Journal of Engineering, Sciences, Assiut University, Vol. 35, No. 6, pp. 1455-1465, November 2007

EFFECT OF GEOMETRICAL ARRANGEMENT OF POWER TRANSFORMER INSULATION AND ITS TEMPERATURE ON DIELECTRIC RESPONSE MEASUREMENTS

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(Received June 4, 2007 Accepted October 23, 2007)

This paper investigates the modelling of dielectric response measurements for power transformer condition assessment. The insulation of a power transformer consists of oil and cellulose (insulation paper). The dielectric properties of both materials generally change during the life of the transformer and dielectric measurements have therefore been applied to assess the quality of the transformer insulation system. Recently, a new method, the Frequency Domain Spectroscopy (FDS) measurements, has been applied which is based on the measurements of the dielectric response of the insulation in the frequency domain. In this paper, the effect of transformer insulation geometry and the insulation system temperature on the transformer insulation properties are studied. Different transformer insulation geometrical arrangements and their temperatures are simulated using the dielectric spectroscopy program MODS from General Electrical company (GE). It is used to model different cases of insulation geometry arrangement by changing the percentage ratio of oil and paper of insulation.

KEYWORDS: *geometrical arrangement oil-paper insulation, dielectric response, frequency domain spectroscopy, real and imaginary permittivity, dielectric loss.*

1. INTRODUCTION

The insulation condition assessment for transformers, motors, generators and bushings is very important. Some problems in insulation system may cause failure of insulation and hence failure of the machine. This failure causes interruption of the power system. Therefore, the scheduled maintenance and diagnosis of the insulation system is very important for detecting the pre-fault problems and solve them before insulation failure.

New methods, based on dielectric response measurements of transformer insulation system, have been studied to evaluate the effect of aging and moisture content on the insulation system quality. These techniques are namely the Recovery Voltage Measurement (RVM), Polarization and Depolarization Current (PDC) measurement and Frequency Domain Spectroscopy (FDS) measurements. The first two techniques operate in the time domain whereas the third technique operates in the frequency domain [1-3]. The FDS technique is used to measure the properties of insulation system, real permittivity ε', imaginary permittivity ε'' and dissipation factor $\tan\delta$. The dielectric response measurements in the time and frequency domains reflect the changing in insulation properties. The PDC, RVM and tan δ measurements are affected by moisture content and aging state of the insulation system [4-6]. These measurements are performed at certain times based on the maintenance scheduled time. The new measurements are compared with the previous measurements to detect the changes in insulation system properties. Therefore, the variations of moisture content and aging state are detected [7,8]. One of these factors is the temperature during measurements where the equilibrium of moisture content between paper and oil is affected by temperature [9]. The second factor is the different designs of power transformers, leading to different geometrical arrangements of their insulation system. Thus, the percentage ratio between the liquid and solid insulation is not constant. An experimental measurement has been investigated on oil paper insulation model [3]. It shows clearly the variation of the dissipation factor **tan δ** due to the changing of aging state and moisture content. The measurement has been performed on oil paper insulation model having fixed geometry and constant insulation temperature. Therefore, this paper studies the effect of variation of geometrical arrangement of insulation system on measurements of insulation properties. Also, the impact of insulation system temperature is considered.

2. GEOMETRICAL ARRANGEMENT OF POWER TRANSFORMER INSULATION

Figure 1 shows the typical winding and insulation arrangement of a power transformer. It shows that the low voltage LV winding is usually surrounded by the high voltage HV winding and these windings are separated by the main insulation duct that consists of pressboard layers and oil channels. Therefore, response measurements between HV and LV windings are affected by the composite insulation system properties.

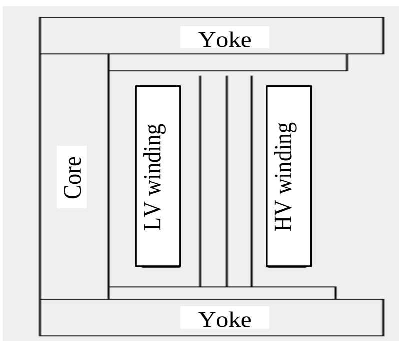

Fig. 1: Typical winding configuration of a power transformer

2.1 Model Parameters

To make precise modelling of the composite insulation of a transformer, information is needed about the geometrical design, conductivity and permittivity of the transformer insulation. In a core type transformer, the main insulation consists of a number of cylindrical shells of pressboard barriers, separated by axial spacers as shown in Fig. 2.

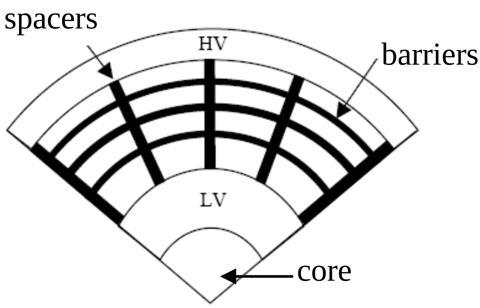

Fig. 2: Cross section of the main insulation of a core type transformer

The complex geometrical arrangement, shown in Fig. 2, can be modified by combining all oil ducts, barriers and spacers separately, which simplifys the modelling. Then the main insulation is simplified to the so called X-Y model, shown in Fig. 3, where the parameter X is the ratio of the sum of all the thickness of the all barriers in the duct, lumped together, and divided by the duct width. The spacer coverage, Y, is defined as the total width of the spacers divided by the total length of the periphery of the duct. In real power transformer, X and Y often vary in the ranges 0.2 - 0.5 and 0.15-0.25, respectively [10].

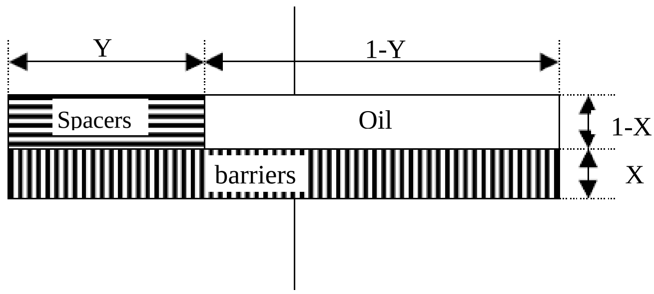

Fig. 3: Simplified insulation structure of a core type power transformer [10]

The composite dielectric permittivity, $\boldsymbol{\varepsilon_{duct}}$, of the insulation duct is calculated as [11].

$$\varepsilon(\omega,T)_{duct} = \frac{Y}{\frac{1-X}{\varepsilon_{spacer}} + \frac{X}{\varepsilon_{barrier}}} + \frac{1-Y}{\frac{1-X}{\varepsilon_{oil}} + \frac{X}{\varepsilon_{barrier}}} \qquad (1)$$

where ω and T are angular frequency and temperature respectively. Fig. 4 shows a simplified diagram of the dielectric response measurement for a power transformer.

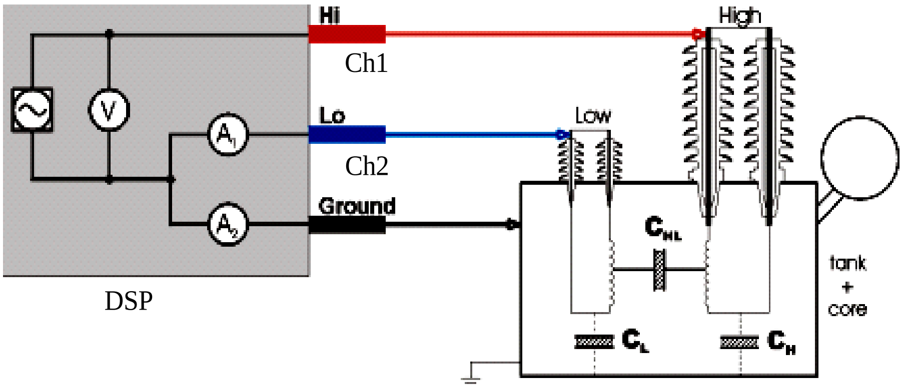

Fig. 4: Simplified diagram of capacitance measurement (frequency domain) for power transformer

During the measurements, all the terminals of HV and LV windings are short-circuited separately. The tank is connected to the ground electrode. Channels Ch1 and Ch2 in the digital signal processing (DSP) board are used for measuring the magnitude and phase of the applied voltage $\hat{U}(\omega)$ and the resultant current $\hat{I}(\omega)$, respectively. As shown in Fig. 4, three parts of insulation can be identified:

i. C_{HL} represents the capacitance of all barriers, oil and winding insulation between the high and low voltage windings.
ii. C_H represents the capacitance of all insulation between the high voltage winding inclusive bushing, oil and winding insulation, and grounded parts (tank and magnetic core).
iii. C_L represents the capacitance of all insulation between the low voltage winding inclusive bushing, oil and winding insulation, and grounded parts (tank and magnetic core).

The measured current originates exclusively in a well defined geometry between HV and LV windings and it is taken from LV terminations. All leakage currents on the bushing surfaces or between windings and core or tank, are directly conducted to ground and do not superpose to the measuring current. The complex capacitance $\hat{C}(\omega)$ is defined from the relation between the measured current and the measured voltage. Then the complex capacitance of the test object is calculated using the following equation [11,12].

$$\begin{aligned}\hat{I}(\omega)&=j\omega\hat{C}(\omega)\hat{U}(\omega)\\&=j\omega\{C'(\omega)-jC''(\omega)\}\,\hat{U}(\omega)\end{aligned} \tag{2}$$

where $\hat{U}(\omega)$ is the applied voltage. $C'(\omega)$ and $C''(\omega)$ are the real and imaginary components of the complex capacitance $\hat{C}(\omega)$, respectively. The frequency dependent loss factor $\tan\delta(\omega)$ can be defined as follow

$$\tan\delta(\omega)=\frac{C''(\omega)}{C'(\omega)}, \tag{3}$$

which lead to :

$$\tan\delta(\omega)=\frac{\varepsilon''(\omega)}{\varepsilon'(\omega)} \tag{4}$$

where $\boldsymbol{\varepsilon'(\omega)}$ and $\boldsymbol{\varepsilon''(\omega)}$ are the real and imaginary components of a complex permittivity $\boldsymbol{\varepsilon(\omega)}$, respectively. It is well known that the real part of $\boldsymbol{\varepsilon}$ represents the relative permittivity used to calculate the capacitance of the system or the energy storage capability. The imaginary part of $\boldsymbol{\varepsilon}$ represents the energy loss in the dielectric medium as the dipoles try to polarize with the applied external field.

3. SOFTWARE SIMULATION

The effect of geometry and temperature of composite insulation system of a power transformer on dielectric response measurements in the frequency domain will be studied using the dielectric spectroscopy MODS program, being provided by the manufacturer of insulation diagnostic instrument (IDA 200) [13]. This program calculates the insulation parameters, real permittivity $\boldsymbol{\varepsilon'}$, imaginary permittivity $\boldsymbol{\varepsilon''}$ and dissipation factor $\mathbf{tan}\ \boldsymbol{\delta}$ based on the input information about the geometrical design of power transformer like X and Y. Also the insulation temperature and moisture content will be given. The insulation parameters $\boldsymbol{\varepsilon'}$, $\boldsymbol{\varepsilon''}$ and $\mathbf{tan}\ \boldsymbol{\delta}$ will be calculated in a frequency range from 0.001 to 1000 Hz.

3.1 Effect of Transformer Insulation Geometry

The effect of geometry will be studied by modelling the insulation system with different percentage ratios between the liquid insulation (oil) and the solid insulation (paper) by changing the values of X and Y as shown in Table 1. The temperature of the insulation and moisture content are 20°C and 1% respectively. To show clearly the effect of the percentage ratio between the solid and liquid insulation, two simulation cases will be studied. One case is for pure oil insulation sample and the other is for pure paper insulation sample. Cases 3, 4 and 5 show composite insulation with different percentage ratios of paper where the values of X and Y are assumed to be identical to the real transformer.

Table 1

Case No.	Temperature	Moisture Content	X	Y
Case 1 (Pure oil)	20°C	1%	0%	0%
Case 2 (Pure paper)	20°C	1%	100%	100%
Case 3	20°C	1%	20%	20%
Case 4	20°C	1%	20%	15%
Case 5	20°C	1%	20%	25%

The values of ε', ε'' and **tan δ** have been calculated by the MODS program versus the desired frequency range. Fig. 5 shows that the value of real permittivity ε' increases by increasing the paper percentage ratio Y, the significant increase of ε' at low frequencies confirms the influence of the interfacial polarization of the oil-paper composite. Where the insulating material composed of two materials (oil and paper) that contain dispersed macroscopic impurity regions, then with the application of an electric field a space charge builds up at the microscopic interfaces as a result of differences in conductivity and permittivity of its individual components. Due to the accumulation of charges at the border of the conducting regions, it causes ε' to increase in values at low frequencies. As the frequencies increases, ε' decreases and the losses exhibit the same slope as normal ionic conductivity. In case of pure oil, the real permittivity ε' have a constant value of 2.2 at different frequencies, but with pure paper, it changes from 4.8 to 4.14 in the frequency range from 0.001 to 1000 Hz.

Fig. 6 shows that the value of imaginary permittivity ε'' is dependent on the percentage ratios of oil-paper insulation system. The strong variations of ε' and ε'' with frequency are due to the various polarization mechanisms as the frequency changes. The frequency dependent response is due to many different factors. For electronic and atomic polarization the inertia of orbiting electrons must be accounted for. Due to this inertia effect, these polarization mechanisms will be small for any frequency other than the resonant frequency. Far below this frequency little contribution to ε' and ε'' is given from these mechanisms. At the resonant frequency a peak in ε'' will occur and a dispersion will occur in ε'. Fig. 7 show that the value of **tan δ** is dependent on the percentage ratios of oil-paper insulation system where the value of **tan δ** is a ratio of real and imaginary permittivity. Noting that the values of ε', ε'' and **tan δ** are dependent on the geometrical arrangement of transformer insulation system. Therefore, when the new suggested measurement methods (FDS) are used to compare and evaluate the insulation properties of various transformers should be performed on transformers having the same insulation arrangement.

3.2 Effect of Transformer Insulation Temperature

To study the effect of temperature on measurements of insulation system properties ε', ε'' and **tan δ**. These values have been calculated by MODS program for case 3 (X=20%, Y=20%) at 20°C and 40°C. Figs. 8-10 show the variation of the calculated values due to the temperature variation. Fig. 8 shows the variation of ε' with frequency. It is maximum at high temperature and low frequency of 0.001 Hz. It means that the energy storage capability increases at high temperature. Also, the DC conductivity $\sigma_{d.c}$ increased by increasing the insulation temperature. The values of dielectric loss **tan δ** at 40°C are less than the values at 20°C for a frequency range from 50 to 1000 Hz. But at frequencies less than 50 Hz, the values of dielectric loss **tan δ** at 40°C are greater than the values at 20°C. Therefore any variation in temperature will result in variation in dielectric properties measurements. This variation is due to the effect of temperature upon the polarization mechanisms. Electronic polarization is relatively unaffected by temperature. However, atomic polarization is effected since the binding forces between ions or atoms changes with temperature. The ability of a dipole to rotate in an applied field is also temperature dependent and so orientation polarization will be effected. Finally, since charge mobility is temperature dependent, the interfacial mechanism will also be temperature dependent.

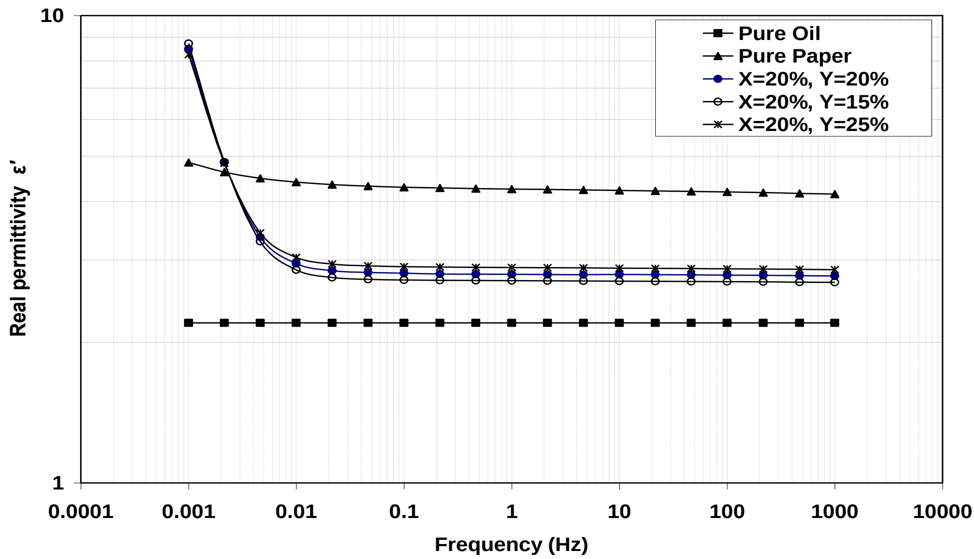

Fig. 5: Influence of transformer insulation geometry arrangement on frequency domain measurements of real permittivity $\varepsilon'(\omega)$.

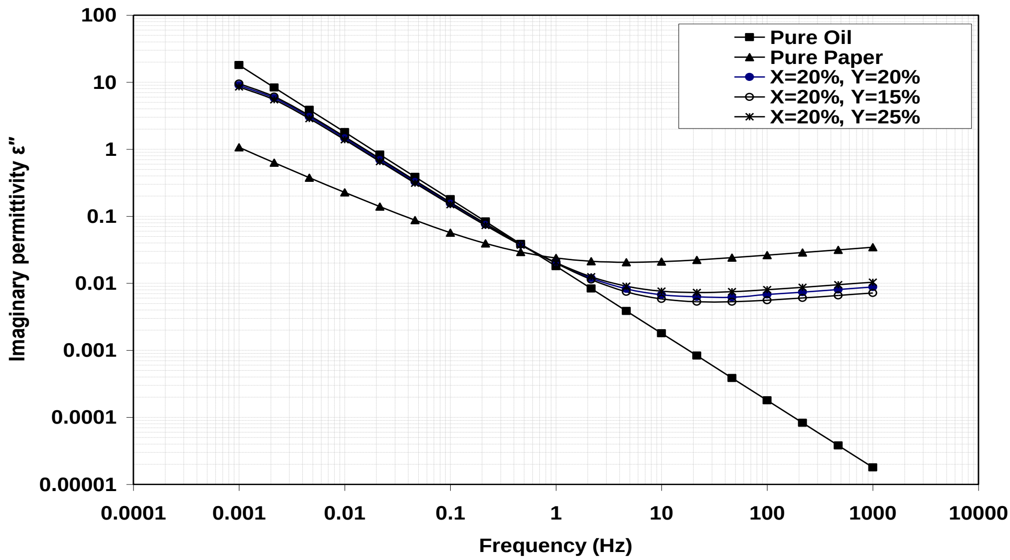

Fig. 6: Influence of transformer insulation geometry arrangement on frequency domain measurements of imaginary permittivity $\varepsilon''(\omega)$.

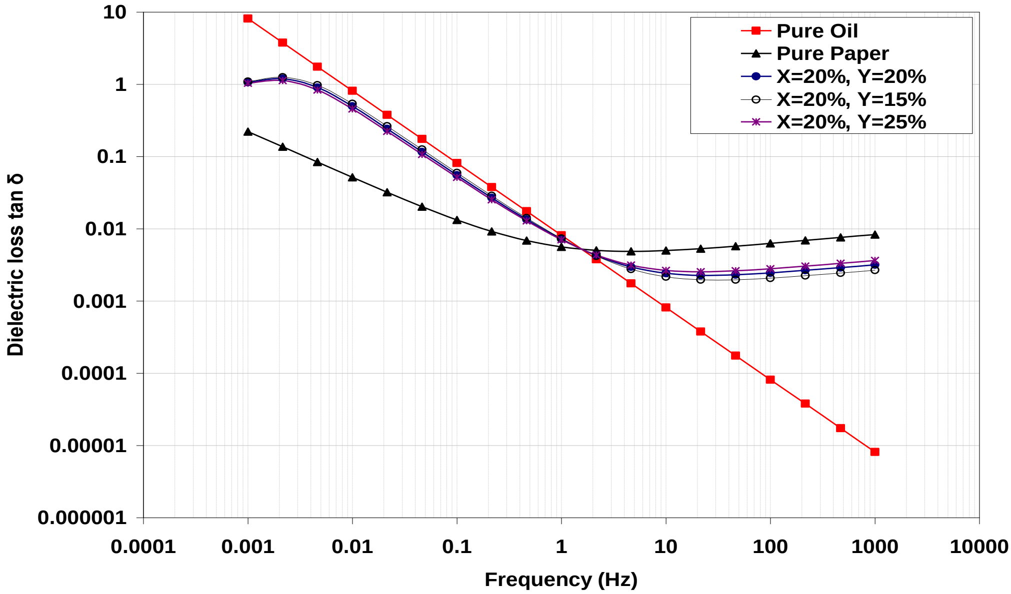

Fig. 7: Influence of transformer insulation geometry arrangement on frequency domain measurements of dielectric loss $\mathbf{tan\delta(\omega)}$.

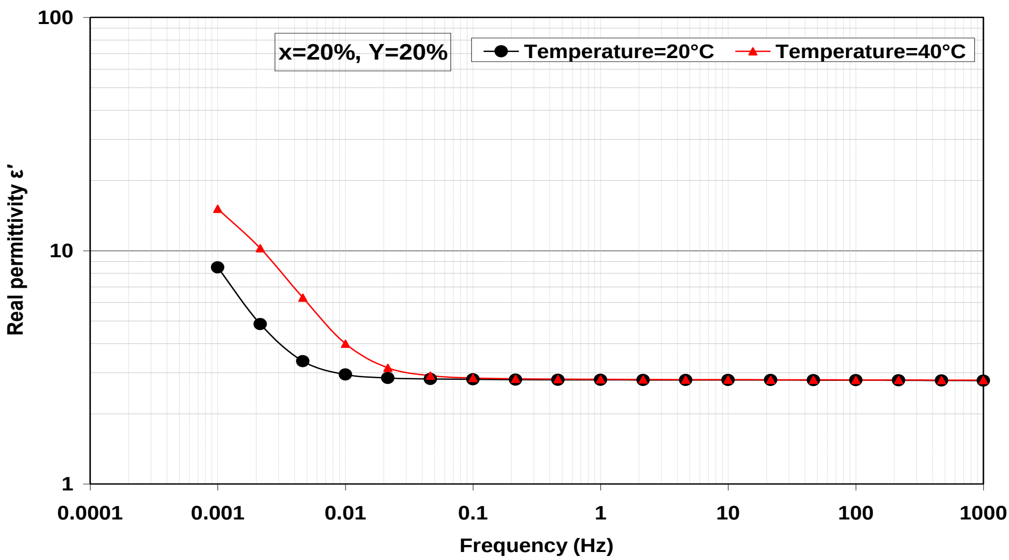

Fig. 8: Influence of transformer insulation temperature on frequency domain measurements of real permittivity $\boldsymbol{\varepsilon'(\omega)}$.

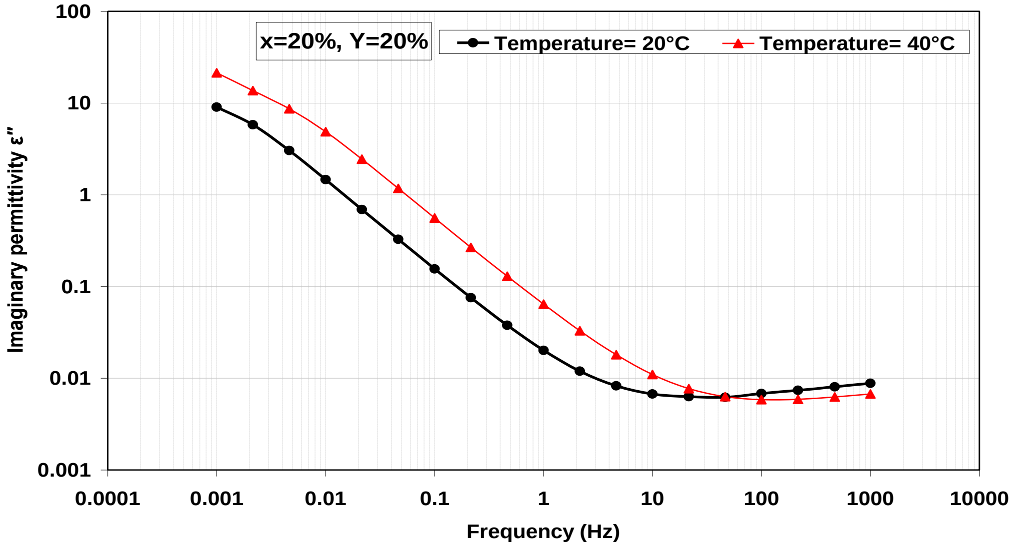

Fig. 9: Influence of transformer insulation temperature on frequency domain measurements of imaginary permittivity $\varepsilon''(\omega)$.

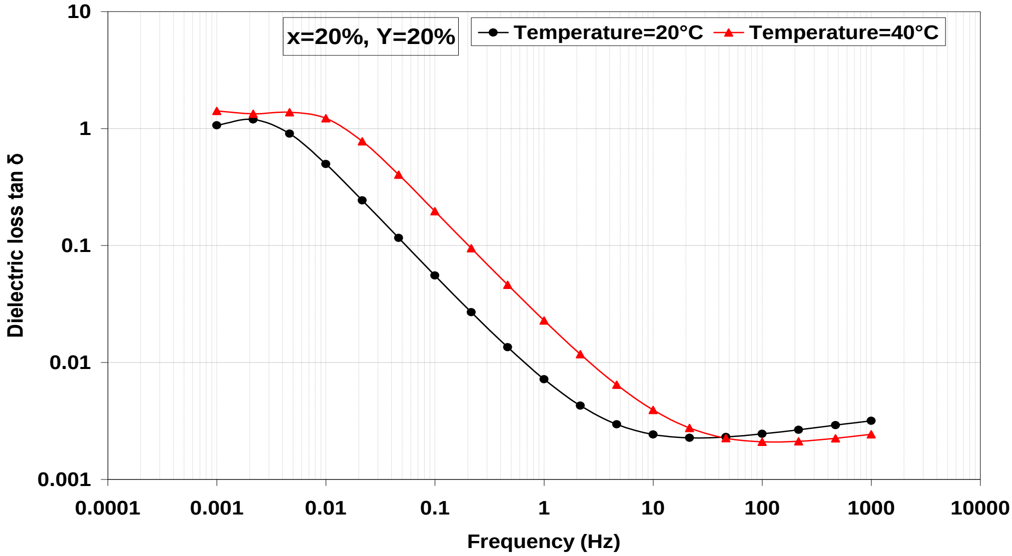

Fig. 10: Influence of transformer insulation temperature on frequency domain measurements of dielectric loss $\tan\delta(\omega)$.

4. CONCLUSIONS

Investigation of the frequency domain spectroscopy FDS diagnostic method under the influence of insulation geometry and insulation temperature was performed using modelling of dielectric program MODS. The effect of geometry was studied by modelling of insulation system with different percentage ratios between the liquid insulation (oil) and the solid insulation (paper). We found that the values of ε', ε'' and $\tan\delta$ are dependent on the geometrical arrangement of transformer insulation system. Also the effect of temperature on measurements of insulation system properties ε', ε'' and $\tan\delta$ was studied at different temperature. The values of real permittivity ε' increased obviously due to the increase in temperature at frequencies below 0.1 Hz but above 0.1 Hz the increase of ε' is insensible. At 40°C the values of imaginary permittivity ε'' and dielectric loss $\tan\delta(\omega)$ are less than their values at 20°C for the frequencies from 50 to 1000 Hz. At 40°C the values of imaginary permittivity ε'' and dielectric loss $\tan\delta(\omega)$ are greater than their values at 20°C for the frequencies less than 50 Hz. Therefore, when the frequency domain spectroscopy measurements (FDS) are applied to investigate the insulation conditions, we should put into consideration, the temperature must be constant during the measurement. And when the measurements repeated as a scheduled maintenance program, the temperature must be the same as in all measurements. Also, these measurements can not be used to compare the insulation quality of various transformers having different design of insulation arrangement, where the values ε', ε'' and $\tan\delta(\omega)$ depend on the percentage ratio of oil and paper of composite insulation system.

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تأثير الشكل الهندسي لعازل المحول الكهربي ودرجة حرارته علي قياسات استجابة العزل

يناقش هذا البحث كيفية تمثيل قياسات استجابة العزل لمحولات القدرة لتقييم حالتها، حيث يتكون العزل في هذه المحولات من المادة الصلبة السليولوز (ورق العزل) والمادة السائلة (الزيت)، كلا المادتين تتغير خواص العزل لديها علي امتداد عمر المحول، من هنا يتضح مدي أهمية أجراء قياسات للعزل لتقييم مدي كفاءته. حديثاً تم تطبيق طريقة جديدة للقياس تسمي قياس استجابة العزل عند الترددات المختلفة. في هذا البحث تم دراسة مدي تأثير الشكل الهندسي للعزل وأيضاً درجة الحرارة له علي قياس استجابة العزل عند الترددات المختلفة. وقد تم عمل تمثيل لأشكال هندسية مختلفة للعزل بواسطة استخدام برنامج تمثيل استجابة العزل من إصدار شركة جنرال اليكتريك وذلك عن طريق تغيير النسبة المئوية للزيت والورق في نظام العزل للمحول.