

# Dielectric Response Function for Nonhomogeneous Insulations

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**Abstract-** Dielectric response function  $f(t)$  of an insulation allows its behavior estimation in any electric field, constant or time variable. Generally, for the  $f(t)$  computation, a DC voltage  $U_0$  is applied, for a long enough period of time, on the insulation and the resorption (depolarization) current  $i_r(t)$  is measured. In the present paper, the dielectric response function is determined based on its Fourier transform, taking into account the frequency variation curve of real part of complex permittivity.

Thus, the time variation curve of resorption currents and frequency variation curve of real part of complex permittivity have been determined and, based on them, the dielectric response function has been calculated for two different kinds of samples, mineral oil impregnated paper and water treed polyethylene. Finally, the time variation curves of  $f(t)$  obtained with both methods are analyzed.

## I. INTRODUCTION

Diagnosis and monitoring of in-service electrical equipment insulation systems (rotating machines, power transformers, cables etc.) are one of the most important problems of their manufacturers and users [1-3]. There are several recommended methods, but the time domain spectroscopy (TDS)–based on absorption/resorption currents measurement – and frequency domain spectroscopy (FDS) – based on complex permittivity components measurements – are more and more used [4-11]. As long as the measured quantities depend on charge carriers (TDS) and electric dipoles (FDS) concentration, which are strongly influenced by the degradation processes whereat the insulations are subjected to, these methods are used for diagnosis and monitoring of in-service insulation systems.

Thus, inside of medium and high voltage polyethylene cables' insulations, besides polyethylene thermo-oxidative reaction products, water trees (which are high local concentrations of water molecules and ions) can appear, enhancing the conduction and polarization phenomena. In the case of oil impregnated paper insulation of power transformers, several chemical reactions occur (oxidation, hydrolysis etc.) which favor the generation of by-products, ions and molions, as well as increasing the electrical conduction and polarization phenomena [12]. Therefore, the values of current density and electrical polarization which occur inside the insulations depend on the electric field strength and their degradation condition.

If a step-like electric field of magnitude  $E_0$  is applied to a dielectric at any time  $t_0$  and assuming that this field remains constant for  $t \geq t_0$ , the specific polarization  $P(t)$  of the dielectric is given by the equation:

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

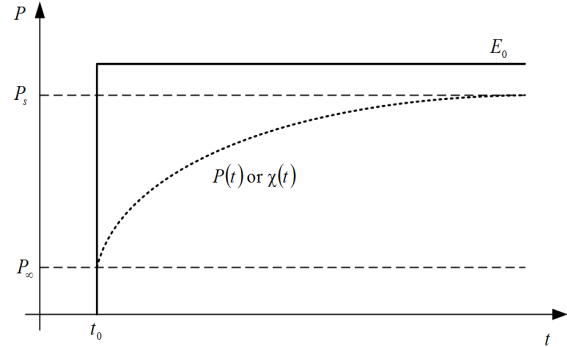


Fig. 1. Polarization of a dielectric exposed to a step electric field of magnitude  $E_0$  at  $t = t_0$ .

where  $\chi(t)$  is the dielectric susceptibility,  $\varepsilon_0$  is the free space permittivity and  $l(t)$  indicates the unit step for the electric field  $E_0$ .  $P(t)$  and  $\chi(t)$  represent step response functions in time domain [13-15].

In Fig. 1, the first part of the function  $P(t)$  is simplified considering an ideal step to account for the very fast polarization processes  $P(t_0) = P_\infty$ .

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:

$$P(t) = \varepsilon_0 [\chi_\infty - (\chi_s - \chi_\infty)] \cdot g(t - t_0) \cdot E_0, \quad (2)$$

where  $g(t)$  is a dimensionless monotonously increasing function [14].

For a time dependent excitation  $E(t)$ , the time dependent polarization  $P(t)$  is found (by the use of Duhamel's Integral) using the equation:

$$P(t) = \varepsilon_0 \chi_\infty E(t) + \varepsilon_0 \int_{-\infty}^t f(t - \tau) E(\tau) d\tau, \quad (3)$$

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

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

which is obviously a monotonously decreasing function and inherent to the dielectric being investigated [14].

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:

$$j(t) = \sigma_r E(t) + \varepsilon_0 [\varepsilon_\infty \delta(t) + f(t)] \cdot E(t), \quad (5)$$

where  $\sigma_r$  represents the DC conductivity.

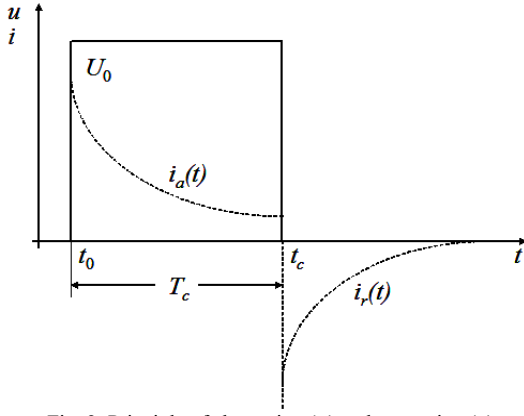


Fig. 2. Principle of absorption ( $i_a$ ) and resorption ( $i_r$ ) currents measurement.

Equation (5) is the first basis for the measurement of the dielectric response function  $f(t)$ , and also for characterizing dielectrics using the time-domain method (TDM).

On the other hand, if a DC voltage  $U_0$  is suddenly applied to the test object, a current  $i_a(t)$  occurs through the test object (Fig. 2):

$$i_a(t) = C_0 U_0 \left[ \frac{\sigma_t}{\varepsilon_0} + \varepsilon_\infty \delta(t) + f(t) \right], \quad (6)$$

where  $C_0$  is the geometric capacitance of the 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  $\sigma_t$  of the test object and is independent of any polarization process, the last one represents all the activated 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 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. (6) (which is again a very short current pulse), we obtain for  $t \geq (t_0 + T_c)$ :

$$i_r(t) = -C_0 U_0 [f(t) - f(t + T_c)]. \quad (7)$$

From relation (7), it can be seen that the resorption current is proportional to the dielectric response function  $f(t)$ , as the DC conductivity  $\sigma_t$  of the dielectric is not involved, but can easily be calculated from the difference between the absorption and the resorption currents. Equation (7) is the second basis for the measurement of the  $f(t)$  dielectric function and also for characterizing dielectrics' response in time domain.

Supposing that  $T_c$  is high enough so that  $f(t + T_c) \approx 0$ , it results from (7):

$$f(t) \approx -\frac{i_r(t)}{C_0 U_0}. \quad (8)$$

Considering that an AC voltage of pulsation  $\omega$  is applied to a capacitor, that the polarization processes are instantaneous, and  $\underline{F}(\omega)$  is the Fourier transform of the dielectric response

function  $f(t)$ , respectively the complex susceptibility  $\underline{\chi}(\omega)$ , it results:

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

$$\chi'(\omega) = \int_0^{+\infty} f(t) \cos(\omega t) dt \quad (10)$$

$$\chi''(\omega) = \int_0^{+\infty} f(t) \sin(\omega t) dt \quad (11)$$

$$\text{tg} \delta = \frac{\chi''(\omega) + \frac{\sigma_t}{\varepsilon_0 \omega}}{1 + \chi'(\omega)} \quad (12)$$

$$f(t) = \frac{2}{\pi} \int_0^{\infty} \chi'(\omega) \cos(\omega t) d\omega, \quad (13)$$

where  $\chi'$  and  $\chi''$  represent the real and imaginary parts of complex susceptibility and  $\text{tg} \delta$  is the loss factor [15].

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 [5], [7], [9], [11].

Therefore, dielectric response functions  $f(t)$  allow the assessment of dielectric properties values of insulations and, consequently, their degradation condition. The equations (8)-(9)-(10) can be used in order to calculate these functions for several homogeneous dielectrics [15]. Regarding the inhomogeneous dielectrics, the  $f(t)$  computation based on resorption currents is more difficult, because  $T_c$  values are relatively high for  $i_r(t + T_c) \approx 0$ .

In this paper, the  $f(t)$  functions for two kinds of inhomogeneous insulations (water treed polyethylene and oil impregnated paper) are determined using (10), based on experimental determined curves of  $\varepsilon_r(\omega)$ . The obtained functions are then compared to those given by (8) (based on resorption currents time variation).

Thus, an analytical form has been proposed for  $\chi'(\omega)$ :  $\chi'(\omega) = a e^{-b\omega}$ , where  $a$  and  $b$  are material constants (Table 1).

TABLE I  
VALUES OF  $a$  AND  $b$  CONSTANTS

Sample	$a$	$b$ [s]
A	6.34	13.15
B	6.15	164.12

## II. EXPERIMENTS

The experimental study was carried out using two kinds of insulation samples, mineral oil impregnated paper and water treed PE. The used samples were  $60 \times 60 \text{ mm}^2$  plates with 0.25 mm thickness (samples A – oil impregnated paper) and 0.5 mm thickness (samples B - water treed PE), respectively. For both kinds of samples, the resorption currents ( $i_r(t)$ ) and the complex permittivity components ( $\varepsilon_r'$  and  $\varepsilon_r''$ ) were measured.

In order to measure the  $\epsilon_r'$  and  $\epsilon_r''$  quantities, a NOVOCONTROL impedance analyzer was used. The AC voltage applied was  $U = 1$  V and the electric field frequency took values between  $f_m = 10^{-3}$  Hz... $10^3$  - for A samples - and between  $f_m = 10^{-5}$ ... $10^6$  Hz - for B samples [16]. All the measurements were performed at  $T = 30$  °C. The resorption currents were measured using a 6517 Keithley Electrometer, applying a DC voltage  $U_0 = 300$  V for 1 h (Fig. 3) [17].

The  $60 \times 60 \times 0.5$  mm<sup>3</sup> PE samples made of LDPE were subjected to the simultaneous action of electric field and water. In order to accelerate the water trees development rate, several surface defects have been created on one side of the sample. In this way, sandpaper has been used and a pressure of 10 tf for 2 minutes has been applied on the samples-sandpaper system [17]. The samples have been stuck in PE cylinders, creating a special cell which was then filled with 0.1 mol/l concentration H<sub>2</sub>O and NaCl solution. The experimental set up for water trees accelerated development is presented in Fig. 4.

Groups of five cells were subjected to the electric field and water action for different time intervals  $\tau = 24 \dots 72$  h, applying a sinusoidal voltage  $U_a = 2$  kV with frequency  $f_a = 3-5$  kHz. Then, the voltage was removed and the absorption/resorption currents and complex permittivity components were measured.

### III. RESULTS. DISCUSSIONS

In Fig. 5, the variation of real part of complex permittivity as a function of  $f_m$  frequency is presented for both mineral oil impregnated paper as well as for water treed polyethylene samples. It can be seen, for both samples, a significant increase in permittivity for low frequencies. This tendency is due to inhomogeneous polarization enhancement at oil/paper and PE/water interfaces, as a result of charges separation between homogeneous areas inside the samples. On the other hand, because of the samples' high water content, the dispersion phenomenon at low frequencies appears [18].

In Fig. 6, the time variation of resorption currents is presented for both A and B samples. The high values of resorption current in the range of nA can be noticed. In case of oil impregnated paper, this happens because of the samples' high water content (around 3 %) [12]. Also, it can be seen that, for both samples, these currents do not converge to zero, even after one hour.



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

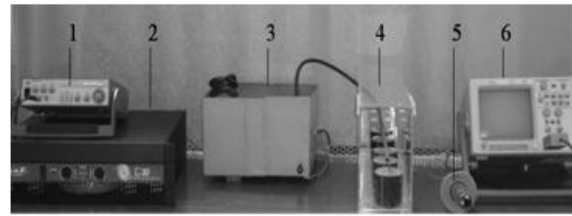


Fig. 4. Setup used for water trees development: 1 – Signal generator, 2 – Amplifier, 3 – Transformer, 4 – Sample holder, 5 – Probe, 6 – HP Scope.

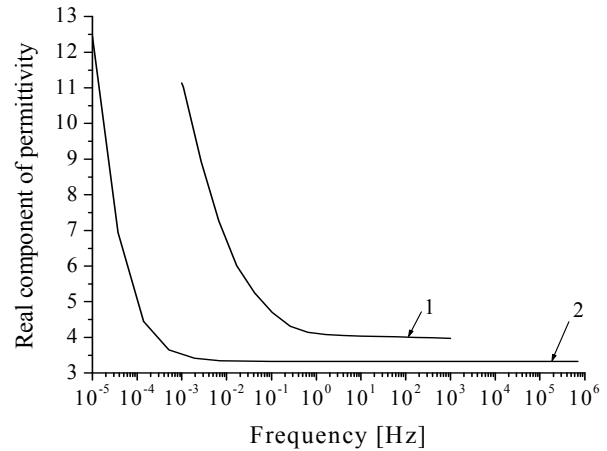


Fig. 5. Frequency variation of real part of complex permittivity for oil impregnated paper (1) and water trees polyethylene (2) ( $U = 1$  V,  $T = 30$  °C,  $U_a = 2$  kV,  $f_a = 5$  kHz,  $\tau = 24$  h).

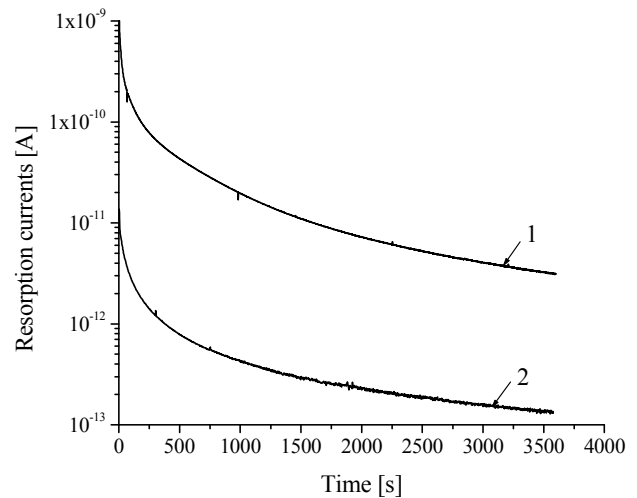


Fig. 6. Time variation of resorption currents for oil impregnated paper (1) and water trees polyethylene (2) ( $U_a = 2$  kV,  $f_a = 5$  kHz,  $\tau = 24$  h,  $U_0 = 300$  V).

Fig. 7 presents the time variation of dielectric response function  $f(t)$  for A sample, calculated based on  $\chi'(\omega)$  and  $i_r(t)$  respectively. It can be observed that the  $f(t)$  curves obtained using both methods are close enough, the percentage error taking values less than 1 %.

The time variations of  $f(t)$  dielectric response function calculated based on  $\chi'(\omega)$  and  $i_r(t)$  curves corresponding to water treed polyethylene samples (B) are presented in Fig. 8. In this case, small differences could be noticed as well between the  $f(t)$  function values calculated using both methods (lower than 1 %).

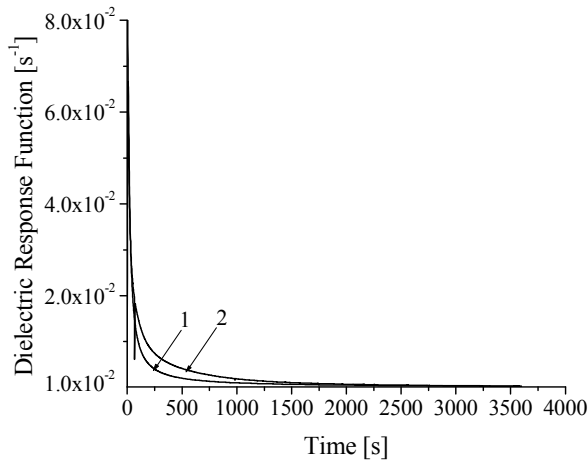


Fig. 7. Time variation of  $f(t)$  dielectric response function for A sample calculated based on (8) (curve 1), and (10) (curve 2).

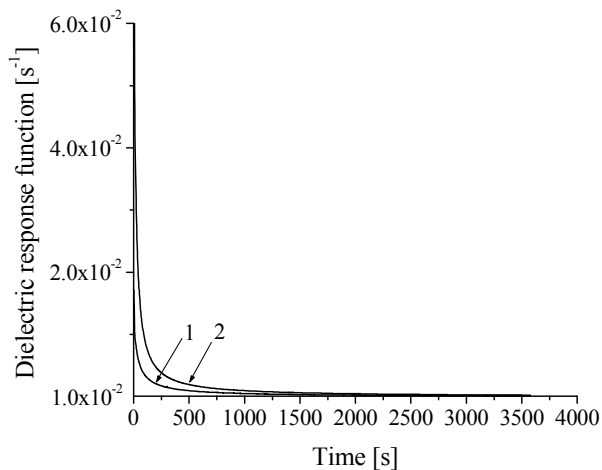


Fig. 8. Time variation of  $f(t)$  dielectric response function for B sample calculated based on (8) (curve 1), and (10) (curve 2).

#### IV. CONCLUSIONS

The experimental determination of real part of complex permittivity allows the  $f(t)$  dielectric response function assessment.

Based on  $f(t)$  function, the complex permittivity components ( $\epsilon_r'$  and  $\epsilon_r''$ ) and loss factor  $\text{tg}\delta$  can be determined, while measurement at low frequencies requires long times.

The differences between  $f(t)$  values determined based on the time variation curve of resorption current ( $i_r(t)$ ) and the frequency variation curve of real part of complex permittivity  $\epsilon_r'(\omega)$  are below 1 % for oil impregnated paper and water treed polyethylene.

#### ACKNOWLEDGMENT

The authors are grateful to the Romanian Ministry of Education, Research, Youth and Sport for the financial support under the project DEDIC 34/2010, CABDIAG 22122 /2008 and POSDRU/6/1.5/S/16 5159.

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