



## DIELECTRIC LOSSES IN CELLULOSE-BASED INSULATIONS

Petru V. NOTINGHER<sup>1</sup>, Laurentiu BADICU<sup>1</sup>, Laurentiu Marius DUMITRAN<sup>1</sup>, Gabriel TANASESCU<sup>2</sup> and Dorin POPA<sup>3</sup>

<sup>1</sup>University Politehnica of Bucharest, petrnot@elmat.pub.ro

<sup>2</sup>SIMTECH INTERNATIONAL Ltd.

<sup>3</sup>ICMET Craiova

**Abstract** - Assessment of the power transformers insulation condition is a permanent concern for carriers and distributors of electrical energy. Different methods for their monitoring and diagnosis were developed in recent years. The aim of this work is to present the basis of the dielectric spectroscopy method and the first results obtained in time-domain and in frequency domain that permit to estimate the dielectric losses in pressboard. At the end, the possibility to use this method for off-line and on-line transformer monitoring is analyzed.

**Keywords:** dielectric losses, dielectric spectroscopy, cellulosic insulation, power transformers, absorption and resorption currents

### 1. INTRODUCTION

Cellulosic materials form the basis elements of power transformers insulation systems. If in 1939 the cellulose insulation were used especially for paper capacitors, paper-insulated power cables and telephone cables, and the annual consumption of paper was estimated at 18 thousand tons, nowadays the annual consumption is measured in million tons, especially for oil filled HV power cables, condenser bushings and power transformers [1].

Electrical grade paper and pressboard are mostly made from wood pulp processed by the Kraft board. Cellulose, the essential component of paper and pressboard, is a polymer of glucose units linked to one another in a special manner as shown in Fig. 1. It may be represented simply as  $[C_6H_{10}O_5]_n$ , ignoring the extra atoms on the end groups, where  $n$  is the degree of polymerization (DP). The DP values for paper samples of Kraft pulps range from 1100 to 1200 but mixed pulp fibers can have much higher DP (1400...1600) [1].

The most important disadvantage of cellulosic materials for electrical use is that they are hygroscopic and need to be processed and maintained dry. At room temperature (20 – 25 °C) cellulose can hold from 4 to 8 % moisture in the relative humidity range of 30 to 70 % typical on factory floors in winter and summer conditions. The moisture level in

insulation in a newly built transformer should be about 0.5 %.

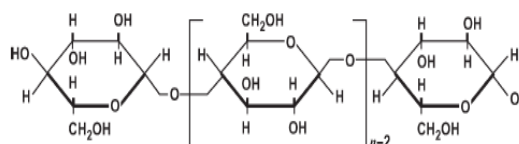


Fig. 1. Chemical structure of cellulose polymer.

For regular Kraft paper the life would be lowered by half for every doubling of moisture content, though for upgraded paper the loss of life is not so drastic. From a temperature perspective, the temperature rises above 75 °C for the mechanical strength to decrease to half be dependent on the moisture content of the paper (for 1 % moisture content, the doubling interval is for every 24 °C, and for 8 % moisture it is 8 °C).

Degradation products based on cellulose is the exhibition of three chemical important reactions: pyrolysis (resulting small chain, CO, CO<sub>2</sub>, H<sub>2</sub>O, and furans), oxidation (resulting CO, CO<sub>2</sub>, H<sub>2</sub>O and acids) and hydrolysis (resulting smaller chains). Ageing of cellulose would lower the DP by depolymerization, which involves breakage of the linkage by hydrolytic decomposition and by the break up of the ring structure that would give CO, CO<sub>2</sub>, and water as ultimate products. Intermediate products of paper degradation include five-membered heterocyclic compounds known as furanic compounds of which 2- furfural is the most important. The presence of – OH and – CH<sub>2</sub>OH groups makes cellulose not only hygroscopic but also vulnerable to oxidative degradation. On the other hand, processes such as cyanoethylation on the – CH<sub>2</sub>OH groups make them less susceptible to oxidation.

Because the water from cellulose insulation essential contributes to the degradation of this, detection and elimination of the water from the transformers solid insulation is very important for their operation.

Usually, the methods used to estimate the water content in the cellulose insulation are: Fabre and Oommen diagrams [2, 3], capacitive humidity sensor [4], infrared spectroscopy [5], polarization index measurement [6], polarization and depolarization currents measurement, return voltage method [6] etc. On the other hand, water presence in cellulose insulation causes a severe increase of the dielectric losses (respectively of the imaginary permittivity component  $\epsilon''$  and to the loss factor  $\text{tg } \delta$ ), especially at low frequencies. In this paper the use of the dielectric spectroscopy to estimate the dielectric losses of the pressboard transformers insulation is presented and the first experimental results are analyzed.

## 2. 2. DIELECTRIC RESPONSE METHOD

### 2.1 Spectroscopy in Time Domain (TDS)

If an electric field of magnitude  $E_0$  is applied to a dielectric at any time  $t_0$  and that this field remains constant for  $t \geq t_0$ , the polarization  $P(t)$  is the response in the time domain of the dielectric and it is given by the equation:

$$P(t) = \epsilon_0 \chi(t) l(t) E_0, \quad (1)$$

where  $\chi(t)$  is the dielectric susceptibility,  $\epsilon_0$  – the permittivity of vacuum and  $l(t)$  – the unit step for the electric field  $E_0$ .  $P(t)$  and  $\chi(t)$  represent step response functions of the dielectric [7]...[9].

Considering an ideal step for  $E_0$ , the polarization corresponding to all very fast polarization processes of the dielectric (electronic, ionic etc.) is  $P(t_0) = P_\infty$ . As the polarization finally becomes static (respectively,  $P(t \rightarrow \infty) = P_s$ , Fig. 2) the polarization  $P(t)$  can be written as:

$$\begin{aligned} P(t) &= P_\infty + (P_s - P_\infty) \cdot g(t - t_0) = \\ &= \epsilon_0 [\chi_\infty - (\chi_s - \chi_\infty)] \cdot g(t - t_0) \cdot E_0, \end{aligned} \quad (2)$$

where  $g(t)$  is a dimensionless monotonously increasing function.

On the other hand, for a time dependent excitation  $E(t)$  the time dependent polarization  $P(t)$  is done (by the use of Duhamel's Integral) by the equation:

$$P(t) = \epsilon_0 \chi_\infty E(t) + \epsilon_0 \int_{-\infty}^t f(t - \tau) E(\tau) d\tau, \quad (3)$$

where  $f(t)$  is the so called dielectric response function

$$f(t) = (\chi_s - \chi_\infty) \cdot \frac{\partial g(t)}{\partial t} = (\epsilon_s - \epsilon_\infty) \cdot \frac{\partial g(t)}{\partial t}, \quad (4)$$

which is obviously a monotonously decreasing function and inherent to the dielectric being investigated.

When a dc voltage  $U_0$  is suddenly applied to a condenser, a current  $i_a(t)$  appears through the test object (Fig. 3):

$$i_a(t) = C_0 U_0 \left[ \frac{\sigma_t}{\epsilon_0} + \epsilon_\infty \delta(t) + f(t) \right], \quad (5)$$

where  $C_0$  is the geometric capacitance of condenser,  $\sigma_t$  is the dc conductivity of the dielectric and  $\delta(t)$  is the delta function from the suddenly applied step voltage at  $t = t_0$ .

The absorption current contains three terms: the first in related to the intrinsic conductivity  $\sigma_t$  of the test object and is independent of any polarization process, the last one represents all the activate polarization processes during the voltage application and the middle part with the delta function cannot be recorded in practice due to the large dynamic range of current amplitudes inherent with the very fast polarization processes.

If the test object is short-circuited at  $t = t_c$ , the resorption current  $i_r(t)$  can be measured. The sudden reduction of the voltage  $U_0$  is regarded as a negative voltage step at time  $t = t_c$  and neglecting the second term in (5) we get

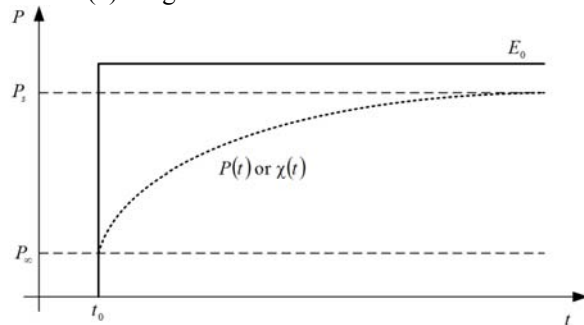


Fig. 2. Polarization of a dielectric exposed to a step electric field of magnitude  $E_0$  at  $t = t_0$ .

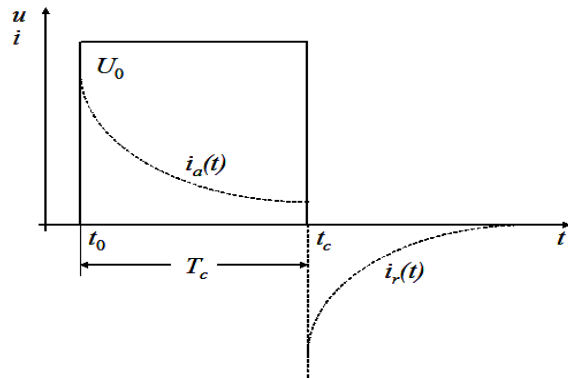


Fig. 3. Principle of absorption ( $i_a$ ) and resorption ( $i_r$ ) currents measurement.

for  $t \geq (t_0 + T_c)$ :

$$i_r(t) = -C_0 U_0 [f(t) - f(t + T_c)]. \quad (6)$$

Equation (8) is the second basis for the measurement of the dielectric function  $f(t)$  and also for characterizing dielectrics response in time domain.

Assuming that the polarization period  $T_c$  is sufficiently long, so that  $f(t+T_c) \approx 0$ , the dielectric response function  $f(t)$  is proportional to the resorption current and:

$$f(t) = -\frac{i_r(t)}{C_0 U_0}. \quad (7)$$

For cellulose insulation systems  $f(t)$  can be expressed in parametric form as:

$$f(t) = \frac{A}{\left(\frac{t}{t_0}\right)^n + \left(\frac{t}{t_0}\right)^m}, \quad (8)$$

when the terms  $A$ ,  $t_0 > 0$ ,  $m > n > 0$ , and  $m > 1$  can be obtained from (6), (7), and (8) [9].

## 2.2 Spectroscopy in Frequency Domain (FDS)

Considering that an AC voltage is applied to a condenser, that the polarization processes are instantaneous, and  $\underline{F}(\omega)$  is the Fourier Transform of the dielectric response function  $f(t)$  or the complex susceptibility  $\underline{\chi}(\omega)$ , it results:

$$\underline{F}(\omega) = \underline{\chi}(\omega) = \chi'(\omega) - j\chi''(\omega) = \int_0^{\infty} f(t) \exp(-j\omega t) dt, \quad (9)$$

$$\underline{\varepsilon}_r(\omega) = 1 + \chi'(\omega) - j\chi''(\omega) = \varepsilon_r' - j\varepsilon_r'', \quad (10)$$

$$\text{tg}\delta = \frac{\varepsilon_r'' + \frac{\sigma_t}{\varepsilon_0 \omega}}{\varepsilon_r'}, \quad (11)$$

where  $\omega$  is the pulsation of the electric field fixed into the capacitor dielectric,  $\underline{\varepsilon}_r$  - complex relative permittivity,  $\chi'$ ,  $\varepsilon_r'$ ,  $\chi''$  and  $\varepsilon_r''$  - real and imaginary parts of the quantities  $\underline{\chi}$  and respectively,  $\underline{\varepsilon}_r$ . Equation (9) represents the link between time and frequency domains. Thus it is obvious that the complex susceptibility  $\underline{\chi}(\omega)$  and its real and imaginary parts can be converted to the dielectric response function  $f(t)$  and vice versa [8]...[11].

## 3. EXPERIMENTS

### 3.1 Samples and setups

For experiments were used samples from pressboard of 0.25 mm and 0.5 mm thickness specially manufactured for transformer insulation. The absorption/resorption currents were measured on groups of 6 samples of 100x100 mm<sup>2</sup>, and for complex permittivity measurement and the loss factor were used groups of 6 disks with 20, 30, and 40 mm diameter.

The samples were thermally conditioned in an oven for 48 h at 50 °C (samples B), 24 h at 90 °C (samples C), 48 h at 90 °C (samples D), and 48 h at 130 °C (samples E)

The measurement of the sample's permittivity was carried out using a Novocontrol spectrometer (Fig. 4). The absorption/resorption currents were measured using a Keithley electrometer and a test fixture (Fig. 5) with an applied voltage  $U_0$  between 100 and 500 V.

### 3.2 Results

The absorption/resorption currents and complex permittivity on the unconditioned samples (A) and thermally conditioned samples (B, C, D and E) were measured. In this paper only a few representative results are presented.

Fig. 6 presents the time variation of the absorption and resorption currents obtained for the applied voltage  $U_0 = 300$  V for thermally conditioned samples at 90 °C. When the conditioned time  $\tau$  increases, the absorption and the resorption currents decrease, due to the diminution of the moisture content which implies a diminution of all currents components: polarization, space charge and conduction.

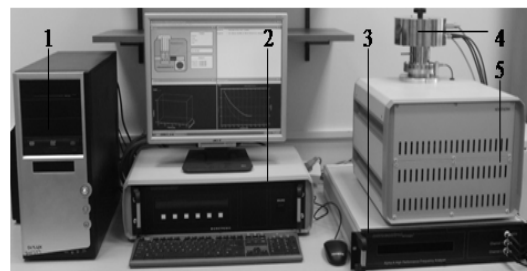


Fig. 4. Novocontrol spectrometer: 1 – PC, 2 – Control System, 3 – Modular Measurement System, 4 – Measurement Cell, 5 – Temperature Control System.

On the other hand, the diminution of the absorption currents values leads to the higher volume resistivity ( $\rho_v$ ) values of the samples (Fig. 7): at  $t = 3600$  s,  $\rho_v$  increase from  $1.99 \cdot 10^{11} \Omega\text{m}$  - for unconditioned samples (A) - to  $8.56 \cdot 10^{14} \Omega\text{m}$  - for thermally conditioned samples (E) (see Table 1).

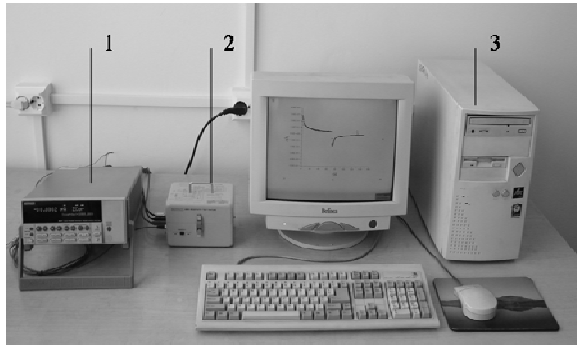


Fig. 5. Experimental set-up for absorption/resorption currents measurement: 1 – Electrometer Keithley 6517, 2 – Resistivity Test Fixture Keithley 8009, 3 – PC.

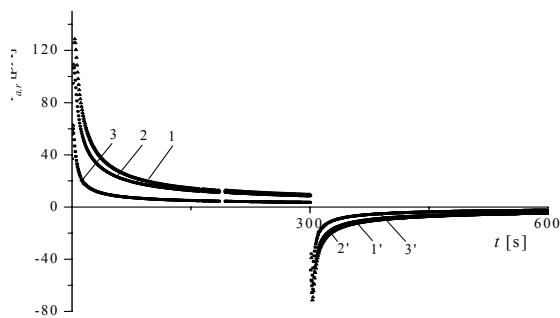


Fig. 6. Time variation of absorption  $i_a$  (1, 2, 3) and resorption  $i_r$  (1', 2', 3') currents for samples C (1, 1'), D (2, 2') and E (3, 3') ( $U_0 = 300$  V).

Due to the high water content of the A and B samples, it results relatively important values of the absorption currents (Table 1): for samples A, the maximum absorption currents values are about  $10^5$  times higher than the currents values obtained for E samples and the resistivity values calculated for  $t = 3600$  s are about 4300 times smaller.

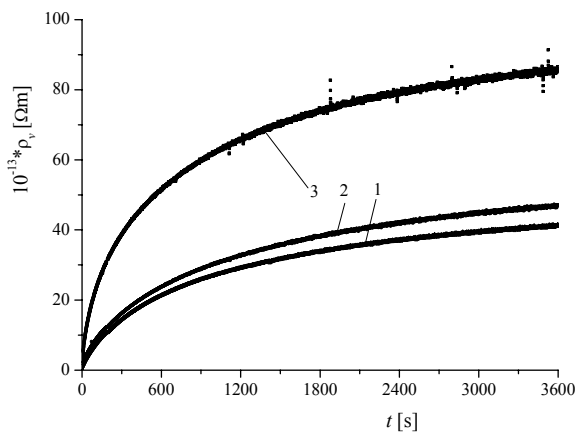


Fig 7. Time variation of volum resistivity  $\rho_v$  for samples C (1), D (2) and E (3) ( $U_0 = 300$  V).

Table 1 - Maximum values of absorption ( $I_{a,max}$ ) and resorption ( $I_{r,max}$ ) currents and volume resistivity  $\rho_v$  (measured at  $t = 3600$  s) ( $U_0 = 300$  V).

Sample	$I_{a,max}$ [nA]	$I_{r,max}$ [nA]	$\rho_v$ [ $\Omega m$ ]
A	720	5.79	$1.99 \cdot 10^{11}$
B	1.88	1.29	$9.96 \cdot 10^{13}$
C	0.095	0.056	$4.12 \cdot 10^{14}$
D	0.061	0.055	$4.68 \cdot 10^{14}$
E	0.045	0.042	$8.56 \cdot 10^{14}$

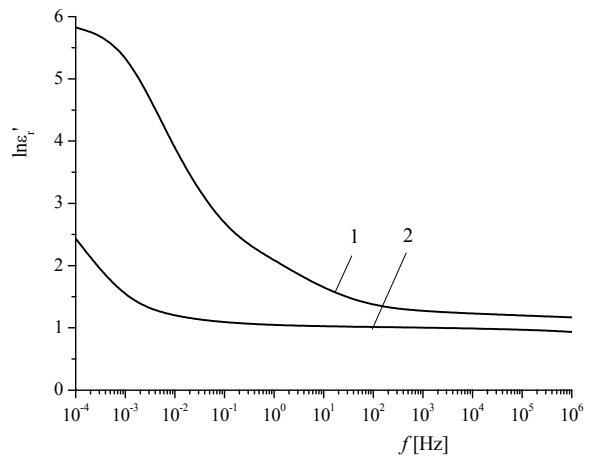


Fig. 8. Variation of the real permittivity component  $\epsilon_r'$  with frequency  $f$ , for samples A (1) and E (2).

The variations of the real and imaginary complex permittivity components  $\epsilon_r'$  and  $\epsilon_r''$  and loss factor  $\text{tg}\delta$  with the frequency are shown in Figs. 8-10. It can be seen that, for low frequencies ( $10^{-3} - 10^{-2}$  Hz) all three quantities take important values. For high water contents in the samples, the increase of these parameters values is most important (results in accordance with [11]).

The increase of  $\epsilon_r'$  with the moisture content is due, firstly, to the increase of dipoles concentration and secondly, to the increase of ions concentration (space charge) which are separated at the interfaces between homogeneous areas (layers of cellulose) of the samples.

On the other hand, charge separation at the interfaces between the homogeneous zones of the samples determines an increase of the interfacial polarization (and, thus, of  $\epsilon_r'$ ).

The interfacial polarization increase causes a growth of the term of the loss factor ( $\text{tg}\delta$ ) corresponding to the polarization phenomenon ( $\text{tg}\delta_h = \epsilon_r''/\epsilon_r'$ ), especially if the frequency is very small ( $10^{-5} - 10^{-4}$  Hz). But, the large values of the loss factor at low

frequencies are due, too, to the increase of its second term  $\text{tg}\delta_\sigma = \sigma/(\epsilon_0\epsilon_r'\omega)$ , that takes high values when the frequency diminishes and the dc conductivity increases (especially in areas nearby electrodes [12].

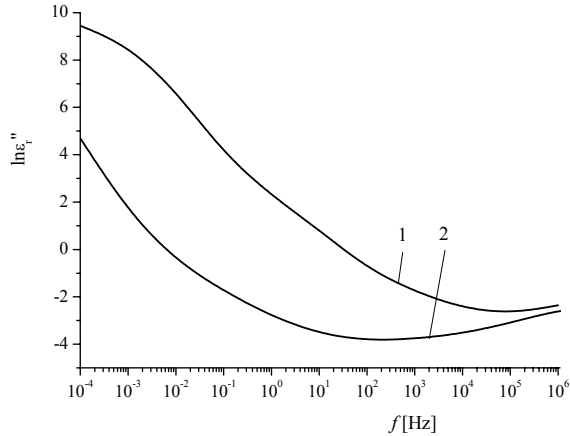


Fig. 9. Variation of the imaginary permittivity component  $\epsilon_r''$  with frequency  $f$ , for samples A (1) and E (2).

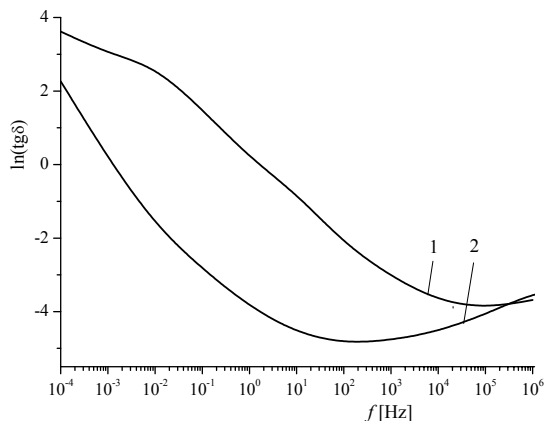
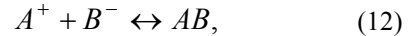


Fig. 10. Variation of the loss factor  $\text{tg}\delta$  with frequency  $f$ , for samples A (1) and E (2).

For A samples (unconditioned samples in which water content is relatively high) a major importance in the increase of permittivity and loss factor values represents the low frequency dispersion process [9], [13]. In this process, the material is assumed to include “clusters” of water. Both intra-clusters and inter-clusters motions contribute to the final dielectric response, respectively to increasing of the quantities  $\epsilon_r''$  and  $\text{tg}\delta$  [14], [15].

On the other hand, because the samples contain both positive ions ( $A^+$ ) as well as negative ions ( $B^-$ ) depending on the relative distances between them, the pairs  $A^+$  and  $B^-$  form electric “dipoles”, whose size and orientation vary with ions motion under the electrical field influence. When the ions pass one

another day form for a time a neutral compound ( $AB$ ) according to the symbolic equation:



This process is capable of retaining a large amount of charge without creating any electric field, only a potential which is associated with be electrochemical potential of the system [14]. Likewise, some energy is supplied either in the formation of the compound, or in its dissociation, so that either way an irreversible energy loss will be incurred in every change of orientation of ionic “dipole” consequently, the values of  $\epsilon_r''$  and  $\text{tg}\delta$  will increase for very low frequencies.

Both the real and imaginary permittivity components, as well as the loss factor, are strongly influenced by dielectric temperature, respectively  $\epsilon_r'$ ,  $\epsilon_r''$  and  $\text{tg}\delta$  are temperature functions (Figs. 11-13).

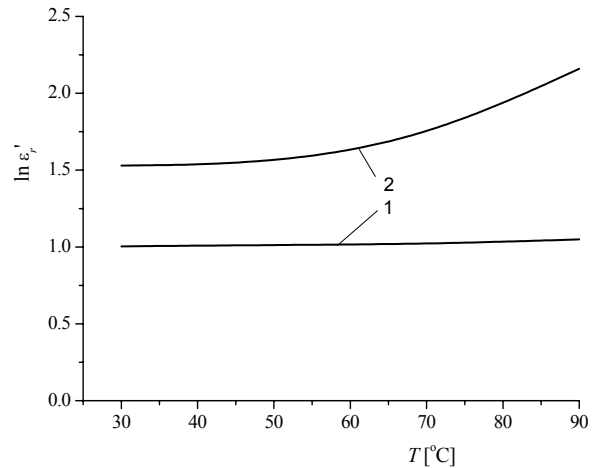


Fig. 11. Variation of the real permittivity component  $\epsilon_r'$  with the temperature  $T$  at  $10^6$  Hz (1) and  $10^{-3}$  Hz (2).

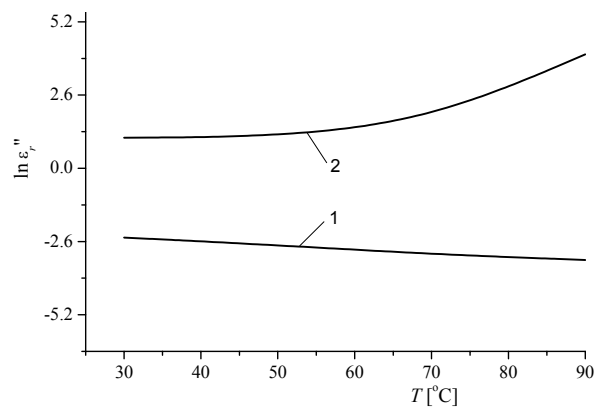


Fig. 12. Variation of the imaginary permittivity component  $\epsilon_r''$  with the temperature  $T$  at  $10^6$  Hz (1) and  $10^{-3}$  Hz (2).

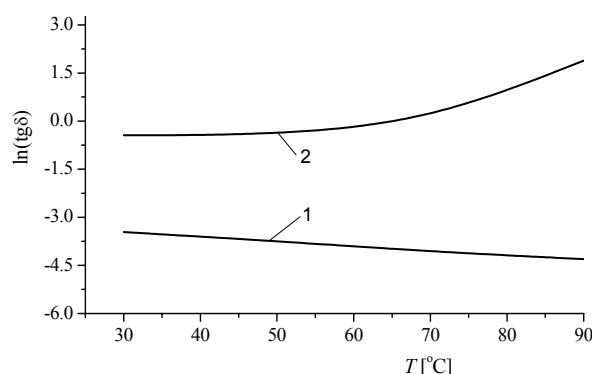


Fig. 13. Variation of the loss factor  $\text{tg}\delta$  with the temperature  $T$  at  $10^6$  Hz (1) and  $10^{-3}$  Hz (2).

The shapes of the variation curves with temperature also depend on the applied voltage frequency. Thus, for high frequencies (Fig. 11, curve 1)  $\epsilon_r'$  slightly increases with temperature due to the increase of the radicals and polar molecules energies. On the other hand, the increase of dipoles energy facilitates their motions under electric field action and, therefore, the decrease of the dielectric losses, respectively of the values of  $\epsilon_r''$  and  $\text{tg}\delta$  (Figs. 11 and 12, curve 1).

In case of low frequencies, all three quantities present important variations with temperature (Figs. 11-13, curves 2). The increase of the real permittivity component is due to the increase of the electric dipoles thermal energy (which, for values below a critical value, facilitates the orientation of the dipoles in electric field), and the losses increase can be produced by the facilitation in interfacial polarization (intra-clusters and inter-clusters motions) and the temporary formation of new „ionic dipoles” (equation (12)).

#### 4. CONCLUSIONS

The first measurements of dielectric characteristics of the power transformer pressboard samples show that the

analyses of the absorption/resorption currents can lead to important and useful information concerning the water content of the solid transformer insulation.

The dielectric losses measured values are strongly influenced by the samples water content, temperature and voltage frequency, and at very low frequencies ( $10^{-4}$  Hz) they can increase by several orders of magnitude compared to those measured at industrial frequencies.

The results obtained by the absorption/resorption currents measurements are confirmed by the spectroscopy in frequency domain, respectively by the measured permittivity  $\epsilon_r'$  and loss factor values. It results that a direct dependence exists between the measured parameter values ( $I_{a,max}$ ,  $\rho_v$ ) and the

condition of the cellulosic insulation exposed to electrical, thermal, etc. strengths.

Using the resorption currents curves  $i_r(t)$ , the response function  $f(t)$  can be calculated that permit to obtain the variations of  $\epsilon_r'$  and  $\epsilon_r''$  with the electric field frequency.

#### ACKNOWLEDGEMENT

This work was supported in part by the Romanian Ministry of Education, Research and Innovation, PNCDI II Program, Project MIDMIT 22 080/2008.

#### References

- [1] T.A. Prevost, T.V. Oommen, “Cellulose insulation in oil-filled power transformers: Part I – History and development”, IEEE Electrical Insulation Magazine, vol 22, 1, pp. 28 – 35.
- [2] J. Fabre, A. Pichon, “Deteriorating processes and products of paper in oil-application to transformers”, CIGRE, Paris, France, Report No. 137, 1960.
- [3] T. V. Oommen, “Moisture equilibrium in paper-oil insulation”, Proc. of the 16th Electrical/Electronics Insulation Conference, Chicago, USA, pp. 162-166, 1983.
- [4] T. V. Oommen, “On-line moisture sensing in transformers”, Proc. 20th Electr. Electronics Insul. Conf., Boston, USA, 1991.
- [5] R. Neimanis, L. Lennholm, and R. Eriksson, “Determination of moisture content in impregnated paper using near infrared spectroscopy”, IEEE Conf. Electr. Insul. Dielectr. Phenomena, pp. 162-165, 1999.
- [6] T.K.Saha, “Review of modern diagnostic techniques for assessing insulation condition in aged transformers”, IEEE Trans. Dielectr. and Electr. Insul., vol. 10, 5, pp. 903-917, 2003.
- [7] W.S. Zaengl, “Dielectric spectroscopy in time and frequency domain for HV power equipment, Part I: theoretical considerations”, IEEE Electrical Insulation Magazine, vol. 19, 5, pp. 5-19, 2003.
- [8] A.K. Joncher, “Dielectric relaxation in solids”, Chelsea Dielectrics Press, London, 1996.
- [9] A.K. Joncher, “The Universal Dielectric Response: Part I”, IEEE Electrical Insulation Magazine, vol 6, 2, pp 16-21, 1990.
- [10] U. Gafvert, “Condition assessment of insulation systems: Analysis of dielectric response methods”, Proc. of Nordic Insulation Symposium NORD IS 96, Trondheim, Norway, pp. 1-19, 1996.
- [11] D. Linhjell, L.Lundgaard, U.Gafvert, “Dielectric response of mineral oil impregnated cellulose

- and the impact of aging*”, Trans. Dielectr. Electr. Insul., vol. 14, 1, pp. 156-169, 2007.
- [12] V. Adamec, J.N. Calderwood, “*Electrode polarization in polymeric dielectrics*”, IEEE Trans Dielectr. Electr. Insul. Vol.24, pp. 205-219, 1989.
- [13] L.A. Dissado, R.M. Nill, “*Anomalous low frequency dispersion, near direct current conductivity in disordered low-dimensional materials*”, J. Chem. Soc., Faraday Trans. II, vol. 80, pp. 291-319, 1984.
- [14] T. P. Hong, O. Lesaint and P. Gonon, “*Water absorption in a glass/mica/epoxy composite. Part I: Influence of electrical properties*”, IEEE Trans. Dielectr. and Electr. Insul., Vol. 6, No. 1, pp. 1-10, 2009.
- [15] J.Gielniak, M.Ossowski, *Dielectric response of oil-paper insulation systems of large moisture temperature inhomogeneity*, Proc. of XIVth Int. Symp. On High Voltage Eng., Beijing, China, Paper G-111, pp. 1-5, 2005.