Current Response of Insulation Systems Based on ReMica Materials and Accelerated Thermal Degradation

Roman Cimbala, Iraida Kolcunova, and Igor Krsnak

***Abstract*—This paper describes the behavior of ReMica material Relanex during accelerated thermal stress. Samples were stressed at temperature 186°C. Polarization processes were observed due to direct voltage application. Absorption curves were measured and the isothermal relaxation current analysis was realized. Also capacitance and loss factor development was monitored.**

***Index Terms*—Accelerated thermal ageing, diagnostics, insulation system, polarization processes.**

I. Introduction

PRESENT state of knowledge does not offer us a single complex method that could determine the state of insulation systems itself. That is why the set of methods has to be applied. As equipment are different the set of methods has to be different too. Also, one kind of equipment can be made with different kinds of insulation systems. Then it is necessary to utilize selected computing evaluation [1]. The knowledge of current condition and a possible lifetime calculation of expensive equipment (transformers, generators, etc.) is important to ensure a safe operation, especially by older equipment and higher electrical power networks strain.

Ageing has a direct impact on the electro-physical structure of materials and the structure itself has a major influence on the breakdown voltage and the lifetime. As shown in Fig. 1, for the real objects there is no direct method to calculate the electrical strength of lifetime from stress parameters. But useful diagnostic method can describe the electro-physical structure and observing changes of relevant diagnostic parameters can describe ageing process. In this occasion the condition orientated maintenance of insulation of equipment in electrical power supply includes a lot of possible diagnostic methods and techniques to detect the of typical failures, defects and dangerous ageing effects.

Typical diagnostic methods versus the application on different equipment are summarized in [2]. The rest of this paper is organized as follows. Section II explains the application DC diagnostic methods for the test of insulation systems. The experiments and their results are presented in Section III. These results are discussed later in Section IV. Finally, Section V concludes the paper.

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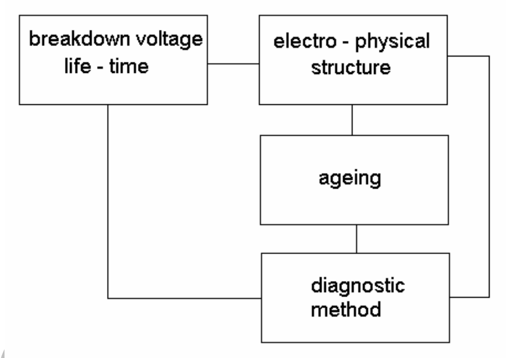

Fig. 1. Diagnostic method principle.

II. The application of DC methods

As was mentioned previously, there are many diagnostic methods for insulation systems. The application of DC methods is narrowly connected with the bandwidth of observing spectrum. The most information of the common insulation material is concentrated in the 10^{-4} to 10^{5} seconds interval

A. Macroscopic Point of View

Direct methods are based on the observation of current or voltage time responses. The most well-known methods are polarization indices, relaxation current analysis, recovery voltage or self-discharge analysis, etc.

It was proved that the characteristic shape of the current curve changes during the ageing of the insulating material as the electro-physical quality is changed. It is possible to observe other changes of electrical quantities during service ageing.

The analysis of the polarization spectrum of the insulating material is based on the measurements of relaxation currents.

Equation (1) describes the total current. It consists of three components:

$$i_t(t) = i_c(t) + i_v + i_a(t) \qquad (1)$$

$i_t(t)$ - Total current
$i_c(t)$ - Geometrical capacity current
$i_a(t)$ - Absorption current
i_v - Steady current.

Geometrical capacity current is too quick (about 10^{-12} s) and it is possible to neglect it. Then (1) can be written as

$$i_t(t) = \frac{U_0}{R_0} + \sum_{i=1}^{n} I_{mi} \exp\left(\frac{-t}{\tau_i}\right) \qquad (2)$$

U_0 - Applied direct voltage
R_0 - Insulation resistance in infinity time
I_{mi} - Amplitude of i -th elementary polarization current
τ_i - Time constant of stabilization of of i -th elementary polarization process,
t - Time.

The equivalent model of the insulating material is based on n independent Debye polarization processes. Each process has its own time constant of stabilization τ_I and maximum of elementary current I_{mi} and by observing its changes it is possible to get information about the state of insulation system.

B. Microscopic Point of View

The base information of problem background can be found in work of Simmons and Tam [3]. According to this work the probability of negative charges emission from trapping level with activation energy can be given by

$$W_T = W_L - W_H \tag{3}$$

$$e_N(W.T) = v \cdot \sigma_N \cdot N_L \cdot e^{-\frac{W_T}{k \cdot T}} \tag{4}$$

W_H - Energy of trapping level
W_L - Energy of low conduction level
W_T - Activation energy for charge emission from trapping level
v - Escape frequency
N_L - Effective density in conduction level
k - Boltzmann's constant
T - Temperature
V - Thermal velocity of electrons
σ_N - Probability of electron trapping

Trapping energy level can be described as (5) according to [4]

$$\Gamma(W) = \frac{v \cdot \sigma_N \cdot n_s}{v \cdot \sigma_N \cdot n_s + v \cdot \sigma_P \cdot n_P} \tag{5}$$

$\Gamma(W)$ - Initialization of occupation of trapping level
n_s - Free density of electrons in stationary state
n_p - Fee density of holes in stationary state

Observing current for surface unit is in (6) and (7)

$$i_N(t) = \frac{q \cdot d}{2} \cdot \int_{W_F}^{W_L} \Gamma(W) \cdot V(W) e_N(W,T) \cdot e^{-e_N(W,T) \cdot t_{dW}} \tag{6}$$

$$i_N(t) \cdot t = \frac{q \cdot d \cdot k \cdot T}{2} \cdot \Gamma(W) \cdot V(W) \tag{7}$$

W_F - Fermi's level
$V(W)$ - Energy spectrum of trapping levels
q - Charge
d - Thickness of sample

W_H is time dependent because during the occupation of energy level it retreats from conducting level.
Then it is directly proportional to time

$$W_T(t) = W_L - W_H = k \cdot T \cdot \ln(v \cdot t)\ . \tag{8}$$

Energy spectrum can be written as

$$\Gamma(W) \cdot V(W) = \frac{2t}{q \cdot d \cdot k \cdot T} \left[I_0 + \sum_{1=1}^{n} a_i \cdot e^{-\frac{t}{\tau_i}} \right]. \tag{9}$$

As it can be seen, the result is obtained as (9) with steady state element in the square brackets that represents steady current from (1) or element from (2). Element represents absorption current from (1) or it is identical with element from (2).

The conclusion is that the macroscopic and microscopic views of polarization processes during direct voltage application lead to the same results.

III. Test and Results

In this research the main aim was to determine the temperature influence on chosen diagnostic parameters during accelerated thermal stress and the entire lifetime.

To find out the influence of thermal ageing on chosen diagnostic parameters laboratory tests were carried out. The samples were made from ReMica material Relanex®. It is a combination of mica paper and glass cloth, impregnated with epoxy resin. It is rigid after curing. It is used as the primary insulation (slot and endwinding) for coils of low and high voltage machines. This material is frequently used in Czech and Slovak Republic. The size of sheet samples were $100 \times 100 \times 0.4$ mm. The samples were obtained directly from their producer.

They were stressed in drying-oven with enclosed air recirculation. Temperature was electronically controlled. The accelerated ageing was reached. According to the Relanex® manufacturer, the material is thermal class F and in temperature of 155 °C the lifetime is 20,000 hours.

Arhenius law defines the temperature, under which ageing process is not present. This temperature is higher than room temperature. It means that under this temperature the lifetime is in reality almost infinite and we cannot observe any significant changes of material. That is why the stress temperature was increasing during our tests. As temperature increases, the lifetime is shortened. If we want to overcome the entire lifetime in a reasonable time, we have to increase the temperature. But there is an upper threshold for temperature increase. Above this threshold different mechanism of ageing is present and the slope of the lifetime curve is breaking down.

According to the Relanex® manufacturer this threshold is equal to 190 °C. That is the reason why the samples were thermally stressed at 186 °C during 6144 hours. We accelerated ageing to obtain the results within a reasonable time. The cataloged dataset were measured. There were 11 sets each with seven samples. All figures and tables show typical changes of monitored features. The measurement time steps are selected in a logarithmic manner.

The time steps of 0 (new material), 12, 24, 48, 96, 192, 384,768, 1536, 3072 and 6144 hours were pre-selected. Currents were analyzed and characteristic parameters from (2), i.e. I_{mi} and τ_i, then the relative error of calculation were computed. The results for one elementary polarization process $n=1$ are shown in Figs. 2 and 3. The test voltage was set to 100VDC. The current responses to DC voltage were measured using electrometer Keithley® 617 measuring instrument which was controlled by a personal computer (PC) via an IEEE 488.2 interface. Samples were placed in electrode system chamber Keithley® 8008. The instrument supply voltage was also set equal to 100 VDC.

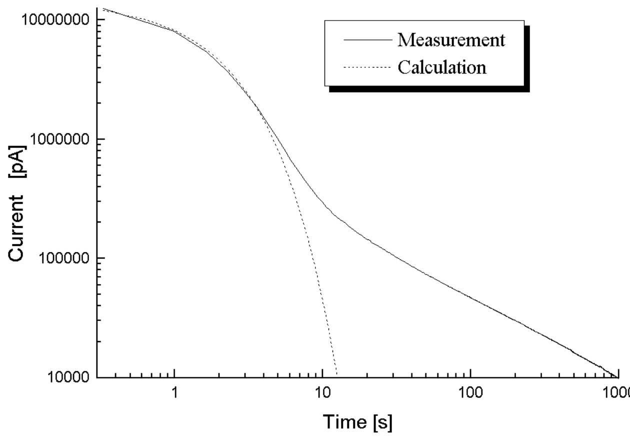

Fig. 2. Measured and calculated data for one element.

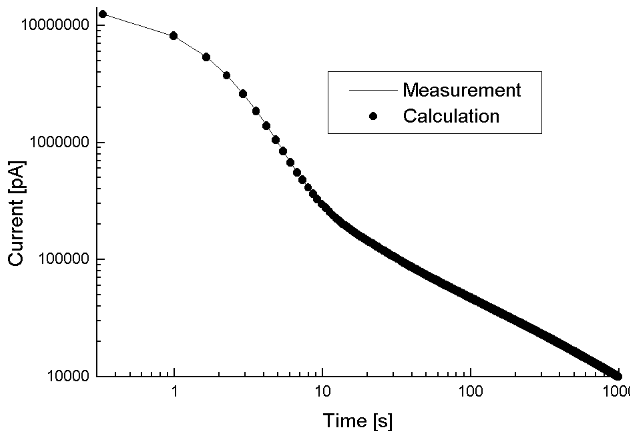

Fig. 4. Measured and calculated data for seven elements.

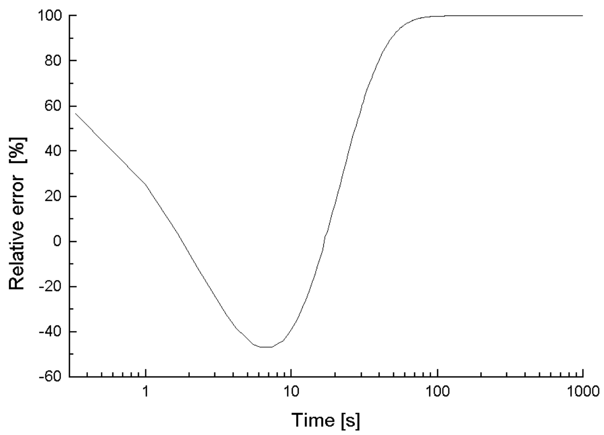

Fig. 3. Calculation of relative error for one element.

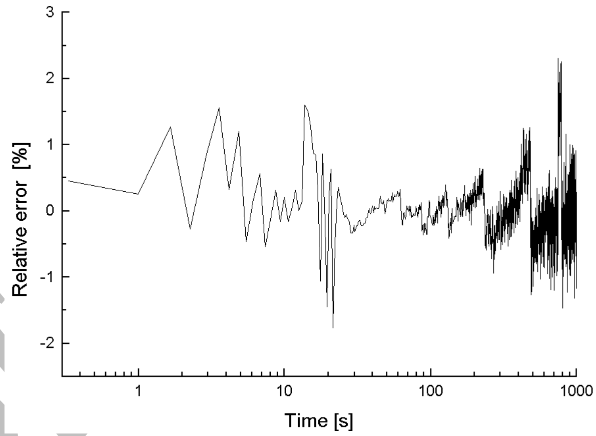

Fig. 5. Calculation of relative error for seven elements.

TABLE I
POLARIZATION PROCESSES PARAMETERS I_{mi}

Element Aging Hours	1st	2nd	3rd	4th	5th	6th	7th
0	1000	258	185	12	2.19	0.38	0.24
12	248	45	15	2.9	1.25	0.35	0.23
24	182	24	7.11	1.8	1.06	0.33	0.23
48	168	22	4.67	1.4	0.78	0.30	0.14
96	162	21	3.89	1.2	0.60	0.27	0.10
192	154	20	3.61	1.1	0.50	0.20	0.05
384	147	20	3.54	1.0	0.47	0.16	0.03
768	132	20	3.70	1.1	0.44	0.17	0.04
1536	117	20	3.80	1.1	0.50	0.18	0.06
3072	104	19	3.24	1.1	0.52	0.17	0.05
6144	93	18	3.00	1.0	0.58	0.17	0.04

TABLE II
POLARIZATION PROCESS PARAMETER τ_i

Element Aging Hours	1st	2nd	3rd	4th	5th	6th	7th
0	0.3	4.7	30	189	897	2514	35638
12	1.7	9.0	35	245	1017	5000	39845
24	2.2	10.5	37	354	1256	7055	44171
48	2.6	13.1	39	417	1495	7759	46027
96	2.8	13.7	41	443	1643	8358	48665
192	2.6	13.1	49	330	1704	9845	51547
384	2.4	12.5	59	257	1823	13110	52309
768	2.5	12.7	64	362	2416	13759	54239
1536	2.6	13.0	70	416	2784	14151	62654
3072	2.8	13.0	71	443	2804	15357	200154
6144	2.9	14.7	87	487	2447	14007	256743

As shown in Figs. 2 and 3, the results for one polarization process are not acceptable. The error from real object is very large. The experiments determined that up to seven elements is necessary to model real current response of material based on ReMica. The results are depicted in Figs. 4 and 5.

The relative error, I_{mi}, and τ_i parameters were calculated. This is a very important point. We replaced real measured current response with the current consists of n-elements. Therefore, we had to know how exact is our calculation of real signal. As can be seen in Fig. 5, the relative error is small, i.e. less than 3% of the signal value. That is the calculation has an acceptable accuracy.

Table I shows the behavior of each of seven elementary polarization processes parameters I_{mi} in pA during ageing. Table II shows the behavior of each of seven elementary polarization process parameter τ_i in seconds during the ageing process. We also obtained one-minute polarization index P_1 and ten-minute polarization index P_{10} as shown in Figs. 6 and 7.

The capacitance and dissipation factor were measured too, but without reasonable results. Noticeable influences of voltage were observed only in dissipation factor measurements but without any correlation to ageing.

We can modify (2) according to the electro-physical model of insulation system as shown in Fig. 8. In accordance with (2) and Fig. 8 the model is based on n-elementary polarization processes as

$$i_t(t) = \frac{U_0}{R_0} + \sum_{i=1}^{n} \frac{U_0}{R_i} \exp\left(\frac{-t}{R_i.C_i}\right). \qquad (10)$$

Then we can calculate values of elements for equivalent model of insulation system.

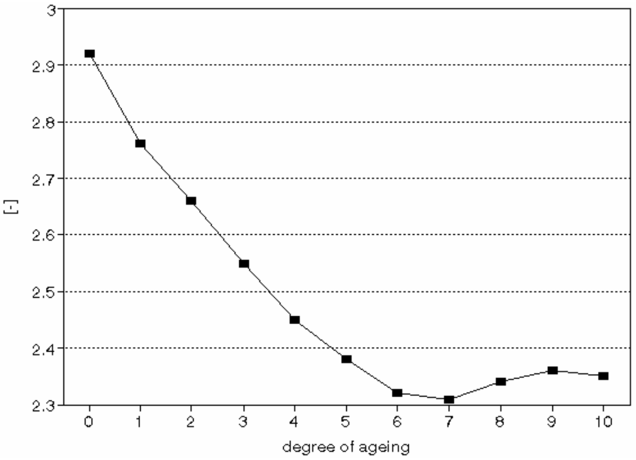

Fig. 6. One-minute polarization index P_1.

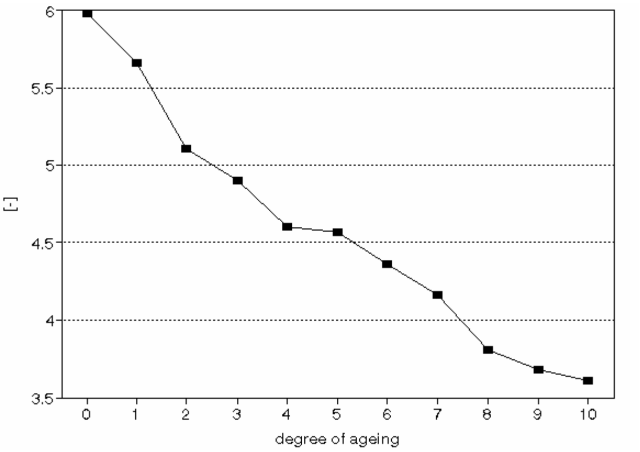

Fig.7. Ten-minute polarization index P_{10}.

The values of each element in Fig. 9 in equivalent model of insulation material allow us to model real object as mathematic object.

IV. Discussion

The dielectric relaxation from the point of classical Debye relaxation and modern energy trap levels analysis (Isothermal relaxation current analysis) was studied. The relaxation behavior can be observed depending on internal structure of the system and electrical properties of the material.

As was described previously, 11 set each with seven samples were examined during the material lifetime. Magnitudes I_{mi} and time constants of stabilization τ_i of elementary polarization currents were calculated as diagnostic parameters for observing changes in relaxation spectrum. Accuracy of replacement of real current response with mathematical–physical model was verified with relative error calculation. The shift of both parameters is significant in Table II. Authors are aware that it is only a single test with 11 sets of seven samples. We obtain data from thermal ageing under simplified condition - constant temperature and no other stress influence were presented.

The used materials are composition of several elements and various failures can be presented. From general point of view on materials we have to use different methods. They are sensitive on failures or degradation processes. The method described hereinbefore is only one of possible diagnostic method.

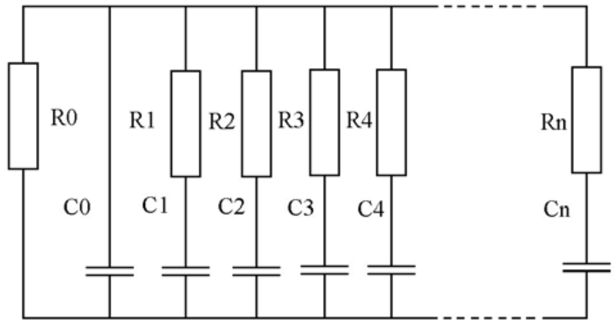

Fig. 8. Electro-physical model of insulation system.

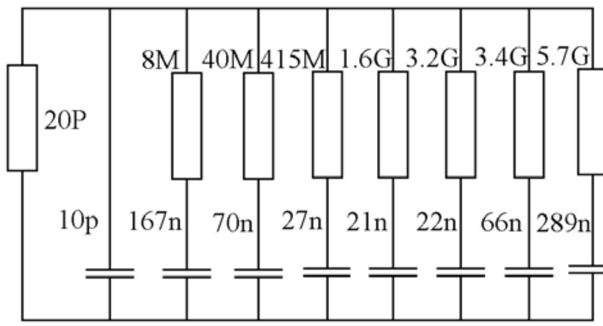

Fig. 9. Values of elements of equivalent model.

Only one type of material was investigated. It is evident that other materials will have different behavior during accelerated thermal stress and the measured data cannot be simply generalized. On the other hand,, we obtained information for a specific material with widespread uses for insulation system of high voltage machines in our country. Materials with same or similar composition would have alike general behavior because of its close connection to material structure and changes of its elementary components during ageing. Mica is very resistant material under thermal ageing. Epoxy resin works as binding component and it is weak element of insulation system and it powders during ageing and makes delamination process. We assume that main changes were occurred in epoxy resin as delamination process was observed in final state of material. In addition, another components are presented, but they have not as much volume in material as those mentioned before.

V. Conclusion

The aim of this research was obtaining of characteristic behavior of nowadays used diagnostic parameters from initial ageing process up to the end of the lifetime. Data of Relanex® samples during its lifetime under simple thermal stress were measured and calculated. Therefore measuring the unknown object and comparing calculated elements with those from experiment can give us information about approximate position of insulation systems in thermal degradation lifetime curve.

We obtain data only for one material. Other kind of materials will apparently present different results. In present state of ageing knowledge, there is not a single diagnostic method that can determine the state of insulation material. It is necessary to mention that other diagnostic measurements have to be carried out to determine the complex state of any material (measuring of partial discharges, differential thermal analysis, analysis of surface protection layers, etc.)

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Roman Cimbala was born in Kosice, Slovakia, in 1962. He graduated in electrical power engineering, field of generation and transmission of electrical energy, Faculty of Electrical Engineering and Informatics, Technical University Kosice in 1986. He received the Ph.D. degree in electric power engineering from Slovak Technical University in Bratislava in 1994.

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His research interest is in the area of diagnosis of high voltage insulation systems, especially in isothermal relaxation current analysis. He developed control and evaluation software for diagnosis of high voltage insulation systems based on Hewlett Packard Virtual Engineering Environment. He teaches different subjects in the field of generation of power energy and utilization of computer technique for diagnostic purposes based on artificial neuronal networks.

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