

Use of Dielectric Spectroscopy to Estimate the Condition of Cellulose-Based Insulation

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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 moisture content in pressboard. At the end, the possibility to use this method for off-line and on-line transformer monitoring is analyzed.

Keywords: dielectric spectroscopy, cellulosic insulation, power transformers, absorption and desorption currents.

I. 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, telephone cables and the annual consumption 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.

Cellulosic insulation is used primarily in oil-filled transformers from distribution to large power units covering a wide range from 10 kVA to 1500 MVA and from line voltage to 1000 kV. In terms of physical size, it ranges from the pole and pad – mounted units on our streets to large substation units that can have several tons of cellulosic insulation (paper and pressboard) immersed in 40.000 to 100.000 l of oil. The insulation structure consists of not only the HV and LV insulation but also different prefabricated items: support structures, winding tubes, spacer blocks, and formed items for end closing [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 $[C_5H_{10}O_5]_n$, 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].

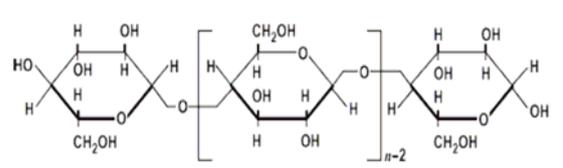


Fig. 1. Chemical structure of cellulose polymer.

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 %. In a wet insulation partial discharges inception becomes significant above 3 % moisture level (and may result in gas bubbles and release of hydrogen), insulation power factor would be above acceptance limits, paper degradation an aging be excessive.

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 rise above 75 °C for the mechanical strength to decrease to half is 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, CO₂, H₂O, and furans), oxidation (resulting CO, CO₂, H₂O and acids) and hydrolyze (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, CO₂, 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 –CH₂OH groups makes cellulose not only hygroscopic but also vulnerable to oxidative degradation. On the other hand, processes such as cyanoethylation on the -CH₂OH groups make them less susceptible to oxidation.

Because water from cellulose insulation essential contributes to the degradation of this, detection and elimination of the water from the transformers solid insulation has a big importance 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/depolarization currents measurement, return voltage method [6] etc.

In the present work the use of the dielectric spectroscopy to estimate the water content of the pressboard power transformers insulation is presented and the first experimental results are analyzed.

II. DIELECTRIC RESPONSE METHOD

A. Spectroscopy in Time Domain (TDS)

Let us assume that a step-like 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 specific polarization $P(t)$ of the dielectric is the response in the time domain of the dielectric and is given by the equation:

$$P(t) = \varepsilon_0 \chi(t) l(t) E_0, \quad (1)$$

where $\chi(t)$ is the dielectric susceptibility, ε_0 – the permittivity of vacuum and $l(t)$ indicates the unit step for the electric field E_0 . $P(t)$ and $\chi(t)$ represent step response functions [7]...[9].

In Fig. 2 the first part of the function $P(t)$ is simplified considering an ideal step to account for the very fast polarization processes - an instantaneous polarization - $P(t_0) = P_\infty$, which includes all very fast polarization processes (electronic, ionic etc.). This step can be recorded, neither in the time, nor in an equivalent frequency domain.

As all polarization processes are finite in magnitude and will settle at long times, the polarization finally becomes static ($P(t \rightarrow \infty) = P_s$) and $P(t)$ can be written as:

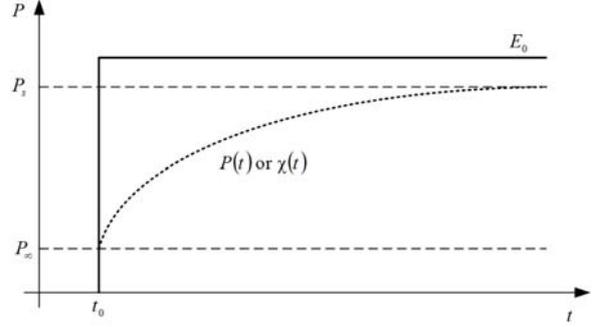


Fig. 2. Polarization of a dielectric exposed to a step electric field of magnitude E_0 at $t = t_0$.

$$P(t) = P_\infty + (P_s - P_\infty) \cdot g(t - t_0) \quad (2)$$

or

$$P(t) = \varepsilon_0 [\chi_\infty - (\chi_s - \chi_\infty)] \cdot g(t - t_0) \cdot E_0, \quad (3)$$

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:

$$P(t) = \varepsilon_0 \chi_\infty E(t) + \varepsilon_0 \int_{-\infty}^t f(t - \tau) E(\tau) d\tau, \quad (4)$$

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

$$f(t) = (\chi_s - \chi_\infty) \cdot \frac{\partial g(t)}{\partial t} = (\varepsilon_s - \varepsilon_\infty) \cdot \frac{\partial g(t)}{\partial t}, \quad (5)$$

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

The field $E(t)$ generates a total current density $j(t)$, which can be written as a sum of conduction, vacuum and polarization displacement current densities:

$$j(t) = \sigma_t E(t) + \frac{\partial D(t)}{\partial t} = \quad (6)$$

$$\sigma_t E(t) + \varepsilon_0 \frac{\partial E(t)}{\partial t} + \frac{\partial P(t)}{\partial t}$$

$$j(t) = \sigma_t E(t) + \varepsilon_0 [\varepsilon_\infty \delta(t) + f(t)] \cdot E(t), \quad (6')$$

where σ_t represents the dc conductivity.

Equation (6') is the first basis for the measurement of the dielectric response function $f(t)$ also for characterizing dielectrics using the time-domain method (TDM).

If a DC voltage U_0 is suddenly applied to the test object, a current $i_a(t)$ through the test object (Fig. 3):

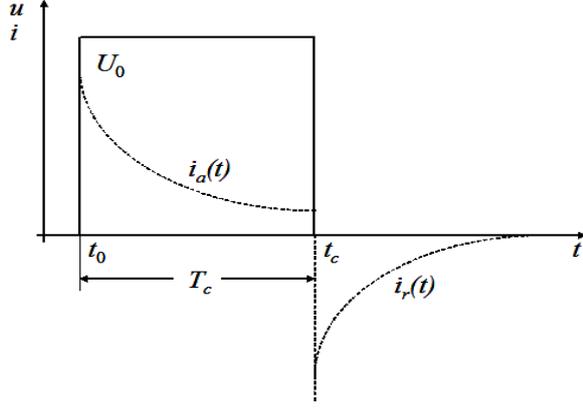


Fig. 3. Principle of absorption (i_a) and resorption (i_r) currents measurement.

$$i_a(t) = C_0 U_0 \left[\frac{\sigma_t}{\varepsilon_0} + \varepsilon_\infty \delta(t) + f(t) \right], \quad (7)$$

where C_0 is the geometric capacitance of test object 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 is related to the intrinsic conductivity σ_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 eq. (7) (which is again a very short current pulse) we get for $t \geq (t_0 + T_c)$:

$$i_r(t) = -C_0 U_0 [f(t) - f(t + T_c)]. \quad (8)$$

From eq. (8) it can be seen that the resorption current is proportional to the dielectric response function $f(t)$, as the dc conductivity σ_t of the dielectric is not involved, but can easily be calculated from the difference between the absorption and the resorption currents. Equation (8) is the second basis for the measurement of the dielectric function $f(t)$ and also for characterizing dielectrics response in time domain.

Assumig 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:

$$f(t) = -\frac{i_r(t)}{C_0 U_0}. \quad (9)$$

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

$$f(t) = \frac{A}{\left(\frac{t}{t_0}\right)^n + \left(\frac{t}{t_0}\right)^m}, \quad (10)$$

when the terms A , $t_0 > 0$, $m > n > 0$, and $m > 1$ can be obtained from (8), (9), and (10).

B. Spectroscopy in Frequency Domain (FDS)

Considering that the polarization processes are instantaneous, from (4) and (6) it results:

$$j(t) = \sigma_t E(t) + \varepsilon_0 \frac{dE(t)}{dt} + \varepsilon_0 \frac{d}{dt} \int_0^t f(t-\tau) E(\tau) d\tau. \quad (11)$$

With $j(t) \rightarrow j(p)$, $E(t) \Rightarrow E(p)$, $E'(t) \rightarrow pE(p)$, $f(t) \Rightarrow F(p)$ and considering the convolution of the last term in this equation we get:

$$j(p) = \sigma_t E(p) + \varepsilon_0 p E(p) + \varepsilon_0 p F(p) E(p), \quad (12)$$

where p is the Laplace operator.

As p is the complex frequency $j\omega$, the equation (12) becomes:

$$\underline{j}(\omega) = \underline{E}(\omega) [\sigma_t + i\omega \varepsilon_0 (1 + \underline{F}(\omega))]. \quad (13)$$

Thus $\underline{F}(\omega)$ is the Fourier Transform of the dielectric response function $f(t)$ or the complex susceptibility

$$\underline{\chi}(\omega) = \underline{F}(\omega) = \chi'(\omega) - i\chi''(\omega) = \int_0^\infty f(t) \exp(-i\omega t) dt. \quad (14)$$

From (13) and (14) it results:

$$\underline{j}(\omega) = \{\sigma_t + \varepsilon_0 \omega \chi'(\omega) + j\omega \varepsilon_0 [1 + \chi'(\omega)]\} \cdot E(\omega), \quad (15)$$

$$\underline{\varepsilon}(\omega) = 1 + \chi'(\omega) - i\chi''(\omega) = \varepsilon_r' - j\varepsilon_r'', \quad (16)$$

and

$$\text{tg}\delta = \frac{\varepsilon_r'' + \frac{\sigma_t}{\varepsilon_0 \omega}}{\varepsilon_r'}. \quad (17)$$

The equation (14) represents the link between time and frequency domains. Thus it is obvious that the complex susceptibility $\chi(\omega)$ and its real and imaginary

parts can be converted to the dielectric response function $f(t)$ and vice versa [8]...[11].

III. EXPERIMENTS

A. Samples and setups

For experimental work were used the cellulose products manufactured by Weidmann: Kraft paper of 0.08 mm thickness and pressboard of 0.25 mm and 0.5 mm thickness specially manufactured for power transformer insulation. Several hundreds samples were made one part for making the measurements and another part to be immersed inside of a charge power transformer. The immersed samples will be removing in time from transformer in view to estimate the changes of their proprieties. The absorption/resorption currents was measured on 6 samples of $100 \times 100 \text{ mm}^2$, 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.

B. Results

The absorption/resorption currents and complex permittivity were measured on the unconditioned samples (A) and thermally conditioned samples (B, C, D and E). 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 $U_0 = 300 \text{ V}$ for thermally conditioned samples at 90 °C when the conditioned time τ increase, due to the

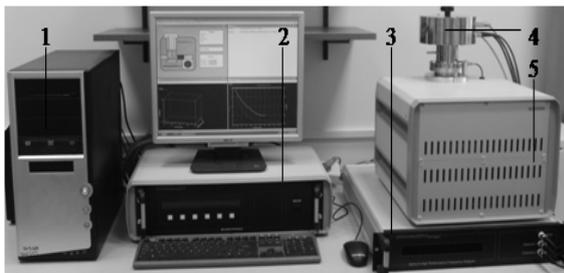


Fig. 4. Novocontrol spectrometer: 1 – PC, 2 – Control System, 3 – Modular Measurement System, 4 – Measurement Cell, 5 – Temperature Control System.

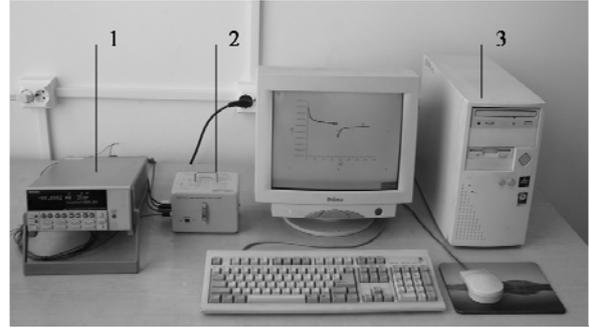


Fig. 5. Experimental set-up for absorption/resorption currents measurement: 1 – Electrometer Keithley 6517, 2 – Resistivity Test Fixture Keithley 8009, 3 – PC.

diminution of the moisture content which implies a diminution of all absorption and resorption currents components (polarization, space charge and conduction).

On the other hand, the diminution of the currents values leads to the higher volume resistivity values of the samples (Fig. 7): at $t = 3600 \text{ s}$, ρ_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).

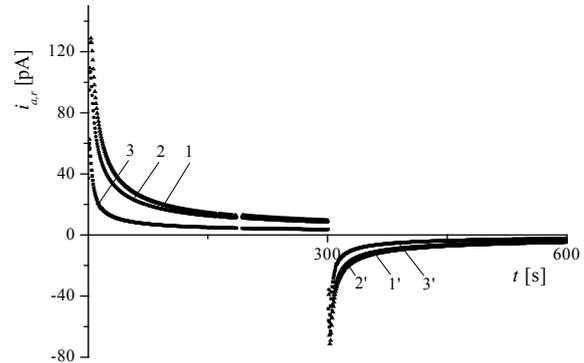


Fig. 6. Time variation of absorption i_a (1, 2, 3) and resorption i_r (1', 2', 3') currents for samples C (1, 1'), D (2, 2') and E (3, 3') ($U_0 = 300 \text{ V}$).

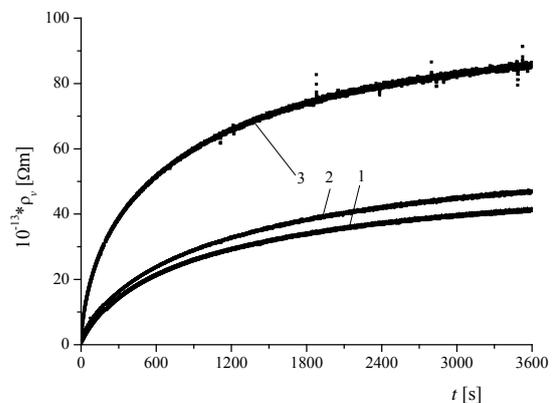


Fig. 7. Time variation of volum resistivity ρ_v for samples C (1), D (2) and E (3) ($U_0 = 300 \text{ V}$).

TABLE 1. Maximum values of absorption ($I_{a,max}$) and resorption ($I_{r,max}$) currents, volume resistivity ρ_v (measured at $t = 3600$ s), polarization index k_p and conductivity coefficient k_c ($U_0 = 300$ V).

Sample	$I_{a,max}$ [nA]	$I_{r,max}$ [nA]	ρ_v [Ωm]	k_p	k_c
A	720	5.79	$1.99 \cdot 10^{11}$	1.04	1.00
B	1.88	1.29	$9.96 \cdot 10^{13}$	1.13	1.39
C	0.095	0.056	$4.12 \cdot 10^{14}$	4.23	1.80
D	0.061	0.055	$4.68 \cdot 10^{14}$	3.85	1.77
E	0.045	0.042	$8.56 \cdot 10^{14}$	3.30	1.89

Due to the high water content of the A and B samples, it results relatively important values of the absorption current (Table 1): for samples A, the maximum absorption current is about 10^5 times higher than the current obtained for E samples and the resistivity calculated for $t = 3600$ s is about 4300 times smaller. Moreover, it results that the polarization index is very close to 1 for A samples and take high values for C, D and E samples, as a consequence of important water content values in unconditioned samples. On the other hand, the increase of the water contents determines a diminution of the conductivity coefficient values k_c (from 1.89 - for the samples E - to 1 - for the samples A). It results that the k_c values can be used to estimate the moisture content of the cellulosic insulation.

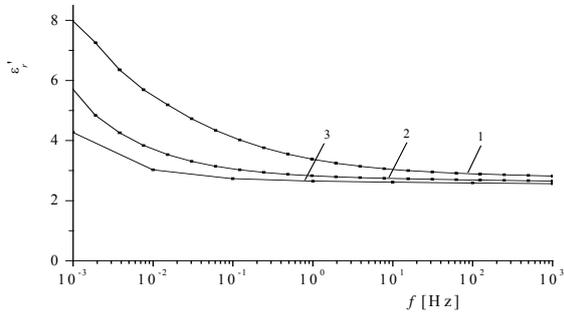


Fig. 8. Variation of the real permittivity component ϵ_r' , for samples C (1), D (2) and E (3) with frequency f .

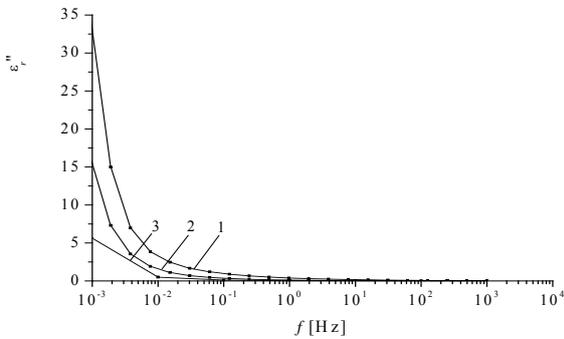


Fig. 9. Variation of the imaginary permittivity component ϵ_r'' , for samples C (1), D (2) and E (3) with frequency f .

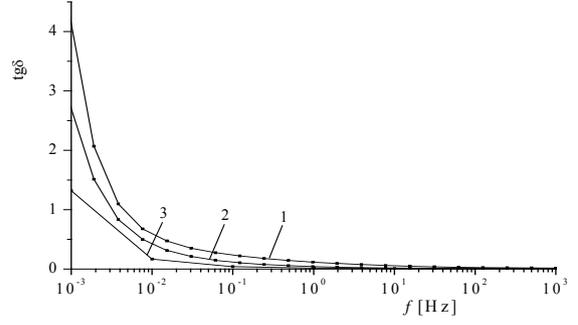


Fig. 10. Variation of the loss factor $tg\delta$, for samples C (1), D (2) and E (3) with frequency f .

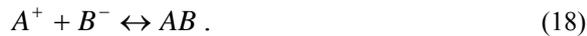
The variations of the real and imaginary complex permittivity components ϵ_r' and ϵ_r'' and loss factor $tg\delta$ with the frequency are shown in Figs. 8-10. It can be seen that, for low frequencies ($10^{-3} - 10^{-2}$ Hz) all three factors take important values. For high water contents in the samples,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

The interfacial polarization increase causes a growth of the term of the loss factor ($tg\delta = \epsilon_r'' / \epsilon_r'$), 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 $tg\delta_\sigma = \sigma / (\epsilon_0 \epsilon_r' \omega)$, that take high values when the frequency diminishes and the dc conductivity increases (especially in areas nearby electrodes, due to their polarization) [12].

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 ϵ_r'' and $tg\delta$ [14].

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 movent 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 the electromechanical 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 ϵ_r'' and $\tan\delta$ will increase for very low frequencies.

IV. 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 k_p and k_c values can be used to estimate the moisture content of the cellulosic insulation.

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

Making periodic measurements of absorption and resorption currents and permittivity components on the cellulosic samples removed from charged power transformers it is possible to estimate the condition of insulation. A most efficient evaluation of the insulation condition is possible by making complementary measurements: paper polymerization degree, furans content, etc. In a future paper, new results concerning the tests of solid and liquid power transformer insulation will be presented.

ACKNOWLEDGEMENT

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

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