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Evaluation of the measurement system for determination of frequency characteristics of functional blocks used in AC impedance bridges

***Abstract**. The paper presents a measurement system developed for determination of frequency characteristics of functional blocks used in precise automated AC impedance bridges. The paper presents the design assumptions, construction and results of investigation of the system detailing a range of tests necessary to assess its metrological properties.*

***Streszczenie.** Przedstawiono system pomiarowy przeznaczony do wyznaczania charakterystyk częstotliwościowych bloków funkcjonalnych stosowanych w precyzyjnych automatycznych mostkach impedancji. Przedstawiono założenia, konstrukcję oraz wyniki badań systemu pozwalające ocenić jego podstawowe właściwości metrologiczne.*
*(**Ocena systemu pomiarowego do wyznaczania charakterystyk częstotliwościowych bloków funkcjonalnych stosowanych w mostkach prądu przemiennego**).*

Keywords: measurement system, voltage ratio measurement, calibration.
Słowa kluczowe: system pomiarowy, pomiar stosunku napięć,kalibracja.

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Introduction

The increase of accuracy and bandwidth of modern instruments and measurement systems used for accurate AC measurements imposes high demands on metrological properties of their constituent functional blocks. Comprehensive study of metrological characteristics of these blocks are necessary to assess their suitability to achieve the goals. More and more frequently used approach to improve the accuracy and expand the range of systems used in accurate measurements is determination of the actual characteristics of their functional blocks or deviations from their nominal characteristics and using them in software algorithms controlling the measurement systems [1, 2, 3]. Such a method of improving the metrological characteristics of measuring instruments is very popular today. However, its implementation at the part per million uncertainty requires a comprehensive study of these blocks, including the determination of their stability over time and temperature. Such studies require the use of more sophisticated methods and measurement techniques [4, 5, 6, 7].

In this paper, we present a measurement system developed for determination of frequency characteristics of the amplitude and phase of the functional blocks of high-end digital multi-phase sinusoidal voltage sources designed for digital non-quantum automated impedance bridges. These sources are being developed by the authors in the Joint Research Project SIB53 AIM QuTE “Automated impedance metrology extending the quantum toolbox for electricity” [8].

Requirements

It is assumed that the measuring system has to meet the following requirements:

- it should be able to measure frequency and amplitude characteristics in the frequency range from 20 Hz to 20 kHz;
- it should be able to measure AC voltages of maximum amplitude equal to 10 V and the maximum value of the phase in the range ± π;
- it should allow determination of spectral parameters of measured signals;
- the controlling software should be able to save a large amount of data in a form suitable for further analysis;
- the controlling software should be easily modifiable,
- the measuring system shall be capable of generation a synchronizing signal for optional external measuring equipment;
- the relationship between the frequency of the synchronization signal and the frequency of the test signal applied at the input of the tested block has to be known;
- the system should measure and register the ambient temperature.

Description of the measurement system

A simplified block diagram of the developed system is shown in Fig. 1. The system was built on the basis of the commercial modular PXI measurement system. A key role in the system plays the National Instruments PXI-4461 sampling module card containing a high-end sigma-delta 24-bit analog-to-digital converter (ADC) and a 24-bit sigma-delta digital-to analog converter (DAC). The DAC is used to generate the sinusoidal test signal which is applied at the input of the tested functional block (DUT). The ADC built in the PXI-4461 is used as a precise dual-channel digitizer that samples the signal at the input and output of the DUT.

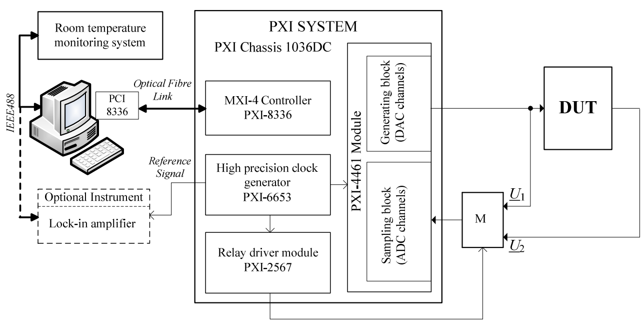

Fig. 1. Simplified diagram of the system for determination of frequency and phase characteristics

Samples of both signals are digitally processed, e.g. by the use of the Discrete Fourier Transform (DFT) to determine all relevant parameters of the DUT. Due to differences between the both ADC channels of the NI PXI-4461 module the sampling system uses a sequential sampling method [9, 10, 11]. In this method only a single channel of the PXI-4461 card is used and its input is switched with an external multiplexer M, whose switching cycle is strictly synchronized with the sinusoidal signal generated by the NI PXI-4461 DAC. The system uses the NI PXI-6653 card acting as a precise source of clock signals to ensure synchronous operation of all PXI modules and the NI PXI-2567 relay driver card, which controls relays of the external multiplexer M. A PC computer equipped with the NI PXI-8336 PCI card and the complementary NI 8336 PXI card serves as a PXI system controller. The both cards are connected with fiber optic cable. All PXI modules are installed in the NI PXI-1036DC chassis. The developed system has the ability to be synchronized with an external measurement instruments such as lock-in amplifiers. The system is complemented with a system for monitoring the ambient temperature. The system software was written in LabWindows/CVI environment using a layered model and the division into threads. The parent thread is responsible for the continuous signal generation and acquisition of samples. The slave thread is engaged in processing of collected samples, presentation of measurement results in a graphical user interface and storing the data. Application of the layered model of the software provides ease of modifying and adjusting its functionality to specific requirements. Results of measurements are stored in text files in CSV format and can be directly exported to Excel for further processing. Separate programs have been developed for PXI system and temperature monitoring system. Exchange of information between the programs is performed via network variables. According to the assumptions the developed system enables the measurement of magnitude and phase of the complex ratio of voltages with relatively small uncertainty in the frequency band from 20 Hz to 20 kHz. It also allows analysis of the stability of the DUT and analysis of spectral properties of the sampled signals, including such parameters as THD, SNR and SFDR.

Evaluation of the measurement system

The PXI-NI4461 sampling module has been comprehensively studied [10, 11]. Although the manufacturer's technical specification provides a lot of important data, such data is insufficient in the case where the sampling module is used at its boundary capabilities. The study included determination of the temperature and time stability of the two channels of the sampling module, determination of the frequency characteristics of the magnitude and phase of the complex voltage ratio (CVR) measured by the sampling module, determination of linearity in the measurement of CVR magnitude ranging from 0.1 to 1, and determination of the measurement resolution of the CVR phase at nearly 0°. Presented below are some selected research results.

The optimal time of CVR magnitude and phase measurements was estimated by means of Allan deviation, calculated for the magnitude and phase of the complex voltage ratio $\underline{U}_2/\underline{U}_1$. It was made for selected values of the U_1 and U_2 amplitude ratio: 0.01, 0.1 and 0.9. In these measurements was used as a reference an inductive voltage divider (IVD). Allan deviation characteristics for two different sources of sinusoidal signals developed based on the NI PXI-4461 and PXI-6733 modules were determined and compared. Figures 2 and 3 show characteristics obtained for a digitizer input voltage range ± 1 V and a maximum amplitude value of U_1 equal to 1 V.

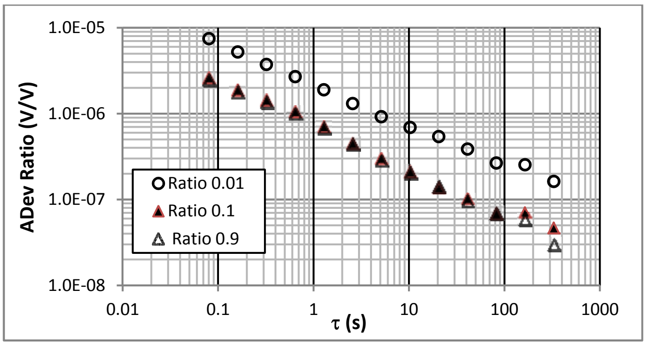

Fig. 2. Allan deviation of the voltage ratio measured at 1 kHz; PXI-4461

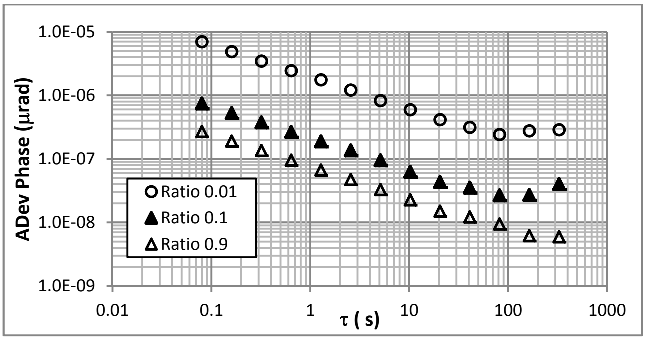

Fig.3. Allan deviation of the phase measured at 1 kHz; PXI-4461

Linearity of the digitizer was determined by using an inductive voltage divider. Fig. 4 shows the deviation of the measured magnitude from the nominal value. The relative ratio error of the divider was at the level of 0.5 *μ*V/V at 1 kHz. The effect of the loading error of the divider caused by connecting the digitizer with an input impedance of 1 MΩ was included in the measurements.

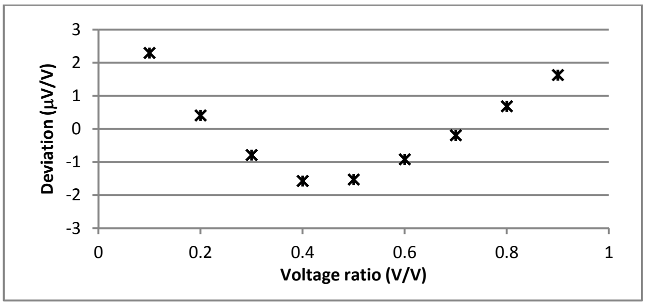

Fig.4. Deviation of the voltage ratio magnitude from the digitizer linearity (1 kHz)

It was also an attempt to calibrate the digitizer. Due to the assumed uncertainty of the measurement magnitude of the complex voltage ratio of 1 μV/V and phase on the level of 1 μrad, the calibration task was difficult to carry out because of the lack of a proper standard. In this situation, the indirect calibration method was used [12]. For evaluating the accuracy of the system were used made itself four two terminal-pair AC standard resistors having following nominal values: 1 kΩ (RV1-1, RV1-2) and 10 kΩ (RV10-1, RV10-2). The resistors were calibrated in GUM (Central Office of Measures) using an impedance comparator at 1 kHz and 1.592 kHz. Then they were used to build the voltage dividers with nominal ratio of 1/2 and 1/11, which were the subject of the research (DUT). Using this system, the frequency characteristics of magnitude and phase of the input and output voltage ratio of the divider at the band from 100 Hz to 20 kHz were determined. Due to the relatively large values of the resistors, in comparison with the input impedance of the digitizer, it was necessary to use the buffer B on the output of the resistor divider (Fig. 5).

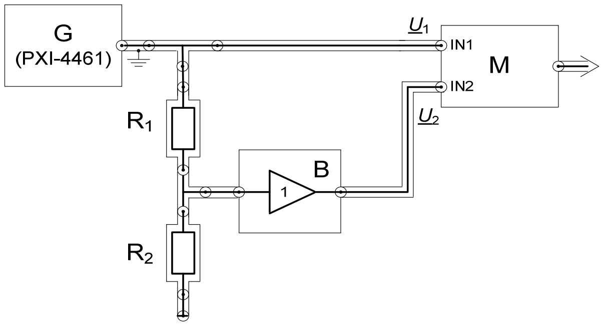

Fig.5. Simplified schematic diagram of the calibration system for the digitizer

On the assessment of the system accuracy have a significant impact the correctness of equivalent circuit (it was used to calculate the magnitude of voltage ratio) and measurement uncertainty of the buffer input impedance. In order to become independent of this influence, for each frequency was performed twice measurement of the voltage ratio $\underline{U}_2/\underline{U}_1$ by swapping placement of the resistors applied to assembling a resistive divider. Exemplary measurement results for its resistance ratios 1:1 are shown in Fig. 6. Thus resulting resistance ratios of the resistors in Fig. 6 are marked as "MS". While the resistance ratio values determined in GUM by direct comparison of the standard resistors using an impedance comparator, in Fig. 6 are marked as "GUM". This approach allows for an indirect way to evaluate the system uncertainty during measurements of the magnitude of complex voltage ratio.

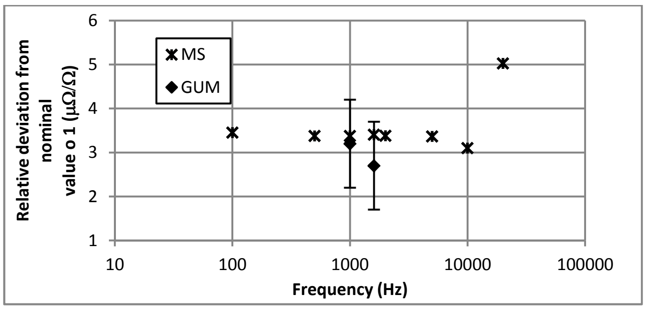

Fig.6. The relative deviations from the nominal value of the resistance ratio of 10 kΩ/10 kΩ (RV10-1/RV10-2) resistors determined by the studied system (MS) and determined by the impedance comparator in GUM (GUM); bar represents the uncertainty of the comparison with the impedance comparator

Standard deviation of the mean of a series of 10 measurements was:

a) below $1{\cdot}10^{-7}$ V/V from 100 Hz to 20 kHz and less than $0.5{\cdot}10^{-7}$ V/V up to 10 kHz for magnitude and,
b) below 0.2 μrad from 100 Hz to 20 kHz and less than 0.1 μrad up to 10 kHz for phase.

Conclusion

The measurement system presented in the paper was developed to study the metrological characteristics of basic functional blocks used in modern instrumentation. The system developed will be used mainly for testing of high-end digital multi-phase sinusoidal voltage sources for digital automatic impedance bridge, but it will be also used to study the properties of output buffers of digital sources of AC voltage, precise voltage amplifiers and low pass filters. Preliminary results confirm the usefulness of the system to study the frequency characteristics of the above functional blocks with a a few ppm uncertainty. Currently the system is tested, particularly in terms of evaluation of the accuracy of the CVR phase measurements.

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