# АВТОМАТИЗАЦІЯ, КОМП'ЮТЕРНО-ІНТЕГРОВАНІ ТЕХНОЛОГІЇ ТА РОБОТОТЕХНІКА

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## ANALYSIS OF CIRCUIT DESIGN METHODS FOR LINEARIZING THE TEMPERATURE CHARACTERISTICS OF NTC-THERMISTORS AND THE MEASUREMENT CHANNEL CHARACTERISTICS

**Background.** Temperature measurement devices play a crucial role in the automation of various systems and in monitoring diverse physicochemical parameters. thermoresistors, thermistors, or thermocouples are commonly used as temperature sensors. However, the nonlinear temperature-resistance characteristic of thermistors presents challenges for accurate temperature-to-electric signal conversion. Therefore, the issue of linearizing the output characteristic of the temperature measurement channel remains highly relevant. The task of linearizing the temperature dependence of the measurement channel can be addressed using hardware (circuit-based), software, or combined hardware-software approaches.

**Objective.** The purpose of the research is to analyse the effectiveness of circuit-based (schematic) methods for linearizing the temperature characteristics of NTC-type thermistors and to evaluate their impact on the overall performance of the temperature measurement channel.

**Methods.** A structural model of a temperature measurement device utilizing an NTC-thermistor as a sensor was developed in the MATLAB Simulink environment. Five different circuit configurations for connecting the thermistor to the measurement channel were analysed to assess the effectiveness of linearization within the temperature ranges of ±15 °C and ±25 °C. Based on the proposed connection schemes, a simulation of the temperature characteristics of NTC-thermistors was carried out.

**Results.** The results of the study for five circuit-based methods of linearizing the temperature characteristics of NTC-thermistors provide an opportunity to evaluate the effectiveness of applying different circuit-based methods for linearizing the temperature characteristics of NTC-thermistors and the measurement channel characteristics in two temperature ranges: ±15 °C and ±25 °C. Based on the presented simulations, it can be stated that by applying these circuit-based methods for linearizing the temperature characteristics of NTC-thermistors and the measurement channel characteristics, the measurement error can be reduced by 40 % in a limited temperature range compared to using a balanced measurement bridge, and corrections for compensating the self-heating effect of the thermistor can be determined.

**Conclusions.** By modelling the circuit-based methods for linearizing the temperature characteristics of NTC-thermistors, it becomes possible to evaluate the effectiveness of linearizing the temperature dependence of the measurement channel while investigating various options for connecting the thermistor to the measurement channel. Additionally, the parameters of the measurement channel elements of the temperature-measuring device can be determined.

**Keywords:** temperature measurement; NTC-thermistor; MATLAB Simulink; linearization.

### Problem statement

Regardless of where temperature measurement is performed using different devices, the primary requirement for the results of such measurements is their accuracy. The overall technical and economic parameters of the temperature measurement system are determined by the sensor, the type of which depends on the requirements needed from the system as a whole. Sensors, particularly commonly used thermistors with a TCR – negative temperature coefficient (or NTC – Negative Temperature Coefficient), have a fairly wide working temperature range, remote monitoring capabilities, can operate in strong magnetic fields, and have small dimensions. One of the most significant drawbacks of thermistors with a negative TCR is the nonlinearity of their $R(T)$ characteristic – the relationship between the

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resistance of the thermistor and its temperature. This relationship has an exponential form.

The linearity of the measurement channel in a temperature measurement device with a thermistor sensor is influenced not only by the nonlinearity of its $R(T)$ characteristic but also by the nonlinearity of the transfer characteristic of the interface circuit to which the thermistor is connected and the self-heating effect of the thermistor when an electric current passes through it. Thus, the task of linearizing the temperature dependence of the measurement channel remains open. Among the circuit techniques, the most common are passive correction circuits and resistive voltage dividers, which allow forming a linear section on the $R(T)$ characteristic within a specific temperature range. These methods are quite economical compared to software methods that require a microcontroller.

The problem can be solved by determining a rational design for the measuring probe, selecting the correct characteristics and operating modes of the thermistor, and implementing optimal operating parameters for the measurement channel. At the stage of developing the temperature measurement device, it is important to carry out mathematical modelling of the measurement channel to choose the optimal linearization method and define the parameters of the components. Creating mathematical models to study linearization methods allows for determining the characteristics of the measurement channel components depending on the specific application. In this work, using the developed mathematical model created in MATLAB Simulink, methods for linearizing the device characteristics were studied, measurement errors were evaluated, and recommendations were developed to improve measurement accuracy.

## Analysis of recent research and publications

Nonlinearity in the characteristics of most sensors and measurement channels in devices is an important problem. Their linearized characteristics simplify the design, and calibration, and improve measurement accuracy. To compensate for the nonlinearity of the characteristics of thermistors and the measurement channel, various linearization methods are presented in the literature. In [1, 2], an analysis of such methods is conducted. These works provide an overview of different methods applied for linearizing sensor characteristics. It is noted that due to the availability of high-performance analogue devices, circuit-based (analogue) methods are still popular among many researchers, although the use of digital methods combined with software methods provides better results and ensures flexibility and efficiency. The popularity of circuit-based linearization methods is explained by the simplicity of implementation and, compared to software methods, their more economical nature.

As is known, the nonlinearity of the characteristics of measurement channels in devices is primarily influenced by: the nonlinearity of the $R(T)$ dependence of the thermistor's resistance on its temperature, the self-heating effect of the thermistor when an electric current passes through it, the nonlinearity of the voltage across the thermistor in a voltage divider or a measurement bridge arm concerning its resistance, and the nonlinearity of the signal amplifier's characteristic.

Modelling the specific implementation of devices with the required characteristics using the necessary linearization method significantly simplifies the development process and helps to optimally and quickly select the required component parameters and achieve the desired result. Manufacturers of nonlinear components also offer their own models for connecting thermistors. For example, online services like "NTC Thermistor Simulation" on the TDK website [3] and the Murata Electronics website [4]. Mitsubishi Materials offers the "Chip Thermistor Resistance Simulator" as an Excel file [5]. The models provided by the manufacturers help solve the problem of selecting a specific type of thermistor for a particular case and partially address the nonlinearity of the thermistor's $R(T)$ characteristic. Scientists, engineers, and specialists also propose their own ways of solving the problem of nonlinearity in the $R(T)$ characteristic of the sensor [6, 7]. These models and methods do not provide a full solution to the problem in the device, considering the specific requirements required from the device as a whole.

The research aims to construct (develop) an original structural-mathematical model of the measurement channel of a temperature measurement device using an NTC-thermistor in the MATLAB Simulink environment, to investigate using the created model different circuit-based methods of linearizing the temperature characteristics of NTC-thermistors and measurement channel elements, analyze the causes of measurement errors, choose the optimal method and characteristics of the measurement channel elements to improve the temperature measurement accuracy. The goal of the work is to investigate, using the built models, various ways of linearizing the temperature characteristics of NTC-thermistors and elements of the measurement channel.

**The presentation of the main research material**

The essence of temperature measurement using an NTC-thermistor is to use the dependence of the thermistor resistance on its temperature, that is, on the temperature of the environment surrounding the thermistor.

The dependence of the electrical resistance of an NTC-thermistor on temperature has the form [8]:

$$R_T = R_N \exp B\left(\frac{1}{T} - \frac{1}{T_N}\right), \quad (1)$$

where: $R_T$ – NTC-thermistor resistance by temperature $T$, K;

$R_{TN}$ – NTC-thermistor resistance at nominal temperature $T_N$, K;

$T$, $T_N$ – temperature, K;

$B$ – constant coefficient that depends on the thermistor material, K.

Fig. 1 shows the dependence of the thermistor resistance on temperature. As can be seen from Fig. 1, this dependence is exponential in nature, and therefore is nonlinear, which creates certain difficulties when creating temperature measuring devices and introduces additional error when attempting to linearize this characteristic. The value of the error will depend on the linearization method used.

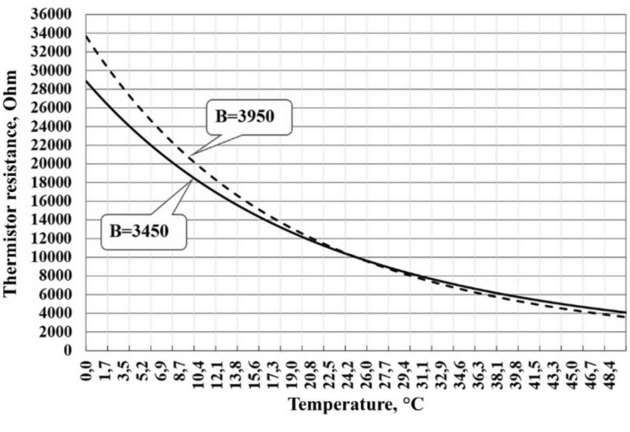



Fig. 1. Dependence of thermistor resistance on temperature at coefficient values $B$ = 3450 K and $B$ = 3950 K

Often, the form of the temperature characteristic of an NTC-thermistor does not meet the requirements for a specific application of the device. The use of passive correction circuits (Linear resistance networks) [6, 7] allows for modifying the $R(T)$ dependence in such a way that a maximally linear dependence segment is achieved within a specific temperature working range.

The simplest circuit-based options for such networks to correct the $R(T)$ dependence of the thermistor are the series, parallel, or series-parallel connection of resistors (Fig. 2), whose temperature coefficient of resistance (TCR) is very small compared to TCR of the thermistor. Connecting a resistor in parallel with the thermistor compensates for its nonlinearity, a series connection adjusts the sensor's sensitivity, and a series-parallel connection creates a linear characteristic with the required slope.

When a resistor is connected in series with the thermistor, the slope of the $R(T)$ characteristic decreases by an amount proportional to the ratio $\frac{R_T}{R_1 + R_T}$, which slightly reduces the non-linearity of the characteristic, but at the same time, the sensitivity of the sensor decreases proportionally. When a resistor is connected in parallel to balance the $R(T)$ characteristic, the resistance of the parallel resistor is determined by the formula (see Fig. 2, b) [9]:

$$R_1 = R_{TN} \times \frac{B - 2T_N}{B + 2T_N}, \quad (2)$$

where: $R_1$ – resistance of a resistor connected in parallel, *Ohm*;

$R_{TN}$ – resistance of the NTC-thermistor at nominal temperature $T_N$, K;

$T$, $T_N$ – temperature, K;

$B$ – constant coefficient that depends on the thermistor material, K.

Series-parallel connection of resistors (see Fig. 2, c) is used to form a linear characteristic with a given slope. The total resistance $R$ in series-parallel connection is determined by the formula [10] (3):

$$R = \frac{(R_1 + R_T)R_2}{R_1 + R_2 + R_T}. \quad (3)$$

If resistors $R_1$ and $R_2$ have a fixed ratio with respect to the resistance of the thermistor at its nominal temperature $R_N$ (average temperature in a given range). So, having made the substitution $R_1 = a \cdot R_N$ and $R_2 = b \cdot R_N$, we can write formula (3) [11] as:

$$R = \frac{(aR_N + R_T)bR_N}{aR_N + bR_N + R_T}. \quad (4)$$

For the predicted linear function to pass at the inflection point of the nonlinear function $T_N$, and the transfer function to have a sensitivity (slope) at this point equal to the desired value of $\Omega/K$, it's necessary to determine the values for a and b. Based on

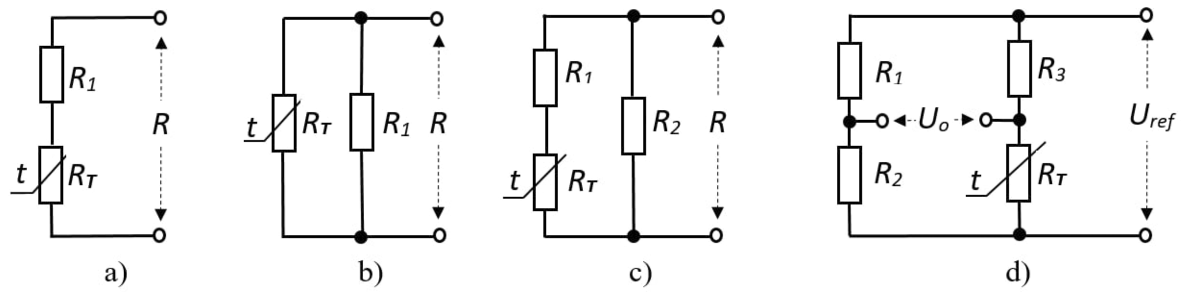



Fig. 2. Correction of the $R(T)$ thermistor dependence by sequential (a), parallel (b), series-parallel (c) resistor connections and using the non-linearity of the voltage divider in the Wheatstone bridge circuit (d)

formula (2), when resistors are connected in parallel to the thermistor $R_1 = a \cdot R_N$ and $R_2 = b \cdot R_N$ the sum of $a$ and $b$ is determined by the formula (5) [10]:

$$a + b = \frac{B - 2T_N}{B + 2T_N}. \quad (5)$$

The coefficients $a$ are respectively equal to [9]:

$$a = \frac{B - 2T_N}{B + 2T_N} - b, \quad (6)$$

and coefficient $b$ [6]:

$$b = \frac{2T_N}{B + 2T_N}\sqrt{\frac{R'_N}{R_N}} = \frac{2T_N}{B + 2T_N}\sqrt{\frac{-mB}{R_N}}, \quad (7)$$

where: $R'_N$ is the nonstandard value and $R'_N$ – is the standard value thermistor resistance at nominal temperature $T_N$, $m$ – required slope of the linearized transfer function, $\Omega/K$.

Temperature measurement using a thermistor can be carried out by measuring the voltage across the thermistor, connected to a DC source or through a divider to a voltage source. The voltage across the thermistor $U_T$ is proportional to its resistance and, accordingly, proportional to the temperature of the thermistor. The diagram of such a divider is shown in Fig. 3.

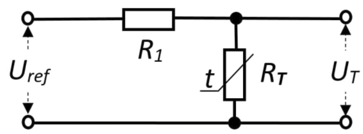



Fig. 3. Voltage divider circuit

The voltage dependence on the thermistor in the divider has the form (8):

$$U_T = U_{ref} \times \frac{R_T}{R_1 + R_T}. \quad (8)$$

In Fig. 4, the dependence of the voltage across the thermistor on its resistance is shown for different ratios $k = \frac{R_1}{R_{TN}}$, where $R_{TN}$ is the resistance of the NTC-thermistor at the nominal temperature $T_N$, assuming the resistance of the thermistor changes linearly. In this case, for example, $U_{ref} = 10$ V, and the thermistor's resistance changes linearly from 30 $k\Omega$ to 4 $k\Omega$. The resistance range is based on the characteristics of the RH18 6H103 thermistor from Mitsubishi Materials, with a temperature range from 0 °C to +50 °C. At 25 °C, the resistance of RH18 is $R_{TN} = 10\ k\Omega \pm 1\ \%$.

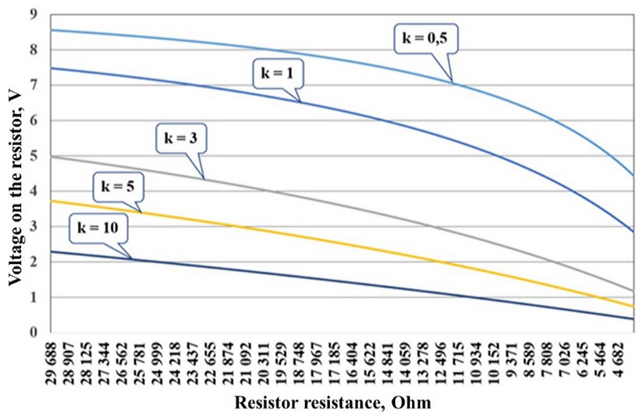



Fig. 4. Dependence of the voltage across the $R_T$ resistance on the thermistor resistance at different ratios $k$, where $k = R_1/R_{TN}$

As seen from formula (8) and Fig. 3, the nonlinearity has a hyperbolic nature, and as the value of $k$ increases, i.e., as the resistance of resistor $R_1$ increases, the degree of linearity – the approximation of the curve $U_T(R_T)$ to a straight line – grows. This feature is used to correct the nonlinear dependence $R(T)$ of the NTC-thermistor. By selecting the appropriate value of $k$ (the resistance of resistor $R_1$) in the voltage divider, a certain degree of linearity of the characteristic can be achieved.

For accurate measurement of the electrical parameters of sensors when creating the interface circuit, Wheatstone impedance bridges are widely used. This bridge circuit consists of two legs of voltage dividers, one of which contains the thermistor. Wheatstone bridge circuits are designed to measure an unknown electrical resistance by unbalancing two sides of the bridge circuit — one of which contains an unknown component. The bridges can be symmetric, asymmetric, balanced, and unbalanced. Wheatstone bridge circuits are simple, efficient, and very useful for temperature monitoring.

The Wheatstone bridge has a single element with a variable impedance, and the further its resistance is from the balance point, the more the voltage in the bridge diagonal becomes nonlinear with respect to the resistance of the element with variable impedance. When using the Wheatstone bridge for compensating the nonlinearity of the thermistor, the character of the bridge's nonlinearity should be opposite to that of the thermistor's nonlinearity. This is difficult to achieve, but partial compensation can be obtained in a narrow temperature range.

To compensate for the nonlinearity of the Wheatstone bridge, researchers and developers propose several circuit design solutions [11], which are based on introducing feedback with a specific coefficient β, defined by the formula:

$$\beta = \frac{1+k}{G \cdot k}, \qquad (9)$$

where: β — feedback coefficient; $G$ — bridge unbalanced amplifier gain; $k$ — coefficient of the ratio of the resistances of the resistors in the bridge arm,

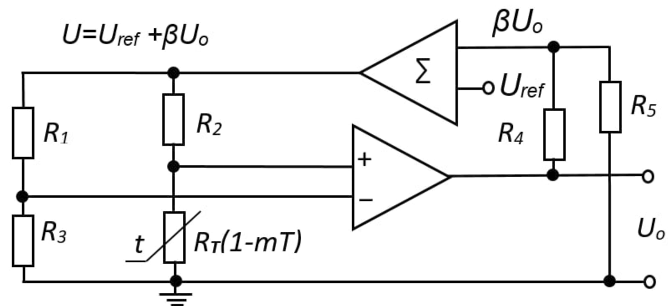
$$k = \frac{R_2}{R_{TN}}.$$

Among the simple and common circuit solutions for compensating for the nonlinearity of the Wheatstone bridge, the circuits shown in Fig. 5 [11, 12] are used.

In the electrical circuit of the temperature measurement device, an electric current flows through the NTC-thermistor, which heats it up. This phenomenon is called the self-heating of the thermistor. The self-heating temperature of the thermistor depends on the magnitude of the current passing through it, the materials and design of the sensor, and the thermal conductivity of the surrounding environment [13, 14]. This phenomenon is used in devices for measuring the thermal-physical properties of materials or the rate of substance flow [14, 15, 16]. The self-heating of the NTC-thermistor leads to an additional decrease in the thermistor's resistance, which distorts the measurement result. Therefore, in temperature measurement devices, a correction must be applied to the obtained measurement result, and the calculation of this correction is performed using the following formula [13]:

$$T_A = T - \frac{U^2}{\delta_{th} + R(T)} = T - \frac{I^2 \times R(T)}{\delta_{th}}, \qquad (10)$$

a)




b)

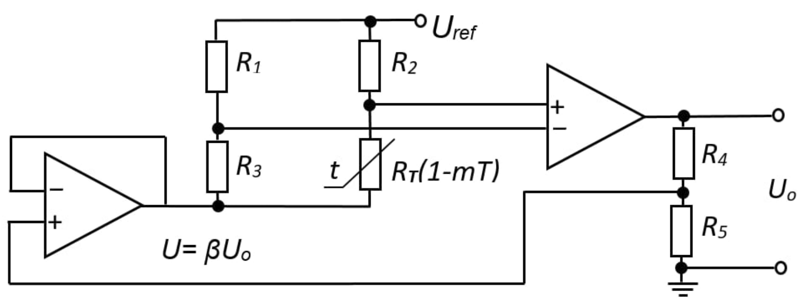



Fig. 5. Schematic solutions for compensation of Wheatstone bridge nonlinearity using feedback: a — with adjustment of the bridge supply voltage, b — with regulation of the voltage of the base (zero) pole of the bridge

where: $T_A$ – the actual value of the controlled temperature; $T$ – the measured temperature value; $U$ – the instantaneous voltage across the thermistor; $I$ – the instantaneous current flowing through the thermistor; $R(T)$ – the thermistor resistance corresponding to the temperature $T$; $\delta_{th}$ – the thermal dissipation coefficient in the measurement environment.

Using as a basis the circuit solutions presented in Fig. 2, 3, 5, a model of methods for compensating for the nonlinearity of the dependence of the thermistor resistance on its temperature and the influence of the thermistor self-heating effect, taking into account the nonlinearity of the transfer function of the sensor interface circuit, was designed and implemented.

Fig. 6 shows the developed measurement channel model in MATLAB Simulink, which meets these requirements.

The model consists of 3 groups of blocks for simulating the electrical circuit of the measurement channel: the "*Sensor interfacing circuit*" group, the "*Amplifier*" group, and the "*Feedback*" group.

The "*Sensor interfacing circuit*" group is the connection scheme of the thermistor model – "*Thermistor*" RT to the differential amplifier model "*Fully Differential Op-Amp*" in the "*Amplifier*" group via the appropriately configured resistor connection models "*Resistor*" R1, R2, R3, ..., R7.

The "*Thermistor*" can be connected to the Wheatstone bridge leg R1, R2, R3, RT or simply through the voltage divider $R_2/R_T$ to the "*Fully Differential Op-Amp*". The Wheatstone bridge legs R1-R3 and R2-RT can be connected using the switch models "*Switch*" S1, S2, S3 to current source models "*Current Source*" or voltage source models "DC Voltage Source".

The electrical "*Feedback*" group consists of a resistive voltage divider R8/R9, which defines the feedback coefficient β, an operational amplifier, and switches S4, S5, which are used to configure the feedback circuit for compensating the nonlinearity of the Wheatstone bridge.

To form the current temperature value over a time series, the "*Repeating Sequence*" model is used, where a sequence of time-temperature values is input. The temperature values are then converted from Simulink format to physical signal data (temperature in K) using the "*Simulink-PS Converter*". These data are sent to the "*Controlled Temperature Source*", which is an ideal energy source in the thermal network that can maintain the controlled temperature difference. From this source, the physical temperature data are sent to the thermistor's T port.

The "*Solver Configuration*" module determines the general modelling parameters.

The "*Amplifier*" group consists of the differential amplifier model "*Fully Differential Op-Amp*" and the ideal operational amplifier model "*Op-Amp*", which provide the necessary voltage gain of the Wheatstone bridge imbalance G.

Using the "*Voltage Sensor*" models, the voltage values at the output of the "*Amplifier*" and across the

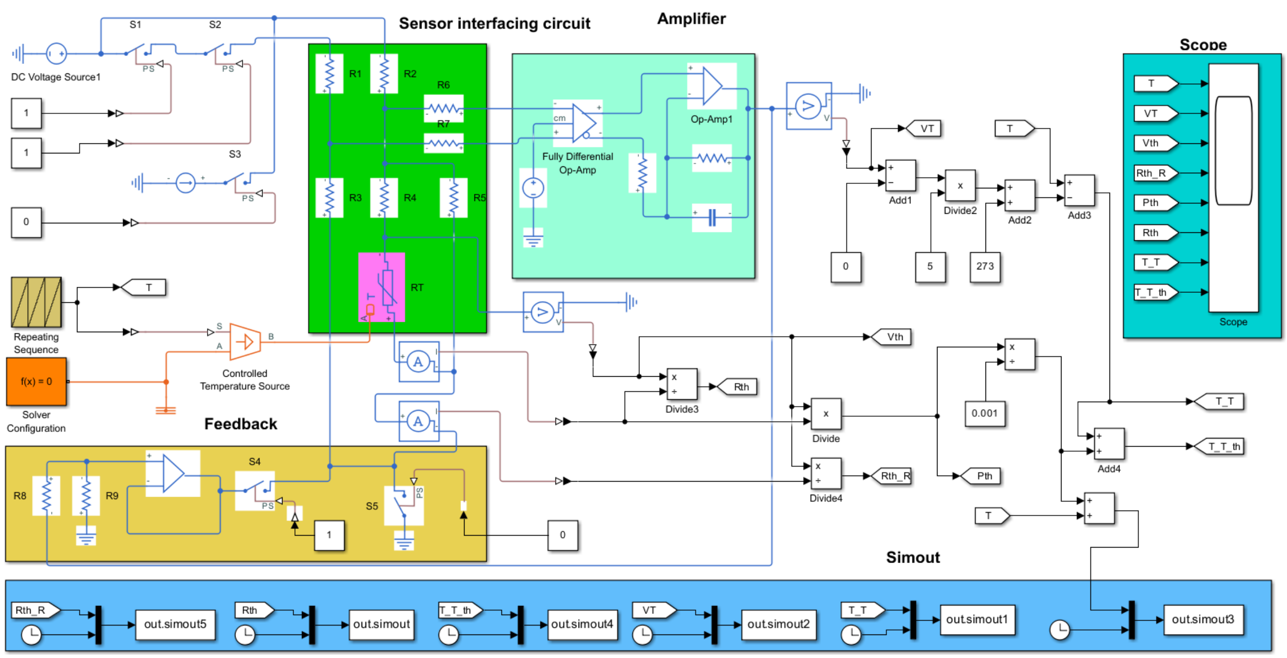



Fig. 6. Measurement channel model in MATLAB Simulink

"Thermistor" at the current time are recorded. Using the "*Current Sensor*" model, the current passing through the thermistor is recorded.

The "*PS-Simulink Converter*" modules convert the input physical electrical signal (voltage or current value) to the output signal in Simulink format. The output signal format in Simulink corresponds to the physical signal format. Then, in Simulink format, mathematical operations for calculating the current value of the thermistor's resistance, its power, and the thermistor's self-heating temperature are performed using the "*Add*" (addition or subtraction) or "*Divide*" (multiplication or division) modules. Constant coefficients and values are input using the "*Constant*" block.

The current voltage value at the output of the "*Amplifier*" is proportional to the set temperature at the current time. Using the "*PS-Simulink Converter*" module, this is converted into an output signal in Simulink format, then multiplied by the necessary coefficient in the "*Divide*" block and converted into the temperature value in K. The calculated self-heating temperature of the thermistor is added to this value. The obtained data of each measured value are recorded by the oscilloscope "*Scope*" and saved to the specified time series or array in the base workspace of MATLAB Simulink using the "*Simout*" module group.

**Research Results**

The research was conducted in two temperature ranges for the thermistor: 298±25 K and 298±15 K, corresponding to the ranges of 0 ... +50 °C and +10 ... +40 °C, respectively. The parameters of the thermistor used were similar to those of the RH18 thermistor from Mitsubishi, with $R = 10\ k\Omega$ (25 °C) and coefficients $B = 3450$ K and $B = 3950$ K. This thermistor has an epoxy resin casing and small dimensions (diameter 1.8 mm, length 7 mm), making it sensitive to self-heating ($\delta_{th} = 1$ mW/°C in air). This allows for the investigation of the effect on measurement errors from linearization methods in different temperature ranges with various $B$ coefficient values, as well as determining correction values from the impact of the thermistor's self-heating effect.

The simulation was carried out using five different interface circuit configurations for connecting the thermistor:

**Variant 1.** The thermistor is placed in one leg of the balanced Wheatstone bridge, where the resistance of the bridge resistors equals the thermistor's resistance at the nominal temperature of 25 °C (R1, R2, R3, $R_{TN} = 10\ k\Omega$). The bridge is powered by a 10 V DC voltage source. Is given by S1 – switch by MATLAB Simulink model, given in Fig. 6.

Fig. 7 shows the error dependence for temperature determination in the temperature ranges from 0 °C to 50 °C and from 10 °C to 40 °C, respectively.

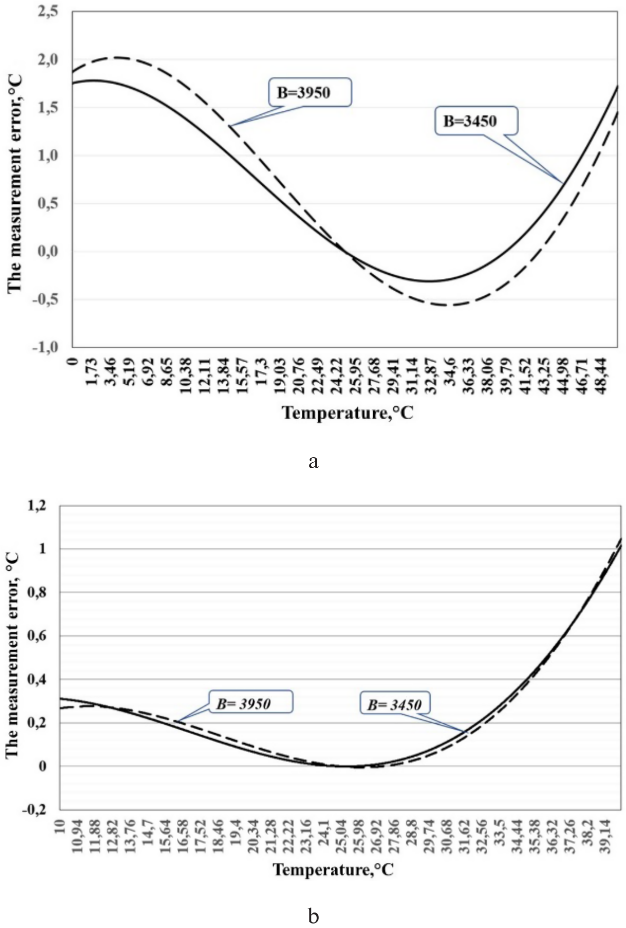
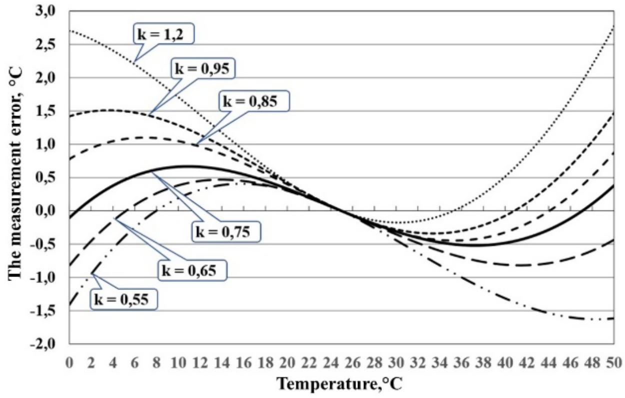


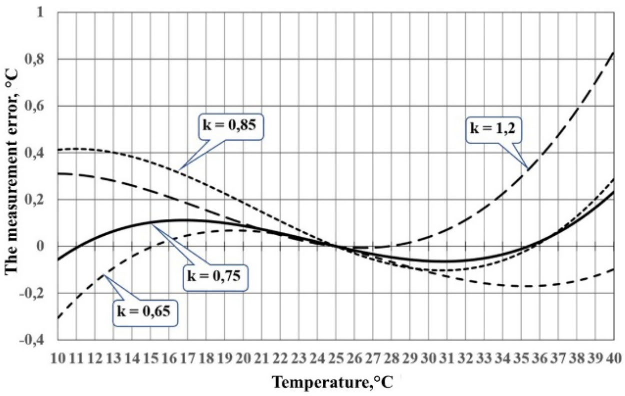

Fig. 7. Dependence of temperature determination error in temperature ranges from 0 °C to 50 °C (a) and from 10 °C to 40 °C (b)

The values of the root mean square (RMS) error in different temperature ranges for different values of the thermistor's B coefficient are shown in the table. These values are used for comparison with the error values when applying other linearization methods.

**Variant 2.** Is given by S2 – switch by MATLAB Simulink model, given in Fig. 6. The thermistor is placed in one leg of the Wheatstone bridge at different resistance ratios of the bridge $\frac{R_1}{R_3} = \frac{R_2}{R_{TN}} = k$. The bridge is powered by a 10 $V$ DC voltage source. It was determined that the minimum error value occurs at $k = 0.75$ in each of the temperature ranges for both values of the thermistor's $B$ coefficient, that is shown in Fig. 8.




a




b

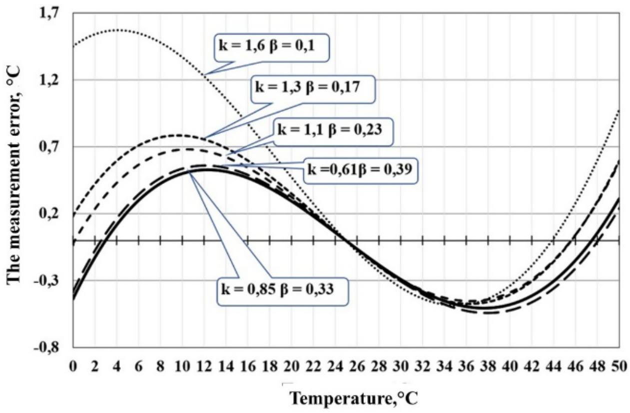
Fig. 8. Dependence of temperature measurement error in the temperature ranges from 0 °C to 50 °C (a) and from 10 °C to 40 °C (b) for the thermistor with $B = 3450$ K

The root mean square (RMS) error values in different temperature ranges for different values of the thermistor's $B$ coefficient at $k = 0.75 \pm 0.05$ are shown in Table 1.

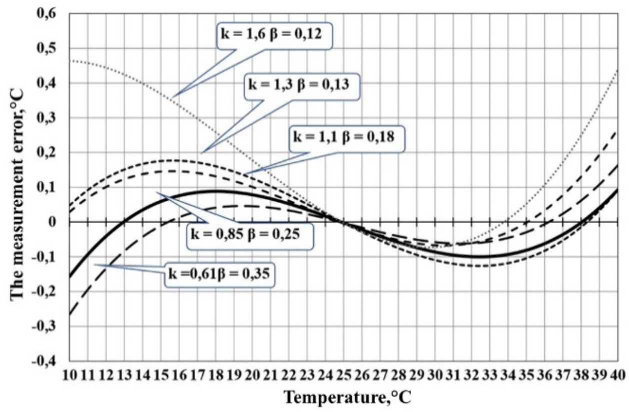
**Variant 3.** Is given by S3 – switch by MATLAB Simulink model, given in Fig. 6. The thermistor is placed in one leg of the Wheatstone bridge with the parallel connection of resistor R5 = 7054 Ω for the thermistor with $B = 3450$ K and R5 = 7378 Ω for the thermistor with $B = 3950$ K (Fig. 9 a, b), at the resistance ratio $\frac{R_1}{R_3} = \frac{R_2}{R_p} = k$, where:

$$R_p = \frac{R_{TN} \times R_5}{R_5 + R_{TN}}. \quad (11)$$

The values of R5 are determined by formula (2). The bridge is powered from a 10 V DC voltage source.




a




b

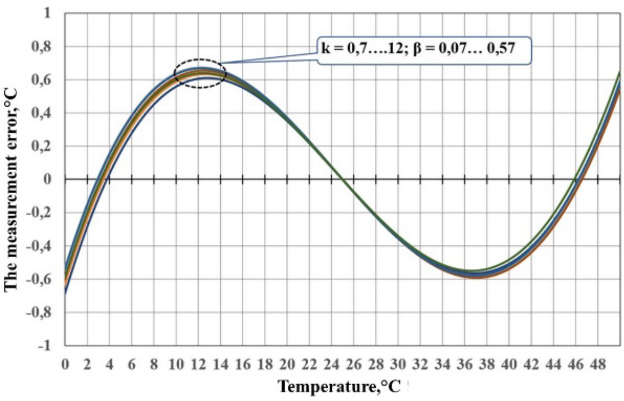
Fig. 9. Dependence of temperature measurement error in the temperature ranges from 0 °C to 50 °C (a) and from 10 °C to 40 °C (b) for the thermistor with $B = 3450$ K

In this variant, the error has a minimum value at $k = 0.85$ in each temperature range and for both values of the thermistor's $B$ coefficient. The root mean square (RMS) error value – σ in different temperature ranges for different values of the thermistor's $B$ coefficient at $k = 0.85 \pm 0.05$ is shown in Table 1.

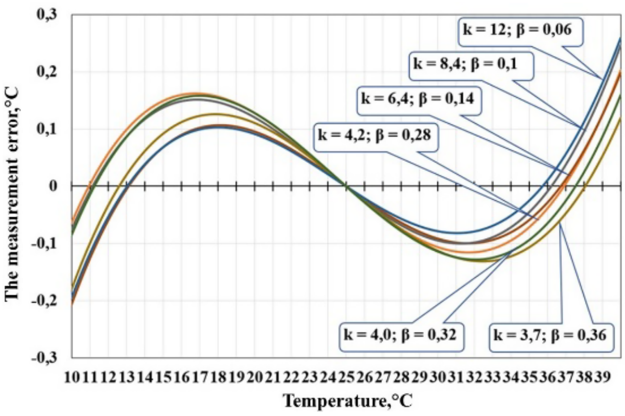
**Variant 4.** The thermistor is placed in one leg of the Wheatstone bridge with the parallel connection of resistor R5 = 7054 Ω for the thermistor with $B = 3450$ and R5 = 7378 Ω for the thermistor with $B = 3950$ (see formula (2)) at the resistance ratio $\frac{R_1}{R_3} = \frac{R_2}{R_p} = k$ (see formula (11)). Is given by S4 – switch by MATLAB Simulink model, given in Fig. 6. For linearizing the bridge characteristic, feedback is introduced on the operational amplifier with a feedback coefficient β, which is equal to:

$$\beta = \frac{R_9}{R_9 + R_8}. \quad (12)$$

The bridge is powered with a 10 V DC voltage source. In this case, that's shown in Fig. 10, the error has approximately the same value for $k$ from 0.7 to 12 in each temperature range and for both values of the thermistor's $B$ coefficient.




a




b

Fig. 10. Dependence of temperature measurement error in the temperature ranges from 0 °C to 50 °C (a) and from 10 °C to 40 °C (b) for the thermistor with $B = 3950$ K

The average value of the root mean square (RMS) error – σ in different temperature ranges for different values of the thermistor's $B$ coefficient is shown in the table. With an increase in $k$, the gain coefficient of the differential amplifier G increases, while the feedback coefficient β decreases.

**Variant 5.** Is given by S5 – switch by MATLAB Simulink model, given in Fig. 6. The thermistor is directly connected to the input «–» of the amplifier with the parallel connection of resistor R5 = 7054 Ω (R4 = 0 Ω) for the thermistor with $B = 3450$ K and R5 = 7378 Ω for the thermistor with $B = 3950$ K. The thermistor is powered through a resistor from a constant current source from 300 μA to 1 mA via resistor R2 = 4154 Ω for the thermistor with $B = 3450$ K and R2 = 4246 Ω for the thermistor with $B = 3950$ K. The value of R2 corresponds to the value of $R_p$ (see formula (7)), then $k = 1$. The «+» input of the amplifier is connected to a voltage divider $\frac{R_1}{R_3} = k = 1$. The voltage source of this divider is a constant DC voltage source of 10 V.

In this variant, the thermistor is powered through a resistor from a constant current source from 300 μA to 1 mA. Regardless of the current value, the RMS error in each temperature range remains unchanged. As the current value increases, the gain coefficient of the amplifier $G$ decreases and the correction value $U$ – the offset voltage, or $T$ – the temperature correction value for compensating the self-heating effect of the thermistor increases.

The generalized data of the research results are presented in Table 1. The results of the research for five circuit-technical methods of linearization of the temperature characteristics of NTC-thermistors provide an opportunity to evaluate the effectiveness of the application of different variants of circuit-technical methods of linearization of the temperature characteristics of NTC-thermistors and the characteristics of the measuring channels.

Notes: 1 – The range of $k$, where $k = \frac{R_2}{R_p}$ ($R_p$ is calculated using formula (7)); 2 – The average value of RMS in the range of $k$; 3 – The value increases as $k$ decreases; 4 – The value increases as $k$ decreases; 5 – For current values of the current source from 300 μA to 1 mA; 6 – The average value of RMS for current source values from 300 μA to 1 mA; 7 – The value increases as the current source current decreases; 8 – The value decreases as the current source current decreases.

## Conclusions

In the conducted study, a structural-mathematical model of the measurement channel in MATLAB Simulink was developed to study different methods of linearizing the temperature characteristics of NTC-thermistors and the measurement channel. After modelling, graphical dependencies of the temperature measurement error were obtained in the temperature ranges from 0 °C to 50 °C and from 10 °C to 40 °C for thermistors with values of $B = 3450$ K and 3950 K, using several methods for linearizing the temperature characteristics of NTC-thermistors and the measurement channel. The smallest error value was achieved by using the method of linearizing the temperature characteristic

***Table* 1.** The results of the study for five circuit-based methods of linearizing the temperature characteristics of NTC-thermistors

| Variant | $k$ | $B$, K | $\Delta T$, K | Without self-heating thermistor | | | Taking into account the self-heating temperature of the thermistor in air | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | σ, K | Parameters | | σ, K | Amendments | | | |
| | | | | | G | β | | G | β | $U$, B | $T$, K |
| 1 | 1 ±0.05 | 3450 | ±25 | 0.74 | 1.5 | – | 0.61 | 0 | – | –0.53 | –2.65 |
| | | | ±15 | 0.24 | 1.4 | – | 0.20 | 0 | – | –0.53 | |
| | | 3950 | ±25 | 0.92 | 1.35 | – | 0.80 | 0 | – | –0.52 | –2.6 |
| | | | ±15 | 0.24 | 1.35 | – | 0.19 | 0 | – | –0.52 | |
| 2 | 0.75 ±0.05 | 3450 | ±25 | 0.41 | 1.55 | – | 0.41 | +0.05 | – | –0.7 | –3.5 |
| | | | ±15 | 0.07 | 1.45 | – | 0.09 | +0.02 | – | –0.7 | |
| | | 3950 | ±25 | 0.39 | 1.35 | – | 0.54 | +0.04 | – | –0.7 | |
| | | | ±15 | 0.07 | 1.4 | – | 0.09 | +0.03 | – | –0.7 | |
| 3 | 0.85 ±0.05 | 3450 | ±25 | 0.36 | 2.2 | 0.33 | 0.35 | +0.16 | 0 | –1.0 | –5 |
| | | | ±15 | 0.07 | 2.1 | 0.25 | 0.07 | 0 | 0 | –1.0 | |
| | | 3950 | ±25 | 0.41 | 2.0 | 0.30 | 0.41 | +0.16 | 0 | –0.97 | –4.85 |
| | | | ±15 | 0.08 | 1.5 | 0.17 | 0.09 | +0.06 | 0 | –0.96 | –4.8 |
| 4 | 0.7 … 12[1] | 3450 | ±25 | 0.35[2] | 4.3...13.1[3] | 0.07...0.57 | 0.37[2] | 0...+0.2[4] | 0 | 0...–0.65[4] | 0...–3.25[4] |
| | | | ±15 | 0.09[2] | 4.0...12.6[3] | 0.06...0.36 | 0.08[2] | 0...+0.3[4] | 0 | 0...–0.62[4] | 0...–3.1[4] |
| | | 3950 | ±25 | 0.44[2] | 3.7...11.2[3] | 0.07...0.41 | 0.46[2] | 0...+0.25[4] | 0 | 0...–0.62[4] | |
| | | | ±15 | 0.1[2] | 3.5...10.6[3] | 0.07...0.41 | 0.1[2] | 0...+0.3[4] | 0 | 0...–0.62[4] | |
| 5 | 1 | 3450 | ±25 | 0.31[6] | 2.1...7.2[7] | – | 0.33[6] | 0...–0.17[8] | – | 0...–0.2[8] | 0...–1[8] |
| | | | ±15 | 0.07[6] | 2.0...7.0[7] | – | 0.07[6] | 0...–0.1[8] | – | 0...–0.2[8] | |
| | | 3950 | ±25 | 0.47[6] | 1.9...6.4[7] | – | 0.45[6] | 0...–0.1[8] | – | 0...–0.2[8] | |
| | | | ±15 | 0.09[6] | 1.8...6.9[7] | – | 0.08[6] | 0...–0.1[8] | – | 0...–0.2[8] | |

of the NTC-thermistor with a parallel resistor connection and introducing feedback to the Wheatstone bridge (variant 4). Additionally, the minimum error is achieved by applying variant 5 of the thermistor connection – connecting it to a DC source with linearization of the characteristic by connecting a parallel resistor. This method has the drawback of requiring high accuracy in the current value of the current source. The measurement error when applying these methods is reduced approximately two times compared to the error obtained when connecting the thermistor in a balanced Wheatstone bridge arm (variant 1). As the $B$ coefficient of the thermistor increases, the error increases for all the specified methods, while narrowing the temperature range reduces the error. Thus, in the temperature range of ±15 °C, measurement accuracy can reach less than 0.1 °C (RMS).

As the coefficient $k$ decreases, i.e., when the current flowing through the thermistor increases, the self-heating temperature of the thermistor increases, introducing an error in the measurement. Except in cases where this phenomenon is used [14, 15, 16], the current value should be kept at a minimum – less than 100 μA.

As seen from the obtained modelling results, this mathematical model can be used to investigate various temperature measurement circuits, select the circuit, and determine the optimal characteristics of the measurement channel elements to achieve maximum accuracy and meet the required specifications.

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## АНАЛІЗ СХЕМОТЕХНІЧНИХ МЕТОДІВ ЛІНЕАРИЗАЦІЇ ТЕМПЕРАТУРНИХ ХАРАКТЕРИСТИК NTC-ТЕРМІСТОРІВ І ХАРАКТЕРИСТИК ВИМІРЮВАЛЬНОГО КАНАЛУ

**Проблематика.** Пристрої вимірювання температури відіграють важливу роль для автоматизації різних систем і моніторингу різних фізико-хімічних параметрів. Як сенсори використовують терморезистори, термістори або термопари. Утім, нелінійна температурна характеристика термісторів створює труднощі для точного перетворення температури в електричний сигнал, тому питання лінеаризації вихідної характеристики вимірювального каналу пристрою для вимірювання температури залишається актуальним досі. Завдання лінеаризації температурної залежності вимірювального каналу може бути вирішене апаратними (схемотехнічними), програмними та апаратно-програмними методами.

**Мета дослідження.** Метою роботи є аналіз ефективності схемотехнічних методів лінеаризації температурних характеристик термісторів NTC-типу, а також їх впливу на загальну характеристику вимірювального каналу.

**Методика реалізації.** Розроблено структурну модель пристрою для вимірювання температури із сенсором на основі термістора у середовищі MATLAB Simulink. Проведено аналіз п'яти схемотехнічних способів підключення термістора до вимірювального каналу з метою дослідження ефективності лінеаризації у межах температурних діапазонів ±15 °C та ±25 °C. На основі запропонованих способів підключення термістора здійснено моделювання температурних характеристик NTC-термісторів.

**Результати дослідження.** Результати досліджень для п'яти схемотехнічних способів лінеаризації температурних характеристик NTC-термісторів надають можливість оцінити ефективність застосування різних варіантів схемотехнічних методів лінеаризації температурних характеристик NTC-термісторів і характеристик вимірювального каналу у двох температурних діапазонах: ±15 °C та ±25 °C. На основі поданого моделювання можна стверджувати, що за рахунок застосування вказаних схемотехнічних способів лінеаризації температурних характеристик NTC-термісторів і характеристик вимірювального каналу можна зменшити похибку вимірювання на 40 % в обмеженому діапазоні температур порівняно з використанням збалансованого вимірювального мосту, і визначити потрібні корекційні заходи для компенсації ефекту саморозігріву термістора.

**Висновки.** За рахунок моделювання схемотехнічних способів лінеаризації температурних характеристик NTC-термісторів надано можливість оцінювати результативність лінеаризації температурної залежності вимірювального каналу, досліджуючи при цьому різноманітні варіанти підключення до вимірювального каналу термістора, а також визначити параметри елементів вимірювального каналу пристрою для вимірювання температури.

**Ключові слова**: вимірювання температури; NTC-термістор; MATLAB Simulink; лінеаризація.

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