U.P.B. Sci. Bull., Series A, Vol. 73, Iss. 3, 2011 ISSN 1223-7027

ANALYSIS OF INSULATION SYSTEM OF POWER TRANSFORMERS BY POLARIZATION/DEPOLARIZATION CURRENTS METHOD

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Este propus un circuit echivalent simplificat pentru izolația transformatoarelor de putere şi ecuațiile corespunzătoare utilizând metoda de polarizare / depolarizare. Pe această bază au fost studiate două transformatoare de putere. Au fost obținuți parametrii fizici ai transformatoarelor şi conținutul de umiditate. Concordanța curbele teoretice cu datele experimentale a fost foarte bună. Rezistența uleiului obținută a fost de aproximativ trei ordine de mărime mai mică decât cea a hârtiei. Aceasta a fost atribuită creşterii concentrației de ioni de cupru în ulei.

A simplified equivalent circuit for the insulation of power transformers was proposed and the corresponding equations for using the polarization/depolarization method to investigate this insulation were found. On this basis, two power transformers were studied. The physical parameters of the transformers and the moisture content were found. The agreement between the theoretical curves and the experimental data was very good. The oil resistance was found to be about three orders of magnitude smaller than that of the paper. This was attributed to the increase of the copper ion concentration in oil.

Keywords: PDC, insulation, moisture, ionic conduction.

1. Introduction

It is well known that the power transformers are a key part of any transmission and distribution electrical network. Their functioning is conditioned by the state of the insulation system [1, 2]. Therefore, it is of maximum importance to be able to evaluate this state, in order to perform the appropriate maintenance operations at the proper moments. The main trouble that arises during the functioning of a transformer is due to the humidity. The penetration of water or water vapors in the paper-oil insulation results in its ageing, increasing the leakages and reducing the breakdown voltage. More than that, abrupt variations of the temperature may lead to bubbles formations, causing internal discharges and therefore local

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breakdowns. This is why it is so important to be able to evaluate the moisture level by non-destructive methods.

Several methods were proposed for the investigation of the insulation quality. Obviously, the preferred ones are the non-destructive methods. Among these, one can mention the frequency response analysis (FRA) [3 ÷ 5], the return voltage measurements (RVM) [6 ÷ 8] and polarization-depolarization current (PDC) investigation [4, 8 ÷ 14]. While FRA works mainly in a.c. regime and strongly depends on the frequency (generally higher than the industrial one), RVM and PDC work in d.c. transient regime, closer to the real situation. This is why most researchers prefer to use PDC.

The present paper proposes a model for the analysis of insulation system of power transformers by using the PDC method. The idea is to model the transformer insulation by an equivalent circuit, complex enough to properly describe the studied system, and simple enough to allow real-time computations during the measurements. Section 2 presents this model. Section 3 discusses the results. The last Section summarizes the conclusions.

2. Theoretical model

Usually, a dielectric placed between the plates of a capacitor behaves like a capacitor C_∞ connected in parallel with a resistor R_0. The capacitance $C_\infty = \varepsilon_\infty C_0$, where C_0 is the "*geometrical*" capacitance, represents the dielectric behavior in the high frequency (HF) limit, while R_0 represents the d.c. losses. However, at intermediate frequencies, this description is no longer accurate.

There are two ways to improve it. The first is to consider both the capacitor permittivity and the resistor conductivity (i.e. both the real and imaginary parts of the dielectric constant) as functions of the frequency. This allows taking into account the microscopic behavior of the different parts of the dielectric [15]. This method is convenient for laboratory measurements, where the geometrical part is well described. That is not the case with the non-destructive investigation of a power transformer.

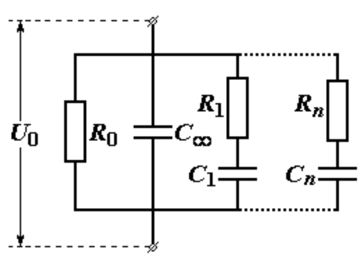

Fig. 1. Equivalent circuit for a real dielectric (according to [16])

The second method is to consider a number of series-coupled resistor - capacitor pairs, connected in parallel with R_0 and C_∞ (see Fig. 1). Each pair stands for a relaxation mechanism [16]. Therefore, this method is better to be applied for d.c. transient regime, using the Laplace transform method (see Fig. 2).

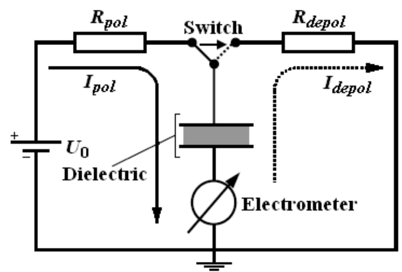

Fig. 2. PDC measurement set-up (according to [16])

A power transformer with paper-oil insulation also has some spacers to separate the sheets of paper for better access of the oil. Therefore, the equivalent scheme consists of two blocks like the one in Fig. 1, one for oil and one for the spacers, connected in parallel, with the set connected in series with a third block for the paper. Nevertheless, the study of paper and oil obtained from dismantled old transformers proved that the paper moisture can be expressed in percents, while the oil moisture is to be expressed in *ppm*. Therefore one generally agrees that the oil block can be simplified by eliminating the relaxation mechanisms and by using a simpler scheme (see Fig. 3) [16]. Even that scheme can be simplified further if one observes that one can replace the resistors and capacitors connected in parallel with their equivalents, $R_e = R_{oil}R_s/(R_{oil} + R_s)$ and $C_e = C_{oil} + C_s$, respectively. This means two blocks connected in series.

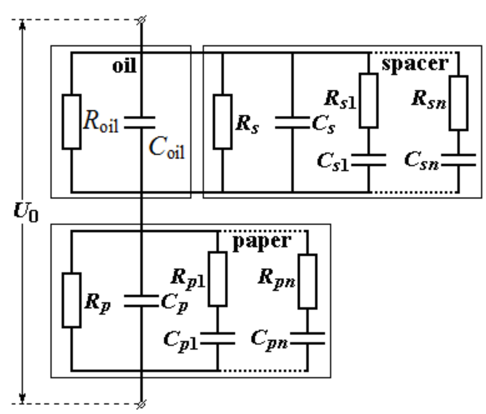

Fig. 3. Equivalent scheme for the paper-oil insulation (according to [14])

However, even such a scheme is too intricate. To begin with, the existence of several relaxation mechanisms leads to expressions that cannot be manipulated by the usual PC mathematical software for symbolic Laplace transform. True, one could use a more powerful computer to perform the transform, but then one has other problems. Most important, the number of fit parameters becomes smaller than the number of physical parameters, so that one cannot solve the problem anymore.

If one takes into account that the spacers' contributions are quite small compared with the oil one, one can neglect the spacer block. As the main relaxation mechanism for the paper is induced by the moisture, one reaches the simplest possible scheme keeping the full physical significance, as presented in Fig. 4.

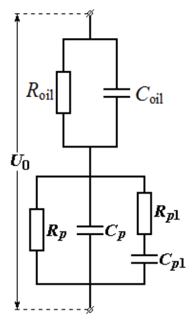

Fig. 4. Equivalent scheme for the paper-oil insulation, as proposed in the present paper

The Laplace transform of the admittance for the simplified circuit from Fig. 4 is

$$Y = \frac{1 + as + bs^2 + cs^3}{\alpha + \beta s + \gamma s^2} \tag{1}$$

where:

$$a = R_{oil}C_{oil} + R_pC_p + R_{p1}C_{p1} + R_pC_{p1} \tag{2a}$$

$$b = R_pC_p\left(R_{oil}C_{oil} + R_{p1}C_{p1}\right) + R_{oil}C_{oil}\left(R_{p1}C_{p1} + R_pC_{p1}\right) \tag{2b}$$

$$c = R_{oil}R_pR_{p1}C_{oil}C_pC_{p1} \tag{2c}$$

$$\alpha = R_{oil} + R_p \tag{2d}$$

$$\beta = R_{oil}R_p\left(C_{oil} + C_p + C_{p1}\right) + \left(R_{oil} + R_p\right)R_{p1}C_{p1} \tag{2e}$$

$$\gamma = R_{oil}R_pR_{p1}C_{p1}\left(C_{oil} + C_p\right) \tag{2f}$$

By performing the inverse Laplace transform for *Y*/*s*, we obtain the polarization current (in the limit $R_{pol} = 0$):

$$I_{pol} = I_0 + I_+ \exp\left(-\frac{t}{\tau_+}\right) + I_- \exp\left(-\frac{t}{\tau_-}\right) \tag{3}$$

where:

$$I_0 = \frac{U_0}{\alpha} \tag{4a}$$

$$I_+ = \frac{I_0}{\gamma^2}\frac{\tau_+\tau_-}{\tau_+ - \tau_-}\left[\left(\beta\gamma - a\alpha\gamma + c\alpha^2\right) - \left(\gamma^2 - b\alpha\gamma + c\alpha\beta\right)\tau_+^{-1}\right] \tag{4b}$$

$$I_- = \frac{I_0}{\gamma^2}\frac{\tau_+\tau_-}{\tau_+ - \tau_-}\left[\left(\gamma^2 - b\alpha\gamma + c\alpha\beta\right)\tau_-^{-1} - \left(\beta\gamma - a\alpha\gamma + c\alpha^2\right)\right] \tag{4c}$$

$$\tau_+ = \frac{2\gamma}{\beta - \sqrt{\beta^2 - 4\alpha\gamma}} \tag{4d}$$

$$\tau_- = \frac{2\gamma}{\beta + \sqrt{\beta^2 - 4\alpha\gamma}} \tag{4e}$$

When the system reaches the steady state, $I_{pol,\infty} = U_0 / \alpha$, the three capacitors are charged with $q_{oil} = I_{pol,\infty} R_{oil} C_{oil}$, $q_p = I_{pol,\infty} R_p C_p$, and $q_1 = I_{pol,\infty} R_p C_{p1}$, respectively. Starting from these values, a similar analysis can be made for the depolarization current.

One can see that, even for this simplified circuit, we have a problem. We have six physical parameters (R_{oil}, R_p, R_{p1}, C_{oil}, C_p, and C_{p1}), but only five fit parameters (I_0, I_+, I_-, τ_+, and τ_-). To solve the problem, we need supplementary information. The simplest way to obtain it in a non-destructive manner is to take out of the transformer a little oil, to measure its relative permittivity and conductivity, and to put it back. Then, using these data, we obtain the relaxation time of oil:

$$\tau_{oil} = \varepsilon_0 \frac{\varepsilon_{oil}}{\sigma_{oil}} \tag{5}$$

where ε_0 is the permittivity of vacuum, we can find all parameters by fitting the experimental data.

3. Application

We have analyzed two power transformers of 200/200/60 MVA, 231/121/10.5 kV (hereafter quoted as T_1 and T_2), from, by using the PDC method as described in the previous Section. The polarization and depolarization currents were measured using a NOVA PDC-01 [17].

The experimental data for the investigated transformers are listed in Table 1.

Table 1

Experimental data for the investigated transformers

Transformer	T1	T2
U_0 = applied d.c. bias (V)	2011	2029
T = measured temperature (^{o}C)	31	29
$\varepsilon_{r_{oil}}$ = oil relative permittivity	2.2	2.2
σ_{oil} = oil conductivity at 20 ^{o}C (S/m)	4.51×10^{-13}	3.2×10^{-13}
σ_{oil1} = oil conductivity at 90 ^{o}C (S/m)	7.41×10^{-12}	5.26×10^{-12}

The measured currents are presented in Fig. 5.

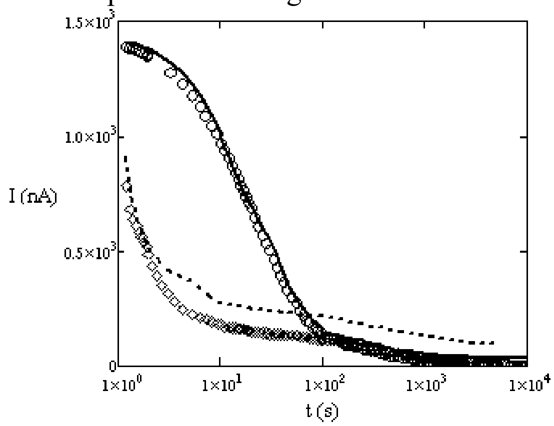

Fig. 5. Measured polarization and depolarization currents for the two transformers (—: I_{pol}, T1; - -: I_{pol}, T2; ○: I_{depol}, T1; ◇: I_{depol}, T2)

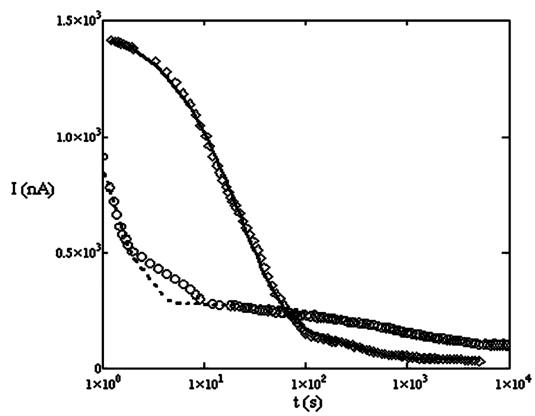

Fig. 6. Experimental values (◇: I_{pol}, T1; ○: I_{pol}, T2) and theoretical fit (—: I_{pol}, T1; - -: I_{pol}, T2) of the polarization currents for the two transformers

The oil conductivity has a temperature dependence described by the equation [18]:

$$\sigma_{oil}(T) = A\, exp\left(-\frac{E_a}{k_B T}\right) \tag{6}$$

where A is a proportionality constant related to the ion mobility in oil and E_a is the activation energy for the ion diffusion process. Using the data from Table 1, one obtains $E_a = 0.2164\,\text{eV}$ for both transformers. By means of Eq. (6), we are able to estimate the oil conductivity, and therefore to compute τ_{oil}, at any temperature.

Table 2

Fit parameters for the polarization currents

Transformer	T1	T2
I_0 (nA)	44.346	119.478
I_+ (nA)	2.824×10^4	1.647×10^3
I_- (nA)	4.134×10^4	7.204×10^4
τ_+ (s)	22.283	0.937
τ_- (s)	242.621	449.007

We have fitted the experimental polarization currents using Eq. (3). The results are presented in Fig. 6. The fit parameters are listed in Table 2. The linear correlation coefficient is higher than about > 0.999, confirming the accuracy of the model.

By using the relations (2a) – (2f), (4a) – (4e), and (5), we are able to compute the physical parameters of the two transformers. The results are listed in Table 3. The oil relaxation time τ_{oil} was computed by means of Eqs. (5), (6) at the temperatures the PDC measurements were performed for each transformer.

Table 3

Physical parameters of the investigated transformers

Transformer	T1	T2
τ_{oil} (s)	31.72	47.21
τ_p (s)	2191×10^3	285.8×10^3
τ_1 (s)	147.3	94.78
τ_2 (s)	240.1×10^3	350.2×10^3
R_{oil} (MΩ)	18.31	24.47
R_p (MΩ)	45.30×10^3	16.96×10^3
R_1 (MΩ)	27.79	4.590
C_{oil} (μF)	1.732	1.945
C_p (μF)	48.37	16.85
C_1 (μF)	5.301	20.65

To find out the moisture contents, one considers a linear dependence of the material resistivity on the water concentration [10]:

$$\sigma_i = \frac{\sigma_i \sigma_w}{\sigma_i x_w + \sigma_w (1 - x_w)}, \quad i = oil, p \tag{7a}$$

where x_w is the water concentration. A similar relation may be found for permittivity:

$$\varepsilon_{r_i} = \frac{\varepsilon_i \varepsilon_{r_w}}{\varepsilon_i x_w + \varepsilon_{r_w} (1 - x_w)}, \quad i = oil, p \tag{7b}$$

By applying these relations, one finds that, at 20 ^{o}C, the paper moisture is 1.99% for T1 and 2.97% for T2, while the oil moisture is 2.43 ppm for T1 and 5.01 ppm for T2. These results are in excellent agreement with the initial assumption that we can neglect the water relaxation processes in oil.

It is surprising that the oil resistence is about three orders of magnitude smaller than that of the paper, in spite of the paper moisture. The reason seems to be related to the ionic conduction in oil. We expect that the ageing of the transformers, as well as the moisture, strongly increase the copper ions content of the oil and therefore its conductivity. This supposition is in agreement with the small value of the activation energy found before. The ion mobility in paper is obviously far smaller than in oil, so that they do not significantly affect the paper conductivity.

4. Conclusions

We have discussed the PDC method and found out a simplified equivalent circuit and the corresponding equations to describe the insulation of power transformers. By using this method, we have analyzed two power transformers. We have obtained the physical parameters of the transformers and the moisture content, which is of the order of 2 %÷ 3 % for paper and 2.5 ppm ÷ 5 ppm for oil. The linear correlation coefficient between the experimental data and the theoretical curves is of the order of 0.999 or greater, proving the accuracy of the model. The oil resistance is about three orders of magnitude smaller than that of the paper, seemingly due to the increased content of copper ions with respect to the new transformers. Their activation energy was estimated to be $E_a = 0.2164$ eV, justifying the above supposition.

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