THERMAL AGEING OF OIL IMPREGNATED PAPER FOR POWER TRANSFORMERS INSULATION SYSTEMS

Laurentiu BADICU[1], Petru V. NOTINGHER[1], Laurentiu DUMITRAN[1], Gabriel TANASESCU[2], Dorin POPA[3] and Gheorghe BATIR[4]

[1] *University POLITEHNICA of Bucharest, Splaiul Independenței, No.313, Bucharest, Romania*
E-mail:lvbadicu@elmat.pub.ro.

[2] *Simtech International, str. Berceni, no. 8, Sector 4, Bucharest, Romania.*

[3] *ICMET Craiova, B-dul Decebal, no. 118 A, 200746, Craiova, Romania.*

[4] *Electrica Serv, Stefan cel Mare, no 1A, Bucharest Romania.*

Abstract **— The assessment of conditions and life time reserves of power transformers is generally done based on the analysis of characteristics of main components of insulation systems (oil and paper).**
During operation, the insulation systems of power transformers are subjected to different stresses (thermal, electrical, mechanical, other stresses); the most important for transformers operation are the thermal stresses which lead to degradation reactions of their insulation system.
This paper presents a study concerning the ageing of some pressboard samples impregnated with NYNAS transformer oil subjected to accelerated thermal stress at the 155 ºC for time intervals between 0 and 750 h. For certain values of the real and the imaginary parts of complex conductivity and relative permittivity and the loss factor were measured for different values of the temperature and frequency. Variation curves of these quantities with ageing time were drawn.
The results show that the increases of temperature and ageing time determine important increases of the real part of relative permittivity and real part of electrical conductivity and these increases are more important for low electric field frequencies. Using the values of real and imaginary parts of relative permittivity and conductivity and the loss factor the condition of oil impregnated paper can be obtained.

Keywords: *insulation systems, oil impregnated paper, thermal ageing, dielectric spectroscopy, conductivity.*

1. INTRODUCTION

Most power transformers used in electric energy distribution and transmission systems have their insulation systems made of cellulose paper and mineral oil (which is almost 75 – 80 % of the insulation system weight) [1]. From this point of view, the studies regarding on-line/off-line monitoring and diagnosis of their insulation systems represent a very important topic [2].
Due to the permanent increase of the power consumption, the level charge of transformers has increased, and that involves their operation at a temperature nearby insulation class limit of oil and paper. Insulation system temperature increase causes its ageing and some reactions products can appear. These reactions products worsen dielectric characteristics of insulation systems. The studies carried out up to the present show that the thermal stresses effects are more obviously in case of paper [3]. The paper role is to insulate electric conductors constructing the windings. Paper is also used to fix winding turns mechanically and the winding layers to each other.
Knowledge of the paper properties and chemical reactions which occur in the presence of oxygen, humidity, temperature etc. lead to understanding the degradation processes whereat it is subjected. These ageing mechanisms can be detected by various tests which measure chemical, physical and optical properties of paper. At molecular level, cellulose, (which is the most stable component of paper) – has properties required by the structure which contains amorphous and crystalline areas. The amorphous areas allow water penetration, while crystalline areas are ordered, rigid, inert and relatively impermeable [4].
Lifetime determination of cellulose based insulation is generally made based on the results obtained from the laboratory accelerated ageing. High temperature and humidity exposure leads to the initiation of thermal degradation reactions. These reactions could depend on conditions and time exposure. Dry oven ageing of the paper at 90 ºC leads to production of very little glucose, but ageing at 150 ºC, generates a greater number of reaction products [4].

2. ELECTRICAL CONDUCTIVITY AND PERMITTIVITY OF DIELECTRICS IN DC AND AC

Generally, electric conductivity of an insulation material σ is determined based on the current which appears between two metallic electrodes fixed on sample surfaces supplied with a DC voltage U_0.

The increase of charge carriers concentration and their mobility involves the increase of electric conductivity value of insulation materials. The actions of electric field, radiation, temperature etc. lead to the increase of volume concentration of charge carriers.

If DC applied voltage is $U_0(t) = U_0\delta(t)$ between two electrodes fixed on the insulator, through it appears the current $i_a(t)$ [5]:

$$i_a(t) = C_0 U_0 [\frac{\sigma_{cc}(t)}{\varepsilon_0} + \varepsilon_\infty \delta(t) + f(t)], \quad (1)$$

where C_0 is the geometrical capacity of test object, ε_0 is vacuum permittivity, $\sigma_{cc}(t)$ is the dc conductivity, $f(t)$ is the dielectric response function and $\delta(t)$ is the delta function (which characterizes the voltage step at $t = t_0$):

$$\delta(t) = \begin{cases} 0, & \text{if } t_0 > t > T_C \\ 1, & \text{if } t_0 \le t \le T_C \end{cases}. \quad (2)$$

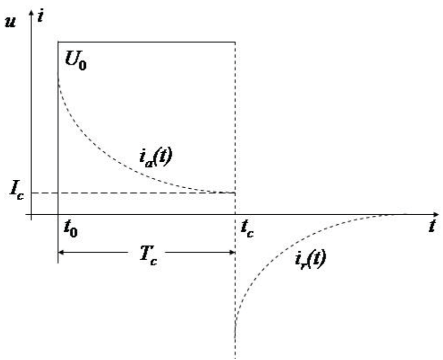

Figure 1: Time variation of absorption *(i_a)* and resorption *(i_r)* currents.

The absorption current contains three terms: the first is related to the intrinsic conductivity of the test object and is independent of any polarization process, the last one represents all the active 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 to the very fast polarization processes.

If the two electrodes are short-circuited at $t = t_c$, the resorption current $i_r(t)$ can be measured:

$$i_r(t) = -C_0 U_0 [f(t) - f(t + T_c)]. \quad (3)$$

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:

$$f(t) = -\frac{i_r(t)}{C_0 U_0}. \quad (4)$$

By measuring absorption and resorption currents, the conduction current $i_c(t)$ can be obtained:

$$i_c(t) = i_a(t) - i_r(t). \quad (5)$$

Based on this current the conductivity $\sigma_{cc}(t)$ can be calculated:

$$\sigma_{cc}(t) = \frac{i_a(t) - i_r(t)}{U_0} \cdot \frac{l}{S}, \quad (6)$$

where l represents the thickness of the sample or the distance between the electrodes, and S is the electrodes surface.

Also, the electrical conductivity $\sigma_{cc}(t)$ can be calculated in relation to geometrical capacity of the measurement cell electrodes [5]:

$$\sigma_{cc}(t) = (i_a(t) - i_r(t)) \cdot \frac{\varepsilon_0}{C_0 U_0}. \quad (6')$$

Also the quantity $\sigma_{cc}(t)$ can be written:

$$\sigma_{cc}(t) = \sigma_0 + \sigma_v(t), \quad (7)$$

where σ_0 is a time invariable component and $\sigma_v(t)$ is a time variable component which is canceled out for long periods of time.

When the two electrodes are supplied with a time variable voltage $U(t)$ (a harmonic electric field $E(t)$), the Fourier transform of the dielectric response function $\underline{F}(\omega)$ is:

$$\underline{F}(\omega) = \underline{\chi}(\omega) = \chi'(\omega) - i\chi''(\omega), \quad (8)$$

where $\underline{\chi}(\omega)$ is the complex susceptivity and $\underline{\varepsilon}(\omega)$:

$$\underline{\varepsilon}(\omega) = 1 + \chi'(\omega) - i\chi''(\omega) = \varepsilon_r^{'} - j\varepsilon_r^{''}, \quad (9)$$

is the complex relative permittivity.

Equation (8) represents the link between time and frequency domains. Thus, it is obvious that the complex susceptivity $\underline{\chi}(\omega)$ can be converted to the dielectric response function $f(t)$ and vice versa [6], [7].

Such as complex relative permittivity, complex conductivity is the sum between its real and imaginary components:

$$\sigma^* = \sigma^{'} - j\sigma^{''} = \omega\varepsilon_0\varepsilon_r^{''} - j\omega\varepsilon_0\varepsilon_r^{'}, \quad (10)$$

At low frequencies, $\sigma^{''} << \sigma^{'}$ and it can be considered that $\sigma^* \cong \sigma^{'}$.

The real part of electric conductivity $\sigma^{'}$ can be defined by the following relation [8]:

$$\sigma^{'} = \omega\varepsilon_0\varepsilon_r^{''}. \quad (11)$$

The AC conductivity is given by the power law following (12):

$$\sigma^{'} = \sigma_0 + a \cdot f^n, \quad (12)$$

where σ' is the real part of AC conductivity, f is the frequency of measurement voltage and a and n are constants.
In order to establish linkages that occur between thermal ageing time and ageing condition, in this paper some aspects regarding the variation of electric conductivity and relative permittivity of mineral oil impregnated paper with the ageing time τ are presented.

3. EXPERIMENNTAL SET-UP

In order to perform the experimental measurements, samples of oil impregnated paper (0.5 mm thick) were used. These samples were subjected to accelerated thermal ageing at temperature T = 155 ºC, for time intervals between 0 and 750 h.
Absorption and resorption currents were measured using a Keithley 6517 electrometer and a measurement cell equipped with guard electrode [1]. The value of DC voltage was U_0 = 300 V, and the measurement time was 120 min.
In order to measure both complex conductivity as well as complex relative permittivity, a NOVOCONTROL dielectric spectrometer was used [1]. The AC voltage applied to the test sample was 1 V and frequency took values between 1 mHz and 10 MHz.

4. RESULTS

According to relations (6) and (6'), to determine the DC conductivity it is necessary to measure the absorption and resorption currents for oil impregnated paper samples. The Fig. 2 and 3 present the time variations of the absorption and resorption currents for different values of thermal ageing time τ: (150 h, 450 h and 750 h). It can be seen that absorption and resorption currents values increase when thermal ageing time τ increases.
Fig. 4 shows the variation with thermal ageing time τ of DC conductivity measured at different time intervals since the voltage U_0 was applied. It can be seen that, the conductivity of the oil impregnated paper increases, regardless of the time interval since the measurement voltage was applied. The increase of electric conductivity in relation to thermal ageing time is due to the increase of charge carriers concentration, which occurs after the breaking of cellulose chains.
In order to determine complex relative permittivity components (ε_r' and ε_r''), complex conductivity components (σ' and σ'') and loss factor tgδ, for different values of electric field frequencies and for different measurement temperatures T_m, the oil impregnated paper samples were subjected to the frequency domain dielectric spectroscopy.

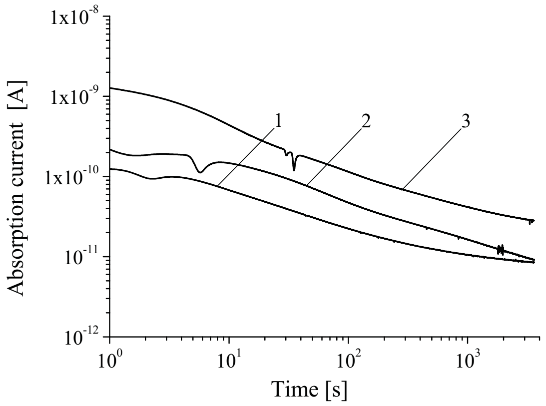

Figure 2: Time variation of absorption currents of oil impregnated paper aged at T = 155 ºC for different times τ: 150 h (1), 450 h (2), 750 h (3) (U = 300 V).

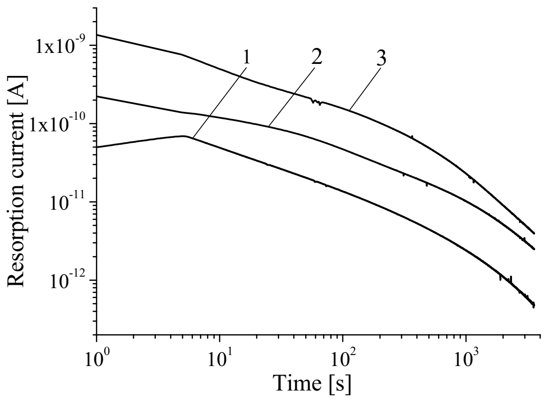

Figure 3: Time variation of resorption currents of oil impregnated paper aged at T = 155 ºC for different times τ: 150 h (1), 450 h (2), 750 h (3) (U = 300 V).

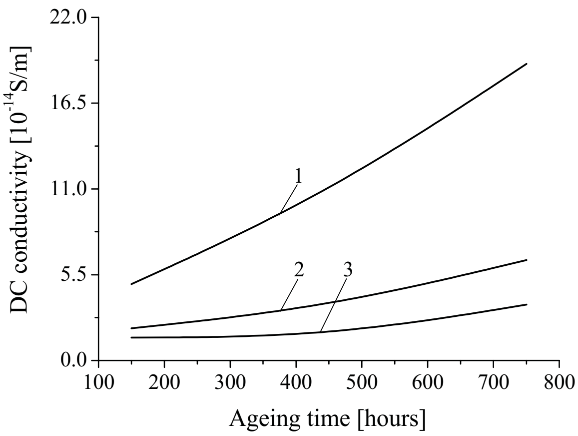

Figure 4: Variation with ageing time τ of DC conductivity $\sigma_{cc}(t)$ of oil impregnated paper at different times t: 60 s (1), 600 s (2), 3600 s (3) (U = 300 V).

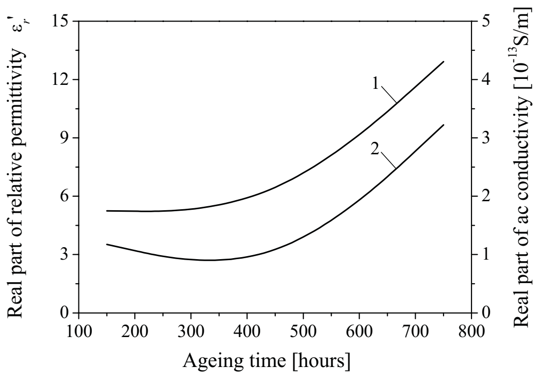

Figure 5: Variation with ageing time τ of oil impregnated paper of real part of relative permittivity (1), and electrical conductivity (2) (T = 155 ºC, f = 1 mHz).

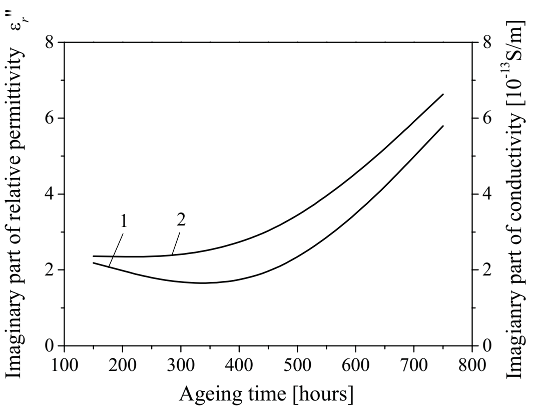

Figure 6: Variation with ageing time τ of oil impregnated paper of imaginary part of relative permittivity (1) and electrical conductivity (2) (T = 155 ºC, f = 1 mHz).

The hypothesis that the concentration of charge carriers increases with ageing time is supported by the variation of real part of relative permittivity $\varepsilon_r^{'}$ (Fig. 5 – curve 1), which shows the variation of quantities $\varepsilon_r^{'}$ with thermal ageing time for electric field frequency f = 1 mHz. Using the quantity $\varepsilon_r^{'}$, the imaginary component of complex conductivity $\sigma^{"}$ has been calculated. In Fig. 6 – curve 2, it can be seen that imaginary part of conductivity $\sigma^{"}$ increases with thermal stress time. The variation of the quantities $\varepsilon_r^{"}$ and $\sigma^{'}$ with the thermal stress time are shown in Fig. 5 and 6. With the increase of thermal ageing time, an increase of charge carriers concentration occurs, which involves both electric conductivity $\sigma^{'}$ increase (Fig. 5, curve 2) as well as losses increase (conduction and polarization losses) (Fig. 9).

Figures 7 – 9 show the variation with both frequency f (10^{-3} – 10^{7} Hz) as well as measurement temperature T_m (30 – 90 ºC) of relative permittivity components ($\varepsilon_r^{'}$ and $\varepsilon_r^{"}$) and loss factor tgδ. Thus, it was found that these quantities take important values as the frequency of electric field decreases and measurement temperature increases. Also, complex conductivity components ($\sigma^{'}$ and $\sigma^{"}$) increase with measurement temperature (fig. 10 and 11).

The results presented above can be explained based on conduction mechanisms specifics to the amorphous solids [9]. At low temperature, the number of charge carriers which have enough energy to pass over the potential barriers is much reduced. At the same time with temperature increase, the thermal excitation of the charge carriers also increases and the jumps over the potential barrier are facilitated. Consequently the complex conductivity components ($\sigma^{'}$ and $\sigma^{"}$) increase with measurement temperature.

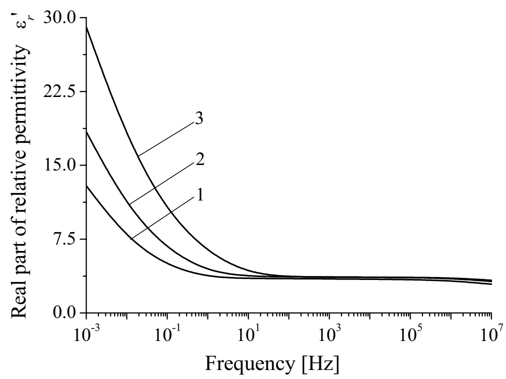

Figure 7: Variation with frequency and temperature of real part of relative permittivity of oil impregnated paper aged at T = 155 ºC and τ = 750 h for T_m = 30 ºC (1), 50 ºC (2), 90 ºC (3).

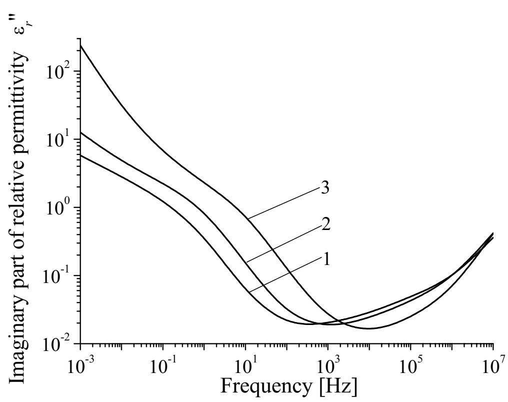

Figure 8: Variation with frequency and temperature of imaginary part of relative permittivity of oil impregnated paper aged at T = 155 ºC and τ = 750 h for T_m = 30 ºC (1), 50 ºC (2), 90 ºC (3).

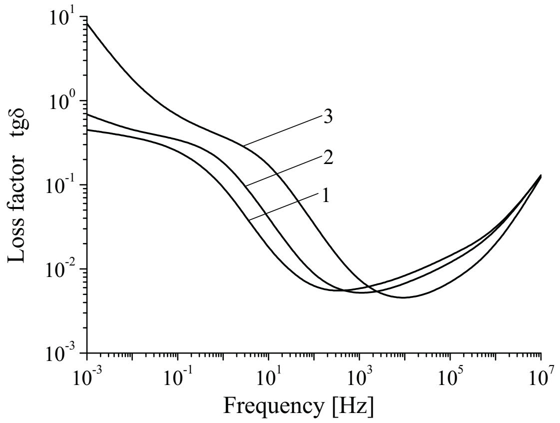

Figure 9: Variation with frequency and temperature of loss factor of oil impregnated paper aged at T = 155 ºC and τ = 750 h for T_m = 30 ºC (1), 50 ºC (2), 90 ºC (3).

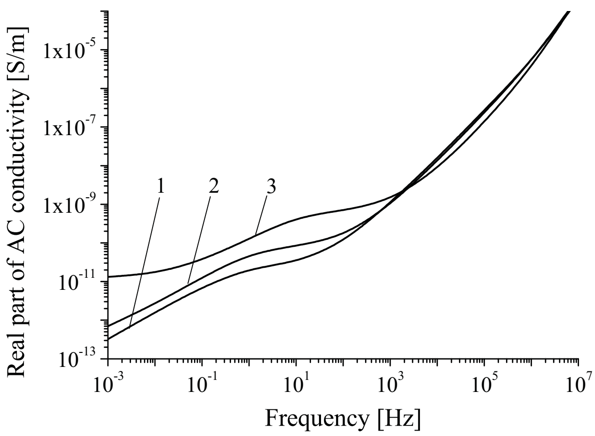

Figure 10: Variation with frequency and temperature of real part of conductivity of oil impregnated paper aged at T_m = 155 ºC and τ = 750 h for T_m = 30 ºC (1), 50 ºC (2), 90 ºC (3).

By extrapolating of the curve 1 from Fig. 10, for $f \rightarrow 0$ it results the value of real part of complex conductivity $\sigma'(0) \cong 10^{-14}$ S/m that is very close to the $\sigma_{cc}(t)$ conductivity. Therefore the values of oil impregnated paper resistivity can be determined based on AC measurements carried out on samples with reduced dimensions.

Chemical reactions which appear at high temperature values generate reactions products which worsen the electric properties of the paper. From these products, the most important are: 5-HMF, 2-FOL, 2-FAL, 2-ACF [10]. These products are developing in certain percentage (in relation to the ageing temperature) and lead to the increase of both electric conductivity as well as dielectric losses into the insulation systems of power transformers, finally producing their breakdown.

To complete the results presented above, the degree of polymerization of aged oil impregnated paper sample was determined. According to Fig. 12, accelerated thermal ageing leads to the decrease of polymerization degree. The high temperature generates the breaking of the cellulose chain and the decrease of polymerization degree.

The decrease of polymerization degree under 200 causes a main reduction of mechanical strength of the paper; in this case the paper becomes flawed with dielectric strength values extremely low [11]. This means that the accelerated thermal ageing break down the cellulose macromolecule, a certain number of glucose molecules disjointing from the chain and becoming free.

5. CONCLUSIONS

In this paper a study regarding the accelerated thermal ageing of certain paper samples (0.5 mm thickness) impregnated with NYNAS transformer oil is presented. Several properties were monitored: components of complex relative permittivity (ε_r' and ε_r'') and conductivity (σ' and σ''), dielectric loss factor tgδ, and polymerization degree.

It was found that both real relative permittivity ε_r', as well as imaginary relative permittivity ε_r'' increase when ageing degree increases too. The quantities ε_r' and ε_r'' take important values for both high measurement temperatures T_m as well as at low values of electric field frequencies f.

The thermal ageing time affects in a negative way both DC conductivity as well as AC conductivity. These quantities increase when the thermal ageing time increases.

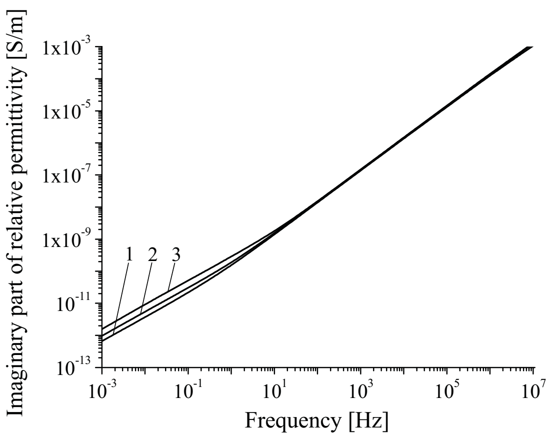

Figure 11: Variation with frequency and temperature of imaginary part of conductivity of oil impregnated paper aged at T = 155 ºC and τ = 750 h for T_m = 30 ºC (1), 50 ºC (2), 90 ºC (3).

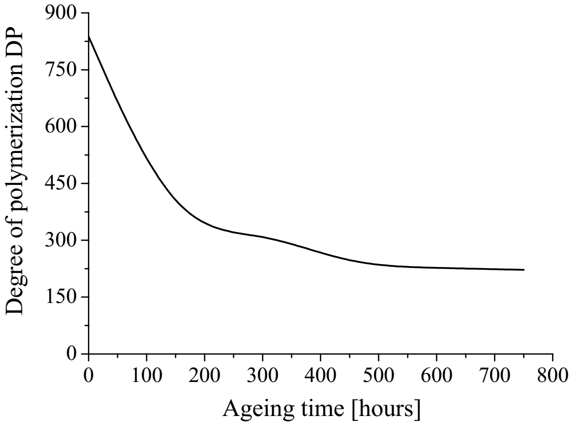

Figure 12: Variation with thermal ageing time of polymerization degree (T = 155 ºC, τ = 750 h).

The growth of complex relative permittivity and complex conductivity is mainly due to the increase of charge carriers concentration as a result of breaking cellulose chain.

The high charge carriers concentration leads to the enhancement of conduction phenomenon and to the increase of conduction losses.

The decrease of degree of polymerization shows the breakdown of the cellulose chain which explains the growth of charge carriers concentration leading to the increase of complex components of conductivity and permittivity.

The quantities σ', σ'', ε_r' and ε_r'' provide important information about the ageing condition of oil impregnated paper.

Acknowledgment

This work was supported by the Romanian Ministry of Education, Research and Youth, PNCDI II Program, Project MIDMIT 22 080/2008, POSDRU 89/15/S/ 62557 Project and POSDRU 5159 Project.

References

[1] L.V. Badicu, P.V. Notingher, L. M. Dumitran, G. Tanasescu, D. Popa *Use of Dielectric Spectroscopy to Estimate the Condition of Cellulose-Based Insulation,* Journal of Electrical and Electronics Engineering, vol. 2, no. 1, pp 7 – 12, 2009.

[2] T.A. Prevost, T.V. Oommen, *Cellulose Insulation in Oil-Filled Power Transformers: Part I – History and Development*, IEEE Electrical Insulation Magazine, vol. 22, no. 1, pp. 28 – 35, 2006.

[3] H. P. Moser, V. Dahinden *Transformerboard II,* Graphics DOK MAN, Zurich, 1999.

[4] Dianne Van Der Reyden, *Recent Scientific Research in Paper Conservation,* Journal of the American Institute for Conversation, vol. 31, pp 117-138, 1992.

[5] A. Bouaicha, and I. Fofana, *Dielectric Spectroscopy Techniques as Qualiti Control Tool: A Fesability Study,* IEEE Electrical Insulating Magazine, vol. 25, no. 1, pp. 6 – 14, 2009.

[6] A.K. Joncher, *The Universal Dielectric Response: Part I*, IEEE Electrical Insulation Magazine, vol. 6, no. 2, pp. 16-21, 1990.

[7] D. Linhjell, L.Lundgaard, U.Gafvert, *Dielectric Response of Mineral Oil Impregnated Cellulose and the Impact of Aging*, Transactions on Dielectrics and Electrical Insulation, vol. 14, no. 1, pp. 156-169, 2007.

[8] A.K. Joncher, *Dielectric Relaxation in Solids*, Xi'An Jiaotong University Press, 2008.

[9] P. V. Notingher, *Materials for Electrotechnics*, vol. 1, Politehnica Press, Bucharest, 2005.

[10] J. Scheirs, G. Camino, M. Avidano, W. Tumiati, *Origin of Furanic Compounds in Thermal Degradation of Cellulosic Insulating Paper*, Journal of Applied Polymer Science, vol. 69, pp. 2542-2547, 1998.

[11] C. D. Nenitescu, *Organic Chemistry*, vol II, Editura Didactica si Pedagogica, Bucharest 1980.