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IMPROVEMENT OF THE FAST IMPEDANCE SPECTROSCOPY METHOD USING SQUARE PULSE EXCITATION

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Abstract – The paper presents a new method of impedance measurement for impedance spectroscopy. The method is based on square pulse excitation and digital signal processing of sampled current and voltage response. The main innovation in the proposed method is sampling moments optimisation adequate to the object under test. The method was tested by Matlab simulations and results are not worse than in previous version of the method while assuring smaller number of samples (lower processing efforts) and wider impedance spectrum frequency range.

Keywords: impedance spectroscopy, voltage pulse, time domain response

1. INTRODUCTION

There are many technical [1] and biological [2] objects which can be modelled by electrical equivalent circuit in form of two-terminal RC network. Diagnostics of such object is usually performed using impedance spectroscopy (IS). The IS is well-know research method [3] and consists of two stages: impedance spectrum measurement and equivalent circuit components parametric identification. The first phase, measurement one, is highly dependant on the object to be measured. Due to economical and safety reasons, one of the popular tested objects are anticorrosion coatings. Modern coatings represent very high resistance (of an order of hundred GΩ) and shunting capacitance (of an order of hundred pF). Testing of such objects requires measurements in a wide frequency range including very low frequencies (below 1 mHz). This leads to a very long measurement time (several hours). Additionally, more and more tested objects are located directly in the field, like bridges [1], pipelines, fuel tanks etc. Due to limited time access, the measurement time should be kept as short as possible.

Most commercially available IS instruments [4] use traditional single-sine technique which is based on sequential measurements of the spectrum point by point. This way, the total time of spectrum measurement is a sum of each frequency point measurement time, which finally gives a long lasting procedure.

There are some proposals of using multisine technique [5] and other measurement signals [6] proposed by other authors. Also the authors of this paper have proposed the method using square pulse excitation [7], which allows to shorten an impedance spectrum measurement time. Authors' works have allowed improvement of the method by some modifications, which are presented in the paper.

2. EXEMPLARY OBJECT UNDER TEST

As was mentioned before, one of the popular tested objects are anticorrosion coatings. Fig. 1 presents an equivalent circuit with typical values of components of anticorrosion coating during exploitation in the early stage of the undercoating rusting.

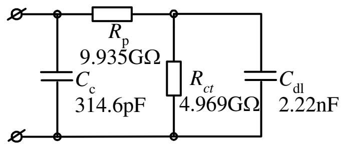


Fig. 1. Schematic diagram of the object under test.

The presented object will be used as a test engine for the presented method. It is worth to note, that in case of anticorrosion coatings monitoring, the state of the object changes rather slowly, so between consecutive measurements the changes are rather small. Such assumption allows using an approach known from diagnostics of analog electronic circuits: when starting measurements, we assume some state of the object with known, nominal values of the components (e.g. see Fig. 1). For this starting point and assuming changes of each component in the range from 0.1 up to 10 times of the nominal value, we determine the conditions of the measurement using before-test simulations, as it will be shown in subsection 3.2.

3. PRINCIPLES AND IMPROVEMENTS OF THE METHOD USING SQUARE PULSE

The description of the basic method was given in [7]. The measured object is excited with a square pulse with given parameters (amplitude and pulse duration according to selected range) and an object's response is sampled in two channels to obtain two sets of samples of signals $u_1(t)$ and $u_2(t)$ proportional respectively to current and voltage. For those signals, a representation in frequency domain can be calculated using continuous Fourier transform according to (1):

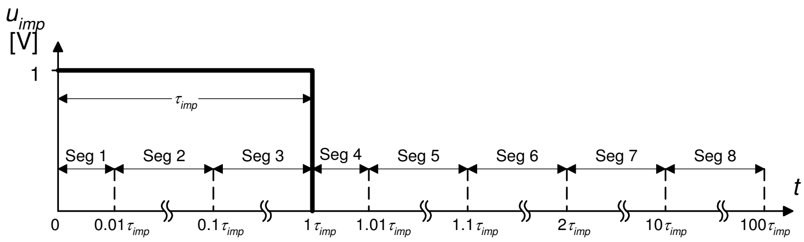


Fig. 2. Time segments of sampling process of an object response on excitation with a square pulse.

$$U_i(j\omega) = \int_0^{\infty} u_i(t)\exp(-j\omega t)\,dt\,, \quad \text{where: i = 1, 2} \qquad (1)$$

To calculate estimate of the transform, the sampled signals need to be approximated as shown in (2):

$$U_i(j\omega) \approx \sum_{n=1}^{N-1} \int_{t_n}^{t_{n+1}} \tilde{u}_i(t)\exp(-j\omega t)\,dt\,, \qquad (2)$$

where $\tilde{u}_i(t)$ is a linear approximation between samples of the response signal (current or voltage).

In the previous method, the acquisition (sampling of the response signals) was organized as shown in Fig. 2, the whole process was divided into 8 segments with different sampling frequencies. This allowed to minimize the number of acquired samples while assuring good enough sampling frequency.

3.1. Idea of the proposed improvement

The idea of new method lies in sampling process organization better fitted to sampled signals. The difference between the old and the new improved methods is shown in Fig. 3.

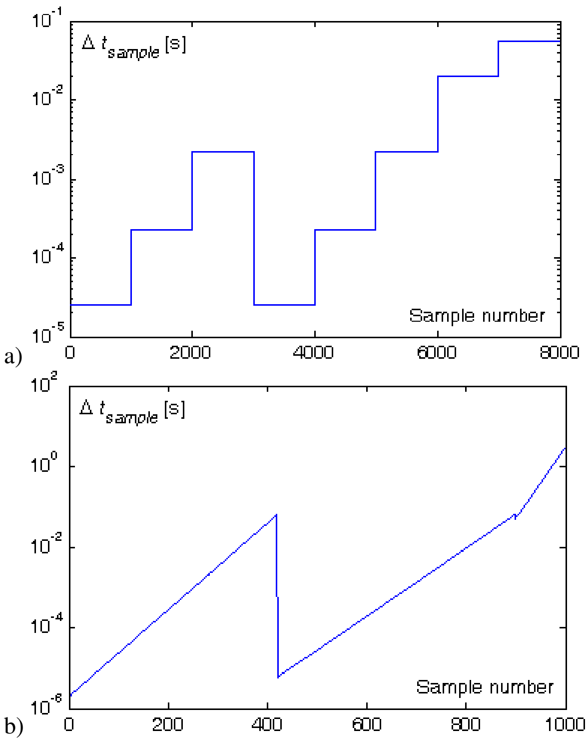


Fig. 3. Samples spacing during acquisition a) the old method, b) the new method.

The number of samples in each time segment in the old method was constant as well as the sampling frequency, calculated according to the time duration of the segment. In the proposed new method, the sampling frequency changes continuously and only 3 regions were set: one inside pulse and two regions after pulse. Thanks to better designed sample spacing, the total number of acquired samples can be lowered (in the presented example, the number was decreased from 8000 to 1000 samples).

3.2. Sampling moments optimization

In the current work authors propose modification of the method, which depends on decrease of the total number of samples through better sampling moments selection. This process will decrease computational effort of the method while preserving accuracy of impedance spectrum calculations with relation to the previous method.

Comparing (1) and (2) it is seen that a source of an error of impedance spectrum calculations mainly lies in difference between integrals obtained for continuous and discrete time. In order to decrease that error distances between linear approximations $\tilde{u}_1(t)$, $\tilde{u}_2(t)$ used in (2) and response signals $u_1(t)$, $u_2(t)$ used in (1) should be lowered. That condition generally can be satisfied be adjusting sampling moments density to curvature of signals $u_1(t)$ and $u_2(t)$ (the more bent curves are, the higher sampling density should be used). A measure of a signal curvature is a value of second derivative of that signal. Fig. 4 presents the modulus of the second derivative of voltage response signal $u_2(t)$ for the circuit shown in Fig. 1, with assumption of a square pulse excitation signal with a duration of τ_1 = 2.5 s.

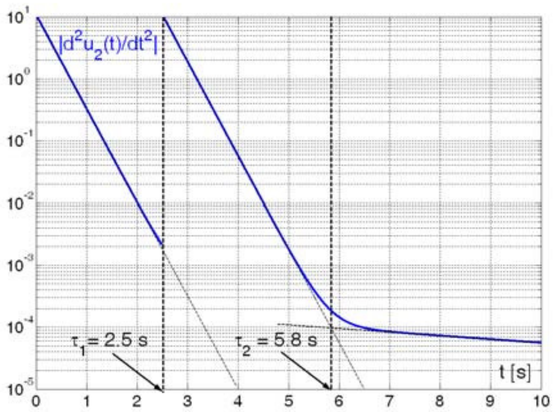


Fig. 4. The modulus of second derivative of signal $u_2(t)$.

The second derivative curve is shown only for ten seconds of signal acquisition, while for greater times the slope of that curve remains unchanged. Also a maximum acquisition time was set to $T_{acq} = 80$ s, since assumption of longer time did not improve impedance spectrum accuracy evaluation.

Fig. 4 shows that a curve representing logarithm of the modulus of the second derivative of $u_2(t)$ is almost linear in three time segments with limits $\tau_1 = 2.5$ s (where curve is not continuous) and $\tau_2 = 5.8$ s (where curve changes its slope). Hence it is clearly seen that acquisition time should be divided into 3 segments with sampling moments spaced logarithmically within each segment. The same conclusion could be drawn, if one have analysed signal $u_1(t)$. A following formula was used to obtain sampling moments in each time segment:

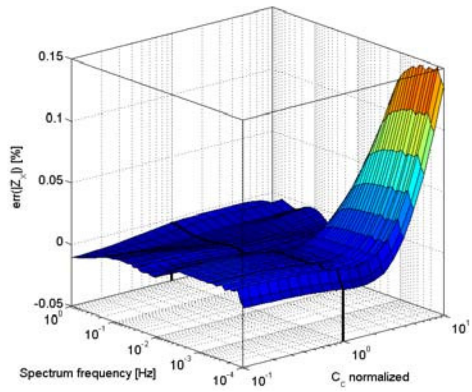
$$t_n^{(k)} = t_1^{(k)} + T^{(k)} \frac{10^{\frac{n-1}{N^{(k)}-1}\cdot w^{(k)}} - 1}{10^{w_i} - 1}, \quad n = 1, 2, \ldots, N^{(k)}, \qquad (3)$$

where: $t_n^{(k)}$ is an n-th sampling moment in the segment k, $t_1^{(k)}$ is the beginning time of the segment, $T^{(k)}$ is the time width of the segment, $N^{(k)}$ is a number of samples in the segment and $w^{(k)}$ is a parameter influencing sampling density. From (3) it is seen that for the tested circuit 12 parameters in the proposed sampling method needs to be evaluated. Parameters $t_1^{(k)}$ and $T^{(k)}$ are obtained from Fig. 4 and equals: $t_1^{(1)} = 0$ s, $t_1^{(2)} = 2.5$ s, $t_1^{(3)} = 5.8$ s, $T^{(1)} = 2.5$ s, $T^{(2)} = 3.3$ s, $T^{(3)} = 74.2$ s ($T^{(1)} + T^{(2)} + T^{(3)} = 80$ s). The rest 6 parameters ($N^{(k)}$, $w^{(k)}$, $k = 1, 2, 3$) are obtained through an optimisation procedure in which minimum values of impedance spectrum errors for the tested object are searched. Simulations performed for nominal values of the components of the tested object shown that these errors changes monotonically or have one minimum when changing value of any of those 6 parameters. Finally optimisation procedure led to the following parameters values: $N^{(1)} = 420$, $w^{(1)} = 4.5$, $N^{(2)} = 480$, $w^{(2)} = 4.05$, $N^{(3)} = 100$, $w^{(3)} = 1.8$. Hence the total number of sampling moments in modified version of the method equals $N = 1000$.

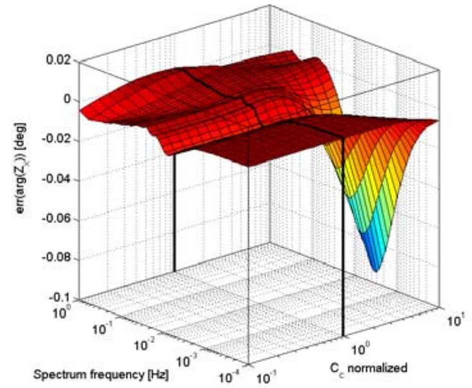
4. VERIFICATION BY SIMULATION

The proposed method was verified by simulation in Matlab to find out the limitations and to prepare for a next step – an implementation in the laboratory system based on a DAQ card.

As was mentioned in section 2, the nominal point for simulations was assumed for components' values shown in Fig. 1. The change of each component in the range form 0.1 up to 10 times of the nominal values was also assumed. Fig. 5-7 shows obtained errors of impedance modulus (a) and argument (b) when measuring using the presented method. Values of components were normalized to their nominal values. The errors were determined with reference to values of the object impedance calculated theoretically.

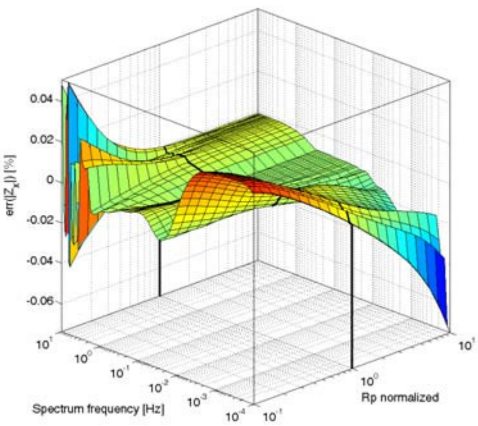


a)

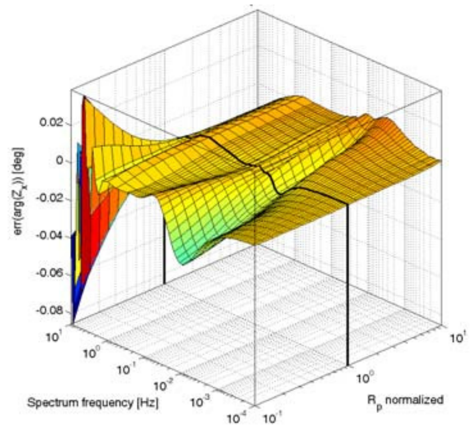


b)

Fig. 5. Measurement error of impedance modulus (a) and argument (b) as a function of the C_c changes.



a)



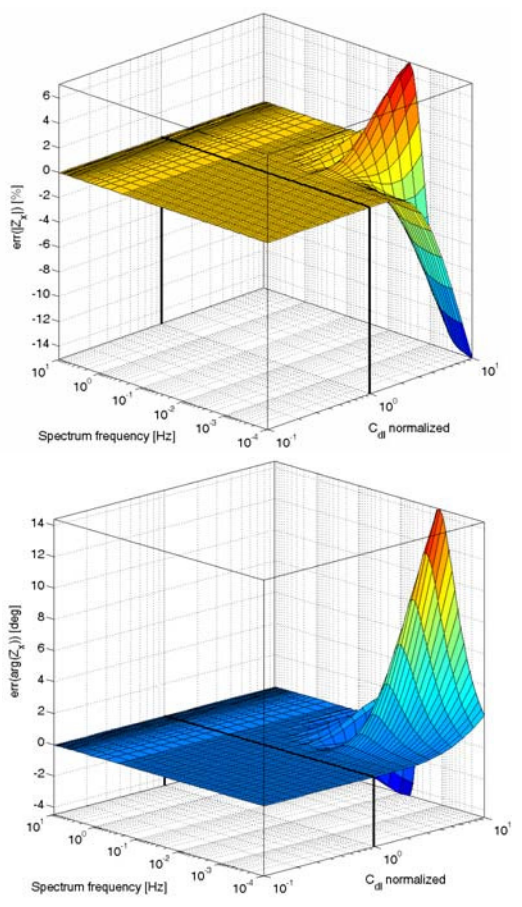
b)

Fig. 6. Measurement error of impedance modulus (a) and argument (b) as a function of the R_p changes.

Fig. 5 presents results of component C_c testing. As one can see the obtained errors are quite small, thanks to the placement of this component in the structure of the two-terminal RC network modelling the object. When the value of the Cc increases, the errors slightly increase, especially in low frequency range.

Fig. 6 shows errors for component R_p which is also not deeply buried in a structure of the object's equivalent circuit. Modulus measurement errors increase when the value of R_p increases, the measurement conditions are getting worse.

Fig. 7 shows errors for component C_{dl} which are very similar to results for component R_{ct}. Both components are buried in a structure of the object's equivalent circuit, so the level of obtained errors are significantly greater when the value of the component differs form the nominal. These errors are especially visible for lower frequencies range, because for higher frequencies these buried components less influence the impedance (the impedance of the object is mainly determined by C_c and R_p).



a) b)

Fig. 7. Measurement error of impedance modulus (a) and argument (b) as a function of the C_{dl} changes.

The presented results are only a part of tests. The method was only tested by simulations at the time of paper preparation because some implementation problems exists with such kind irregular sampling. Commercially available DAQ-cards does not allow direct implementation of irregular sampling. So, the authors are designing own circuit for generating sample clock with designed pattern.

5. CONCLUSION

The proposed method allows to achieve satisfying accuracy with shorter acquisition time (the measurement time was shorten from 250s to 80s when comparing to previous method). Additionally, thanks to limited number of acquired samples, the processing capability of the measurement instrument implementing the method can be lowered, thus allowing easier implementation in field-worthy, low-power instruments. The achieved accuracy is comparable to the previous method, so the proposed method is expected to be implemented first in a laboratory impedance spectroscopy system and then in the instrument for testing objects directly in the field.

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