Fast impedance measurement method using Laplace transformation

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Abstract- The paper presents the impedance measurement method using a real-life step pulse as a perturbation signal and Laplace transformation as a tool for analyzing the response of the object under test. The method is addressed to explore different technical object (like anticorrosion coatings, gas sensors, ceramics, dielectrics biological tissues etc.) when the measurement time cannot be long. The presented method is known, but is not very popular because of some limitation. The paper presents the influence of the limitations on the accuracy of the equivalent circuit parameters identification.

I. Introduction

There are many technical objects which can be tested using impedance measurement. Impedance spectroscopy is commonly used to explore electrical properties of objects in which some processes, characterized by different time constants, exist. The measurement procedure of impedance spectroscopy consists of measurement phase, when the object impedance is measured as a function of a measurement frequency (impedance spectrum) and then the analysis phase, when the RC parameters of the equivalent circuit of the tested object are identified on the basis of impedance spectrum using Complex Nonlinear Least Square Fitting algorithm [3-5].

One of the most important application of the impedance spectroscopy is diagnostics of the anticorrosion coatings performed in laboratory on test samples and also on objects directly in the field (e.g. on bridges, pipelines etc.) [1, 2]. Modern anticorrosion coatings can reach very high impedance $|Z_x|>1\text{G}\Omega$. To test and find out the components of equivalent circuit of such objects, it is necessary to measure impedance in a wide frequency range from very low (on the level of 100μHz) up to 100kHz. This causes that the impedance spectrum measurement lasts long time of a level of a few hours. It is especially onerous in case of measurement done on objects directly in the field, so the authors have proposed in papers [6-7] methods using bilinear transformation to identify components of the equivalent circuit on the basis of the measurements at a few frequencies which number is equal to the number of the elements to be identified. This allows to reduce the number of measurement frequencies to be measured and as a consequence reduces the measurement time. Unfortunately, for some objects (like anticorrosion coating) the required values of measurement frequencies include very low ones of an order of few mHz, what implies long measurement time, even in case of bilinear method. Due to this facts, there is the need of very fast measurement – identification method which will allow 'one shot' measurement. Some authors [8-12] have proposed usage of the pulse signal and an analysis of the response signal in time domain mostly using Laplace transformation. None of this papers discuss the influence of the perturbation signal shape, performance of the measurement circuit on the accuracy of the method. The authors decided to evaluate method by means of simulation and check the influence of the measurement time in relation to the time constants of the circuit and number of acquired samples.

II. Impedance measurement method

Presented method uses computational power of personal computer and implements DSP algorithm for processing of quantized measurement signal to calculate impedance parameters of measured object. To realize the measurement using the method, it is necessary to feed the measured two terminal network Z_x with the voltage step signal and than sample and quantize signal proportional to current flowing thru Z_x using A/D converter. The architecture of the measurement system using the mentioned method is presented in Fig. 1.

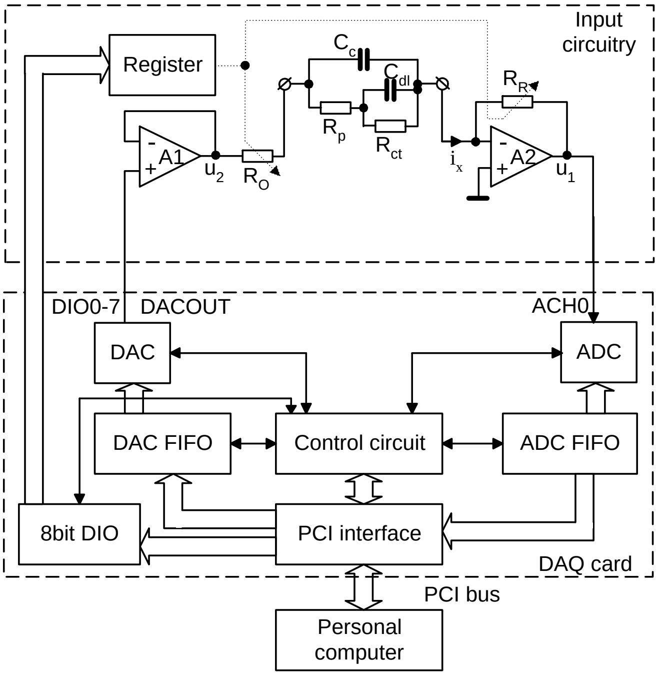


Figure 1. Block diagram of the measurement system using the proposed method

The system consists of the personal computer with installed DAQ card and the input circuitry connected to measured object Z_x represented by equivalent electrical circuit in form of two terminal four-element network (C_c, R_p, C_{dl}, R_{ct}).

The excitation signal for measured impedance Z_x is prepared using D/A converter located on DAQ card. In order to limit maximal value of current flowing thru measured object, the programmed resistor R_O was used on the output of voltage follower A1 acting as the source of excitation signal. Current i_x is converted to voltage u_1 by current-to-voltage converter realized with amplifier A2. The current conversion range change is obtained by resistor R_R which can be programmed decadely. This allows to fit measurement signal u_1 to a range of A/D converter located on DAQ card.

On the basis of u_1 samples collected in memory, using Laplace transformation s-domain representation $U_1(s)$ is calculated according to formula (1):

$$U_1(s) \approx \sum_{k=1}^{N} u_1(k) \cdot \exp(-s \cdot t(k)) \text{, where } s = \sigma + j\omega \tag{1}$$

The dumping factor σ should be selected to prevent the integration result from oscillation. The range of frequencies for which the obtained spectrum is valid is dependant on the sampling parameters, e.g. lower frequency limit f_L depends on the measurement time T_m and high frequency limit f_H depends on the sampling frequency f_s, where

$$f_L = 1/T_m \qquad f_H = f_s/2 \tag{2}$$

Knowing the Laplace transform of excitation signal U_2(s), on the basis of impedance definition, the impedance spectrum is determined using formula (3):

$$Z(s) = \frac{U_2(s)}{U_1(s)} \cdot R_R \tag{3}$$

where: R_R – range resistor of current-to-voltage converter.

At the last stage of proposed method, using the obtained impedance spectrum of the measured object and the fitting program LEVM [3], the values of components (C_c, R_p, C_{dl}, R_{ct}) of equivalent circuit of measured object can be determined.

III. Evaluation of the method by simulations

The presented method was evaluated by means of simulation performed with the aid of Matlab. The two-terminal network used for tests represents typical equivalent circuit of impedance of anticorrosion coatings in the early stage of exploitation (C_c=314.6pF, R_p=10GΩ, C_{dl}=2.226nF, R_{ct}=5GΩ,). The simulations were performed for 1V step signal. At the first stage, the impedance response was analyzed as time function and as a Nyquist plot of impedance spectrum. At the second stage the analysis of identification accuracy of equivalent circuit components was performed.

A. The analysis of impedance spectrum

At the first stage, the influence of resistor R_O on current flowing thru measured impedance was examined by simulations (Fig. 2). The tests were performed for two values of R_O: 1GΩ and 100MΩ. The greater value of R_O is more appropriate because the current dynamics is getting lower ca. 10 times (it is better situation for A/D converter) and initial current change is extended up to 1s. Due to this fact, for next simulations the values of R_O was assumed 1GΩ.

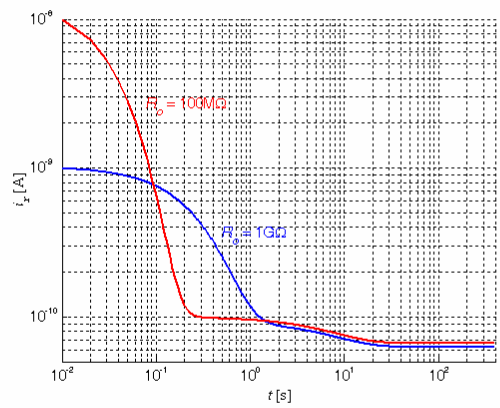


Figure 2. Impulse response of object under test

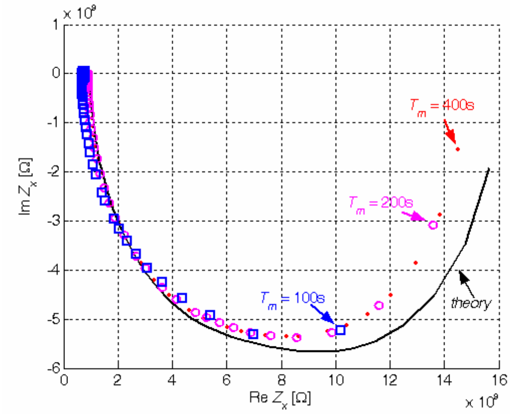
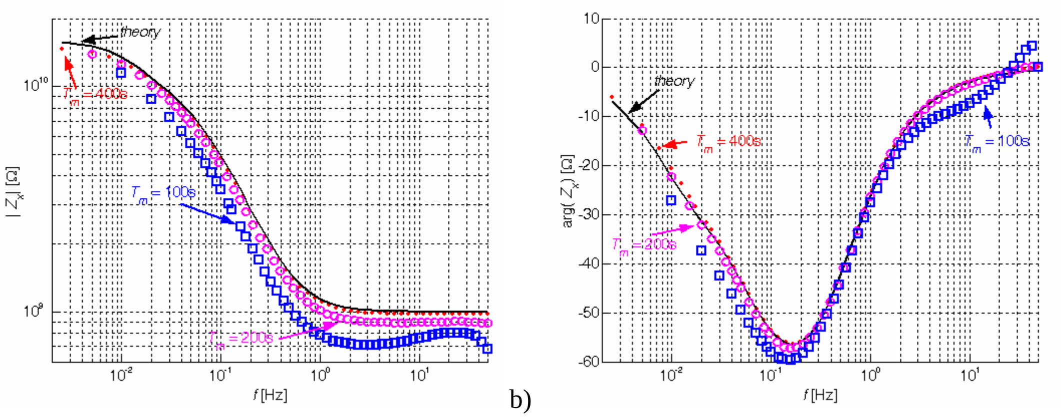


Figure 3. Nyquist plot of impedance spectra

At the next stage, the influence of time of samples acquisition (T_m=100s, 200s, 400s) on the shape of impedance spectrum of the object was analyzed. The spectra were calculated on the basis of formulas (1) and (3) using constant sampling frequency f_s=100Hz. The test results of four-element two-terminal network were presented in fig. 3, 4a and 4b, where the Nyquist plot (fig. 3) and Bode plot (fig. 4a and 4b) of impedance spectra were shown. The graphs also present the reference spectra (continuous line) of the tested object calculated using known values of the RC components.



a) b)

Figure 4. Bode plot of modulus (a) and argument (b) of impedance spectra

When analyzing graphs, it can be noted, that the obtained impedance spectrum is closest to the theoretical one when the acquisition time is the longest T_m=400s. Because of very wide range of impedance modulus and argument changes, the presented curves make no possibility of precise evaluation of the influence of analyzed parameters on the measurement accuracy.

Due to above fact, it was decided to perform evaluation of accuracy of identification of components of the equivalent circuit of measured impedance Z_x on the basis of the obtained impedance spectrum.

B. Errors of determination of components of equivalent circuit

The obtained impedance spectra have allowed identification of parameters of components of equivalent circuit of the tested object. To do this, the LEVM Complex Nonlinear Least Square

Immitance Fitting Program [3] was used. The program allows iterative finding of parameters of function describing two-terminal network with assumed structure to impedance spectrum obtained on the basis of formulas (1) and (3). Relative errors of identified components were calculated for two acquisition times T_m=200s (fig. 5a) and T_m=400s (fig. 5b) as a function of sampling frequency of current signal (u_1~i_x).

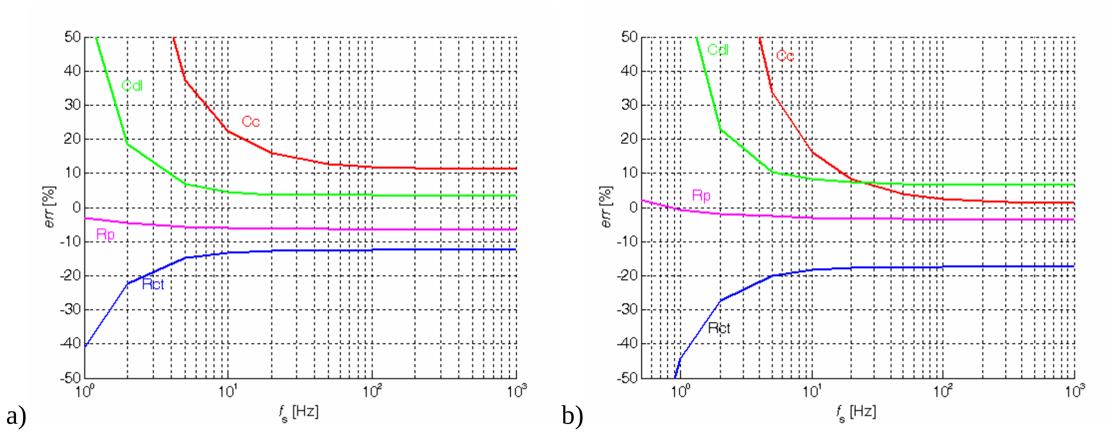


Figure 5. Errors of component identification for measurement time of 200s (a) and 400s (b)

It can be seen that the relative errors of each component have minimal values for frequencies above 100Hz. For elements C_c and R_p, the errors are on the level of 2-3% in case of acquisition time of T_m=400s, but for elements C_{dl} and R_{ct} better situation appear for T_m=200s, when the errors are on the level of 4% and 12% respectively. The identification results were placed in Table 1.

Table 1. Identification results for the tested object

Method	C_c [pF]	δ_{Cc} [%]	R_p [GΩ]	δ_{Rp} [%]	C_{dl} [nF]	δ_{Cdl} [%]	R_{ct} [GΩ]	δ_{Rct} [%]	Meas. Time [s]
Classical impedance spectroscopy	323.4	2.8	9.89	-1.1	2.32	4.2	4.92	-1.6	3900
Proposed method T_m=400s	318.5	1.2	9.63	-3.7	2.37	6.5	4.13	-17.4	400
Proposed method T_m=200s	350.0	11.3	9.35	-6.5	2.30	3.3	4.38	-12.4	200

In order to use classical impedance spectroscopy method, the values of modulus and phase of the test object were generated for frequencies in a range of 1mHz÷20kHz using 3 points per decade in 1-2-5 steps. The measurement time was calculated assuming 2 periods of each measurement frequency.

Analyzing Table 1, it can be noticed that the proposed method using Laplace transformation gives correct result and fulfills requirements especially for measurements directly in the field, meaningfully shortens measurement time (from 3900s in case of classical spectroscopy to 400s).

IV. Conclusions

The impedance measurement method using step excitation signal and Laplace transformation to analyze response signals allows shortening measurement time necessary to obtain impedance spectrum. When comparing to classical impedance spectroscopy using frequency response analyzer with sequential frequency scanning, the Laplace based method is more sensitive to different sources of errors. Due to this fact the Laplace based method is not so popular, but shorter measurement time can be important feature especially in case of instruments designed to work directly in the field. Till now, the research has allowed to shorten measurement time 10÷20 times with acceptable level of identification error of each component of equivalent circuit of the tested object when comparing to classical impedance spectroscopy. Further research is aimed to optimize the proposed method in order to lower the error of identification of equivalent circuit components.

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