Measuring of the dielectric properties of mineral oil

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Abstract: - Power transformers activity in optimal conditions largely depends on their insulation system condition. Therefore it lays emphasis on dielectric properties measurement of their basic components (paper and oil).

In this paper, one of the new methods for dielectric properties measurement of mineral oil, respectively dielectric response method in frequency domain, is presented.

With the NOVOCONTROL spectrometer, experiments were made on two types of mineral oil (MOL virgin oil and NYNAS virgin oil) with different water content and the variation curves of relative complex permittivity components ($\varepsilon_r'$ and $\varepsilon_r''$) and of dielectric loss $\tan\delta$ with frequency and temperature were plotted. It can be seen that $\varepsilon_r'$, $\varepsilon_r''$ and $\tan\delta$ increase at low frequencies and their values depend on temperature values and temperature variation way.

Key-words: - transformers, insulation system, mineral oil, dielectric spectroscopy, relative permittivity, loss factor.

1 Introduction

The basic components of the insulation systems of power transformers are cellulosic parts and mineral oil, the oil representing about 75 – 80 % of the insulation system.

During transformers operation, a decrease of dielectric characteristics of the paper and oil (respectively, their degradation) is registered due to the thermal stresses, electrical stresses, oxygen, water etc. to which are submitted. Degradation products based on cellulose are the result of three chemical important reactions: pyrolysis (resulting small chains, CO, CO$_2$, H$_2$O, and furans), oxidation (resulting CO, CO$_2$, H$_2$O and acids) and hydrolysis (resulting smaller chains).

Due to the oxygen action, different products appear inside the oil (water, gases, sludges), which worsen their dielectric properties and increase their viscosity (some of these being deposited on the winding and blocking heat transmission). Under heat (which causes a chemical degradation) and oxygen action, oil color changes, the electric strength and interfacial tension decrease and the dielectric loss and acidity index increase. Water contamination leads to a sharp decrease of the dielectric properties of the oil. Water can appear from external medium and/or due to the degradation processes of the paper and oil.

The evaluation of oil condition can be done using several methods, like water content determination, dissolved gases analyses, interfacial tension measuring, the oxygen method, the acidity index method, the electric strength method, the loss factor method etc. The new methods used are based on relative permittivity measurement, loss factor measurement, absorption/resorption currents measurement, polarization index measurement, conductivity factor measurement, return voltage method [1, 2] etc. In previous paper [3] some experimental results concerning the variations of electrical properties (resistivity, permittivity, loss factor, conductivity coefficient, polarization index) of the power transformer insulation paper (pressboard) with water content and temperature were presented. In this work the first results obtained by dielectric spectroscopy concerning temperature influence and its way of variation on electric properties of mineral oil are presented.

2 Dielectric Response Method

Dielectric spectroscopy is based on interactions between applied electric field and electric dipoles of the material under test, frequency values being between 10$^{-6}$ and 10$^{10}$ Hz [4].

If an electric field of magnitude $E_0(t) = E_0^{-1}t(t)$ (Fig.1) the response of the dielectric at $t \geq t_0$ is polarization $P(t)$:
\[ P(t) = \varepsilon_0 \chi(t) l(t) E_0 \]  

(1)

where \( \chi(t) \) is the dielectric susceptibility (dielectric response function), \( \varepsilon_0 \) – the permittivity of vacuum and \( l(t) \) – the unit step [5,6].

Considering an ideal step for an electric field, the adequate polarization for the very fast polarization processes (electronic, ionic etc.) takes the value \( P(t) = P(t_0) = P_\infty \). In case of big values for \( t \), the polarization finally becomes static, respectively \( P(t \to \infty) = P_\infty \) (Fig.1).

![Fig.1 Polarization of a dielectric exposed to a step electric field of magnitude \( E_0 \) at \( t = t_0 \).](image)

For a time dependent excitation \( E(t) \), the time dependent polarization \( P(t) \) is done (using the Duhamel’s integral) by the equation:

\[ P(t) = \varepsilon_0 \chi_\infty E(t) + \varepsilon_0 \int_{-\infty}^{t} f(t-\tau) E(\tau) d\tau \]  

(2)

where \( f(t) \) is the dielectric response function (a monotonous and increasing function).

If a dc voltage \( U_0(t) = U_0 \delta(t) \) is applied to the condenser coating which contains the test object, a current \( i_a(t) \) through the test object (Fig.2) appears:

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

(3)

where \( C_0 \) is the geometric capacitance of test object, \( \sigma_t \) is the dc conductivity and \( \delta(t) \) is the delta function (which characterizes the voltage step at \( t = t_0 \)).

\[ \delta(t) = \begin{cases} 0, & \text{if } t_0 > t > T_c \\ 1, & \text{if } t_0 \leq t \leq T_c \end{cases} \]  

(4)

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 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 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.2 Time variation of absorption \( i_a(t) \) and resorption \( i_r(t) \) currents.](image)

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:

\[ f(t) = \frac{i_r(t)}{C_0 U_0} \]  

(6)

In case of applying an harmonic electric field \( E(t) = E \sqrt{2} \sin \omega t \) and considering that all the polarization processes are instantaneous, and \( \chi(\omega) \) (the Fourier Transform of the dielectric response function \( f(t) \)), the complex susceptibility and \( \tan \delta \) dielectric loss factor result:

\[ F(\omega) = \chi(\omega) = \chi'(\omega) - j \chi''(\omega) = f(t) \exp(j\omega t) dt \]  

(7)

\[ \varepsilon(\omega) = 1 + \chi'(\omega) - j \chi''(\omega) = \varepsilon_r - j \varepsilon_i, \]  

(8)

\[ \tan \delta = \frac{\varepsilon_r + \frac{\sigma_t}{\varepsilon_0 \omega}}{\varepsilon_i}. \]  

(9)
3 Experiments

For experimental study, two types of transformers oil were used: MOL virgin oil and NYNAS virgin oil.

3.1 Water content measurement

Water content determination was made by Karl-Fischer method, using the experimental set-up from Fig.3.

Table 1 Water content values for oils [ppm].

<table>
<thead>
<tr>
<th>Oil</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Medium</th>
</tr>
</thead>
<tbody>
<tr>
<td>NYNAS</td>
<td>15.9</td>
<td>14.3</td>
<td>14.7</td>
<td>14.2</td>
<td>15.3</td>
<td>14.9</td>
</tr>
<tr>
<td>MOL</td>
<td>20.8</td>
<td>21.9</td>
<td>20.6</td>
<td>20.4</td>
<td>21.2</td>
<td>20.9</td>
</tr>
</tbody>
</table>

The results of the measurement (Table 1) highlighted that the water content is 30% higher in MOL oil than NYNAS oil.

3.2 Relative permittivity and loss factor measurement

To measure the relative complex permittivity $\varepsilon'$ and loss factor $\tan\delta$, a NOVOCONTROL spectrometer (Fig.4) fitted with a liquids cell (Fig.5) was used.

The three electrode cylindrical sample cell avoids the errors related to the thermal expansion of the measured liquid, protects against sample leakage and prevents evaporation. It also increases the accuracy of the measurement by decreasing the influence of fringing fields. The voltage applied had effective value 1 V and frequency between 1 mHz and 10 kHz.

![Fig.4 Novocontrol spectrometer: 1 – PC, 2 – Control System, 3 – Modular Measurement System, 4 – Measurement Cell, 5 – Temperature Control System.](image)

![Fig.5 Cell for dielectric properties of liquids measurement: 1 – inner electrod; 2 – ground connecter; 3 – guard electrode; 4 – outer electrod; 5 – sample liquid; 6 – teflon; 7 – hole; 8 – metal container; 9 – hole with spring; 10 – teflon isolating rings; 11 – teflon cap.](image)

To check the accuracy and reproducibility of the experimental results, each sample was measured three times (the measurements $M_1...M_3$ for MOL and respectively $N_1...N_3$ for NYNAS) in the same condition.

The measurements were carried out at $T = 30 ^\circ C$ and the obtained values for real component of relative permittivity for three values of frequency are presented in Table 2.

Table 2 Real component of relative permittivity $\varepsilon'$.

<table>
<thead>
<tr>
<th>$f$</th>
<th>$M_1$</th>
<th>$M_2$</th>
<th>$M_3$</th>
<th>$N_1$</th>
<th>$N_2$</th>
<th>$N_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mHz</td>
<td>4.21</td>
<td>4.17</td>
<td>4.23</td>
<td>3.09</td>
<td>2.97</td>
<td>2.97</td>
</tr>
<tr>
<td>10 Hz</td>
<td>2.36</td>
<td>2.35</td>
<td>2.36</td>
<td>2.43</td>
<td>2.43</td>
<td>2.43</td>
</tr>
<tr>
<td>10 kHz</td>
<td>2.34</td>
<td>2.35</td>
<td>2.35</td>
<td>2.43</td>
<td>2.43</td>
<td>2.43</td>
</tr>
</tbody>
</table>

It results that, for both samples, values of $\varepsilon'$ increase when frequency decreases. This is due, in a great measure, to the interfacial polarization increase.

3.3 Temperature influence

Both components of complex relative permittivity ($\varepsilon'$ and $\varepsilon''$), as well as loss factor $\tan\delta$ values are strongly influenced by test sample
temperature (Fig.6 – 8, 12 – 14) and the temperature variation way (Fig.9 – 11).

The temperature increase allowed a pronouncedly orientation of the electric dipoles and, so, an increase of polarization and \( \varepsilon_r \), too (Fig.6). This phenomenon is more intense in case of low frequencies (1 mHz). When an electric field is applied to a dielectric, heat build-up occurs inside due to Joule-Lenz effect, because the material conductivity is not zero. In case of time variable electric field, losses by dielectric hysteresis are produced (electric viscosity), (electric polarization does not vary in phase with the electric field).

With temperature increase, the electric dipoles oscillation and the mobility of charge carriers also increase, respectively the liquid conductivity increases, both phenomena leading to the increasing of dielectric losses. The increase of dielectric losses is highlighted by the increase of imaginary component of relative permittivity values \( \varepsilon'' \) and of loss factor \( \tan \delta \), both at high frequencies as well as low frequencies (Figs.7, 8, curves 1, 1’, 2, 2’).

3.4 The influence of the temperature variation way

In figures 9 – 11, the influence of the temperature variation way on the relative permittivity components \( \varepsilon_r \) and \( \varepsilon'' \) and loss factor \( \tan \delta \) for frequency 1 mHz is presented. In this case, the temperature was modified by increasing, respectively decreasing between 30 °C to 90 °C. It noted that, the values obtained for all three quantities at the temperature decrease are greater than those obtained at the temperature increase.
3

4

Conclusions

After experimentes carried out on the two types of oil (MOL oil and NYNAS oil), it can be noted that their representative dielectric properties, respectively complex permittivity (characterized by real and
imaginary components $\varepsilon_r'$ and $\varepsilon_r''$) and loss factor are strongly influenced by samples temperature and by the voltage supply frequency.

Another parameter which highly influenced the experimental results was the temperature variation way, the values of quantities $\varepsilon_r'$, $\varepsilon_r''$, and $\tan\delta$ being higher when the temperature decreases from 90 ºC to 30 ºC. All the three quantities take higher values for frequencies near $10^{-3}$ Hz. The water content of the two types of oil is too high than norm imposed limit of operation and they cannot be used into power transformers without a previous drying treatment.

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References