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DIELECTRIC PARAMETERS ESTIMATION BY THE MEASUREMENT OF THE RELAXATION CURRENT

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Abstract – Paper describes new method of the estimation of the relaxation properties of dielectric materials based on the direct estimation dipole R,C parameters and from the decomposed isothermal current, which is represented by multiexponetial function. Proposed least mean squared optimization is resistant on the accumulation of error in the successive component estimation. Moreover takes into account mutual influence of parameters on the time constants and peak values of the exponential components.

Keywords: Dielectric parameter measurement, Isothermal current analysis, LMS optimization

1. INTRODUCTION

Relaxation is a physical effect which can be observed during the polarization of the dipoles in the dielectric materials from their initial positions under influence of the electrostatic field. Reverse process takes place after disconnecting the electrical field. The dipoles represent the structural components in the dielectric and are characterized by its relaxation time and peak value of current from the polarization initial point.

The electrical model of this phenomenon is represented by Maxwell-Wagner model, which consists of the parallel $R_{i,}C_i$ branches(Fig.1). Each one corresponds to the dipole moment of a chemical component in the dielectric material mixture. (Fig.1). After switching on the voltage source U_0, the $R_{i,}C_i$ circuits generate the superimposed exponential charging currents with different time constant and peak value. Similar superposition of the exponential components can determines the output voltage across the capacity C_1 in the discharging phase.

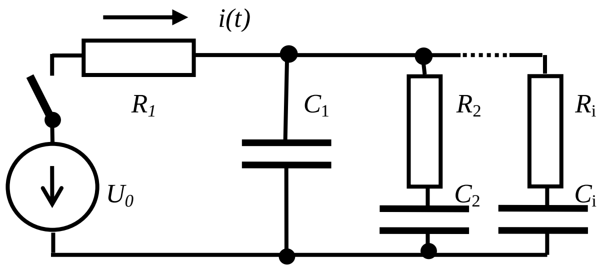

Fig.1.Electrical model of the relaxation process in the dielectrics.

The measurement of relaxation processes in dielectrics is more important in the non-destructive diagnostic of insulating systems [3] [4]. Process of the insulation aging is demonstrated by the changes in the $R_{i,}C_i$ branches in comparison with their initial values.

Similar relaxation processes in dielectrics determine dielectric absorption of capacitors. It is manifested by their "memory", and influence on the final error in Sample and Hold Circuits or on the linearity of dual slope AD converters [1], [2].

The analysis of the current $i(t)$ is the basic approach for diagnostic of dielectric properties in the HV dielectric cables or the insulting systems made from calcined mica papers and polyethylenetereftalat's foil banded together by epoxy compound. It allows recognizing changes of the material structure due to degradation. At the present many methods allows to measure changes in the insulation structure due to ageing. Method based on the current analysis (IRC - Isothermal Current analysis) is based on the identification of time constants and peak values of the exponential components. Several polarization processes occurs in common insulation system and they are described by n parallel RC branches in Fig.1. According to common parameters of the measured sample the maximal number of parallel branches is seven and the recording time achieves 1000s.

$$i(t) = A_1 e^{-B_1 t} + \sum_{i=2}^{n} A_i e^{-B_i t},$$
$$A_1 = \frac{U_0 - u(t)}{R_1},\ B_1 = \frac{-1}{R_1 C_1} \qquad (1)$$

Where A_i is the peak value of the current and B_i is the inverse value of the time constant of each parallel $R_{i,}C_i$ branch in the model Fig.1.

Number of members of expansion n is dependent on the structure and homogeneity of the dielectric and the time at which the polarizing action are measured [5].

The actual measuring approach performs the IRC analysis under assumption of the ideal voltage source U_0 connected to the dielectrics by the ideal switch. The current $i(t)$ from the voltage source U_0 is utilized for identification of coefficients A_i,B_i in (1). The assumption of low serial resistance R_1 of voltage source and ideal voltage switch allows to consider the first component in (1) in form of Dirac pulse $A_1 \to \infty$, $B_1 \to \infty$. The other coefficients $A_{i,}$ B_i in (1) are calculated with an approximation algorithm [6] based on the estimation of any exponential component from the current $i(t)$ by the Least Mean Squared (LMS) method. Here the inverse values of relaxation time B_2 and peak value A_2 is determined the best fitted exponential functions from the measured current $i(t)$ using LMS method. Successively, this component is subtracted from the input current. The residual current $i_2(t)=i(t)-A_2e^{B2t}$ is used for the estimation of third component A_3,B_3. Similarly, constants B_i and A_i of i-th exponential are determined from the current $i_i(t)$ after removal the best fitted exponential components from previous approximation steps.

The superimposed noise of various origin causes that error from the estimation of the (i-th) exponential component is transferred in the estimation of the successive component. The uncertainty in the each consecutive step is accumulated. [1].

2. PROPOSED METHOD

In order to suppress errors caused by the final value of input resistance of DC supply, accumulation of the uncertainty in the estimation of each exponential component by the usually used approximation algorithm and mutual influence of parallel R_i,C_i components on the A_i, Bi constants authors proposed the estimation of R_i,C_i by direct optimisation algorithm. It is based on the method when the charging current $i(t)$ is calculated analytically for the circuit Fig.1 as the functions of the circuit components R_i,C_i . The voltage source U_0 and switch S is considered as real component with internal resistance R_1.

2.1. Analytical description of IRC process

Charging process is being described by the n linear differential equations.

$$du/dt = \boldsymbol{A}.\boldsymbol{u} + \boldsymbol{b}, \quad where$$

$$\boldsymbol{u} = \begin{bmatrix} u_1(t) \\ u_2(t) \\ \vdots \\ u_n(t) \end{bmatrix}; \quad \boldsymbol{b} = \begin{bmatrix} U_0/R_1C_1 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \qquad (2)$$

Voltages $u_i(t)$ across the capacitors C_i represent state variables. Using steady-state circuit description the components of the matrix A are as follows:

$$\boldsymbol{A} = \begin{bmatrix} -\frac{G_T}{C_1} & \frac{G_2}{C_1} & \frac{G_3}{C_1} & \cdots & \frac{G_n}{C_1} \\ \frac{G_2}{C_2} & -\frac{G_2}{C_2} & 0 & \cdots & 0 \\ \frac{G_3}{C_3} & 0 & -\frac{G_3}{C_3} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \frac{G_n}{C_n} & 0 & 0 & \cdots & -\frac{G_n}{C_n} \end{bmatrix} \qquad (3)$$

where $G_T = \sum_{i=1}^{n} \frac{1}{R_i}$ and $G_i = \frac{1}{R_i}$

Analysed voltages $u_i(t)$ aree determined by the analytical solution of the matrix equation (2). The relaxation current $i(t)$ is obtained by the equation

$$i(t) = \frac{U_0 - u_1(t)}{R_1}; \quad where$$
$$u_1(t) = \sum_{i=1}^{n} \alpha_i e^{-\beta_i t} \qquad (4)$$

Theoretical analysis of the differential equation system (2) for the matrix $\boldsymbol{A}$ components show that the peak values A_i and its exponential coefficients B_i are mutually banded with all circuit components. The direct determination R_i and C_i components in one parallel branch from exponential signal parameters A_i and B_i is valid under the assumption of their significant difference. Simplified relation between C_i,R_i parameters and parameters A_i,B_i is.

$$B_i = \frac{1}{R_i C_i}; \quad A_i = \frac{U_0}{R_i} \qquad (5)$$

Authors showed in their previous article [8] high sensitivity of C_i,R_i estimation accuracy on the exponential component spacing .

The exact values R_i, C_i are determined by complex dependence of all components in the circuit Fig.1.

$$\left.\begin{array}{l} A_i = f_i(R_j, C_j,) \\ B_i = g_i(R_j, C_j,) \end{array}\right\} for \begin{array}{l} i = 1,..n \\ j = 1,..n \end{array} \qquad (6)$$

Analytical solution of L ordinary differential equations of first order is calculated using the solution for homogenous system a superimposed particular integral. It is determined by the right side of the inhomogeneous ordinary differential equations (2). Analytical solution is set of steady state voltages $u_i(t)$ expressed by

$$u_j(t) = \sum_{i=1}^{n} {}^j\alpha_i e^{-({}^j\beta_i)t} \qquad (7)$$

Where constants ${}^j\beta_i = \beta_i$ are eigenvalues of matrix $\boldsymbol{A}$ and are the same for all voltages u_i(t). Peak values ${}^j\alpha_i$ are complex functions of eigenvector and initial conditions. The analytical expression of the differential equation solution has been programmed in the LabVIEW environment. The input parameters to this programme are values of the parameters R_i,C_i of the analysed circuit Fig.(1). The circuit parameters R_i,C_i determine parameters of the matrix $\boldsymbol{A}$ using steady state representation (2). The eigenvector, eigenmatrix is calculated using block vi available in the LabVIEW toolbox Mathematics. The relaxation current $i(t)$ is calculated from the voltage $u_1(t)$ acquired by the DAQ board across final input resistance R_1. This resistance includes even the input resistance of DAQ in parallel with serial resistance of the voltage source and switch.

2.2. Optimization algorithm

Relaxation model parameters are estimated by the least mean squared (LMS) fitting of the expected current from the source (4) with the measured one. The signal parameters A_i,B_i are linked by the circuit parameters C_i,R_i. In order to avoid an additional step represented be the estimation of circuit parameters C_i,R_i from measured constants A_i,B_i, the direct optimization method was utilized. Analytical solution of the differential equation system (2) in LabVIEW serves for direct calculation of the current $i(t,\boldsymbol{a})$ as function of the C_i,R_i parameters. The matrix $\boldsymbol{a}$=[C_1,R_1,C_2,R_2,… C_n,R_n] represents the circuit parameters in Fig.1. LMS optimization by a suitable optimization algorithm minimizes the cost function $CF_{LMS}(\boldsymbol{a})$,

$$\min\left(CF_{LMS}(\boldsymbol{a})\right) = \min\left(\sum_{l=1}^{L}\left(y(t_l) - i(t_l,\boldsymbol{a})\right)^2\right) \quad (8)$$

Here $y(t_l)$ are the measured values in time instants t_l.

There are several optimization strategies with different requirement on the limits of the initial conditions. Authors proposed optimization procedure in two steps. Differential evolution (DE) was used as the first optimization step. It is based on the trial to improve iteratively the candidate solution with regard to a given measure of quality. Such methods are commonly known as metaheuristics as they make no assumptions about the problem being optimized. It can search very large spaces of candidate solutions. The Levenberg–Marquardt (LM) algorithm was used as second optimization steps with the goal to improve precision of the of the DE optimization. The initial candidates of A_i,B_i parameters for DE optimization were achieved by successive approximation algorithm [6] and first forecast by (5).

3. EXPERIMENTAL RESULTS

Authors assessed accuracy of the proposed method of the estimation of the relaxation components represented by the circuit Fig.1. The circuit model was simulated by the PSpice. The .TRAN Analysis was chosen in the simulation profile. Properties of switch were updated in its model. Output data used for optimization were recorded in the .csd format. Time instants of the recorded data from the transient analysis are not equidistant. PSpice .csd data were converted into 2D array, time instants and current $y_S(t)$ values.

Accordance of the PSpice model with analytical calculation was verified by comparison of both output current in the same time points. Figure 2 shows small differences between simulated and analytically calculated transient response. The initial oscillations caused by the numerical calculation of the .TRAN response have no impact on the optimization procedure.

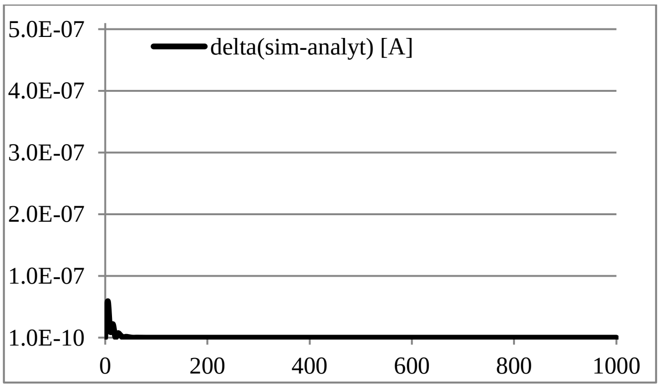

Fig. 2 Estimation error for L time instants using final LM optimization and successive estimation of the best fitted exponential.

Time instants were utilized as input for analytical solution of the steady state representation of $i(t)$. Estimation error as function of the number L of time sample was assessed by the relative error $\varepsilon(L)$.

$$\varepsilon(L) = \frac{\sum_{l=1}^{L}\left(y(t_l) - i(t_l,\boldsymbol{a})\right)^2}{L} \quad (9)$$

The comparison of the relative error of the estimation using initial ED optimization algorithm and final LM with the method of successive best fitted LM exponential functions decomposed are shown on Fig.3.

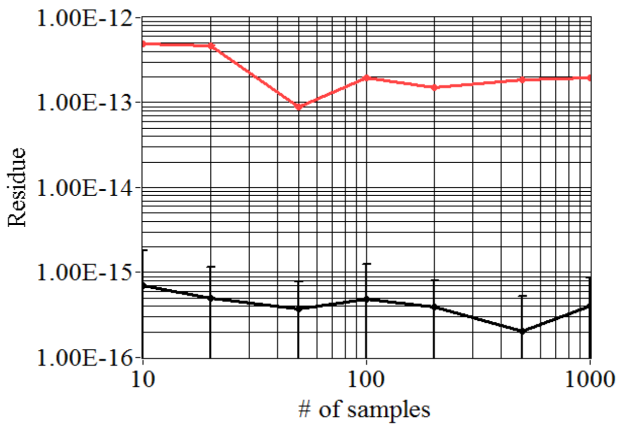

Fig. 3 Estimation error for L time instants using final LM optimization and successive estimation of the best fitted exponential.

Fig. 4 shows process of the estimation matrix $\boldsymbol{a}$ components starting with DE algorithm and final refinement by the LMS optimization algorithm for increasing number of samples in the time record. Parameters of the assessed circuit model are represented by the vector $\boldsymbol{a}$=[10uF, 20kΩ, 398 nF, 8 MΩ ,324 nF,40 M Ω, 1nF, 1GΩ].

The estimation error for different L is expressed by the relative deviation between the estimated and simulated circuit parameter P_i.

$$dP_i(L) = \frac{\left({}^{es}P_i(L) - {}^{sim}P_i\right)}{{}^{sim}P_i} \quad [\%] \quad (10)$$

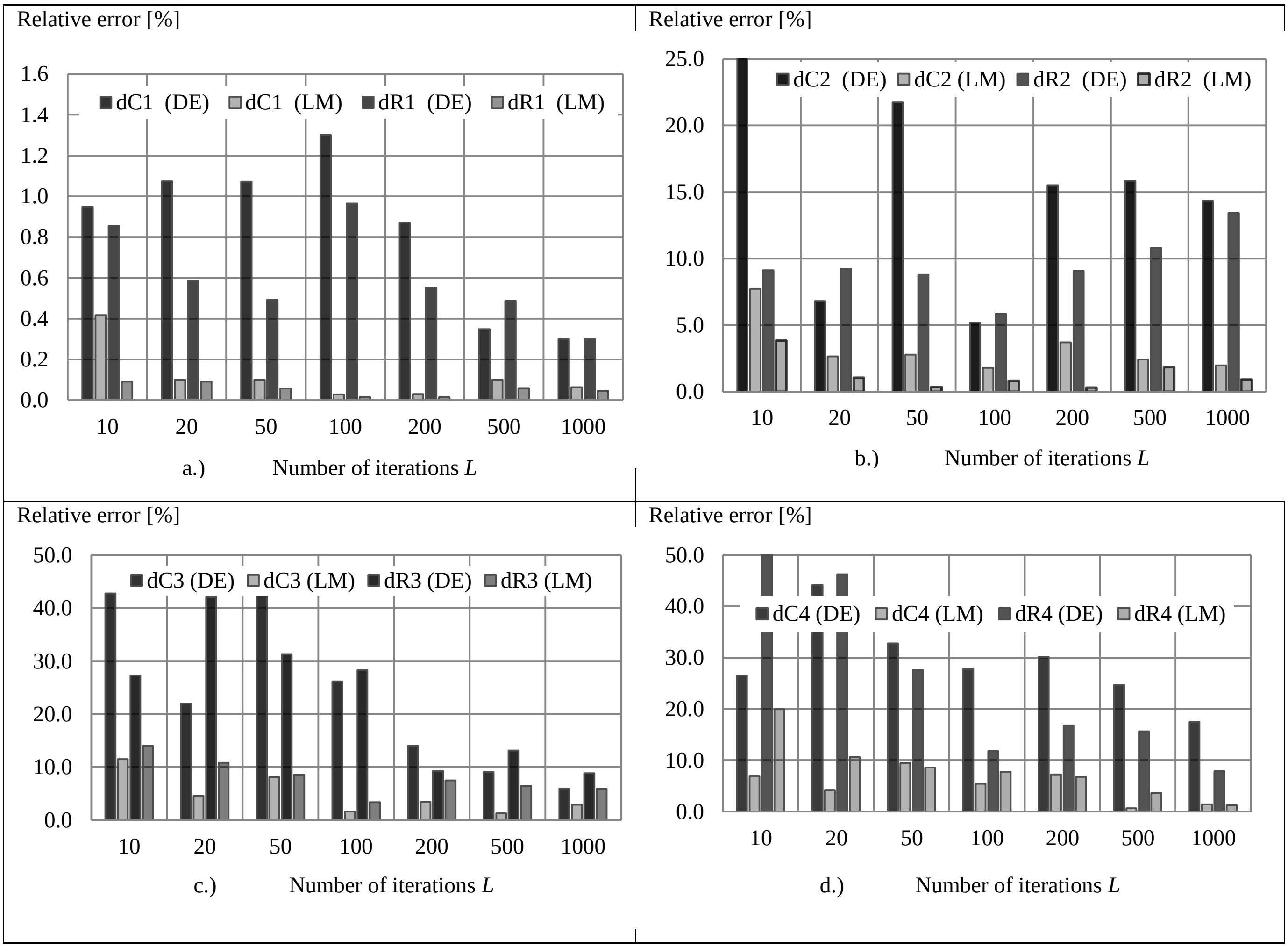

*Fig. 4 The evolution of the matrix **a** estimation for variousnumber of iteration L using both algorithms*

Maxwell-Wagner circuit model of dielectric relaxation	**Estimated by proposed method**	**Reference Prony-like [9]**	**relative uncertainty**
Epoxy Remikaflex 45.004.	4.97 µF	4.55 µF	- 9%
	498 MΩ	523 MΩ	-5%
	152 nF	154 nF	- 0%
	5.97 MΩ	5.93 MΩ	- 0%
	5.15 nF	4.7 nF	+ 9%
	510.6 MΩ	430 MΩ	+18%

Tab. 1 Relative uncertainty of the dielectric parameter estimations for the Remikaflex 45.004 insulation material

The proposed iteration algorithm was verified in the case of the Remikaflex 45.004 thermosetting insulation material with observable relaxation proces. Material is made from calcined mica paper of Remik, from glass cloth and from polyethylenetereflat’s foil. Everything is bind together by epoxy. Remikaflex 45.004 is used to insulation coil ends of high-voltage equipments working in temperature up to 155°C. Charging current was acquired by Keithley 617 programmable electrometer with resolution 4 ½ with internal voltage source and adjustable sampling interval. Measured current in the sampling instants was used for estimation of Maxwell-Wagner model parameters by the proposed method. The estimated parameters were compared with results achieved by semi analytical Prony’s method [9] for the same data record. The method supposes ideal voltage source causing that the first component is represented by Dirac pulse. Tab.1 shows relative uncertainty in estimation of dielectric parameters.

4. CONCLUSIONS

Paper presents new method for the measurement of the hidden parameters of the dielectric materials, mainly insulants using standardized IRC diagnostics. The method reduces the errors of the actually used signal processing approaches where parameters are determined successively. Proposed method estimates all parameters contemporary, which suppress transfer of estimation error from one approximation to another caused by the additional noise. Lack of orthogonality among exponential components requires concurrent calculation of all estimated parameters. The method is suitable not only for assessment of dielectric degradation by Isothermal Relaxation Current-analysis but with similar analytical circuit model can be used for measurement of the dielectric absorption of capacitors.

Another advantage of the proposed method is taking into account fact of the real resistance R_1 in the series with voltage switch. Data from the beginning are most significant in the optimization and their simplification by the Dirac pulse reduces the precision of the estimation of the exponential components with longer relaxation time.

Last advantage is based on the direct estimation of circuital components C_i,R_i without their estimation from exponential signal parameters. As shown in [8] then precision of the recommended method depends on the proximity of their time constant and the time instants of component calculation.

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REFERENCES

[1] Kuenen, J.C.; Meijer, G.C.M., "Measurement of dielectric absorption of capacitors and analysis of its effects on VCOs," Instrumentation and Measurement, IEEE Transactions on , vol.45, no.1, pp.89,97, Feb 1996 doi: 10.1109/19.481317

[2] Menendez, E., "Dielectric Absorption of Multilayer Organic (MLO™) Capacitors," Technical papers, AVX Online®, cit. 2014-05-02, on-line: http://www.avx.com/docs/techinfo/MLO%20Dielectric%20Absorption.pdf

[3] Koval',F., Cimbala,R.: IRC Analysis of insulation systems. Acta Electrotechnica et Informatica, Kosice, No4, Vol,7, 2007, pp.1-7.

[4] Hofmann R., Kranz H.G., Steinbrink D.: IRC-Analysis: Destruction free dielectric diagnosis of mechanical and service aged polymeric insulation. ISH 1999, Conference Publication No 467, 1999

[5] Cimbala, R.: Starnutie vysokonapäťových izolaných systémov,TUKE, Košice, 2007, 188p. ISBN: 978-80-8073-904-1.

[6] Hoff,G., Kranz, H.-G.: Correlation Between Return Voltage and Relaxation Current Measurements on XLPE Medium VoltageCables, 11th ISH 1999, London.

[7] Beigert,M.,Kranz,H.-G.: "Destruction Free Ageing Diagnosis of Power Cable Insulation Using the Thermal relaxation Current" IEEE Symposium on Electrical Insulation, Pittsburgh,PA USA, June 5-8,1994,pp.17-21.

[8] Michaeli,L.,Šaliga,J.,Godla,M.,Lipták,J.:Measurement of Dielectric Absorption of Capacitors by Signal Decomposition. Proc.of IMEKO TC-4 Symposium, Benevento 2014,pp. 107-111.

[9] Coluccio, A. Eisinberg, G. Fedele: "A Prony-like method for non-uniform sampling, " Signal Processing, Vol. 87, No. 10, 2007, pp. 2484-2490.