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Measurement of Dielectric Absorption of Capacitors by Signal Decomposition

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***Abstract* – The paper presents method of the measurement of dielectric absorption components by the analysis of discharging exponential signal from the capacitor. The method uses maximum likelihood estimation as an alternative to the Prony' s method. The advantage of the proposed method is the suppression of the uncertainties of recovering process caused by finite input resistance and vaguely defined discharging time. The possibility to minimize the effects of integral nonlinearities of Analog-to-Digital Converter is another advantage. The comparison of the experimental results with the simulation allows assessing the accuracy of proposed approach.**

I. INTRODUCTION

Dielectric absorption is a physical effect caused by the relaxation process of the dipoles in the dielectric. The polarized dipoles do not turn back in their initial positions when the capacitor is discharged. In a capacitor with dielectric absorption, the charge on the primary capacitor will be recovered after discharging phase. Dielectric absorption differs for variety of dielectric materials. The most popular model of this phenomenon is represented by the parallel R_iC_i branches in parallel to the primary capacity C_1 (Fig.1). Each parasitic R_iC_i circuit generates a superimposed exponential component with longer time constant and smaller peak value in comparison to the main exponential component caused by the primary capacity C_1 [1].

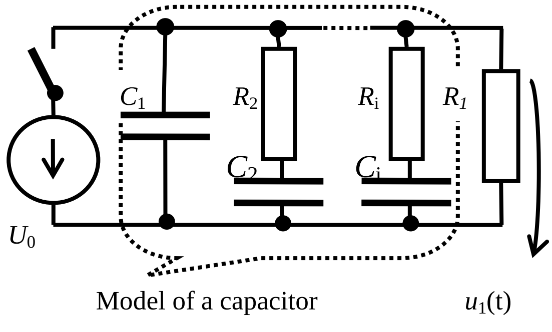

Fig.1.Model of the capacitor with the discharging circuit.

Dielectric absorption causes a problem in sample/hold (S/H) circuits. The memory capacitor is recharged from absorption components during in the hold phase and causes the output voltage error at V_{out}. Similar physical phenomena influenced the error of Analog-to-Digital Converters (ADC) based on the integration principle and errors of the Voltage Controlled Oscillators (VCO).

After the introductive section, the second section presents new method proposed by authors based on the identification of discharging exponentials distorted by dielectric absorption. Implementation of the maximum likelihood method for the estimation of absorption parameters is described in the third section. Influence of acquisition process on the measurement accuracy was studied by the simulation in the fourth section and experimentally verified in fifth section.

II. DIELECTRIC ABSORPTION EFFECTS

The standardized approach (MIL-C 19778) of the dielectric relaxation measurement is based on the signal decomposition in time domain [2]. The capacitor is charged to a voltage U_0 of the voltage source before the test is initiated. The charging time must be long enough to ensure that the all capacitors C_1,C_2..C_i achieved voltage U_0. The capacitor under test (CUT) is then short-circuited during the discharging period. The open-circuit voltage $u_1(t\to\infty)\to U_A$ is successively measured by data recorder with extremely high input resistance in the relaxation phase. It increases from zero to its steady value U_A. Output voltage U_A allows to calculate the Dielectric Absorption (DA) coefficient defined as $DA = {}^{U_A}\!/_{U_0}\, 100\%$. The process of the voltage recovery at the primary capacitor from the charge redistribution from the absorption capacitors C_i is shown on Fig.2.a.)

The uncertainty of the standardized method is caused by the i) influence of the input resistance of the data recorder, ii) vagueness in definition of the discharging period and finally iii) finite resistance of the switch in off state. The final input resistance of the data recorder causes that voltage U_A after reaching a maximum decreases. The discharging period as the second systematic error source must be longer than discharging time constant but shorter than time constant of the shortest time constant of the absorption R_2C_2 branch. The analytical expression for the voltage at the primary capacitor was derived in the paper [3]. The parameters of the absorption R_iC_i branches are necessary for the prediction of systematic errors in the analog preprocessing circuits (Sample and Hold circuits, Voltage Controlled oscillator, Integrating ADCs) caused by the dielectric absorption of the implemented capacitors.

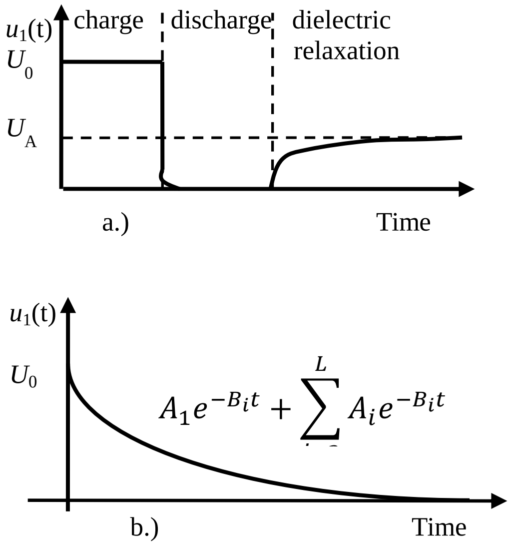

Fig.2 Measurement of dielectric absorption parameters by relaxation a.) and discharging b.)using using circuit Fig.1

Discharging circuit (Fig.1) generates the output signal (Fig.2.b) in the form of the multiexponential function (1) with the time constants R_iC_i of dielectric branches discharging to zero output value

$$u_1(t)=A_1e^{-B_1t}+\sum_{i=2}^{L}A_ie^{-B_it} \qquad (1)$$

The proposed approach avoids some uncertainty sources from the standardized method:

1.) Parameters of the measuring circuit. Finite impedances of the used discharging resistor together with the input resistance of the data recorder and analog switch connected in parallel are represented by the total discharging resistance R_1. Decreasing value of discharging resistor allows to omit the influence of unknown switch-off resistance.
2.) The method avoids problem with the vagueness in the definition of the discharging period.

Authors adapted the maximum likelihood method (ML) for the measurement of exponential signal distortion, when the output voltage from discharging circuit was used for dynamic ADC tests using unconventional stimulus signal [4].

III. MEASUREMENT OF ABSORPTION COMPONENTS FROM ESTIMATED EXPONENTIALS

Measurement of the discharging voltage $u_1(t)$ is performed by a Data Acquisition Board (DAQ) which includes analog preprocessing blocks with input resistance R_1 and ADC with resolution N-bit. The integral nonlinearity *INL*(*d*) of whole DAQ has been acquired in advance by the standardized test method [5]. The digital signal from the DAQ output d(*j*) is sampled with period τ_s

$$d(j)=\sum_{i=1}^{L}A_i.e^{-B_i.j\tau_S}+n(j\tau_S) \qquad (2)$$

Here $n(j\tau_s)$ represents quantization noise together with thermal noise from the DAQ input. Constants B_i are inverted values of time constants and A_i are peak values of i-the RC branch in the capacitor's model.

The optimization objective is to achieve best matching of the considered input signal (1) to the real code intervals corresponding to the recorded digital shape (2). The best matching is assessed by the maximum likelihood procedure (ML). Non-sensitivity on the pdf of the quantization noise is the main advantage in contrary to the least square (LMS) method [5]. ML method is asymptotically optimal from this point. Another advantage of ML method is the possibility to involve the tested nonlinearity *INL*(*d*) of the DAQ in the probabilistic model of the DAQ conversion characteristic. The best estimation of the input signal $u_1(t)$ on the basis of the output record is that which best matches the corresponding digital samples d(*j*). Mathematical expression for the matching probability for any time *j* is expressed by one of the probabilities in (3)

$$P(d(j)=0\,|\,u_1(j),\sigma)=1-F(T[0],u_1(j),\sigma) \qquad (3)$$
$$P(d(j)\,|\,u_1(j),\sigma)=$$
$$=F(T[d(j)-1],u_1(j),\sigma)-F(T[d(j)],u_1(j),\sigma)$$
$$P(d(j)=(2^N-2)\,|\,u_1(j),\sigma)=F(T[2^N-2],u_1(j),\sigma)$$

The real transient code level $T[k]$ considers the shift of their ideal values *k*.Q by additional nonlinearity *INL*(*k*) $T[k]=T_{id}[k]+INL(k)Q$. The probabilistic profile of the code bin *k* with actual transient code level $T[k]$ is $P(k,u_1,\sigma)=F((T[k-1]-u_1),\sigma)-F((T[k]-u_1),\sigma)$, where F(z,μ,σ) is the normal cumulative distribution function with zero mean and standard deviation σ.

The probability of the input sample $u_1(t)$ matching with the channel profile for the corresponding sample d(j)is determined by one from the equation (3). Overrun of DAQ Full Scale Range at lower and upper scale limit is described by the first and third rows in (3), respectively. The joint probability P_{final} equals the product of the individual probabilities for any of J samples d(j) (independent events):

$$P_{final} = \prod_{j=0}^{J} P((d(j) \,|\, u_1(j), \sigma) \qquad (4)$$

The joint probability P_{final} (4) achieves its maximum in the optimal matching of signals (1) with (2). In order simplify the task, the minimum of the negative log-likelihood cost function $CF(p)=-\log(P_{\text{final}})$ is sought, where p represents the set of parameters A_i, B_i, C, σ

$$\begin{aligned} CF(p) &= -\log P_{final} = \\ &= -\sum_{j=0}^{J} \log P(k(j), u_1(j)) \end{aligned} \qquad (5)$$

The optimization method chosen for following experiments was the differential evolution strategy [6]. The choice of the initial signal parameters is a necessary first step in the optimization procedure. The analytical Prony's method [8] is an option how to assess signal parameters. The method is suitable for determination of the initial conditions for successive estimation improvement by ML method. The implementation of the Prony´s method is restricted on the decreasing signal only.

The steady-state representation of the voltages $u_i(t)$ across capacitors C_i is described by (6). The initial voltages on all main and absorbing capacitors are $u_1(0)=..=u_i(0)=U_O$. R_1 represents the total discharging resistance for the DAQ board and analog switch off resistance. Steady state representation of the voltage is:

$$\begin{bmatrix} u_1' \\ u_2' \\ u_3' \\ \\ u_i' \end{bmatrix} = \begin{bmatrix} -{}^{G_T}\!/_{C_1} & {}^{G_2}\!/_{C_1} & {}^{G_2}\!/_{C_1} & \cdots & {}^{G_i}\!/_{C_1} \\ {}^{G_2}\!/_{C_2} & -{}^{G_2}\!/_{C_2} & 0 & \cdots & 0 \\ {}^{G_3}\!/_{C_3} & 0 & -{}^{G_3}\!/_{C_3} & \cdots & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ {}^{G_i}\!/_{C_i} & 0 & 0 & \cdots & -{}^{G_i}\!/_{C_i} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ \vdots \\ u_i \end{bmatrix} \qquad (6)$$

where $G_T=(G_1+G_2+..G_i)$ and $G_1=R_1^{-1}$, $G_3=R_3^{-1}$.

Mathematical integration of the system allows determinate basic and superimposed components A_i, B_i, C of the signal $u_1(t)$ which are linked with the parameters of the capacitor´s model (Fig.1). Each exponential components represents discharging of absorption capacitors C_i through corresponding resistance R_i The parameters A_i,B_i allow to determine the parameters R_i C_i successively from time instances j_3,j_2 by the set:

$$\begin{aligned} &C_1 = {}^{-1}\!/_{B_1 R_T} \cong {}^{-1}\!/_{B_1 R_1} && C_3 \cong {}^{-1}\!/_{B_3 R_3} \\ &R_3 = \frac{\left[A_3.e^{-B_3 j_3 \tau_S} - u_1(j_3\tau_S)\right]}{u_1(j_3\tau_S)} R_1 && C_2 \cong {}^{-1}\!/_{B_2 R_2} \\ &R_2 = \frac{\left[A_2.e^{-B_2 j_2 \tau_S} - u_1(j_2\tau_S)\right]}{\left[A_3.e^{-B_3 j_2 \tau_S} - u_1(j_2\tau_S)\right] G_3 - u_1(j_2\tau_S) G_1} && (7) \end{aligned}$$

IV. SIMULATION RESULTS

The sensitivity of the ML method on the number of samples and initial instant of the recorded time window was studied by the simulation in the LabVIEW environment. The multiexponential input signal $u_1(j\tau_s)$ with adjustable signal components (A_i,B_i,C) was generated by a software generator. Parameters of the generated signal were achieved from the model of the discharging circuit (Fig.1.).

In order to identify influence of resolution N on the identification precision PXI DAQ board was taken in the consideration with the resolution of 16bits. The quantization noise was studied for different number of most significant bits (MSBs). The nonlinearity of DAQs was already known from the preceding ADC test. The parameters of equivalent circuit model of a capacitor Z5U with nominal capacity 10 μF was taken from [3] with two absorption branches in parallel with primary capacitor C_1. The influence of DAQ resolution is presented in the Tab.1. The nonlinearity of utilized boards from the standardized ADC test was implemented in the ADC model and also in the probabilistic profiles (4). The estimation precision was assessed by relative errors

$$\delta_{Ai} = \frac{{}^{e}A_i - A_i}{A_i}\,[\%];\ \delta_{Bi} = \frac{{}^{e}B_i - B_i}{B_i}\,[\%], \qquad (8)$$

where A_i,B_i are generated and ${}^{e}A_i$,${}^{e}B_i$ are estimated parameters.

The main drawback of the identification of exponential components using discharging of the circuit from the Fig.1 is the predominance of the first exponential in comparison with the distorting components i=2,3…i. The main component hides effects of smaller exponentials from absorption R_iC_i branches.

Resolution N of DAQ	δA_1	δA_2	δA_3	δB_1	δB_2	δB_3
6	1,99	41,34	18,34	1,86	1,78	2,10
8	0,04	6,53	0,19	1,28	0,45	1,57
12	0,00	0,10	0,14	0,001	0,19	0,83
14	0,01	2,28	0,32	0,02	0,11	0,04
16	0,00	0,47	0,39	0,00	0,34	0,52

Tab.1 Estimation error for diffetrent DAQ resolutions sampling period $\tau_S = 1\mu s$

In order to avoid overloading of recorded data by first component which hides second and third component, the signal was estimated from data record delayed by ΔJ samples. The simulation results in the Tab.2 compare inherent and estimated signal parameters for different length of recorded data. The constant sampling interval τ_s=1µs. The DAQ resolution in this case is N=14 bit. Transient effects at the discharging beginning were suppressed taking record delayed for $\Delta J=5$ samples. The recorded value d(ΔJ) was considered as initial value of discharging process.

Number of samples	δ_{A1}[%]	δ_{A2}[%]	δ_{A3}%]	δ_{B1}[%]	δ_{B2}[%]	δ_{B3}[%]
1000	11,47	362,4	231,6	9,078	93,4	28,9
2000	0,004	0,65	0,11	0,03	1,31	6,55
3000	0,003	3,07	0,67	0,008	0,084	2,51
5000	0,002	0,93	0,35	0,006	0,091	1,61
8000	0,013	0,830	0,42	0,022	0,165	0,03
10000	0,003	0,424	1,03	0,015	4,795	0,281
12000	0,005	1,616	8,39	0,03	1,824	0,33
15000	0,050	14,03	4,6	0,021	0,47	0,34

Tab.2 Estimation error for diffetrent record length

The errors involved in the expressions in second and third row are caused by the neglecting of mutual interfering of parallel branches. Such errors are decreasing proportionally with increasing spacing in the values of the time constants $^1/_{B_1}$, $^1/_{B_2}$ and $^1/_{B_3}$.

V. EXPERIMANTAL MEASUREMENT

The results from the analytical study and simulations were verified by experimental measurement and using results from the SPICE model of a real circuit in Fig. 1. The ceramic capacitor 10 µF type Z5U was considered for experiments [3]. The capacitor was realized by the polypropylene capacitors by WIMA with extremely low absorption and parallel absorption branches. Capacitor C_1=10 µF represents the main capacity and two parallel R_2C_2 and R_3C_3 branches modelled the effects of dielectric absorption. Their values were R_2=8 MΩ, C_2=398 nF and R_3=39,8 MΩ, C_3=324 nF were taken from the measurement using relaxation method [3] . The values of capacitors and resistors ensured that the residual absorption effects of the WIMA capacitors were hidden.

In order to make constant B_1 significantly different from B_2 the discharging resistor is R_1=1 kΩ. The time record of the signal $d(j)$ was compared with the signal from simulator SPICE. The simulator served as a proof of conformity of the real circuit parameters with those assumed in the analytical expression. The acquired signal was decomposed on the three exponential components by ML and by Prony's method. The values of hidden absorption capacitors C_i and resistors R_i were calculated from estimated parameters A_i,B_i using eq.(8). The length of the time record was 36000 samples. Time instants $t_3=j_3\tau_S$, $t_2=j_2\tau_S$ as in the simulation. This length covers the most important part of processed signal and excludes the fade-out signal tail from processing. Measurement of the signal parameters from the output of the tested circuit are shown in Fig. 3.

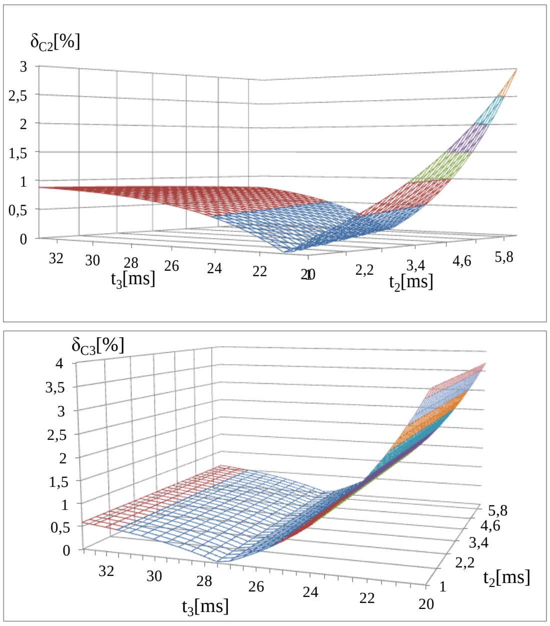

Fig.3 Realative errors in measurement of n capacitor's absorptiod parameters for different time instants t_3,t_2.

Figures show influence of time instants choice on the relative error in estimation of the absorption parameters by eq.(8). There is optimal choice of both intervals represented by the minima in both graphs.

VI. CONCLUSIONS

The proposed ML method is suitable to identify parasitic components representing dielectric absorption in the capacitors. The measurement uncertainty was improved by the implementation of signal component measurement using signal decomposition by the ML method. The simulation model allowed studying the sensitivity of ML method for the various parameters of the recording data. Experiments showed dependency of the relative accuracy of absorption parameter measurement as function of time instants and time window of the recorder signal.

Another advantage of the proposed ML method is its universality for signal decomposition in the case of the relaxation and discharging of the capacitor under test. Implementation proposed method for discharging process allows avoiding error caused by discharging time period and influence of finite input resistance of data recorder in the relaxation phase.

Maximum likelihood method for signal decomposition is universal for any particular signal components caused by material imperfection caused by parasitic components in the model, like hysteresis processes in magnetic materials.

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