ACTA TEHNICA CORVINIENSIS – Bulletin of Engineering
Tome VIII [2015] Fascicule 1 [January – March]
ISSN: 2067 – 3809

[1.] Richard JANURA, [2.] Jozef JURČÍK, [3.] Miroslav GUTTEN, [4.] Daniel KORENČIAK

TRANSFORMER INSULATION ANALYSIS BY TIME DOMAIN METHOD

[1-4.] Department of Measurement & Applied Electrical Engineering, Faculty of Electrical Engineering, University of Žilina, Žilina, SLOVAKIA

Abstract: *The article discusses the state of transformer insulation. For a more accurate determination of the transformer insulation state are used three methods. The measurement of insulation resistance is the basic method and is set in the standard, value demonstrates the state of total insulation of transformer. Because the determination of moisture content of the paper insulation of transformer is very difficult process and it is necessary take a sample of paper, in this case is used method of return voltage. Return voltage measurement is more complex method and in many cases is determine a clear result very difficult. For evaluation of results have mainly impact moisture content and degree of aging of paper insulation and of course, content of conductive impurities in oil. Because the moisture content in oil is much lower than in the paper, return voltage measurement is used to determine the moisture content in paper insulation only. To confirm the results of return voltage measurement is used frequency domain spectroscopy, which clearly, according computational model, calculates the moisture content in the paper insulation.*

Keywords: *transformer; return voltage; insulation resistance; polarization index; time domain; paper; oil*

INTRODUCTION

Operating conditions has a major impact on aging of individual parts of transformer and also affect the change 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 level 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.

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 [2].

MEASUREMENT THEORY

A. Insulation resistance of winding

Insulation resistance usually responds to the weakest point of the transformer insulation system and its decline is often coupled with the influence of conductive impurities and moisture. In measuring of the insulation resistance are read two values of the absorption current in 15 and 60 seconds after the applied of voltage. Absolute size of the insulation resistance is value measured in 60 seconds after the applied of voltage. Both values of the absorption current are necessary for the determination of polarization index p_i from the equation:

$$p_i = \frac{i_{15}}{i_{60}}, \tag{1}$$

where i_{15} is the absorption current to 15 seconds and i_{60} is the absorption current in 60 seconds after the applied of voltage to the transformer [1].

Additional variable characterizing the transformer insulation system is the time constant τ, whose absolute value is independent of the geometric dimensions of the winding. Time constant is calculated from measured values of insulation resistance and capacitance of the transformer.

$$\tau = R_{60} C_{50} \tag{2}$$

where R_{60} is insulating resistance in 60 seconds after the applied of voltage and C_{50} is capacitance of insulation measured at 50 Hz.

The value of the polarization index for new and transformers after revision should be at least 1.7 [1].

B. Return voltage

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 [3], [4].

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

$$j(t)=\sigma E(t)+\frac{dD}{dt}, \qquad (3)$$

where σ is the direct conductivity, and is the electric displacement given by (4).

$$D(t)=\varepsilon E(t)+\Delta P(t)=\varepsilon_0\varepsilon_r E(t)+\Delta P(t) \qquad (4)$$

where ε_0 is the vacuum permittivity, and ε_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 (5).

$$\Delta P(t)=\varepsilon_0\int_0^t f(t-\tau)E(\tau)d\tau . \qquad (5)$$

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

$$j_p=E(\sigma+\varepsilon_0 f(t)). \qquad (6)$$

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

$$i_p=C_0U_a\left(\frac{\sigma}{\varepsilon_0}+f(t)\right). \qquad (7)$$

If the step voltage is now disconnected from the insulation

$$i_d=-C_0U_a\left[f(t)-f(t+t_{ch})\right] \qquad (8)$$

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 (8) 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:

$$f(t)=\frac{A}{\left(\frac{t}{t_0}\right)^n+\left(\frac{t}{t_0}\right)^m}. \qquad (9)$$

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

$$j(t)=\sigma E(t)+\varepsilon_0\varepsilon_r\frac{d}{dt}E(t)+\varepsilon_0\frac{d}{dt}\left[\int_0^t f(t-\tau)E(\tau)d\tau\right] \qquad (10)$$

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 (10) shows that the return voltage depends on the conductivity σ, relative permittivity ε_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 (7) and (8) 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 (10), 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 [5]. A modeling tool can be very useful to investigate the impact of geometry on return voltage results [6].

TRANSFORMER MEASUREMENT

A. Insulation resistance and polarization index

The measurement was performer in the laboratory of the Department of measurement and applied electrical engineering on the transformer, which parameters are given in table 1.

Table 1. Tested transformer parameters

Connection	Yz1
Power	30 kVA
Voltage transfer	22 / 0.4 kV
Current ratio	0.787 / 43.3 A
Year of production	1958
Manufacturer	BEZ

The transformer wasn't before this measurement in operation for over two years and the oil state was deliberately under the operation level. Firstly the insulation resistance and polarization index was measured by MEGGER series 1-5000. The low and high voltage terminals were connected to test voltage 2500 V in measuring the insulation resistance of the windings. Results of the measurement are shown in table 2.

Table 2. Insulation resistance measured values

Test voltage	2500 V	
Insulation resistance	After 1 min	3.85 GΩ
	After 5 min	5.8 GΩ
	After 10 min	6.33 GΩ
Polarization index	1.64	

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

B. Measurement and evaluation of return voltage

To measure of return voltage can be used, for example, device RVM 5462. Because we used two separated devices – DC source and switch panel, which consists of electromechanical switching relays, the disadvantage is theimpossibility to perform measurements at *charging times below 1 second. Return voltage measurement consists of four steps (figure1 and figure 2):*

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

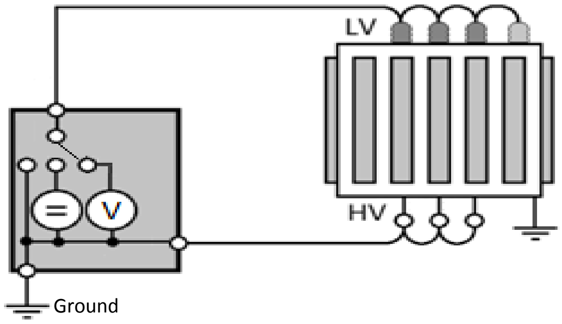

Figure 1. *Return voltage measurement connection*

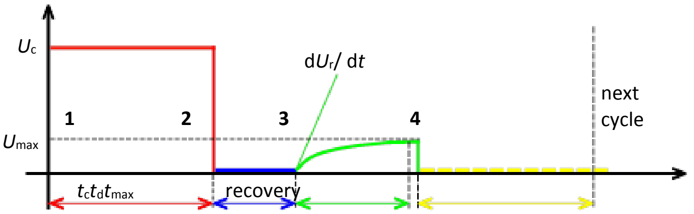

Figure 2. *The test voltage shape*

Table 3 shows the measured and calculated values from return voltage measurement. The time constant is equal to the time, at which the value of voltage $0.63U_{ss}$ is reached: $t(U_\tau) \cong t(0.63U_{SS})$. The voltage U_{ss} is steady-state value at different times of charging.

Table 3. *Measured and calculated values of return voltage*

t_c (s)	U_{max} (mV)	t_{max} (ms)	U_{ss} (mV)	U_τ (mV)	τ (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 (fig. 3-fig. 6). Figure 3 shows the measured voltage values at time for different times of charging. From this curves it is obvious that the maximum voltage response was reached at the time of charging $t_c = 2$ s.According to [7] and [8] could be stated that the maximum size of voltage response was reached at the point 2 s, which implies that the moisture content is approximately 3.5%.

Figure 5 shows time in which the maximum voltageis reached for different charging times. As the curve shows, the longest time to achieve the maximum voltage response was for charging time $t_c = 24$ s.

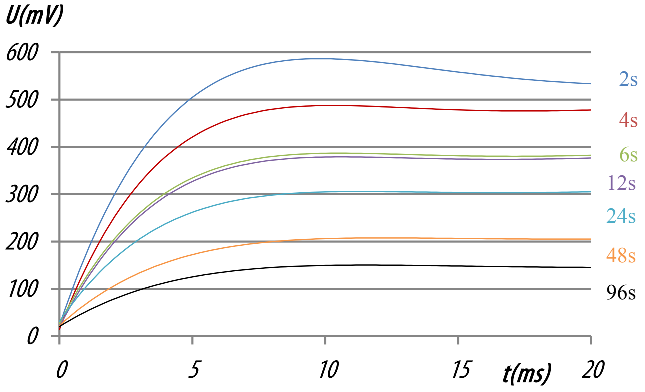

Figure 3. *Dependence of voltage in time at different times of charging*

Figure 4 shows the dependence of the maximum voltage response by charging time, from which is apparent that at lower 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 oil filtration andthen slowly increase the transformer load by reason of residual moisture content in paper insulation.

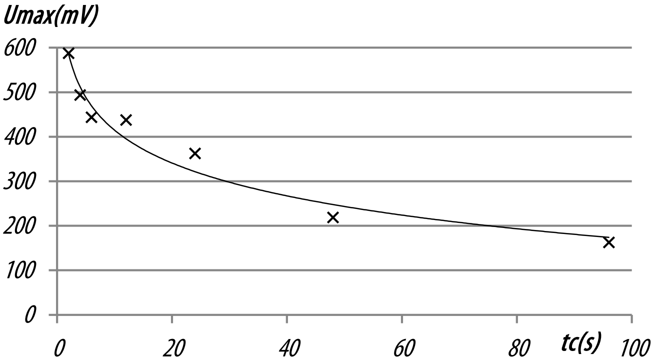

Figure 4. *Maximum voltage response at different times of charging*

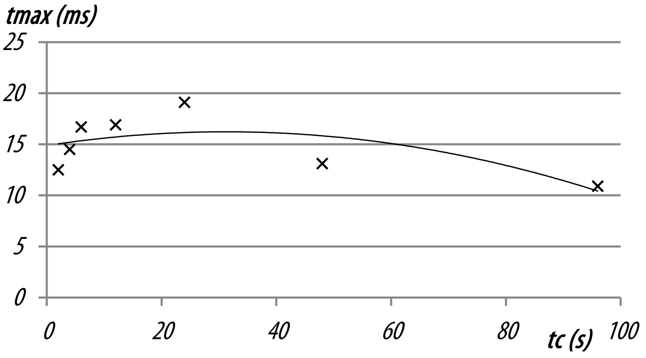

Figure 5. *Time in which the voltage peak was achieved at different times of charging*

From the measured values,the time constant at different charging times was calculated.The curve is depicted on fig. 6. It shows that the values at different charging times are not much uneven, so could be declared that the dependence of the time constant of the equivalent circuit of the insulation system is independent on time of operation of DC voltage in the range of measured times. The average value was $\tau_A = 2.417$ ms.

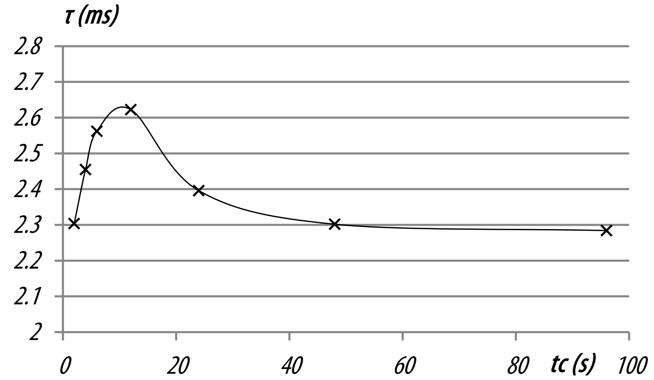

Figure 6. *Time constant at different times of charging*

CONCLUSION

Return voltage measurement was designed for cable insulation state investigation. The most of measuring devices for cable investigations don't allow measurement at different times of charging or discharging. Whereas the cable insulation like transformer windings insulation could this measuring method use also for transformers. It doesn't matter whether the insulation is dry or oleic. Due to the large use of oil transformers was this measurement aimed right at them. We could obtain moisture level content in oil transformers with using the RVM method too. An attempt has been made in order to use the initial slope of the decay voltage and the initial slope of the return voltage (single cycle) to separately investigate the moisture and ageing in the oil impregnated paper insulation. From the results, it could be seen that in some situations the initial slope of the decay voltage could provide a good indication of the moisture level. The initial slope of the single cycle RVM reflects the combined effect of ageing and moisture. As in many other methods also in RVM is difficult to evaluate the results but in combination with PDC method a more accurate evaluation of the measurement results could be achieved. Moisture content in paper and oil insulation of transformer could be more reliably determined using FDS method. The final moisture contents of the paper insulation by RVM and FDS methods are almost identical. Moisture content determined by RVM is approximately 3.5 % and by the FDS method is 3.3%. The advantage of using both methods is their similarity and accurate determination of moisture content in paper insulation of transformer is therefore simpler.

Acknowledgment

This work was supported by the Grant Agency VEGA from the Ministry of Education of Slovak Republic under contract 1/0624/13.

References

- *[1.] MENTLÍK, V. et al., Diagnostics of electrical equipment. Prague: BEN, 2008. 439 p. ISBN 978-80-7300-232-9.*
- *[2.] MONATANARI G. C., Polarization and space charge behavior of unaged and electrically aged crosslinked polyethylene, IEEE Trans. Dielectr. Electr. Insul., vol. 7, pp 474-479, 2000.*
- *[3.] GAFVERT, U. et al., Modeling of dielectric measurements on power transformers, in Proc. CIGRE Session, Paris, France, Aug. 30-Sept. 5, 1998, Paper 15-103.*
- *[4.] JONSCHER, A. K., Dielectric relaxation in solids. New York: Chelsea Dielectric, 1984.*
- *[5.] Electrical and chemical diagnostics of transformer insulation, Part A: Aged transformers samples, IEEE Trans. Power Delivery, vol. 12, pp. 1547-1554, Oct. 1997.*
- *[6.] SAHA, T. K., YAO, T. Z. Experience with return voltage measurements for assessing insulation conditions in service-aged transformers, IEEE Trans. Power Delivery, vol. 18, pp. 128-135, Jan. 2003.*
- *[7.] JURČÍK, J.: Analysis of insulating state on transformer model using PDC method, Elektro 9^{th} International Conference, Rajecké Teplice, SR, pp. 423-426, May 2012.*
- *[8.] FILIPOVIĆ-GRČIĆ, B., FILIPOVIĆ-GRČIĆ, D., UGLEŠIĆ, I.: Modeling of polarization in oil-paper insulation using recovery voltage measurements. In: International review of electrical engineering. Vol. 6, 2011, ISSN 1827-6660, No. 1, p. 430-437.*
- *[9.] JURČÍK, J., GUTTEN, M., KORENČIAK, D.: Analysis of transient actions influence in power transformer, In: Advances in Electrical and Electronic Engineering, Vol. 9, 2011, ISSN 1804-3119, No. 2, p. 65-69.*
- *[10.] BRANDT, M., FAKTOROVÁ, D., SEEWALD, R.: Identification of the breakdown and analysis of transformer 22/0,4 kV, In: Materials Engineering, Vol.20, No.4, 2013, ISSN 1338-6174.*
- *[11.] PROSR, P., BRANDT, M., MENTLÍK, V., MICHALÍK, J.: Condition asssessment of oil-paper transformer insulating system. In: Journal of energy and power engineering. Vol. 5, 2011, ISSN 1934-8975, No. 2, p. 173-178.*

ACTA Technica CORVINIENSIS
BULLETIN OF ENGINEERING
ISSN:2067-3809

University POLITEHNICA Timisoara, Faculty of Engineering Hunedoara,
5, Revolutiei, 331128, Hunedoara, ROMANIA
http://acta.fih.upt.ro