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Analysis transformer insulation by PDC method

***Abstract**. Paragraph is about mathematical interpretation of transformer insulation system. Base of this system is composed by two elements oil and paper. We need to simulate this system for more precisely results from measurement. Section three describes how to calculate relaxation currents and how that currents are generated. So we are able to compare measured and computed values and deduce actual condition of this insulation system.*

Streszczenie.** W artykule przedstawiono matematyczną interpretację izolacji papierowo-olejowej transformatora. W sekcji trzeciej opisano sposób obliczania prądu rozładowującego i sposób jego generacji co pozwala na porównanie wartości pomierzonej i obliczonej i określenie stanu izolacji. **(Analiza izolacji transformatora metodą PDC).

Keywords: Insulation, oil, paper, winding, transformer, polarization, depolarization, diagnostics.
Słowa kluczowe: izolacja, olej, papier, uzwojenie, transformator, polaryzacja, depolaryzacja, diagnostyka

Introduction

The diagnostic of the transformers is important part of its operation. We need to know how system (transformer - insulation) works for running of the diagnostic system in ideal conditions. This is way to enable us to mathematic calculation for individual parameters. Mathematical calculation is relatively difficult in system like transformer. We only attend to a small part of mathematical simulation of this system for this reason. We angle for simulation of the polarization depolarization current method. In this method we analyze generation of this currents and we shows from what the currents are made. [1]

Theory bases

In last few years several diagnostic techniques have been developed and used to determine the power transformer insulation. That means this techniques must determine insulator composed from transformer oil and paper in main. Named techniques are DGA (Dissolved Gas Analysis), DP (degree of polymerization) and Furan analysis by HPLC (High Performance Liquid Chromatography). In nowadays is possible to capture very low current involved in dielectric relaxation process. This is door open to technique like RVM (Return Voltage Measurement) or PDC (Polarization Depolarization Current). Those techniques have been introduced in 90's. This measurements technique has gained popularity for its ability to assess the condition of oil and paper separately without opening the transformer tank. [2]

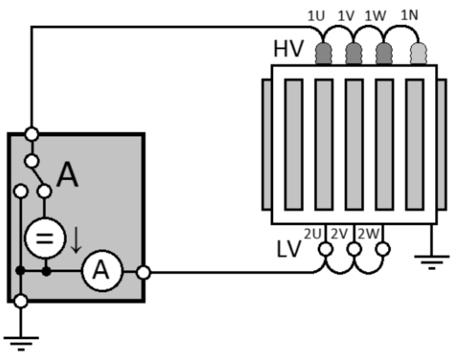

Fig.1. Simply PDC measurement system

For PDC analysis is DC voltage step (amplitude U_0) of some 100V is applied between HW (high voltage) and LV (low voltage) windings during a certain time t_p, the so-called polarization duration. Thus a charging current of the transformer capacitance, i.e. insulation system, the so-called polarization current, flows. It is a pulse-like current during the instant of voltage application which decreases during the polarization duration to a certain value given by the conductivity of the insulation system. After elapsing the polarization duration t_p, the switch A goes into the other position and the dielectric is short circuited via the ammeter. Thus, a discharging current jumps to a negative value, which goes gradually towards zero. Both kinds of currents ("relaxation currents") are displayed. This simple measurement system is shown in Fig.1 [3]. Next picture (Fig.2) shows polarization current and its response in this measurement system.

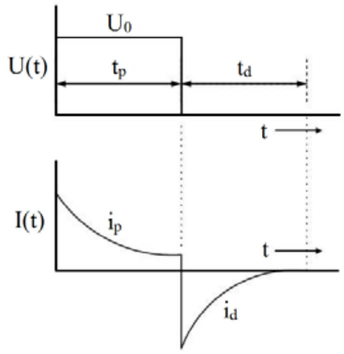

Fig.2. Principle waveform of relaxation currents [4]

Mathematical interpretation of polarization process in dielectric material

When a dielectric material is polarized with an electric field $E(t)$, the current density of dielectric is the sum of the conduction current and displacement current density, which can be expressed as following:

$$J(t) = \sigma \cdot E(t) + \frac{dD}{dt} \tag{1}$$

Here, $J(t)$ is the total current density, σ is DC (direct current) conductivity, $D(t)$ is electric density flux, which has the following relationship with polarization and vector of the electric field:

$$D(t) = \varepsilon_0 \cdot E(t) + P(t) \tag{2}$$

where ε_0 is permittivity of vacuum.

While the observed polarization, $P(t)$, contain two element parts:

$$P(t) = P_{\mathrm{rapid}}(t) + P_{\mathrm{slow}}(t) \tag{3}$$

where $P_{\mathrm{slow}}(t)$ is slow polarization, $P_{\mathrm{rapid}}(t)$ represents instantaneous polarization processes in the material, which can follow the changes of electric field, so $P_{\mathrm{rapid}}(t)$ can be expressed as:

$$P_{\mathrm{rapid}}(t) = \varepsilon_0 (\varepsilon_{\mathrm{r}} - 1) \cdot E(t) \tag{4}$$

where ε_{r} is high frequency relative permittivity of the material. In general, a material cannot polarize instantaneously in response to an applied field. Therefore, the slow polarization process is delayed response polarization due to dipolar and interfacial polarization processes. The polarization is a convolution of the electric field $E(t)$ with time-dependent dielectric response function $f(t)$.

For any arbitrary electric field $E(t)$, the show polarization processes can be given as:

(5) $$P_{\text{slow}}(t) = \varepsilon_0 \cdot \int_0^t f(t-\tau) \cdot E(\tau) d\tau$$

where $f(t-\tau)$ represents the degree of delay.

Therefore, the observed polarization can be rewritten as:

(6) $$P(t) = \varepsilon_0 \cdot (\varepsilon_r - 1) \cdot E(t) + \varepsilon_0 \cdot \int_0^{-\infty} f(t-\tau) \cdot E(\tau) d\tau$$

By combining (1), (2) and (6), the total current density $J(t)$ due to a constant electric field can be written as follows:

(7) $$j(t) = \sigma \cdot E(t) + \varepsilon_0 \cdot \varepsilon_r \cdot \frac{dE(t)}{d\tau} + \varepsilon_0 \cdot \frac{d}{dt}\left\{\int_0^t f(t-\tau) \cdot E(\tau) d\tau\right\}$$

Moreover, according to (7), we can find that the behavior of the dielectric material is characterized by conductivity σ, high frequency dielectric permittivity ε_r and the dielectric response function $f(t)$ in the time domain. Three characteristic quantities provide important information of insulating material. [5]

Shape of polarization curve and simulation

In (Fig.2.) we can see the polarization (charging) current. This current can be expressed as:

(8) $$i_{\text{pol}}(t) = C_0 \cdot U_0 \cdot \left[\frac{\sigma_r}{\varepsilon_0} + f(t)\right]$$

where C_0 is the geometric capacitance, σ_r is the average conductivity of the composite insulation system, ε_0 is the vacuum permittivity and $f(t)$ is the dielectric response function of the composite insulation, U_0 is the applied charging voltage.

It can also be shown that the depolarization current can be expressed as:

(9) $$i_{\text{depol}}(t) = C_0 \cdot U_0 \cdot [f(t) + f(t + t_c)]$$

where t_c is the time during which the voltage was applied to the insulation. We are able to dismantle real shape of dielectric response curve to base equations. These equations can be calculated by simulating program. [5]

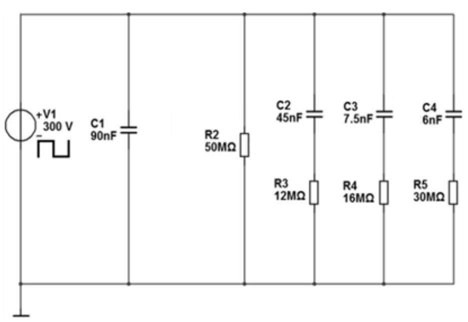

Fig.3. Principle circuit for simulating relaxation currents

For the best result in simulation we use extended Debye model for calculating the current. Because of many factors affect the polarization process of oil-paper insulation, such as aging, moisture and temperature of insulation, which can cause a series of different relaxation time constant. So single RC circuit (Fig.3.) cannot follow measured dielectric response exactly. Thus, it is difficult to reflect the complex polarization by the equivalent circuit with single Debye relaxation time. This is the reason why we need extended model. But for simplicity of calculation we use model with three relaxation elements.

We picked-up current through this circuit and then we obtain curves which are shown in Fig.4. Values of parameters used in simulation are measured from tested object (transformer TESLA 230V~24V; 16,8VA; 50Hz - Fig.4.).

This transformer is old transformer in a good condition. Transformer was selected as a sample for value of a direct current. Measured value of direct current is bigger because the old insulation had lower insulation resistance. For this case the measured curve is better for analyzing. Measured parameters are in Table 1.

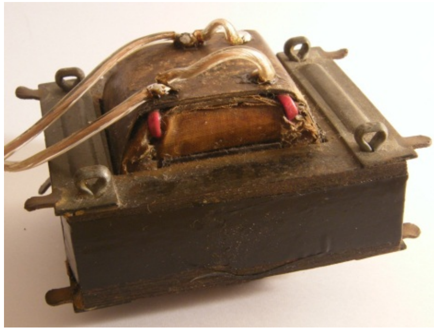

Fig.4. Measured transformer TESLA 230V~24V

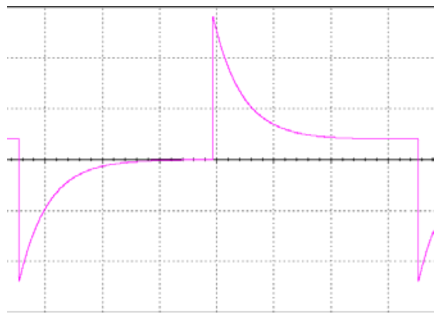

Fig.5. Simulation of PDC with extended Debye model.

Table 1. Measured parameters of transformer

	R_i [MΩ]	C_i [nF]	R [MΩ]	C_{50} [nF]
1	12	45	50	90
2	16	7,5		
3	30	6		

These values are substituted in equations and draw a curve consequently.

The result of simulation of polarization and depolarization current with extended Debye model is shown in Fig.5. Fig.5 shows the charge and the discharge currents obtained on transformer using parameters of Table 1. Calculated value of maximal voltage of simulated curve is ±4,287 V. The calculated value of direct current was 0,433 V. Now we had dielectric model for a real transformer. In the next we need to measure real curve from the simulated transformer.

Experimental measurement

For PDC measurement a step-like dc charging voltage of magnitude Uc is applied to the test object. Dielectric memory of the test object must be cleared before PDC measurement. Charging voltage should be free of any ripple and noise, in order to measure the small polarization current. Then a polarization current $i_{\text{pol}}(t)$ through the test object can be recorded. The charging process takes a long time until the polarization current becomes either stable or very low. Immediately following the polarization, the depolarization current $i_{\text{dpol}}(t)$ can be measured by subsequent short circuiting of the test object.

The setup is equipped with high voltage source and picoampermeter, which is composed by oscilloscope and shunt resistor which was sensed by a personal computer. All measurements were carried out at 300V after lacquer-paper moisture equilibrium was achieved. Before the test began, the specimen remained in short circuit case until very low-level detectable current was achieved in order, to ensure similar condition for the measurements. Principle scheme of measuring device is showed on Fig.6.

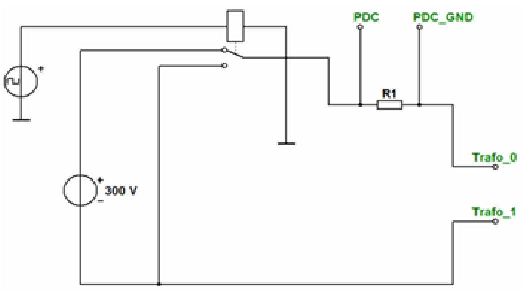

Fig.6. Principle circuit for measuring relaxation currents

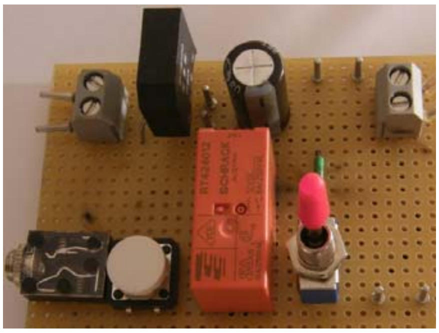

Fig.7. Principle circuit for measuring relaxation currents

For measurement purpose the switch is switched like on Fig.6, so that the polarization current flows in insulation specimen and decreases to zero during application of voltage. For the investigated samples the current decreases from some mili ampere to some micro ampere. After polarization duration, which takes for example l000s, switch was flipped and the specimen is short circuited. Similar to polarization duration, depolarization current in this stage flows, but in another direction. Both currents are stored for analysis in computerized measuring system.

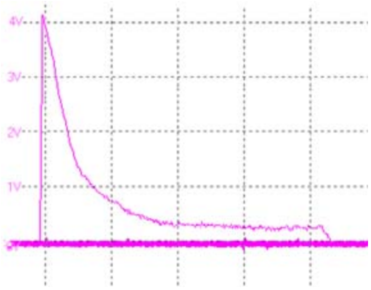

Fig.8. Measured curve of polarization current

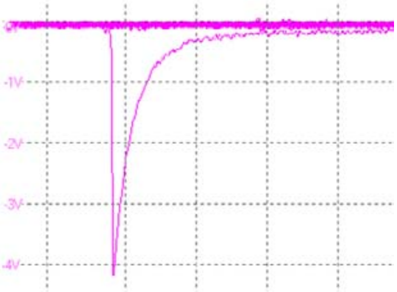

Fig.9. Measured curve of depolarization current

Connection of simple measurement circuit is showed on Fig.7. When the circuit is connected to the PC and to the measured specimen, we obtain time response of polarization and depolarization current (Fig.8, 9). Then we are able to compare measured and simulated value of polarization (depolarization) current.

When we connect specimen to polarization voltage *U*=300V we measured maximal voltage on shunt resistor. This voltage was 4,158V at maximum. It corresponds to 4 mA at maximum peak value. The direct current is corresponding to a 468μA in stable state. Shape of curve of polarization current is showed on Fig.8.

Now polarization voltage is disconnected and measured transformer is connected to ground, depolarization current flows through the circuit. Measured voltage on sample was -4,202V at maximum peak. . It corresponds to 4 mA at maximum peak value. Shape of curve of polarization current is showed on Fig.9.

Conclusion

Depolarization current analysis shows important information about insulation which is moisture content or ageing status of transformer.

Difference between measured and calculated values was 0,085V which correspond to a 0,5% of a maximum peak value of a measured current. Direct current difference of a polarization process was 7% of stabilized curve. That means the lacquer and paper conductivity must be corrected for further calculation.

PDC measurement is important and exact method for diagnostic the state of transformer insulation. This method could be used in small transformer or in distribution transformer with oil-paper insulation.

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