

## Diagnostics of transformer with insulation oil-paper

**Streszczenie.** Artykuł omawia metody opisujące stan izolacji transformatorów. Przez określenie jej stanu jest poznanie pomiarów napięcia powrotnego oraz pomiarów rezystancji izolacji uzwojeń. Metoda pomiaru napięcia powrotnego jest metodą szeroko opisującą stan, która nie jest objęta normami ale w wielu przypadkach umożliwia uzyskanie jasnych i dokładnych wyników. Wyniki przede wszystkim pokazują zawartość wilgoci, zawartość przewodzących zanieczyszczeń w oleju oraz wpływ stopnia starzenia na papier izolacyjny. (**Diagnostyka transformatorów z izolacją papierowo-olejową**).

**Abstract.** The article deals with method describing the state of transformer insulation. By the determining its state is acquainted return voltage measurement and measurement the insulation resistance of windings. Return measurement voltage method is wide state specifying method which is not set in standards but in many cases is a method which is determining a clear and exact result. The results have mainly shows moisture content, content of conductive impurities in oil and degree of aging of paper insulation impact.

**Słowa kluczowe:** napięcie powrotne, rezystancja izolacji, wskaźnik polaryzacji, transformator.

**Keywords:** return voltage, insulation resistance, polarization index, transformer.

### Introduction

Influence of operating conditions leads to aging of individual parts of transformer, and also to changes of the major electrical and mechanical properties. To the check of the condition greatly contributes electro-technical diagnosis, whose main task is to find a clear relation between the change in functional characteristics of the machine and some measurable values. The assessment of these measured values must be visible not only the rate of change, but also whether it is a permanent or reversible state. The aim of diagnostics of transformers is to verify that the machine complies with the determined conditions in accordance with standards [1].

Economically reliable and effective power delivery always is the primary concern to utilities all over the world. Insulation diagnostics is one of the requirements for safe operation of transformers. Conventional methods to assessment of insulation condition are its loss factor, insulation resistance and partial discharge measurement, etc. These methods, however, provide only partial picture about the polarization processes in insulating material [2].

Deregulation of power market has increased the competition and also emphasized on the search for the new, efficient and effective methods for diagnosing the insulating system. The use of the return voltage method is significant way to detect ageing of the insulation of operating power transformer in a non-destructive manner [3].

### Theory fundamentals of PDC and RVM method

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 [4].

For PDC analysis is DC voltage step (amplitude  $U_0$ ) of some 100 V 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.2 [5].

Next picture (Fig.3) shows polarization current and its response in this measurement system [6].

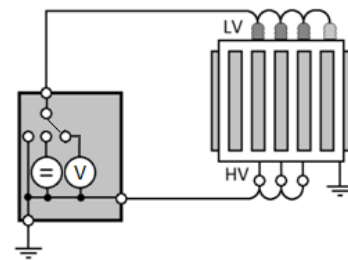


Fig.2. Simply RVM measurement system [5]

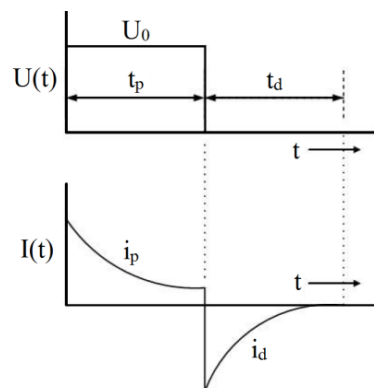


Fig.3. Principle waveform of the relaxation currents [6]

## Mathematical interpretation of the polarization process in dielectric material

When a direct voltage is applied to a dielectric for a long period of time, and is then short circuited for a short period, after opening the short circuit, the charge bounded by the polarization will turn into free charges i.e., a voltage will build up between the electrodes on the dielectric. This phenomenon is called the return voltage. Now, the process of polarization and the equations to describe this process will be described in [7, 8].

When a dielectric material is charged with an electric field the material become polarized. The total current density is the summation of the displacement current density and the conduction current density, which is given by

$$(1) \quad j(t) = \sigma E(t) + \frac{dD}{dt},$$

where  $\sigma$  is the direct conductivity, and is the electric displacement given by (2).

$$(2) \quad D(t) = \varepsilon E(t) + \Delta P(t) = \varepsilon_0 \varepsilon_r E(t) + \Delta P(t),$$

where  $\varepsilon_0$  is the vacuum permittivity, and  $\varepsilon_r$  is the relative permittivity at power frequency. The  $\Delta P(t)$  term is related to the response function  $f(t)$  by the convolution integral shown in (3).

$$(3) \quad \Delta P(t) = \varepsilon_0 \int_0^t f(t-\tau) E(\tau) d\tau.$$

If we expose the insulation to a step voltage at time  $t = 0$  the charging current density is given by

$$(4) \quad j_p = E(\sigma + \varepsilon_0 f(t)).$$

If we consider the case where an insulation system with geometrical capacitance  $C_0$  is exposed to a step voltage,  $U_a$ , the polarization current can be given by

$$(5) \quad i_p = C_0 U_a \left( \frac{\sigma}{\varepsilon_0} + f(t) \right).$$

If the step voltage is now disconnected from the insulation

$$(6) \quad i_d = -C_0 U_a [f(t) - f(t+t_{ch})]$$

gives the depolarization current. The charging time normally should be at least ten times larger than the time for which the response function is calculated then the second term in (6) can be neglected.

Therefore, the response function becomes proportional to the depolarization current. Hence, the response function and conductivity can be calculated simultaneously by using polarization and depolarization currents. Very often, the response function needs to be expressed in a parameterized form. The response function can be written in the general form:

$$(7) \quad f(t) = \frac{A}{\left(\frac{t}{t_0}\right)^n + \left(\frac{t}{t_0}\right)^m}.$$

The response function describes the fundamental memory property of any dielectric system and can provide significant information about the insulation material. After

opening the short circuit, the charge bounded by the polarization will turn into free charges i.e., a voltage will build up between the electrodes on the dielectric. This phenomenon is the return voltage. The return voltage arises from the relaxation processes inside the dielectric material. The current density during the return voltage measurement is zero and

$$(8) \quad j(t) = \sigma E(t) + \varepsilon_0 \varepsilon_r \frac{d}{dt} E(t) + \varepsilon_0 \frac{d}{dt} \left[ \int_0^t f(t-\tau) E(\tau) d\tau \right]$$

gives the expression of current density, where  $E(t)$  is the electric field resulting from the return voltage build up across the open circuited dielectric. Equation (8) shows that the return voltage depends on the conductivity  $\sigma$ , relative permittivity  $\varepsilon_r$  and dielectric response function  $f(t)$ .

These parameters are all affected by aging and moisture in the insulation. The response function can be obtained from the polarization and depolarization currents. These currents depend on the geometric capacitance and on the applied step excitation. The response function and conductivity can be calculated from equations (5) and (6) if the geometric capacitance of the transformer composite insulation is known. If the proper geometry of the transformer oilpaper insulation is known then by solving (8), return voltage for a transformer can be estimated. The return voltage also depends on the applied electric field and if the dielectric material is assumed to be linear this problem is resolved easily for the interpretation of results [9]. A modelling tool can be very useful to investigate the impact of geometry on return voltage results [10].

## Measurement of the insulation resistance

The measurement was performed in the laboratory of the Department of measurement and applied of electrical engineering on the transformer (Fig.4), which parameters are given in Table 1.



Fig.4. Measured transformer 30 kVA (black) and its power supply transformer (silver) in the laboratory

Table 1. Label parameters of measured transformer

Manufacturer and year of production	Windings connection and oil type	Voltage transfer and current ratio
BEZ Bratislava 1958	Yzn1 ITO 100	22 / 0.4 kV 0.787 / 43.3 A

The transformer was not before this measurement in operation for over two years and the oil state was deliberately under the operation level. The first was measured the insulation resistance and polarization index with device MEGGER series 1-5000.

In measuring the insulation resistance of the windings was to terminal 1 and 2 connected test voltage 2500 V. Results of this measurement are shown in Table 2.

Table 2. Measurement of the insulation resistance.

Test voltage	Insulation resistance R15	Insulation resistance R60	Polarization index
2500 V	2.35 GΩ	3.85 GΩ	1.64

According to (1), the absolute size of the insulation resistance is equal to 3.85 GΩ. As expected, the value of polarization index is below 1.7, but 1.64 is a value well above the assumptions and says that the insulation is in pretty good condition. The value of the polarization index in such transformers is of the order 1.4.

### Return voltage measurement

To measure of return voltage can be used, for example, device RVM 5462. Because the department does not have this device, it was necessary to use separate devices: MEGGER series 1-5000 and switch panel, which is consist of electromechanical switching relays.

The disadvantage is that is not possible to perform measurements at times of order of charging under 1 second because it is currently still working on the creation of the measuring device, which allows measurements at significantly less times.

Return voltage measurement consist four steps (Fig.5 and Fig.6) [11]:

1. Charging (to terminals 1 and 2 is connected voltage 2500 V during the time  $t_c$ ),
2. Discharging (terminals 1 and 2 are short-circuited during the time  $t_d = t_c/2$ ),
3. Measurement  $U_{max}$  and  $t_{max}$  (between terminals 1 and 2 is measured voltage),
4. Recovery before the next cycle (terminals 1 and 2 are short-circuited during the time  $t = t_c$ ).

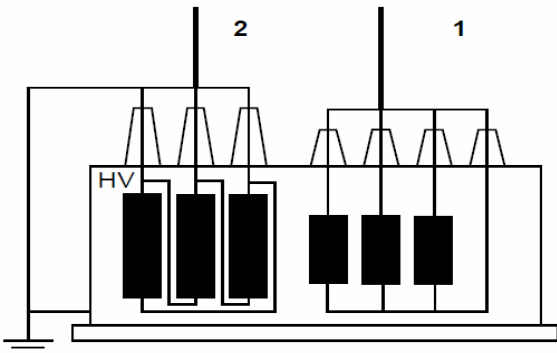


Fig.5. Return voltage measurement connection

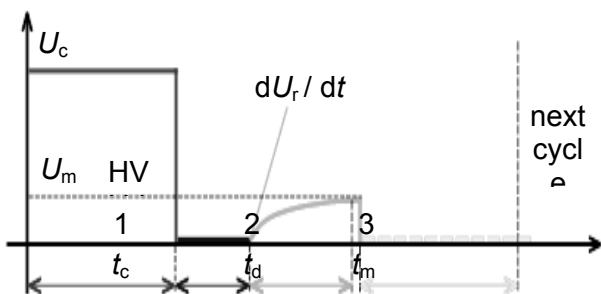


Fig. 6. Shape of test voltage end of the line.

Measured values of the RVM are given in table 3.

Table 3. Return voltage measurement values

$t_c$ , s	$U_{max}$ , mV	$t_m$ , s	$U_{ss}$ , mV	$U_\tau$ , mV	$\tau$ , ms
2	587.50	12.5	542.41	341.72	2.3034
4	493.75	14.5	481.69	303.46	2.4547
6	443.75	16.7	386.16	243.28	2.5621
12	437.50	16.9	390.35	239.62	2.6224
24	362.50	19.1	312.05	196.59	2.3956
48	212.50	13.1	208.48	131.34	2.3016
96	162.50	10.9	147.77	93.09	2.2839

From the measured values were compiled curves (Figs.7-9).

Fig.7 shows the measured values of voltage at time, for different charging times. From this curves follows that the maximum voltage response was reached at the time of charging  $t_c = 2$  s. According to [12] and [13] can be stated that the maximum size of voltage response was reached at the time 2 s, which implies that the moisture content is of the order 4%.

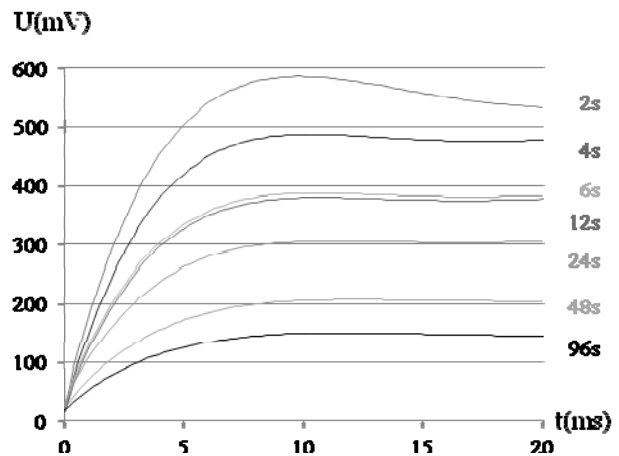


Fig.7. Voltage curves in time at different times of charging

Dependence of the maximum voltage response by charging time shows Fig.8, from which is apparent that at lower of charging times  $t_c < 2$  s, the curve took the opposite, thus decreasing tendency. This phenomenon shows that the transformer insulation is on the border of operable condition and before the full load of transformer is necessary to carry out filtration of oil and before slowly load of transformer because in paper insulation is residual moisture.

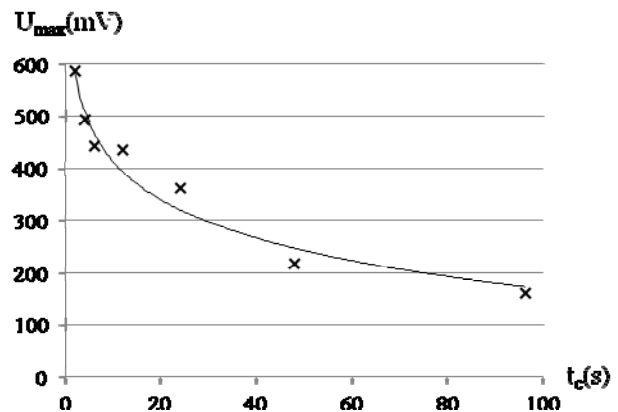


Fig.8. Maximum response of voltage at different times of charging

Fig.9 shows time to reach the voltage maximum for different times of charging. As the curve shows, in charging

time  $t_c = 24$  s, was the longest time to achievement of the maximum voltage response.

From the measured values was calculated time constant at different charging times, which curve is shown on Fig.10. It shows that the values at different charging times are not much uneven, with average value  $\tau_A = 2.417$  ms.

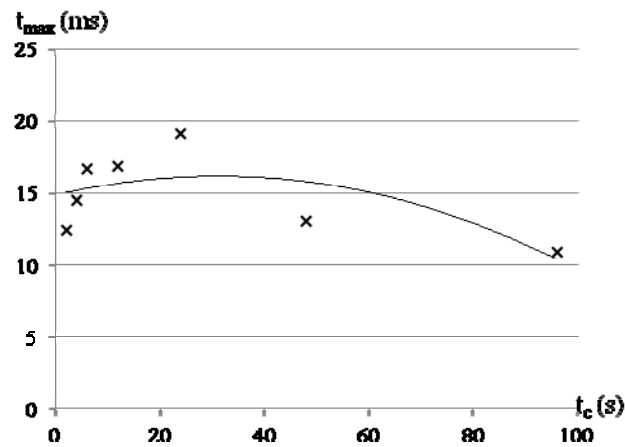


Fig.9. Time to voltage peak at different times of charging

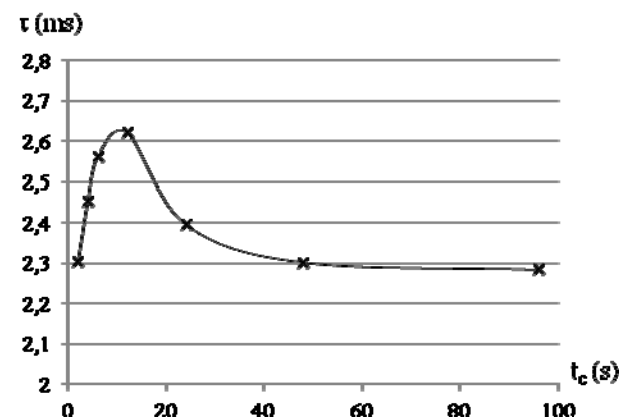


Fig.10. Time constant at different times of charging

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