ПРОБЛЕМНО І ФУНКЦОНАЛЬНО ОРІЄНТОВАНІ КОМП'ЮТЕРНІ СИСТЕМИ ТА МЕРЕЖІ

UDC 536.531
DOI: 10.20535/SRIT.2308-8893.2026.1.04

POLYNOMIAL-BASED METHOD FOR LINEARIZING THE TEMPERATURE RESPONSE OF NTC THERMISTORS

S.N. MATVIENKO, G.S. TYMCHYK

Abstract. The objective of this research is to develop a circuit-based method for linearizing the temperature characteristics of thermistors using a polynomial digital technique for NTC-thermistor temperature characteristics, together with the characteristics of the designed measurement channel, by means of an original MATLAB Simulink model. A model of a temperature-measurement device employing a thermistor-based sensor is proposed. The polynomial digital method for linearizing the temperature characteristics of NTC thermistors in the developed device has been simulated. To improve measurement accuracy, the components of the measurement channel were selected such that they enable simulation with minimal error. Methods for introducing correction-coefficient values into the model have been determined to compensate for error-inducing factors, including the thermistor's self-heating effect. The proposed data-processing algorithm offers advantages for implementation in a low-cost, low-power microcontroller.

Keywords: temperature measurement, NTC thermistor, MATLAB Simulink, linearization.

INTRODUCTION

Temperature measurement devices play a critical role across various industrial and consumer domains, particularly within Internet of Things (IoT) networks that leverage Smart technologies, including smart cities, smart homes/digital houses, smart grids, and smart sensors. A fundamental requirement for temperature sensors in such applications is high measurement accuracy over a wide temperature range, which is primarily determined by the type and characteristics of the sensor.

Negative Temperature Coefficient (NTC) thermistors are widely employed as temperature sensors due to their broad operational temperature range, capability for remote monitoring, resistance to strong magnetic fields, and compact physical dimensions. However, one of the primary limitations of thermistors, shared by many sensor types — is the nonlinear nature of their resistance–temperature characteristic $R(T)$, which adversely affects measurement accuracy.

Additionally, the transfer characteristics of the thermistor interface circuitry and the voltage signal amplifier are also nonlinear. Since nonlinearities introduce measurement errors, improving the linearity of the transfer function of the entire measurement channel is essential for achieving high accuracy. The task of linearizing the temperature dependence of a measurement system can be addressed through analog, digital (software-based), or mixed hardware-software digital techniques.

Analog methods can reduce measurement error to some extent but typically only within a narrow temperature range. In contrast, digital linearization techniques not only improve measurement accuracy but also significantly extend the effective temperature measurement range. These techniques are implemented via software or through the use of analog-to-digital interface circuits that generate a linear signal response.

Among analog approaches, passive compensation networks are the most common; they enable the creation of quasi-linear segments on the $R(T)$ curve within specific temperature intervals. Analog methods are generally more cost-effective compared to digital techniques, which require microcontrollers, field-programmable gate arrays (FPGAs), digital signal processors (DSPs), or personal computers. Nevertheless, digital methods provide a substantial improvement in accuracy over a wider temperature range.

With advancements in digital signal processing and the availability of increasingly capable digital integrated circuits, the implementation of such methods has become significantly more practical and accessible.

RELEVANCE OF THE WORK

Increasing the accuracy of temperature measurement is achieved by optimizing the design of the measuring probe and selecting the appropriate characteristics of the thermistor. Accuracy can also be increased by setting the optimal parameters for the measuring channel and implementing effective digital data processing algorithms. During the design phase of a temperature measurement device, it is essential to conduct mathematical modeling to determine the optimal linearization method, select component parameters, and define the appropriate data processing algorithm.

The development of mathematical models enables the identification of suitable characteristics for the components of the measurement channel and the data processing algorithms, tailored to the specific requirements of the application. In this research, a custom-designed model implemented in MATLAB Simulink is used to investigate a digital method for linearizing the device characteristics by applying polynomial functions to the measured data. The model facilitates the estimation of measurement errors and the development of calibration recommendations aimed at improving overall measurement accuracy.

ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

Linearized sensor characteristics significantly simplify the design and calibration processes and improve measurement accuracy. To compensate for the inherent nonlinearity of thermistor characteristics and the measurement channel, both analog and digital linearization methods have been widely reported in the literature. Researches such as [1–3] provide an in-depth analysis of these techniques and offer a comprehensive overview of various approaches used for sensor characteristic linearization.

It is noted that digital methods, particularly when combined with software-based processing, yield superior results in terms of flexibility and performance. Software algorithms implemented in digital systems have proven to be more effective, practical, and adaptable than traditional analog methods. Common software-based linearization techniques include spline fitting, polynomial curve approximation, and advanced intelligent methods such as artificial neural networks (ANNs) [4].

Among these, the use of polynomial functions remains the most widespread technique for correcting measured data [1]. A single high-order polynomial can be used to model the full sensor response. However, to reduce computational complexity, the entire temperature range is often divided into smaller sub-ranges, each approximated with a lower-order polynomial. This segmentation improves processing efficiency without sacrificing accuracy.

Additionally, alternative enhanced techniques based on lookup tables are also employed, including piecewise linear interpolation (PWLI), piecewise linear equations (PWLE), and programmable gain amplifiers (PGA) [1]. In PWLE, the processor selects the appropriate linear equation based on the input value and retrieves stored coefficients from memory. In some implementations, the processor dynamically determines the applicable linear equation for each measurement based on pre-calibrated data points.

Depending on the complexity of the data processing algorithm, various hardware platforms can be used, such as microcontrollers, FPGAs, DSPs, or PCs. More complex algorithms typically require higher-cost solutions and result in increased power consumption. A comparison of selected algorithms can be found in [5]. Therefore, it is critical to choose the most suitable linearization approach and its hardware implementation based on the specific performance requirements of the temperature measurement device.

Mathematical modeling of the device and its linearization method can significantly streamline the design process, enabling efficient selection of component parameters and processing algorithms to meet the required accuracy specifications. Manufacturer-provided models [6–8] are also beneficial in selecting appropriate thermistor types for specific applications and offer detailed characteristic data that can be used to address $R(T)$ nonlinearity.

Researchers and engineers have proposed a wide range of algorithms to address the nonlinearity problem of the $R(T)$ characteristic [1; 3–5; 9–11]. Given the diversity of available digital linearization techniques, selecting the optimal algorithm and its hardware implementation can be challenging and depends on the specific application requirements.

During the modeling stage, it is essential to evaluate the achievable measurement accuracy, the impact of hardware element characteristics, and the feasibility of implementing calibration procedures. In this research, a classical linearization approach is explored, using polynomial correction of measured data with segmentation of the full measurement range into smaller sub-ranges. This approach reduces the required polynomial order, thereby lowering the computational load on the processing hardware. Consequently, cost-effective microcontrollers can be used, and device calibration functionality can be feasibly integrated into the system.

Therefore, **the purpose of our work** is to develop a mathematical model of the measurement channel of a temperature sensing device based on an NTC thermistor within the MATLAB/Simulink environment. Using the developed model of digital linearization methods for NTC thermistor temperature characteristics — based on polynomial approximations — it is intended to determine the required specifications of the components within the measurement channel. Additionally, an analysis of the sources of measurement error will be conducted to improve temperature measurement accuracy across a wide temperature range.

The aim of this work is to investigate digital methods for linearizing the temperature characteristics of NTC thermistors and the associated measurement channel components using the developed simulation models.

RESEARCH METHODOLOGY AND RESULTS

Measuring temperature using an NTC thermistor involves using the dependence of the thermistor's 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 [12]:

$$R(T) = R_N \exp\left[\mathrm{B}\left(\frac{1}{T} - \frac{1}{T_N} \right) \right], \tag{1}$$

where $R(T)$ — *is* the resistance of the NTC thermistor at temperature *T* in *K*; R_N — NTC thermistor resistance at nominal temperature T_N in *K*; *T* — the current temperature (in *K*) value at which the thermistor resistance R_N is calculated; T_N — nominal temperature (in *K*), i.e. the reference or standard temperature at which the nominal resistance of the thermistor is known; *B* — is a constant coefficient that depends on the thermistor material in *K*.

This dependence is nonlinear, which creates certain difficulties in creating temperature measurement devices and introduces additional error. The value of the error will depend on the linearization method used.

Fig. 1 shows the developed structural and mathematical model of a device for measuring temperature using an NTC thermistor in the MATLAB Simulink environment.

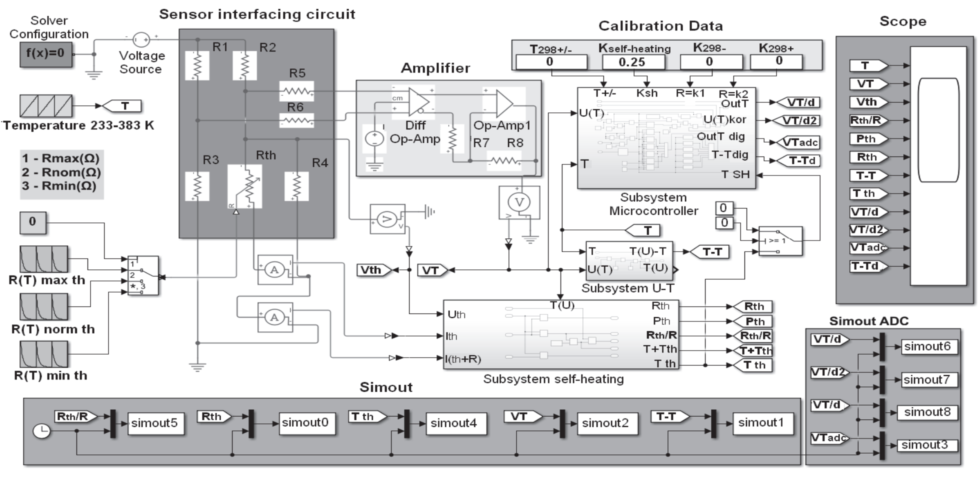

Fig. 1. Functional diagram of a temperature measurement device in the MATLAB Simulink environment

The model consists of 2 groups of blocks for modeling the electrical circuit of the measuring channel, these are the sensor interface group “*Sensor interfacing circuit*” and the “*Amplifier*” group, 3 software modules “*Subsystem*” — “*Subsystem Microcontroller*”, “*Subsystem U-T*” and “*Subsystem self-heating*”.

The group “*Sensor interfacing circuit*” is a diagram of connecting the thermistor model — R_{th} to the differential amplifier model “*Fully Differential Op-Amp*” of the group “*Amplifier*” using a correspondingly configured diagram of connecting the resistor models “*Resistor*” *R1,.. R6*.

R_{th} can be connected to the Wheatstone bridge arm *R1*, *R2*, *R3*, R_{th} to the “*Fully Differential Op-Amp*”. The Wheatstone bridge arms *R1-R3* and *R2-* R_{th} are connected to the “*Voltage Source*” model.

In the MATLAB Simulink environment there is a model “*Thermistor*” in the library that simulates the operation of a thermistor according to the set parameters, but in this model the resistance of the thermistor is calculated by formula (1) depending on the temperature. In a real thermistor, the coefficient *B* is not a constant value, but varies depending on the temperature. Fig. 2 shows the difference between the $R(T)$ characteristic of the thermistor of the “*Thermistor*” MATLAB Simulink model and the characteristic built from tabular data for a thermistor type RH18 6Y103 Mitsubishi Materials.

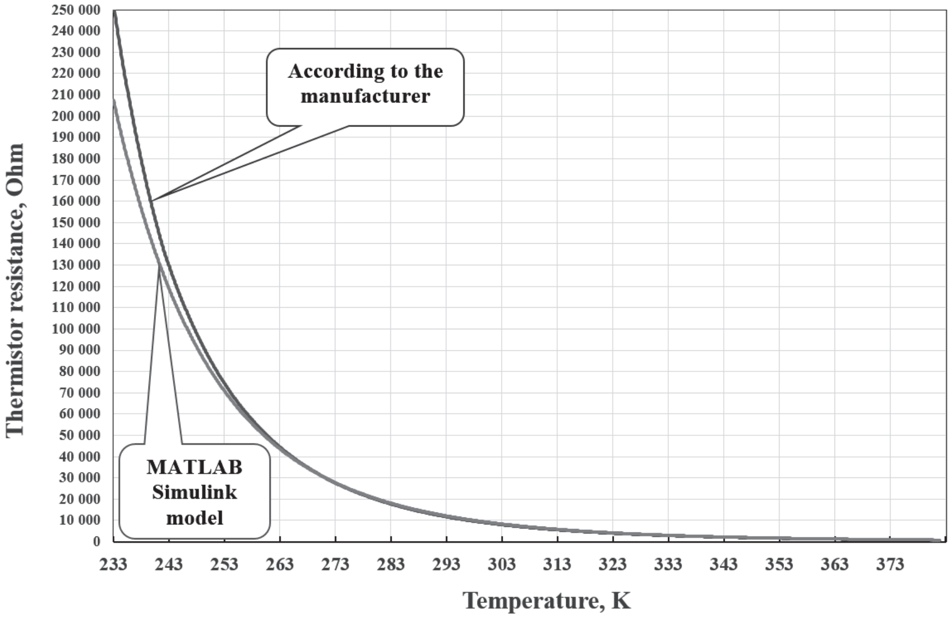

Fig. 2. Graph of the difference in $R(T)$ characteristics for the thermistor model “Thermistor” and tabulated data for the thermistor type RH18 6Y103 Mitsubishi Materials in the range from 233 *K* to 383 *K*

If the thermistor is used within a narrow temperature range and moderate measurement accuracy is acceptable, the built-in “*Thermistor*” block in MATLAB Simulink may be employed for modeling purposes. However, when the temperature range is wide and high measurement accuracy is required, the simulation should rely on tabulated data provided by the manufacturer for the specific thermistor type.

In the presented model, the thermistor is implemented using the “*Variable Resistor*”, whose resistance is defined based on the manufacturer’s tabular data via three “*Repeating Sequence*” blocks. These sequences correspond to the nominal, minimum, and maximum resistance values of the thermistor. The resistance value used in the simulation “R_{max}”, “R_{nom}” and “R_{min}” is selected using switch S1.

To convert the temperature value measured by the thermistor into a corresponding voltage output, a widely adopted namely “*Sensor interfacing configuration*”, the Wheatstone bridge (Fig. 1) — is utilized. To reduce the nonlinearity of the thermistor’s resistance-temperature characteristic $R(T)$, a circuit-level linearization technique is applied by connecting a resistor *R4* in parallel with the thermistor (Fig. 1). This approach minimizes the deviation between the linearized and actual nonlinear characteristics of the “*Sensor interfacing circuit*” output, thereby enhancing the accuracy of polynomial correction methods.

The resistance of the parallel resistor used to linearize the $R(T)$ characteristic is determined according to the following formula [13]:

$$R_4 = R_{thN} \times \frac{B - 2T_N}{B + 2T_N},$$

where R_4 — resistance of a parallel-connected resistor, Ohm; R_{thN} — NTC thermistor resistance at nominal temperature T_N in *K*; *T*, T_N — temperature in *K*; *B* — is a constant coefficient that depends on the thermistor material in *K*.

The total resistance of a thermistor with a resistor connected in parallel is determined by the formula:

$$R_p = \frac{R_{thN} \times R_4}{R_4 + R_{thN}}.$$

For thermistor RH18 6Y103F Mitsubishi Materials with $B_{25/85}$ = 3435 *K* and resistance 10 kOhm±1% at temperature T_N = 298 *K* (25 °*C*) R_4 = 7043 Ohm a R_p =4142 Ohm.

The “*Amplifier”* group consists of the “*Fully Differential Op-Amp*” and the ideal operational amplifier model “*Op-Amp*”, which together provide the required voltage gain *G* for the Wheatstone bridge imbalance signal.

The software module “*Subsystem U-T*” is used to obtain the uncorrected analog signal, whose voltage is proportional to the measured temperature. This output is necessary for evaluating the effectiveness of the digital linearization method. The block diagram of the “*Subsystem U-T*” module is shown in Fig. 3, *a*.

The instantaneous voltage at the output of the “*Amplifier*” block, which is proportional to the set temperature, is converted by the “*PS-Simulink Converter*” into a signal compatible with the Simulink environment. This signal is then scaled using the “*Divide*” block by an appropriate gain coefficient and converted into the corresponding temperature value in *K*. The computed thermistor self-heating temperature, determined by the “*Subsystem self-heating*”, is then added to this value.

The “*Subsystem self-heating*” module is employed to calculate the self-heating temperature of the thermistor as a function of its operating temperature.

The internal structure of this module is depicted in Fig. 3, *b*.

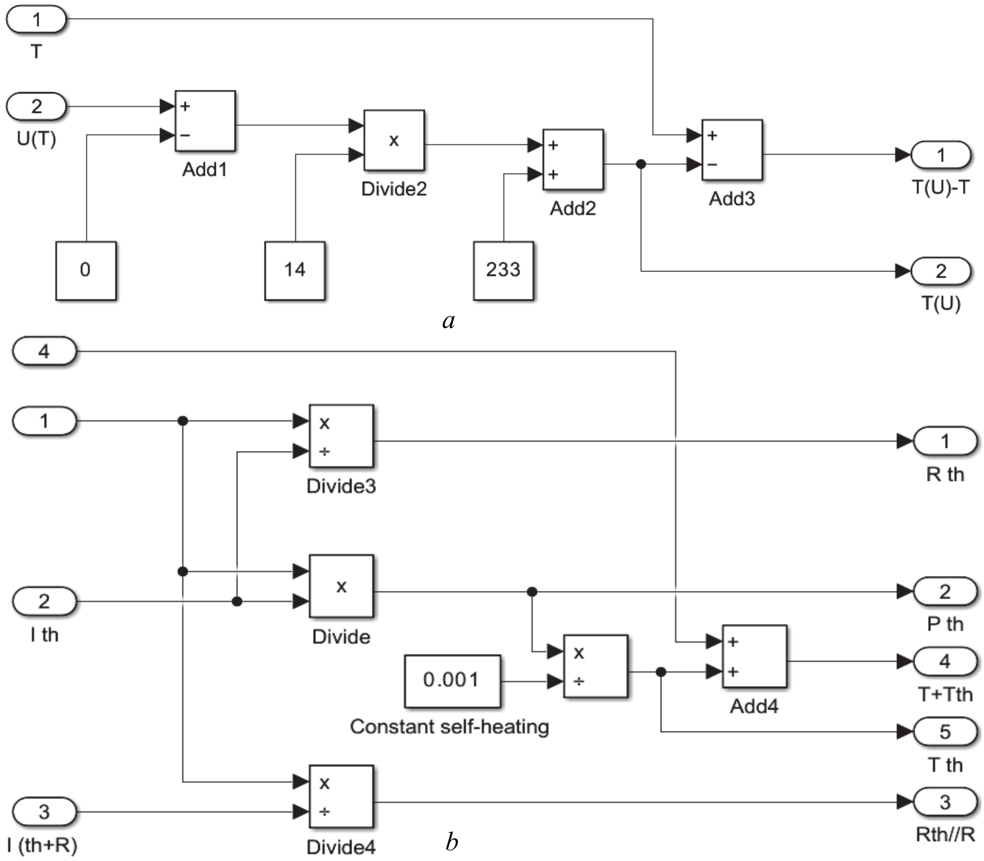

Fig. 3. Functional diagram “*Subsystem UT*” of the device module — *a*; functional diagram of the “*Subsystem self-heating*” device module — *b*

The thermistor’s self-heating temperature is influenced by the magnitude of the current flowing through it, the materials and structural design of the sensor, as well as the thermal conductivity of the surrounding medium [12; 14]. This phenomenon is utilized in devices for measuring thermophysical properties of materials [15–17], as well as in systems for determining fluid flow velocity [18].

Self-heating in NTC thermistors causes an additional decrease in their resistance, which leads to distortion in the measurement result. Therefore, in temperature measurement systems, a correction must be applied to the measured value. This correction is computed using the following formula:

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

where T_N — actual value of the controlled temperature; T — Measured temperature value; U — instantaneous value of the voltage on the thermistor, I — instantaneous value of the current flowing through the thermistor; $R(T)$ — the value of the resistance of the thermistor corresponding to the temperature T; δ_{th} — heat dissipation coefficient in the measuring medium.

Using the voltage sensor model “*Voltage Sensor*” the voltage values on the “*Variable Resistor*” at the current time are recorded, and using the current sensor models "*Current Sensor*" the current value passing through the "*Variable Resistor*" is recorded. From these data, the self-heating temperature of the thermistor for air is determined by formula (2). This data is used to correct the measurement data in the "*Subsystem Microcontroller*" module.

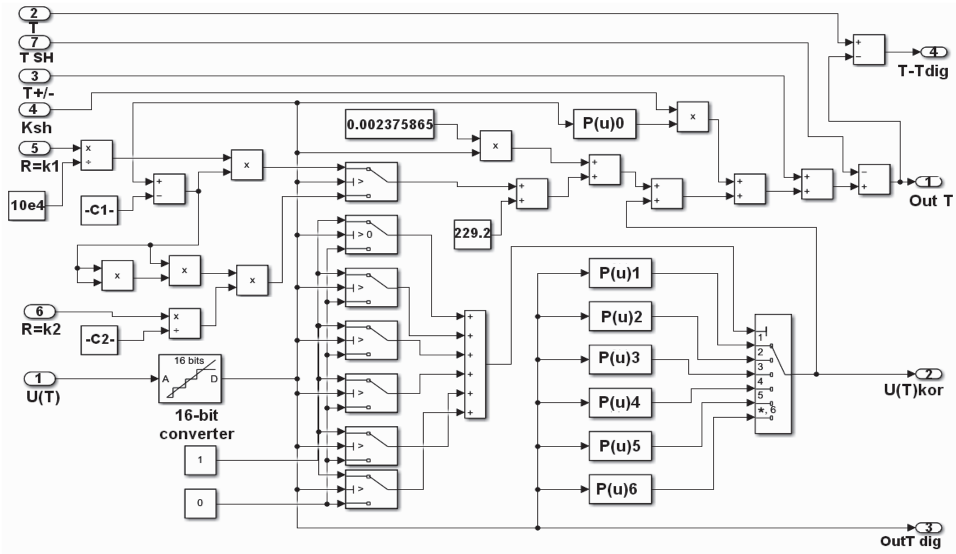

Fig. 4. Functional diagram of the "Subsystem Microcontroller" device module

For correction of measured data in the "*Subsystem Microcontroller*" module "*The model implements*" a digital linearization algorithm using polynomials with the division of the full measurement range into small subranges. Fig. 4 shows a model of the software module "*Subsystem Microcontroller*".

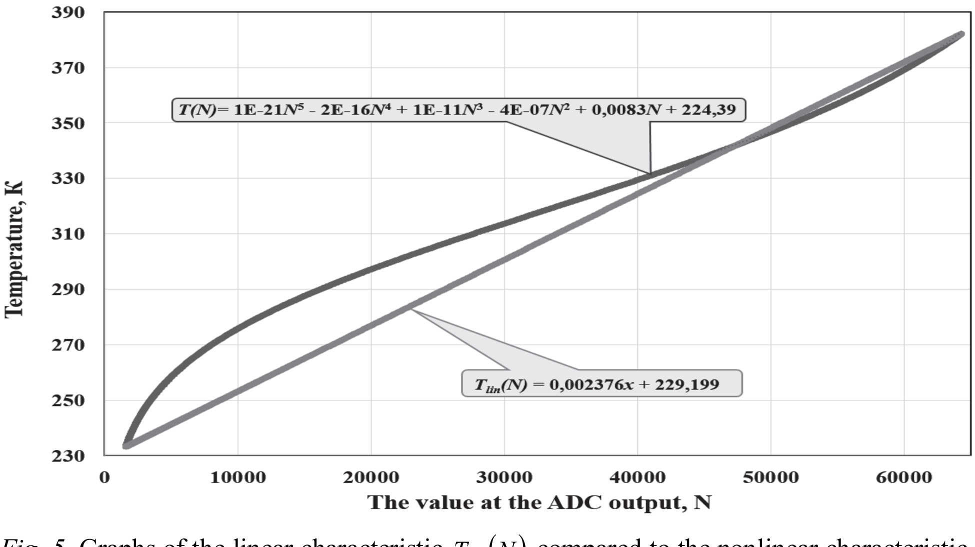

Fig. 5. Graphs of the linear characteristic $T_{lin}(N)$ compared to the nonlinear characteristic $T(N)$

N by means of a 16-bit ADC "*Idealized ADC quantizer*". Due to the nonlinearity $R(T)$ of the thermistor characteristic, the nonlinear transfer characteristic of the Wheatstone bridge circuit, the differential amplifier and the ADC, the characteristic of the source code at the ADC output is $N(T)$ will also be nonlinear. The task of the "Subsystem Microcontroller" module is to form a linear characteristic $T_{lin}(N)$.

Fig. 5 shows the generated linear characteristic $T_{lin}(N)$ compared to the non-linear characteristic $T(N)$.

Formation of linear characteristic $T_{lin}(N)$ so that it connects the starting point of the nonlinear characteristic $T(N)$, when the value at the ADC output $N_{\min}$ corresponds to the temperature $T_{\min} = 233\ K$, and the end point of the range, when the value at the ADC output $N_{\max}$ corresponds to the temperature $T_{\max} = 383\ K$, i.e., it corresponds to the expression:

$$T_{lin}(N) = a \times N + T_{\min},$$

where a — characteristic slope coefficient, which is determined by the formula:

$$a = \frac{T_{\max} - T_{\min}}{N_{\max} - N_{\min}}.$$

Then, for the correcting function should be equal to:

$$\Delta T(N) = T(N) - T_{lin}(N).$$

That is, to obtain the measured temperature value at the output of the "*Microcontroller Subsystem*" module, it is necessary to add to the calculated temperature value by the linear function $T_{lin}(N)$ the correction value at point N, which corresponds to ΔT at point N. This value can be calculated using the polynomial function:

$$P(N) = c_n N^n + c_{n-1} N^{n-1} + c_{n-2} N^{n-2} + \dots + c_1 N^1 + c_0$$

where $c_n, c_{n-1}, c_{n-2}, \dots c_1, c_0$ — polynomial coefficients, which are determined by the polynomial trend line of the function $\Delta T(N)$. In this model, this is done using Excel using saved time series data or an array in the basic MATLAB workspace by the "*Simout ADC*" module group.

Therefore, to calculate the measured temperature value at the output of the "*Microcontroller Subsystem*" module, the value of the polynomial $P(N)$ at point N is added to the calculated temperature value according to the linear function $T_{lin}(N) = a \times N + T_{\min}$, which corresponds to the value of ΔT at point N, and therefore the measured temperature value is equal to:

$$T(N) = a \times N + T_{\min} + P(N).$$

To do this, the value N from the ADC output is fed to 6 polynomial evaluation modules, which calculate the value of the polynomial $P(N)$ with a given polynomial array of coefficients c depending on the value of N. The polynomial array of coefficients for each of the subranges is determined separately. Depending on the current value of N, the corresponding module $P(u)$ is connected, where the value of the polynomial $P(u)$ is cleared with the corresponding subrange given polynomial array of coefficients. These values are added to the formed linear characteristic $T_{lin}(N)$. Also, the "*Microcontroller Subsystem*" module implements the possibility of correcting the output characteristic according to the calibration results, and introducing correction coefficients for the self-heating correction of the thermistor depending on the thermal conductivity of the environment.

The "*Solver Configuration*" module defines general simulation parameters. The obtained data of each of the obtained values is recorded by the oscilloscope "*Scope*" (Fig. 6) and entered using the "*Simout*" module group into the specified time series or array in the basic MATLAB workspace for further data processing.

"*Calibration Data*" block consists of "*Constant*" modules, in which the values of the coefficients K_{298-}, K_{298+} and $T_{298+/-}$ and $K_{self-heating}$, which allows the calibration data to be used to adjust the original measurement data accordingly to compensate for the influence of possible causes of error.

To generate the current temperature value over a time series, the "*Repeating Sequence*" model is used, where a sequence of numbers time-temperature value is entered. Next, the temperature values are converted from Simulink format to physical signal data-temperature in *K* using the "*Simulink-PS Converter*". This data is used to compare the measured temperature value with the set value corresponding to the current thermistor resistance value.

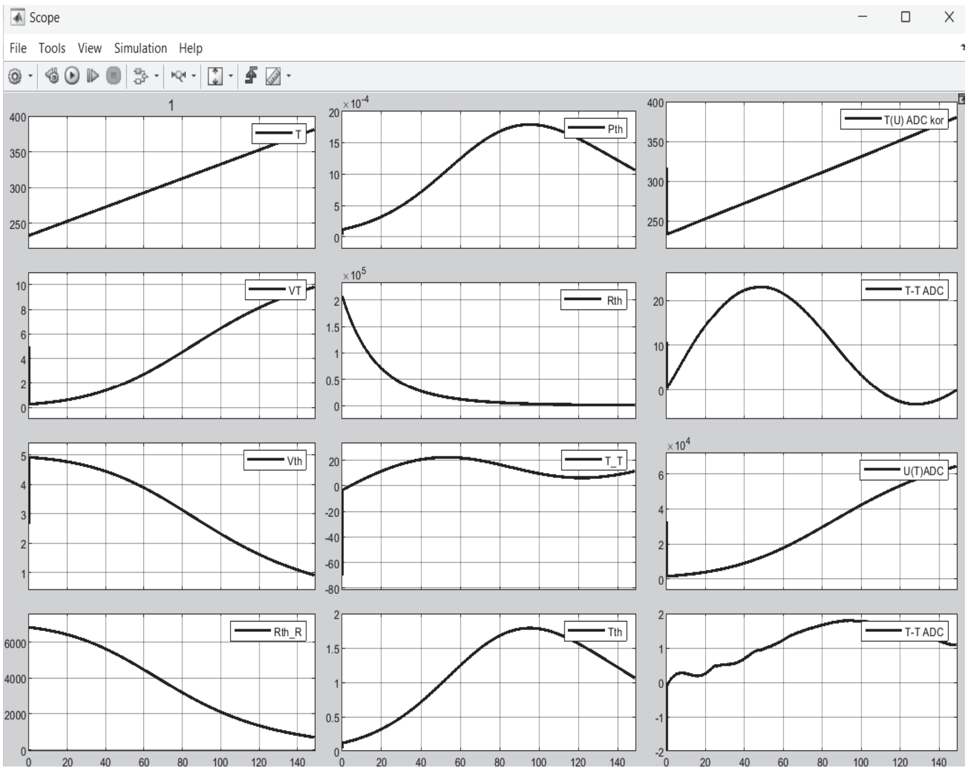

Fig. 6. Graphs of changes in parameter values during the simulation of temperature measurement in MATLAB Simulink

RESULTS OF THE RESEARCH

The research was conducted over the full temperature range of the thermistor, from 233 *K* to 383 *K* (i.e., from −40°*C* to +110°*C*). The operational temperature range and parameters of the thermistor corresponded to those of an RH18-type thermistor manufactured by Mitsubishi, with a nominal resistance of $(R) = 10\,\text{k}\Omega$ at 25°*C* and a $B_{25/85}$ constant of 3435 *K*. This thermistor is encapsulated in epoxy resin and features compact dimensions (1.8 mm in diameter and 7 mm in length), making it particularly sensitive to self-heating effects (thermal dissipation constant $\delta_{th}) = 1\,\text{mW}/^\circ\text{C}$ in air). This characteristic enables a comprehensive analysis of the impact of linearization methods on measurement error across the entire temperature range, as well as the determination of correction values accounting for the self-heating effect of the thermistor.

During simulation, temperature measurement error was evaluated at the analog output of the amplifier, both without correction and with the application of digital signal processing using a high-order polynomial function for data correction over the full temperature range. Additionally, the measurement range was divided into three and six smaller subranges, where lower-order polynomial functions were applied, respectively, to evaluate the influence of segmentation on measurement accuracy.

Fig. 7 illustrates the dependence of measurement error on the current temperature value. The corresponding measurement data are presented in tabular form.

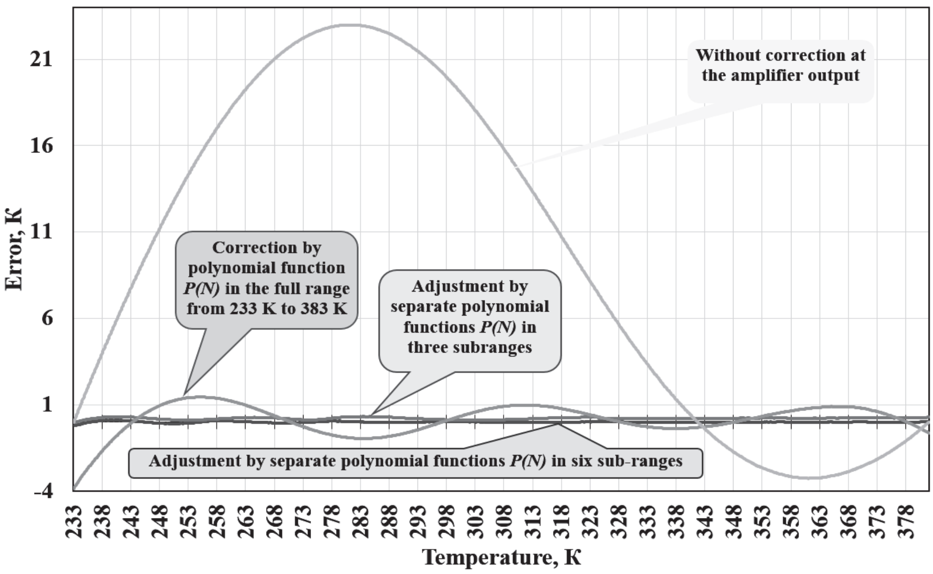

Fig. 7. Dependence of measurement error on the current temperature value

As shown in Fig. 7 and the data table, increasing the number of subranges into which the full measurement range is divided results in a reduction of measurement error and allows for the use of lower-degree polynomial correction functions.

Table 1 presents the simulation results for the digital signal processing algorithm used to correct the measured data, based on polynomial functions of varying orders applied over the full temperature range and over its division into three and six smaller subranges.

Table 1. Research results data

Number of subbands	Adjustment	Error	
		Average value ($\overline{\Delta T}$), K	Root mean square value σ, K
1 (Full)	No adjustment	9.589	9.518
1(Full)	6th order polynomial	0.145	0.859
3 subbands	4th order polynomial	0.111	0.055
6 subbands	3rd order polynomial	-0.002	0.036

Fig. 8 presents the actual temperature measurement error values at resistance points $R_{\min}$, R_{nom} and $R_{\max}$, obtained using third-order polynomial correction functions within each of the six subranges. The values of $R_{\min}$ R_{nom}, and $R_{\max}$, over the temperature range from 233 K to 383 K (– 40°C to +110°C) were taken from the datasheet provided by the manufacturer of the RH18 6Y103 thermistor (Mitsubishi Materials).

As observed from the plots, the minimum measurement error occurs at the nominal temperature of 298 K (+25°C), while the error increases as the temperature approaches the lower $T_{\min}$ and $T_{\max}$ bounds of the range. Calibration of the device allows for the determination of additional correction coefficients, denoted as K_{298-}, K_{298+} and $T_{298+/-}$ aimed at reducing the measurement error.

The coefficient K_{298-} — compensates for the slope deviation of the linear characteristic within the range from 233 K to 298 K (–40°C to +25°C), while K_{298+} serves the same purpose in the range from 298 K to 383 K (+25°C to +110°C). The coefficient $T_{298+/-}$ represents a temperature offset at the nominal point T_N =298 K (+25 °C), as determined during calibration. The developed model provides the capability to input these coefficients to enhance measurement accuracy.

Fig. 8 demonstrates the potential for reducing measurement error through the inclusion of the correction coefficients K_{298-}, K_{298+} and $T_{298+/-}$.

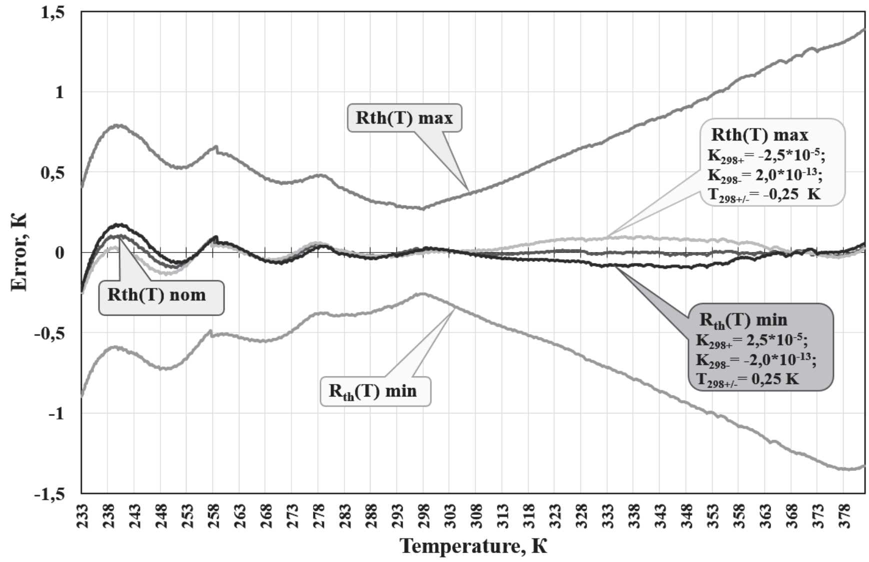

Fig. 8. Actual value of temperature measurement error at $R_{\min}$, R_{nom} and $R_{\max}$ when correcting measured data using 3rd order polynomial functions in each of the 6 subbands

Fig. 9 shows the actual temperature measurement error under conditions of a reference voltage shift in the Wheatstone bridge circuit, U_{ref} on ΔU_{ref} = ±0.05V (±0.5 %), using third-order polynomial correction functions in each of the six subranges. The results are shown for both uncalibrated conditions and after applying the additional calibration coefficients.

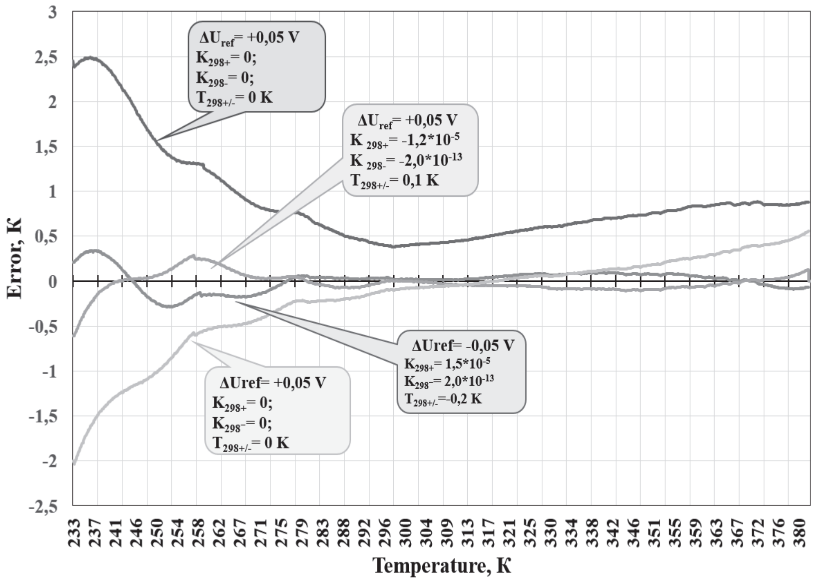

Fig. 9. Actual value of temperature measurement error when shifting the reference voltage of the Wheatstone bridge U_{ref} at ΔU_{ref} = ±0.05 V

Fig. 10 presents the actual temperature measurement error resulting from a deviation of the amplifier gain coefficient from its ideal value by ΔG = ±0.01, using third-order polynomial correction functions within each of the six subranges. The results are shown both without and with the application of additional calibration coefficients.

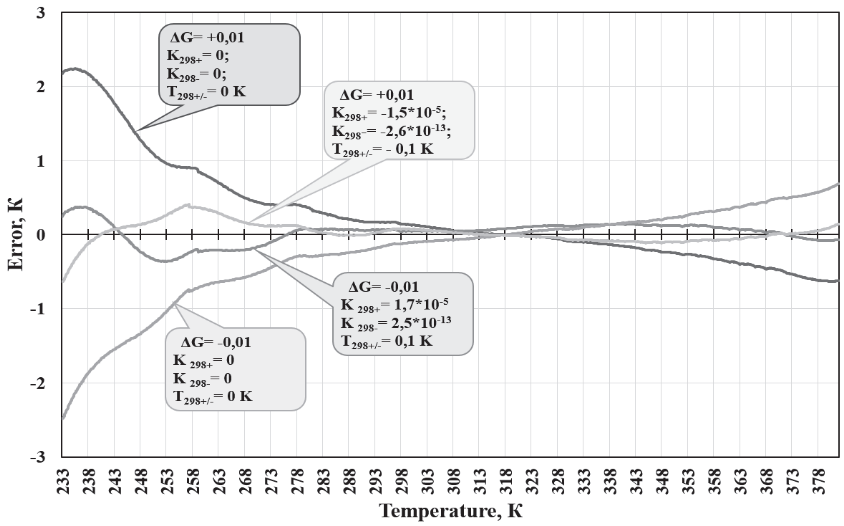

Fig. 10. The actual value of the temperature measurement error when the actual value of the amplifier gain deviates from its ideal value by ΔG = ±0.01

Fig. 11 illustrates the actual temperature measurement error due to thermistor self-heating, corrected using third-order polynomial functions within each of the six subranges, with the inclusion of various values of the $K_{self-heating}$ coefficient: 0, 0.25, 0.5, 0.75, and 1.0.

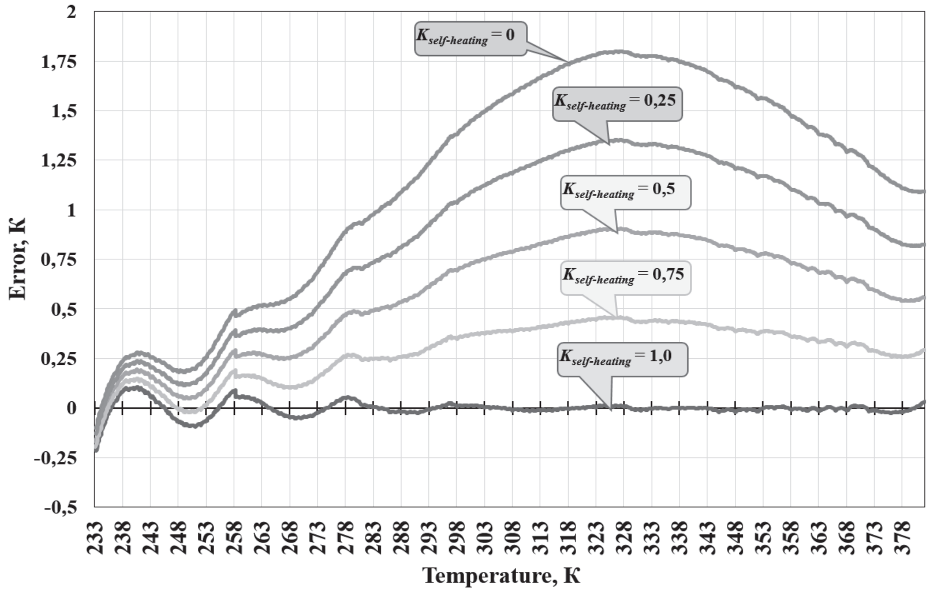

Fig. 11. Actual value of temperature measurement error taking into account thermistor self-heating when correcting measured data using 3rd order polynomial functions in each of 6 subranges with the input of $K_{self-heating}$ = 0; 0.25; 0.5; 0.75; 1.0

The summarized data of the research results are presented in Table 2.

To investigate the measurement error caused by the self-heating effect of the thermistor and the potential for compensating this error, the model includes a dedicated module, "*Subsystem self-heating*". This module determines the self-heating temperature of the thermistor at a given ambient temperature under still air conditions, which is used as the baseline reference. This approach is justified by the fact that thermistor manufacturers typically specify the thermal dissipation constant δ_{th} only for still air.

When the thermistor operates under different environmental conditions (e.g., in liquids or moving air), the actual δ_{th} value must be determined experimentally. Subsequently, the self-heating correction coefficient $K_{self-heating}$ should be adjusted proportionally relative to the value of $K_{self-heating}$ determined under still air conditions.

In the case of stationary water, which has a significantly higher thermal conductivity compared to air, the thermal dissipation constant δ_{th} increases by a factor of 2 to 5, depending on the thermistor's design, the material of its protective coating, and other structural factors. Consequently, the self-heating temperature of the thermistor is reduced, and a correction must be introduced by applying a corresponding self-heating compensation coefficient $K_{self-heating}$ typically ranging from 0.2 to 0.5.

Table 2. Summary of research results

Parameter	Calibration factors				Error	
	K_{298+}	K_{298-}	$T_{298+/-}$	$K_{self-heating}$	$\overline{\Delta T}$, K	σ, K
R_{nom}	-				-0.002	0.036
$R_{\min}$	-				0.678	0.305
	2.5*10^{-5}	-2.0*10^{-13}	0.25 K	-	-0.018	0.057
$R_{\max}$	-				-0.689	0.309
	-2.5*10^{-5}	2.0*10^{-13}	-0.25 K	-	0.016	0.057
U_{ref} = 10.00 V	-				-0.002	0.036
ΔU_{ref} =+0.05 V (+0.5%)	-				0.896	0.525
	-1.2*10^{-5}	-2.0*10^{-13}	0.1 K	-	0.011	0.119
ΔU_{ref} = –0.05 V (–0.5%)	-				-0.198	0.529
	1.5*10^{-5}	2.5*10^{-13}	-0.2 K	-	-0.018	0.108
G = 1.6	-				-0.002	0.036
ΔG = +0.01 (+0.63%)	-				0.258	0.695
	-1.5*10^{-5}	-2.6*10^{-13}	-0.1 K	-	0.026	0.150
ΔG = –0.01 (–0.63%)	-				-0.246	0.659
	1.7*10^{-5}	2.5*10^{-13}	0.1 K	-	0.026	0.140
$\Delta T_{self-heating}$	-			0	1.141	0.551
				0.25	0.855	0.413
				0.5	0.569	0.276
				0.75	0.282	0.141
				1.0	-0.002	0.036

CONCLUSIONS

The issue of sensor characteristic linearization is critically important for real-time applications across various fields, as most sensors exhibit nonlinear behavior. Digital linearization methods offer greater flexibility and improved measurement accuracy over a wide range of measured quantities. These methods can be implemented using software on a personal computer or via dedicated hardware platforms such as microcontrollers, FPGAs, or DSP processors.

This work proposes a method for linearizing the temperature characteristics of NTC thermistors using digital correction based on polynomial functions. The proposed approach can be implemented on low-power, cost-effective microcontrollers through sequential execution of programmed arithmetic operations.

The method was validated using a newly developed simulation model of a temperature measurement device based on an NTC thermistor, created in the MATLAB Simulink environment. This model includes a data processing algorithm capable of generating all necessary polynomial functions, incorporating correction coefficients obtained through calibration.

Simulation results demonstrated that the highest measurement accuracy over a wide temperature range can be achieved using a polynomial correction algorithm that divides the full measurement range into multiple subranges. Increasing the number of subranges enables the use of lower-order polynomial functions within each subrange, which in turn enhances overall measurement accuracy. Specifically, when the full temperature range from 233 *K* to 383 *K* was divided into six subranges, third-order polynomial functions were used for data processing. Under these conditions, the measurement error did not exceed 0.1 *K* (RMS).

The research identified several factors that influence measurement accuracy: deviations of the actual thermistor resistance from its nominal value due to the temperature dependence of the *B*-parameter; instability of the Wheatstone bridge reference voltage ΔU_{ref}; deviation of the amplifier gain from its ideal value ΔG; and errors introduced by self-heating of the thermistor. To achieve a measurement error within 0.1 *K* (RMS), the accuracy of the *B*-parameter, ΔU_{ref}, and ΔG must be within 0.5%, and the thermistor current I_{th} must be limited to no more than 100 μA. At this current level, self-heating of the thermistor does not exceed 0.1 *K* and therefore does not significantly affect measurement results.

To further enhance the effectiveness of temperature characteristic linearization of NTC thermistors based on the proposed method, future research will focus on improving the mathematical model. This will support the design and analysis of various temperature measurement circuits aimed at achieving the desired measurement accuracy using optimally selected sensors and components of the measurement channel.

REFERENCES

1. T. Islam, S.C. Mukhopadhyay, “Linearization of the sensors characteristics: a review,” *Int. J. Smart Sens. Intell. Syst.*, vol. 12, no. 1, pp. 1–21, 2019. doi: https://doi.org/10.21307/ijssis-2019-007
2. A.J. Lopez-Martin, A. Carlosena, “Sensor signal linearization techniques: A comparative analysis,” in *2013 IEEE 4th Latin Amer. Symp. Circuits Syst. (LASCAS)*, *Cusco, Feb. 27–Mar. 1, 2013*, pp. 1–4. doi: https://doi.org/10.1109/lascas.2013.6519013
3. J.M. Dias Pereira, P.M.B. Silva Girao, O. Postolache, “Fitting transducer characteristics to measured data,” *IEEE Instrum. & Meas. Mag.*, vol. 4, no. 4, pp. 26–39, 2001. doi: https://doi.org/10.1109/5289.975463
4. T. Nenov, S. Ivanov, “Linearization of characteristics of relative humidity sensor and compensation of temperature impact,” *Sensors Mater.*, vol. 19, no. 2, pp. 095–106, 2007.
5. H. Erdem, “Implementation of software-based sensor linearization algorithms on low-cost microcontrollers,” *ISA Trans.*, vol. 49, no. 4, pp. 552–558, 2010. doi: https://doi.org/10.1016/j.isatra.2010.04.004
6. “Chip NTC Thermistor Simulation | Sensors and Sensor Systems - Temperature Sensors (NTC) - Chip NTC Thermistors (Sensor),” *TDK Product Center*. Accessed on: May. 5, 2025. [Online]. Available: https://product.tdk.com/en/search/sensor/ntc/chip-ntc-thermistor/simulation
7. “NTC Thermistor Performance Simulator,” *Murata Manufacturing Co*. Accessed on: May 5, 2025. [Online]. Available: https://ds.murata.co.jp/simsurfing/ntcthermistor.ht

ml?rgear=suaykx&rgearinfo=com&md5=67c837df0f254f67edb244383dec4b71

8. "Chip thermistor resistance simulator | SOLUTIONS / KNOWLEDGE | Electronic materials and components | Mitsubishi Materials," *Mitsubishi Materials*. Accessed on: May 6, 2025. [Online]. Available: https://www.mmc.co.jp/adv/en/solution/simulator.html
9. J.G. Webster, *Measurement, Instrumentation and Sensors Handbook*. Taylor Francis Group, 1998, 2608 p. doi: https://doi.org/10.1201/9781003040019
10. L.E. Bengtsson, "Lookup table optimization for sensor linearization in small embedded systems," *J. Sensor Technol.*, vol. 02, no. 04, pp. 177–184, 2012. doi: https://doi.org/10.4236/jst.2012.24025
11. S.B. Stankovic, P.A. Kyriacou, "Comparison of thermistor linearization techniques for accurate temperature measurement in phase change materials," *J. Phys.: Conf. Ser.*, vol. 307, Art. no. 012009, 2011. doi: https://doi.org/10.1088/1742-6596/307/1/012009
12. "NTC Thermistors, General technical information," *TDK Electronics - TDK Europe*. Accessed on: May 6, 2025. [Online]. Available: https://www.tdk-electronics.tdk.com/download/531116/19643b7ea798d7c4670141a88cd993f9/pdf-general-technical-information.pdf
13. J. Jovanović, D. Denić, "NTC thermistor nonlinearity compensation using wheatstone bridge and novel dual-stage single-flash piecewise-linear ADC," *Metrol. Meas. Syst.*, vol. 28, no. 3, pp. 523–537, 2021. doi: https://doi.org/10.24425/mms.2021.136616
14. H. Ebrahimi-Darkhaneh, "Measurement error caused by self-heating in NTC and PTC thermistors," *Analog Des. J.*, pp. 1–8, 2019. Available: https://www.ti.com/lit/an/slyt774/slyt774.pdf?ts=1736163042225
15. S. Matvienko, S. Vysloukh, A. Matvienko, A. Martynchyk, "Determination thermal and physical characteristics of liquids using pulse heating thermistor method," *Int. J. Eng. Res. & Sci.*, vol. 2, no. 5, pp. 250–258, 2016.
16. G. Tymchik, S. Matvienko, I. Sikorsky, P. Kisała, K. Nurseitova, A. Iskakova, "Improving the way of determination substances thermal physical characteristics by direct heating thermistor method," *Przeglad Elektrotechniczny*, vol. 1, no. 4, pp. 123–128, 2019. doi: https://doi.org/10.15199/48.2019.04.21
17. S. Matvienko, S. Vysloukh, O. Martynchyk, "Increasing accuracy of measuring thermal conductivity of liquids by using the direct heating thermistor method," *Eastern-Eur. J. Enterprise Technol.*, vol. 4, no. 5(82), pp. 20–30, 2016. doi: https://doi.org/10.15587/1729-4061.2016.75459
18. M.V. Nikolic, B.M. Radojcic, O.S. Aleksic, M.D. Lukovic, P.M. Nikolic, "A Thermal Sensor for Water Using Self-Heated NTC Thick-Film Segmented Thermistors," *IEEE Sensors J.*, vol. 11, no. 8, pp. 1640–1645, 2011. doi: https://doi.org/10.1109/jsen.2010.2103309

Received 11.06.2025

INFORMATION ON THE ARTICLE

Sergey N. Matvienko, ORCID: 0000-0002-7547-4601, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Ukraine, e-mail: s.matvienko@kpi.ua

Grygoriy S. Tymchyk, ORCID: 0000-0003-1079-998X, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Ukraine, e-mail: deanpb@kpi.ua

СПОСІБ ЛІНЕАРИЗАЦІЇ ТЕМПЕРАТУРНИХ ХАРАКТЕРИСТИК NTC-ТЕРМІСТОРІВ ЗА ДОПОМОГОЮ ПОЛІНОМІНАЛЬНОГО МЕТОДУ / С.М. Матвієнко, Г.С. Тимчик

Анотація. Мета роботи – розроблення схемотехнічного способу лінеаризації температурних характеристик термісторів із використанням поліномінального цифрового методу температурних характеристик NTC-термісторів та характеристик розробленого вимірювального каналу за допомогою розробленої оригінальної моделі в MATLAB Simulink. Запропоновано модель пристрою для вимірювання температури із сенсором на базі термістора. Виконано моделювання поліномінального цифрового методу лінеаризації температурних характеристик NTC-термісторів розробленого пристрою. Для підвищення точності вимірювань вибрано елементи вимірювального каналу з параметрами, що дають змогу здійснювати моделювання вимірювань із мінімальною похибкою. Визначено методи внесення значення корекційних коефіцієнтів у модель для компенсації факторів впливу на похибку включно з ефектом саморозігріву термістора. Запропонований алгоритм оброблення даних має переваги за реалізації в мікроконтролері невисокої вартості та низької потужності.

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