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Experience with transformer diagnostics based on dielectric response measurements in time domain

***Abstract**. The paper presents results of diagnostic measurements on different transformers performed in time domain. New approaches for interpretation of the results are proposed and discussed. Modelling and calculations of different diagnostic values including dielectric response function are provided.*

***Streszczenie.** W artykule opisano wyniki badań diagnostycznych transformatorów metodą odpowiedzi dielektrycznej w dziedzinie czasu. Zaproponowano nowy sposób interpretacji uzyskanych wyników. Opisano sposób modelowania i obliczania parametrów diagnostycznych funkcji odpowiedzi dielektrycznej. (**Doświadczenia z badań diagnostycznych transformatorów metodą odpowiedzi dielektrycznej w dziedzinie czasu**).*

Keywords: dielectric response, polarisation current, recovery voltage, time constants, conductivity.
Słowa kluczowe: odpowiedź dielektryczna, prąd polaryzacji, napięcie powrotne, stałe czasowe, przewodnictwo.

Introduction

Several different methods such as an oil analysis or/and different electrical measurements are available to perform the condition assessment of oil filled transformers. The estimation of the dielectric parameters of oil-paper insulation takes an important part of existing methods. The measurement of the dielectric response can be performed in the time or/and frequency domain [1, 2, 3].

The experimental results and modelling of the dielectric response in the time domain for transformer diagnostic known from the literature show high sensitivity of the results to the change of the basic material properties such as conductivity [4]. As it shown in [5] the moisture and contamination tend to increase the conductivity of the solid and liquid dielectric in the transformer.

According to [6] the use of the measurement methods in the time domain show advantages especially for the condition assessment of complex transformer geometries.

The measurement of dielectric response in the field conditions requires reliable solutions and technique to be able to minimize the influence of the surround conditions in the field and to reduce also the time needed for diagnostics.

The new approach (PCRV) is based on combination of the measurements of the polarisation current (PC) and recovery voltage (RV). Figure 1 presents basic principle of the method and shows different stages of the measurement procedure.

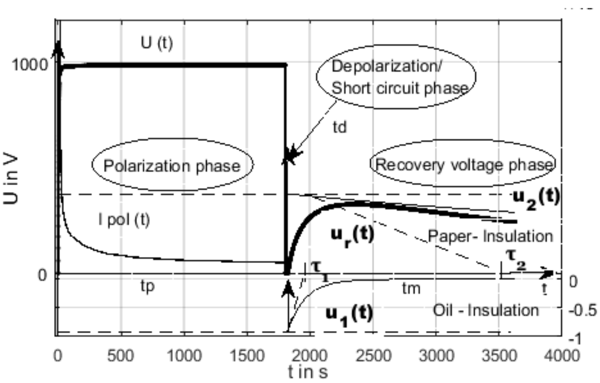

Fig.1. Basic principle of the measurements according to PCRV

In the first step the polarisation of the dielectric is performed so that a DC voltage up to 2500 V is applied for about 1800 s and the polarisation current is measured. In the second step the dielectric is shorted via short circuit impedance to discharge the geometrical capacitance. The duration of the second phase is typically few seconds. And in the third step the recovery voltage is recorded.

The combination of the results obtained from polarisation current and recovery voltage allow to estimate several parameters such as insulation resistance, time constants and conductivity of the dielectric components used in the insulation. As it will be described below the total duration of the dielectric measurements is less as one hour.

For the most of the presented investigations the measurement instrument [7] was coupled to the low voltage terminals of transformer and high voltage terminals and the transformer tank were grounded (LV-All test setup).

To avoid the influence of the remaining voltage between different tests an automatic procedure has been applied and the transformer was grounded till acceptable voltage level was reached.

Measurements on transformers

The dielectric response measurements have been performed on transformers from different manufacturers with different age, power and ageing conditions. The table below provides a short overview about the main transformer data.

Table 1. Basic transformer data

Unit	Manufacturer	Year	Power [MVA]	Voltage [kV]
TR1	CG	2013	4	6,6 / 0,72
TR2	BBC	1984	2	6,3 / 0,4
TR3	BBC	1966	0,25	20 / 0,4

All three units have relative low power rating and are used in the distribution network in different industrial companies. Due to relatively low price of the low power transformers as presented above in comparison with transformers in 110 kV network and above, is it not typically practice to apply several sophisticated diagnostic methods to estimate the condition of such transformers. For condition assessment of such small power units are typically used: ratio, winding resistance and insulation resistance measurements at 15 s, 60 s and partly also at 600 s.

Presented method PCRV also allow to perform a precise estimation of the insulation resistance values from the polarisation current measurements. The Figure 2 presents corresponding results for three units.

The recording of the whole curve allows to detect significant difference between units especially in the first part of curve.

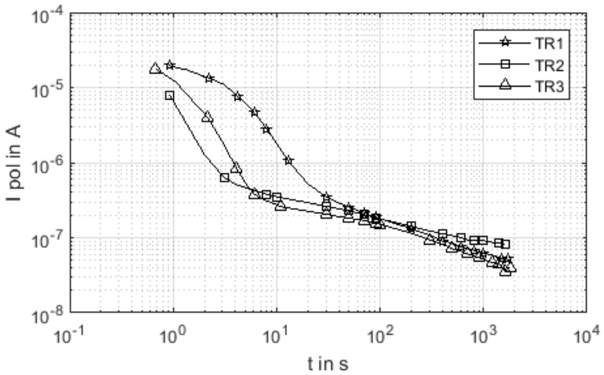

Fig.2. Polarization current Ip for 3 units at 1 kV (LV-All setup)

The Table 2 present the results of the measurement of the insulation resistance and corresponding absorption coefficients derived from the performed polarisation current measurements shown above in the Figure 2.

Table 2. Measured values from polarization current (PC)

Unit	Time [s]	Insulation resistance [GΩ]	Parameters	Value
TR1	15	1,34	R_{60}/R_{15}	3,03
	60	4,07	PI-Index (R_{600}/R_{60})	3,10
	600	12,61		
TR2	15	2,67	R_{60}/R_{15}	1,44
	60	3,86	PI-Index (R_{600}/R_{60})	2,00
	600	7,73		
TR3	15	2,27	R_{60}/R_{15}	2,12
	60	4,82	PI-Index (R_{600}/R_{60})	2,86
	600	13,78		

The transformer TR2 shows also high absolute values for the insulation resistances as other both units, but the corresponding values for absorption coefficient and PI-Index have reduced values.

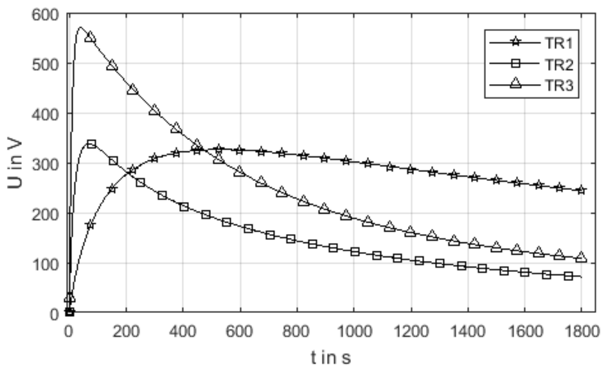

Fig.3. RV-curves for TR1, TR2, TR3 (LV-All test setup)

The Figure 3 presents the results of the recovery voltage measurements on all three units and also allows a clear differentiation between all three transformers.

The Table 3 below shows recovery voltage parameters (U_m, t_m, s and *p-factor*) estimated from measuring curves presented in the Figure 3.

Table 3. Estimated values from recovery voltage (RV)

Unit	Um (V)	Tm (s)	S (V/s)	p
TR1	326,2	520,8	2,39	0,26
TR2	337,6	69,0	19,37	0,25
TR3	565,3	43,9	61,47	0,21

As it can be seen in the table, the main difference between three units is that the maximum of the voltage is reached significantly earlier for transformers TR2 and TR3 and TR3 has higher maximum value for recovery voltage.

The using of the classical parameters and even of the such parameter as *p-factor* [8] do not allow to distinguish between the singular effects of the aging of the oil or solid insulation and more situated for cable diagnostics.

Influence of the measuring setup

The results of the dielectric measurements on transformers depend on several factors such as geometrical characteristics of the tested object, properties of the dielectrics (oil and solid insulation), temperature and measuring setup.

All the named above parameters could lead to significant change of the measured curves and therefore to overlapping with ageing effects in the insulation. Figures 4 and 5 below present measured curves for transformers TR2 and TR3 at different measuring configurations.

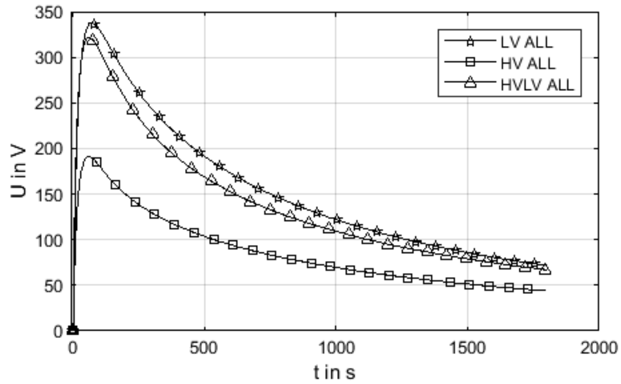

Fig.4. RV-curves measurements on TR2 (U_p = 1 kV, t_p = 1800 s)

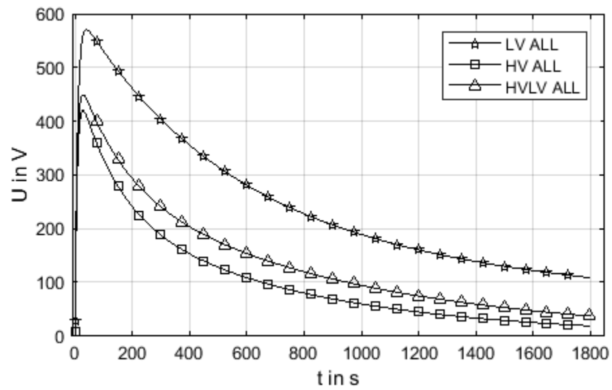

Fig .5. RV-curves measurements on TR3 (U_p = 1 kV, t_p = 1800 s)

Both setup configurations such as HV-All and LV-All allow to measure response in the main insulation of the transformer. In the third configuration HV,LV-All only the distances between windings to ground are measured and the main insulation is not included.

Due to different design and correspondingly different geometry of the transformers the measured curves could differentiate in dependence on the measuring setup. This effect can be observed in the figures 4 and 5.

In the present paper the results of the measurements for the selected setup LV-All are presented and discussed.

Modelling of the recovery voltage curves

As shown above there is a need to estimate additionally diagnostic parameters especially from recovery voltage curves for better differentiation between the investigated units.

For real data recovery voltage graph our goal is to represent it using sum of the different series exponential equations with the variables.

(1) $U_{r(i)}(t) = f(t_i, U_i, \tau_i) + e_i$, for i=0, 1, 2.… n

where $U_r(t)$ is the recovery voltage (V) varying with time. The variables U_i and the time constants $\tau_i=R_iC_i$ in the above equation are determined by using Gauss-Newton algorithm.

<u>Description of Gauss-Newton algorithm</u>

(2) $U_{r(i)}(t) = f(t_i, U_i, \tau_i) + e_i$

for i = 0, 1, 2...n, which indicates number of data points $U_{r(i)}(t)$ = *Measured recovery voltage data (V)*

Due to DC exponential step response of RC element modeling we took nonlinear exponential curve fit for the recovery voltage response is modeled by $f(t_i, U_i, \tau_i)$, which is dependent on following variables like input time t_i, voltage across individual capacitors U_i and their time constants τ_I, e_i *i*ndicates the residual error which can be minimized after every iteration of the Gauss-Newton algorithm.

For simple understanding we are approaching the following simplified notation:

(3) $Y_i = U_{r(i)}(t)$ and $f(x_i) = f(t_i, U_i, \tau_i)$

implified equation is: *Measured data fit = Curve fit + Residual error*.

With the knowledge of Newton-Raphson method, via Taylor series expression we are able to find the unknown variables, which helps us to fit the measured data into series of the modeled exponential function forms.

<u>Taylor series</u>

(4)
$$f(x_i)_{j+1} = f(x_i)_j + \sum_{i=0}^{n}\left(\frac{\partial f(x_i)_j}{\partial U_i}\cdot \Delta U_i\right) + \sum_{i=0}^{n}\left(\frac{\partial f(x_i)_j}{\partial \tau_i}\cdot \Delta \tau_i\right) + \ldots + Higher\ order\ terms$$

Here we considered up to 3 terms only.

Expression $f(x_i)_{j+1}$ represents modeled function value at the $(j+1)^{th}$ iteration at i^{th} data point, we are repeating the iterations until modelled function is very close to measured data.

$$f(x_i)_{j+1} = Curve\ fit + residual\,error = measured\ data$$

(5) $Y_i = f(x_i)_{j+1}$ at $(j+1)^{th}$ iteration

At $(j+1)^{th}$ iteration measured data equals to curve fit with negligible residuals

(6)
$$Y_i = f(x_i)_{j+1} = f(x_i)_j + \sum_{i=0}^{n}\left(\frac{\partial f(x_i)_j}{\partial U_i}\cdot \Delta U_i\right) + \sum_{i=0}^{n}\left(\frac{\partial f(x_i)_j}{\partial \tau_i}\cdot \Delta \tau_i\right) + \sum_{i=0}^{n} e_i$$

(7)
$$Y_i - f(x_i)_j = \sum_{i=0}^{n}\left(\frac{\partial f(x_i)_j}{\partial U_i}\cdot \Delta U_i\right) + \sum_{i=0}^{n}\left(\frac{\partial f(x_i)_j}{\partial \tau_i}\cdot \Delta \tau_i\right) + \sum_{i=0}^{n} e_i$$

We can represent the n point's partial derivative equations (PDE) into simplified one line equation as a matrix form as below

(8) $[D] = [Z_j]*[\Delta A] + [E]$

Where we give simplified notation to

(9) $[D] = \left[Y_i - f(x_i)_j\right]$

$$[D] = \begin{bmatrix} Y_0 - f(x_0)_j \\ Y_1 - f(x_1)_j \\ Y_2 - f(x_2)_j \\ '' \quad '' \\ Y_n - f(x_n)_j \end{bmatrix}$$

We use one matrix to represent the partial derivative values which we name it as $[Z_j]$ indicates Jacobian matrix like in the following

$$[Z_j] = \begin{bmatrix} \frac{\partial f_1}{\partial U_0} & \frac{\partial f_1}{\partial U_1} & \frac{\partial f_1}{\partial U_2} & \frac{\partial f_1}{\partial \tau_0} & \frac{\partial f_1}{\partial \tau_1} & \frac{\partial f_1}{\partial \tau_2} \\ \frac{\partial f_2}{\partial U_0} & \frac{\partial f_2}{\partial U_1} & \frac{\partial f_2}{\partial U_2} & \frac{\partial f_2}{\partial \tau_0} & \frac{\partial f_2}{\partial \tau_1} & \frac{\partial f_2}{\partial \tau_2} \\ '' & '' & '' & '' & '' & '' \\ \frac{\partial f_n}{\partial U_0} & \frac{\partial f_n}{\partial U_1} & \frac{\partial f_n}{\partial U_2} & \frac{\partial f_n}{\partial \tau_0} & \frac{\partial f_n}{\partial \tau_1} & \frac{\partial f_n}{\partial \tau_2} \end{bmatrix}$$

The above Jacobian matrix $[Z_j]$, contains 6 variables. Expression $\frac{\partial f_1}{\partial U_1}$ indicates the function partial derivative value with respect to U_1 at i^{th} data point. Similarly, other terms can be understandable.

$[\Delta A] = [\Delta U_0\ \ \Delta U_1\ \Delta U_2\ \Delta \tau_0\ \Delta \tau_1\ \Delta \tau_2]^T$ – is matrix contains difference in previous iteration voltage or time constants and will be updated in the new iteration values respectively

This is for three exponential terms only. Similarly, we can use it for any number of exponential terms.

Matrix $[E] = [e_0\ e_1\, e_2\, e_{(3)} \ldots e_n]^T$ contains individual voltage residuals at each measured time. Upon doing iterations $[E]$ will be reduced to zero.

When $[E] = 0$ our new equation would be

(10) $[D] = [Z_j]*[\Delta A]$.

Multiply $[Z_j]^T$ transpose of Jacobian matrix, above equation on both sides

(11) $[Z_j]^T * [Z_j]*[\Delta A] = [Z_j]^T * [D]$

$$Variable\ value\ at\ (j+1)^{th}\ iteration =$$
$$= Variable\ value\ at\ (j)^{th}\ iteration +$$
$$+ Difference\ calculated\ in\ the\ (j)^{th}\ iteration$$

(12) $U_{i\,j+1} = U_{i\,j} + \Delta U_{i\,j}$, for i =0, 1….n

(13) $\tau_{i\,j+1} = \tau_{i\,j} + \Delta \tau_{i\,j}$, for i =0, 1….n

Start with initial guess values for above variable and repeat the iteration process until our desired stopping criterion condition satisfied. Stopping criterion could be looks like

(14) $\left| \dfrac{U_{i\,j+1} - U_{i\,j}}{U_{i\,j}} \right| \cdot 100 \le 10^{-4}$, for i =0, 1….n

(15) $\left| \dfrac{\tau_{i\,j+1} - \tau_{i\,j}}{\tau_{i\,j}} \right| \cdot 100 \le 10^{-4}$, for i =0, 1….n

By selecting i = 1 or 2 which means the recovery voltage equation consists of three exponential terms.

(16) $U_r(t) = U_0 exp^{-t/\tau_0} + U_1 exp^{-t/\tau_1} + U_2 exp^{-t/\tau_2}$, for i = 2

According to the above presented modeling approach for the recovery voltage curves the measuring data have been analyzed and approximated with 2 and 3 elements of the Maxwell equivalent circuit.

In the most cases an approximation with only 2 elements and in some cases a fitting with 3 elements provides a satisfied matching of the measured curves as it can be seen in the pictures 6, 7 and 8.

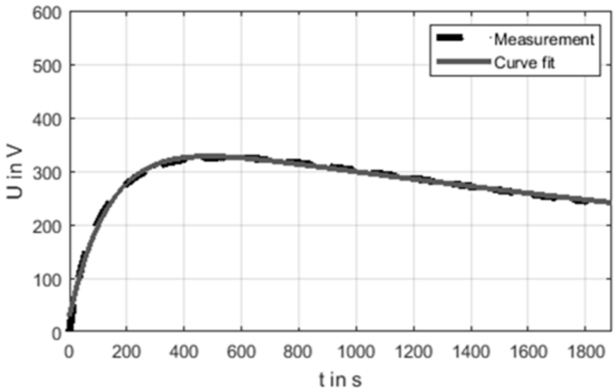

Fig.6. Curve fit for TR1 at LV ALL with 2 elements

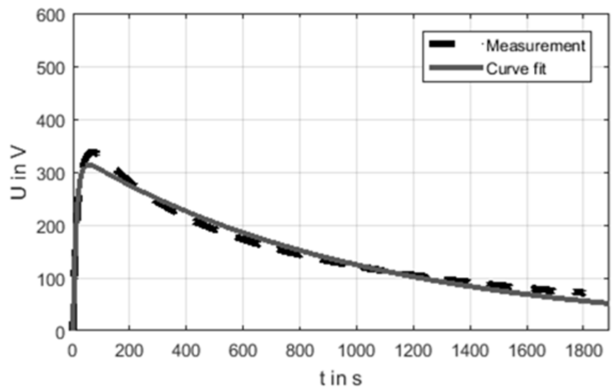

Fig.7. Curve fit for TR2 at LV ALL with 2 elements

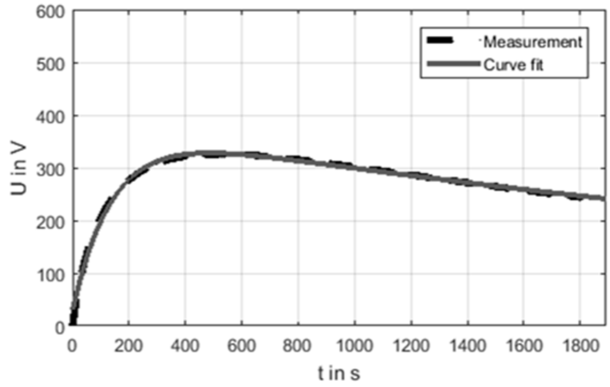

Fig.8. Curve fit for TR2 at LV ALL with 3 elements

Estimation of the conductivities

As soon the corresponding time constants are estimated, the further parameters can be calculated.

One of the mainly important parameters is the conductivity of the oil and solid insulation as it shown in the following formulas below.

(17) $\tau = RC$

(18) $\tau = \varepsilon_r \varepsilon_0 / \sigma$

(19) $\sigma = \varepsilon_r \varepsilon_0 / \tau$

(20) $\sigma(T) = \sigma_0 e^{-\frac{E_{ac}}{KT}}$ (Arrhenius equation)

were:
K = 8.62E-05 eV/K (Boltzmann's constant)
$E_{ac\ oil}$ = 0.4 eV, $E_{ac\ paper\ =}$ 0, 87 eV
ε_o = 8.854E-12 As/Vm (permittivity of vacuum)
ε_{roil} = 2.2 (oil relative permittivity),
ε_{rpb} = 4.4 (paper relative permittivity).

Table 4 presents the results of the modelling and calculation for three transformers for measuring configuration LV-All.

Table 4. Estimated diagnostic values from recovery voltage (RV)

Unit	τ_1 [s]	τ_2 [s]	σ_{oil} [fS/m]	σ_{pb} [fS/m]
TR1	141,9	4119	137,27	9,46
TR2	12,04	1011	1617,84	38,53
TR3	7,13	938,5	2731,95	41,51

As it is shown in Table 4, the values for oil conductivity are significantly higher for TR2 and TR3 as for TR1, which has the value corresponds to new oil level. And also the values for conductivities for the solid insulation are higher as for the unit TR1.

Using the achieved results it is much easier to perform the follow up of the ageing of insulation and to differentiate between both dielectrics.

Conclusions

This paper presents a novel method PCRV to assess the condition of the transformer insulation. The polarization current measurements at voltages up to 2500 V it is possible to calculate the traditional Insulation resistance, capacitances and absorption coefficients.

The performed analysis of the recovery voltage measurements with the nonlinear exponential modelling allow to distinguish the insulation properties between oil and solid Insulation via time constants correlated to their individual conductivities. The proposed approach is also applicable to large power transformers.

The presented results are showing that the measurements in the time domain by using of the new approach can provide a reliable diagnostic of the transformers. It is shown how the effects of the fluid and solid insulation can be distinguished and used to detect the aging process.

REFERENCES

[1] Houhanessian V.D., Zaengl W.S., Time domain measurements of dielectric response in oil-paper insulation systems, *Conference Record of the 1996 IEEE Int. Symp. on Electrical Insulation, Montreal, Canada, 1996, 47-52*

[2] Zaengl W.S., Applications of dielectric spectroscopy in time and frequency domain for HV power equipment, *IEEE Electrical Insulation Magazine*, vol. 19, no. 6, 2003, 9-22

[3] Gafvert U., Adeen L., Tapper M., Ghasemi P., Jonsson B., Dielectric spectroscopy in time and frequency domain applied to diagnostics of power transformers, *Proceedings of the 6th International Conference on Properties and Applications of Dielectric Materials (Cat. No.00CH36347)*, Xi'an, 2000, 825-830

[4] Frimpong G., Gafvert U., Fuhr J., Measurement and modeling of dielectric response of composite oil/paper insulation, *Proceedings of 5th International Conference on Properties and Applications of Dielectric Materials*, Seoul, 1997, 86-89

[5] Saha T.K., Purkait P., Investigation of polarization and depolarization current measurements for the assessment of oil paper insulation of aged transformers, *IEEE Trans. on Dielectrics and Electrical Insulation*, vol. 11, no. 1, 2004, 144-154

[6] Kouzmine O., Kornhuber S., Niehus D., Comparison of time- and frequency-domain-based diagnostic procedures for condition assessment of distribution and power transformers, *Conference: Grenzflächen in Elektrischen Isoliersystemen, 4. ETG-Tagung, 12-13.11.2013, Dresden, Germany*

[7] Measuring instrument manual DDA 2500, Formsmedia GmbH, 2017, Germany

[8] Patsch R., Kouzmine O., Selection of Diagnostic Parameters in Return Voltage Measurements of Medium Voltage Cables, in *WSEAS Conference on Power Systems and electromagnetic Compatibility, Corfu, Greece, Aug.23-25, 2005, 514-521*