USE OF TIME DOMAIN SPECTROSCOPY FOR ASSESSMENT OF OIL IMPREGNATED PAPER CONDITION

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Spectroscopia în domeniu timp reprezintă una dintre cele mai eficiente metode de evaluare a comportării dielectricilor in câmp electric. Funcţia de răspuns dielectric, obţinută prin măsurarea curentului de resorbţie la aplicarea unei tensiuni treaptă, permite calculul componentelor permitivităţii şi conductivităţii complexe a dielectricului în câmpuri armonice.

În această lucrare, este prezentat un studiu privind calculul componentelor permitivităţii relative ($\varepsilon_r^{'}$ şi $\varepsilon_r^{''}$), a componentelor conductivităţii complexe ($\sigma^{'}$ şi $\sigma^{''}$) şi a factorului de pierderi tgδ, pornind de la curbele de variaţie în timp ale funcţiei de răspuns dielectric. Valorile calculate ale mărimilor $\varepsilon_r^{'}$, $\varepsilon_r^{''}$, tgδ, $\sigma^{'}$ şi $\sigma^{''}$ sunt verificate prin măsuratori cu ajutorul unui spectrometru dielectric Novocontrol. Toate mărimile analizate prezintă variaţii importante cu durata de îmbătrânire şi cu frecvenţa de măsurare. În final, se analizează avantajele utilizării spectroscopiei în domeniu timp în evaluarea stărilor izolaţiilor.

Time domain spectroscopy is one of the most efficient methods used to assess the dielectrics' behavior under electric fields. The dielectric response function, obtained using resorption current measurement when a step voltage is applied, allows the components of complex permittivity and conductivity calculation under harmonic fields.

In this paper, a study regarding the calculation of complex relative permittivity ($\varepsilon_r^{'}$ and $\varepsilon_r^{''}$), conductivity components ($\sigma^{'}$ and $\sigma^{''}$) and loss factor (tgδ), starting from time variation curves of dielectric response function, is presented. The calculated values of the quantities $\varepsilon_r^{'}$, $\varepsilon_r^{''}$, tgδ, $\sigma^{'}$ and $\sigma^{''}$ are verified by measurements performed using a Novocontrol dielectric spectrometer. All the analyzed quantities show important variations with ageing time and electric field frequency. Finally, the advantages of using time domain spectroscopy to assess the insulators conditions are analyzed.

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1. Introduction

The degradation phenomena of power transformers insulation systems are irreversible processes which involve the change of physico-chemical condition of their components, the cellulosic paper and the mineral oil [1]. The temperature and oxygen are the key factors which start the main degradation (thermo-oxidative) reactions which appear inside insulation systems during the transformers' service [2]. When the temperature increases, the breaking of cellulosic chain and the decomposition of hydrocarbons inside the oil are produced, and several reaction products with a lower molecular weight can appear (H_2O, H_2, CO, CO_2, CH_4, and furanic components) [3-5]. Consequently, these degradation processes lead to the increase of charge carriers and dipolar concentrations inside the insulation systems, intensifying the conduction and polarization phenomena. Based on these changes, the conditions of the power transformers insulation systems could be estimated by the assessment of conduction and polarization phenomena which occur inside them. The quantities which characterize these phenomena are the electric conductivity, permittivity and loss factor [6-7].

A very useful method for condition assessment of oil impregnated paper (the most vulnerable component of power transformers insulation) is based on measuring the real and imaginary parts of the complex permittivity and conductivity [8-9]. Unfortunately, the method's main deficiency is the long measurement time, especially at low electric field frequencies.

In order to assess much more rapidly the condition of the power transformers insulation systems, their dielectric responses can be used [10-16]. Using the time domain dielectric spectroscopy, the dielectric response function $f(t)$ can be calculated, which allows the determination of complex relative permittivity $\varepsilon_r^{'}$ and $\varepsilon_r^{''}$ and conductivity $\sigma^{'}$ and $\sigma^{''}$ components and the dielectric loss factor tgδ [17-18].

In this paper, a study regarding the determination and the use of dielectric response function $f(t)$ of the oil impregnated paper is presented. Therefore, the time variation curves of absorption and resorption currents were drawn. They were also used to obtain the dielectric response function and the frequency variation of the dielectric properties ($\varepsilon_r^{'}$, $\varepsilon_r^{''}$, tgδ, $\sigma^{'}$ and $\sigma^{''}$) of the oil impregnated paper.

2. Dielectric response function

If an electric field of magnitude $E_0(t) = E_0 \cdot 1(t)$ is applied to a dielectric at time t_0, the dielectric response at $t \geq t_0$ is the polarization $P(t)$:

$$P(t) = \varepsilon_0 \chi(t) 1(t) E_0 , \tag{1}$$

where $\chi(t)$ is the dielectric susceptivity, ε_0 – the vacuum permittivity and $1(t)$ – the unit step function [12].

Considering an ideal step for an electric field, the equivalent polarization for the very fast polarization processes (electronic, ionic etc.) takes the value $P(t) = P(t_0) = P_\infty$. In case of high t values, the polarization finally becomes static, respectively $P(t \to \infty) = P_s$ and $\chi(t \to \infty) = \chi_\infty$. For an excitation $E(t)$, the time dependent polarization $P(t)$ is given (using the Duhamel's integral) by the equation [4]:

$$P(t) = \varepsilon_0 \chi_\infty E(t) + \varepsilon_0 \int_{-\infty}^{t} f(t-\tau) E(\tau) d\tau, \tag{2}$$

where $f(t)$ is the dielectric response function (a monotonous and decreasing function).

If a dc voltage $U_0(t) = U_0 \delta(t)$ is applied to a capacitor which contains the test object for a period T_c, a current $i_a(t)$ appears through the dielectric (Fig. 1) [14]:

$$i_a(t) = C_0 U_0 [\frac{\sigma_0}{\varepsilon_0} + \varepsilon_\infty \delta(t) + f(t)] , \tag{3}$$

where $i_a(t)$ is the absorption current, C_0 is the geometric capacitance of the test object, σ_0 is the dc conductivity and $\delta(t)$ is the delta function (which characterizes the voltage step at $t = t_0$)

$$\delta(t) = \begin{cases} 0, & \text{if } t_0 > t > T_C \\ 1, & \text{if } t_0 \leq t \leq T_C \end{cases} . \tag{4}$$

The absorption current $i_a(t)$ contains three terms: the first is related to the intrinsic conductivity σ_0 of the test object (and is independent of any polarization processes), the middle one is related to the fast polarization processes and the last

one is related to all the active polarization processes during the voltage application.

If the test object is short-circuited at $t = T_c$, the resorption current $i_r(t)$ can be measured:

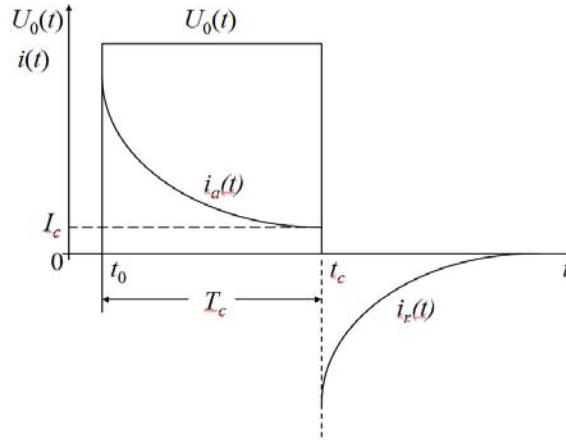$$i_r(t) = -C_0 U_0 [f(t) - f(t+T_c)].$$ (5)

Fig. 1. Time variation of absorption $i_a(t)$ and resorption $i_r(t)$ currents [6].

If 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 [15]:

$$f(t) = -\frac{i_r(t)}{C_0 U_0}.$$ (6)

When an harmonic electric field $E(t) = E\sqrt{2}\sin\omega t$ is applied and considering that all the polarization processes are instantaneous, and $\underline{F}(\omega)$ is the Fourier transform of the dielectric response function $f(t)$, $\underline{\chi}(\omega)$ is the complex susceptivity and $\mathrm{tg}\delta$ is the dielectric loss factor, it results [16-17]:

$$\underline{F}(\omega) = \underline{\chi}(\omega) = \chi'(\omega) - j\chi''(\omega) = \int_0^\infty f(t)\exp(-j\omega t)\mathrm{d}t,$$ (7)

$$\chi'(\omega) = \int_0^{+\infty} f(t)\cos(\omega t)dt,$$ (8)

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

$$\chi''(\omega) = \int\limits_0^{+\infty} f(t)\sin(\omega t)dt, \tag{9}$$

$$\varepsilon_r^{'} = 1 + \chi^{'}(\omega), \tag{11}$$

In practice, there are no devices which can distinguish the "pure" conduction losses and the polarization losses. Therefore, some differences can appear between measured imaginary part of complex relative permittivity and ε_r'' defined by (10). In order to balance these differences, the term $\dfrac{\sigma_0}{\omega\varepsilon_0}$ is used on the left side of the following relation [12]:

$$\varepsilon_r^{''} = \frac{\sigma_0}{\omega\varepsilon_0} + \chi^{''}(\omega), \tag{12}$$

$$\mathrm{tg}\delta = \frac{\varepsilon_r^{''} + \dfrac{\sigma_0}{\varepsilon_0\omega}}{\varepsilon_r^{'}}, \tag{13}$$

where ω is the angular frequency.

On the other hand, using the complex relative permittivity components, the complex conductivity components can be calculated [19,20]:

$$\sigma^{'} = \omega\varepsilon_0\varepsilon_r^{''}, \tag{14}$$

$$\sigma^{''} = \omega\varepsilon_0\varepsilon_r^{'}. \tag{15}$$

The equation (7) represents the link between time and frequency domains. Thus, it is obvious that the complex susceptivity $\chi(\omega)$ can be converted to the dielectric response function $f(t)$ and vice versa [17]. Thus, the dielectric response

function $f(t)$ (obtained with (6)) allows the determination of the main insulation properties.

In the case of oil impregnated paper insulation, the dielectric response function can be approximated with a simplified function [7]:

$$f(t) = \frac{A}{\left(\dfrac{t}{t_0}\right)^n + \left(\dfrac{t}{t_0}\right)^m} \tag{16}$$

where A, m, $n > 0$ and $m > 1$ are dielectric constants. This relation comes from the Curie-von Schweidler universal law: $i_r(t) \approx A \cdot t^{-n}$, which approximates the resorption current variation of the tested dielectric sample [11].

3. Experiments

The samples used for the experiments were mineral oil impregnated paper samples (with 0.24 mm thickness). They were subjected to accelerated thermal stress at $T = 135$ ºC for different time intervals between 0 and 2100 hours. The absorption and resorption currents were measured using a Keithley electrometer 6517 and a measurement cell equipped with a guard ring [7]. The applied voltage was 300 V and the time measurement of each current was 3600 s.

4. Results and discussions

The absorption/resorption currents measured on oil impregnated paper samples for different ageing times are presented in Fig. 2. It can be seen that, the currents values increase with the thermal ageing time τ, mainly due to the growth of the charge carriers and dipoles concentrations (water, organic radicals etc.) inside the tested samples volume [21].
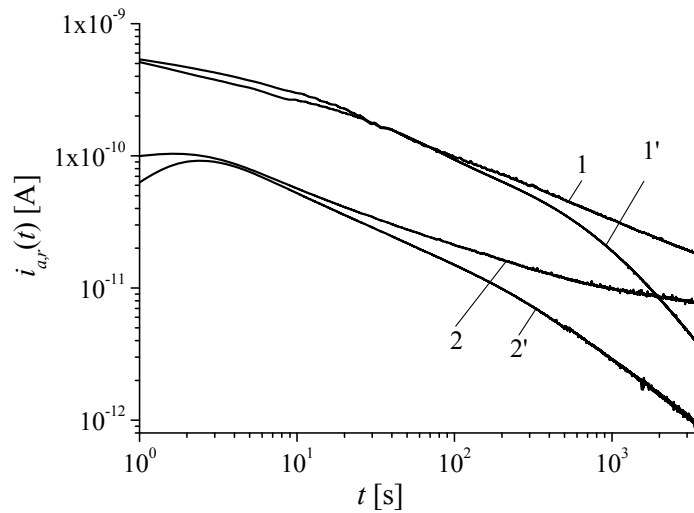
Fig. 2. Time variation of absorption (1, 2) and resorption (1', 2') currents for
$\tau = 150$ h and $\tau = 820$ h.

Based on the resorption currents curves, the dielectric response functions *f*(*t*) were calculated (Fig. 3) using equation (6). For the calculation of the dielectric response function coefficients *A*, *m*, *n*, and t_0 values, the Matlab software (Trust-Region algorithm and Non Linear Least Squares Method) was used. The results are presented in Table 1.

Using the equations (11), (12) and (13), the real ε_r' and imaginary ε_r'' parts of complex relative permittivity and the loss factor tgδ of the oil impregnated paper samples were calculated. The variations of these quantities with electric field frequency *f* and ageing time τ, are shown in Figs. 4, 5, 6 and 7. It can be seen that quantities ε_r', ε_r'' and tgδ increase with ageing time. This phenomenon is due to the increase of charge carriers and electric dipoles concentrations [7], generated by degradation processes (respectively, by the formation of H_2O, H_2, CO, CO_2, CH_4 etc.).

Table 1

Dielectric response function coefficients and conductivity σ_0 values

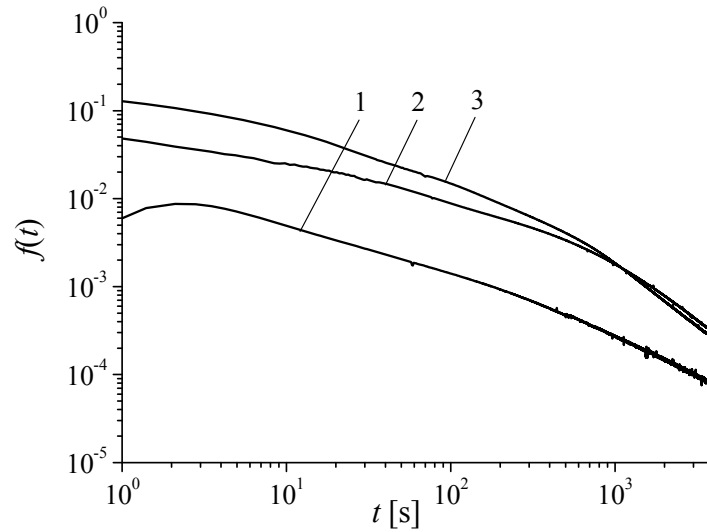|	$\tau = 0$ h	$\tau = 150$ h	$\tau = 820$ h	$\tau = 2100$ h
A	0,00256	0,00105	0,008781	0,0692
m	1,591	1,098	1,192	1,006
n	0,4494	0.4254	0,299	0,2345
t_0 [s]	832,2	430,4	329,1	34
σ_0 [S/m]	$1.62*10^{-14}$	$5.6*10^{-15}$	$1.18*10^{-14}$	$1.93*10^{-14}$

Fig. 3. Time variation of dielectric response functions (1, 2, 3) for oil impregnated paper aged at τ = 150 h (1), τ = 820 h (2) and τ = 2100 h (3).

The increase of ε_r' with the ageing time 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 [6].
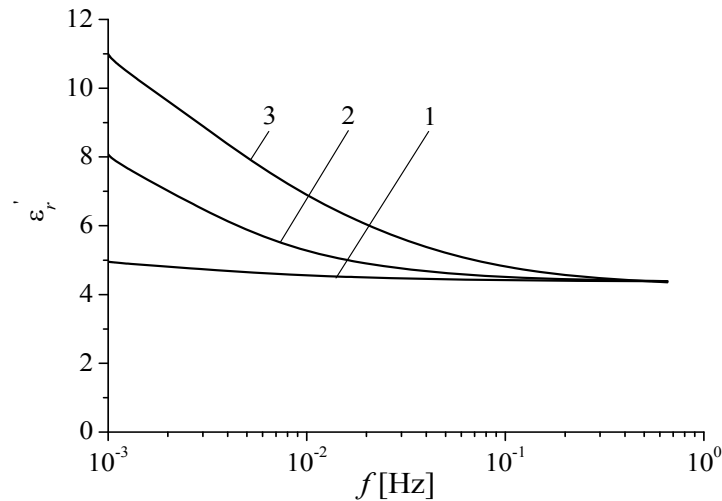

Fig. 4. Frequency variation of calculated real part of relative permittivity ε_r' for aged oil impregnated paper at τ = 150 h (1), τ = 820 h (2) and τ = 2100 h (3).
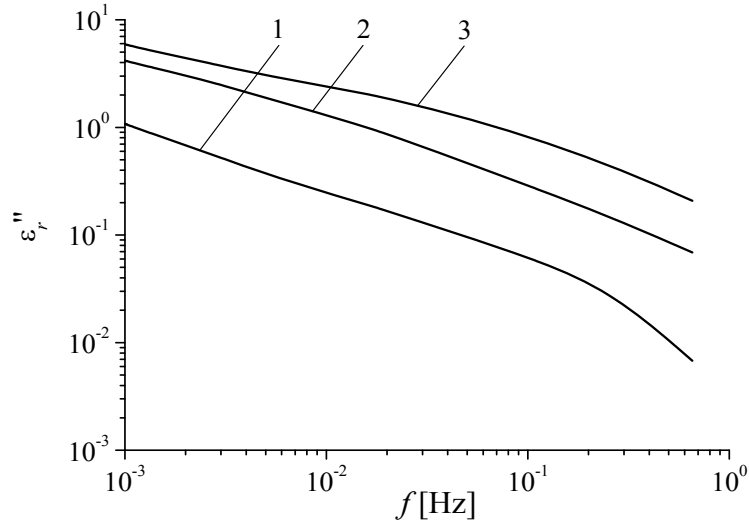
Fig. 5. Frequency variation of calculated imaginary part of relative permittivity ε_r'' for aged oil impregnated paper at $\tau = 150$ h (1), $\tau = 820$ h (2) and $\tau = 2100$ h (3).
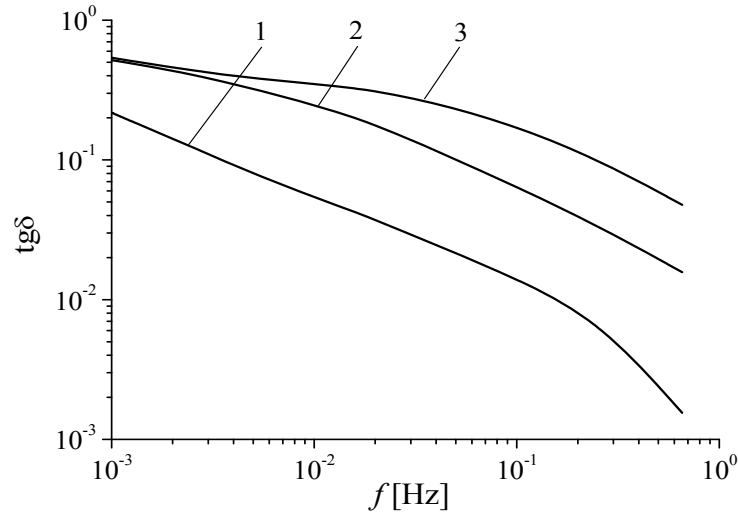

Fig. 6. Frequency variation of calculated loss factor tgδ for aged oil impregnated paper at $\tau = 150$ h (1), $\tau = 820$ h (2) and $\tau = 2100$ h (3).
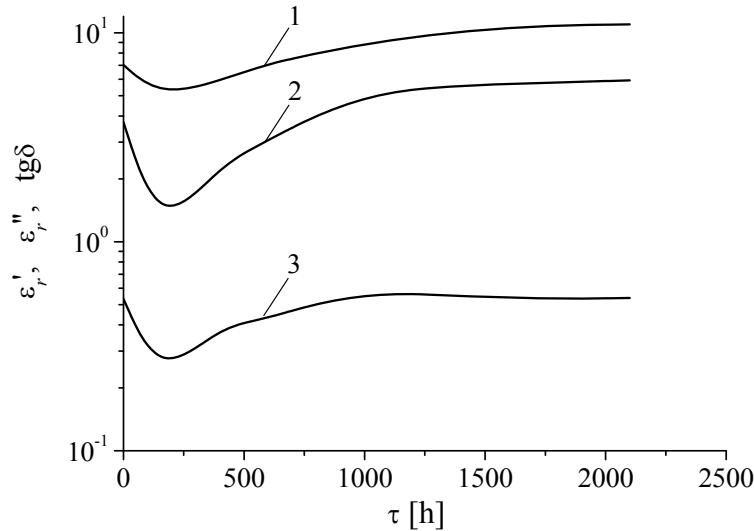
Fig. 7. Variation with ageing time τ of real (1) and imaginary part of relative permittivity (2) and loss factor (3).

Charge separation determines an increase of the interfacial polarization and thus of $\varepsilon_r^{'}$. The interfacial polarization increase, causes a growth of the losses and, consequently, of $\varepsilon_r^{''}$ and tgδ, especially if the frequency is very small (10^{-5} – 10^{-4} Hz). The large values of the loss factor at low frequencies are also due to the increase of its second term $tg\delta_\sigma = \sigma_0 / (\varepsilon_0 \varepsilon_r^{'} \omega)$, which takes high values when the frequency diminishes and the dc conductivity increases (especially in areas nearby electrodes, due to their polarization) [22].

For the samples in which water content is relatively high, a major importance in the increase of permittivity and loss factor values is represented by the low frequency dispersion process [18], [23].

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 the increase of quantities $\varepsilon_r^{''}$ and tgδ [23-24].

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 movement under the electrical field influence. When the ions pass one another, they form (for a small time) a neutral compound (AB) according to the symbolic equation:

$$A^+ + B^- \leftrightarrow AB .$$ (17)

This process is able to retain a large amount of charge without creating any electric field, only a potential which is associated with the electromechanical

potential of the system [23]. 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 $\varepsilon_r^{''}$ and tgδ will increase for very low frequencies.

In order to verify the calculated results using the dielectric response function, the complex relative permittivity components and loss factor were measured using a NOVOCONTROL dielectric spectrometer [25].

In Figs. 8, 9, and 10, variations of calculated (curves 1) and measured (curves 2) values of these quantities with frequencies are presented. It can be seen that, the calculated and experimental curves have the same variations and the differences between the measured and calculated values of $\varepsilon_r^{'}$, $\varepsilon_r^{''}$ and tgδ are less than 10 %.

Using the relations (14) and (15), the complex conductivity components ($\sigma^{'}$ and $\sigma^{''}$) were calculated. In Figs. 11 and 12, the variation curves of complex conductivity components (obtained based on calculated values of complex permittivity components $\varepsilon_r^{'}$ and $\varepsilon_r^{''}$) with electric field frequency and ageing time are presented. It was noticed that these quantities increase with ageing time, due to the increase of charge carriers and electric dipoles concentrations, respectively to the increase of conduction, polarization and space charge current densities [18]. Also, it can be seen that the values of the quantities $\sigma^{'}$ and $\sigma^{''}$ increase (almost linearly) with electric field frequency as in the equations (14) and (15).
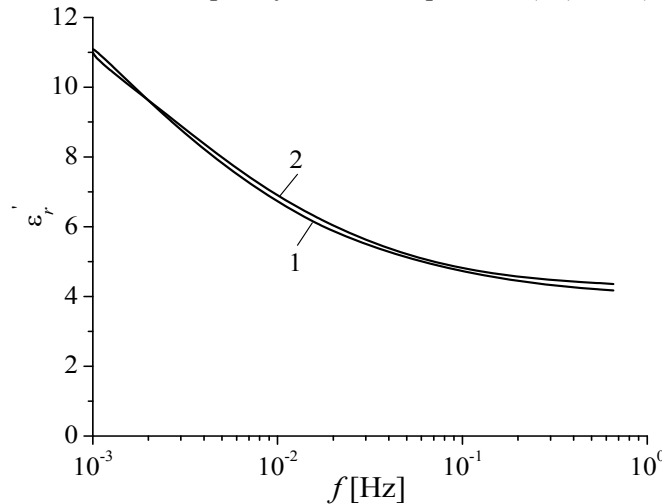
Fig. 8. Frequency variation of real part of relative permittivity $\varepsilon_r^{'}$ for thermal aged oil impregnated paper ($\tau = 2100$ h): (1) – measured and (2) - calculated.
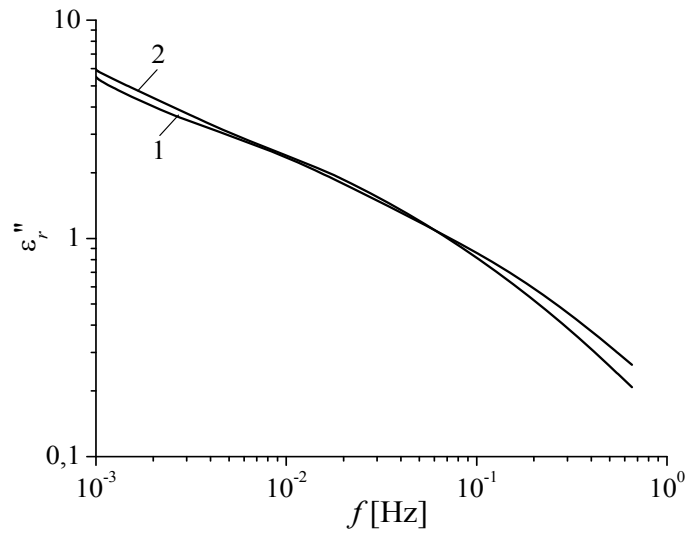
Fig. 9. Frequency variation of imaginary part of relative permittivity $\varepsilon_r^{''}$ for thermal aged oil impregnated paper ($\tau = 2100$ h): (1) – measured and (2) - calculated.

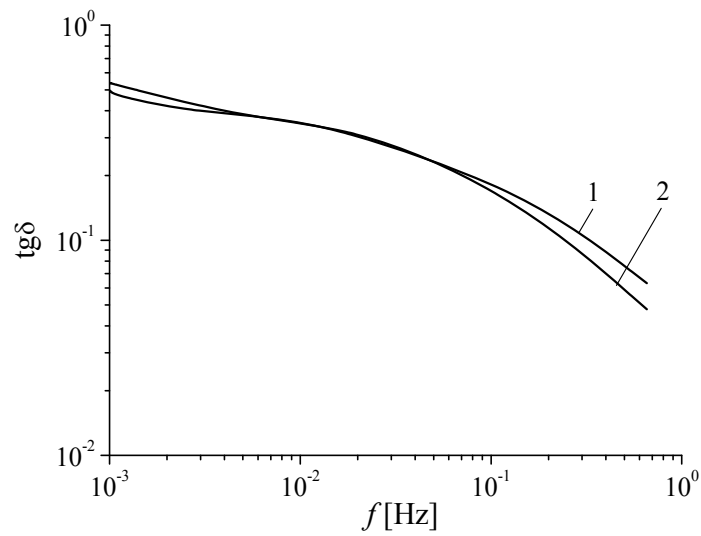

Fig. 10. Frequency variation of loss factor tgδ for thermal aged oil impregnated paper ($\tau = 2100$ h): (1) – measured and (2) - calculated.
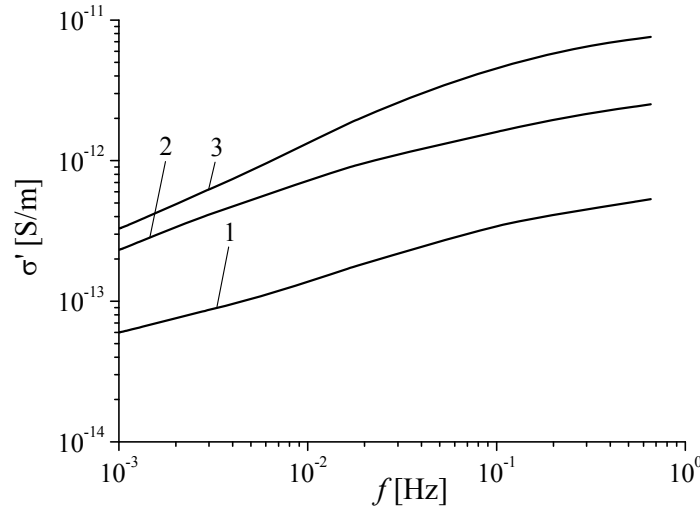
Fig. 11. Frequency variation of calculated real part of complex conductivity σ' for thermal aged oil impregnated paper at $\tau = 150$ h (1), $\tau = 820$ h (2) and $\tau = 2100$ h (3).

For low values of the electric field frequency ($f \to 0$), the values of real part of complex conductivity σ' converge to the dc conductivity values σ_0 obtained based on absorption and resorption currents [6].
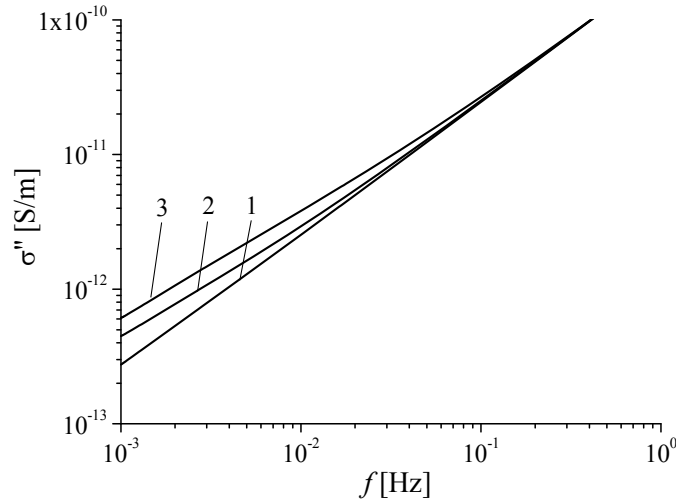

Fig. 12. Frequency variation of calculated imaginary part of complex conductivity σ'' for thermal aged oil impregnated paper at $\tau = 150$ h (1), $\tau = 820$ h (2) and $\tau = 2100$ h (3).

Also, like for ε_r', ε_r'' and tgδ, the differences between values of σ' and σ'' determined based on dielectric response function $f(t)$ and the experimental values are relatively reduced (below 10 %).

From the presented results, it can be seen that for assessment of oil impregnated paper ageing conditions, the values of quantities ε_r', ε_r'' and tgδ measured at low frequencies (10^{-3} – 10^{-5} Hz) can be used. Unfortunately, the necessary time for these quantities measurement is too long. For example, in case of measurement at frequency $f = 10^{-4}$ Hz, the needed time is 48 hours.

On the other hand, the requested time for absorption and resorption currents measurement is about two hours, and the time for dielectric response function $f(t)$ and quantities ε_r', ε_r'' and tgδ calculation at frequency $f = 10^{-4}$ Hz is few minutes.

Furthermore, the differences between the measured and the calculated values of the quantities ε_r', ε_r'' and tgδ are very small (less than 10 %). Thus, the time domain spectroscopy is a very useful method for assessment conditions of mineral oil impregnated paper of power transformers.

5. Conclusions

The assessment of oil impregnated paper conditions can be done with high accuracy based on the values of quantities ε_r', ε_r'' and tgδ measured at very low frequencies (10^{-3} – 10^{-4} Hz). The differences between measured and calculated (using the dielectric response function) values of quantities ε_r', ε_r'', σ', σ'' and tgδ are relatively small (below 10 %).

As long as the necessary time for absorption/resorption current measurement and function $f(t)$ calculation is very short (about two hours), the use of time domain spectroscopy to determine the quantities ε_r', ε_r'', σ', σ'' and tgδ values is recommended.

The presented results indicate that time domain spectroscopy can be a useful tool for the assessment of power transformers insulation systems.

A future work will be focused on the assessment of power transformers mineral oil condition using the same method based on the oil dielectric response function.

Acknowledgments

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