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doi:10.15199/48.2019.05.27

Improvement of dynamic characteristics of thermoresistive transducers with controlled heating

***Abstract**. The work is devoted to the research and improvement of dynamic characteristics of thermoresistive transducers. The proposed structure of thermoresistive transducer provides the possibility of controlled heating, is implemented in microelectronic performance and can be integrated with the humidity sensor. The increase of speed of temperature measurement is achieved through the use of the track and hold circuit for the signal* memorization *of the transition process at a given instant with its additional amplification to the final signal value.*

***Streszczenie.** Praca poświęcona jest badaniom i poprawie charakterystyk dynamicznych przetworników termorezystancyjnych. Zaproponowana struktura przetwornika termorezystancyjnego zapewnia możliwość kontrolowanego ogrzewania, jest realizowana w mikroelektronicznym wykonaniu i może być zintegrowana z czujnikiem wilgotności. Wzrost prędkości pomiaru temperatury uzyskuje się przez zastosowanie układu próbkowania i utrzymywania dla zapamiętywania sygnału procesu przejściowego w danej chwili z jego dodatkowym wzmocnieniem do końcowej wartości sygnału końcowego. (**Poprawa charakterystyk dynamicznych przetworników termorezystancyjnych z kontrolowanym ogrzewaniem**).*

Keywords: temperature, integrated humidity and temperature sensors, temperature measurement, RTD, fast operation of sensor
Słowa kluczowe: temperatura, zintegrowane czujniki wilgotności i temperatury, pomiar temperatury, RTD

Introduction

Microprocessor sensory systems as a component of information and communication technologies are an integral attribute of human society at the present stage. The sphere of sensory systems application is constantly expanding. Special place belongs to sensors of temperature and humidity. These sensors are widely used in automated control systems at food and light industry, agriculture, oil and gas pipelines, medical and environmental monitoring systems [1-5]. Measuring the humidity and temperature of air and industrial gases is important for ensuring the quality of final products. For example, changing the temperature of gas in gas pipelines can cause condensation of water vapour, which leads to negative consequences, such as corrosion, the formation of aggressive chemicals, etc. Changing of temperature also influence the characteristics of different sensors, for example, of capacitive sensors [6].

In order to measure humidity the sensors based on polymeric or ceramic materials that are sensitive to humidity are used [7]. The measurement of low humidity (up to 20% RH) was not sufficiently investigated, and was accompanied with difficulties due to significant errors in the nonlinearity of humidity sensors. Modelling of polymer-based capacitive humidity sensors carried out in [8] allowed to explain the nature of nonlinearity and suggests a logarithmic relationship between the relative humidity and the output value of the sensor.

The combination of the results of researches of humidity sensors (in particular their accuracy and calibration [9-10]) and temperature sensors (in particular linearization of the transfer function of thermoresistive transducers [11-12], cold-junction compensation in thermocouples [13]) will allow for comprehensive control of the parameters of technological processes. It is advisable to use integrated temperature and humidity sensors in which temperature compensation can improve the accuracy of humidity sensors or extend the temperature range [14-17]. For temperature compensation it is necessary to implement controlled heating regimes and temperature measurement, which is possible using the RTDs.

In addition, in some emergency situations, the response time of monitoring sensors is crucial, as it can lead to deterioration in the quality of the end product or other effects that disturb the technological regime [7, 18, 19]. In this article we will discuss in more detail methods for improvement of the dynamic characteristics of thermoresistive transducers.

The fast operation of the thermoresistive transducers mainly depends on the value of the RTD's time constant. Film technologies of RTD production can provide the time constant less than 0.2 s [20].

In order to increase the fast operation of the thermoresistive transducers, the RTD pre-heating to the initial temperature value of the temperature measuring range is used [21]. In order to further improve the fast operation, the RTD resistance at the given time constant of the transition process is measured with subsequent calculation of the measured temperature value [19]. In this case, the accuracy of temperature determination is mainly defined by the accuracy of time determination of the transition process and the accuracy of RTD resistance determination.

Designing of the measuring thermoresistive transducer

The developed structural scheme of the thermoresistive transducer with controlled RTD heating and RTD's resistance measurement at a given time constant is given in Fig.1.

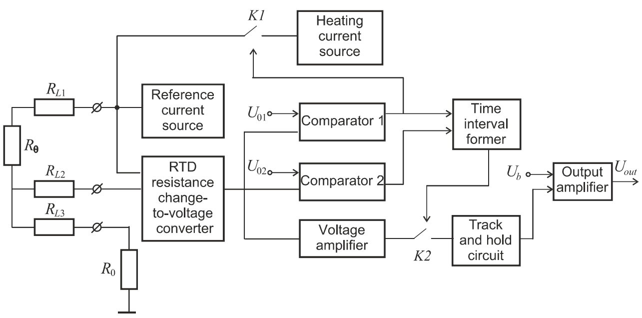

Fig. 1. Structural scheme of the thermoresistive transducer

The structural scheme of the thermoresistive transducer consists of the reference current source, the RTD resistance change-to-voltage converter, the heating current source, the keys *K1* and *K2*, the comparators 1 and 2, the former of time interval of RTD voltage memorization, the voltage amplifier, the track and hold circuit, the output amplifier, the standard resistor R_0.

RTD R_θ is connected to the thermoresistive transducer with the three lead wires R_{L1}, R_{L2}, R_{L3}. Prior the measurement the key *K1* is switched off and through the RTD R_θ the standard current I_0 and the heating current I_h are flowing. Accordingly, the voltage at the output of the RTD resistance change-to-voltage converter is equal to:

(1) $$U_{RVC} = (I_0 + I_h)(R_\theta - R_0),$$

where R_θ is RTD's resistance value, R_0 is standard resistor resistance value.

If the condition $R_\theta < R_0$ is met, the output negative polarity voltage of the RTD resistance change-to-voltage converter is formed. Accordingly, the output zero level voltages of the comparator 1 and comparator 2 are formed.

If the following condition $U_{RVC} \geq U_{01}$ is met (where U_{01} is the standard offset voltage), at the output of the comparator 1 the positive polarity voltage is formed and is applied to the input of the key *K1*. Accordingly, the key switches off and the heating current through the RTD does not flow. In this case, only the standard current I_0 flows through the RTD.

After placing the RTD R_θ in the measuring medium, the RTD is heated only under the influence of the measuring temperature. When $R_\theta \geq R_0$ the output voltage of the RTD resistance change-to-voltage converter $U_{RVC} \geq 0$ is formed. Accordingly, at the output of the comparator 2 a positive voltage is formed, and the former of time interval of RTD voltage memorization fixes the start of the RTD's resistance change under the measured temperature and forms the time of determination of the RTD's voltage change value.

At the initial moment of time the RTD's resistance changes exponentially [22] and its value at time t is determined by the following expression:

(2) $$R_\theta(t) = R_{\theta 0} + (R_{\theta m} - R_{\theta 0}) \cdot \left(1 - e^{-\frac{t}{\tau}}\right),$$

where $R_{\theta 0}$ is the RTD's resistance value at the initial temperature of the measuring range θ_0; $R_{\theta m}$ is the RTD's resistance value at the measured temperature θ_m; τ is the RTD's time constant; t is the measurement time (from the moment of RTD placing into the measuring medium).

Accordingly, the output voltage of the RTD resistance change-to-voltage converter is equal to:

(3) $$U_{RVC} = I_0(R_{\theta m} - R_{\theta 0}) \cdot \left(1 - e^{-\frac{t}{\tau}}\right).$$

The time dependencies of the output voltage of the RTD resistance change-to-voltage converter for different ranges of RTD's resistance change are depicted in Fig.2.

From the analysis of dependency graphs it can be seen that to increase the speed of temperature measurement the range of RTD's resistance changes should be reduced.

The output voltage of the voltage amplifier is expressed as follows:

(4) $$U_{VA} = I_0(R_{\theta m} - R_{\theta 0}) \cdot \left(1 - e^{-\frac{t}{\tau}}\right) \cdot k,$$

where k is amplification factor of the voltage amplifier.

When the following equality is satisfied $k = \dfrac{1}{\left(1 - e^{-\frac{t}{\tau}}\right)}$, one can obtain the following output voltage of the voltage amplifier:

(5) $$U_{VA} = I_0(R_{\theta m} - R_{\theta 0}).$$

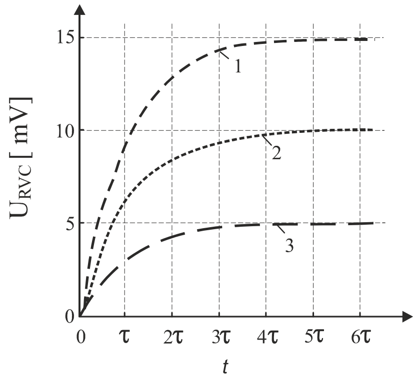

Fig.2. The time dependencies of the output voltage of the RTD resistance change-to-voltage converter for different ranges of RTD's resistance change: 1 – 15 Ω, 2 –10 Ω, 3 – 5 Ω 15 Ω, 2 – 10 Ω, 3 – 5 Ω

At the moment of the end of the output pulse of the former of time interval of RTD voltage memorization, the key *K2* is switched off, and the track and hold circuit memorizes the input voltage and, accordingly, its output voltage is equal to:

(6) $$U_{T/H} = I_0(R_{\theta m} - R_{\theta 0}) \cdot \left(1 - e^{-\frac{t_m}{\tau}}\right) \cdot k,$$

where t_m is measurement time the value of which is determined by the duration of the output pulse of the former of time interval of RTD voltage memorization.

The time dependencies of the output voltage of the track and hold circuit are graphed in Fig.3.

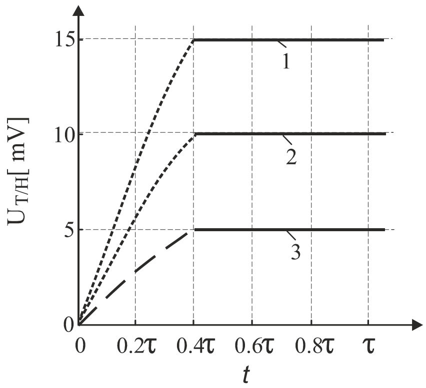

Fig.3. The time dependencies of the output voltage of the track and hold circuit for different ranges of RTD's resistance change: 1 – 15 Ω, 2 –10 Ω, 3 – 5 Ω

From the dependency graphs it can be seen that the time of output signal setting does not depend on the measurement range, but mainly depends on the moment of memorization.

The output voltage of the track and hold circuit is passed to the input of the output amplifier. The output voltage of the output amplifier can be described by the following expression:

(7) $$U_{VA} = I_0\left(R_{\theta m} - R_{\theta 0}\right) + U_b \,.$$

When using RTD with linear dependence of the resistance value on the temperature change:

(8) $$R_{\theta m} = R_{01}\left(1+\alpha\theta_m\right),\; R_{\theta 0} = R_{01}\left(1+\alpha\theta_0\right)$$

(where R_{01} is RTD's resistance at temperature 0°C) and fulfilling the following condition:

(9) $$U_b = I_0 R_0 \,,$$

we will obtain the value of the output voltage of the output amplifier equal to:

(10) $$U_{out} = I_0 R_{01} \alpha \theta_m \,.$$

If the following equality holds true: $I_0 R_{01} \alpha \theta_m = 1$, the value of the output voltage of the output amplifier is numerically equal to the value of the measured temperature.

Analysis of dynamic characteristics

The metrological characteristics of the developed structure of the thermoresistive transducer are mainly determined by the accuracy of the conversion of the RTD's resistance change into the voltage, the accuracy of the memory of the output voltage of the voltage amplifier by the track and hold circuit, and the accuracy of the standard voltages (U_{01}, U_{02} and U_b). Dynamic characteristics are determined by the frequency characteristics of the used element base and the accuracy of the input voltage memorization by the track and hold circuit at a certain time point. The modern semiconductor element base provides high frequency properties and, accordingly, their influence can be neglected. Accordingly, the dynamic characteristics of the thermoresistive transducer depend on the accuracy of voltage memorization by track and hold circuit, which is determined by the accuracy of the formation of the time interval from the moment of initial heating to the moment of memorization t_m.

RTD output voltage taking into account the error of the time interval formation is determined by the following expression:

(11) $$U_{out} = U_b + I_0\left(R_{\theta m} - R_{\theta 0}\right)\cdot\left(1 - e^{-\frac{t+\Delta t}{\tau}}\right)\cdot\frac{1}{1-e^{-\frac{t_m}{\tau}}} \,,$$

where Δt is the absolute error of time interval formation.

When $\Delta t = \delta t$, where δ is the relative error of the time interval formation, the output voltage at time t_m is equal to:

(12) $$U_{out} = U_b + I_0\left(R_{\theta m} - R_{\theta 0}\right)\cdot\left(1 - e^{-\frac{t_m(1+\delta)}{\tau}}\right)\cdot\frac{1}{1-e^{-\frac{t_m}{\tau}}} \,.$$

In this case, the absolute error of the output voltage is determined by the following expression:

(13) $$\Delta U_{out} = I_0 R_0 \alpha\left(\theta_m - \theta_0\right)\frac{1}{1-e^{-\frac{t_m}{\tau}}}\left(e^{-\frac{t_m}{\tau}} - e^{-\frac{t_m(1+\delta)}{\tau}}\right).$$

The equivalent value of the absolute error of temperature measurement is determined by the following expression:

(14) $$\Delta\theta = \left(\theta_m - \theta_0\right)\frac{1}{1-e^{-\frac{t_m}{\tau}}}\left(e^{-\frac{t_m}{\tau}} - e^{-\frac{t_m(1+\delta)}{\tau}}\right).$$

Accordingly, the relative error of measuring the temperature difference is determined by the following expression:

(15) $$\delta = \frac{\Delta\theta}{\left(\theta_m - \theta_0\right)} = \frac{1}{1-e^{-\frac{t_m}{\tau}}}\left(e^{-\frac{t_m}{\tau}} - e^{-\frac{t_m(1+\delta)}{\tau}}\right).$$

The dependencies of the absolute error of temperature measurement on the relative error of time interval formation for different values of resistance change in the measuring range are shown in Fig.4.

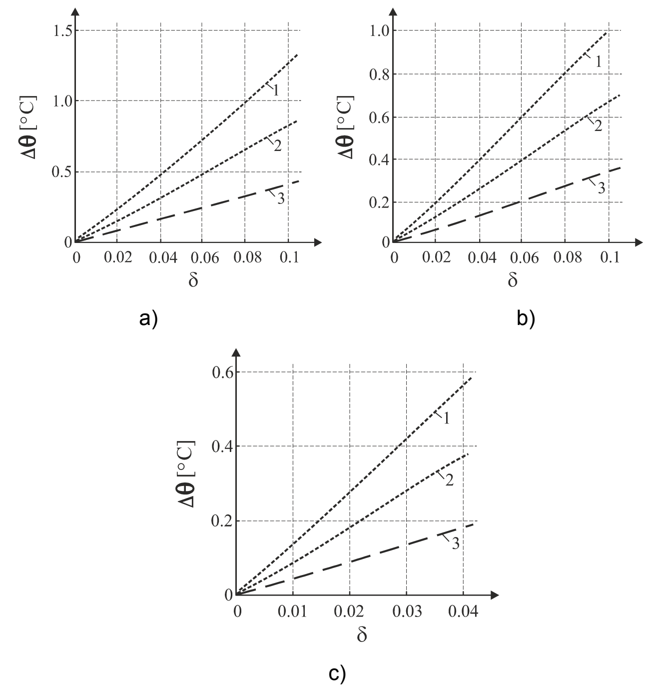

Fig.4. The dependencies of the absolute error of temperature measurement on the relative error of time interval formation for different values of resistance change in the measuring range: 1 – 15 Ω, 2 – 10 Ω, 3 – 5 Ω at t_m=0.4τ (a), t_m=0.8τ (b) and t_m=0.1τ (c).

As can be seen from the dependency graphs, at the errors of time interval formation δ = 0.04 and δ = 0.02 the absolute errors does not exceed 0.5 °C and 0.1 °C, relatively, when the resistance is changed in the range of 5 Ω and t_m=0.1τ.

Conclusions

The method of the temperature measuring with controlled RTD heating and measuring the RTD resistance at a certain time point of the transition process with subsequent amplification to the real value of the measurement temperature is proposed. The structural scheme of the thermoresistive transducer based on the proposed method is developed.

This method allows to reduce the measurement time up to 0,1 τ as well as conduct the controlled heating of RTD, improving the metrological characteristics of integrated humidity and temperature sensors.

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REFERENCES

[1] Khan S. M., Shaikh S. F., Qaiser N., Hussain M. M. Flexible Lightweight CMOS-Enabled Multisensory Platform for Plant Microclimate Monitoring. *IEEE Transactions on Electron Devices*, 65 (2018), No.11, 5038-5044.

[2] Miloshevich L. M., Vömel H., Paukkunen A., Heymsfield A. J., Oltmans S. J. Characterization and correction of relative humidity measurements from Vaisala RS80-A radiosondes at cold temperatures. *Journal of Atmospheric and Oceanic Technology*, 18 (2001), No.2, 135-156.

[3] Chen Z., Lu C. Humidity sensors: a review of materials and mechanisms. *Sensor letters*, 3 (2005), No.4, 274-295.

[4] Rittersma Z. M. Recent achievements in miniaturised humidity sensors—a review of transduction techniques. *Sensors and Actuators A: Physical*, 96 (2002), No. 2-3, 196-210.

[5] Sumorek A. System do pomiarów obciążenia wiatrem rusztowań elewacyjnych. *Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska*, 6 (2016), nr.4, 37-42.

[6] Stolarczuk P.; Yatsuk V.; Majewski J., Małaczywski P., Michalewa M. Usage of capacitive sensors for fast checking of parameters of multicomponent solutions. *Przegląd Elektrotechniczny*, 86 (2010), No. 10, 92-95.

[7] Kang U., Wise K. D. A high-speed capacitive humidity sensor with on-chip thermal reset. *IEEE Transactions on Electron Devices*, 47(2000), No. 4, 702-710.

[8] Majewski J. Low Humidity Characteristics of Polymer-Based Capacitive Humidity Sensors. *Metrology and Measurement Systems*, 24 (2017), No.4, 607-616.

[9] Qiu Y. Y., Azeredo-Leme C., Alcacer L. R., Franca J. E. A CMOS humidity sensor with on-chip calibration. *Sensors and Actuators A: Physical*, 92 (2001), No. 1-3, 80-87.

[10] Hübert T., Tiebe C., Detjens M., Majewski J. On-site calibration system for trace humidity sensors. *Measurement*, 91 (2016), 251-257.

[11] Hotra O., Boyko O. Analogue linearization of transfer function of resistive temperature transducers. *Proceeding of SPIE Photonics Applications in Astronomy Communications Industry and High-Energy Physics Experiments*, 9662 (2015), 966247-8.

[12] Trump B. Analog linearization of resistance temperature detectors. *Analog Applications Journal*, 4Q (2011), 21-24.

[13] Duff M., Towey J. Two ways to measure temperature using thermocouples feature simplicity, accuracy, and flexibility. *Analog dialogue*, 44 (2010), No. 10, 1-6.

[14] Humidity Sensor Theory and Behavior. Application Sheet. *Honeywell. Sensing and Control.* 2008. Availeble from: https://sensing.honeywell.com/index.php?ci_id=49925&la_id=1

[15] Hassan A. S., Juliet V., Raj C. J. A. MEMS Based Humidity Sensor with Integration of Temperature Sensor. *Materials Today: Proceedings*, 5 (2018). No.4, 10728-10737.

[16] Qu W., Wlodarski W. A thin-film sensing element for ozone, humidity and temperature. *Sensors and Actuators B: Chemical*, 64 (2000), No. 1-3, 42-48.

[17] Le Neel O., Shankar R., Cherian S., Leung C., Loh, T. C., Kam S.Y. Integrated multi-sensor module U.S. Patent No. 9,689,824. Washington. (2017).

[18] Tetelin A., Pellet C., Laville C., N'Kaoua G. Fast response humidity sensors for a medical microsystem. *Sens. Actuators B, Chem.*, 91 (2003), 211–218.

[19] Boyko O., Hotra O. Correction of dynamic characteristics of temperature measuring devices. *Proceeding of SPIE,* 10808 (2018), 1080858 -7.

[20] D'Aleo F.P., Stalder R., Prasser H.M. Design and development of resistive temperature detector arrays on aluminium substrates. Measurements in mixing experiments. *Flow Measurement and Instrumentation*. 45 (2015), 176–187.

[21] Hotra O., Boyko O., Zyska T. Improvement of the operation rate of medical temperature measuring devices, *Proceeding of SPIE*, 92914 (2014), 92910A-6.

[22] Frankiewicz M., Gołda A., Kos A. Analysis and verification of integrated circuit thermal parameters. *Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska*, 4(2014), 11-15.