A.A. MIKHAL[1]
D.V. MELESHCHUK[1]
Z.L. WARSZA[2]

APPLICATION OF THE HYBRID BALANCED RATIOMETRIC MEASUREMENT METHOD IN THE HIGH-PRECISION AC THERMOMETRY BRIDGES

The paper article describes the circuit of an automatic AC bridge for high precision temperature measurements using a standard platinum SPRT sensor. An original method for measuring the impedance parameters of SPRT sensor which allows to carry out the measurement process without loss of accuracy, is described in detail. This measurement method is proposed to name as hybrid method. It is a combination of a balanced method for rough compensation of the circuit and a ratiometric method which accurately measures the ratio of two values of the imbalance signal, before and after its known change. With this method, the measuring circuit also does not require a circuit to compensate for the reactive component of the SPRT sensor impedance. The inductive voltage divider with lower number of digits is needed only for the coarse compensation. This circuit is simpler and at lower cost of the hardware resources allows to achieve the same accuracy as the most accurate thermometric bridges with fully balanced circuits

Keywords: high precision temperature measurement, AC bridge, balanced-ratiometric measurement method, hybrid method

INTRODUCTION

Modern trends in improving the metrological support for temperature measurements are associated with a new definition of the unit of measure of the Kelvin degree. The advantage of redefining this unit will be the advancement of the technique of direct measurements of the thermodynamic temperature in parallel with the methods described in the IST. However, it takes some time to introduce modern trends into practice. Therefore, the following conclusions are made in the CCC document: "Report to the CIPM on the importance of changing the definition of the base unit kelvin" [1]. «IST-90 in the foreseeable future will be used as the most accurate and reliable approximation of the thermodynamic scale ... In the

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[1] Institute of Electrodynamics, National Academy of Science of Ukraine, Kiev, a_mikhal@ukr.net
[2] Industrial Research Institute of Automation and Measurement (PIAP) Warszawa, Poland, zlw@op.pl

foreseeable future, the key range of the scale -200 ... + 960°C will continue to be carried out with the help of platinum resistance thermometers.»

At present, according to IST-90, temperatures in the range between the triple point of equilibrium hydrogen (13.8033 K) and the solidification point of silver (961.78°C) are carried out using standard platinum thermal resistance transducers (SPRT). Measurement of the value of the informative parameter (active resistance SPRT) is performed on a constant or alternating current. In most cases, the SPRT is connected as one of arms of an AC bridge. Since the error of interpolation of IST-90 is 0.00013 K, the thermometric bridges should have an error, brought to the end of the range, not worse than (1-3) 10^{-7}. Such a measurement error is realized using AC bridges with voltage (or current) dividers with close inductive coupling (IVD) as scaling converters.

Practical application of specialized thermometric circuits with inductive dividers begins with AC axes of Hill, Gibbings, Furd [2-4]. The main requirements for them were: high accuracy of the arm ratios and an effective four-clamp connection of the standard measure and the thermometer. Further progress in increasing the accuracy of measurements was the use of two-stage [5, 6] and multistage transformers. The best automatic thermometric AC bridges of ASL company (models F18, F900) or Tinsley (model 5840C) are built using such schemes. Obviously, IVD is the main part of these devices and determines the complexity and cost of the bridge and other instruments needed in the lab stand.

This article describes the semi balanced method of measuring only the resistance component of the impedance of SPRT sensor. This method allows to simplify the structure of the inductive voltage divider in precision AC thermometric bridges.

Functional diagram of the thermometric AC bridge

The functional diagram of high precision bridges as for example type F18 or F900 ASL [12] is presented in Fig. 1. To obtain the sensitivity needed in high precision temperature measurements, the inductive divider (winding m_1) must contain 7-8 decades. Note that, on an alternating current, the impedance ($Z_x \equiv Z_T$) of SPRT sensor has a two-element serial inductive equivalent circuit

$$Z_T = R_T + j\omega\omega_T = R_T + jQ_T = R_T\left(1 + jtg\,\varphi_T\right) \qquad (1)$$

where: $tg\,\varphi_T$ is the tangent of the phase angle, i.e. the ratio of the reactive component Im (Z_T) to active component Re(Z_T), ω_T is the frequency of the bridge circuit and Q_T is the reactance.

To eliminate the influence of the reactive component on the sensitivity of the instrument, additional compensation circuits are necessary. In models F18 and F900, this problem is solved by connecting an additional current source $I_{\mathrm{Var.}Q}$ to point A - Quadrature Servo Range. Its phase must differ from the phase of generator G strictly by 90°. The error must not exceed the LSB (least significant bit) of the inductive divider. Therefore, the current source $I_{\mathrm{Var},\,Q}$ is a complex module. For a further description of the method, another circuit for compensating the quadrature impedance parameter of SPRT sensor it is convenient to use. It is usually applied in universal RLC bridges. The circuit contains a multi-decade voltage divider with an adjustable number of turns m_2 and a quadrature phase shifter (QS), which provides a phase shift of the winding voltage m_2 by an angle of $\pi/2$ (conversion factor - j). The compensation circuit is connected between points B and C - in series to the voltage comparison circuit. Instead of an equilibrium detector, a vector voltmeter VV is used. Thus, the detector of the balance in precision thermometric bridges is a vector device. This device makes the thermometric bridge more complex and expensive. The AC-bridge complexity depends on two components. Firstly, it is the main inductive divider with secondary winding m_1 of 6-8 decimal decades. Secondly, it is an additional divider (winding m_2) and a precision phase shifter (QS).

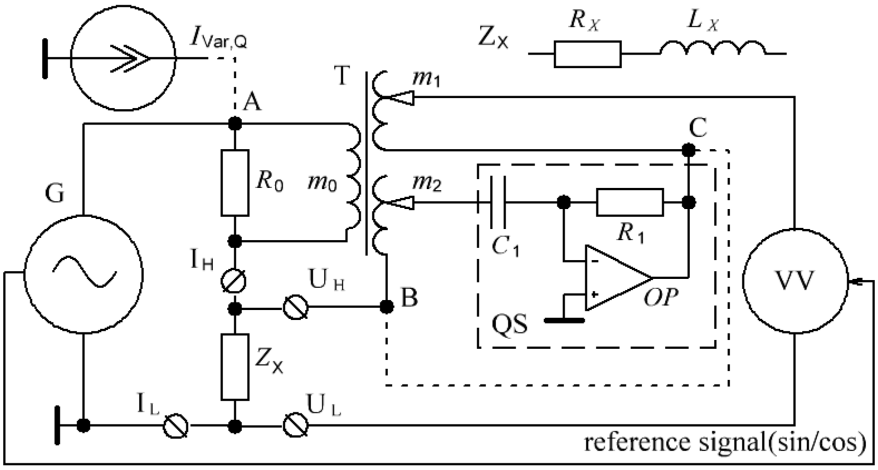

Fig. 1. Functional diagram of the measuring circuit of AC bridge (R_0 is the standard resistor)

Hybrid measuring method

The combined balanced-ratiometric method, called below shortly as hybrid method, eliminates the additional divider (winding m_2) and substantially simplifies the main divider (winding m_1). To achieve such results, a priori information on the phase characteristics of the SPRT is an important condition, i.e. the value of the tgφ_T parameter at the maximum operating frequency of different SPRT types. Frequency characteristics of SPRT, which are often used in Ukraine, will be presented below.

The hybrid method is based on two other well known methods. This is the method of balancing and the method of ratiometric transformation of two signals before and after their variation. Therefore, the hybrid method contains two stages.

Firstly, the bridge is balanced by an inductive divider m_1 with a limited resolution. Evaluation of the unbalance signal at this stage determines simultaneously the control codes of the converter and the values of the highest digits of the measurement result. On the second stage the measurement result is refined. Evaluation of the unbalance signal at this stage only determines the values of the least significant bits of the measurement result. At both stages, the unbalance signal is estimated by means of a ratiometric transformation. Its essence consists in the formation of a variation test impact with the help of IVD and calculation of the bridge disequilibrium from the ratio of the unbalance signals before and after the variation. The use of the signal ratio makes it possible to exclude several errors introduced by the elements of the measuring device. This method is called "variational" by its authors [7]-[9]. It was first used to correct the error of transformer bridges in measurements of high-resistance capacitive objects with a parallel substitution circuit [8]. As an extrapolation method of balancing thermometric bridges, it is presented in [9].

Variational method of balancing the AC bridge

A vector voltmeter VV is used to measure imbalance output voltage U_D of the AC bridge and gives results of measuring two orthogonal components of it. If phases of the supply generator signal and VV voltmeter coincide, then these components are named: in-phase component U_S (sin) and quadrature component U_Q (cos).

$$U_D = U_S + j\,U_Q = IR_S\left(p + jq - \frac{Z_T}{R_S}\right) \tag{2}$$

where: $p = m_1/m_0$ and $q = m_2/m_0$ - initial adjustable parameters of the common-mode and the quadrature-mode signal component respectively; $I \equiv I_H$- operating current.

The transmission coefficient QS at a fixed frequency, for simplicity, is equal to unity, i.e. $\omega\tau = 1$ (τ is the time constant of Z_x).

In the initial (unbalanced) stage of the circuit, each adjustable parameter is the sum of two parts: with indexes: B corresponding to the balanced state and E for the unbalance state, i.e.:

$$p = p_B + p_E, \qquad q = q_B + q_E \tag{3}$$

When the circuit is in balance, $U_D = 0$. From (1) and (2) follows the balance condition

$$p_B + jq_B = R_T/R_S + jQ_T/R_S \tag{4}$$

The circuit imbalance is determined by the error of balance E, which is a vector quantity Then:

$$\boldsymbol{E} = p_E - \boldsymbol{j} q_E\,, \quad p_E = p - \frac{R_T}{R_S}\,, \quad q_E = q - \frac{Q_T}{R_S} \tag{5a,b,c}$$

The balance parts (p_B, q_B) of the controlled parameters determine the components of the impedance of the measured object Z_T:

$$R_T = (p - p_E)R_S = p_B R_S\,, \qquad Q_T = (q - q_E)R_S = q_B R_S \tag{6a,b}$$

In the first cycle the AC bridge circuit is balanced by the variational method, but not completely and the components of the balance error E_1 are determined.

1. The non-balance components (in-phase U_{S1} and quadrature U_{Q1}) of the initial signal U_{D1} are measured

$$U_{D1} = U_{S1} + jU_{Q1} = I\,R_S E_1 \tag{7}$$

2. The variation of the adjustable parameter p is performed by changing the number of turns of winding m_1. The value of the variation is equal to $p_{V1} = m_{\mathrm{MSB}}/m_0$. As a rule, this value is equal to the unit of discreteness of the older decade.

3. The components (in-phase U_{S2} and quadrature U_{Q2}) of the received U_{D2} imbalance signal are measured:

$$U_{D2} = U_{S2} + jU_{Q2} = IR_S\left(E_1 + p_{V1}\right) \tag{8}$$

From the joint solution of (6a,b) and (7) the expression of error E_1 is obtained. As a vector quantity, this error contains the real A_1 and the imaginary part B_1.

$$E_1 = p_{V1}\frac{U_{D1}}{U_{D2} - U_{D1}} = p_{V1}\left(A_1 + jB_1\right) \tag{9}$$

After substitution of the equation (2) to (9) with the allowance of indices, expressions for the coefficients A_1 and B_1 can be received, i.e.:

$$A_1 = \frac{U_{S1}\left(U_{S1} - U_{S2}\right) + U_{Q1}\left(U_{Q1} - U_{Q2}\right)}{\left(U_{S1} - U_{S2}\right)^2 + \left(U_{Q1} - U_{Q2}\right)^2}\,; \quad B_1 = \frac{U_{S1}U_{Q2} - U_{Q1}U_{S2}}{\left(U_{S1} - U_{S2}\right)^2 + \left(U_{Q1} - U_{Q2}\right)^2} \tag{10a,b}$$

4. From (5) and (9), the components of errors of regulated parameters are calculated as

$$p_{E1} = A_1 p_{V1}\,, \quad q_{E1} = B_1 p_{V1} \tag{11a,b}$$

Equations (11a,b) make it possible to obtain a coefficient that determines the degree of the non-balance stage expressed in terms of the variation activity. It is important to note that variation in the form of a change of the number of turns of the inductive divider has a potential high accuracy, which can exceed 0.1 ppm. The accuracy of (11a,b) calculations depends also on the LSB of the vector voltmeter. It is possible that this voltmeter LSB will be smaller than the LSB of inductive divider. Then the process of determining the components of the imbalance state can be iterative.

5. The values of controlled parameters of the measuring circuit determined on the first stage of balancing process are:

$$p_B = p - p_{E1}, \qquad q_B = q - q_{E1} \tag{12a,b}$$

The advantage of this method (equations 2-12) is due to a priori information about the impedance of the SPRT sensor. It is known that the reactive component Q_T of the impedance Z_T (1) is several orders of magnitude smaller than the active component R_T. Then the format of the number q_B, will be represented with zeros in the upper digits. For example, q_B = 0.000358. Zero values do not make any sense to write to the divider registers m_2 (Fig. 1). To comply with this requirement, we restricted the minimum discretization of the divider by the natural number N_{IVD}. The conditions are as follows:

$$10^{-N_{IVD}} < tg\varphi \text{ - for the divider with decade structure,} \tag{13a}$$

$$2^{-N_{IVD}} < tg\varphi \text{ - for the divider with the binary structure.} \tag{13b}$$

With an error of LSB of the inductive divider, we have the following relations: $B_1 \approx 0$ and $q_{B1} \approx 0$. Under conditions (13a,b), the quadrature divider m_2 and the phase shifter Q_S in the circuit of Fig. 1 can be eliminated. The results of calculations of the basic parameter p_{B1} are recorded in the registers of the inductive divider and in registers of the upper bits of the computing device. As a result of the first stage, the bridge will be balanced to within 0.5 LSB of the inductive divider.

6. At the second cycle of the measurement process, the signal of the bridge imbalance $0{,}5 \cdot 10^{-N_{IVD}}$ is amplified. The variation is accomplished by changing the number of turns of the minor decade $p_{V2} = m_{\mathrm{LSB}}/m_0$ and operations 1-5 are repeated.

7. The value of the error E_2 and the balanced values of the adjusted parameters p_{B2} and q_{B2} of equations (12a,b) are determined, similarly as p_{B1} and q_{B1} of E_1:

$$E_2 = p_B - \frac{R_T}{R_S} - j\frac{Q_T}{R_S} = p_{V2}(A_2 + jB_2)$$

$$p_{E2} = A_2 p_{V2}, \qquad q_{E2} = B_2 p_{V2} \tag{14}$$

The accuracy of calculation of the error components and balance values adjusted in the second stage (by analogy with the first stage) depends on the variation and the digit capacity of the vector voltmeter. By analogy with the first stage, this accuracy is also high. Then it is possible not to balance the measuring circuit for the least significant bits of the divider m_1. This accordingly simplifies the construction of the inductive divider and the circuit. In this case, the calculated balanced values of the parameters p_{B2} and q_{B2} are recorded only in the low-order registers of the computing device. Therefore, the number of digits in the calculator is summed.

8. In general, the measurement result of the informative parameter can be represented in the form:

$$R_T = R_S \cdot (p - p_{E1} - p_{E2}) = R_S \cdot (p - A_1 p_{V1} - A_2 p_{V2}) \tag{15a}$$

$$Q_T = R_S \cdot (q - q_{E2}) = R_S \cdot (q - B_2 p_{V2}) \tag{15b}$$

The reactive component Q_T of a SPRT sensor is not a informative parameter. But the Q_T/R_T ratio can be used to control if the quadrature parameter of the SPRT impedance is not in the limited range. Thus, when a combined hybrid measurement method is used, the resolution of the voltage divider may not be as high as needed for the measurement result. It is enough when voltage divider determines only numbers of the highest digits of the measurement result. They are added to the lower orders, which are determined in the second cycle. This will simplify the design, reduce the dimensions, weight and also the cost of the device.

The high accuracy and linearity of this method is due to several factors.

a) The presence of the high accuracy normalized levels of dividing by IVD and the ratiometric processing of imbalance signals before and after the variation. This ensures the invariance to the working current and phase changes in the filters of the generator, amplifier and other modules.

b) The variation of the signal is formed by changing the number of turns of a particular decade, which provides a connection with the LSB of inductive divider. The accuracy of the ratio of the non-balance level and variation is determined by the accuracy of the ratio of numbers of turns. It can be less than 0.1ppm.

c) A transformer voltage divider with a close inductive coupling has potentially higher linearity in comparison with the discreteness. For example, the linearity of 4-decade division may be better than 0.1 ppm (7 decades). This method have been experimentally tested and has two weaknesses also.

Firstly, the variational method of balancing requires two measurements: before and after the signal variation. As the result of this method the RMS of the Gaussian noise in the signal will increase by $\sqrt{2}$ times. This can be compensated by expanding the sample for averaging.

Secondly, with the incomplete balancing, the influence of the resistance of the connecting wires will not be completely eliminated.

To create cryogenic bridges for operation at very low cryogenic temperatures, this method still requires further development.

Implementation of the hybrid method in AC bridge

The e hybrid method was used in the precision thermometric AC bridge CA 300 (Fig. 2) [8-11].

Fig. 2. Automatic bridge AC type CA 300

Some features of the construction of chains of equipotential protection and metrological support of this bridge are considered in [10, 11]. From experimental studies, it is known that the SPRT sensors with a nominal resistance of 0.6 to 25 Ω (types of VTS, PTS-10, ТСПН-4В ТСПН-4В) at a frequency of 100 Hz have a phase angle tangent of not more than 0.0003. The optimal situation occurs when the inductive divisor is binary. It is easy to show from (13b) that the minimum number of digits (for a given maximum value of tgφ) should be N =12. To test the method, in the CA300 bridge a 12-bit inductive voltage divider and a vector voltmeter with a 12-bit ADC have been used. Its scheme is shown in Fig. 3 (In Fig. 3 the temperature sensor is marked by symbol "R_t").

In the first cycle, the imbalance voltage (as a 12-bit equilibrium code) is written to the inductive divider registers and in the high order digits of the calculator. In the second cycle, the imbalance voltage is written only in the registers of the calculator as low-order bits. The microcontroller combines the data of the registers into a 24-bit format, carries out the necessary calculations for the system calibration and put the result on the display. A balanced AC bridges with an inductive divider of seven decades corresponds to this hybrid circuit.

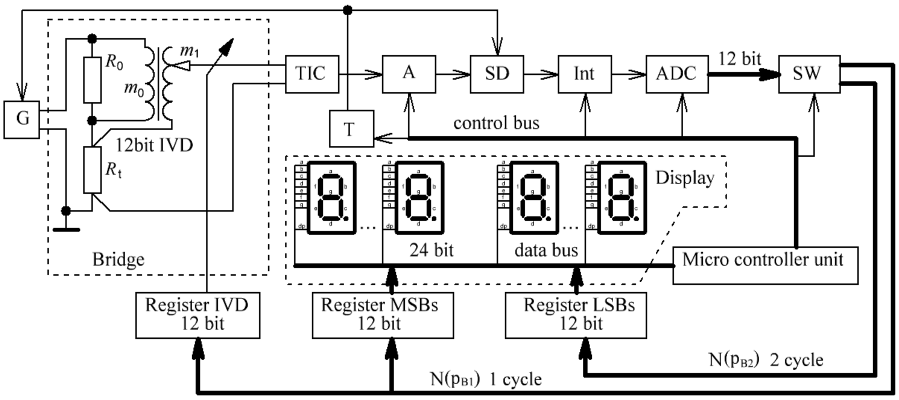

Fig. 3. A scheme working with combined - hybrid measurement method that provides a 24-bit effective number of binary digits: G - AC sinusoidal generator, TIC - matching transformer, A - amplifier, SD - two-channel (Re\Im) synchronous detector, Int - two-channel (Re\Im) integrator, ADC - analogue to digital converter, SW - switch, T - timing system.

An inductive voltage divider with a resolution of 12 bits (transformer m_1) for balancing the bridge is shown in Fig. 4.

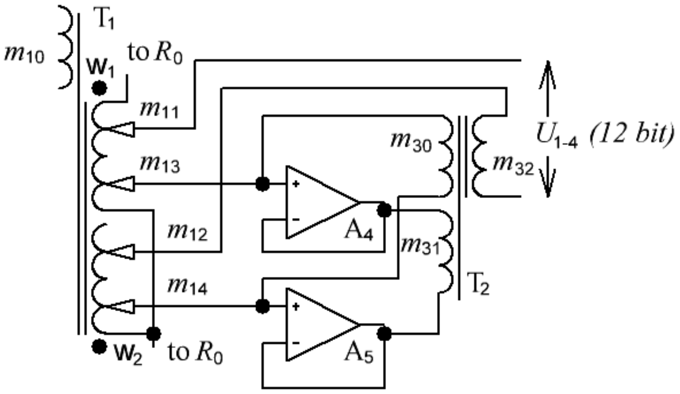

Fig. 4. Binary 12-bit inductive voltage divider IVD

The circuit contains two two-stage transformers T_1 and T_2. The weight coefficients of the windings w_1 and w_2 have a ratio of 1/8. Each of the windings m_{11} - m_{14} is switched by a system of electronic keys and realizes a voltage divider with a 3-bit capacity. Transformer T_2 has a transformation ratio of 1/64. Therefore, the summary voltage with a discreteness of 12 bits will be generated at the output of winding m_{14}. Transformers T_1 and T_2 are made on toroidal cores in the size 40 x 25 x 11 mm. The core material is amorphous cobalt (Co) iron with an initial magnetic permeability of μ=(1-2) 10^5. The divider has linearity no worse than 0.2 ppm at a working frequency of 125 Hz.

This new method based on the 12-bit ADC made it possible to realize the following main technical data of the bridge: LSD related to the full range - 0.06 ppm, linearity - 0.2 ppm, RMS at 0.05 Hz - 0.08 ppm. Such characteristics are comparable to those of the F18 ASL model [12]. Note that the bridge CA300 has dimensions of no more than 290 x 120 x 320 mm and a weight of not more than 6 kg. The level of the RMS indicates a certain reserve in the signal/interference ratio and is the possibility to add another decade. If a 16-bit ADC will be used, then with the same weight and dimensions is possible to get the parameters of an 8-decade bridge, for example equal to CTR9000 WIKA [12].

CONCLUSIONS

The tangent of the phase angle of standard platinum temperature sensors (SPRT) is very small [11,12]. Then the balancing process of measuring circuit of thermometric bridges it is possible to limit only for the active component of the SPRT impedance as the informative parameter about temperature. The circuit of AC bridge is simplified because it is transformed from a vector converter to a scalar converter.

The combined balanced-ratiometric method of the impedance measurement, named the hybrid method is proposed. This method is based on a variational method for estimating the bridge imbalance state, which allows you to significantly simplify the procedure of the AC bridge balancing.

The hybrid method allows also to use in AC measurement bridges a ratio transformer or an inductive divider IVD with a bit capacity smaller than is needed for the measurement result. The high resolution of the measurements will be retained by estimating the residual bridge imbalance. The high accuracy of measurements (LSD related to the full range - 0.06 ppm, linearity - 0.2 ppm, RMS at 0.05 Hz - 0.08 ppm.) by this method is provided by using the variational method of bridge balancing. It is based on the ratiometric transformation of signals before and after the variation and ensures invariance to phase changes of signals in the generator, amplifier and other bridge modules.

The use of a hybrid impedance measurement method significantly reduces hardware costs of the precision thermometric AC bridges manufacturing. At the same time, linearity and sensitivity remain the same as for fully balanced bridges with 7 to 8 decades of IVD.

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ZASTOSOWANIE HYBRYDOWEJ KOMPENSACYJNO-ILORAZOWEJ METODY POMIARU W WYSOKO PRECYZYJNYCH TEMPERATUROWYCH MOSTKACH AC

W artykule opisano oryginalną zasadę budowy układu pomiarowego automatycznego mostka AC (prądu przemiennego) do bardzo dokładnych pomiarów temperatury za pomocą wzorcowego platynowego czujnika SPRT. Wykorzystuje się oryginalną kombinowaną, tj. kompensacyjno-ilorazową metodę pomiaru, którą nazwano tu krócej: metodą hybrydową. Obejmuje ona połączenie metody kompensacyjnej do zgrubnego zrównoważenia układu i metody ilorazowej (*ratiometric*), którą wyznacza się stosunek dwu wartości sygnału nierównowagi, przed i po znanej jego zmianie. Układ pomiarowy nie wymaga stosowania obwodu do kompensacji wpływu reaktancji czujnika SPRT. Zmniejsza się też niezbędna liczba dekad dzielnika indukcyjnego kompensującego zgrubnie sygnał składowej rezystancyjnej czujnika. Układ taki pozwala w prostszy sposób i przy niższych kosztach wykonania uzyskać tę samą dokładność co najdokładniejsze termometryczne mostki AC o układach całkowicie zrównoważonych.

Słowa kluczowe: dokładny pomiar temperatury, mostek AC, metoda hybrydowa, metoda kompensacyjno-ilorazowa

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