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

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
The performance of the sensor depends on the material it is made of. Most RTD sensors, 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].

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The paper presents a method of precise evaluation of a real temperature value in a large range of temperature $T_C = 0 \div 850 \, ^\circ\text{C}$ 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 $T_C = 0 \div 850 \, ^\circ\text{C}$, 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 $R_t$.](image-url)

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.
\[ \Delta U_{(A-B)} = U_A - U_B = 0 \] (1)

A change in temperature causes a change in the resistance value \( R_t \), which introduces 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:

\[ U_B = U_Z \left( \frac{R_X}{R_X + R_t} \right) \] (2)

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

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

If \( R_A = R_B \), then \( \alpha \) in (3) is equal to: \( \alpha = \frac{1}{2} \).

\[ U_A = U_Z \left( \frac{R_A}{R_A + R_B} \right) = \frac{1}{2} \cdot U_Z \] (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:

\[ \Delta U_{(A-B)} = U_A - U_B = U_Z \cdot \left( 1 - \frac{R_X}{R_t + R_X} \right) \] (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.

\[ \Delta U_{(A-B)} = \frac{U_Z}{2} \left( \frac{R_t - R_X}{R_t + R_X} \right) \] (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.

\[ R_t = R_0 \left( 1 + A \cdot T_C + B \cdot T_C^2 \right) \] (7)

\( R_t \) — 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), \( R_0 = 100 \ \Omega \) (or 500 \( \Omega \), and also 1000 \( \Omega \)), \( A, B \) — constants connected with the material property of platinum Pt according to the standard (EN-60751 + A2), \( A = 3.9083 \times 10^{-3} \ (1/°C), B = -5775 \times 10^{-7} \ (1/°C²) \).

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 \( R_t \):

\[ T_C = -\frac{A}{2B} - \sqrt{\left( \frac{A}{2B} \right)^2 + \frac{1}{B} \left( \frac{R_t}{R_0} - 1 \right)} \] (8)
In the Formula (8), the fragment described by the relation (9) is important;

\[
\left( \frac{R_t}{R_0} - 1 \right).
\]  

(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);

\[
\left( \frac{R_t}{R_0} - 1 \right) = S_K \cdot U_P.
\]  

(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 \( I = I_{\text{const}} \) in the bridge branch with a Pt100 thermoresistor.](image)

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 \( R_t \). 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 temperature value directly according to Formula (1).

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

\[
U_A = U_Z \cdot \left( \frac{R_A}{R_A + R_B} \right) = \alpha \cdot U_Z
\]  

(11)

\[
U_B = U_Z \cdot \left( \frac{R_X + r_p}{R_X + R_t + 2r_p} \right)
\]  

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

(13)

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

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

(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 \( U_{REF} \).

\[ U_{REF} = I \cdot R_X = I \cdot R_0 \]  

(15)

\[ U_{REF} = I \cdot R_X = \frac{U_Z}{R_X + R_t + 2r_p} \cdot R_X \]  

(16)

\[ U_Z = \frac{U_{REF} \cdot (R_X + R_t + 2r_p)}{R_X} \]  

(17)

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

\[ \Delta U_{(A-B)} = U_A - U_B = \frac{U_{REF}}{2} \left( \frac{R_t}{R_X} - 1 \right) \]  

(18)

Or

\[ U_{OUT} = \Delta U_{(A-B)} \cdot K_{WI} = (U_A - U_B) \cdot K_{WI} = K_{WI} \cdot \frac{U_{REF}}{2} \left( \frac{R_t}{R_X} - 1 \right) \]  

(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:

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

(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).

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

(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):

\[ T_C = \frac{-A}{2B} - \sqrt{\left( \frac{A}{2B} \right)^2 + \frac{1}{B} \left( \frac{R_t}{R_0} - 1 \right)} \]  

(22)

or

\[ T_C = \frac{-A}{2B} - \sqrt{\left( \frac{A}{2B} \right)^2 + \frac{2}{B} \cdot \frac{U_{OUT}}{K_{WI} \cdot U_{REF}} \cdot U_{OUT}} \]  

(23)

where \( S_K \)—denotes the calibration constant equal to:
3. Selection of the Partition Coefficient $\alpha$ and the Resistance $R_0$

In Formulas (3) and (11), the division coefficient $\alpha$ was introduced. Theoretically, in the bridges under consideration, it is possible to assume any resistance value in the range $100 \div 1000 \ \Omega$, 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 $\alpha$ 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 $T_C = 0 \ ^\circ\text{C}$, the resistor value $R_0$ must be $R_0 = 100.00 \ \Omega$. 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 $\Omega$ and 330 $\Omega$.

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 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 $R_1 = 100.00 \ \Omega$ it is possible to obtain a voltage value of $\Delta U_{(A-B)} = 0.00 \ \text{V}$ (measured with the use of a 6i/2-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 thermoresitor $R_t$, 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 $t \ [\ ^\circ\text{C}]$ 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 $t \ [\ ^\circ\text{C}]$ 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 ($x_1$ $i$ $x_2$) to wire terminals denoted as $z_1$ $i$ $z_2$, 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.

\[
S_K = \frac{2}{B \cdot K_{W1} \cdot U_{REF}}.
\]
When the temperature value \( t \) [°C] is measured in an air (gas) environment, the heat transfer from the heated sensor is weak. In an aqueous environment (liquids), the heat transfer from the heated sensor is more intensive. Therefore, lower values of the value \( t \) in the water environment. (e.g., in district heating systems).

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].

\[
R_{(z1 \div z2)} = R_t + 2r_p
\]

(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 \( R_{Pt100} \approx 100.00 \Omega \). 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 $x_1$, $x_2$ and $z_1 \div z_3$ 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 $z_3$ and $x_1$ serves to transfer the potential of the $x_1$ point to the $z_3$ terminal of the measuring bridge. The use of the terminal $z_3$ 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 $W_I$, the resistance value $R_{in}$ is very high. Therefore, the problem raised here does not exist in it.

![Image of measuring bridge circuit](image-url)

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

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![Image of operational amplifier](image-url)

**Figure 8.** The operational amplifier $W_Ox$ 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 $W_I$ 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 $W_Ox$ 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 $W_Ox$ 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 $W_Ox$ amplifier is equipped with compensation (capacitor $C_8$), which effectively eliminates the excitation possibility of the $W_Ox$ 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 IC 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.

![Image of schematic diagram of the LM723 IC](image-url)
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) $R_t = 100.00 \, \Omega$ for $T_C = 0 \, ^\circ\mathrm{C}$;
(b) Measure the output voltage value between points A and B of the active measuring bridge;
(c) Set the output voltage $\Delta U_{(A-B)} = 0.00 \, \mathrm{V}$ 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) $U_{\text{out}} = 0.00 \, \mathrm{V}$, 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) $R_t = 313.71 \ \Omega$, which corresponds to the temperature value $T_{C, \text{MAX}} = 850 ^\circ C$;

(f) On the output of the measuring bridge amplifier set the value of the output voltage $U_{\text{out}} = 5.00 \ \text{V}$; 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 $T_C = 850 ^\circ C$. This value can be reached by entering the pre-calculated value of the calibration constant $S_K$. For example, for the temperature value $T_C = 850 ^\circ C$ and the voltage $U_{\text{out}} = 5 \ \text{V}$ 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 $T_C = 850.0 ^\circ C$ 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 $T_C (^\circ C)$ 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.

| $R_t$ (\(\Omega\)) | $T$ (\(^\circ C\)) |
|---------------------|-------------------|
| 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 $T_{C, \text{MAX}} (^\circ C)$, different values of the calibration constant $S_K$ must be adopted. The calibration constant always refers to the maximum voltage value $U_{\text{out}} = 5 \ \text{V}$, 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 $U_{IN-AD} = 5 \ \text{V}$. 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 \( U_{out} = 5 \text{ V} \) is obtained.

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

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

Formula (28) is the universal calculation formula of the calibration constant value \( S_K \). Formula (28) assumes the value of \( B, R_0, \) and \( U_{out} = 5 \text{ V} \). 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 \( U_{out} = 5 \text{ V} \).

| Maximum Value of the Measured Temperature \( t_{MAX} \) [°C] | \( R_t \) [Ω] | \( S_K = -346,320.34632 \cdot \left( \frac{R_t}{R_0} - 1 \right) \) |
|---|---|---|
| 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.

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

\[
t = \frac{-A}{2 \cdot B} - \sqrt{\left( \frac{A}{2 \cdot B} \right)^2 + S_K \cdot U_{OUT}} = \frac{-0.0039083}{2 \cdot (-0.0000005775)} = \frac{-0.0039083}{2 \cdot (-0.0000005775)} = 3383.80952380(80952380) \tag{31}
\]
\[
\left( \frac{A}{2 \cdot B} \right)^2 = (3383.80952380)^2 = 11,450,166.8933
\]

\[
t = \frac{-A}{2 \cdot B} - \sqrt{\left( \frac{A}{2 \cdot B} \right)^2 + S_K \cdot U_{OUT}} = 3383.8095238 - \sqrt{11,450,166.8933 + S_K \cdot U_{OUT}}
\]

\[
t = 3383.8095238 - \sqrt{11,450,166.8933 + S_K \cdot U_{OUT}}
\]

**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:

\( S_K = -1,005,991.341991 \).

\[
t = 3383.8095238 - \sqrt{11,450,166.8933 - 1005.341991 \cdot U_{OUT}}
\]

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

\[
t = 3383.8095238 - \sqrt{11,450,166.8933 - 1005.341991 \cdot 5 \text{ V}}
\]

For the assumed temperature range \( T_C = 0 \div 850 \) °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.

\[
U_{OUT} = \left( \frac{R_t}{R_0} - 1 \right) = 1.72128890115 \cdot \left( \frac{R_t}{R_0} - 1 \right)
\]

By applying the voltage within the range \( U_{out} = 0 \div 5 \) 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 → \( U_{IN-A/D} = 0 \div 5 \) V. Table 3 presents the
calculated intermediate values of the voltage $U_{IN/A/D}$ for the range of the temperature value measurement $T_C = 0 \div 850 ^\circ C$.

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

| MEASUREMENT RANGE $t = 0 \div 850 ^\circ C$ | $T$ ($^\circ C$) | $R_t$ [$\Omega$] | $U_{out}$ (V) |
|---|---|---|---|
| $S_K = -1.005,991.341991(341991)$, $B = -0.0000005775$ | $U_{out} = U_{IN/A/D} = 5 \text{ V}$ for $t = 850 ^\circ C$ | |
| 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 $\alpha$.

$$\alpha = \frac{R_{100} - R_0}{R_0 \cdot 100 ^\circ C}$$  \hspace{1cm} (38)

where:
- $R_{100}$—the resistance value of the thermoresistor Pt100 at temperature $T_C = 100 ^\circ C$, $R_{100} = 138.51 \Omega$,
- $R_0$—the resistance value of the thermoresistor Pt100 at temperature $T_C = 0 ^\circ C$, $R_0 = 100.00 \Omega$.

The value of $\alpha$ according to the definition given by Formula (38):

$$\alpha = \frac{R_{100} - R_0}{R_0 \cdot 100 ^\circ C} = \frac{138.51[\Omega] - 100.00[\Omega]}{100.00[\Omega] \cdot 100 ^\circ C} = 3.851 \cdot 10^{-3} \left( ^\circ C^{-1} \right)$$  \hspace{1cm} (39)

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

Figure 13 shows the course of the temperature indication difference $\Delta T_C$ for the linear and quadratic approximation.
For example (Figure 7): for the temperature value $T_C = 500 \, ^\circ C$ the difference $\Delta T_C$ of $T_C$ temperature readings will be $+30 \, ^\circ C$. The value of the $\Delta T_C$ 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 $\geq 100 \, ^\circ C$ [14–17].
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 \( T_C = 0 \div 850 ^\circ C \). 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 \( T_C \) 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 (\( T_C = 0 \div 850 ^\circ C \)) 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.

Funding: The project was financed within the program of the Ministry of Science and Higher Education called “Regionalna Inicjatywa Doskonalności” in the years 2019–2022, the project number 006/RID/2018/19, the sum of financing 11 870 000 PLN.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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