Selection of excitation signals for high-impedance spectroscopy

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Selection of excitation signals for high-impedance spectroscopy

Michal Kowalewski

Gdansk University of Technology, Faculty of Electronics, Telecommunications and Informatics, Department of Metrology and Optoelectronics, Gdansk, Poland

E-mail: michal.kowalewski@eti.pg.gda.pl

Abstract. The method of fast impedance spectroscopy of technical objects with high impedance ($|Zx| > 1$ GΩ) is evaluated in this paper. An object is excited with a signal generated by digital-to-analog converter (DAC) located on the U2531A DAQ module. Response signals proportional to current flowing through and voltage across the measured object are sampled by analog-to-digital converters (ADC) in the DAQ module. The object impedance spectrum is obtained with use of continuous Fourier transform on the basis of acquired signals. Different excitation signals (square, triangle, sawtooth and sinc) were compared in order to estimate accuracy of impedance spectrum evaluation. The method is evaluated by means of simulation and practical experiment in a measuring system on an exemplary object in the form of multi-element two-terminal RC network modelling of an anticorrosion coating impedance.

1. Introduction

Diagnosis of technical [1] and biological [2] objects and materials [3] with use of impedance spectroscopy is still an open research field. This is due to a fact, that there is no universal method capable to diagnose different objects in comparable, short time and also with high accuracy. Usually higher accuracy of impedance spectroscopy requires more time.

Conventional measurement technique used for impedance spectroscopy is based on single sine technique (SST). An object is excited with a harmonic signal and two signals are measured: voltage across and current through the object. Measurements are repeated for different frequencies in order to obtain impedance spectrum in several decades. For high impedance objects ($|Zx| > 1$ GΩ), e.g. high-thickness anticorrosion coatings or dielectric materials, this leads to very long measurement times (of an order of hours), because measurements must be performed for very low frequencies (1 μHz, 1 mHz). This kind of diagnosis is acceptable only in laboratory conditions and can not be used directly in the field, e.g. on bridges, pipelines or flood banks.

In order to shorten time of measurements different methods were proposed. These methods use multi-sine technique [4, 5] or other measurement signals [6-10]. A promising technique depends on usage of a square pulse for excitation of an object and measuring signals proportional to voltage across and current through the object with ADCs [11]. The object impedance spectrum is then obtained with use of continuous Fourier transform on the basis of linear approximations between samples of discrete response signals. Simulations and experimental research of this method had been performed in [11, 12], but in this paper the method is evaluated by means of different excitation signals (square, triangle, sawtooth and sinc). Accuracy of impedance spectrum evaluation for exemplary model of high impedance anticorrosion coating is compared for each excitation.

2. Description of the method

In the presented method a measured object Z_x is excited with an arbitrary waveform $u_o(t)$ and signals proportional to voltage $u_x(t)$ across and current $i_x(t)$ through the object are measured. The excitation signal is generated by DAQ module U2531A and applied to the object from DAC through A_{out}. The programmed resistor R_L is used at the output of the amplifier A_1 in order to limit the maximum value of current flowing through the object. Response signals $i_x(t)$ and $u_x(t)$ are converted to signals $u_1(t)$ and $u_2(t)$ and applied to ADCs in the DAQ module through A_{in1} and A_{in2}. Current $i_x(t)$ is converted to voltage u_1(t) by current-to-voltage converter (CVC) realized with amplifier A3. Range of the CVC can be changed with resistor R_R in order to fit the measured signal u_1(t) to the range of the ADC.

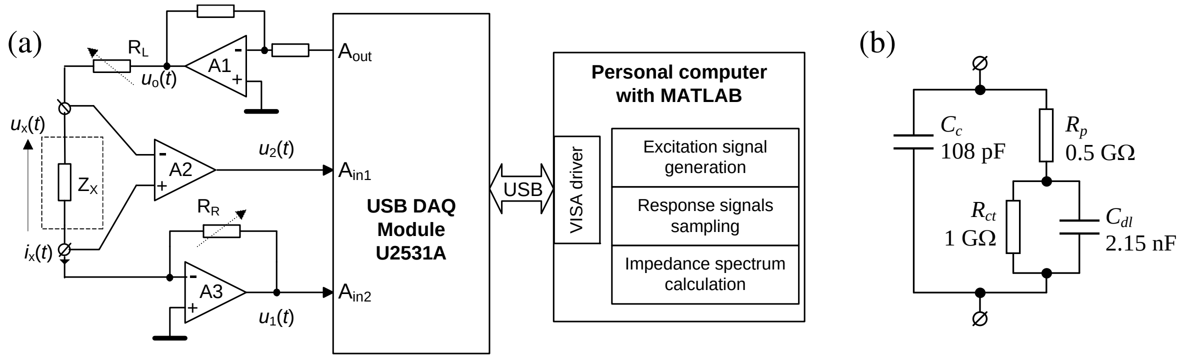

Figure 1. Block diagram of the measuring system (a),
the equivalent circuit of anticorrosion coating impedance (b).

Impedance spectrum of the object is calculated from the formula

$$Z(\omega) = \frac{\mathrm{Re}U_2(\omega) + j\,\mathrm{Im}U_2(\omega)}{\mathrm{Re}U_1(\omega) + j\,\mathrm{Im}U_1(\omega)} R_R\,, \tag{1}$$

where $U_1(\omega)$ and $U_2(\omega)$ are continuous Fourier transforms of signals $u_1(t)$ and $u_2(t)$ obtained as follows

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

Response signals $u_1(t)$ and $u_2(t)$ are discrete, while continuous Fourier transform requires continuous signals, hence linear approximations $\tilde{u}_i(t)$ between samples are used in (2).

The method is useful for diagnosis of high-impedance objects, eg. anticorrosion coatings. An example of the equivalent circuit of anticorrosion coating is shown in figure 1b.

In the previous research of the method a unipolar square pulse signal was used as an excitation. However it is interesting to investigate efficiency of the method, when measured object is excited with different arbitrary waveform. The following signals were chosen for comparison: bipolar square, triangle, sawtooth and sinc (figure 2a).

Important problem during selection of an excitation signal is analysis of its spectrum (figure 2b). A shape of the spectrum determines allowable range of measurement frequencies and accuracy of object's impedance calculations for each frequency. First experiment [11] assumed usage of a unipolar square pulse. Spectrum modulus $|U_0|$ for this signal is given by a function of type $\sin(x) / x$, where $x = \pi \cdot k \cdot \tau / T$ (k - spectral line number, τ - square pulse duration, T - acquisition time). If the argument x reaches the value $m{\cdot}\pi$, then modulus $|U_0|$ equals zero. For this excitation moduli $|U_1|$ and $|U_2|$ of signals $u_1(t)$ and $u_2(t)$ are also given by a function of type $\sin(x) / x$ and it is unable to obtain impedance of an object for frequencies k/τ. Also near these frequencies very high impedance calculation errors are obtained. The limitation of the method was minimized in [12] by division of measurement frequencies in the required range from $f_{\min}$ to $f_{\max}$ ($f_{\min} < 1/\tau < f_{\max}$) into 2 groups:

- logarithmically spaced frequencies within the range ($f_{\min}$, 0.75/τ),
- linearly spaced frequencies (1.5/τ, 2.5/τ, …, $f_{\max}$).

For the object shown in figure 1b optimal value of unipolar square pulse duration equals $\tau = 5$ s [11], hence the following set of 15 measurement frequencies placed within 3 decades from $f_{\min} = 1$ mHz to $f_{\max} = 1$ Hz were selected: 1 mHz, 1.7 mHz, 2.7 mHz, 4.5 mHz, 7.4 mHz, 12.2 mHz, 20.2 mHz, 33.4 mHz, 55.1 mHz, 90.9 mHz, 0.15 Hz, 0.3 Hz, 0.5 Hz, 0.7 Hz, 0.9 Hz.

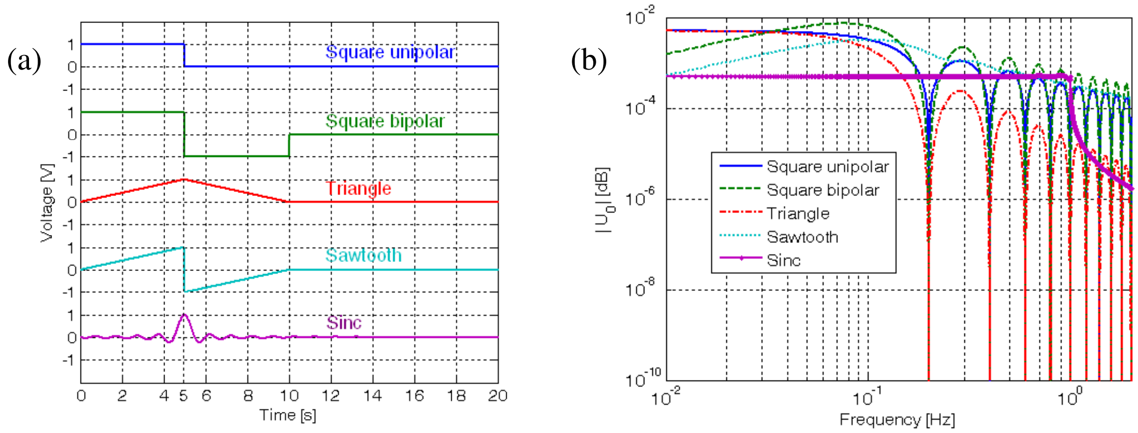

Figure 2. Excitation signals (a) and their spectra (b).

As is shown in figure 2b, the same limitation of the method occurs for triangle excitation, while for sawtooth and sinc signals modulus $|U_0|$ is non-zero for all frequencies in the assumed range and there is no limitation in measurement frequencies selection. However for comparison purposes the same set of measurement frequencies previously obtained for unipolar square pulse was used in simulations.

3. Simulation results

Efficiency of the method of high impedance spectrum calculation for different excitation signals was verified on the model of anticorrosion coating shown in figure 1b. The following parameters of the method were selected: constant sampling frequency ($f_s = 10$ kHz), $T = 100$ s, resolution of ADC (14-bits). Excitation signals with parameters shown graphically in figure 2a were used. Obtained impedance modulus and argument calculation errors are presented in figure 3.

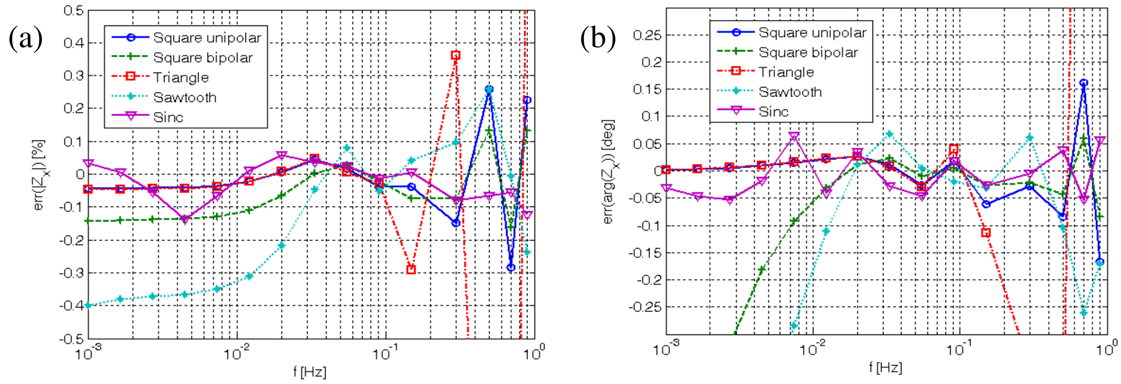

Figure 3. Impedance modulus (a) and argument (b) calculation errors for different excitation signals.

The replacement of an unipolar square excitation with its bipolar form insignificantly improve accuracy of impedance calculations for higher frequencies due to greater values of modulus of bipolar square signal, but worsen accuracy for lower frequencies, especially for impedance argument. Errors increased up to ± 1 °.

Results obtained for triangle and unipolar square excitations are the same for lower frequencies. This is comprehensible, because in this case moduli of both signals have the same values. However for higher frequencies modulus of triangle excitation has significantly lower values, which causes increase of impedance spectrum calculation errors up to ± 3 % for modulus and ± 3 ° for argument.

Efficiency of usage of sawtooth excitation is in the middle between square pulse and triangle. Maximum calculation errors are contained in ranges ± 0.4 % for modulus and ± 2.6 ° for argument.

The best results were obtained for sinc excitation. Due to constant value of modulus of that signal in the whole range of measurement frequencies, dispersion of impedance calculation errors is uniform and changes in the range ± 0.14 % for modulus and ± 0.06 ° for argument. Since usage of a unipolar square pulse gives better results only for lower frequencies, maximum errors for frequencies closer to 1 Hz grow for that signal up to ± 0.3 % for modulus and ± 0.17 ° for argument. Important benefit of sinc excitation also results from the fact that it doesn't have steep edges and there is no need to use irregular sampling method (higher sampling frequencies just after steep edge of an excitation), as in case of square pulse signal. The problem of irregular sampling was discussed in [11, 12].

4. Optimization of the method for sinc excitation

A characteristic feature of the sinc function is that its continuous Fourier transform is a rectangular function. In order to guarantee constant modulus value of that function for measurement frequencies up to $f_{\max}$ a following formula can be used

$$u_0(t) = U_0 \operatorname{sinc}\left(2\pi f_{\max}\left(t-\tau\right)\right), \tag{3}$$

where: U_0 - maximum amplitude, τ - time shift, $f_{\max}$ – maximum frequency in impedance spectrum.

It was assumed that $U_0 = 1$ V and $\tau = T/2$, hence maximum value of $u_0(t)$ occurs in the middle of acquisition time $u_0(\tau) = 1$ V.

Important point is determining proper value of T, because starting generation of sinc signal for $T \neq kf_{\max}^{-1}$, ($k = 1, 3, 5, \ldots$) causes occurrence of violent changes in values of signals $u_0(t)$ and $u_1(t)$ at the beginning of the sampling process ($t = 0$). To omit necessity of usage of high sampling rates it is justified to select optimal value of T from the range $T = kf_{\max}^{-1}$.

A simulation focused on selection of optimal value of T for the model of anticorrosion coating was performed, which indicated that maximum calculation errors decrease below ± 1 % for modulus and ± 1 ° for argument when $T > 17$ s. Obtained calculation errors are presented in figure 4.

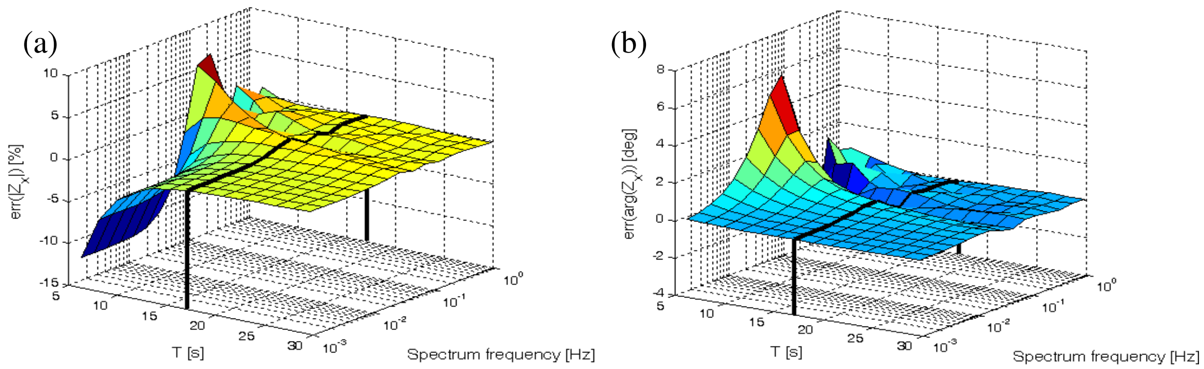

Figure 4. An influence of acquisition time T on impedance modulus (a) and argument (b) calculation errors.

Simulations with use of sinc excitation indicated also that constant sampling frequency can be used and influence of its value on the accuracy of the method is negligible (with assumption that at least 1000 samples are acquired).

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5. Experimental results

Measuring system shown in figure 1a was used to supply sinc excitation and obtain impedance spectrum of the model of anticorrosion coating in the form of 4-element RC network shown in figure 1b. In the first step a following values of parameters of the method were assumed: $U_0 = 1$ V, $\tau = 8.5$ s, $T = 17$ s, $f_s = 10$ kHz, $f_{min} = 1$ mHz, $f_{max} = 1$ Hz, which gave significant errors (several times greater than in simulations, especially for low frequencies). It was caused by omitting condition $T \geq f_{min}^{-1}$ required to fulfill in order to evaluate impedance spectrum from frequency f_{min}. Hence, in the second step it was assumed that $T = 1000$ s. In that case impedance spectrum calculation errors decreased insignificantly, because of very high dynamic range of signal $u_0(t)$ - response signals $u_1(t)$ and $u_2(t)$ were measurable only in time range $|t - \tau| < 20$ s.

Performed experiments led to the conclusion that in order to significantly increase accuracy of impedance spectrum calculations in the method with sinc excitation, it is required to decrease range between f_{min} and f_{max}, which will cause that the magnitude $|U_0|$ of that signal rises (figure 5b). This will lead to greater robustness against measurement disturbances and decrease dynamic range of excitation and measured signals. Different shapes of sinc excitation destined to evaluate impedance spectrum in one, two or three decades from $f_{min} = 1$ mHz are shown in figure 5a.

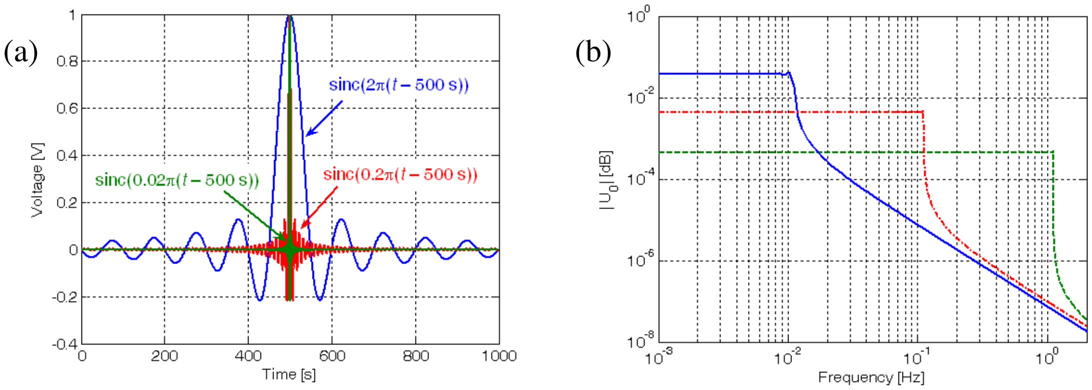

Figure 5. Exemplary sinc excitation signals destined to evaluate impedance spectrum in one (*blue*), two (*red*) or three (*green*) decades (a) and their spectra (b).

In the last step frequency range was limited to only one decade from $f_{min} = 10$ mHz to $f_{max} = 100$ mHz and the following parameters of the method were assumed: $U_0 = 1$ V, $\tau = 50$ s, $T = 100$ s, $f_s = 1$ kHz. Statistical analysis for a series of 10 measurements was performed. Obtained results, shown in figure 6, are satisfactory. Mean values of impedance calculation errors are in the range ± 2 % for modulus and ± 1 ° for argument, while standard deviations are comparable in the entire range of measurement frequencies ($\sigma_{|Zx|} < 1$ %, $\sigma_{\arg(Zx)} < 0.6$ °).

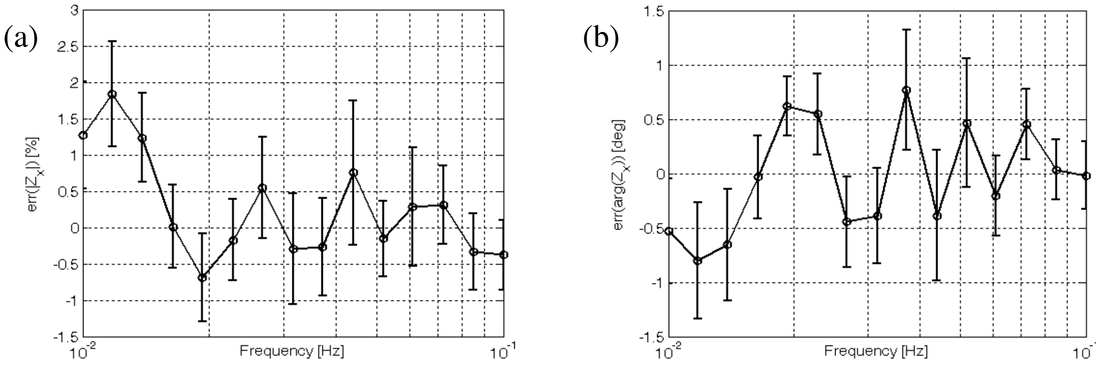

Figure 6. Mean and standard deviation of impedance modulus (a) and argument (b) for a series of 10 measurements of the model of anticorrosion coating.

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6. Conclusions

The method of fast impedance spectroscopy of high impedance objects with use of continuous Fourier transform requires selection of an optimal excitation signal. Previous research of the method was performed with use of unipolar square pulse. Due to steep edges of the excitation and response signals there was a need to use irregular sampling methods (division acquisition time into segments with different sampling frequencies or usage of logarithmically changed sampling frequency).

In this paper different excitation signals were compared by taking into account their spectra and impedance spectrum calculation errors. Performed research shows usefulness of sinc excitation, because this signal is free of steep edges, can be developed to have constant spectrum in assumed range of measurement frequencies and also guaranties to obtain lowest object's spectrum calculation errors for all analyzed excitations. There is no need to use high sampling frequencies as in case of a square pulse. Practical experiments in measuring system led to the conclusion that it is justified to decrease range between $f_{\min}$ and $f_{\max}$ in order to increase accuracy of impedance spectrum calculations.

Replacement of the square pulse with sinc excitation offers better conditions to implement the method with continuous Fourier transform in portable instruments designed for diagnosis of technical objects located directly in the field.

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