# THE CALCULATION OF POLARIZATION SPECTRUM AND ACTIVATION ENERGY OF INSULATION DURING ACCELERATED THERMAL STRESS

Roman CIMBALA
Department of Electric Power Engineering, Faculty of Electrical Engineering and Informatics,
Technical University of Košice, Mäsiarska 74, 040 01 Košice, Slovak Republic, tel.: +421 55 602 3557,
E-mail: roman.cimbala@tuke.sk

**SUMMARY**

*One of the cardinal properties of the insulation system of the electrical equipment is its electrical strength. Usually it is expressed as value of breakdown voltage. There is not electrical destruction of material under this one. The determination of breakdown voltage exactly is possible only by doing electrical strength test. It is a destructive test on insulation system made by solid material. This test is not suitable for service condition. There isn't only one test method that can complex diagnose the state of insulation system. The utilization of set of diagnostic methods is necessary. The biggest meaning in monitoring of high voltage insulation system ageing consists in methods based on regular non-destructive diagnostics. The analysis of results from several diagnostic methods is the principle. The issue of such diagnostics is detailed information about ageing process of insulation system of high voltage equipment. The high voltage motor is a very important element in the production process. A breakdown of its insulating system may cause a loss to the production. Therefore the importance of measuring and testing of its electrical properties is increasing more and more in conjunction with advances of power engineering equipment. This paper describes the use of polarization spectrum determination for diagnostic purposes, especially for insulating systems of high voltage machines. The study of absorption current during accelerated thermal degradation is presented in this paper. Absorptive currents are analyzed. The thermal behavior of a simple model of multi-layer insulation material based on ReMica is described together with recommendation for practical utilization. The activation energy during accelerated thermal stress is calculated and analyzed.*

***Keywords:*** *activation energy, insulating system, degradation, current response, equivalent model, polarization process, time of stabilization*

## 1. INDRODUCTION

The high voltage motor is a very important element in the production process. A breakdown of its insulating system may cause a loss to the production. Therefore the importance of measuring and testing of its electrical properties is increasing more and more in conjunction with advances of power engineering equipment.

## 2. POLARIZATION SPECTRUM

As can be seen from Fig. 1 the application of method is narrowly connected with bandwidth of observing spectrum. The most information is in interval from $10^{-4}$ to $10^{5}$ s.

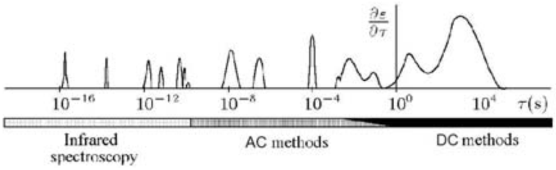



**Fig. 1** Common polarization spectrum of insulation material

DC methods are based on observing current or voltage time responses. The well-known are polarization indeeces, absorptive or resorptive current analysis, recovery voltage or self-discharge analysis [1]. There is no problem with power supply as in case of AC diagnostic method. For example, the measurement of capacitive object with capacity about 10nF and applied voltage 10 kV the requisite current is about 100mA. This is quite huge supply.

Not so far ago the polarization spectrum of insulation material was scanned only by polarization indeeces. They are described very easy as a ratio of observing absorptive or resorptive currents at the determined time applying DC voltage.

$$p_1 = \frac{R_{60}}{R_{15}} = \frac{i_{15}}{i_{60}} \tag{1}$$

$$p_{10} = \frac{R_{600}}{R_{60}} = \frac{i_{60}}{i_{600}} \tag{2}$$

where

| | |
|---|---|
| $p_1$ | – 1minute polarization index |
| $p_{10}$ | – 10minute polarization index |
| $R_{15}$ | – resistance in time 15 s |
| $R_{60}$ | – resistance in time 60 s |
| $R_{600}$ | – resistance in time 600 s |
| $I_{15}$ | – observing current in time 15 s |
| $I_{60}$ | – observing current in time 60 s |
| $I_{600}$ | – observing current in time 600 s |

### 2.1. Maxwell – Wagner's model for insulation

Macroscopic response on direct voltage step in insulating system is an absorptive and during discharges resorptive current. The analysis of the polarization spectrum of the insulating material is based on their measurements. They were carried out on insulation samples of ReMica material Relanex degraded by thermal stress. The material is used to the high voltage rotating machine insulating system construction.

According to Maxwell - Wagner equivalent model for multi-layer dielectrics the total current consists of three components:

$$i_t(t) = i_c(t) + i_0 + i_a(t) \qquad (3)$$

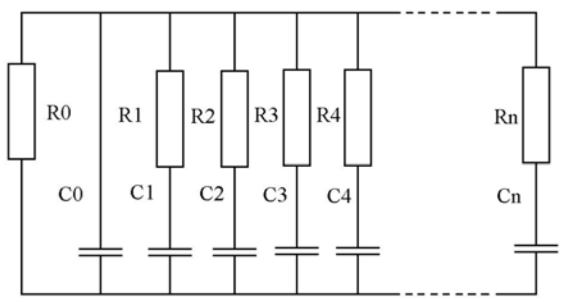



**Fig. 2** Maxwell - Wagner equivalent model

When direct voltage with amplitude $U_0$ is applied, then it is possible to write out equation (3) using ***R*** and ***C*** elements from equivalent model according to Fig.1

$$i_t(t) = i_c(t) + \frac{U_0}{R_0} + \sum_{i=1}^{n} \frac{U_0}{R_i}.\exp\left(\frac{-t}{R_i.C_i}\right) \qquad (4)$$

where

$R_i$,$C_i$- elements of the model,
$U_0$ - applied direct voltage,
$R_0$ - steady resistance,
$i_0$ - steady current,
$i_c(t)$ - geometrical capacity current,
$i_a(t)$ - absorptive current.

The response time constant of the geometrical capacity current is about $10^{-12}$ s and it is possible to neglect it practically. In the case of dry insulation system the steady current is reduced in value than absorption current. In the case of material with moisture the steady current component appears in calculation data. On this base it is possible to distinguish low insulation resistance caused by humidity or by ageing.

The equivalent model of the insulating material is described in [1] and it is based on n independent Debye's polarization processes. The time response constants $\tau_i$ and elementary currents $I_{mi}$ were calculated from the equivalent model according to

$$\tau_i = R_i.C_i \qquad (5)$$

$$I_{mi} = \frac{U_0}{R_i} \qquad (6)$$

It was proved in [3] that the characteristic shapes of the current curve were changed during the thermal ageing.

### 2.2. Isothermal relaxation current

There are several different methods to increase validation of polarization spectrum change observing.

Isothermal relaxation current has close connection to trap value of energy in band model of atom. The trapping bands of energy are discrete distributed. If recombination of charges is neglected, during excitation or discharging of material there is direct determination of trapping energy level from measures current response can be done.

Initialization and occupation of trapping energy bands is results of applying electrical field. The density of measured current is calculated from emission of negative charge carriers.

In the case of all electrons above trapping energy band $W_H$ are ejected and electrons in energy bands under $W_H$ are reserved with initialization energy. Energy band $W_H$ retreats from conduction band $W_L$ during time. It is valid for each trapping band $W_H$. Energy $W_T$ can be determined as [2].

$$W_T(t) = W_L - W_H = k \cdot t \cdot \ln(\nu \cdot t) \qquad (7)$$

$W_L$ – energy of low conduction band
$W_T$ – activation energy for charge emission from trapping band
$W_H$ – energy of trapping band

As macroscopic performance of electron transmission between energy bands is current response, external current for plane insulation can be derived as

$$i_N(t) \cdot t = \frac{q \cdot d \cdot k \cdot T}{2} \cdot \Gamma(W_T) \cdot V(W_T) \qquad (8)$$

$$\Gamma(W_T) \cdot V(W_T) = \frac{2}{q \cdot d \cdot k \cdot T} \cdot t \cdot \left[ I_0 + \sum_{i=1}^{3} a_i \cdot e^{-\frac{t}{\tau_i}} \right] \qquad (9)$$

where

$\Gamma(W_T)$ – initialization of occupation of trapping bands,
$i_N(t)$ – measured current refered to planar unit,
$V(W_T)$ – energy spectrum of trapping bands,
q – charge,
d – thickness of insulation.

As can be seen relationship between ***I.t*** and ***ln t*** leads towards to contribution of each trapping energy level to total current. Ageing process changes this distribution.

### 2.3. Test

As can be seen, both ways of polarization spectrum evaluation – macroscopic way represented with equation (4) and microscopic way represented with equation (9) describe the same process of excitation but from different point of view. The expressions are similar – sum of exponential function with parameters $\boldsymbol{I_{mi}}$ and $\boldsymbol{\tau_i}$. The test was carried out using macroscopic view and will be described bellow.

The method is described in [3] in detail. The absorption process can be characterized by several independent Debye's polarization processes. The current amplitudes from each of elementary processes were decreasing and the times of stabilization were increasing during ageing unambiguously. The thermal ageing influence on the polarization was accomplished.

The test was carried out on the insulation material Relanex based on ReMica. Insulation system samples were subjected to accelerated thermal stress at 220$^o$C. Therefore the life-time decreased from 20.000 hours to 1.344 hours. The test consisted of 24 sets, each with 7 samples. The 0-th set with 7 samples was without stress. The last 24-th set was subjected to thermal field for 7.000 hours to achieve the state over the life-time point.

The samples were measured according the scheme on Fig. 3.

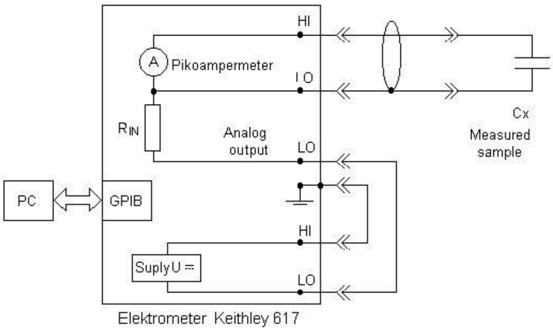



**Fig. 3** Scheme for measuring of absorptive current of sample

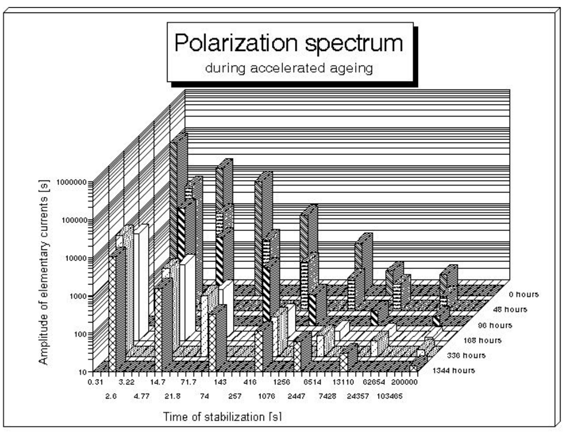



**Fig. 4** Polarization spectrum during accelerated thermal stress

Fig. 4 illustrates the times of stabilization and amplitudes of elementary currents of 7 polarization processes during the ageing.

The calculation of the times of stabilization of Debye's independent polarization processes and elementary currents is described in [3] in detail.

## 3. DEGREE OF THE ACTIVATION ENERGY

Another macroscopic quantity can be calculated. DC resistance of insulation system can be represented as resistance $\boldsymbol{R_0}$ from Maxwell – Wagner's equivalent model. It can be evaluated as resistance in time leads to infinity. It has close connection to thermal behavior of activation energy. [4]. That is why the temperature influence on the resistance was observed during thermal ageing. The test temperatures were 20, 50, 90, 110, 130 and 155$^o$C. According to the equation [4]

$$\gamma = n.q.u \tag{10}$$

$$\gamma = q.\left[N.\exp\left(-\frac{W_d}{2.k.T}\right)\right].\left[\frac{q.\lambda^2.\upsilon}{6.k.T}.\exp\left(-\frac{W_0}{k.T}\right)\right] \tag{11}$$

$$\gamma = \frac{N.q^2.\lambda^2.\upsilon}{6.k.T}.\exp\left(-\frac{W_d+2.W_0}{2.k.T}\right) \tag{12}$$

where

- $W_d$ - activation energy necessary for defect origin,
- $W_0$ - activation energy of molecule,
- N - total count of ion couples,
- Q - electrical charge,
- $\lambda$ - mean free path of ions,
- $\upsilon$ - frequency of self oscillation of captured molecules,
- n - count of charge carriers,
- u - mobility,
- T - temperature,
- k - Boltzmann's constant,
- $\gamma$ - conductance.

According to the simplified equation in observing interval of temperature

$$\gamma_{0T} = \frac{N.q^2.\lambda^2.\upsilon}{6.k.T} \tag{13}$$

and

$$\alpha = \frac{W_d+2.W_0}{2.k} \tag{14}$$

$$\gamma = \gamma_{0T}.\exp\left(-\frac{\alpha}{T}\right) \tag{15}$$

$$R_{0T} = \frac{1}{\gamma_{0T}} \tag{16}$$

it is possible to write the resistance equation

$$R = R_{0T}.\exp\left(-\frac{T}{\alpha}\right) \qquad (17)$$

where

α - degree of activation energy,
T - temperature,
R - resistance.

The temperature influence on resistance was measured at mentioned temperatures. After that the exponential regressions were carried out. The example for the new material (0 hours of stress) is in the Fig. 5.

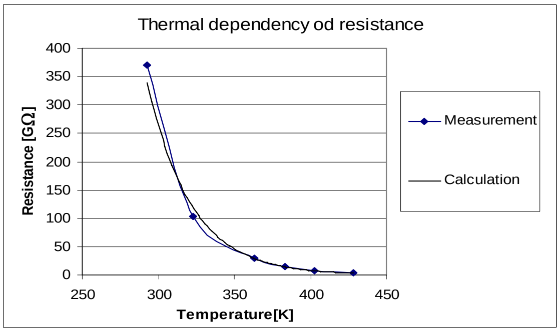
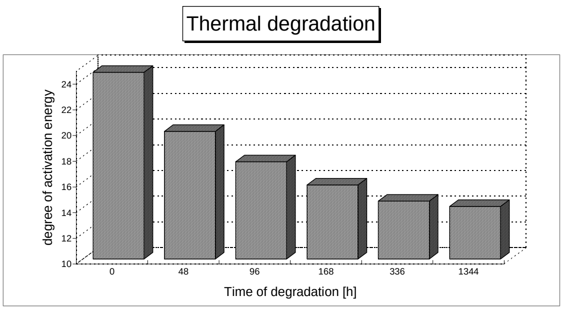



**Fig. 5** The exponential regression for the new material

The observing time was chose to have equidistant step at the logarithmic time scale. The calculated results are in Tab. 1 and Graph 1.

| Time of thermal degradation | Degree of activation energy α |
|---|---|
| 0 hours | 24.5 |
| 48 hours | 19.95 |
| 96 hours | 17.57 |
| 168 hours | 15.77 |
| 336 hours | 14.51 |
| 1344 hours | 14.1 |

**Tab. 1** Degree of activation energy during ageing




**Graph 1** Degree of activation energy during ageing

Theoretical assumptions were confirmed. Ageing of material decreases its breakdown voltage and it is causes due to decreasing of activation energy.

## 4. CONCLUSION

It was demonstrated how it is possible to calculate elements of equivalent model for dielectric materials. Base principles of methods were described and values of electrical quantities as $\boldsymbol{R_i}$ and $\boldsymbol{C_i}$ were calculated. During the scanning of thermal ageing influence on polarization spectrum behavior the degree of activation energy was calculated. It was proved that the degree is decreasing during ageing monotonously. According to theses results this quantity could be added to the diagnostic test set to determine the state of insulation system of electrical equipments.

## REFERENCES

[1] Németh, E., Horváth, T.: Fundamental of the stimulation of dielectric processes of insulations, 8-th ISH, Yokohama, Japan 1993.
[2] Beigert, M., Kranz, H.-G., Kaubisch, D., Meurer, D.: Computer – Aided Destruction Free Ageing Diagnosis for Medium – Voltage Cables, 8-th ISH Yokohama, Japan, paper 67.11, 1993.
[3] Cimbala, R.: Current response in multilayer insulation at ultra-low frequencies, PhD Thesis, Department of High Voltage Technique, Faculty of Electrical Engineering, Technical University Košice, Košice 1993.
[4] Poljak, F.: Dielectrics and insulations, Alfa 1983, Bratislava.

## BIOGRAPHY

**Roman Cimbala** was born in Košice, 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 Košice in 1986. He received the Ph.D. degree electric power engineering from Slovak Technical University in Bratislava in 1994, and associate professor degree from Technical University Košice in power engineering diagnostics in 1998.
He is a member of IEEE, Working Group "Insulation Diagnostics" and invited member of Working Group "Electrostatics". He is a member of Slovak Commission for Technical Normalization, and Slovak Association for Technical Diagnostics.
He is personally interested in diagnostics of high voltage insulation systems. He teaches subjects aimed to generation of power energy and utilization of computer technique for diagnostic purposes based on artificial neuronal networks.

This work was supported by grants VEGA 1/3142/06 and APVV-20-006005.