A New Method for Dielectric Parameters Testing and Model Identification Based on Differential Evolution

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Abstract. *The paper describes a new method for direct estimation of dielectric material relaxation properties expressed by values of R and C in equivalent electric circuit. The unknown R,C values are calculated by the minimization of the cost function represented by the least square difference between measured charging current from the Isothermal Relaxation Current (IRC)-analysis of insulating materials and analytical description of the equivalent circuit. Proposed optimization by the differential evolution allows to determine R,C parameters in one step. It avoids uncertainty in R,C parameter calculus from time constants and peak values of single exponential components for finite resistance of the voltage source, switch and data acquisition board. The proposed method was verified by using PSpice model and optimization of analytical model in LabVIEW.*

Keywords: Dielectric IRC analysis, Signal decomposition, Differential evolution optimization

1. Introduction

Dielectric absorption of capacitors and charging process of insulating materials like HV cables is determined by the polarisation of dipoles in dielectrics and the latency in their polarization ([1], [2], [3], [4]). The charging/discharging relaxation process of dielectric dipole components in their final position is particularly delayed ([5], [6]). Relaxation processes cause memory effects in capacitors which limits precision of sample and hold circuits or linearity in of the conversion in integrating Analog to Digital Converters. Generally the polarisation effect can be modelled by electric Maxwell-Wagner circuit model, which consists of N parallel R_iC_i branches shown in Fig. 1.

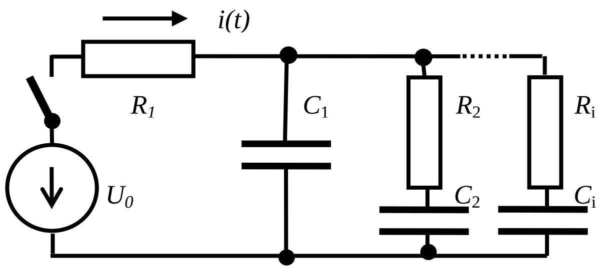

Fig. 1. Electrical model of the relaxation process in the dielectrics.

Each RC branch corresponds to the dipole moment of a chemical component in the mixture of dielectric materials used in the capacitor or cable isolation. After switching on the voltage source U_0, the R_iC_i circuits cause that the charging current $i(t)$ is in form of superposition of N exponential functions:

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

where A_i are the peak values and B_i are the inverse values of the time constants of the current components (1). The currently used IRC test method assumes the ideal voltage source U_0 ($R_1 \to 0$) and the ideal switch. Moreover, the data acquisition board (DAQ) measuring current is considered with internal resistance equal to zero. This assumption leads to the idealised simplified result that the first component in (1) is represented by the Dirac pulse ($A_1 = U_0/R_1$, $B_1 \to \infty$.). Parameters A_i, and B_i of other components are estimated by least square (LS) fit of successively added of the exponential components in (1) and acquired current $i(t)$ ([4] - [6]). The achieved fit for *i-th* exponential component is used as initial value for estimation of successive (i+1)-*th* exponential in (1). The fitting process is finished when all A_i, and B_i constants are achieved.

Because of the fact that signal components (1) are not the orthogonal under the influence of the real additive noise the successive identification of particular components leads into accumulation of errors transferred from previous fitting step. Real value of serial resistance R_1 represents mutual effect of real voltage source and input resistance of DAQ whose transverse voltage is used for measurement of the current $i(t)$. The estimation accuracy of R_i and C_i considering independent dipoles is highly sensitive on the distances among the exponential components A_i and B_i [4], [7].

2. New Proposed Method

Authors proposed the method of direct optimization of R_i,C_i components in circuit Fig. 1 with the aim to minimize difference between analytically expressed current $i(t)$ and its measured values $i_m(t_l)$in sampling instants t_l.

The charging process can be described by N linear differential equations for steady state circuit in Fig.1.:

$$\frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}t} = \boldsymbol{A}.\boldsymbol{u} + \boldsymbol{b}, \quad \text{where}$$

$$\boldsymbol{u} = \begin{bmatrix} u_1(t) \\ u_2(t) \\ \vdots \\ u_N(t) \end{bmatrix}, \quad \boldsymbol{A} = \begin{bmatrix} -\frac{G_T}{C_1} & \frac{G_2}{C_1} & \frac{G_3}{C_1} & \cdots & \frac{G_N}{C_1} \\ \frac{G_2}{C_2} & -\frac{G_2}{C_2} & 0 & \cdots & 0 \\ \frac{G_3}{C_3} & 0 & -\frac{G_3}{C_3} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \frac{G_N}{C_N} & 0 & 0 & \cdots & -\frac{G_N}{CN} \end{bmatrix}, \quad \boldsymbol{b} = \begin{bmatrix} U_0/R_1C_1 \\ 0 \\ \vdots \\ 0 \end{bmatrix}, \tag{2}$$

$$G_T = \sum_{i=1}^{N} \frac{1}{R_i}, \quad \text{and} \quad G_i = \frac{1}{R_i}$$

Theoretical analysis of the differential equation system (2) for the matrix **A** shows the exact values A_i and B_i are determined by the system of equations:

$$\left.\begin{aligned} A_i &= f_i(R_j, C_j,) \\ B_i &= g_i(R_j, C_j,) \end{aligned}\right\} \quad \text{for } i = 1,\ldots, N, \quad j = 1,\ldots, N \tag{3}$$

Analytical solution of N ordinary differential equations of the first order is being programmed in the LabVIEW subroutine. It is obtained as solution of homogenous system (2) with the superposed particular integral. Analytical calculated steady state voltage $u_1(t)$ determines the charging current $i(t)$.

$$i(t) = \frac{U_0 - u_1(t)}{R_1} = \frac{U_0 - \sum_{i=1}^{N} \alpha_i e^{-\beta_i t}}{R_1}; \tag{4}$$

Where the constants β_i are the eigenvalues of matrix **A** for the voltages $u_1(t)$ and the peak values α_i are complex functions of eigenvector and initial conditions.

Optimization procedure estimates the parameters R_i and C_i with the scope to minimize cost function CF_{LS} represented by least squared difference between analytically expressed current $i(t)$ (4) and measured one $i_m(t)$ in the same time instants t_l.

$$\min(\mathrm{CF}_{\mathrm{LS}}(\mathbf{a})) = \min\left(\sum_{l=1}^{L} (i_{\mathrm{m}}(t_l) - i(t_l, \mathbf{a}))^2\right) \tag{5}$$

Here t_l are sampling instances and analytically expressed current $i(t,\mathbf{a})$ is a function of the circuit parameters $\mathbf{a} = [C_1, R_1, C_2, R_2, C_n, R_n]$ (Fig.1). Different strategies can be used to minimize (5). The authors utilized optimization method based on differential evolution which is metaheuristic method. Its main advantage is searching the possible solutions in very large space with higher resistance on convergence into local minima.

3. Experimental Results

The proposed method was tested in simulation. The model in Fig. 1 was first implemented in PSpice including model of real switch and source of voltage. Result from the Result from the PSpice TRANS analysis was recorded in a file and consequently circuit parameters **a** were optimized by the differential evolution optimization. Circuit parameters were input into program calculating analytically current $i(t,\mathbf{a})$ for (5). The results achieved by the simulated test using different number of samples L are listed in Table 1.

Table 1. The values of the matrix **a** with estimations of circuit parameters for different L using both algorithms.

L	C1	R1	C2	R2	C3	R3	C4	R4	ε(*L*)
	10u	20k	398n	8M	324n	40M	1n	1G	
10.	10.09u	20.00k	498.5n	7.693M	492.6n	123.6M	19.09n	1.499G	7.0 E-16
20.	9.993u	20.00k	370.8n	7.916M	375.3n	44.31M	135.1n	156.2M	4.9 E-16
50	9.996u	19.99k	484.5n	7.397M	486.7n	77.41M	2.748n	275.9M	3.7 E-16
100	10.00u	19.99k	377.3n	7.533M	408.7n	37.65M	178.6n	582.3M	3.6 E-16

Estimation precision was assessed by the averaged error $\varepsilon(L) = \frac{1}{L}\sum_{l=1}^{L}(i_m(t_l) - i(t_l, \mathbf{a}))^2$ between measured and estimated current for L samples in the time window $(0, t_L)$

The efficiency of the circuit parameters R_i,C_i direct estimation in comparison with methods based on the exponential signal decomposition and successive circuit parameters estimation was studied under two scenarios. The estimation of the circuit parameters for real insulation material represents first scenario. Measured material sample consists of calcined mica paper with glass cloth and polyethylenetereflat's foil. Everything is bind together by epoxy Remikaflex 45.004. The measured data representing second scenario were acquired from PSpice model. Here the inherent circuit parameters R_i,C_i are known and compared with parameters estimated by the proposed method and by exponential signal decomposition. Table.2 shows real and estimated parameters with relative error of their estimation.

Table 2. Estimation of the Maxwell-Wagner circuit model of polarisation effects

Maxwell-Wagner circuit model of dielectric relaxation		Estimated by proposed method	relative error	Two step estimation [3]	relative error
1st scenario	5μF	4.97 μF	- 1%	4.55 μF	- 9%
	500MΩ	498 MΩ	- 0%	523 MΩ	+ 5%
	150nF	152 nF	+ 2%	154 nF	+ 3%
	6MΩ	5.97 MΩ	- 0%	5.93 MΩ	- 1%
	5nF	5.15 nF	+ 3%	1.257 μF	+N/A
	300MΩ	510.6 MΩ	+70%	10.7 GΩ	+N/A
2nd scenario	10μF	10.13 μF	+ 1%	9.722 μF	- 3%
	1MΩ	0.978 MΩ	- 2%	1.034 MΩ	+ 3%
	500nF	357.4 nF	-29%	569.3 nF	+14%
	10MΩ	12.2 MΩ	+23%	12.08 MΩ	+21%
	25nF	39.0 nF	+56%	234.4 nF	+838%
	100MΩ	147 MΩ	+47%	166.1 MΩ	-83%

4. Conclusions

Paper deals with new method for measurement of the hidden parameters of the dielectric materials, mainly insulants using standardized IRC diagnostics. The method estimates all parameters contemporary which suppress transfer of estimation error from one approximation of exponential function to another caused by the additional noise. Another advantage of the proposed method is the consideration of the real resistance R_1 of the voltage source and the switch.

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