Evaluation of cable paper performance, by use of space charge measurements

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Abstract-: Focused on the analysis of space charge evolution in papers for DC cables insulation, the article tries to identify some parameters derived from PEA measurements, able to characterize accurately the space-charge associated phenomena under certain poling conditions, in order to be further correlated with charge mobility and, eventually, with the physical/chemical structure consequent to the manufacturing process of the insulating material.

I. Introduction

In order to investigate the behavior of oil-paper cables, some recent techniques, such as pulsed electroacoustic (PEA), have been developed towards obtaining valuable quantitative information about space-charge associated phenomena. Most polymers seem to be significantly affected under DC stress by charge accumulation and internal field alteration, due to low mobility of space charges. This work is part of an extended study about space charge and conduction current features of paper-oil insulation for DC cables application, and deals with the influence of poling field upon space charge evolution in paper materials, trying to point out the occurrence of a threshold, similar with the one detected for some other polymeric materials, [1].

II. Experimental part

The phenomena relating space charge distribution were investigated by means of the PEA method, [2]. This kind of systems for space charge measurements is able to provide profiles of charge and electric field gradient, under a certain value of the applied field, as function of poling and depolarization time. The quantities derived from PEA experiment are defined according with [1, 3] and obtained under the steady-state regime for the given poling field. Total absolute stored charge magnitude:

$$Q(t) = (l/g) \int_0^g Q_p(x, t)\, dx \qquad (1)$$

where $\boldsymbol{Q_p}$ is the charge magnitude profile detected inside the specimen, $\boldsymbol{g}$ is the distance between electrodes (or sample thickness in field direction), and $\boldsymbol{t}$ is the poling/depoling time. $\boldsymbol{Q(t)}$ can be derived at any time of the poling interval $\boldsymbol{(0, t_P)}$, or depoling interval $\boldsymbol{(t_P, t_o)}$, but its experimental estimation can be inaccurate. In order to analyze more precisely the stored charge evolution versus time, the charge density $\boldsymbol{q_o(t)}$ is defined, by relating $\boldsymbol{Q(t)}$ measured during depolarization to the stored charge value at the beginning of the depolarization, $\boldsymbol{Q_o}$.
The time evolution of $\boldsymbol{q_o}$ parameter is considered of great importance in defining the material behavior under DC stress:

$$q_0(t) = [(l/g) \int_0^g Q_p(x, t)\, dx\,] / Q_0 \qquad (2)$$

The $\boldsymbol{Q_o}$ value can be obtained by space charge measurements performed immediately after turning off voltage and short-circuiting the specimen (volt-off), and become a reference value for an experimental stage, i.e. a defined poling time, poling field and specimen type:

$$Q_0 = \lim_{t_0 \to t_p} [(1/g) \int_0^g Q_p(x, t)\, dx\,] \qquad (3)$$

III. Results and discussion

Comparing only to usual plastic sheet samples, the laminated paper requires a very carefully calibration of PEA system response. In our study oil-wetted and conditioned paper specimens were used to simulate the paper condition within DC cables.

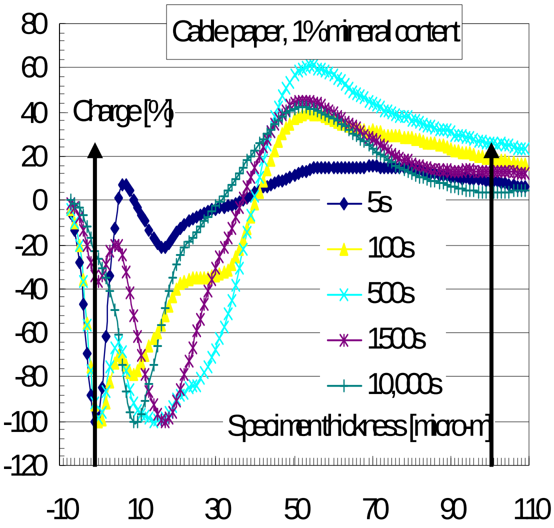

Figure 1. Space charge profiles at different poling times

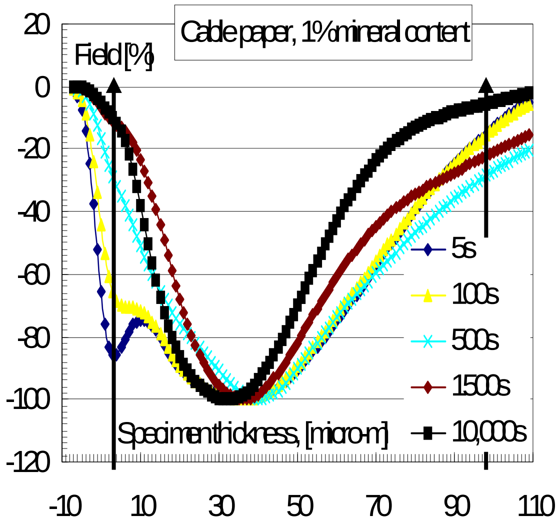

Figure 2. Internal field profiles at different poling times

The measurements here presented were carried out upon specimens of insulation paper - 100µm thick, 1% mineral content, according to a polarization/depolarization program involving a poling field of about 80% of specimen breakdown strength, a poling time t_P = 10,000s and a depolarization time t_o = 1000s.

The evolutions of space charge and internal field are presented in figures 1 and 2, as function of specimen thickness, at 8kV/mm poling field (electrodes spatial positions are marked by arrows). The characteristics are presented in [%], by reporting all instant values to the minimum value of the series, in order to facilitate the general interpretation of charge processes and to emphasize the relative regional growth of internal charge and field. At the beginning, a short homocharge process (lasting a few seconds) was noticed in the vicinity of the cathode, causing an increased field value. After that, the charge close to cathode becomes negative (likely due to injection) and interfacial cathode field decreases, figures 1 and 2. As a consequence of field effect and continuous charge injection, charge penetrates in the insulation, reaching the anode and giving rise to hetrocharge formation. Progressively, the field value increases towards the bulk of specimen. It takes a relatively long period, up to 10,000s, to reach the regime conditions of charge, i.e. the equilibrium between charge injection, extraction and transport.

This period can be finally identified by reaching the maximum field strength in the middle of the specimen thickness (figure 2), even if, as regards the field behavior, the regime conditions seem to be accomplished much earlier (immediately after 500s).

Secondly, the specimens were submitted progressively to a constant poling field, up to 80% of specimen breakdown strength, till the maximum space accumulation is reached.

As regards the internal charge and field evolution versus time, it was shown that the characteristics obtained at a poling field up to 40% of breakdown strength differs clearly comparing to the ones obtained for poling fields in the vicinity of breakdown strength.

The reference characteristic of charge evolution versus field value is presented in figure 3, and referring to a Laplacian (constant) equivalent field along material dimension (thickness). But, taking into account the fact that the apparent integrated charge depends mainly on maximum field reached versus thickness, the data were re-plotted for both versus Laplacian and maximum (real) internal field, figure 4 (linear coordinates).

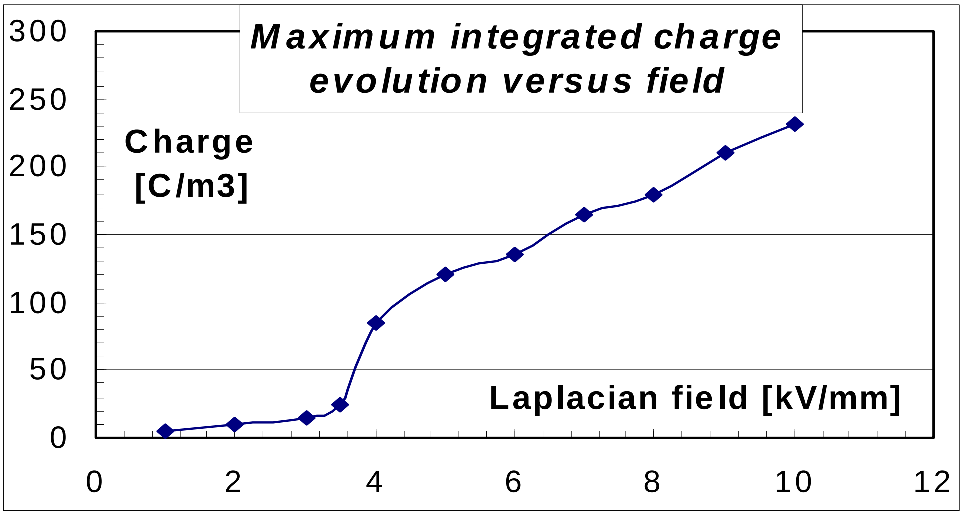

Figure 3. Maximum integrated charge evolution vs. Laplacian field

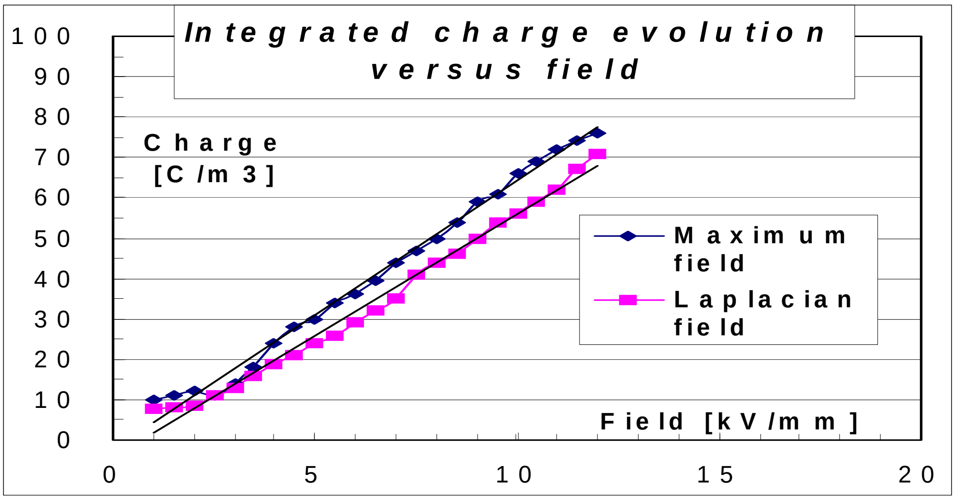

Figure 4. Integrated charge evolution vs. field

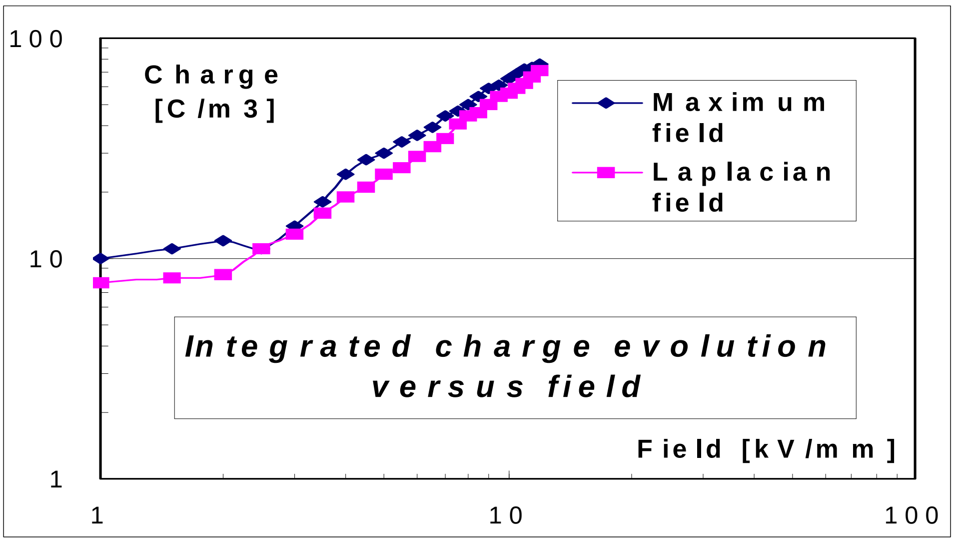

Figure 5. Integrated charge evolution vs. field

Both characteristics in figures 3 and 4 are clearly leading to a threshold value, which occurs even more clearly by use of logarithmic coordinates, figure 5. The phenomenon is comparable with those described in [ ] for XPLE and LDPE polymers. The cable paper presents its own (much lower) threshold value of space charge accumulation, which may depend on mineral content, being e.g. E_T = 3.6 kV/mm for 1% mineral content.
It is assumed that the higher the internal charge and lower the threshold factor, the higher the risk of premature aging.
New research activity will be focused in the direction of correlating the quality of paper materials technology (i.e. the refining, demineralization, lamination processes etc.) with some peculiar values of the parameters derived from PEA measurements, in order to improve the reliability of DC cables insulation.

IV. Conclusions

The space charge phenomena in paper for cable applications are complex, presuming a dynamic equilibrium between charge extraction, transport and recombination.
Cellulose material support seems to present a similar threshold of charge accumulation $\mathbf{E_T}$ as other polymeric materials, but of a lower value, due to their peculiar porous structure. The emphasis of $\mathbf{E_T}$ identification may allow a direct quantitative correlation between space charge and degradation mechanism of paper materials and could represent a valuable procedure towards estimating and improving the lifetime of DC cables insulation.

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