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IMPLEMENTATION OF ACCELERATED IMPEDANCE SPECTRUM MEASUREMENT METHOD

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Abstract − The paper presents the implementation of accelerated impedance spectrum measurement method, oriented for technical objects modelled by a linear equivalent circuit, e.g anticorrosion coatings. The method is based on multisine signal stimulation of an object and response analysis by triangle window filter-banks. It has several advantages, as compared with conventional point-by point spectrum measurement. The method was implemented in an experimental measurement system, based on a DAQ card. The achieved experimental results are discussed and compared with simulation results, in terms of measurement time reduction and accuracy.

Keywords impedance spectroscopy, multisine measurement signals, anticorrosion coatings diagnosis

1. INTRODUCTION

The modelling of many technical and biological objects with electrical circuits has recently become very popular. The reason is that such modelling allows monitoring and diagnosing of their state with the aid of well-developed tools and methods designed for electrical circuits. Particularly popular is the impedance parameters identification of objects modelled by multi-element, two-terminal equivalent circuits: anticorrosion coatings [1], materials [2], sensors [3], reinforced concrete constructions [4] and biological objects like physiological fluids and tissues [5].

Impedance spectroscopy is the conventional method of finding equivalent circuit parameter values. It is based on measurement of object impedance spectrum, usually point-by point with single frequency impedance analysers and fitting the parameter-dependant model to measurement data, usually by Complex Non-linear Least Squares (CNLS) method [6].

The main disadvantage of such process is the spectrum measurement time. The frequency range starts, in case of some objects, from order of mHz and μHz, thus implicating a very long measurement time (order of hours).

The need for reduction of impedance spectrum measurement time, even at the cost of accuracy is motivated by several technical and economical reasons. Firstly, field measurements lasting hours are both unpractical and very expensive. Secondly, there is a need for impedance spectrum measurement of dynamic or quasi-dynamic objects, where conventional, time consuming methods are not reliable due to object's parameter variation during measurement.

The impedance spectrum of linear objects can be measured, according to the superposition principle in one cycle (potentialy faster) with multisine stimulus.

However, the conventional multisine approach to DFT method [7] is inconvenient to implement in practice due to problems with long period of multisine. The measurement of coherently sampled multisine measurement with proper DFT window length could last longer than point-by point, single frequency method.

To circumvent these disadvantages, the authors have proposed the digital filter bank analysis of multisine signals with triangle window low-pass FIR filters. The idea of the method, several test multisine signals, the simulation results

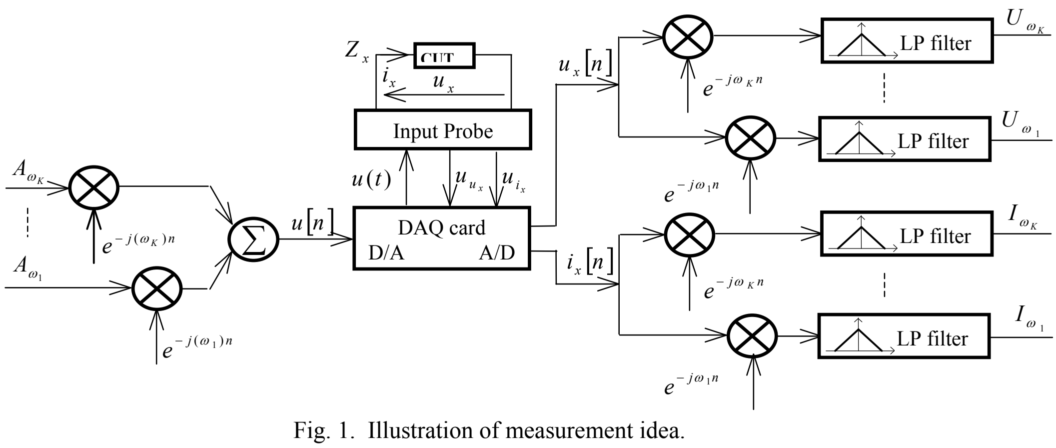

Fig. 1. Illustration of measurement idea.

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and comparison to single frequency DFT method (used in modern impedance analysers) were discussed in [8]. The method was proven, by means of simulation, to be faster than other methods currently used.

This paper describes the practical verification in a dedicated virtual impedance analyser, based on a data acquisition (DAQ) card. The structure of the system is presented and the experimental results are compared with simulations conducted before.

2. THEORETICAL BASICS OF METHOD

2.1. Measurement idea

The measurement idea of multisine method with filter bank analysis is presented in Fig. 1. The *K*-component multisine stimulation signal *u*[n] is synthesised in summation node in a sample-by sample (iterative) manner. Thus, there is no necessity of storing long multisine period in the memory, as in conventional Arbitrary Waveform Generators. The multisine is characterised by pulsations $_k$, and complex amplitudes $A\omega_k$ (amplitude and phase shift information).

The input probe apply the stimulus voltage to the circuit under test (CUT) and extracts the signals proportional to impedance voltage u_{ux} and current u_{ix}. Both signals are sampled simultaneously producing the digital forms u_x[n] and i_x[n], which are analysed by two identical, digital filter banks. Every filter bank channel is built from a modulator and low-pass filter. Modulator shifts the spectrum in frequency domain, according to the modulation principle. The spectral component corresponding to modulating frequency is shifted to DC. Its complex amplitude is extracted by low pass filter present in every filter bank channel [9]. Filter-banks calculate the complex amplitudes $U\omega_k$ and $I\omega_k$ of frequency components, corresponding to frequencies present in stimulus. Complex division of these values allows calculating impedance spectrum of an object for a given set of frequencies.

2.2. Multisine stimuli

The verification of method has been conducted for the 4 multisine signals, noted S1-S4. Signals S1-S3 consist of 14 sines covering the 2 decade frequency range.

The signal S1 has a lin-log distribution of frequencies (linear inside decade, and logarythmicall in decades). None of sine periods is a multiplication of other sine period. As a consequence, the multisine period is extremaly long, order of $7{,}5\cdot 10^{17}$ samples. The signal was chosen to check the method in a very unfavourable conditions.

The signal S2 is a heuristically optimised version of S1 signal with small frequency shifts. As a result, the multisine period is shorter ($2{,}3\cdot 10^{7}$ samples) and period of lowest frequency component is a multiplication of several periods of other frequencies. The signal was chosen to test the effectiveness of multisine frequencies optimisation.

The signal S3 is an optimal multisine, with a very low period equal to doubled period of the first sine. This signal can be filtered even with a simple rectangular window filter of the length equal to that period (2580 samples), covering all the periods of components. The frequencies in signal S3 were formed by summing two geometric progressions, so frequency distribution is quasi-logarithmical. The signal was chosen to test the precision of method in optimal, yet very difficult to obtain conditions.

The signal S4 is a simple logarythmical distribution of 25 frequencies (8 per decade) covering the 3 decade frequency range. The frequencies form the geometric progression. The signal was choosen to test the method in case of simple, technical frequency scale in 3 decade range.

All the signals above have been described in previous papers by authors (e.g [8]) and up till now, tested by means of simulation.

2.3. Triangle window filter bank analysis

A digital, low pass filter calculates the average value at output of modulator (Fig. 2), being the complex amplitude of multisine component with frequency equal to modulating frequency. Although the task seem to be frequency domain related, the time-domain optimised filters with sharp step response and fast impulse response need to be used as the average must be calculated as soon as possible in a predictable time in order to accelerate measurements. The finite impulse response (FIR) filters were chosen, due to their performance, stability, and settling time equal to filter window length.

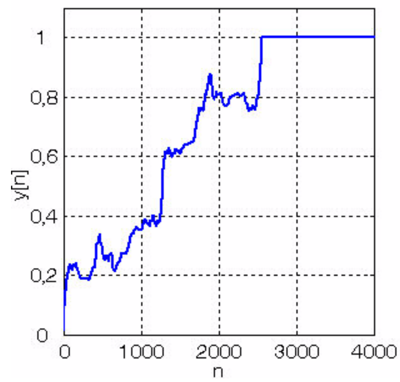

Fig. 2. The settling of normalized value at output of exemplary FIR filter with window length 2580 samples.

The investigations have shown, that the main FIR disadvantage – the amount of calculations required for convolution of the signal with long filter kernels – does not apply here. The 2 considered filters are the special cases of FIR which can be implemented recursively, drastically decresing the number of calculations. It can be easily seen by comparing the convolution (1) and recursive (2) form of the rectangular window MA filter (Moving Averager):

$$y[n]=\sum_{k=0}^{M-1}\frac{1}{M}x[n-k], \tag{1}$$

$$y[n]=\frac{1}{M}x[n]-\frac{1}{M}x[n-M-1]+y[n-1]. \tag{2}$$

The previous investigations have shown, that the MA filter works good when its length is a multiplication of multisine period (e.g. for signal S3). In other cases, a good choice is the triangle window filter, which, despite wider main lobe has better attenuation of higher frequencies. The *M*-length triangle window filter also have its recursive form: a cascade connection of two *M/2*-length recursive rectangular filters.

Filter characteristics are heavily dependant on filter length. The longer is filter kernel, the better selectivity is achieved, yet, the measurement time is longer. Moreover, the earlier experiments have shown, that the problem with filter selectivity usually occurs for lowest frequency of multisine, so it is desirable for the filter length to be a multiplication of T_1.In order to achieve measurement acceleration, the filter length M must be lower than single frequency measurement time, which is similar to sum of periods in signal.

3. EXPERIMENTAL MEASUREMENT SYSTEM

The experimental measurement system was designed according to the idea presented in Fig. 1. It has a form of virtual instrument based on PCI-6111E data acquisition card and a dedicated input impedance probe. The architecture of the system is presented in Fig. 3. There are 2 hardware blocks (input impedance probe, data acquisition card) and a dedicated, software block.

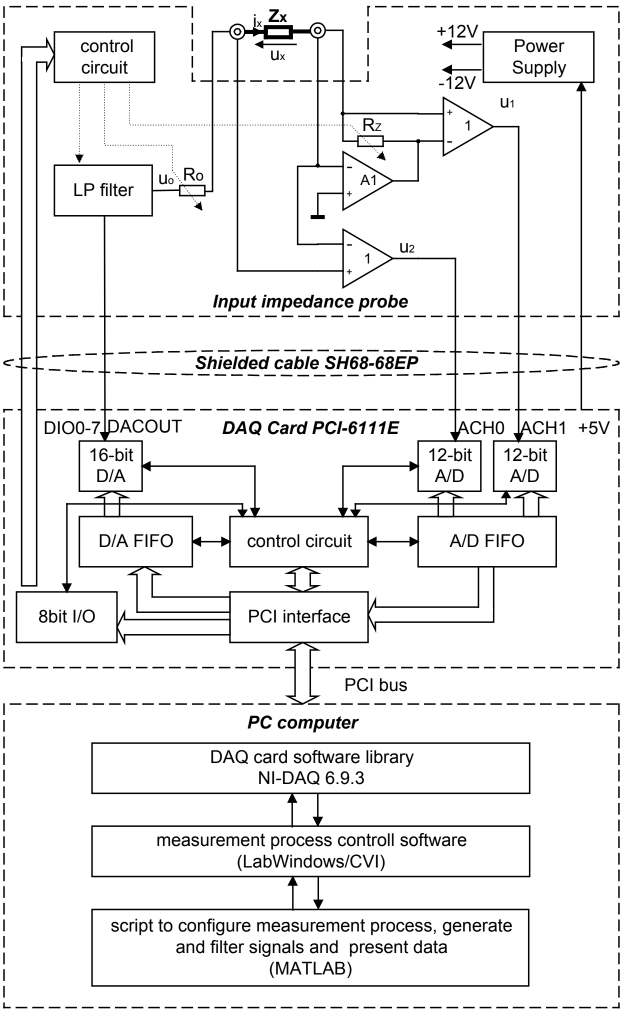

Fig. 3. Architecture of experimental measurement system.

The input impedance probe does the analogue-analogue conversions as described in measurement idea chapter: conditioning of stimulus and extracting the signals proportional to current and voltage at the object. The probe is configured by 8 digital lines – the configurated items are: the resistors in current-voltage converter, analogue filters cut-off frequency, etc. The object (Circuit Under Test) can be placed in terminal clamps on the casing of the probe or connected via a dedicated socket.

Fig. 4. View of the setup with a experimental impedance analyzer.

The Data Acquisition Card (DAQ), placed inside the PC class computer samples coherently the 2 extracted signals proportional to current and voltage and synthesises the stimulus via DDS (Direct Digital Synthesis) method. Moreover, the card generates the control signals to configure the measurement probe. The probe and the DAQ board are connected with a shielded SH68-68EP cable. Such a design allows to handle sensitive signals at high impedance circuits in a shielded box, far from noisy PC inside.

The laboratory setup with the experimental measurement system and a DSO is presented in Fig. 4. There is an exemplary multisine stimulus present on DSO display. The impedance object realised from discrete RC-elements is placed in the terminal clamps of impedance probe. The PC screen shows the panels of system software. The exemplary oscillogram of 14 component logarythmic, 2 decades multiharmonic stimulus and response is presented in Fig. 5.

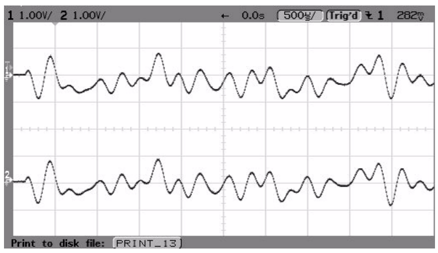

Fig. 5. Examplary oscillograms voltage (upper) and current (lower) signals for logarythmic multisine with 14 frequencies in 2 decades.

The software of experimental system is a 3 layer solution, designed in 2 programming environments: Matlab and LabWindows/CVI.

The main, functional software of virtual impedance spectrum meter was written in Matlab environment as a script (m-file). The script realises the measurement process according to a configuration data written in a text batch file, prepared by the user. The configuration involves multisine components amplitude and frequency, sampling frequency, impedance probe configuration, type of filtering, filter window length, and the form of result presentation.

For the given set of frequencies, the script calculates the measurement time, real frequencies of multisine components (frequency grid is dependant on sampling frequency), component phase shift (according to Schroeder's equation) and finally, a record of stimulus samples.

Then, the measurement process controll software *DAQmeasure* is invoked. The software, written in LabWindows/CVI controls the measurement itself – it configures the generation of stimulus on the basis of data prepared by the script. It configures the acquisition of voltage and current responses by ADC, reads waveform and writes data on disk. The DAQ card operations are realised by the NI-DAQ library, which handles the DAQ card in the operating system of a PC and offer a general programming interface for DAQ card operations.

After the sampling is finished, the Matlab script continues the operation, modulating and filtering the signals, thus calculating the complex impedance spectra, which can be presented in various forms: Bode plot of magnitude and phase, Nyquist plot or tabular form.

The software architecture has several advantages in terms of scientific experiment. The use of matlab allows to batch process and automatise several experiments on the same circuit with different stimuli or analysis methods. Moreover, the results (and indirect results) stay present in Matlab environment after finishing the measurement thus allowing e.g. to filter same set of data in different conditions witout the need to repeat the experiment itself.

4. EXPERIMENTAL VERIFICATION OF METHOD

The aim of experimental verification was to validate the conclusions from simultations decribed in [8]. Thus, the same test object and signals S1-S3 were used, to compare spectrum measurement in 2 decade frequency range with different filtering and multisine designing strategies. The second part of experimental verification is the 3 decade spectrum measurement with a conventional, logarythmical distribution of 25 frequencies.

4.1. Test object.

The spectrum measurement method has been tested on the Randles model (Fig. 6). That simple 3-element two-terminal is very popular in electrochemistry (e.g. to model early stages of underpaint corrosion) and it is frequently used as a test engine to compare various impedance spectrum estimation methods. The model equivalent circuit was realised from discrete RC elements: $R_e = 99{,}95\Omega$, $R_p = 99{,}97\Omega$, $C_{dl} = 4{,}68\mu F$.

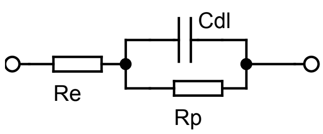

Fig. 6. The Randles model.

4.2. Spectrum measurement in 2 decades freqency range with MA and triangle window filters.

The spectrum measurement was conducted for 3 signals S1-S3 and 2 types of filters: a MA filter with rectangular window and a triangle window filter. The results are presented in the form of Bode and Nyquist plots. A thin line represents the theoretical spectrum for given element values, whereas the thick line connects the impedance values at measurement frequencies (circles). The plots for worst case – non-optimised multisine and MA filter are in Fig. 7. The measurement error is rather high (up to few percent), which can be seen especially on the Nyquist plot.

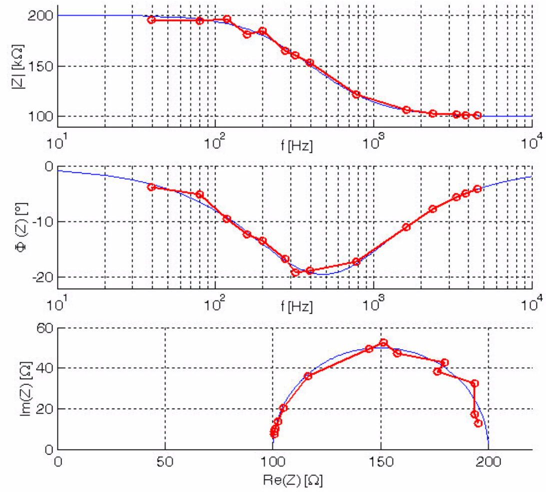

Fig. 7. Bode and Nyquist plot of impedance spectrum, signal S1, MA filter.

The Fig. 8 presents the best result – measurement with optimal signal S3 with a specific distribution of frequencies (which can be seen as placement of measurement points on Bode plots) and a MA filter of length equal to that multisine period. It can be seen, that in such case the measurement points matches the theoretical spectrum – the relative error is less then 0,18%.

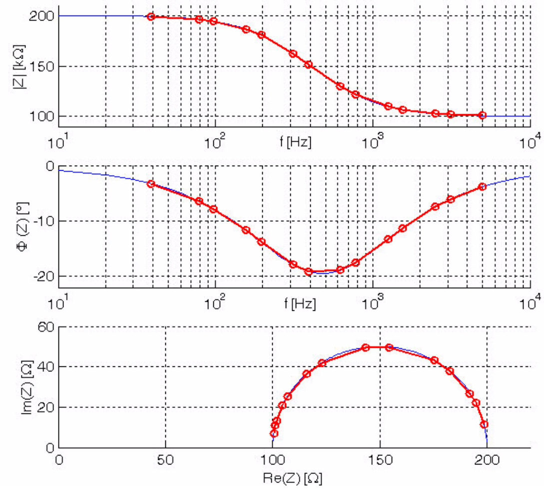

Fig. 8. Bode and Nyquist plot of impedance spectrum, signal S3, MA filter.

The experiment with signal S2 have confirmed, that a heuristical optimisation of frequencies distribution in multisine, decreases the measurement error to approx. 0,25%. The experiments with triangle window filters have shown that same accuracy can be obtained for non-optimised signal S1 without the need of heuristic optimisation.

The experiments have confirmed the simulation results, that for specific, optimal signals the MA filter is a good choice, but for arbitrary set of frequencies the triangle window filter is better.

4.3. Measurement with triangle window filters and 25 components, 3 decades freqency range multisine.

In the second part of experiment, the multisine had a logarythimical distribution of frequencies, covering the 3 decades range (10Hz-10kHz) with 25 sines (8 per decade). Such distribution of spectrum measurement points is common in practice. According to previous results, the triangle window filter has been applied.

The experiments with several values of filter length were conducted. The lowest filter length was set as not less than doubled period of lowest frequency. In case of recursive triangle window filter of length $M=2T_1$, rectangular MA sub-filter of length $M/2$ "catches" at least 1 period of T_1.

Unfortunately, the measurement error for first decade was too high for precise measurement. The 3D plot (Fig. 9) shows how the magnitude and phase of impedance change (fluctuate) at the output of filter bank channels in case of continous stimulus signal. It is obvious, that the selectivity of filters is insufficient and low frequency components (f_2, f_3,…) interfere with each other.

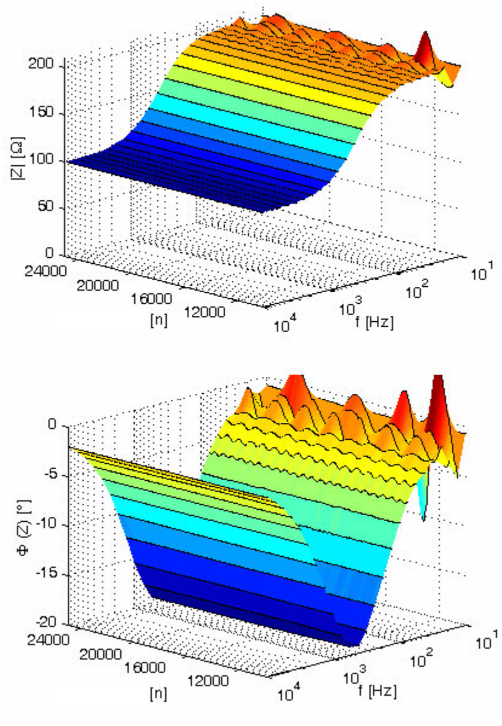

Fig. 9. Changes of impedance spectra (magnitude and phase) signal S4, triangle window filter $M=2T_1$.

The measurement accuracy have been increased, by using longer filter windows in channels 2-25. The plot of filter bank output (Fig. 10) for $M=3{,}2T_1$ shows that fluctuations in magnitude are very low – only the phase spectrum has some minor instabilities.

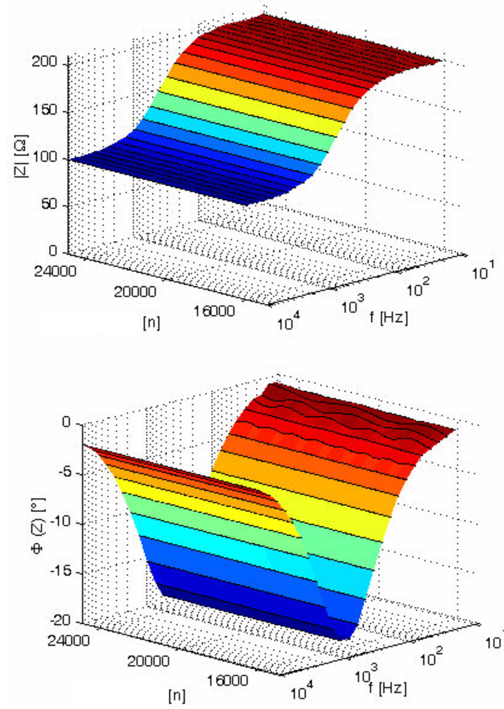

Fig. 10. Changes of impedance spectra (magnitude and phase) signal S4, triangle window filter $M=3{,}2T_1$.

Consequently, the Bode and Nyquist plots of theoretical and experimentally measured impedance spectra are almost undistinguishable (Fig. 11).

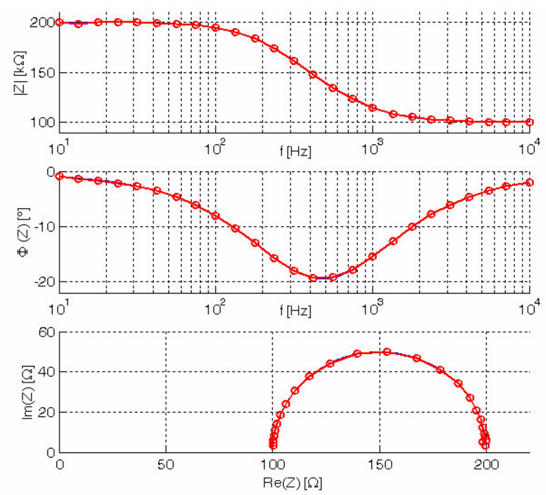

Fig. 11. Bode and Nyquist plot of impedance spectrum, signal S4, triangle window filter $M=3{,}2T_1$.

The measurement time for 3 examined lengths of filter is presented in Tab. 1, and compared with single-frequency

DFT method. Moreover, the measurement acceleration ratio is calculated.

Table 1. Comparison of spectrum measurement time between filter bank method and single-frequency DFT method.

Filter length	Measurement time		
	Filterbank	DFT method	Difference
$M = 2\hat{T}_1$	200 ms	400 ms	-50%
$M = 3\hat{T}_1$	300 ms	400 ms	-25%
$M = 3{,}2\hat{T}_1$	320 ms	400 ms	-20%

In order to specify the measurement error, the relative magnitude error and absolute phase error have been calculated for all 25 multisine components. The plots of error values for 3 tested filter lengths are in the Fig. 12.

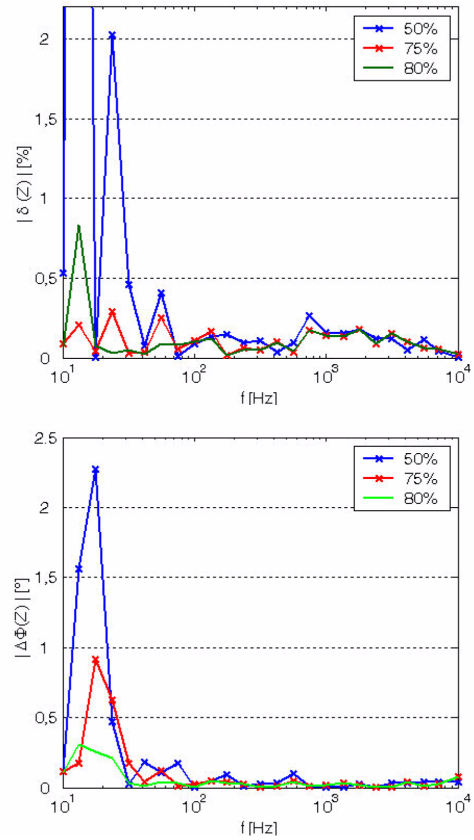

Fig. 12. Relative magnitude error and absolute phase error of impedance spectra measured with signal S4 for 3 different measurement acceleration ratios.

5. CONCLUSIONS

The experimental verification in a dedicated measurement system has confirmed the possibility of accelerating impedance spectrum measurent in few decades of frequency with logarythmic distributuion of spectrum sampling points. The method, based in multisine stimulation and filter-bank analysis circumvents the disadvantages of conventional single frequency or multisine and DFT approaches. The experimental results are in correlation with simulation results from earlier research [8]. The accuracy of method is compareable with commercial, single-frequency, impedance meters.

The experiments with various values of filter length have confirmed main advantage of the filter-bank method: the interchangeability of accuracy and spectrum measurement time. Thus, depending on the required accuracy, the acceleration ratio can be in the range of 20-50%. The cost of high acceleration ratio is the decreased accuracy in 1st decade (the 2nd and 4th component of multisine in Fig. 12). However, the relative magnitude error for such quick, rough measurement is still on the acceptable level of few percent.

Although the absolute times in Tab. 1 are order of ms, it should be stated, that the achieved results would be kept the same in the discrete domain, if the sampling frequency was much lower. Then, in case of very low-frequency 3 decades spectrum measurement the filter bank method could save hours of measurement time.

Although the method and system were oriented at anticorrosion coating diagnosis, the general reasults can be useful for the acceleration of parameter identification of several different objects and phenomena modelled by electric circuits.

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