http://dx.doi.org/10.5755/j01.eee.20.6.7268 ELEKTRONIKA IR ELEKTROTECHNIKA, ISSN 1392–1215, VOL. 20, NO. 6, 2014

Stability of Negative Resistance Coefficient Thermistors for Long-term Temperature Measurement

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***Abstract*—The NTC (negative temperature coefficient) thermistor precision is significantly increased by the calibration process. The full calibration procedure process itself is sophisticated as it requires a set of calibration points when using the Steinhart-Hart equation for the linearization of the *T(R)* (Temperature – Resistance) characteristics. Aging and degradation processes tend to distort the metrological characteristics of the NTC thermistors. The novel method of calibration for groups of thermistors produced by the same manufacturer using the same technology is proposed in this paper. The initial calibration data acquired from the calibration results or from the manufacturer is used for approximate computations. During the additional calibration, the approximate data for the group of thermistors is adjusted using linear transformations. The result analysis for five different types of thermistors (A, B, C, D and E) revealed that the temperature measurement errors in the temperature range from 20 ^{0}C to 80 ^{0}C can be reduced by up to 10 times using the proposed method. The aging and degradation processes were investigated using the thermocycling procedure implemented with steep transitions (100 ^{0}C ... 0 ^{0}C ... 100 ^{0}C). The thermistor *R(T)* characteristics were repeatedly measured after 1000, 2000 and 3000 thermocycles. The results revealed that statistically, the average error of the temperature measurement for the types C, D and E increased significantly after 3000 thermocycles, whereas the measurement error trend of the thermistors of types A and B was insignificant ($p > 0.05$).**

***Index Terms*—Thermistors, measurement, linearity, temperature.**

I. INTRODUCTION

Precise temperature measurement and control is important in many fields of the science and industry, including biochemical, material sciences, energy accounting, process control. Depending on temperature range, performance, throughput and resistance to the environmental impacts, various types of temperature sensors are used that operate on the base of different physical effects. Thermistor is a type of temperature sensor, that delivers a good sensitivity and a competitive price, but the non-linearity of the dependence of the *R(T)* curve and deterioration of the metrological characteristics due to aging and degradation are its main disadvantages. The *R(T)* dependencies are different and depend both on the material properties and technology applied during the manufacturing process. The scatter of the parameters is controlled by the manufacturer by grouping the *R(T)* characteristics.

The temperature-resistance *T(R)* dependencies are assigned to each group by calibrating in discrete steps with intervals of 1 ^{0}C. The Steinhart-Hart equation is used for approximation of the dependencies written as

$$1/T = A_0 + A_1 R_T + A_3 (\ln R_T)^3 + A_5 (\ln R_T)^5, \tag{1}$$

where R_T is the thermistor resistance at the temperature T, and T is the temperature in K, and $A0$, $A1$, $A2$, $A3$, $A4$ and $A5$ are the coefficients.

Steinhart-Hart equation is often expressed in the simplified form

$$1/T = A_0 + A_1 \ln R_T + A_3 (\ln R_T)^3. \tag{2}$$

In order to calculate the coefficients A_0, A_1 and A_3 in certain range of temperatures, it is sufficient to measure the thermistor resistance at three temperature points [1].

Thermistors are available with various types of *T(R)* dependencies. Several variants of the polynomials are offered to approximate the *T(R)* characteristics [2], [3].

As it was shown in [4], when approximating the T(R) characteristics of some types of the thermistors using the fourth-order polynomials, the approximation error is of the order of several mili Kelvins. The complexity of such approximation lies in the fact that a lot of *R(T)* measurement data in the temperature range of the sensor application is required (usually every 1 ^{0}C).

In some cases [5], the *T(R)* characteristics of NTC thermistors can be approximated with the errors of several mili Kelvins from the *R(T)* measurement results by calculating only two parameters, but even in this case, a large amount of the calibration data in the temperature range of the sensor application is required (usually every 1 ^{0}C).

Manuscript received November 18, 2013; accepted February 14, 2014.

The aim of the work is to evaluate the approximation improvement of the NTC thermistor characteristics using the novel method of calibration and to investigate the stability of several types of sensors after their initial calibration. The proposed calibration method requires full calibration at multiple temperature points (or the R(T) characteristic provided by the manufacturer are used alternatively) for only one sensor from the same batch. The calibration results are used to calculate the Steinhart-Hart linearization equation parameters in order to use them for all the sensors from the same batch. Instead of full calibration, the additional individual calibration at only two temperature points is proposed to individually correct the linearization equation parameters.

II. METHODS AND SAMPLES

For all the thermistors the *R(T)* characteristics were measured using a circulatory hot oil thermostat. The used reference temperature measurement channel was equipped with FLUKE type 5610 thermistor (serial No A6B0211 whose absolute accuracy in the 0… 100 ^{o}C temperature range is not worse than 0,015 ^{o}C) connected to the FLUKE type Black Stack 1560 and type 2564 Thermistor readout module thermometer. The bath with the reference and the tested sensors were cooled slowly (in more than 24 hours) from +95 ^{o}C to +25 ^{o}C, thus all R(T) characteristics were acquired for each type of sensors. Each sensor type was represented by five sensors.

The Steinhart–Hart interpolation equation (1) parameters for all the tested sensors were calculated using the data from the experimental *R(T)* curve of the same sensor kind (not from the manufacturer data). This was done for the more realistic evaluation of the *T(R)* curve for different types of the tested sensors. After application of the Steinhart-Hart linearization, the *T(R)* curves of the tested thermistors became approximately linear.

In order to minimize the large offset and gain errors that remain after the application of the same Steinhart-Hart equation for all the sensors from the same batch, the calibration curve for each thermistor of the thermistor group was corrected by using additional data obtained after measuring the resistance of each thermistor of the group at the two points (adjacent to the limits of the temperature range). After the individual calibration, the measurement errors decreased several times. The least squares method was used to estimate the adequacy of the approximation equation. The average error and the standard deviation parameters were used for evaluation of the proposed calibration method.

Subsequently, the sensors were numbered and the thermal stress tests were undertaken to emulate their possible aging problems. The stress tests were carried out by submerging sensors in a hot (+100 ^{o}C) water bath for 30 s, then rapidly (within 10 s) submerging them into a cold (about 0 ^{o}C) water bath for 30 s. Each stress test consisted of 1000 (one thousand) such (100^{0}C... 0 ^{0}C... 100 ^{0}C) cycles.

After each stress test (1000 thermal cycles) the sensor *R(T)* characteristics were measured repetitively and the temperature measurement errors were calculated for the entire +25 ^{o}C… +80 ^{o}C range. The above mentioned individual linearization equations were used for each sensor. Changes in the sensor accuracy were obtained by comparing its characteristics before and after the stress test.

Three separate stress test series were performed, thus the final count of hot-cold cycles for each of the sensors was 3000. The sensor accuracy was evaluated before and after 1000, 2000 and 3000 hot-cold cycles.

III. RESULTS AND DISCUSSIONS

The total of 25 temperature sensors-thermistors was tested, five thermistors for each of five different types: the interchangeable sealed-glass encapsulated sensors – type A and B (accuracy ±0.5 ^{0}C in range 0 ^{0}C– 100 ^{0}C) [6]; standard precision interchangeable epoxy encapsulated thermistors – type C and D (accuracy ±0.1 ^{0}C in range 0 – 70 ^{0}C, operating temperature: -80 °C to +150 °C) [6]; and epoxy encapsulated sensors from a different manufacturer – type E (resistance tolerance ±0,5 % at 25 ^{0}C, operating temperature: -40 °C to 100 °C) [7].

The temperature measurement error using five A type sensors in the temperature range from 25 ^{0}C to 80 ^{0}C, when the Steinhart–Hart interpolation equation (1) with the coefficients A_0, A_1, and A_3 determined by the R(T) measurement data of the 1st sensor (Fig. 1, No. 1) was used for the calculations, are illustrated in the Fig. 1.

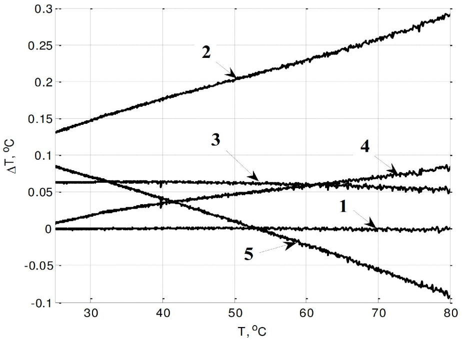

Fig. 1. The temperature measurement errors after the Steinhart-Hart linearization. Five type A sensors were linearized using the 1st sensor's (1 (red) curve) linearization equation's parameters: 1 (red), 2 (green), 3 (blue), 4 (light blue), 5 (magenta) – numbers of the thermistors.

The temperature measurement error using type A sensors ranged from +0.3 ^{o}C to -0.1 ^{o}C, which fall within the error value range declared by the manufacturer. It is also possible to use the numerical *R(T)* data provided by the manufacturer to calculate the coefficients of the Steinhart–Hart interpolation equation (1), but this may lead to larger approximation errors than using one sensor's the calibration data for each batch. As it can be seen (Fig. 1), the measurement errors in the whole tested temperature range become almost linear after the Steinhart-Hart linearization, but there are significant offset and gain errors. These two error types (offset and gain) can be easily eliminated by applying the linear transformations using the data acquired by two point calibration for each sensor individually. The temperature measurement errors using five sensors of type A following additional calibrations of sensors at approx. 25 ^{o}C and 75 ^{o}C points are shown in the Fig. 2.

In this way after performing the proposed additional individual calibration of sensors by using the data of the R(T) measurement only at two temperature values, the measurement error ranged from +0.006 °C (+6 milicentigrade) to -0.0075 °C. (-7.5 milicentigrade). It was determined that using the proposed calibration method the measurement errors were decreased approximately 10-fold.

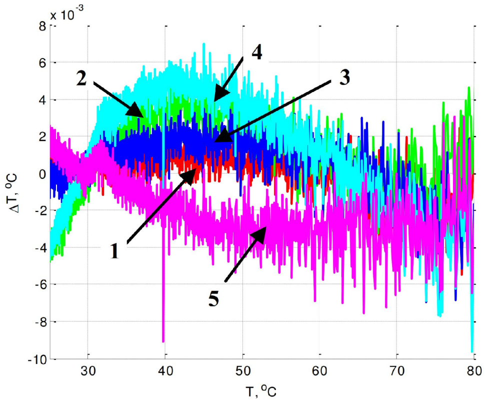

Fig. 2. Temperature measurement errors after two additional point (at approx. 25 °C and 75 °C) individual calibrations of five sensors type A: 1 (red), 2 (green), 3 (blue), 4 (light blue), 5 (magenta) – numbers of the thermistors.

The measurement errors after the thermocycling at two temperature points were compared. The proposed additional individual sensor calibration was performed and the measurement errors that were determined before the thermocycling were considered to be equal to zero.

The temperature measurement error variation trends after 3000 thermocycles are shown in Fig. 3. The error scattering falls into the 0 °C to 0.08 °C range. As it can be seen in Fig. 3, the measurement error of the No. 5 sensor of type A is 2-8 times higher compared to the other four sensors of the same group and it can be considered as a result of structural changes in the sensor body.

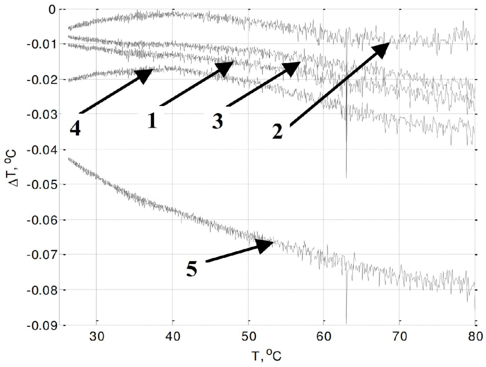

Fig. 3. The temperature measurement errors after 3000 thermo-cycles**:** 1, 2, 3, 4, 5 are the numbers of the thermistors.

The identical linearization, individual calibration and thermocycling procedures were applied to the sensors from the other four types.

After the linearization of the *T(R)* characteristics of type B sensors using the Steinhart–Hart interpolation equation (1) and by using the data from the first sensor (Fig. 4, No. 1), the measurement error ranges from 0 to – 0.35 °C and therefore do not exceed the values declared by the manufacturer.

The measurement errors following two additional individual two point calibrations are presented in the Fig. 5.

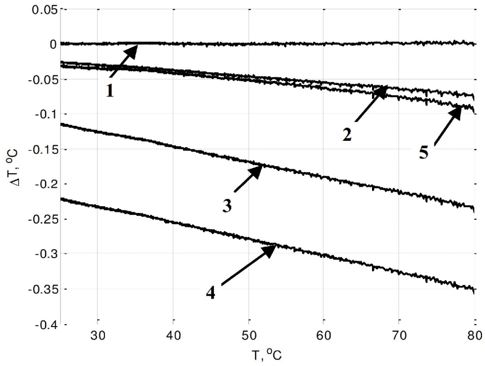

Fig. 4. The temperature measurement errors after the Steinhart-Hart linearization. The 5 type B sensors were linearized using the 1st sensor's linearization equation's parameters: 1, 2, 3, 4, 5 are the numbers of the thermistors.

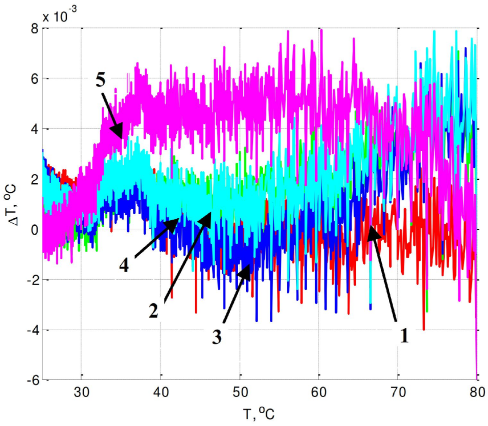

Fig. 5. The typical temperature measurement errors after two additional point (at approx. 25 °C and 75 °C) individual calibrations of sensors type B: 1 (red), 2 (green), 3 (blue), 4 (light blue), 5 (magenta).

Following two additional individual point calibrations of the sensors, the measurement error was decreased and ranged from $+8 \cdot 10^{-3}$ (+8 milicentigrade) to $-4 \cdot 10^{-3}$ °C (-4 milicentigrade). The variation trends of the temperature measurement errors using type B sensors after 3000 thermocycles are shown in the Fig. 6.

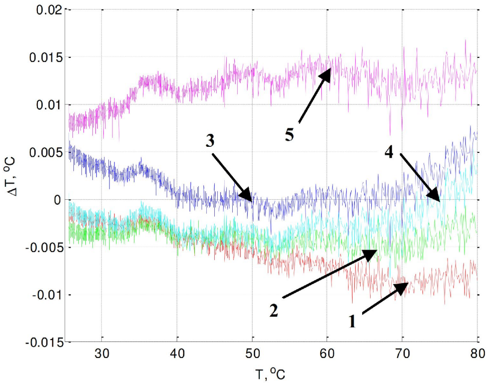

Fig. 6. The temperature measurement errors using five type B thermistors after 3000 thermocycles 1 (red), 2 (green), 3 (blue), 4 (light blue), 5 (magenta) are the numbers of the thermistors.

Even though the measurement error increased after the thermocycling, it still ranged from +0.015 °C to -0.01 °C for the type B thermistors analysed.

The temperature measurement errors after 3000 thermocycles using type C and type D thermistors were within the same range from -0,097 °C to 0,12 °C.

The error variation of type E thermistors (by different manufacturer) show the trends over the temperature range (Fig. 7 and Fig. 8).

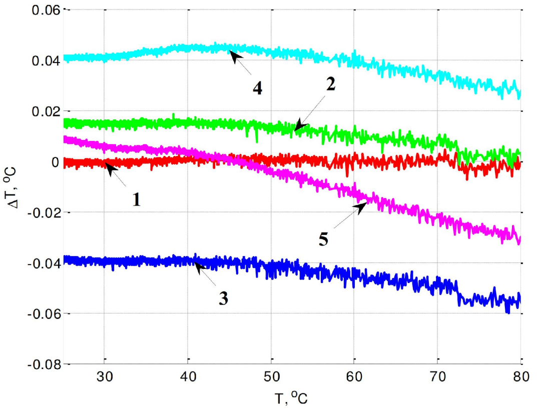

Fig. 7. The temperature measurement errors after the Steinhart-Hart linearization. The 5 type E sensors were linearized using the 1st sensor's (red curve) linearization equation's parameters: 1 (red), 2 (green), 3 (blue), 4 (light blue), 5 (magenta) are the numbers of the thermistors.

The temperature measurement errors after the linearization using Steinhart–Hart interpolation equation (1) using the data from the first sensor (Fig. 7, No. 1) for type E sensors were in the range from +0.045 °C to -0.06 °C. The error variation trends are similar to the ones observed in the previous experiments.

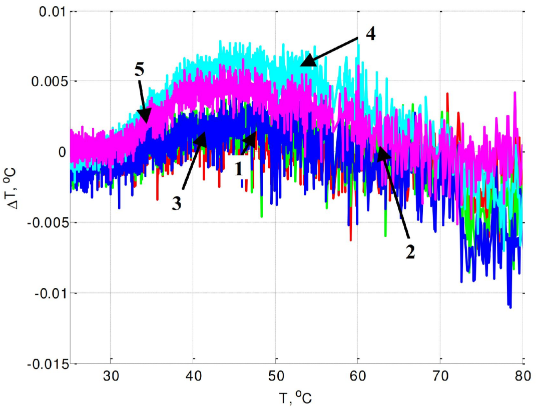

Fig. 8. The temperature measurement errors after two additional point (at approx. 25 °C and 75 °C) individual calibrations of sensors type E.

The temperature measurement errors after the linearization and individual sensor calibrations using the proposed method for type E sensors were in the range from +0,0065 °C to -0.011 °C. The errors for the same sensors increased after 3000 thermocycles and ranged from -0.41 °C to -1.07 °C.

The experiment results prove that statistically the mean temperature measurement error of thermistors of types C, D and E after 3000 thermocycles increased significantly ($p < 0.05$), whereas the error changes of thermistors of type A and B were insignificant ($p > 0.05$).

Therefore, it is feasible that due to a long-term aging effects (which are not discussed in this work) the accuracy of the temperature measurement using type C, D and E thermistors will decrease more over time than in case of the type A and B thermistors.

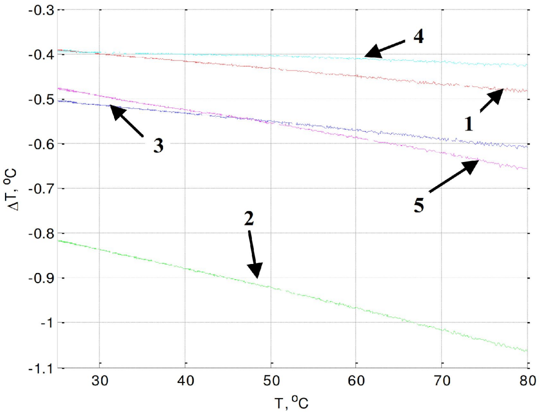

Fig. 9. The temperature measurement errors after 3000 thermocycles using five type E thermistors.

IV. CONCLUSIONS

It was shown that after application of the proposed calibration method using additional individual calibrations of thermistors from the same batch at two points the linear transformations can be used to adjust the initial Steinhart-Hart equation parameters. As a result the temperature measurement precision was increased by 10 times for the entire temperature range. It is recommended to perform a full calibration of one sensor from the batch and to calculate these equation coefficients using the calibration data.

The proposed calibration method is less time and cost consuming than the full individual sensor calibration at multiple points as one temperature reference point at the upper limit of the intended operational range of the thermistors is needed. The temperature close to the room temperature is suitable for the second 25 °C reference point.

The thermocycling revealed the presence of specific temperature measurement error variation trends after 3000 thermocycles for certain types of thermistors which are determined by thermistor properties (type, structure), not by additional *T(R)* linearization.

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