined by its cristallinity degree (ordering degree of polymeric chain).

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