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Methods for the Linearisation of the Transfer Function of Thermoresistive Transducers

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ABSTRACT The article describes digital and analogue methods for linearising the conversion function of thermoresistive transducers, with a detailed analysis of analogue methods. Analogue methods for linearising bridge circuits and measurement circuits based on passing a reference current through a resistance temperature detector (RTD) are considered. Linearisation of bridge circuits is based on the formation of the compensating supply voltage of the bridge circuit, which depends on the change in the measured temperature. When using the measurement method based on passing a reference current through an RTD, nonlinearity compensation is achieved by changing the conversion coefficient of the measuring signal or passing an additional current through the RTD, which linearly depends on the value of the RTD's voltage change (measured temperature value). When passing an additional compensation current through the RTD, the nonlinearity error is not grater than 0.1°C in the range of 0…800°C, and the schematic diagram of the measuring transducer contains a minimum number of elements, which allows to increase its reliability. In general, the choice of a linearisation method depends on the requirements for accuracy, operation rate and resource limitations of the measuring system.

KEYWORDS temperature, temperature measurement, linearisation, RTD.

I. INTRODUCTION

Temperature is among the most frequently measured parameters, with various measurement techniques offering distinct advantages depending on the application [1]. Temperature sensors are widely utilised for this purpose, and their production is expanding rapidly. In 2024, the global temperature sensor market was valued at USD 8.5 billion and is expected to grow from USD 9.3 billion in 2025 to USD 18.3 billion by 2033, reflecting a CAGR of 8.75 % over the forecast period (2025-2033) [2]. The quality and safety of many technological processes considerably depends on the accuracy of temperature measurement.

The temperature sensor market encompasses both contact and non-contact sensors, including resistance temperature detectors (RTDs). RTDs are widely utilised for industrial and scientific temperature measurements due to their high accuracy and long term stability, making them ideal for applications in laboratories, pharmaceuticals and food processing [4-6]. These sensors are typically made from platinum, copper, nickel, or nickel alloys, with platinum being the preferred material for resistance temperature detection. This preference is attributed to several key properties: chemical inertness (platinum is highly resistant to oxidation and corrosion, making platinum RTDs ideal for harsh industrial and laboratory environments), low resistance drift (typically ranging from 0.01 °C to 0.1 °C per year, which is significantly lower than that of thermocouples), interchangeability and standardisation (platinum RTDs follow international standards such as IEC 60751, allowing easy replacement without recalibration), fast response time, broad operating temperature range (from -200 °C to +850 °C [3], or even to 1000 °C).

Platinum RTDs come in two primary forms: wire-wound and thin-film. They operate based on the intrinsic temperature-dependent resistance properties of platinum, offering excellent stability across a broad temperature range. Various physical configurations, resistance, and accuracy values are available. The commonly used designation "Pt100" means a resistance of 100 ohms at 0 °C.

The relationship between resistance and temperature for most metallic materials can be described using a high-order polynomial function with the polynomial order depending on the material properties, required accuracy and temperature range. Within a limited temperature range of -20 °C to 150 °C, platinum RTDs exhibit approximately linear behaviour, with nonlinearity being within ±0.3 % [7]. In a temperature range from -200 °C to 850 °C, the nonlinearity is within 4.42 % [8].

The resistance change of a platinum RTD with temperature can be approximated using the equation:

$$R_t = R_0(1+\alpha t)\,, \tag{1}$$

where R_t is the RTD's resistance at the temperature t, R_0 is the reference resistance at 0 °C, $\alpha = 0.00385$ [°C]$^{-1}$ (European curve, ITS-90) is a constant that allows for a straightforward estimation of the RTD's absolute resistance within the temperature range of -100 °C to +200 °C, with a nominal error of less than 3.1 °C [9].

For higher accuracy temperature measurements or a wider temperature range, the standard Callendar-Van Dusen equation can be applied. For temperatures above 0°C it is defined as follows:

$$R_t = R_0(1+At+Bt^2)\,, \tag{2}$$

where A, B are the constants (according to IEC 60751 and ASTM E1137 standard $A = 3.9083 \cdot 10^{-3}$ [°C]$^{-1}$, $B = -5.775 \cdot 10^{-7}$ [°C]$^{-2}$) [10-11].

Although RTDs exhibit significantly better linearity compared to thermocouples, they still possess a notable nonlinearity of second-order of about 0.38 % per 100 °C [12].

The RTD can achieve a calibrated accuracy of ±0.02 °C or better. However, to attain the highest accuracy, it is essential to employ precise signal conditioning, analogue-to-digital conversion, linearisation and calibration [13].

In practical applications, the main issue when using RTDs is the linearisation of the relationship between temperature and resistance [14].

II. LINEARISATION METHODS

Digital and analogue methods are used to linearise the functional dependence of the output signal of thermoresistive transducers [15].

Digital linearisation methods are mainly used in digital secondary measuring devices built on the basis of microprocessor technology. These methods perform correction after analogue-to-digital conversion using microcontrollers. They include the use of Look-Up Tables, polynomial approximation, piecewise linear approximation and artificial neural networks [13, 16-17].

The use of lookup tables involves storing pre-calculated temperature values for each possible ADC value in the microcontroller's memory. The polynomial approximation is implemented by calculating the temperature using the Callendar-Van Dusen equation. In this case, the microcontroller must have sufficient computing power.

With piecewise linear approximation, the temperature range is divided into intervals, each of which uses a separate linear formula to approximate the resistance versus temperature. This reduces the number of calculations compared to polynomial approximation, while providing good accuracy.

Machine learning models can be trained on RTD response curves to provide highly accurate linearisation, especially in complex environments. However, this method requires significant processing power and memory.

Overall, digital linearisation methods offer greater flexibility and ensure high measurement accuracy. However, these advantages come with certain trade-offs, including increased silicon area usage and longer processing times, which may be impractical for low-cost, low-power applications.

Considering the above, analogue methods continue to be used alongside digital ones.

Analogue methods can be used with various types of secondary measuring devices. These methods include the use of bridge circuits, compensation resistors, voltage dividers and analogue compensation circuits [18-24].

Reducing nonlinearity to 0.11 % in the range -100 – 800 °C can be achieved by calibrating in the middle and at the end of the temperature range [12].

Bridge circuits can provide a linear approximation over a limited temperature range and this method provides only partial compensation.

Precision resistors, sometimes combined with operational amplifiers, create piecewise-linear approximations of the RTD characteristic.

Analogue compensation circuits use diodes, thermistors or other nonlinear components to counteract the nonlinear output of the RTD.

III. METHODS FOR LINEARISATION OF BRIDGE THERMORESISTIVE CIRCUITS

To convert the change in the resistance of a thermistor into voltage, unbalanced bridge resistive circuits are often used, the disadvantage of which is the nonlinearity of the conversion function [20, 21].

One of the methods of linearisation of bridge circuits in a wide range is the method based on the compensation voltage formation of the bridge circuit, which depends on the change in the measured temperature. In order to form the temperature-dependent component of the supply voltage, one can use an additional RTD, which is placed together with the main RTD. Also, to form the variable component of the supply voltage, the output voltage of the bridge circuit or the voltage drop on the RTD can be used.

The formation of a temperature-dependent component of the supply voltage can be implemented using an additional RTD, which is placed with the main RTD. Such a scheme allows to compensate for the nonlinearity of the measurement by creating a temperature-dependent correction signal. The main RTD is used to measure the temperature. The additional RTD is used to create a correction voltage that changes depending on the temperature and compensates for the nonlinearity.

In general, the linearisation scheme of bridge circuits based on the formation of the compensation supply voltage can be presented as given in Fig. 1. It contains a reference voltage source RVS, a compensation voltage former CVF, and a voltage summator VS.

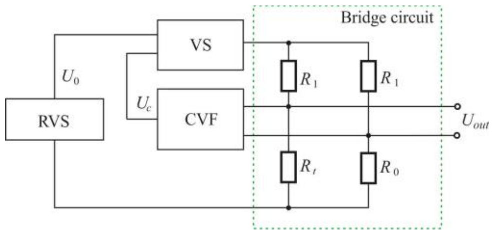

FIG. 1. Generalised scheme for linearisation of bridge circuits based on the compensation voltage formation.

In [21], a generalised feedback compensation scheme is presented, which provides linearisation of the output voltage of the bridge circuit. In this approach, the output voltage of the bridge circuit V_{OB} is amplified by A times (gain A) and its part βAV_{OB} is summed with the reference voltage and fed to the input of the bridge circuit (Fig. 2). Expression (1) was used to describe the conversion function of the RTD.

If the RTD transfer function is described by equation (2), then the nonlinearity of the output signal depends on both the nonlinearity of the RTD transfer function and the nonlinearity of the bridge circuit. The circuit that provides their linearisation is shown in Fig. 3 [23]. The output voltage of the bridge circuit is used to form the compensation supply voltage.

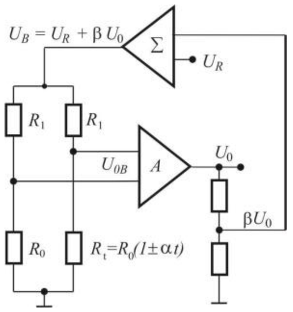

FIG. 2. Generalised feedback compensation scheme for linearisation of the output voltage of the bridge circuit [22].

In order to form the temperature-dependent component of the supply voltage, the output voltage of the bridge thermoresistive circuit is summed with the voltage of the power source with different coefficients depending on the value of the measured temperature. At $t > 600$ °C, another additional component of the compensation voltage is formed using the operational amplifier OA4. In this case, the error of the nonlinearity of the temperature conversion in the range of 0 – 800 °C is not grater than 0.1 °C.

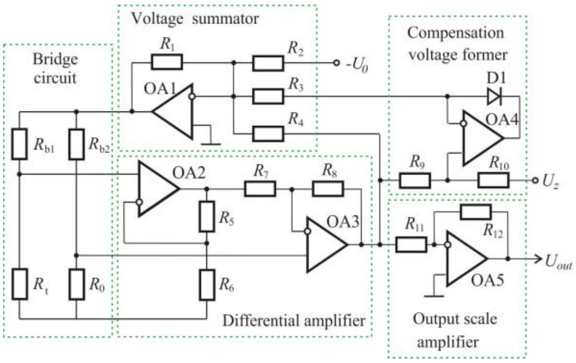

FIG. 3. Structural scheme of linearisation based on the formation of the compensation voltage of the bridge circuit [23].

IV. LINEARISATION METHOD BASED ON COMPENSATION CURRENT FORMATION

To ensure linearity of the conversion of resistance change into voltage, it is advisable to use a measurement method based on passing a sample current through an RTD. To compensate for the initial value of the RTD resistance at 0 °C or at the initial measurement temperature, a reference resistor is used in series with the RTD. In this case, the value of the reference resistor is chosen equal to the value of the RTD resistance at the corresponding temperatures.

The value of the voltage change across the RTD is expressed as:

$$\Delta U(t) = I_0 R_0 \left(At - Bt^2\right), \tag{3}$$

where I_0 is the value of the reference current.

Compensation of the quadratic component Bt^2 can be achieved by passing an additional current through the RTD, which depends linearly on the value of the measured temperature or on the value of the voltage change on the RTD. The value of the temperature-dependent current is described as:

$$I_t = I_0 R_0 \cdot At \cdot k_1, \tag{4}$$

where k_1 is the conversion coefficient of voltage change into current.

When $R_0 k_1 = k$, the value of the voltage change across the RTD equals:

$$\Delta U(t) = I_0 R_0 \left(At - Bt^2 + A^2 t^2 k - ABt^3 k\right). \tag{5}$$

From the analysis of the expression it is clear that to compensate for the quadratic component it is necessary to ensure the following equality:

$$Bt^2 = A^2 t^2 k \quad \text{or} \quad k = \frac{B}{A^2}. \tag{6}$$

With this choice of the value of the coefficient k, complete compensation of the quadratic component of the change in resistance with temperature is achieved.

The implementation of this method is presented in Fig. 4 [24]. The circuit contains a reference current source RCS, a converter of RTD resistance change into voltage RVC, a former of the temperature-dependent component of the reference current FTC, a reference voltage source RVS and an output amplifier-summator of voltage VAS.

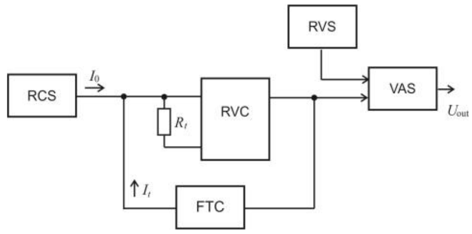

FIG. 4. Structural scheme of linearisation based on the formation of compensation current [24].

In this case, the absolute nonlinearity error is reduced to 2 °C for a single-band converter and to 0.2 °C for a three-band converter in the range 0 – 800 °C.

Reducing the nonlinearity error of a platinum RTD is achieved by passing the compensation current only through the RTD (Fig. 5) [25]. The thermoresistive transducer contains a sample current stabiliser on the operational amplifier (OA) OA1 and a sample voltage source U_0, an RTD resistance-to-voltage converter on the OA2 and an output scaling amplifier on the OA3.

The output voltage is equal to:

$$U_{out} = \left(I_0 \left(R_t - R_0\right) + I_c R_t\right) \frac{R_4}{R_3}, \tag{7}$$

where I_c is the compensation current.

At $I_c = \dfrac{U_{out}}{k_2 R_c}$ and $k_2 = \dfrac{R_4}{R_3}$ we will obtain:

$$U_{out} = I_0 R_{t0} \left(At - Bt^2\right) k_2 \frac{R_c}{R_c - R_t}. \tag{8}$$

By choosing the coefficient k_2, we achieve equality of a voltage value at the output and the measured temperature.

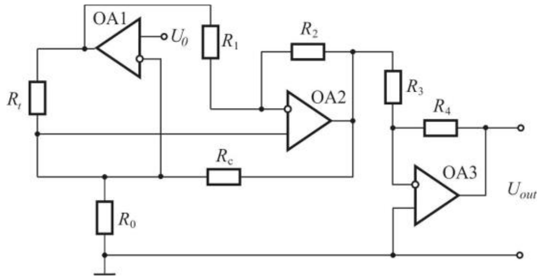

FIG. 5. Schematic diagram of a thermoresistive transducer with compensation current forming [25].

The absolute error of nonlinearity is equal to:

$$\Delta_t = I_0 R_0 \left(At - Bt^2\right) \cdot k_2 \frac{R_c}{R_c - R_t} - t \,. \quad (9)$$

Graph dependencies are shown in Fig. 6.

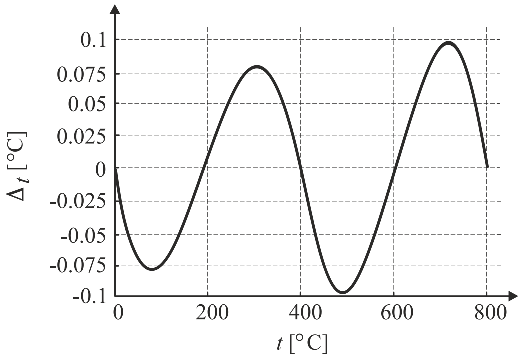

FIG. 6. The plot of the relationship of the temperature vs. absolute error of nonlinearity of the thermoresistive transducer in the range of 0…800°C.

As it can be seen from graph dependence (Fig. 6), the error of nonlinearity is less than 0.1 °C in the range of 0 – 800 °C. At the same time, the schematic diagram of the measuring transducer contains a minimum number of elements, which allows to increase its reliability.

V. LINEARISATION METHOD BASED ON CHANGING THE TRANSFER COEFFICIENT OF THE MEASURING SIGNAL

The method consists in dividing the entire measurement range into separate ranges and calibrating at the end of the first range with a subsequent increase in the transfer coefficient on each subsequent range. The compensation voltage former generates a voltage proportional to the voltage difference between the actual value and the value at the beginning of the measurement range. This voltage is summed with the output voltage on the previous range.

The structural scheme of the thermoresistive transducer is shown in Fig. 7. It consists of a reference voltage source RVS, a reference current source RCS, an output voltage amplifier RTD VA, an output inverting amplifier IA and a compensation voltage formers CVF, the number of which is determined by the range of the measured temperature and the required accuracy.

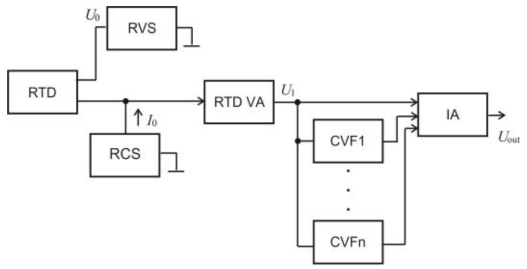

FIG. 7. Structural scheme of a thermoresistive transducer with linearisation based on changing the transfer coefficient of the measuring signal.

The reference voltage source RVS is used to compensate for the initial voltage on the RTD at t = 0 °C.

When the temperature changes, the voltage is applied to the input of the RTD VA and at the output we will obtain the voltage:

$$U_1 = -I_0 k_1 (At + Bt^2) \,, \quad (10)$$

where k_1 is a gain factor of RTD VA.

The output voltage in the first range $t = 0 - t_1$ equals:

$$U_{outt} = I_0 k_1 k_2 (At + Bt^2) \,, \quad (11)$$

where k_2 – conversion coefficient of the output inverting amplifier of the first input voltage.

The values of k_1, k_2 are chosen so that the output voltage at the end point of the measurement range is numerically equal to the measured temperature t.

When $t > t_1$, at the output of the CVF*1* a compensation voltage is formed, the value of which is described by the expression:

$$U_{k1} = U_1 - U_{01} \,, \quad (12)$$

where U_{01} is the voltage value of RTD VA at the end of the first range at $t = t_1$.

This voltage is supplied to the second input of the IA, at the output of which we will obtain the voltage:

$$U_{out2} = U_1 k_2 + (U_1 - U_{01}) k_{c1} \,, \quad (13)$$

where k_{c1} is the conversion coefficient of the output inverting amplifier of the second input voltage.

In each subsequent range, the transfer coefficient increases, ensuring the output voltage at the end of each range to be equal numerically to the temperature value t_i:

$$U_{out} = U_1 k_2 + \sum_{i=1}^{n-1} (U_1 - U_{0i}) k_{ci} \,, \quad (14)$$

where n is number of ranges.

The nonlinearity error does not exceed 0.3 °C in the range of 0 – 800 °C.

VI. CONCLUSIONS

The article describes digital and analogue methods for linearising the RTD conversion function, with a detailed analysis of analogue methods. Digital methods offer greater flexibility and accuracy. However, they have such disadvantages as longer measurement time or a larger number of semiconductor elements, which reduces the reliability of measuring devices.

Analogue methods are advantageous in the conditions of limited computing resources and power consumption. They are characterised by higher operation rate and reliability.

The choice of linearisation method depends on the requirements for accuracy, operation rate and resource constraints of the measuring system. In order to linearise the transfer function of thermoresistive transducers, it is advisable to combine analogue and digital methods.

AUTHOR CONTRIBUTIONS

L.H., O.B. – conceptualization; L.H., O.B. – methodology; L.H., O.B. – investigation; L.H. – writing-original draft preparation; L.H., I.H., H.B. – writing-review and editing; T.K. – visualisation; O.B. – supervision.

COMPETING INTERESTS

The authors declare no conflicts of interest.

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АНОТАЦІЯ У статті проведено аналіз цифрових та аналогових методів лінеаризації функції перетворення терморезистивних перетворювачів, з детальним аналізом аналогових методів. Цифрові методи забезпечують високу точність та гнучкість, однак вони характеризуються більшим часом вимірювань та складнішою апаратною реалізацією. Аналогові методи є оптимальними для застосування в умовах, де важливими є швидкість і надійність вимірювань. Вони є простішими в реалізації, так як не потребують складних мікропроцесорних систем, енергоефективними та менш чутливими до електромагнітних завад, хоч мають обмеження щодо точності та можливостей корекції похибок у порівнянні з цифровими методами. Розглянуто аналогові методи лінеаризації мостових терморезистивних схем та схем вимірювання на основі пропускання зразкового струму через первинний терморезистивний перетворювач. Лінеаризація мостових схем базуються на формуванні компенсаційної напруги живлення мостової схеми, що залежить від зміни вимірюваної температури. При використанні методу вимірювання на основі пропускання зразкового струму через первинний терморезистивний перетворювач компенсації нелінійності досягають шляхом зміни коефіцієнта передачі вимірювального сигналу або пропускання через первинний терморезистивний перетворювач додаткового струму, який лінійно залежить від значення зміни напруги (від значення вимірюваної температури). При пропусканні додаткового компенсаційного струму через первинний терморезистивний перетворювач похибка нелінійності не перевищує 0,1°C в діапазоні 0 – 800°C, а принципова схема вимірювального перетворювача містить мінімальну кількість елементів, що дозволяє підвищити її надійність. Загалом вибір методу лінеаризації залежить від вимог до точності, швидкодії та ресурсних обмежень вимірювальної системи. Доцільним є поєднання аналогових і цифрових методів.

КЛЮЧОВІ СЛОВА температура, вимірювання температури, лінеаризація, терморезистивний перетворювач.