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The Precise Temperature Measurement System with Compensation of Measuring Cable Influence

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Abstract: The article presents an active bridge system that enables the solution of a significant problem consisting in ensuring correct indications of temperature values in a wide measuring range for a Pt100 temperature sensor with properties defined by the standard (EN-60751 + A2). The presented active bridge system combines the properties of the measuring amplifier with the stabilization of the current value in the branch in which the Pt100 sensor was placed. The article focuses on the comparison of the temperature measurement in a typical resistance bridge and the measurement made in the developed active bridge, which has also become the subject of a patent. For the performed tests, in which the correctness of the temperature measurement system operation was verified, and on the basis of the obtained results, the quality of temperature measurements was compared in a wide range of changes.

Keywords: measuring bridge; Pt100 resistance thermometer; voltage compensation; resistance measurement; temperature measurement

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1. Introduction

Temperature sensors are among the most commonly used sensors because the physical quantity of temperature is measured, regulated, recorded, and monitored in a variety of environments and in most technological processes. Almost every device used in domestic, industrial, or laboratory environments, ranging from computers, cars, power trains, air conditioners, measuring devices, or thermostats, uses temperature sensors. The most common types of temperature sensors include thermistors, thermocouples, resistance temperature detectors (RTDs), digital thermometer integrated circuits, and analog thermometer integrated circuits [1–13].

This article describes an accurate thermometer measurement system that includes resistive temperature detectors RTDs, which are temperature sensors that contain a resistor. The resistor used in an RTD changes its resistance value as the temperature changes. The most common example of an RTD detector are Pt100 series temperature sensors, which have been used for many years to measure temperature in laboratory and industrial processes. The Pt100 is one of the most accurate temperature sensors. It does not only provide good accuracy but also excellent stability and repeatability of the measured values. The Pt100 sensors are also relatively resistant to electrical interference and are therefore well suited for temperature measurements in industrial environments, especially around motors, generators, and other high voltage equipment [14–17].

The most RTD temperature detectors consist of a thin and coiled wire that is wrapped around a ceramic or glass core. There are also designs of the sensor in the form of platinum sputtered onto a ceramic substrate. The sensor is usually fragile, so it is often placed in a probe sheath. The RTD sensor is made of a specific material, which is the most important element of this sensor in this case.

The performance of the sensor depends on the material it is made of. Most RTD sensors are made of platinum or nickel. The temperature characteristics of these materials are precisely documented, which makes it possible to precisely determine the temperature based on them. There are two standards for Pt100 thermoresistors, one of which is the European standard, also known as the standard DIN (Deutsches Institut für Normung, Berlin, Germany) or the IEC standard (International Electrotechnical Commission, Geneva, Switzerland) and the American standard ASTM (American Society for Testing and Materials, West Conshehocken, PA, USA). The European standard is considered the world standard for platinum RTD sensors. DIN/IEC 60,751 (or simply IEC751), requires the RTD to have the electrical resistance of 100.00 Ω at 0 °C and the temperature coefficient of resistance (TCR) of 0.00385 O/O/°C over a temperature range from 0 °C to 100 °C [14].

The paper presents a method of precise evaluation of a real temperature value in a large range of temperature T_C = 0 ÷ 850 °C using a thermoresistor Pt100. A special active measuring bridge was developed as well as the method of connecting a thermoresistor, effectively eliminating the influence of the wire's resistance.

An important problem that occurs during temperature measurement using a resistive temperature sensor is the need to limit the influence of the resistance of the wires, by which such a sensor is connected to the measuring system, and which is the cause of erroneous temperature determination by such a sensor. Basically, three approaches are considered [8], i.e., using two wires [9,10], three wires [11], and the third approach, using four wires [13]. It should be mentioned that the described measurement system uses the compensation of the resistance of the lead wires by the three-wire method [16], which was improved and adapted to the system described below in this paper.

The paper presents a method of accurate determination of the actual temperature value of a Pt100 thermoresistor in a wide temperature measurement range T_C = 0 ÷ 850 °C, using an active measuring bridge developed for this purpose and taking into account the compensation of the influence of the wires connecting the sensor. The contents of the article are based on the patent descriptions [16,17], of which the author is a co-author.

2. Active Measuring Bridge with Current Stabilization

In most applications, the Pt100 thermoresistor is used in a passive measuring bridge system, which is made of matched resistors, as shown in Figure 1 [6,7,14].

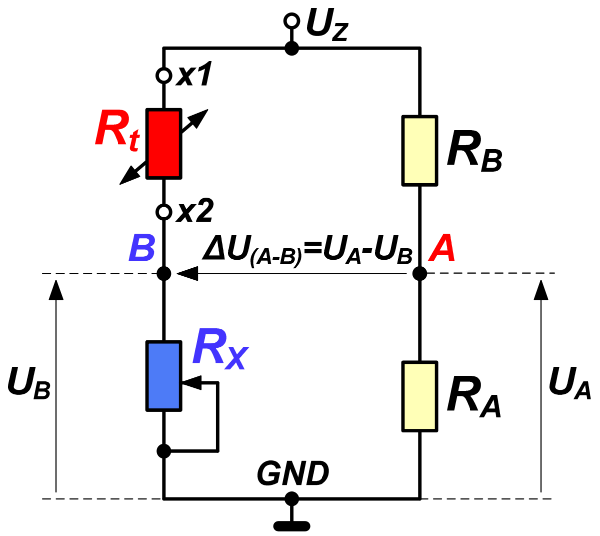

Figure 1. A passive measuring bridge with a thermoresistor Pt100 represented by resistance R_t.

The circuit in Figure 1 is a passive bridge for determining the resistance value R_t. It contains a thermoresistor, represented by resistance R_t, and resistors R_B and R_A, which are placed in the second branch of the bridge. Resistor R_X is connected (in the first branch of the bridge) in series with the resistor R_t. For a specific value of the temperature T_C expressed in [°C], it is possible, by changing the value of the resistance R_X, to bring the voltage U_A = U_B into equilibrium. Then the condition according to Equation (1) occurs.

$$\Delta U_{(A-B)} = U_A - U_B = 0 \tag{1}$$

A change in temperature causes a change in the resistance value R_t, which introduces (Figure 1) a change in the voltage value U_B and it affects the value of the deviation $\Delta U_{(A-B)}$. The change of the U_B value will cause the nonzero $\Delta U_{(A-B)}$ value. Another adjustment of the R_X value will cause the voltage deviation $\Delta U_{(A-B)}$ to approach zero.

The following analysis of the values of voltages U_B and U_A for the passive bridge shown in Figure 1 is carried out in order to obtain a relationship, from which the temperature of a Pt100 thermoresistor can be easily calculated. The voltage drop U_B is expressed by the formula:

$$U_B = U_Z \cdot \left(\frac{R_X}{R_X + R_t} \right) \tag{2}$$

where U_Z—the value of the bridge supply voltage. Whereas the voltage drop U_A is given by the relation:

$$U_A = U_Z \cdot \left(\frac{R_A}{R_A + R_B} \right) = \alpha \cdot U_Z \tag{3}$$

If $R_A = R_B$, then α in (3) is equal to: $\alpha = 1/2$.

$$U_A = U_Z \cdot \left(\frac{R_A}{R_A + R_B} \right) = \frac{1}{2} \cdot U_Z \tag{4}$$

Since the voltage difference $\Delta U_{(A-B)}$ is calculated from Equation (1). Then after substituting the relations (2) and (3) into this formula one can obtain:

$$\Delta U_{(A-B)} = U_A - U_B = U_Z \cdot \left(\frac{1}{2} - \frac{R_X}{R_t + R_X} \right) \tag{5}$$

After ordering the right-hand side of Equation (5), the relation for the voltage difference $\Delta U_{(A-B)}$ (6) is obtained. This relation is crucial in determining the temperature.

$$\Delta U_{(A-B)} = \frac{U_Z}{2} \cdot \left(\frac{R_t - R_X}{R_t + R_X} \right) \tag{6}$$

In the circuit of Figure 1, the measurement and calculation of the resistance value R_t is performed when the principle of voltages' equality $U_A = U_B$ is applied. For the case when $U_A = U_B$, the resistance value R_t corresponds to the resistance value R_X. On the basis of the resistance value R_t and the knowledge of the temperature characteristics of platinum, the temperature value T_C can be calculated based on the formula obtained by solving the quadratic equation included in the European standard EN-60751 + A2 or by using the calculated temperature values, which, in tabulated form, are included in that standard [14–17].

In the European standard (EN-60751 + A2), the change of a platinum thermoresistor Pt100 resistance value (7) was described analytically as the value dependent on the temperature value in the range from 0 to 850 °C.

$$R_t = R_0 \cdot \left(1 + A \cdot T_C + B \cdot {T_C}^2 \right) \tag{7}$$

Rt—the resistance value of the thermoresistor at temperature T_C (°C), R_0—the resistance value of the thermoresistor at temperature T_C = 0 °C, according to the standard (EN-60751 + A2), R_0 = 100 Ω (or 500 Ω, and also 1000 Ω), A, B—constants connected with the material property of platinum Pt according to the standard (EN-60751 + A2), $A = 3.9083 \times 10^{-3}$ (1/°C), $B = -5775 \times 10^{-7}$ (1/°C^2).

By solving the quadratic Equation (7) the relation according to Equation (8) is obtained [15]. It determines the temperature value T_C of the thermoresistor depending on the resistance value R_t;

$$T_C = \frac{-A}{2 \cdot B} - \sqrt{\left(\frac{A}{2 \cdot B} \right)^2 + \frac{1}{B} \cdot \left(\frac{R_t}{R_0} - 1 \right)}. \tag{8}$$

In the Formula (8), the fragment described by the relation (9) is important;

$$\left(\frac{R_t}{R_0} - 1\right). \tag{9}$$

The calculation of the temperature value directly according to Formula (8) introduces a great simplification, whereas if one introduces into Formula (8) the voltage value U_P resulting from the measurement of this voltage in the bridge system, a new relation is obtained equal to the product of the proportionality coefficient (S_K) and the measurement voltage (U_P) (10);

$$\left(\frac{R_t}{R_0} - 1\right) = S_K \cdot U_P. \tag{10}$$

An important disadvantage of the passive bridge presented in Figure 1 is the fact that the output voltage $\Delta U_{(A-B)}$ according to Formula (6) does not represent the relations given in (9) and (10). This passive bridge limitation evoked considerations about an active resistance bridge using an operational amplifier presented in Figure 2 [10,13]. This solution permits stabilizing current I = I$_{\text{const}}$ flowing through the thermoresistor R_t.

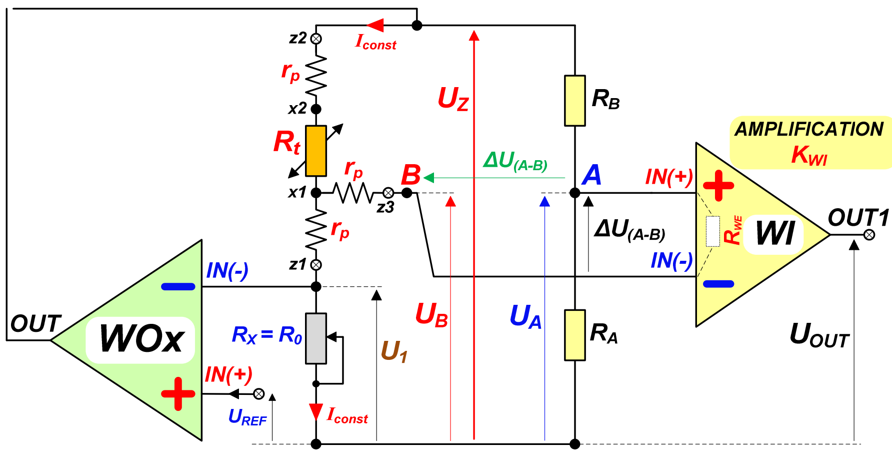

Figure 2. Scheme of an active measuring bridge with the current value stabilization $I = I_{const}$ in the bridge branch with a Pt100 thermoresistor.

Operational amplifiers have been known for many years in electronics, and due to their well-known properties, they are still used in many applications [16–21]. The amplifier marked as *WOx* in Figure 2 acts as a current source, whose task is to stabilize the current in the bridge branch, including the resistor *Rt*. On the other hand, the instrumental amplifier marked as *WI* acts as a scaling circuit for the output voltage representing the measured temperature [13,14].

Similarly as in the case of the passive bridge (Figure 1), the analysis of the system in Figure 2 is carried out below. Its aim is to derive the relation, which allows calculating the relation given by the Equation (1).

At the beginning of the analysis, voltage drops U_A and U_B were determined according to the scheme presented in Figure 2:

$$U_A = U_Z \cdot \left(\frac{R_A}{R_A + R_B}\right) = \alpha \cdot U_Z \tag{11}$$

$$U_B = U_Z \cdot \left(\frac{R_X + r_p}{R_X + R_t + 2 \cdot r_p}\right) \tag{12}$$

where r_p—resistance of the wire used to connect the thermoresistor.

If in the Formula (11) $R_A = R_B$, then $\alpha = 1/2$. The relation $\Delta U_{(A-B)}$ for an active measuring bridge is equal to:

$$\Delta U_{(A-B)} = U_A - U_B = U_Z \cdot \left(\alpha - \frac{R_X + r_p}{R_X + R_t + 2 \cdot r_p} \right) \tag{13}$$

After reducing it to a common denominator and applying the substitution $\alpha = 1/2$, we obtain:

$$\Delta U_{(A-B)} = U_Z \cdot \left(\frac{0.5 \cdot R_X + 0.5 \cdot R_t - R_X}{(R_X + R_t + 2 \cdot r_p)} \right) = \frac{U_Z}{2} \cdot \left(\frac{R_t - R_X}{R_X + R_t + 2 \cdot r_p} \right) \tag{14}$$

For the purpose of stabilizing the current value I in the bridge branch, in which the thermoresistor R_t is placed, Formula (15) expresses the dependence of the current value I on the voltage U_{REF}.

$$U_{REF} = I \cdot R_X = I \cdot R_0 \tag{15}$$

$$U_{REF} = I \cdot R_X = \frac{U_Z}{R_X + R_t + 2 \cdot r_p} \cdot R_X \tag{16}$$

$$U_Z = \frac{U_{REF} \cdot (R_X + R_t + 2 \cdot r_p)}{R_X} \tag{17}$$

Inserting into Equation (14) the expression (17), one can obtain the form:

$$\Delta U_{(A-B)} = U_A - U_B = \frac{U_{REF}}{2} \cdot \left(\frac{R_t}{R_X} - 1 \right) \tag{18}$$

Or

$$\begin{aligned} U_{OUT} &= \Delta U_{(A-B)} \cdot K_{WI} = (U_A - U_B) \cdot K_{WI} \\ &= K_{WI} \cdot \tfrac{U_{REF}}{2} \cdot \left(\tfrac{R_t}{R_X} - 1 \right) \end{aligned} \tag{19}$$

where K_{WI}—the gain value of the WI amplifier, U_{REF}—the reference voltage for the adopted measurement range.

In particular, it is important that the relation (9), resulting from the equation solution given in EN-60751 + A2 is equal:

$$\left(\frac{R_t}{R_X} - 1 \right) = \frac{2 \cdot U_{OUT}}{K_{WI} \cdot U_{REF}} \tag{20}$$

On the other hand, if we take the resistor value R_X to be the resistor value R_0 from Formula (9), then Formula (20) will take the form (21).

$$\left(\frac{R_t}{R_0} - 1 \right) = \frac{2 \cdot U_{OUT}}{K_{WI} \cdot U_{REF}} \tag{21}$$

From the analysis presented above, it follows that the structure of the active measuring bridge (Figure 2) with the stabilization of the current value in the bridge branch, in which the thermoresistor R_t is placed, provides the output voltage U_{out} in the form convenient for the substitution into Formula (8).

Comparing Formula (9) with Formula (21), Formula (8) can be written in the form (22) or in the form (23):

$$\begin{aligned} T_C &= \tfrac{-A}{2 \cdot B} - \sqrt{\left(\tfrac{A}{2 \cdot B} \right)^2 + \tfrac{1}{B} \cdot \left(\tfrac{R_t}{R_0} - 1 \right)} \\ &= \tfrac{-A}{2 \cdot B} - \sqrt{\left(\tfrac{A}{2 \cdot B} \right)^2 + \tfrac{1}{B} \cdot \tfrac{2 \cdot U_{OUT}}{K_{WI} \cdot U_{REF}}} \end{aligned} \tag{22}$$

or

$$\begin{aligned} T_C &= \tfrac{-A}{2 \cdot B} - \sqrt{\left(\tfrac{A}{2 \cdot B} \right)^2 + \tfrac{2}{B \cdot K_{WI} \cdot U_{REF}} \cdot U_{OUT}} \\ &= \tfrac{-A}{2 \cdot B} - \sqrt{\left(\tfrac{A}{2 \cdot B} \right)^2 + S_K \cdot U_{OUT}} \end{aligned} \tag{23}$$

where S_K—denotes the calibration constant equal to:

$$S_K = \frac{2}{B \cdot K_{WI} \cdot U_{REF}}. \quad (24)$$

3. Selection of the Partition Coefficient α and the Resistance R_0

In Formulas (3) and (11), the division coefficient α was introduced. Theoretically, in the bridges under consideration, it is possible to assume any resistance value in the range 100 ÷ 1000 Ω, which meets the condition $R_A = R_B = R$, while from the point of view of the resistance measurement R_t it is more important to be able to tune the values of these resistors, e.g., by laser correction. In practical applications, it is possible to take the resistance value R_A and then match the resistance value R_B to it very precisely. You can also do the opposite, i.e., take the value of R_B resistance and then match the value of the resistance R_A to it. The absolute resistance value of R_A and R_B is not important in this case, but the exact value of the ratio of these resistances is very important and must be equal to $\alpha = 1/2$. An accurate value of α contributes to effective influence elimination of the wires resistance r_p connecting the Pt100 sensor to the measuring amplifier system (Figure 2).

Another issue is the selection of the resistor value R_0 (R_X). If the temperature measuring range is to start from $T_C = 0$ °C, the resistor value R_0 must be $R_0 = 100.00$ Ω. Selecting a different resistor value R_0 allows you to set a different reference point for the initial value of the measured temperature. When selecting the resistor value R_0, which is not an easy task, one can try to use highly stable MFR resistors with a small coefficient of the resistance change versus temperature. This type of resistors are difficult to obtain and very expensive. Therefore, a different solution was used in the design of the bridge measuring the amplifier. The resistor R_0 is a more complex design. The resistor value R_X was initially assumed to be a parallel combination of two MRF 1% (25 ppm) resistors with the respective values of 150 Ω and 330 Ω.

The resultant resistance value R_X is $R_X \approx 150\ \Omega//330\ \Omega \approx 103\ \Omega$. Then an additional resistor R_1 with a potentiometer P_1 connected in series was connected in parallel to R_X. By changing the value of the potentiometer P_1 one can vary the resultant value of R_0 around the value $R_0 = 100\ \Omega \pm 1\ \Omega$. By setting the adjustable resistor decade to $R_t = 100.00$ Ω it is possible to obtain a voltage value of $\Delta U_{(A-B)} = 0.00$ V (measured with the use of a 6½-digit voltmeter). Moreover, the potentiometer P_1 makes it possible to change the sign of the voltage value $\Delta U_{(A-B)}$. In this way, the resistance value R_0 can be determined precisely.

The value of the current I_0 flowing through the thermoresistor Pt100 depends on the type of the environment, in which the measuring sensor is located. It is connected with the phenomenon of self-heating of the thermoresistor R_t, because the electrical power $P[W]$ is emitted on the thermoresistor and converted into heat:

$$P[W] = I_0^2 \cdot R_t. \quad (25)$$

When the temperature value t [°C] is measured in an air (gas) environment, the heat transfer between the environment and the thermoresistor R_t (heated due to I_0 current flow) is weak. In an aqueous environment (liquids), the heat transfer from the heated sensor is more intensive. Therefore, lower values of I_0 current are assumed for the measurements in a gaseous environment. In the liquid environment, the value of I_0 current may be higher. In the project, it was initially assumed (for the analysis) that the measurement of temperature t (°C) takes place in the water environment. (e.g., in district heating systems). For this case, the safe current value I_0 is $I_0 = 7$ mA.

4. Problem of Connecting a Pt100 Sensor to a Measuring Amplifier

Figure 3 presents the sensor Pt100 and two wires connecting its terminals ($x1$ i $x2$) to wire terminals denoted as $z1$ i $z2$, which were connected to the operational amplifier input. The measurement system using the thermoresistor Pt100 generates two following problems:

- The resistance r_p of connecting wires is never precisely known;
- The environment temperature influences a change of the resistance r_p value.

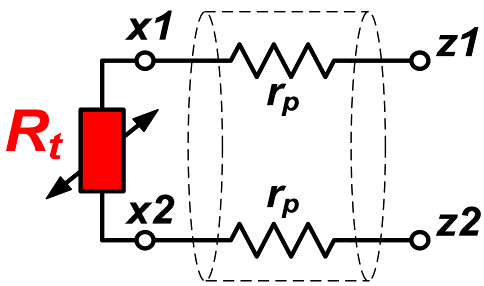

Figure 3. The Pt100 sensor (thermoresistor) with connection wires of the resistance r_p.

Figure 4 shows an incorrect (two-wire) connection of a Pt100 sensor to a bridge measuring the amplifier circuit.

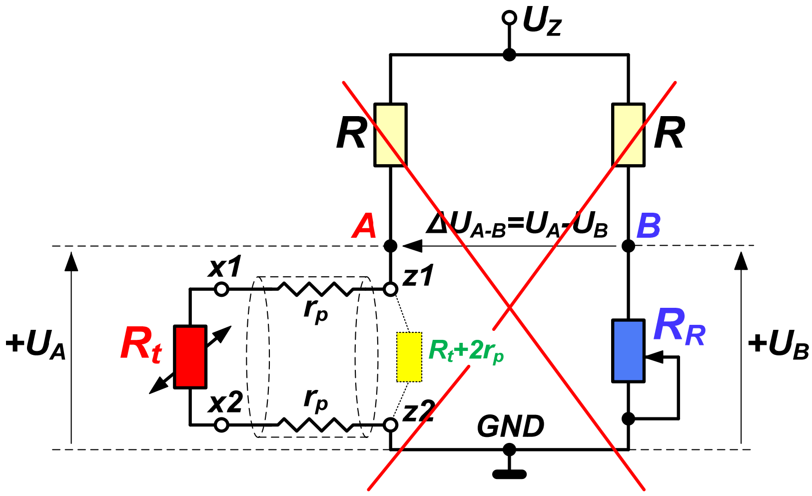

Figure 4. The incorrect connection of the Pt100 sensor to the measuring bridge system.

In the bridge circuit of the amplifier (Figure 4) between terminals $z1$ and $z2$, the value of the measuring resistance defined by Formula (26) must also be taken into account [22].

$$R_{(z1 \div z2)} = R_t + 2 \cdot r_p \tag{26}$$

With the long connection wires between the sensor location and the measuring bridge, the resistance value r_p starts to be comparable to the resistance value of the Pt100 sensor. As a reminder, the resistance value of the Pt100 sensor is $R_{\mathrm{Pt100}} \approx 100.00\ \Omega$. Figures 5 and 6 show the 3-wire method of connecting the Pt100 sensor to the measuring amplifier. The applied 3-wire connection system eliminates the influence of changes in the resistance value r_p on the measurement result of the resistance value of the Pt100 sensor R_t.

Figure 7 shows the method of connecting the Pt100 sensor in a measuring amplifier circuit with the structure of a resistive measuring bridge. The resistance r_p of the connection wire between the $z2$ and $x2$ terminals was connected to the bridge branch, in which the Pt100 measuring thermoresistor was located. The resistance r_p of the connection wire between the $z1$ and $x1$ terminals was connected to the bridge branch, in which the reference resistor $R_X = R_0$ was located. This method of connection effectively eliminates the influence of the wires resistance r_p. This property is due to the fact that the resistance of the connection wires r_p in this connection adds simultaneously to the resistance of the thermoresistor ($R_t + r_p$) and the reference resistance ($R_0 + r_p$) in the corresponding branches of the measuring bridge. On the other hand, such a connection does not disturb the balance of the measuring bridge because the changes in the resistance r_p value (also due to temperature changes) take place simultaneously in both branches of the measuring bridge included in the measuring amplifier circuit (Figure 2).

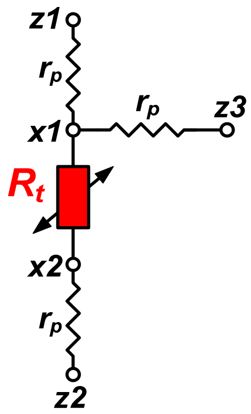

Figure 5. The 3-wire circuit to connect the Pt100 sensor takes into account the wire's resistance r_p between the $x1$, $x2$ and $z1 \div z3$ terminals incorrect connection of the Pt100 sensor to the measuring bridge system.

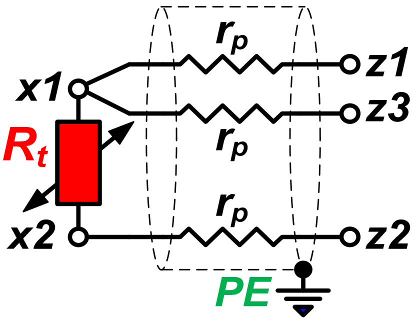

Figure 6. The 3-wire circuit for the Pt100 sensor includes the wire's resistance r_p and their insulation.

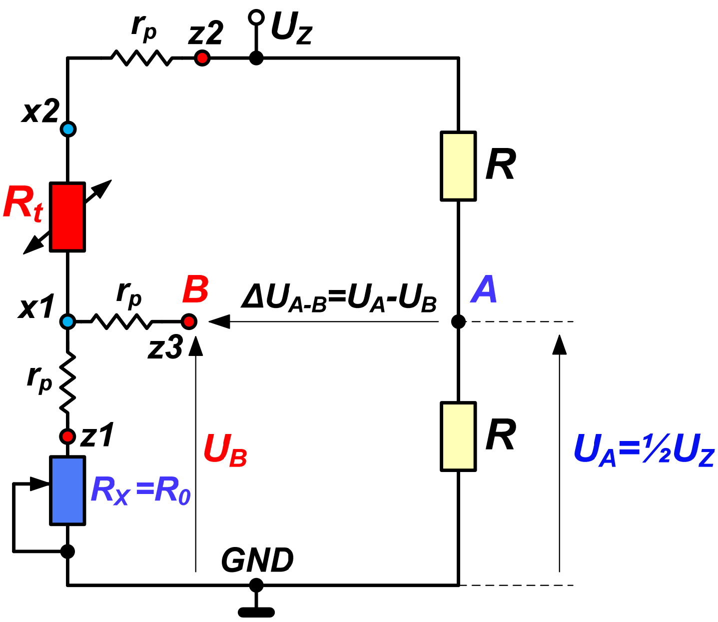

Figure 7. The measuring bridge circuit with a 3-wire Pt100 sensor connection.

The resistance r_p of the connection cable between the terminals $z3$ and $x1$ serves to transfer the potential of the $x1$ point to the $z3$ terminal of the measuring bridge. The use of the terminal $z3$ requires the use of a bridge measuring amplifier WI with a high value of the input resistance R_{in}. The value of the input resistance R_{in} of the instrumental amplifier WI (Figure 8) cannot cause a significant voltage value drop on the resistance r_p between the terminal *x*2 and *z*3. In the actual circuit of the instrumental amplifier *WI*, the resistance value R_{in} is very high. Therefore, the problem raised here does not exist in it.

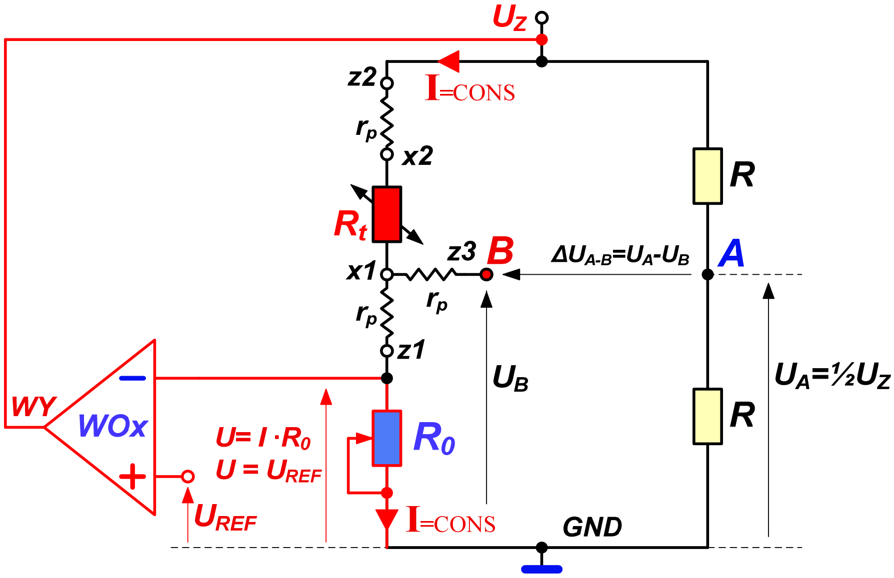

Figure 8. The operational amplifier *WOx* forming the structure of the current source, stabilizing the current I value connected to the bridge circuit.

5. Implementation of the Active Measurement Bridge on the LM723 IC

The LM723 integrated circuit and the *WI* instrumental amplifier were used to build the measurement amplifier. The LM723 integrated circuit is a voltage stabilizer containing in its structure (Figure 9) all components appearing in Figure 2, i.e.:

- The operational amplifier *WOx* with the maximum output current I = 150 mA;
- The reference voltage source (temperature stable) with the voltage value U_{REF} = 7.15 V;
- The output amplifier *WOx* has short-circuit protection which can occur between the wires connecting the Pt100 sensor and the measuring amplifier. The value of limiting current I_{ZW} is set by the resistor value R_{ZW};
- The *WOx* amplifier is equipped with compensation (capacitor C8), which effectively eliminates the excitation possibility of the *WOx* amplifier.

Figure 9 shows a schematic diagram of an active measuring bridge with I value stabilization in the branch, where a Pt100 thermoresistor is placed. An important limitation arising from the use of the LM723 integrated circuit is that it is adapted to be supplied only with a single positive voltage. Therefore, the voltage value on the pins number 4 and 5 of this I_C must be higher than 2 V.

The design of the LM723 chip allows the use of short-circuit protection in the form of a current limiter. A short circuit occurs when the failure of the insulation occurs. It happens when the wires connecting the Pt100 sensor to the measuring bridge fell in damage. Such a case is not so rare when there is a large distance between the place of installation of the Pt100 sensor, e.g., on the pipeline, and the place of installation of the measuring amplifier. The resistor value R_{ZW} can determine the limiting current I_O. The maximum value of the I_O output current of the LM723 chip is I_O = 150 mA. The value of the I_O current required for the proper operation of the bridge supply system with a Pt100 thermoresistor does not exceed I_O = 10 mA.

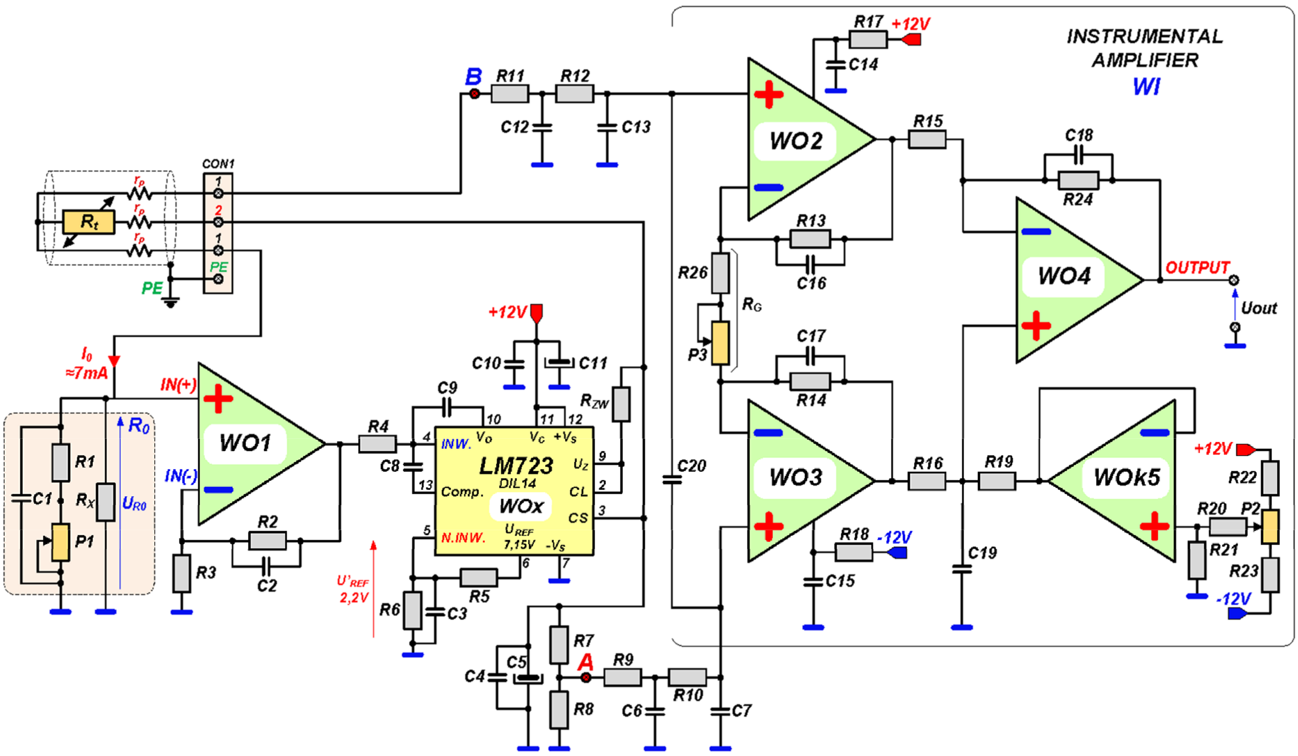

Figure 9. Schematic diagram of the bridge measuring amplifier with current *I* stabilization based on LM723 IC.

Figure 10 shows the connection diagram of the bridge measuring the amplifier module (as the analog measuring part) using the microprocessor computing block. The analog-to-digital (A/D) converter is a circuit that converts the analog voltage from the output of the bridge measuring amplifier to a digital value. The digital form of this voltage value is used by the calculation algorithm. A 16-bit A/D converter was applied. It allows achieving the required accuracy of the t (°C) temperature value calculation. The calculated value of the temperature t (°C) is presented on a digital indicator. Technical capabilities of contemporary microprocessors allow for easy transmission of the measurement results and their archiving.

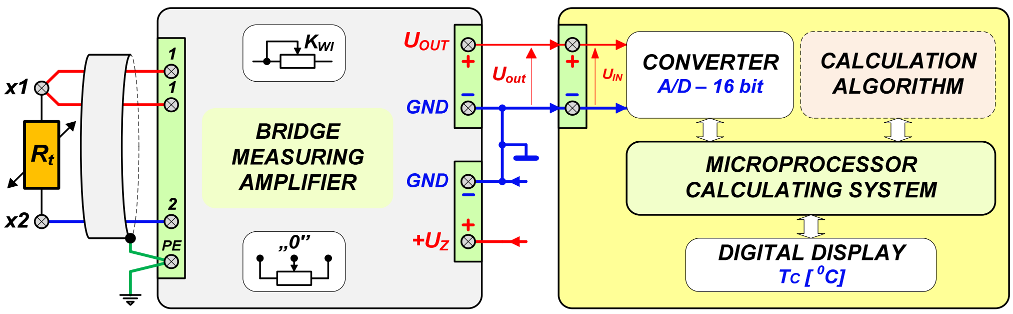

Figure 10. Block diagram of the connection system of the bridge measuring amplifier and the microprocessor system calculating the temperature value.

As soon as the electronic modules have been completed, the entire measurement path should be calibrated. The calibration procedure should be as follows:

(a) Set the value of the resistor R_t (calibration decade) R_t = 100.00 Ω for T_C = 0 °C;
(b) Measure the voltage value between points A and B of the active measuring bridge;
(c) Set the output voltage $\Delta U_{(A-B)}$ = 0.00 V by adjusting the potentiometer P_1 (Figure 10);
(d) With the use of the P_2 potentiometer (Figure 10) establish the output voltage indication (removing *WI* instrumental amplifier unbalance voltage) U_{out} = 0.00 V, the P_3

potentiometer (Figure 4) should be set in the position K_{WI} ensuring the gain required for a given measurement range;

(e) Set the resistor value R_t (calibration resistor decade) R_t = 313.71 Ω, which corresponds to the temperature value T_{C_MAX} = 850 °C;

(f) On the output of the measuring bridge amplifier set the value of the output voltage U_{out} = 5.00 V; the fine adjustment is made with the potentiometer P_3;

(g) Repeat the adjustment process from pt. 3 ÷ 5;

(h) Enter into the calculation program the value of the calibration constant S_K given by the Formula (24).

It is obvious that the exact value of the calibration constant S_K is never known. This is so because the actual platinum used to build the Pt100 thermoresistor may have a different value of the calibration constants A and B (1). Therefore, the tuning of the calibration constant S_K should be performed as follows:

- Using the calculation program based on Formula (2) it is necessary to achieve the indication value of the temperature T_C = 850 °C. This value can be reached by entering the pre-calculated value of the calibration constant S_K. For example, for the temperature value T_C = 850 °C and the voltage U_{out} = 5 V the value of the calibration constant S_K will be $S_K = -1{,}005{,}991.341991(341991)$;
- Then, by correcting the value of the calibration constant S_K, the value of T_C = 850.0 °C on the digital indicator should be obtained;
- Decreasing (e.g., using the calibration decade) the values of the resistor settings R_t according to the values in Table 1; check the correctness of the temperature indication T_C(°C) calculated by the program. The temperature indication value must correspond to the values given in Table 1.

Table 1. The tabulated resistance values of a Pt100 thermoresistor with the corresponding temperatures.

	R_t (Ω)	T (°C)
1	390.48	850.0
2	375.70	800.0
3	360.64	750.0
4	345.28	700.0
5	329.64	650.0
6	313.71	600.0
7	297.49	550.0
8	280.98	500.0
9	264.18	450.0
10	247.09	400.0
11	229.72	350.0
12	212.05	300.0
13	194.10	250.0
14	175.86	200.0
15	157.33	150.0
16	138.51	100.0
17	119.40	50.0
18	100.00	0.0

For other ranges of the maximum measured temperature values T_{C_MAX} (°C), different values of the calibration constant S_K must be adopted. The calibration constant always refers to the maximum voltage value U_{out} = 5 V, which is present at the output of the measuring amplifier. The analog-to-digital converter (A/D converter) used in the project can process the analog input voltage of the maximum value $U_{IN-A/D}$ = 5 V. Therefore, the gain value K_{WI} of the measurement amplifier (representing the resistance/voltage converter—R/U) is regulated in such a way that at its output (for the R_t value resulting from the maximum temperature value) the voltage value U_{out} = 5 V is obtained.

$$S_K = \frac{\frac{1}{B}\cdot\left(\frac{R_t}{R_0}-1\right)}{(U_{OUT}=5V)\cdot B} = \frac{\left(\frac{R_t}{R_0}-1\right)}{5\cdot B} = \frac{\left(\frac{R_t}{R_0}-1\right)}{-5\cdot 0.0000005775} = \frac{\left(\frac{R_t}{R_0}-1\right)}{-0.0000028875} \tag{27}$$

$$S_K = \frac{\left(\frac{R_t}{R_0}-1\right)}{-0.0000028875} = -346,320.34632\cdot\left(\frac{R_t}{R_0}-1\right) \tag{28}$$

Formula (28) is the universal calculation formula of the calibration constant value S_K. Formula (28) assumes the value of B, R_0, and U_{out} = 5 V. For the maximum temperature value t_{MAX} (°C), the corresponding resistance value R_t is assumed according to the calculation results. Table 2 shows the calculated values of the calibration constant S_K, referring to the maximum value of the measuring temperature range t_{MAX} (°C), at which at the measuring amplifier output there will be the voltage of the value U_{out} = 5 V.

Table 2. The calculated values of the calibration constant S_K in relation to the maximum value of the temperature measurement range (value of voltage U_{out} = 5 V of the amplifier *WI*).

	Maximum Value of the Measured Temperature t_{MAX} [°C]	**R_t [Ω]**	**$S_K = -346{,}320.34632\cdot(\frac{R_t}{R_0}-1)$**
1	50.0	119.40	−67,186.147186
2	100.0	138.51	−133,367.965367
3	150.0	157.33	−198,545.454545
4	200.0	175.86	−262,718.614718
5	250.0	194.10	−325,887.445887
6	300.0	212.05	−388,051.948051
7	350.0	229.72	−449,246.753246
8	400.0	247.09	−509,402.597402
9	450.0	264.18	−568,588.744588
10	500.0	280.98	−626,770.562769
11	550.0	297.49	−683,948.051947
12	600.0	313.71	−740,121.212121
13	650.0	329.64	−795,290.043289
14	700.0	345.28	−849,454.545453
15	750.0	360.64	−902,649.350648
16	800.0	375.70	−954,805.194804
17	850.0	390.48	−1,005,991.341991

6. Calculation Software

Figure 11 shows a diagram illustrating the operation of the calculation program that was used in the study. In order to check the correctness of the calculations carried out by the program, an analysis of the algorithm enabling the temperature defining was carried out. The Formulas (44 ÷ 51) present the analysis carried out.

$$t = \frac{-A}{2\cdot B} - \sqrt{\left(\frac{A}{2\cdot B}\right)^2 + \left(\frac{2}{B\cdot K\cdot U_{REF}}\right)\cdot U_{OUT}} = \frac{-A}{2\cdot B} - \sqrt{\left(\frac{A}{2\cdot B}\right)^2 + S_K\cdot U_{OUT}} \tag{29}$$

$$t = \frac{-A}{2\cdot B} - \sqrt{\left(\frac{A}{2\cdot B}\right)^2 + S_K\cdot U_{OUT}} = \frac{-0.0039083}{2\cdot(-0.0000005775)} - \sqrt{\left(\frac{A}{2\cdot B}\right)^2 + S_K\cdot U_{OUT}} \tag{30}$$

$$\frac{-A}{2\cdot B} = \frac{-0.0039083}{2\cdot(-0.0000005775)} = 3383.80952380(80952380) \tag{31}$$

$$\left(\frac{A}{2 \cdot B}\right)^2 = (3383.80952380)^2 = 11,450,166.8933 \tag{32}$$

$$t = \frac{-A}{2 \cdot B} - \sqrt{\left(\frac{A}{2 \cdot B}\right)^2 + S_K \cdot U_{OUT}} = 3383.8095238 - \sqrt{11,450.8933 + S_K \cdot U_{OUT}} \tag{33}$$

$$t = 3383.8095238 - \sqrt{11,450.8933 + S_K \cdot U_{OUT}} \tag{34}$$

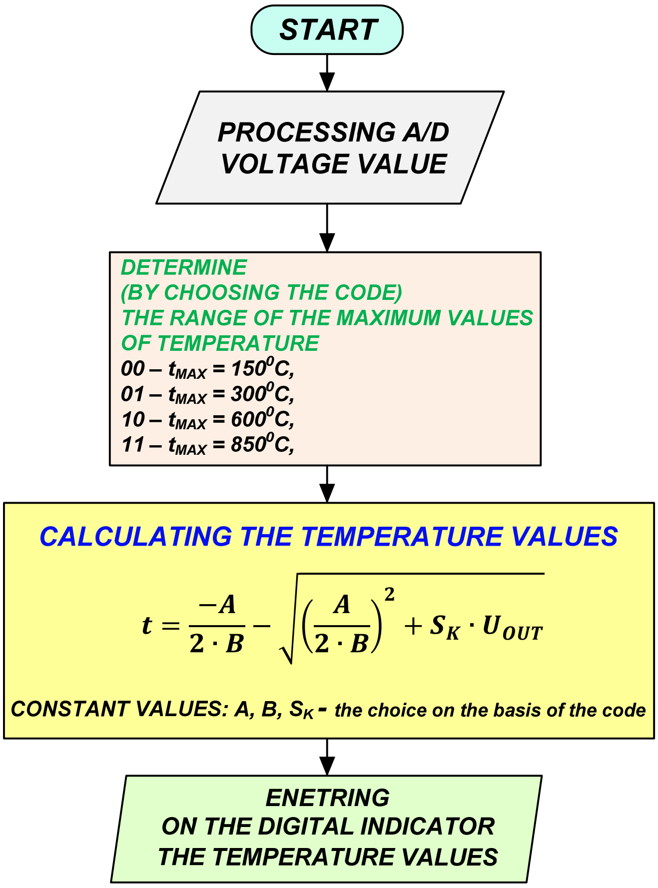

Figure 11. Algorithm scheme for the temperature value t (°C) calculation.

For temperature t = 850 °C and at U_{out} = 5 V, the value of the calibration constant was: $S_K = -1{,}005{,}991.341991(341991)$.

$$t = 3383.8095238 - \sqrt{11,450,166.8933 - 1005.341991 \cdot U_{OUT}} \tag{35}$$

For the output voltage value U_{out} = 5 V, the temperature value t_{MAX} (°C) will be:

$$t = 3383.8095238 - \sqrt{11,450,166.8933 - 1005.341991 \cdot 5\ \text{V}} \tag{36}$$

For the assumed temperature range T_C = 0 ÷ 850 °C the value of the calibration constant S_K can be calculated according to Formula (28). Then, based on Formula (37), the intermediate values of the output voltages U_{out} should be estimated.

$$U_{OUT} = \frac{\left(\frac{R_t}{R_0} - 1\right)}{B \cdot S_K} = 1.72128890115 \cdot \left(\frac{R_t}{R_0} - 1\right) \tag{37}$$

By applying the voltage within the range U_{out} = 0 ÷ 5 V to the input of the A/D converter, it is possible to control the correct intermediate indications of the T_C temperature values. For example, for calibration of the calculating system indications, the following relation was assumed: T_C (°C) = 0 ÷ 850 → $U_{IN-A/D}$ = 0 ÷ 5 V. Table 3 presents the calculated intermediate values of the voltage $U_{IN\ A/D}$ for the range of the temperature value measurement T_C = 0 ÷ 850 °C.

Table 3. The intermediate values of the $U_{IN\ A/D}$ voltages.

MEASUREMENT RANGE *t* = 0 ÷ 850 °C S_K = −1,005,991.341991(341991), *B* = −0.0000005775 U_{out} = $U_{IN\text{-}A/D}$ = 5 V for *t* = 850 °C			
	***T* (°C)**	**R_t [Ω]**	**U_{out} (V)**
1	0	100.00	0.000000
2	50	119.40	0.333930
3	100	138.51	0.662868
4	150	157.33	0.986815
5	200	175.86	1.305770
6	250	194.10	1.619733
7	300	212.05	1.928704
8	350	229.72	2.232856
9	400	247.09	2.531844
10	450	264.18	2.826012
11	500	280.98	3.115189
12	550	297.49	3.399373
13	600	313.71	3.678566
14	650	329.64	3.952768
15	700	345.28	4.221977
16	750	360.64	4.486367
17	800	375.70	4.745593
18	850	390.48	5.000000

Figure 12 shows the change in the resistance value $R_t(\Omega)$ = f(T_C) for a temperature value change using the linear and quadratic approximation. As the T_C temperature value increases, the linear approximation will cause an overestimation of the resistance R_t value. The EN-60751 + A2 standard introduces the possibility of presenting the characteristics of the Pt100 thermoresistor using the linear approximation [14–17]. Formula (38) defines the coefficient α.

$$\alpha = \frac{R_{100} - R_0}{R_0 \cdot 100\ ^{\circ}\mathrm{C}} \tag{38}$$

where:

- R_{100}—the resistance value of the thermoresistor Pt100 at temperature T_C = 100 °C, R_{100} = 138.51 Ω,
- R_0—the resistance value of the thermoresistor Pt100 at temperature T_C = 0 °C, R_0 = 100.00 Ω.

The value of α according to the definition given by Formula (38):

$$\alpha = \frac{R_{100} - R_0}{R_0 \cdot 100\ ^{\circ}\mathrm{C}} = \frac{138.51[\Omega] - 100.00[\Omega]}{100.00[\Omega] \cdot 100\ ^{\circ}\mathrm{C}} = 3.851 \cdot 10^{-3}\ [^{\circ}\mathrm{C}^{-1}] \tag{39}$$

After the transformation of Formula (39), the resistance value R_t is determined for the range of the temperature value changes T_C = 0 ÷ 100 °C. Formula (39) should be applied for the temperature measurement T_{C_MAX} = 100 °C. This is the so-called linear approximation. For the temperature measurements $T_{C\_MAX} \geq$ 100 °C, even up to 850 °C, Formula (7) should be used—the so-called quadratic approximation [14–17].

Figure 13 shows the course of the temperature indication difference ΔT_C for the linear and quadratic approximation.

For example (Figure 7): for the temperature value T_C = 500 °C the difference ΔT_C of T_C temperature readings will be +30 °C. The value of the ΔT_C difference increases with an increase of the T_C temperature value. After the analysis, it is clear that the use of the temperature measuring system presented in this paper very effectively reduces the value of the measurement error of the T_C temperature. Especially in the range of measuring the T_C temperature values ≥ 100 °C [14–17].

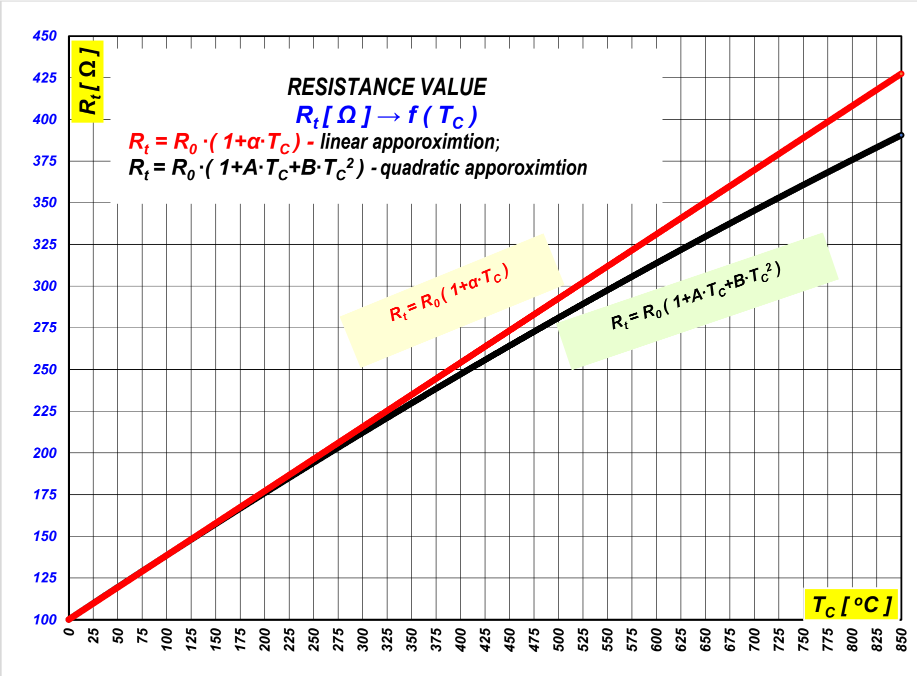

Figure 12. The resistance value $R_t = f(T_C)$ for the linear and quadratic approximation in the range from 0 to 800 °C.

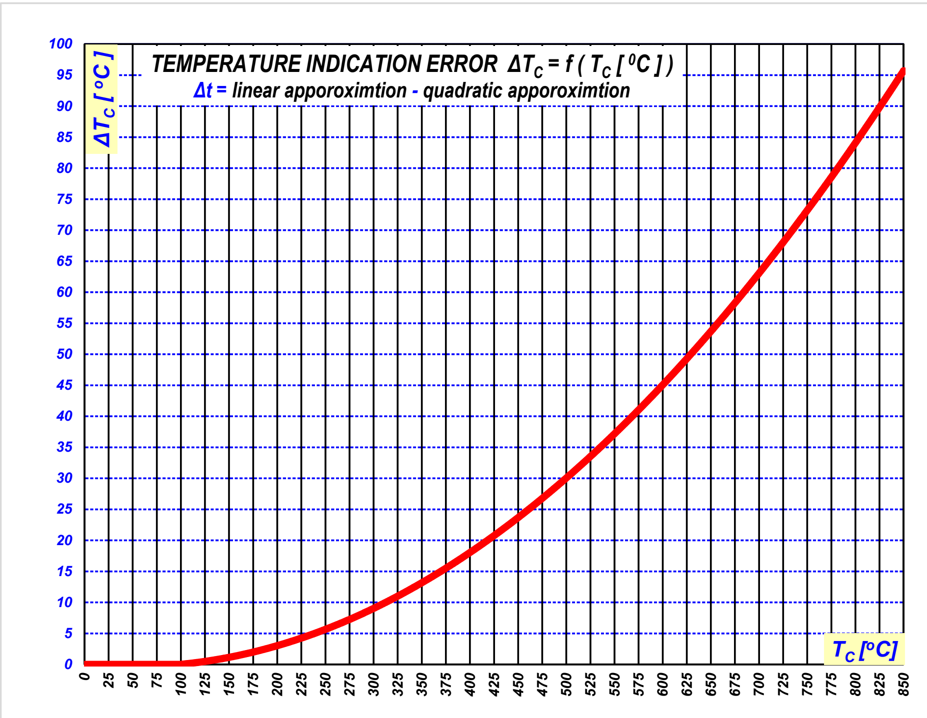

Figure 13. Distribution of the temperature indication error Δt for the linear and quadratic approximation.

7. Conclusions

The material offered in the paper presents a ready to use, measurement circuit of the temperature meter based on Pt100 transducer. The novelty of the solution is proved by the patent PL226444B1 [16,17]. Really, passive and active bridges are well known but are still useful and are not out of the question. Authors suppose that using such a circuit, in order to design a precise and relatively cheap measuring device is probably an optimal decision. They are right that stabilizing the bias current in the device is also known, but it was mandatory to use such a solution in order to obtain the highest accuracy.

The article presents an active bridge system, which makes it possible to solve an important problem consisting in ensuring the correct indications of temperature values in a wide measuring range $T_C = 0 \div 850\ ^\circ\mathrm{C}$. The temperature sensor (thermoresistor) Pt100 used in the system has the properties defined by the standard (EN-60751 + A2). The presented active bridge system integrates the properties of a bridge measuring amplifier with stabilization of the current value in the branch, in which the Pt100 sensor is placed.

According to the standard EN-60751 + A2 the Pt100 resistance temperature dependence has a form of a quadratic function. Solving this function, one can receive the relation between temperature value T_C and the resistance value R_t. The root of the equation has a form (8). In this Formula, one can find a very characteristic term (9). Since the output voltage value U_P is proportional to this term (10), then the temperature *Tc* is directly related to the measurement voltage U_P. A real advantage of the proposed solution is no additional components to correct the temperature value, and it concerns the total measurement range ($T_C = 0 \div 850\ ^\circ\mathrm{C}$) of Pt100.

The paper focuses on the comparison of the temperature measurement in a typical resistive bridge and in the developed active bridge. For the performed tests the correctness of the temperature measuring system using the Pt100 thermoresistor was verified. The highest quality of the measurements in a wide temperature range was analyzed and confirmed the gathered results.

8. Patents

- Piechowski, L. Patent PL272139A1, Linearization amplifier of resistance sensing elements, 30 October 1989.
- Piechowski, L.; Rządkowski, R. Patent PL226444B1, Method and system for determining real temperature of platinum thermoresistor, 21 December 2015.

Author Contributions: Conceptualization, methodology, analysis, supervision, J.I.; resources, analysis, simulation studies, software, writing—review and editing, project administration, A.M.; conceptualization, methodology, resources, analysis, simulation studies, software, writing—review and editing, L.P. All authors have read and agreed to the published version of the manuscript.

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References

1. Chang, H. *Inventing Temperature: Measurement and Scientifc Progres*; Oxford University Press: Oxford, UK, 2004.
2. Michalski, L.; Eckersdorf, K.; Kucharski, J.; McGhee, J. Temperature Measurement. *Meas. Sci. Technol.* **2002**, *13*, 10. [CrossRef]
3. Górecki, K.; Ptak, P.; Janicki, M.; Napieralska, N. Comparison of Properties for Selected Experimental Set-Ups Dedicated to Measuring Thermal Parameters of Power LEDs. *Energies* **2021**, *15*, 3240. [CrossRef]
4. Górecki, P.; Górecki, K.; Zarębski, J. Accurate Circuit-Level Modelling of IGBTs with Thermal Phenomena Taken into Account. *Energies* **2021**, *14*, 2372. [CrossRef]

5. Górecki, K. Influence of the Semiconductor Devices Cooling Conditions on Characteristics of Selected DC–DC Converters. *Energies* **2021**, *14*, 1672. [CrossRef]
6. Padilla, B. *Temperature Sensing with Thermistors*; Texas Instruments: Dallas, TX, USA, 2020.
7. Jack, K.E.; Nwangwu, E.O.; Etu, I.A.; Osuagwu, E.U. A Simple Thermistor Design for Industrial Temperature Measurement. *IOSR J. Electr. Electron. Eng.* **2016**, *11*, 57–66. [CrossRef]
8. Li, W.; Xiong, S.; Zhou, X. Lead-Wire-Resistance Compensation TechniqueUsing a Single Zener Diode for Two-Wire ResistanceTemperature Detectors (RTDs). *Sensors* **2020**, *20*, 2742. [CrossRef] [PubMed]
9. Zhao, Y.; Donaldson, W.R. Systematic Study on Aluminum Composition Nonuniformity in Aluminum Gallium Nitride Metal–Semiconductor–Metal Photodetectors, IEEE Trans. *Electron. Devices* **2018**, *65*, 4441–4447. [CrossRef]
10. Maiti, T.K. A novel lead-wire-resistance compensation technique using two-wire resistance temperature detector. *IEEE Sens. J.* **2006**, *6*, 1454–1458. [CrossRef]
11. Tipparat, J. Interface Circuit for Three-Wire Resistance Temperature Detector with Lead Wire Resistance Compensation. In Proceedings of the 2019 Research, Invention, and Innovation Congress (RI2C), Bangkok, Thailand, 11–13 December 2019; IEEE: New York, NY, USA, 2020.
12. Xu, K. Silicon electro-optic micro-modulator fabricated in standard CMOS technology as components for all silicon monolithic integrated optoelectronic systems. *J. Micromech. Microeng.* **2021**, *31*, 054001. [CrossRef]
13. Erkan, K.; Akkoyunlu, B.; Balkan, E.; Tayanc, M. A portable borehole temperature logging system using the four-wire resistance method. *J. Geophys. Eng.* **2017**, *14*, 1413–1419. [CrossRef]
14. Standard EN-60751 + A2. Industrial Platinum Resistance Thermometers and Platinum Temperature Sensors. 19 September 2008. Available online: https://standards.iteh.ai/catalog/standards/clc/597005af-1426-4595-8a9a-3d65d1563388/en-60751-2008 (accessed on 2 December 2021).
15. Plessis, M.D.; Wen, H.; Bellotti, E. Temperature characteristics of hot electron electroluminescence in silicon. *Opt. Express* **2015**, *23*, 12605. [CrossRef] [PubMed]
16. Piechowski, L. Linearization Amplifier of Resistance Sensing Elements. Patent PL272139A1, 30 October 1989.
17. Piechowski, L.; Rządkowski, R. Method and System for Determining Real Temperature of Platinum Thermoresistor. Patent PL226444B1, 21 December 2015.
18. Robert, A. *Troubleshooting Analog Circuits*; Polish Edition Copyright 2005 by BTC Korporacja; BTC Korporacja: Legionovo, Polish, 1991.
19. Camenzind, H. *Designing Analog Chips by Hans Camenzind*; Polish Edition Copyright 2010 by BTC Korporacja; BTC Korporacja: Legionovo, Polish, 2005.
20. Kitchin, C.; Counts, L. *A Designer's Guide to Instumentation Amplifiers*, 3rd ed.; Analog Devices 2006; Polish Edition Copyright 2009 by BTC Korporacja; BTC Korporacja: Legionovo, Polish, 2006.
21. Carter, B.; Mancini, R. *OP AMPS for Everyone, Texas Instruments Incorporated*; Polish Edition Copyright 2011 by BTC Korporacja; BTC Korporacja: Legionovo, Polish, 2008.
22. Xu, K. Integrated Silicon Directly Modulated Light Source Using p-Well in Standard CMOS Technology. *IEEE Sens. J.* **2016**, *16*, 6184–6191. [CrossRef]