Ročník 2011 electroscope Číslo VI

Radiation Ageing of Flame Retardant XLPE Cables

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Abstract:
The paper discusses the possibilities of using capacitance and tan δ measurements in the range of very low frequencies for investigation of the influence of radiation on the special LOCA cross-linked polyethylene flame retardant cable dielectric. It was found that the measured and calculated parameters depend significantly on the absorbed dose of radiation. The most probable reason of the structural changes in cross-linked polyethylene exposed to radiation is an additional cross-linking. The results also proved that the capacitance measurements in the very low frequency range could be used in practice for estimation of the absorbed dose in polyethylene cables.

INTRODUCTION

Cross-linked polyethylene (XLPE) is used widely in the cables for transmission and distribution purposes and also for other special applications e.g. in flame retardant cables. Because of its low permittivity and tan δ, XLPE is considered as an efficacious insulating material. Like other materials, it undergoes structural degradation in humid environment. This type of degradation has already been observed and quantified as well as the degradation processes under the electric and the thermal stress [1]. But there are not many results concerning the XLPE behavior influenced by the gamma-irradiation. The radiation can worsen but also enhance the electrical properties of an XLPE dielectric. Research in this field is necessary for the future use of XLPE cables in nuclear power stations.

POLYMERS FOR THE CABLE APPLICATIONS

Polymer structure comprises long chains consisting of the dipoles with different size and orientation. Each group of dipoles contributes to the relaxation process by a separate part, which appears as a peak in the frequency dependence of the loss factor. The individual relaxation processes are identified by the signs α, β, γ depending on the peak position in the frequency or temperature scale. The α-process belongs to the peak at the lowest frequency (for the constant-temperature measurements) or to the peak at the highest temperature (for the constant-frequency measurements). We can classify the groups of dipoles relative to their placement in the polymer backbone and also according to the type of their motion in an electric field. Two possibilities of a dipole placement toward the backbone exist: parallel and perpendicular. The dipoles, which are not components of the backbone are arbitrary oriented. As for the dipole motion, three possibilities can appear: the localized motion (at the atom level), the segmental motion (at the level of a macromolecule part) and the chain motion (motion of the whole molecule) [2].

Regarding the above classification it was found that the α-process is based on the segmental motion. This type of the dielectric process is a cooperative phenomenon, i.e. the motion of a selected segment influences the neighbor part of the macromolecule and the neighborhood in a feedback influences the original segment. The α-process is caused mostly by the dipoles with perpendicular orientation toward the backbone. The cooperative nature of the α-process has an important consequence: the temperature dependence of its relaxation time does not obey the well-known Arrhenius law but the Vogel-Fulcher-Tammann (VFT) equation. Except of the ordinary α-process, a similar type of relaxation exists in polymers comprising the dipoles with parallel orientation toward the backbone. It is called the normal mode relaxation and it is based on the chain motion. The relaxation frequency of this process appears below the frequency of the α-process.

The second important relaxation process in polymers is the β-process. It is connected with the segmental motion of the dipoles in the side groups. The relaxation frequency of this process is higher comparing with the α-process. The relaxation time obeys the Arrhenius law. The permittivity increment in the complex permittivity functions is less for the β-process than the one for the α-process. The temperature coefficient of the increment is negative for the β-process and positive for the α-process. In relation with the structure of the side groups in polymers, more than one β-process can be recognized in the relaxation spectrum. These processes are then denoted as γ or δ. We can distinguish these processes by their activation energy. The approximate values of energies are 85, 20 and 5 kJ mol^{-1} for the β- γ- and δ-processes respectively. The degradation degree in power cables during their operation is obviously checked by the dissipation factor (tan δ) measurement. In the time domain the absorption current or recovery voltage can be measured [3]. From these quantities some derived parameters like polarization index are calculated for routine cable evaluation. The parameters acquired by the diagnostic methods mentioned above can individually respond to the changes caused by the long-term operation or to the changes induced by artificial ageing. In this paper the measurements of the complex capacitance and tan δ in the range of very low frequency is used for detecting of the cables degradation caused by irradiation.

EXPERIMENT

Specimens of the length 100 cm were cut from a four-core XLPE flame retardant cable and irradiated to get define dose of radiation. Four different doses were chosen (100, 200, 300 and 400 kGy). The source of radiation was a gamma-emitter ^{60}Co with the dose rate of 950 Gy h^{-1}. The irradiated specimens were compared with a non-irradiated specimen from the same cable.
The three cores of each specimen were short connected to create one electrode of the system. The rest core created the second electrode. A complex capacitance of this electrode system was measured in the frequency range 5 mHz - 1 kHz at temperatures from 30 °C to 90 °C by means of the complex capacitance meter build up in our department. The voltage on the specimens during these measurements was 2 V.

RESULTS AND DISCUSSION

The measured data of capacitance and tan δ are in Figs. 1 - 6.

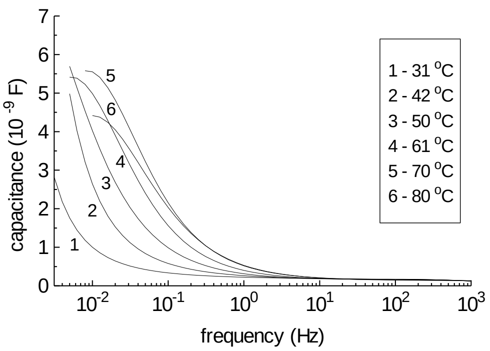

Fig. 1: Capacitance of non-irradiated cable with temperature as parameter

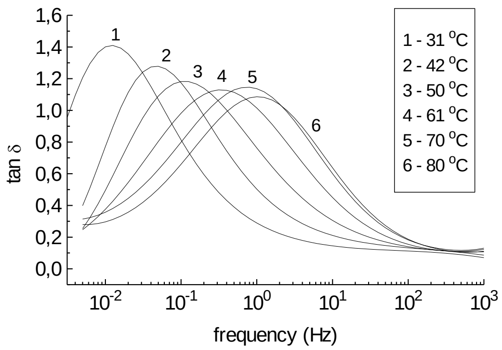

Fig. 2: Dissipation factor of non-irradiated cable with temperature as parameter

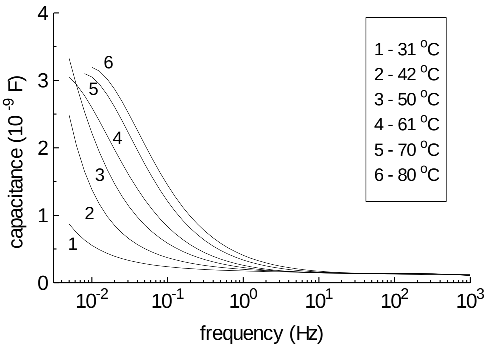

Fig. 3: Capacitance of 400 kGy irradiated cable with temperature as parameter

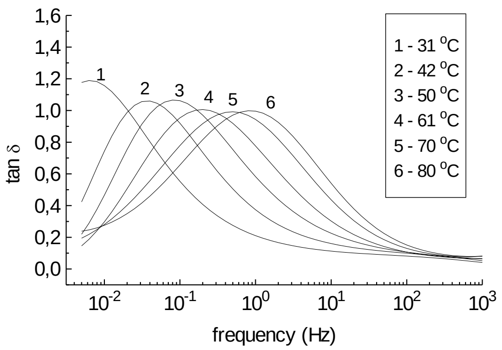

Fig. 4: Dissipation factor of 400 kGy irradiated cable with temperature as parameter

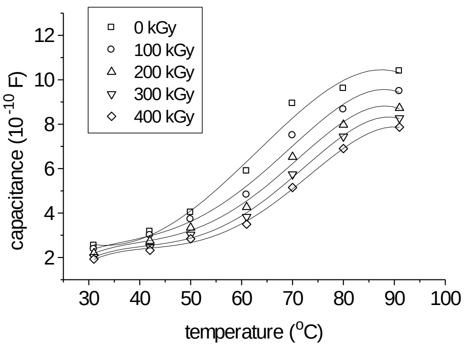

Fig. 5: Capacitance measured at 0.4 Hz with absorbed dose as parameter

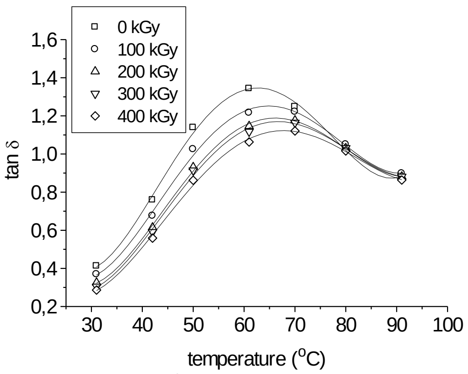

Fig. 6: Dissipation factor measured at 0.4 Hz with absorbed dose as parameter

The frequency dependences of capacitance and dissipation factor in Figs. 1 - 4 are typical for an ordinary relaxation process. The peaks of dissipation factor are shifted to the higher frequency with increased temperature. The relaxation process is present both in the non-irradiated specimen as well as in the specimens with various absorbed dose of radiation. After analyzing the measured data we found that the temperature dependence of relaxation time follows the Arrhenius law. The calculated value of the activation energy of the process was about 60 kJ mol^{-1}. Comparing this value with the data published in literature we can state, that the observed process is of the β-type. As it is seen from Figs. 5 – 6, the polarization process is influenced by the absorbed dose of radiation. Apparently, the dose does not shift the frequency at which the peak of dissipation factor occurs. In this way the activation energy of the observed process undergoes only a very small change with the absorbed dose. By testing the equality of activation energy for various doses we found, that their changes have no statistical significance. It means that the activation energy of the β-process does not depend on the absorbed dose. On the other hand, there is a great influence of the absorbed dose on the peak value of dissipation factor. This value decreases with the dose. As the peak value is determined by the permittivity increment of the polarization process, the polarization descends with the dose. A possible explanation of this effect can be reduction of the number of movable dipoles in a unit volume. It is probably a consequence of new bonds created by radiation (cross linking) [4].

CONCLUSIONS

The results of our measurements showed that the relaxation process of the β-type is present in the XLPE cable already in the initial state. The radiation weakens the process in such a way, that the number of movable dipoles decreases probably as a consequence of an additional cross-linking of the polymer chains. The change of polarization during the radiation ageing is not dangerous for insulation, as the polarization maximum is far from the cables service frequency. In addition, the peak value of dissipation factor decreases with the absorbed dose. Anyway, the dissipation factor is a good indicator of ageing and also a diagnostic tool. The results proved that the dielectric measurements in the very low frequency range could be used for estimation of the absorbed dose in the cross-linked polyethylene cables subjected to the radiation stress. Relative higher value of dissipation factor is probably caused by the presence of flame inhibitors in cable insulation.

ACKNOWLEDGMENTS

This work has been supported by Scientific Grant Agency of the Ministry of Education of Slovak Republic and the Slovak Academy of Sciences under the project VEGA No. 1/0445/10 and Project: “Increase of Power Safety of the Slovak Republic” (ITMS: 26220220077) supported by the Research & Development Operational Programme funded by the ERDF.

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