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Time domain diagnosis of anticorrosion coatings via shape designed measurement signals

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Abstract – The paper presents time domain diagnostic method of anticorrosion coating on the level of equivalent circuit parameter identification. The method is based on applying non-conventional, shape-designed stimuli signals and measuring the object responses (so-called observables) at a given time T. Equivalent circuit parameters are calculated directly from observables using analytical equations, determinated by modelling circuit topology. In the paper the theoretical basis of the method is presented, together with measurement methodology and simulation results for 4 elements anticorrosion coating equivalent circuit.

Keywords: anticorrosion coating diagnosis, parameter identification, non-conventional signals

1. INTRODUCTION

Due to economic and safety reasons, the anticorrosion protection is widely used to protect technical objects. High durability of modern coatings makes testing and diagnosis of these coatings difficult. As the corrosion in its first stage is hard to observe visually, the electrochemical methods, based on electrical measurements of coating's impedance seems to be most effective [1]. The coatings can be modelled by equivalent electrical circuit. Up till now, equivalent circuit parameters have usually been calculated indirectly, by fitting parameter-dependent function to experimentally obtained measurement data. The frequency domain impedance spectroscopy was the most popular method of parameter identification. It relies on measurement of object impedance in a specified frequency range and Complex Non-linear Least Squares (CNLS) fitting of selected parameter-dependant model [2]. The main disadvantage of impedance fitting method is the need of making many measurements in a wide frequency range, starting from very low frequencies (order of mHz), which leads to long measurement time.

In this paper, a new method of obtaining equivalent circuit parameters, based on applying shape-designed signals and calculating parameter values directly from measurement results has been proposed. In the first part of the paper, the measurement idea is explained, and measurement methodology is proposed. For investigation of method, Beaunier's anticorrosion coating equivalent circuit [3] was chosen. The method has been verified by means of numerical simulation. Finally, the simulation results are presented, discussed, and compared with CNLS impedance spectrum fitting method.

2. THE DIRECT METHOD OF MODEL PARAMETERS ESTIMATION

Shape designed signals allow to transfer the measurement numerical effort from post processing to pre-processing phase [4]. The idea of equivalent circuit direct parameter identification is presented in Fig. 1. In the pre-processing phase, the sequence of non-conventional shape-designed stimuli signals u_i is designed. Taking into consideration known equivalent circuit topology and the expected parameters values, the number of signals in sequence and their length is being set. The number of signals is equal to number N of identified parameters in coating equivalent circuit (K resistors and L capacitors); the single measurement time T is proportional to the expected time constant of equivalent circuit. Than, the set of N equations is being solved, thus giving the exact analytical relation between N measured values (so-called observables) and N circuit parameters. This operation can be done with computer symbolic calculation software and the relations

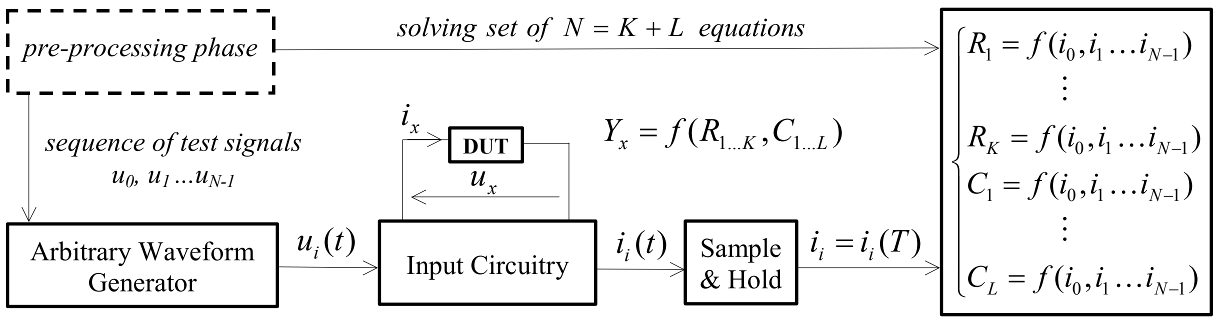

Fig 1. The idea of equivalent circuit direct parameters identification.

derived for most common equivalent circuit topologies (2, 3, 4 elements) can be implemented in measurement system. The measurement procedure consists of generating voltage stimulus with arbitrary waveform generator and measuring DUT current response (the observable) at a given time *T*. The full identification measurement cycle is a sequence of N stimuli and N observable measurements.

The post-processing phase is comparatively simple: by substituting the observables into previously resolved set of equations, one can calculate exact values of circuit parameters.

3. THEORETICAL BASICS OF METHOD

3.1 Circuit description by moments of pulse response

Popular form of describing system's dynamic properties (in this case the two terminal circuit modelling anticorrosion coating) is a transmittance. If we assume linearity and time-invariance of equivalent circuit, for the voltage stimulation and current response measurement, the transfer function is an admittance, in the form of rational function with coefficients a_i and b_i dependent on equivalent circuit RC parameters:

$$Y(s)=\frac{a_m s^m+\ldots+a_2 s^2+a_1 s+a_o}{b_n s^n+\ldots+b_2 s^2+b_1 s+b_o}\,. \tag{1}$$

Alternative form of system description is Taylor's series expansion of function Y(s):

$$Y(s)=\sum_{i=0}^{\infty}k_i s^i\,. \tag{2}$$

The Taylor expansion coefficients k_i, being the alternative method of describing system's dynamic response, are in a strict relation with moments of impulse response $h(t)$ defined as a functional $h(t)$ with power function kernel t^i:

$$\mu_i=\int_0^{\infty}t^i k(t)\,dt\,,\qquad i=0,1,2,\ldots,n\,. \tag{3}$$

By expansion of kernel function in Laplace integral, the following relation between moments μ_i and coefficients k_i can be obtained:

$$\mu_i=(-1)^i\, i!\,k_i\qquad i=0,1,2,\ldots,n\,. \tag{4}$$

Moments (3) are not measurable, due to unlimited integration time. With limited time *T*, the approximants $\mu_i(T)$ of moments can be measured

$$\mu_i(T)=\int_0^{T}t^i h(t)\,dt\,,\quad i=0,1,2,\ldots,N-1\,, \tag{5}$$

with a mirror kernel reflection method proposed by authors in [5]. There is a possibility to measure approximants of moments with just one sample in time T (or few samples in the neighbourhood of T) taken from the output of system, stimulated with shape-designed signal, being mirror reflection of functional (3) power kernel t^i,

$$u_i(t)=(T-t)^i\,1(t)\qquad i=0,1,2,\ldots,n\,. \tag{6}$$

This can be proved by calculating circuit current response as a convolution of shape-designed signal u_i and impulse response $h(t)$:

$$i_i(t)=u_i(t)*h(t)=\int_0^{t}u_i(t-\tau)\,h(\tau)\,d\tau= \tag{7}$$

$$=\int_0^{t}\left[T-(t-\tau)\right]^i h(\tau)\,d\tau\,.$$

It is easy to show, that the sample of current signal at time T is equal to $\mu_i(T)$:

$$i_i(T)=\int_0^{T}\left[T-(T-\tau)\right]^i h(\tau)\,d\tau=\int_0^{T}\tau^i h(\tau)\,d\tau=\mu_i(T)\,. \tag{8}$$

However, if we applied this principle directly to measure higher order moments of impulse response (3), the stimulation signal (6) would be difficult to implement, due to its dynamic. In practice, it is more convenient to measure and to describe parametric properties of system with normalized moments of impulse response:

$$m_i(T)=\int_0^{T}\left(\frac{t}{T}\right)^i h(t)\,dt=\frac{1}{T^i}\mu_i(T)\,,\quad i=0,1,2,\ldots,N-1\,. \tag{9}$$

Mirror kernel reflection principle and other $m_i(T)$ measurement methods with shape-designed signals have been researched and published in authors' environment. The results of that researches show, that the favourable signals are polynomials (in fact being the weighted sum of power signals), with alternate signs of weights. They lead to an internal signal amplitude compression and observable measurement error compensation.

3.2 Polynomial signal based measurement method

Polynomial signal based method allows to evaluate the moments of impulse response by stimulating the circuit with the sequence of *N* polynomial signals P_i of *i*-th order, $i\in[0, N-1]$ and taking samples of circuit response.

Generally, the polynomial stimulation signal of *i*-th order can be expressed in normalized time by the following formula:

$$u_i(t)=P_i\left(\frac{t}{T}\right)=a_i\left(\frac{t}{T}\right)^i+\ldots+a_2\left(\frac{t}{T}\right)^2+a_1\left(\frac{t}{T}\right)+a_0\,, \tag{10}$$

where the leading coefficient is positive, and other weights have alternate signs. That implies the internal signal compression mentioned above, as the high weighted power signal components of polynomial partly compensate each other over a limited period [*0, T*]. Circuit's response on polynomial signal P_i is:

$$i_i(t)=u_i(t)*h(t)=P_i\left(\frac{t}{T}\right)*h(t)=\int_0^{t}P_i\left(\frac{t-\tau}{T}\right)h(\tau)\,d\tau\,, \tag{11}$$

and he polynomial observable is the sample of DUT response signal at time $t=T$:

$$i_i(T)=\int_0^{T}P_i\left(1-\frac{\tau}{T}\right)h(\tau)\,d\tau\,. \tag{12}$$

The relation between polynomial observables and normalized moments m_i can be calculated on the basis of algebra: every polynomial of order *N* can be expressed as a linear combination of *N*+1 polynomials of order *0* to *N*. As the kernel of the moment $m_i(T)$ (9) is a special case of polynomial and polynomials mirror to P_i are of order *0* to *N*, the kernel $(t/T)^i$ can be substituted by a weighted sum of $P_i(1-t/T)$:

$$\left(\frac{t}{T}\right)^i=\sum_{k=o}^{i}w_{ik}P_k\left(1-\frac{t}{T}\right)\,. \tag{13}$$

Then, the functional (9) can be written as:

$$m_i(T)=\int_0^T\left(\frac{t}{T}\right)^i h(t)\,dt=\int_0^T\sum_{k=o}^{i} w_{ik}P_k\left(1-\frac{t}{T}\right)h(t)\,dt=$$
$$=\sum_{k=o}^{i} w_{ik}\int_0^T P_k\left(1-\frac{t}{T}\right)h(t)\,dt\,, \qquad (14)$$

giving the final relation expressing the moments $m_i(T)$ as the linear combination of polynomial observables.

$$m_i(T)=\sum_{k=o}^{i} w_{ik} i_i(T) \qquad (15)$$

Evaluation of moment value from several measured observables decreases the error propagation from the set of observables to the set of moments, and as a consequence, to the set of identified object parameters. The error propagation index can be used as an optimalisation criterion during the shape-designing phase. As a test engine, to examine efficiency and usefulness of polynomial methods in anticorrosion coatings parameter identification the Chebyschev polynomials have been chosen.

3.3 Identification of impulse response moments via Chebyschev polynomial signals

Chebyschev polynomials of first kind, normalized on the interval [0,1] can be used in a polynomial based moment m_i measuring method. They are defined as:

$$C_0\left(\frac{t}{T}\right)=1 \qquad C_i\left(\frac{t}{T}\right)=\sum_{k=0}^{i}\nu_k\left(\frac{t}{T}\right)^k \qquad (16)$$

where

$$\nu_k=(-1)^{i-1}4^k\frac{i}{i+1}\binom{i+1}{i-1}.$$

One of the advantages of Chebyschev polynomials is that they have the greatest leading coefficient among all polynomials having equal amplitudes in a fixed period. Another way of describing this property is that Chebyschev polynomials have the least swing in fixed period among all the polynomials with same leading coefficient. The property presented above implies, that Chebyschev polynomials offer maximum internal power signal compression. The shape of Chebyschev polynomials is presented in Fig. 2.

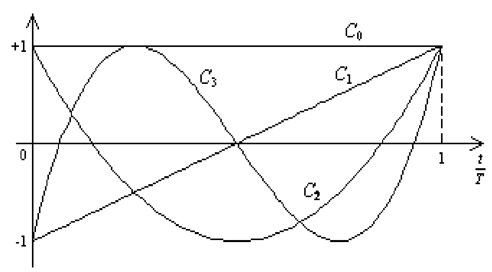

Fig. 2. Chebyschev polynomial signals.

Moreover, these polynomials are self-mirror – they are symmetric or antisymmetric, depending on the order of polynomial:

$$T_i\left(1-\frac{t}{T}\right)=(-1)^i T_i\left(\frac{t}{T}\right). \qquad (17)$$

The self-mirror property simplifies calculations of coefficients w_{ik} (15) giving relation between polynomial observables and moments $m_i(T)$. These coefficients can be obtained by substituting (17) into (12), thus calculating so-called Chebyschev observables as a result of Chebyschev polynomial signal stimulation:

$$c_i=i_i(T)=\int_0^T T_i\left(1-\frac{\tau}{T}\right)h(\tau)\,d\tau=\int_0^T(-1)^i T_i\left(\frac{\tau}{T}\right)h(\tau)\,d\tau=$$
$$=\int_0^T(-1)^i\left[\sum_{k=0}^{i}\nu_k\left(\frac{\tau}{T}\right)^k\right]h(\tau)\,d\tau= \qquad (18)$$
$$=(-1)^i\sum_{k=0}^{i}\nu_k\int_0^T\left(\frac{\tau}{T}\right)^k h(\tau)\,d\tau=(-1)^i\sum_{k=0}^{i}\nu_k\,m_k(T).$$

For a sequence of stimuli it is easy to form a set of equations describing relation between observables c_i and moments m_i:

$$\begin{aligned}
c_0&=m_0(T)\\
c_1&=m_0(T)-2m_1(T)\\
c_2&=m_0(T)-8m_1(T)+8m_2(T)\\
c_3&=m_0(T)-18m_1(T)+48m_2(T)-32m_3(T)\\
&\vdots\\
c_i&=(-1)^i\sum_{k=0}^{i}\nu_k\,m_k(T)
\end{aligned} \qquad (19)$$

From the set of equations, one can obtain the inverse relations, necessary used in practical implementation of the presented method:

$$\begin{aligned}
m_0(T)&=c_0\\
m_1(T)&=\frac{c_0-c_1}{2}\\
m_2(T)&=\frac{3c_0-4c_1+c_2}{8}\\
m_3(T)&=\frac{10c_0-15c_1+6c_2-c_3}{32}\\
&\vdots\\
m_i(T)&=\sum_{k=0}^{i}w_{ik}\,c_k.
\end{aligned} \qquad (20)$$

4. IMPLEMENTATION OF THE METHOD TO ANTICORROSION COATING DIAGNOSIS

The method has been implemented to parameter identification of anticorrosion coating model and investigated on the example of Beaunier's model in the form of equivalent circuit shown in Fig. 3. This circuit is well suited for modelling thick, high impedance anticorrosion coatings in early stage of corrosion. It is also used in literature [3][6], for comparison of different identification methods.

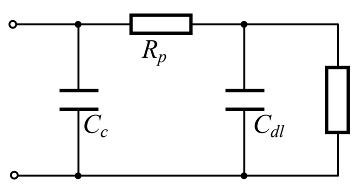

Fig.3. Beaunier's equivalent circuit of anticorrosion coating.

Circuit RC parameters has been assumed typical for thick layer coating:

$$R_p = 100G\Omega, \qquad R_{ct} = 100G\Omega,$$
$$C_c = 10pF, \qquad C_{dl} = 100pF.$$

4.1 Pre-test stage

During the pre-test stage, the relation between moments $m_i(T)$ and equivalent circuit parameters has to be found. The two terminal Beaunier's circuit admittance has the form of:

$$Y(s) = \frac{a_2 s^2 + a_1 s + a_0}{b_1 s + b_0}. \qquad (21)$$

with the a_i and b_i coefficients described as:

$$\begin{aligned} a_2 &= (C_c R_p C_{dl} R_{ct}), \\ a_1 &= (C_c R_p + C_c R_{ct} + C_{dl} R_{ct}), \\ a_0 &= 1, \\ b_1 &= (R_p C_{dl} R_{ct}), \\ b_0 &= (R_p + R_{ct}). \end{aligned} \qquad (22)$$

The coefficients Taylor series expansion of fourth degree coefficients can be calculated as:

$$\begin{aligned} k_0 &= \frac{1}{R_p + R_{ct}}, \\ k_1 &= \frac{C_c R_p^2 + 2C_c R_p R_{ct} + C_c R_{ct}^2 + C_{dl} R_{ct}^2}{(R_p + R_{ct})^2}, \\ k_2 &= \frac{R_p C_{dl}^2 R_{ct}^3}{(R_p + R_{ct})^3}, \\ k_3 &= \frac{R_p^2 C_{dl}^3 R_{ct}^4}{(R_p + R_{ct})^4}. \end{aligned} \qquad (23)$$

These expressions, together with (4) and (9) form the set of equations. Its solution according to Beaunier's circuit parameters' is as follows:

$$\begin{aligned} R_p &= 2\frac{m_3^2}{2m_0 m_3^2 - 9m^2}, \\ R_{ct} &= -9\frac{m_2^2}{m_0\left(2m_0 m_3^2 - 9m_2^3\right)^2}, \\ C_{dl} &= -\frac{1}{54}T\frac{4m_0^2 m_3^4 - 36 m_0 m_3^2 m_2^3 + 81 m_2^6}{m_0\left(2m_0 m_3^2 - 9m_2^3\right)}, \\ C_c &= -\frac{1}{2}T\frac{\left(2m_1 m_3 - 3m_2^2\right)}{m_3} m_0. \end{aligned} \qquad (24)$$

4.2 Numeric simulation stage

The measurement process has been simulated in Matlab environment, using the transient state simulator for models described in s-domain. As the rank of the numerator in Beaunier's circuit admittance $Y(s)$ (21) is higher than rank of denominator, it was impossible to simulate current response on voltage stimulus with this model. The simulations have been conducted for a model expanded with additional, serial resistor modelling the output resistance of arbitrary waveform generator. Moreover, the limited slew rate of generator's amplifiers has been taken into consideration, by means of a specially designed algorithm. The identification measurements of anticorrosion coating have been simulated with T equal to circuit's time constant τ multiplicated by 3, 10 and 15. Each of experiments consisted of generation of 4 Chebyschev shape-designed stimuli sequences and acquisition of 4 c_i observables. For simulation purposes, the measurement error of observables was assumed 0,5%.

4.3 Parameter identification stage

The moments of impulse response m_0, m_1, m_2, m_3, have been calculated on the basis of observables c_i according to (20). Then, due to (24), the model parameters and the relative errors of their estimation have been computed. The results achieved are presented in Table 1 and compared with spectral identification methods: the CNLS method and bilinear transformation based methods, derived in Chair of Metrology and Electronic Systems: the basic bilinear identification methods (PBIL) and modified bilinear transformation method (ZBIL) with dynamic measurement frequency selection [6].

It can be seen in the Table 1, that the accuracy of identification, for all the methods compared is similar. The accuracy of Chebyshev signal method is heavily dependent on the measurement time T. With $T=10\tau$, the new method shortens the model parameters' identification 4 times comparing with CNLS method and 3 times, in comparison with basic bilinear transformation based method (PBIL).

One of the advantages of new method is property of scaling between the measurement time and the approximated identification accuracy. It is profitable in the case of monitoring technical objects anticorrosion coatings, as the degradation of coating is being characterised not by the absolute values of model parameters, but by the relative change of parameters since the previous measurement.

5. RESULTS AND CONCLUSIONS

The aim was to test the usefulness of shape-designed signals, especially the polynomial signals in parameter identification of anticorrosion coatings modelled by electric circuits. Nowadays, the technical resources available allow generating such signals easily. The Chebyschev polynomial signals seems to be particularly interesting shape-designed signals, as they guarantee the smallest oscillation among all the polynomials with equal leading coefficient. That implies the internal compression of power signals, being the part of polynomial signal. Moreover, the properties of Chebyschev polynomial coefficients limit the propagation of measurement errors from the set of observables to set of parameters.

The simulation results have proven the usefulness of Chebyschev signals for parameter identification of anticorrosion coating 4 components Beunier's equivalent circuit. The new method is superior to commonly used techniques in terms of measurement time, which is 4 times faster than the conventional tuned model CNLS method.

Another advantage is the simplicity of measurement

TABLE 1. Simulation results of method evaluation and simulation.

Method	R_p [GΩ]	δ_{Rp} [%]	R_{ct} [GΩ]	δ_{Rct} [%]	C_c [F]	δ_{Cc} [%]	C_{dl} [F]	δ_{Cdl} [%]	Meas. time [s]
CH 15τ	100,33	-0,33	100,67	+0,67	9,91p	-0,89	99,32p	-0,67	600
CH 10τ	100,46	+0,46	100,54	+0,54	9,94p	-0,60	99,45p	-0,54	400
CH 3τ	92,63	-7,36	105,88	+5,88	8,69p	-13,09	91,56p	-8,43	120
CNLS	100,4	+0,4	100,3	+0,3	9,99p	-0,1	100,6p	+0,6	1896,5
PBIL	101,1	+1,1	100,9	+0,9	9,99	-0,1	98,9p	-1,1	1501
ZBIL	100,2	+0,2	99,9	-0,1	10,01p	+0,1	100,5p	+0,5	121

system, which is composed of arbitrary waveform generator, impedance buffer circuitry and sample&hold. The method does not require as much computing power nor synchronous sampling as the systems currently used. It is well suited for realisation of low-cost, portable anticorrosion coating testers.

Currently, the laboratory set-up is being prepared, to verify the method experimentally, together with other shape-designed signals identification methods.

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