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Universal Laboratory Measurement System for Evaluation of the Impedance Spectroscopy Method Based on Multi-harmonic Excitation Signal

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Abstract- The paper presents universal laboratory measurement system for evaluation of the impedance spectroscopy method based on multi-harmonic excitation signal. The system is mainly designed to optimise the method for impedance spectrum digital measurement dedicated to implement in low-cost portable instrument oriented for diagnostics of technical objects located in the field. Due to time constraints during field measurements, it is important to shorten acquisition time of impedance spectrum by using multi-harmonic excitation. Implementation of the method in the field-worthy instrument requires optimisation procedures in terms of hardware complexity and power consumption requirements minimisation. The results of simulation tests as well as experimental verification were presented.

I. Introduction

Impedance spectroscopy (IS) is an advanced research tool, commonly used in science, industry and medicine for diagnosis of the state of different technical [1] and biological [2] objects and materials [3]. IS depends on measurement of an object impedance in a certain frequency range and analysis of the obtained impedance spectrum.

IS nowadays can be performed by instruments using impedance measurement technique based on object excitation with harmonic signal SST (single sine technique) and vector measurement of two signals: voltage across and current through the tested object. Repeating measurements for different frequencies enables obtaining impedance spectrum in required frequency range. The most important disadvantage of SST is a very long measurement time, especially for very low frequencies (mHz). Use of such low frequencies in IS is necessary in case of identification of elements of objects with a very high impedance modulus $|Z_x| > 1$ GΩ. This situation takes place in diagnostics of high-thickness anticorrosion coatings [4] or dielectric materials and causes that the measurement procedure extends significantly to several hours. This kind of diagnosis is acceptable only in laboratory conditions.

The need of diagnosis of objects directly in the field caps tight time constraints. The other factor, which lean towards shortening measurement time of an IS method is changeability of an object, especially physicochemical or biological, which makes quasi-stationarity condition of an object difficult to fulfil.

Therefore, there is a need to develop much faster impedance spectrum measurement methods, dedicated to implementation in low-cost, miniaturized, portable instrumentation, which can be used in laboratory conditions as well as directly in the field. In order to meaningfully shorten impedance spectrum measurement time, the Authors have used multi-harmonic signal for excitation of an object under test and sampling of the signals proportional to voltage across and current through the measured Z_x with analog-to-digital converter A/D.

II. The architecture of the universal laboratory measurement system

The measurement system for verification of the developed measurement method was shown in Fig. 1. The system consists of a personal computer connected via USB interface with DAQ module (Agilent U2531A [5]) and with the developed by Authors input circuitry connected to the test object Z_x. Multi-harmonic excitation signal for Z_x impedance is prepared with the aid of DAC located in DAQ module (A_{out} output). Current $i_x(t)$ is converted to voltage $u_1(t)$ in current-to-voltage converter realised using A3 amplifier. The converted current range change is performed with the aid of programmed resistor R_R. This way the signal $u_1(t)$ is fitted to the measurement range of ADC1 converter in DAQ module. The instrumentation amplifier A2 allows measuring the voltage $u_x(t)$ across Z_x. The A2 output signal $u_2(t)$ is sampled (synchronously with $u_1(t)$) by second converter

ADC2 of DAQ module. Sampled signals are sent to PC in order to calculate impedance spectrum using DFT.

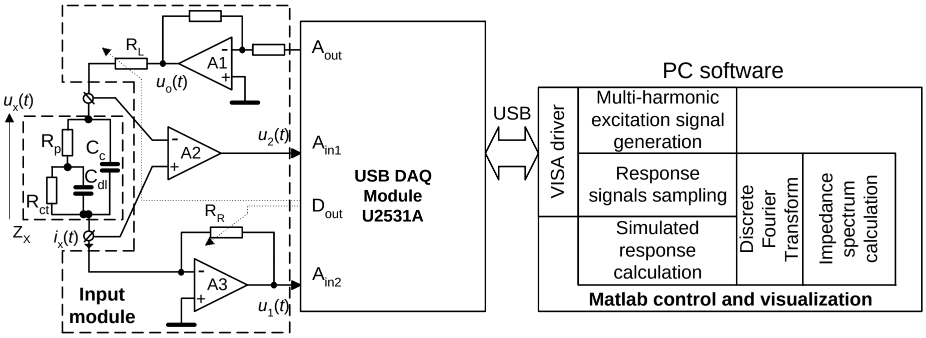

Figure 1. Simplified block diagram of the proposed laboratory measurement system.

It is worth to note, that, according to required impedance modulus range (up to several GΩ) and required frequency range (up to hundreds kHz), the amplifiers A1, A2, A3 have to have good DC parameters (input currents, offset voltages) as well as AC parameters (frequency bandwidth, input impedances) in order to minimize errors introduced by input circuitry [6]. As a compromise, the amplifiers A1-A3 were realised using OPA627 and AD8620 operational amplifiers.

III. Method verification by simulations

The proposed measurement method was tested by means of simulation using Matlab and a test object with the structure shown in Fig 1 and the following components values: $C_c = 107.5$ pF, $R_p = 497.09$ MΩ, $R_{ct} = 988.82$ MΩ and $C_{dl} = 2.15$ nF. The test object represents the model of the anticorrosion coating on the early stage of undercoating rusting. The impedance values obtained from simulations were compared to impedance values calculated theoretically using known components values allowing to calculate relative error of impedance modulus $\delta(|Z_x|)$ and absolute error of impedance argument $\varepsilon(\arg(Z_x))$. The method was tested assuming analysed frequency range 0.01 Hz – 1 Hz at the frequency points specified in Table 1.

Table 1. The list of the components frequencies of the multi-harmonic signal.

Component	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	f_{12}	f_{13}	F_{14}	f_{15}
Frequency [Hz]	0.01	0.02	0.03	0.04	0.06	0.07	0.10	0.13	0.18	0.24	0.32	0.42	0.56	0.75	1,00

The shape of the generated multi-harmonic signal was shown in Fig. 2.

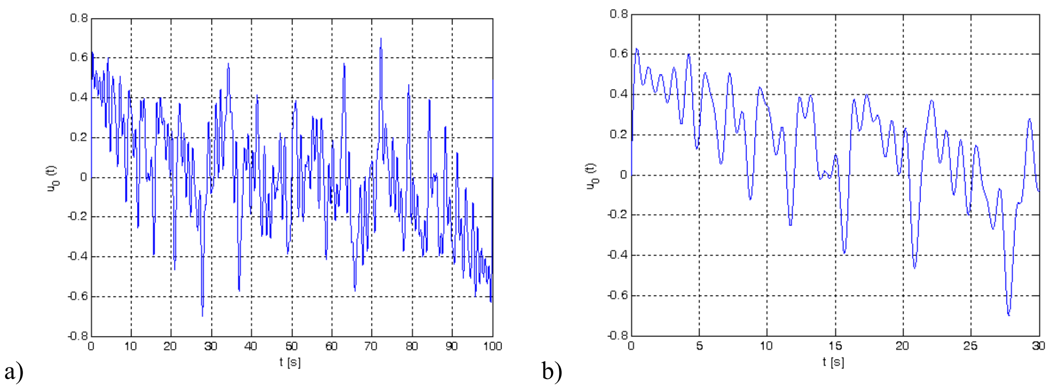

Figure 2. The generated multi-harmonic excitation signal for component amplitude U_0 = 100mV and f_s = 1 kHz in the whole acquisition time and in first 30s .

At first, the accuracy of the method was tested as a function of multi-harmonic signal components amplitude (Fig. 3) assuming sampling frequency equal to f_s = 1 kHz and 14-bit resolution of AD converters. The simulation has shown that the impedance errors increase noticeable when the components amplitude falls below 100 mV. At this amplitude, the peak-peak value of multi-harmonic signal is limited to ±0.7 V. Increasing components amplitude doesn't improve accuracy, but increases the peak-peak value of the excitation signal.

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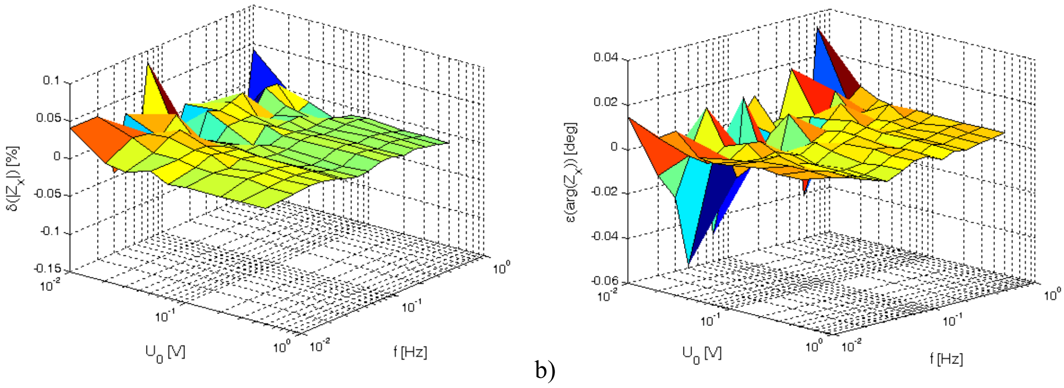
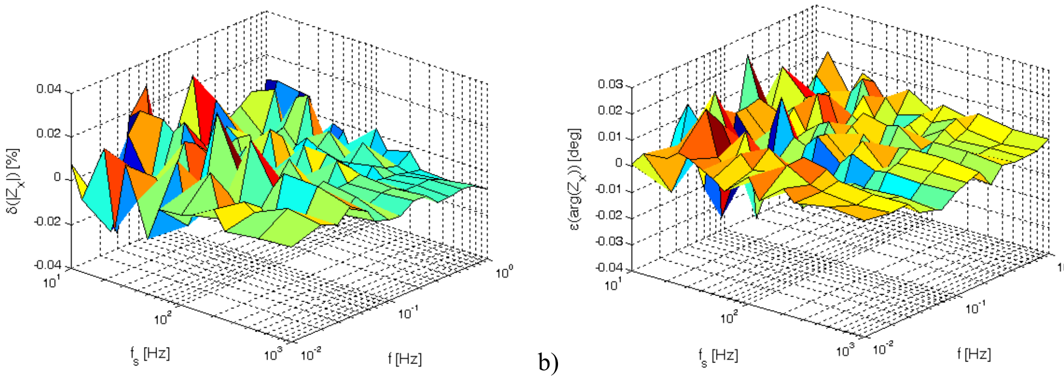


a) b)

Figure 3. The influence of amplitude of components of multi-harmonic measurement signal on the error of impedance modulus (a) and argument (b) measurement of the two-terminal object.

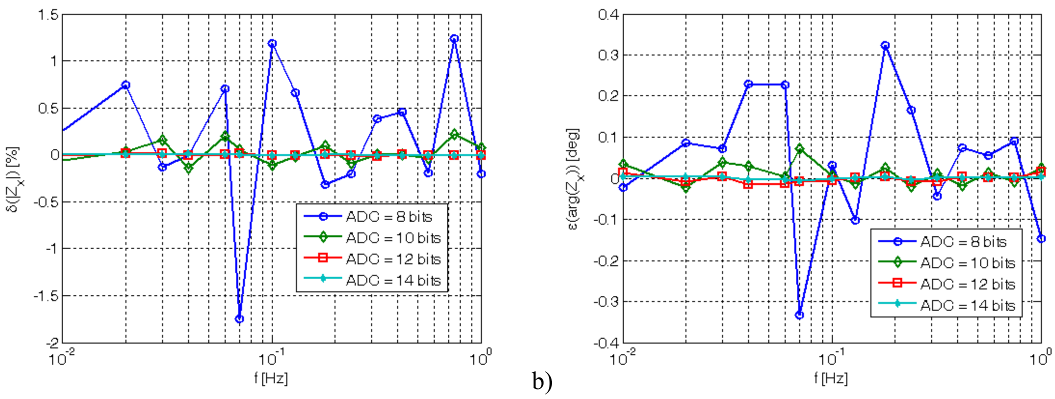
For assumed optimal value of amplitude of components of multi-harmonic measurement signal on the level of 100 mV, the influence of sampling frequency of response signals was investigated (Fig. 4). Decreasing the sampling frequency increases measurement errors. It can be noticed, that for exemplary object, the reducing f_s from 10 kHz to 1 kHz causes 4 times increase of measurement errors in the analysed frequency range.



a) b)

Figure 4. The influence of sampling frequency on the error of impedance modulus (a) and argument (b) measurement of the two-terminal object.

In the next step, the influence of the AD converter resolution was tested for four assumed cases: 8, 10, 12, and 14 bit ADC. As it can be seen in Fig. 5, the ADC resolution decrease from 14 down to 12 bits causes negligible increase of errors. A little greater error increase appears in case of 10 bit ADC. The modulus error reaches 0.25% in this case and argument error 0.08°, respectively. The meaningful error increase can be observed when using 8 bit ADC. This way, the modulus error exceeds ± 1.5% and the argument error is on the level of ± 0.3°.



a) b)

Figure 5. The influence of ADC resolution on the error of impedance modulus (a) and argument (b) measurement of the two-terminal object.

The acquisition of the object response on the multi-harmonic signal excitation should be started with an delay *t*, depending on the time constant of the tested object allowing the transient state to vanish. The required delay value *t* can be estimated when analysing errors of modulus and argument of impedance measurement calculated for different values of time *t* starting from 0 and ending when assuring minimal errors values. The performed simulations (Fig. 6) have indicated that the required delay *t* for the tested object is equal to 5 s.

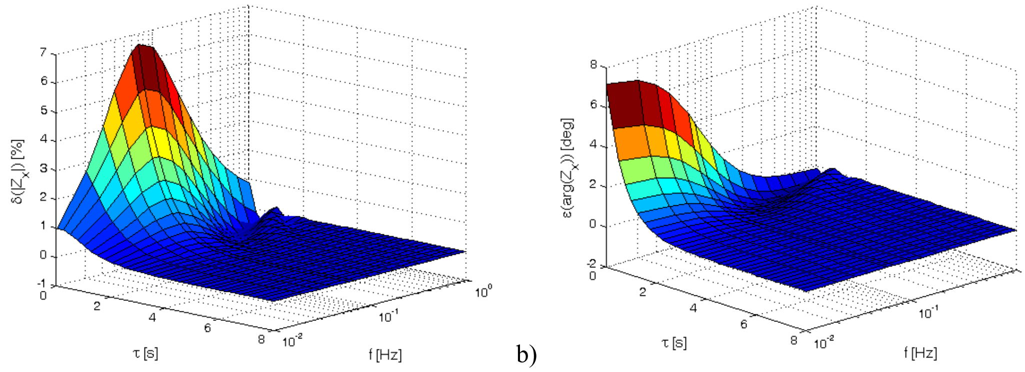


Figure 6. The influence of acquisition delay on the error of impedance modulus (a) and argument (b) measurement of the two-terminal object.

IV. Experimental verification

The experimental verification was performed in the measurement system presented in Fig. 1. The influence of the following parameters was analysed step by step: amplitude U_0 of components of multi-harmonic signal and sampling frequency f_s. In each case, the series of 10 spectrum measurements of the tested two-terminal RC network were performed allowing to present the results in a form of the mean values of errors of the modulus and argument of impedance.

In the first step, the influence of the multi-harmonic signals components amplitude U_0 was tested assuming sampling frequency $f_s = 1$ kHz. Four values of U_0 were taken into account: 20 mV, 50 mV, 100 mV and 500 mV. When analysing the results presented in Fig. 7, it can be noted, that for 100 mV amplitude the noises existing in the measurement system have slightly influenced the results of impedance modulus and argument measurement. The error characteristic for both parameters is similar to those obtained for the highest amplitude (500 mV). The noticeable errors scatter appear when reducing the amplitude down to 50 mV, however the values of errors does not diverge meaningfully when comparing to previous case. The noticeable increase of errors can be observed in case of $U_0 = 20$ mV.

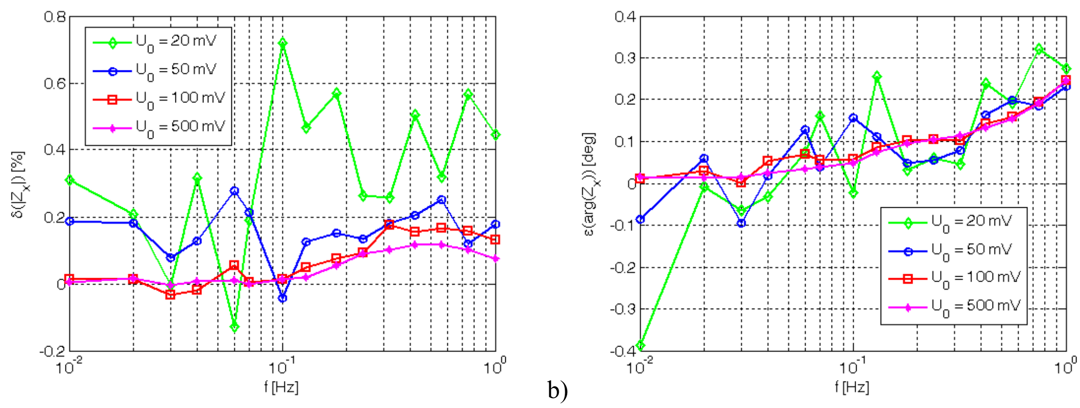


Figure 7. The influence of the multi-harmonic component amplitude on the error of impedance modulus (a) and argument (b) measurement of the two-terminal object in the measurement system.

In the next step, the optimal value of component amplitude $U_0 = 100$ mV was assumed and the influence of sampling frequency f_s was analysed. The f_s frequencies in the range from 10 Hz up to 1 kHz were analysed and the results for a few selected frequencies were presented in Fig. 8.

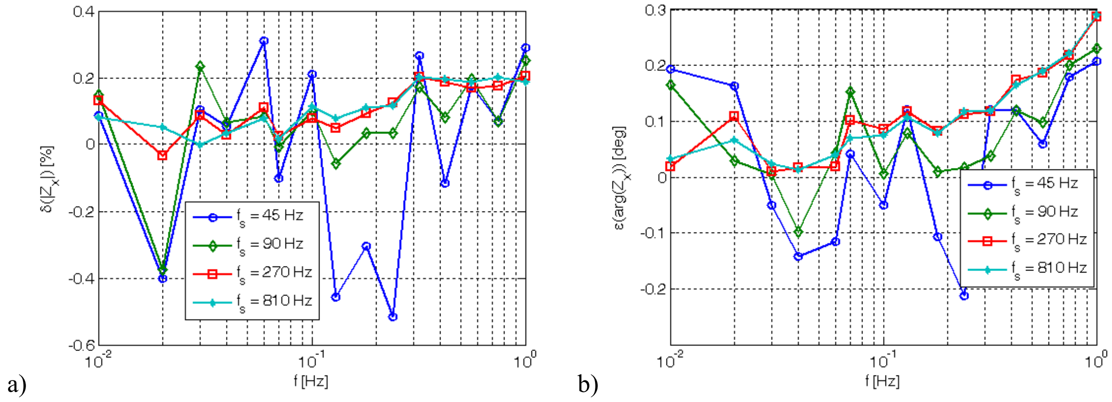


Figure 8. The influence of sampling frequency on the error of impedance modulus (a) and argument (b) measurement of the two-terminal object in the measurement system.

The sampling frequency decrease causes the increase of errors of impedance determination, but even for the lowest analysed frequency (10 Hz), the relative error of modulus and absolute error of argument are limited to acceptable values ($|\delta(|Z_x|)| < 1\%$, $|\varepsilon(\arg(Z_x))| < 0.5^o$).

V. Conclusions

The paper presents the method for digital impedance measurement based on multi-harmonic excitation as well as its verification and optimisation by simulation and experimental verification in the proposed universal laboratory measurement system.

The performed tests of the reference two-terminal RC network (representing equivalent circuit of the anticorrosion coating in the stage of the early undercoating rusting) have allowed to determine errors of impedance measurement (relative errors of modulus $\delta|Z_x| = \pm 1\%$ and absolute of argument $\varepsilon(\arg(Z_x)) = \pm 0.5°$) assuming impedance spectrum measurement time of an order of 100 s (acquisition time + impedance modulus and argument calculation time for 15 frequencies). The measurement time for the same frequencies using SST method (assuming measurement time for each frequency equal to one period of each frequency) would be four times longer (ca. 360 s). The obtained accuracy is fully acceptable in case of the measurements in the field, where the short measurement time and low computational power of impedance analyser CPU are much important.

The developed method was verified in laboratory measurement system, but the performed tests (in case of ADC resolution and sampling frequency minimalization) have shown the possibility of implementation in the portable instrumentation designed for diagnostics of the objects located directly in the field. The evaluation has created base to develop low-cost, autonomic impedance analyser for fast impedance spectroscopy performed directly in the field.

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