Ryszard RYBSKI [1], Adam WALKOWIAK [2]
[1] UNIVERSITY OF ZIELONA GÓRA, INSTITUTE OF METROLOGY, ELECTRONICS AND COMPUTER SCIENCE
Prof. Z. Szafrana 2, 65-246 Zielona Góra, Poland
[2] PRZEDSIĘBIORSTWO WDROŻENIOWE INMEL Sp. z o.o.
Energetyków 7, 65-729 Zielona Góra, Poland

An AC measurement system for use with resistive temperature sensors

Abstract

In the paper, a measurement system based on a universal commercial measuring module of alternating current for accurate temperature measurement by means of resistive temperature sensors is described. There are presented the research results on the basis of which the metrological properties of the system were evaluated. It was shown that this relatively simple measurement system is a competitive solution compared with the most accurate commercial DC measurement systems.

Keywords: AC resistance thermometry, resistance ratio measurement, complex voltage ratio.

1. Introduction

The constant development of technology and industry, introducing new, more and more sophisticated production processes imposes the necessity of tight temperature control and thereby its precise measurement. The current achievements in the field of temperature measurements of highest accuracy, made by national metrology institutes (NMIs), are sufficient to fulfil these needs. However, there is a strong demand for economical and reliable systems with a slightly lower accuracy.

It is known that the most precise temperature measurements are made by means of electrical methods with the application of standard platinum resistance thermometers. From the metrological point of view, the task of temperature measurement corresponds to the measurement of a resistance between 10 Ω and 1000 Ω. This resistance value should be measured with a resolution of the order of 1 μΩ at least and with a relative uncertainty on μΩ/Ω level. Additionally, the current flowing through the compared elements should not exceed a few mA to avoid self-heating of the resistance thermometer. From the vast extent of literature and the overview of currently available commercial devices, it is known that this task is accomplished by direct comparison of the platinum resistance thermometer with a standard resistor. It is performed in both direct current and sinusoidal alternating current systems with a signal frequency up to several dozens of Hz [1, 2]. The known systems of the highest accuracy are based on alternating current, where it is easier to achieve a high sensitivity and also immunity to thermal EMF errors. A primary-standard resistance thermometry bridge, produced by WIKA [3] can be a good example of such a system. It uses multi-decade ratio transformers that provide the ratio resolution of the compared elements and the measurement uncertainty at the level of $1 \cdot 10^{-7}$ (in standard version).

In the field of precision impedance measurement, there is observed a tendency to substitute inductive ratio transformers with high resolution analog-to-digital and digital-to-analog converters is observed. This principle along with advanced digital signal processing algorithms can be utilized in precision temperature measurements.

In our paper, a temperature measuring system based on a commercial data acquisition card (DAQ) of type USB-6211 is proposed. The experiment results allow evaluation of the system usefulness and accuracy.

2. Measurement system

The main purpose of our work was the examination of possible application of a commercial, multifunction data acquisition card of type USB-6211 as a precise thermometer using standard platinum resistance sensors. For this reason, the selection of a measurement system structure was determined by metrological properties and hardware configuration of the data acquisition card [4]. The ability of synchronous sine wave generation and measurement by the digital-to-analog and analog-to-digital converters respectively and also relatively high differential input impedance compared to platinum resistance sensors value determined the system structure. A relatively simple circuit was chosen, based on series current comparator with complex voltage ratio measurement on the resistor under test and a standard resistor (Fig. 1).

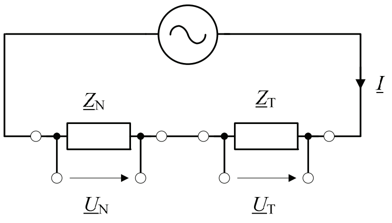

Fig. 1. The circuit comparing the reference resistor with the thermometric one

It is assumed that the compared resistors: thermometric with $\underline{Z}_{\mathrm{T}}$ impedance value and the standard resistor with $\underline{Z}_{\mathrm{N}}$ impedance are four-terminal (4T) connected elements, described by parameters in the series equivalent circuit. Moreover, their impedances are defined by (1) and (2), in which R_{T}, τ_{T} and R_{N}, τ_{N} correspond to the AC resistance (the real part of impedance) and the time constant of the platinum resistor and standard resistor correspondingly, whereas ω is the angular frequency:

$$\underline{Z}_{\mathrm{T}} = R_{\mathrm{T}}\left(1 + \mathrm{j}\omega\tau_{\mathrm{T}}\right), \tag{1}$$

$$\underline{Z}_{\mathrm{N}} = R_{\mathrm{N}}\left(1 + \mathrm{j}\omega\tau_{\mathrm{N}}\right). \tag{2}$$

Assuming that the same current $\underline{I}$ flows through both compared resistors, their impedance ratio is equal to the voltage drop ratio $\underline{U}_{\mathrm{T}}$ and $\underline{U}_{\mathrm{N}}$ and can be written as

$$\frac{\underline{Z}_{\mathrm{T}}}{\underline{Z}_{\mathrm{N}}} = \frac{\underline{U}_{\mathrm{T}}}{\underline{U}_{\mathrm{N}}} = \underline{K} = Ke^{\mathrm{j}\varphi}\ , \tag{3}$$

in which K and φ are the real and imaginary part of the complex voltage ratio $\underline{K}$ respectively, and are known from measurements.

Substituting (1), (2) with (3), after simple transformations, the relationship for resistance value of the thermometric resistor becomes [5]

$$R_{\mathrm{T}} = R_{\mathrm{N}}\left[K\cos\varphi\left(1 - \omega\tau_{\mathrm{N}}\mathrm{tg}\varphi\right)\right]. \tag{4}$$

In the considered frequency range ($f \leq 200$ Hz), with a negligibly small error, the approximate relation that allows calculation of the resistance value of the thermometric resistor without knowing the standard resistor time constant, can be applied

$$R_{\mathrm{T}} \approx R_{\mathrm{N}} K \cos\varphi\ . \tag{5}$$

The block diagram of the system which realizes the described platinum thermometric resistor measurement method is presented in Fig. 2 [6].

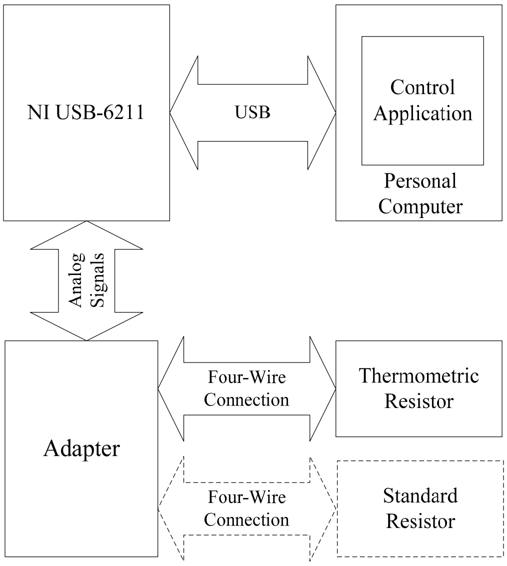

Fig. 2. Block diagram of the system for measuring the resistance of a thermometric resistor

The main component of the system is an NI data acquisition card of type USB-6211, which acts as a sinusoidal voltage source powering the system and also as a digitizer measuring voltage drop across the resistors. The output section of the DAQ card consists of two analog channels with 16 bit digital-to-analog converters. Each of them can source up to 2 mA of current and voltage in the range of ± 10 V. The analog input circuitry features a 16 channel multiplexer and one 16 bit analog-to-digital converter (ADC) with a sample rate up to 250 kS/s. A programmable gain instrumentation amplifier allows selecting the input range between ± 0.2 V and ± 10 V. The software selectable input ground-reference configuration allows e.g. measuring 8 voltages in the differential mode. The implemented system topology is characterized by means of the measuring floating voltage (not referenced to ground). Furthermore, DAQ card analog input channels, connected parallel to the compared resistors, are shunting them. On the basis of these two critical parameters of the DAQ card emerge: CMRR (DC to 60 Hz) at 100 dB level and channel input impedance of 10 GΩ || 100 pF.

The measuring system is controlled by a personal computer with measurement and control software installed, written in National Instruments LabWindows/CVI environment. The software allows full configuration and diagnosis of the USB DAQ including self calibration, choosing circuit connection method and its working conditions. It also performs automatic calculation of the resistance value, temperature by means of Callendar – Van Dusen equation and statistical analysis [6].

Since the DAQ card does not enable for direct connection of the compared resistors, it was necessary to design and build a suitable adapter. The adapter allows a four-terminal connection with coaxial cables and BNC type connectors. In addition, the adapter has a built-in 100 Ω resistance standard with option to connect an external one if the accuracy of the built-in would be insufficient.

3. Experimental verification

The developed measurement system was subjected to experimental verification. The main goal was to evaluate the influence of the system configuration and environmental conditions on the accuracy and uncertainty of resistance measurement. Among the evaluated factors were: signal frequency, measurement time and sampling frequency. The results are presented in Figs. 3, 4 and 5.

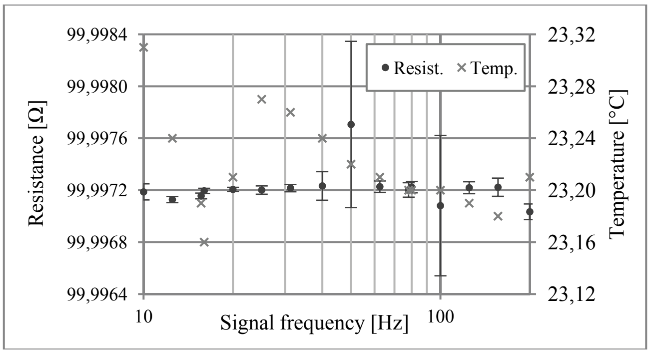

Fig. 3. Influence of the frequency of measurement signal on the result of resistance measurement

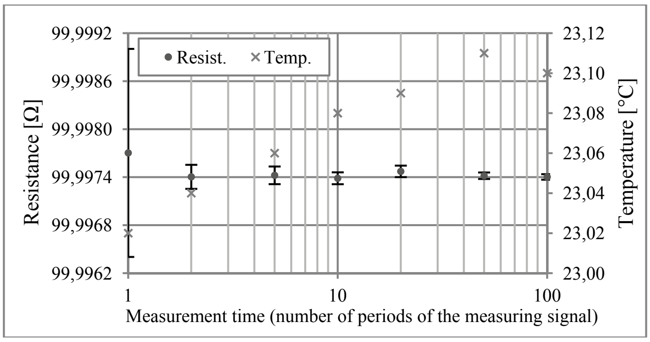

Fig. 4. Influence of the measurement duration on the resistance measurement result

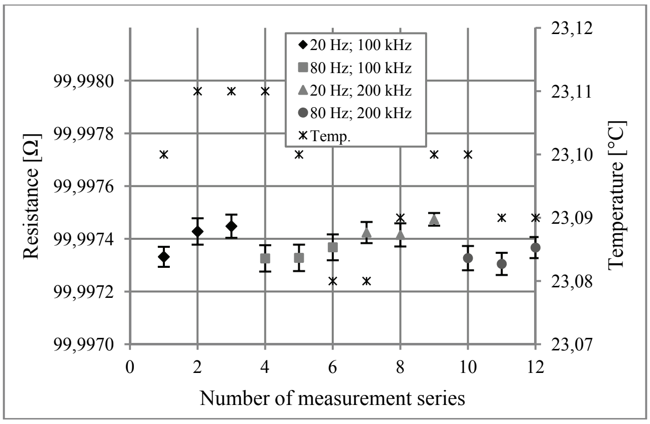

Fig. 5. Influence of the sampling frequency on the resistance measurement result

The measurement results shown in Figs. 3, 4 and 5 were obtained from the comparison of two standard resistors of 100 Ω nominal value. The measurement current flowing through both resistors had the RMS value of 1.3 mA. During the measurements, the resistors were placed inside an ovenized chamber in which the temperature was measured (temperature results are also presented in the graphs). Analyzing the influence of the signal frequency on the resistance comparison accuracy, the frequency was changed from 10 Hz up to 200 Hz for a constant sampling time of 100 periods of the signal (Fig. 3). During the study of measurement time influence on the accuracy (Fig. 4), the measuring system was supplied with a sinusoidal current of a frequency value of 20 Hz. For both cases the sampling frequency was equal to 100 kHz. The analysis of the sampling frequency influence was conducted for two sampling frequency values of 100 kHz and 200 kHz and two signal frequency values of 20 Hz and 80 Hz. As in the previous experiments, the sampling time was equal to 100 periods of the signal (Fig. 5). For each of the four cases, three measurement series were carried out. The Type A expanded uncertainty with the coverage factor $k = 2$ is plotted in the graph.

As expected, the highest uncertainty was obtained at the frequency of 50 Hz. For a further analysis, two signal frequencies were chosen: 20 Hz and 80 Hz, for which the corresponding relative expanded uncertainties were 0.2 μΩ/Ω and 0.4 μΩ/Ω respectively (Fig. 3). The results of the measuring time (averaging time) analysis show that the uncertainty decreases with the increasing time. For the measuring time of 100 signal periods, the uncertainty equals 0.4 μΩ/Ω (Fig. 4). During the experiments, no significant influence of the sampling frequency was observed (Fig. 5). For all the made measurement series, the relative expanded uncertainty was at the level of 0.5 μΩ/Ω. Analysing the impact of the sampling frequency, one has to remember that it also alters the spectrum of the digitally synthesised sinewave signal. This means that for the same signal frequency value, the total harmonic distortion (THD) can have a different level.

The evaluation of the system accuracy was done by comparing two standard resistors. Two VISHAY resistors of 100 Ω nominal value and one TINSLEY resistor of 10 Ω nominal value were used. Multiple series of 1:1 and 1:10 resistance ratio comparisons were carried out. The results were obtained for 1.3 mA root-mean-square current value, 20 Hz signal frequency and 100 kHz sampling frequency. The measurements were taken in 23 °C ± 0.1 °C ambient temperature. For all the performed comparisons, the relative uncertainty of the resistance ratio was at the level of 0.2 ppm. Evaluation of the system accuracy was made by two methods. The first one was based on the substitution method. The accuracy was specified by means of the equation:

$$\delta = \left(\frac{R_X}{R_N}\right)_a \cdot \left(\frac{R_N}{R_X}\right)_b - 1\,, \tag{6}$$

in which a and b correspond to the ratio of the result before and after substitution. For the resistance ratio of 1:1 and 1:10, the following values $\delta \le 0.2$ ppm and $\delta \le 0.8$ ppm were obtained, respectively. In the second method, two resistance ratios were compared - one of the evaluated system and the second one determined from direct current measurements by means of a multimeter. The relative difference of resistance ratios is given by:

$$\delta_k = \frac{k_{AC} - k_{DC}}{k_{DC}}\ . \tag{7}$$

The obtained (for signal frequency of 20 Hz) relative difference δ_k for 1:1 and 1:10 ratios was no bigger than ± 10 ppm, wherein the relative expanded uncertainty with ($k = 2$) coverage factor of the resistance ratio k_{DC} was at the level of 30 ppm.

4. Conclusions

The paper presents a concept and practical implementation of an AC current measurement system designed for temperature measurements utilizing standard platinum resistance thermometers. The temperature measurement system presented here, based on a commercial NI data acquisition (DAQ) card of type USB-6211 and digital sinusoidal voltage generation methods is a competitive solution to commercial direct current based measurement systems of the highest accuracy. The proposed method has large future development abilities. These are for example: implementing data acquisition (DAQ) card with better metrological parameters or improving the complex voltage ratio measurement method. Experimental accuracy evaluation of AC current measurements systems, used for precise temperature measurements (uncertainties of 0.0001°C to 0.001°C) is relatively complex. Realization of this task is only possible by means of high class measurement standards.

5. References

[1] Ramm G., Moser H., Volmert R.: Computer-Controlled Inductive Bridge Standards for Calibrating AC Resistance Thermometry Bridges at Low Frequencies. IEEE Trans. on Instrumentation and Measurement, Vol. 56, No. 2, pp. 547-550, 2007.

[2] Ramm, G.; Moser, H.; Vollmert, R.: Einsatz induktiver Teiler bei kleinen Spannungen und niedrigen Frequenzen für die Kalibrierung von Temperaturmessbrücken. PTB-Bericht PTB-E-92, pp. 1-15, 2006.

[3] Primary-standard resistance thermometry bridge Model CTR9000, http://www.wikapolska.pl/upload/DS_CT6080_en_co_53573.pdf.

[4] NI USB-6211 User Manual, http://www.ni.com/pdf/manuals/371931f.pdf.

[5] Rybski R, Kaczmarek J., Kozioł M.: A high-resolution PXI digitizer for a low-value-resistor calibration system. IEEE Trans. on Instrumentation and Measurement, Vol. 62, No. 6, pp. 1783-1788, 2013.

[6] Walkowiak A.: Digital AC bridge for use with resistive metal temperature sensors. BSc Thesis, University of Zielona Góra Institute of Metrology, Electronics and Computer Science, Zielona Góra, 2015 (in Polish).

Received: 02.05.2016 *Paper reviewed* *Accepted: 01.07.2016*

Ryszard RYBSKI, PhD, DSc

He received the M.S. degree in electrical engineering from the University of Zielona Góra in 1979, the Ph.D. degree from Wrocław University of Technology in 1989, and the D.S. degree from the University of Zielona Góra in 2008. Since 1979, he has been with the Faculty of Computer, Electrical and Control Engineering, Institute of Metrology, Electronics and Computer Science, University of Zielona Góra. His research interests are concerned with high-accuracy measurements of electrical quantities, particularly precision impedance measurements.

e-mail: r.rybski@imei.uz.zgora.pl

Adam WALKOWIAK, BSc

Was born in Świebodzin, Poland, in 1990. Received the BSc degree in electrical engineering from the University of Zielona Góra, Zielona Góra, Poland, in 2015. He is currently pursuing his MSc degree in electrical engineering. Works in Przedsiębiorstwo Wdrożeniowe INMEL Sp. z o.o. as the Electrical Calibration Engineer. His current research interests include precision electrical measurements and industrial metrology.

e-mail: adamoth44@wp.pl