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THE APPLICATION OF THE COLE-COLE MODEL IN DIAGNOSTICS OF THE PAPER-OIL INSULATION CONDITION USING THE RVM METHOD

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ABSTRACT

The paper presents the application of the Cole-Cole model for determining the runs of the return voltage of the paper-oil insulation sample through a computer simulation. Different insulation conditions were simulated through an adequate selection of parameters α and τ of the Cole-Cole model. For calculation purposes, a series – parallel substitute scheme, obtained through approximation of a discrete characteristic operator impedance Z_a of the model applied, was used. The diagnostics of the simulated insulation condition was based on the analysis of a few selected parameters of the return voltage, obtained from time characteristics.

KEYWORDS: paper-oil insulation, RVM diagnostic, Cole-Cole model, power transformers

1. INTRODUCTION

The condition of paper-oil insulation is one of the main factors deciding on the ‘condition’ and its remaining ‘technical life expectancy’ of many appliances of professional power engineering. In spite of a significant progress in development and production of new electroinsulation materials (e.g. insulating board and aramid papers), insulation based on cellulose combined with mineral oil still prevails in most appliances. This is especially true in the case of power transformers – key appliances in relation to safety and reliability of electric power distribution.

The subject matter connected with a correct diagnostication of the degree of dampness and aging of paper-oil insulation of professional power engineering appliances, especially power transformers, remains a challenge for scientific centers scattered all over the world [1, 2]. Unfortunately, the issue of a specific separation of the influence of dampness and aging degree of the appliances under study [3] has not been settled unequivocally. In the case of power transformers, especially units of the highest power, the issue of a correct assessment of the ‘technical life expectancy’ of insulation is extremely significant. In spite of the fact that water amassed in it is a crucial hazard to paper-oil insulation of power transformers, many units will be reaching their end of the ‘technical life’ not only in Poland but also in other countries [4, 5]. Since transformers constitute one of the main elements of companies’ or power enterprises’ assets, there can be expected an increased interest of the firms in a reliable and credible assessment of the actual condition of the units being in use. Hence a continuous development of the diagnostic methods used, including investigations of the analysis methods of the data obtained that would make it possible to estimate precisely the aging degree of insulation, is still valid.

Presently, two radically different ways of carrying out examinations in the scope of assessment of the degree of dampness and aging of paper-oil insulation of power transformers are used. One of them consists in the application of the chromatographic methods on an oil sample taken from a transformer tub. Also the method of the dissolved gas analysis (DGA) with determination of carbon oxides (CO and CO_2), which are products of the thermal aging of cellulose, should be mentioned here. However, the dissolved liquid analysis (DLA) with determination of the furan content, especially 2FAL compound [6], is a much more reliable method of the paper aging degree assessment. Moreover, determining the dampness degree of a transformer insulation oil in a given temperature, it is possible to estimate the dampness degree of the very cellulose using the characteristics of oil-paper hydrodynamic balance [7]. The other way of examining the main insulation of transformers is based on the application of the polarization methods. In this case the methods using the analyses carried out in the time domain and in the frequency domain should be distinguished. One group is constituted by diagnostics analyzing time runs of polarization and depolarization current (PDC) and the recovery voltage current (RVC) methods. The other group is constituted by the methods analyzing the changes of the loss coefficient (tanδ) and electric permittivity (ε) in the function of the frequency dielectric spectroscopy (FDS). The range of low frequencies, i.e. 10^{-4}Hz ÷ 10^{2}Hz is of an extreme significance in paper-oil insulation investigations [2].

The RVM professional measuring apparatus available on the market is presently used mainly for determining the dampness degree of transformer paper-oil insulation [8, 9].

According to author, this situation is caused by a too selective way of carrying out the analyses (insufficient number of parameters describing the runs under study) and in the common use of Debye's model for describing the condition of insulation [10, 11]. This paper presents the way of using the Cole-Cole model as a more suitable model for the insulation type described through the analysis of the selected parameters of the return voltage [12, 13]. Based on this model, a series – parallel substitute scheme of insulation was obtained through the application of approximation of a discrete characteristic operator impedance Z_a of the model. Different conditions of insulation were simulated through an adequate selection of parameters α and τ of the Cole-Cole model. The return voltage run for the diagnostics using the RVM was obtained through the time analysis of the response of the substitute scheme of insulation to an individual excitation with constant voltage.

2. THE COLE-COLE MODEL

In the case of dielectrics with a simple Debey's relaxation model (e.g. with single relaxation times) and leaving out the influence of the interparticle action, a dispersion equation can be described with a formula:

$$\varepsilon = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau} \tag{1}$$

Additional directions:

- ε - electric permittivity,
- ε_∞ - permittivity for $\omega=\infty$,
- ε_s – permittivity for $\omega=0$,
- ω - pulsation,
- τ - relaxation time.

For dielectrics, the structure of which shows, for example, the presence of long-chain polymer molecules, absorbent maxima are significantly lowered, more than indicated by Debey's model (1). A molecule of cellulose corresponds with this description, for which the number of glucose cells in a chain can reach even 1500 (non-aged electrotechnical paper). Then the diagram of the complex electric permittivity ε'-ε" is inside the circle described with the equation when α=1 (2) (Fig. 1) and its empirical form is described by the Cole-Cole equation:

$$\varepsilon = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + (j\omega\tau)^{1-\alpha}} \tag{2}$$

α - coefficient ($0 \le \alpha \le 1$).

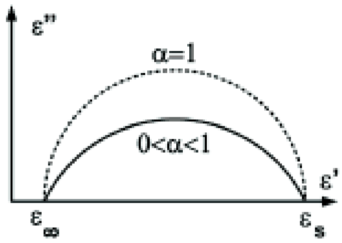

Fig. 1. The Cole-Cole diagram according to equation (2)

3. A SERIES – PARALLEL SUBSTITUTE SCHEME

The Cole-Cole model was built based on four parameters (ε_s, ε_∞, α, τ), the interpretation of which in the form of an electric scheme is shown in Figure 2. The most significant element of the scheme is characteristic impedance Z_a, the value of which depends both on coefficient α and relaxation time τ.

Characteristic impedance Z_a can be determined by removing capacity C_∞ and C_s-C_∞ from the equation of operator admittance Y(s):

$$Y(s) = sC_\infty + \frac{(C_s - C_\infty)s}{1 + (s\tau)^{1-\alpha}} = sC_\infty + \frac{1}{Z_1(s)} \tag{3}$$

$$Z_1(s) = \frac{(s\tau)^\alpha + s\tau}{(C_s - C_\infty)(s\tau)^\alpha s} = \frac{1}{(C_s - C_\infty)s} + Z_a(s) \tag{4}$$

$$Z_a(s) = \frac{\tau}{(C_s - C_\infty)(s\tau)^\alpha} \tag{5}$$

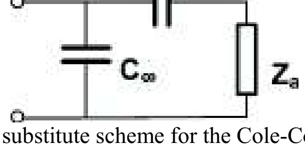

Fig. 2. A substitute scheme for the Cole-Cole model
C_s – system capacity for ω=0, C_∞ - system capacity for ω=∞, Z_a – characteristic impedance

Since operator s of characteristic impedance Z_a is usually in an incomplete power ($0 \le \alpha \le 1$), determining of the element values of the substitute scheme of impedance is possible only through approximation. It consists mainly in creating alternative poles and zero places in the assumed frequency range (f_0-f_1). FDS diagnostics of the paper-oil insulation condition of professional power appliances (mainly power transformers) is carried out in the range of low frequencies of the measurement voltage, i.e. beginning from 10^{-4}Hz. Therefore it was decided to assume the following ranges of the frequencies observed: $f_0=10^{-3}$Hz and $f_1=10^{3}$Hz. Next, for the range determined in this way, a minimum number of poles and zero places N is determined according to the formula:

$$N = \frac{3}{2}\log\frac{f_1}{f_0} \tag{6}$$

Additional directions:

f_0 – initial frequency,
f_1 – final frequency.

The next stage of calculations constitutes determining the frequency values, for which alternative poles and zero places of the impedance approximated occur. Formulae (7) and (8), respectively, present these calculations and formula (9) determines a new approximated characteristic impedance Z_{aa}:

$$f_{pi} = f_0\left(\frac{f_1}{f_0}\right)^{\frac{2i-1-\alpha}{2N}} \tag{7}$$

$$f_{zi} = f_0\left(\frac{f_1}{f_0}\right)^{\frac{2i-1+\alpha}{2N}} \tag{8}$$

$$Z_{aa}(s) = |Z_a(f_0)| \prod_{i=1}^{N} \frac{\frac{s}{\omega_{zi}} - 1}{\frac{s}{\omega_{pi}} - 1} \tag{9}$$

Additional directions:

ω_p – pulsation of impedance pole occurrence Z_{aa},
ω_z – pulsation of zero impedance occurrence Z_{aa},
i=1, 2, …, N.

Figure 3 shows the method of approximation of a discrete characteristic operator impedance Z_a, carried out for exemplary data. The final stage of calculations constitutes impedance distribution $Z_{aa}(s)$ into partial fractions. The result is a series – parallel substitute scheme, shown in Figure 4.

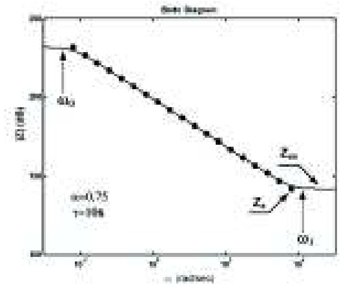

Fig. 3. The method of approximation of a discrete characteristic operator impedance Z_a (parameters α and τ selected as examples)

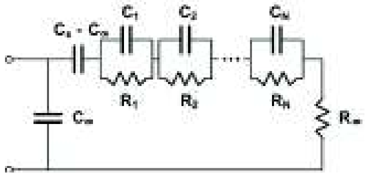

Fig. 4. A series – parallel substitute scheme

4. THE RVM METHOD AND ITS PARAMETERS

Figure 5 shows a classical scheme, which presents an indispensable system of connections for initiating the phenomenon of the return potential in dielectrics. The main part of the system is a three-positional change-over switch which performs a cycle of change-overs: charging - short-circuit – measurement. If the system is to work properly and make it possible to examine various dielectric materials, it must be possible to adjust charging, short-circuit and measurement times, and to ensure an adequately high input resistance of the voltage meter.

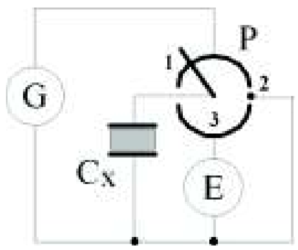

Fig. 5. A diagram of the system for the return voltage measurement
G – constant voltage feeder, C_x – subject under study
E – constant voltage meter, P – switch

Figure 6 shows voltage time runs that occur in the system during the insulation condition diagnostics by the RVM method. Moreover, there are marked selected parameters of the return voltage [14], which will be used for diagnosing the condition of the insulation simulated in the further part of the paper. A collective listing of the parameters is shown in Table 1.

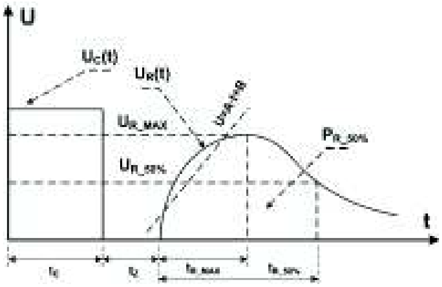

Fig. 6. Voltage runs of the RVM method with selected parameters of the return voltage
$U_C(t)$ – charging voltage, $U_R(t)$ – return voltage, t_C – charging time, t_Z – short-circuit time,
U_{R_MAX} – maximum value of the return voltage, t_{R_MAX} – U_{R_MAX} reaching time,
$U_{R\_50\%}$ – U_{R_MAX} half value, $t_{R\_50\%}$ – $U_{R\_50\%}$ reaching time (beyond the peak),
$U=A \cdot t+B$ – approximating function of $U_R(t)$ growth process,
$P_{R\_50\%}$ – area under $U_R(t)$ curve until reaching $t_{R\_50\%}$

Table 1. Return voltage parameters chosen for the assessment of the condition of the paper-oil insulation simulated

Parameter	Unit
U_{R_MAX}	V
t_{R_MAX}	s
$t_{R\_50\%}$	s
$k_U=t_{R\_MAX}/t_{R\_50\%}$	-
A	V/s
$P_{R\_50\%}$	Vs

5. RESEARCH RESULTS

It was assumed that the object under study will be a paper-oil insulation sample of 2mm thickness and the size of 10x10cm. To evaluate the influence of parameters α and τ of the Cole-Cole model on the values of the return voltage, constant values of capacity C_s and C_∞ were assumed and resistance taking into account the leakage current of 50GΩ was added to the substitute scheme. The calculations were carried out for the data shown as a collective listing in Table 2. For the discrete approximation purposes the frequency range from $f_0=10^{-3}$Hz to $f_l=10^3$Hz was assumed, which is recommended for the investigation of this type of insulation.

Table 2. Parameter values of the Cole-Cole model used for calculations

Parameter	Unit	Value
C_s	pF	250
C_∞	pF	44,25
α	-	0,25; 0,5; 0,75; 0,99
τ	s	10, 100, 500, 1000

Table 3 shows the values of the parameters used during the diagnostics by the RVM method. It was decided that for all selected charging times t_c, short-circuit time t_z would be half of its values (according to the recommendations of the RVM diagnostics application).

Table 3. Parameter values used during the diagnostics by the return voltage method (RVM)

Parameter	Unit	Value
U_c	V	1000
t_c	s	1, 2, 3, 4, 5, 10, 20, 30, 60
t_z	s	$0{,}5 \cdot t_c$

Figure 7 shows the influence of parameter α of the Cole – Cole model on the return voltage parameters (Tab. 1) for the selected relaxation time τ=10s. It should be noted that increasing the value of parameter α also causes a significant increase of such parameters as t_{R_MAX}, $t_{R\_50\%}$ and $P_{R\_50\%}$, especially for the range of longer short-circuit times t_z. Parameters U_{R_MAX}, A and k_U show a significant decrease of their values, and extending the short-circuit time t_z has a stabilizing effect in this case (U_{R_MAX} and A). For α=0.99 the values of parameters U_{R_MAX} and A are constant, regardless of the short-circuit time.

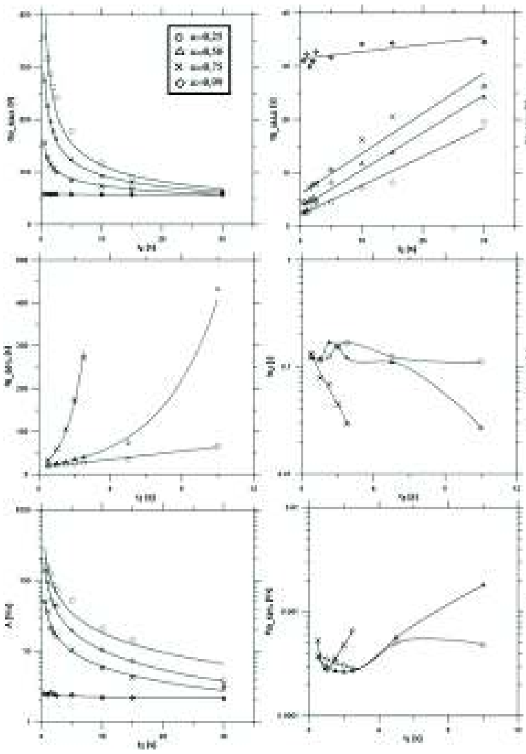

Fig. 7. The influence of parameter α on the return voltage parameters for a selected relaxation time τ=10s

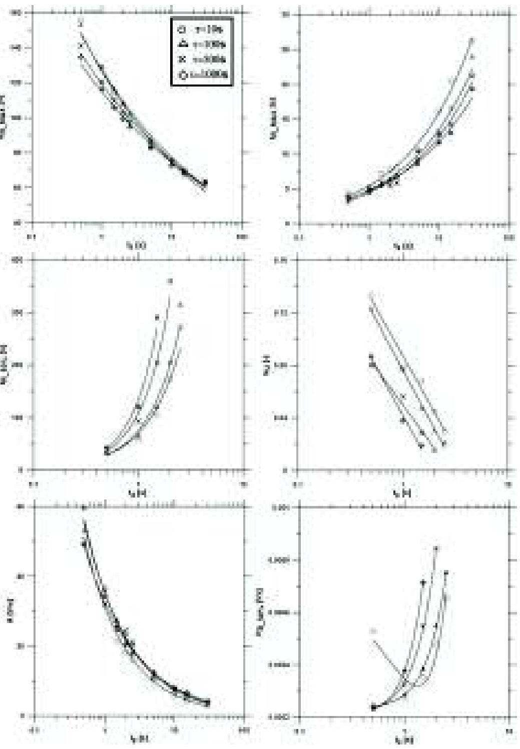

Fig. 8. The influence of the relaxation time τ on the return voltage parameters for a selected parameter α=0.75

Figure 8 shows the influence of the relaxation time τ of the Cole – Cole model on the return voltage parameters (Tab. 1) for the selected parameter α=0.75. It should be noted that relaxation time (of course at a constant value α) practically has no influence on parameters U_{R_MAX} and A, regardless of the length of short-circuit time t_z. However, parameters t_{R_MAX} and $t_{R\_50\%}$ react definitely diversely to an increasing value of relaxation time τ. The former significantly lowers its value while the latter increases it. This is clearly distinct for the range of longer short-circuit times t_z. Parameters k_U and $P_{R\_50\%}$ behave in almost exactly the same way.

6. CONCLUSION

According to author, a series-parallel substitute scheme of the paper-oil insulation sample determined from the Cole-Cole model can be well used in insulation diagnostics of professional power appliances by the use of the polarization methods. Moreover, determining the values of RC elements of the scheme directly from the measurements using the FDS method makes it possible to diagnose the insulation condition of the appliance under study also by PDC and RVM methods through examining the system reaction to an individual activation with voltage by computer simulation. The analysis of the return voltage of the insulation sample simulated, carried out with the recommendations of the RVM method, proves that there is a need to supplement this diagnostic method with the analysis of additional parameters of the return voltage. In this paper a list of parameters was suggested, the application of which makes it possible to estimate parameters α and τ of the Cole-Cole model for the insulation sample under study. Obviously the analysis of the paper-oil insulation condition carried out based on the list of parameters presented, still requires a number of laboratory tests taking into account, for example, the influence of temperature.

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