Innovative Instrumentation System for Improvement of Thermistor Performance

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Abstract—The contribution of this research is in suggesting the design of an instrumentation system that improves thermistors performance as temperature transducers. It reduces considerably the thermistor non-linearity and self-heating effect, as well as increasing thermistors sensitivity in a wider temperature range of measurements and control. The developed instrumentation electronic circuit involves a unique arrangement of a group of thermistors that are connected in a particular Wheatstone bridge configuration. Analysis of the circuit and testing it in real environment proves its effectiveness in improving the performance of this temperature sensor tool.

Keywords—Thermistor; Transducers; Sensors; Characteristics; Stable; Linearity; Self-heating; Sensitivity; Range;

I. INTRODUCTION

In order to put emphasis on the application of thermistor sensors, the following well-known temperature transducers are compared: the Resistance Temperature Detectors (RTD), the thermocouples, the Integrated Circuits (IC) sensors and the thermistors. The RTD transducers are stable and accurate, but expensive. They have low sensitivity and suffer from a considerable self-heating effect. Thermocouples have the widest temperature range of measurement, but a lot of disadvantages, like non-linearity, low sensitivity and especially the requirement of stable reference, are limiting their applications. The IC sensors have most linear characteristics and good sensitivity, but they have very limited temperature range and cannot avoid self-heating effect. Further, the IC sensors have a slow response and require a power supply [1], [2]. Thermistors have more advantages compared with all other temperature transducers. They are simple, very stable, fast, with high output, sensitive in low temperature range. These properties make them widely used in industry.

Unfortunately, the non-linear characteristics, the lower sensitivity for the higher temperature range of measurement and the typical self-heating effect of thermistors are some of their disadvantages that are limiting their applications.

Thermistors, being composed of a mixture of metallic oxides such as manganese, nickel, cobalt, copper, iron and uranium, can be applied in the lower temperature measurement range of –100°C to +300°C. They may have a very wide range of resistance from 0.5Ω to 75MΩ and are available in a wide variety of shapes and sizes. Smallest in size, thermistors are the fastest responding temperature sensors. Thermistors behave as resistors with a high, usually negative temperature coefficient of resistance. Regrettably, due to the thermistors non-linear resistance-temperature characteristics, their high sensitivity is limited to a very small temperature range [3], [4]. The purpose of this research is to suggest the development of an electronic circuit that reduces the thermistor non-linearity, in this way increasing its sensitivity to a wider temperature range of measurements. It also reduces the sensor self-heating effect. The proposed circuit consists of a number of thermistors, connected in a specific Wheatstone bridge configuration.

II. REFLECTION ON THE THERMISTOR RESISTANCE, SENSITIVITY, NONLINEARITY AND SELF-HEATING EFFECT

The relationship betweem the thermister resistance and the temperatute at which it is exposed [4] can be presented as:

$$R_T = R_{REF} e^{\beta(1/T - 1/T_{REF})} \quad (1)$$

where:

R_T is the thermistor resistance at temperature T

R_{REF} is the reference thermistor resistance at a reference temperature T_{REF} (298 °K; 25 °C)

T, T_{REF} are the absolute temperatures in °K

β is a calibration constant that ranges from 3000 °K to 5000 °K

The *Sensitivity S* of a thermistor [2], [5] is obtained from Equation (1) as:

$$S = \frac{\Delta R / R_T}{\Delta T} = -\frac{\beta}{T^2} \quad (2)$$

For a typical thermistor, β = 4000 °K, T = 298 °K, and its *Sensitivity* is S = –0.045/°K, that is more than 10 times larger than the *Sensitivity* of a platinum resistance sensor (S = +0.0035/°K). The very high sensitivity of thermistors results in a large output signal, good accuracy and resolution in temperature measurements. For example, a typical thermistor with R_{REF} = 2000 Ω and S = –0.04/°K exhibits a large resistance change $\Delta R/\Delta T$ = 80 Ω/°K [4], [5] that can be converted to a voltage signal.

Equation (1) indicates that the resistance of a thermistor decreases exponentially with increase in temperature. Since the output from a thermistor is nonlinear, its sensitivity is also affected considerably. The sensitivity of a thermistor is very high at lower temperature ranges, while it reduces significantly in the higher temperature ranges. Linearity of the thermistor output can be improved by using modified potentiometer circuits. However, these circuits are not recommended in their pure form, since they reduce the magnitude of the output signal and therefore the overall sensitivity of the sensor [6], [7]. To facilitate the improved linearity and simultaneously with this to keep the high sensitivity of a thermistor sensor, a modified potentiometer circuit can be imbedded in a Wheatstone-bridge configuration. The bridge output can be further subjected to a signal conditioning to be brought to the desired level.

When temperature is measured by thermistors, errors may occur as a result of the self-heating effect within the sensor unit. The power ($P = I^2R_T$) dissipated in the thermistor will heat it above its ambient temperature. The dissipation constant is usually specified under two conditions: free air and a well-stirred oil bath. This is because of the difference in capacity of the medium to carry heat away from the device. The self-heating temperature rise ΔT is considered as the *Self-Heating Error (SH Error)* [4], [5], [7]. It can be found from the power dissipated by the thermistor and the dissipation constant as follows:

$$SH\ Error = \Delta T = \frac{I^2 R_T}{P_D} = \frac{P}{P_D}, \text{°C} \quad (3)$$

where

ΔT is the temperature rise of the thermistor as a result of the self-heating effect in °C

I is the current through the thermistor

P is the power dissipated in the thermistor in terms of heat in W

P_D is dissipation constant of the thermistor in W/°C

Typical thermistors have dissipation constants in the order of 1 to 10 mW/°C in still air and 25 to 250 mW/°C in a well-stirred oil bath.

Suppose that the thermistor used for the case has a resistance R_T = 3747Ω at 20°C, a *Sensitivity* of –0.035/°C and a dissipation constant P_D = 5mW/°C. It is suggested to use the thermistor in a voltage divider [5], [7], [8], being connected in series to an ordinary resistor with a resistance R = 3747Ω and a supply voltage V_S = 10V, as shown in Figure 1. Neglecting the thermistor self-heating effect, an ammeter connected in series with the thermistor measures its current as I = 1.334mA. A voltmeter measures the voltage drop across the thermistor that is V = 5V, if the the ammeter internal resistance is ignored.

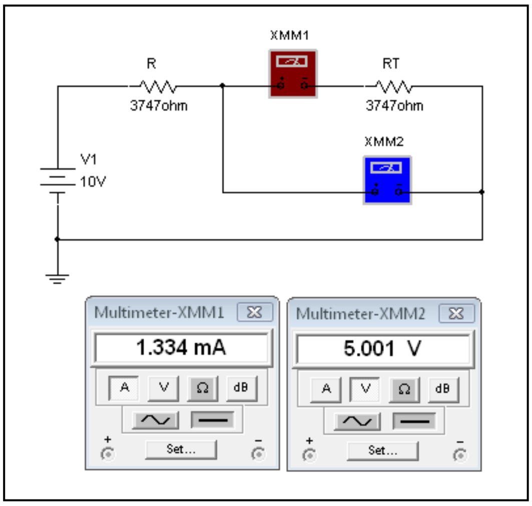

Figure 1. Temperature Measurement of 20°C, Neglecting the Thermistor Self-Heating Effect

The voltage drop across the thermistor and the current through it can be also calculated from the voltage divider, as shown in equations (4) and (5):

$$V = \frac{R_T}{R_T + R} V_S = \frac{3747\Omega}{3747\Omega + 3747\Omega} 10V = 5V \quad (4)$$

$$I = \frac{V}{R_T} = \frac{5V}{3747\Omega} = 1{,}334 mA \quad (5)$$

The power dissipation can be determined either considering the voltage drop or the current through the thermistor, as seen from equation (6) and (7).

$$P = \frac{V^2}{R_T} = \frac{(5V)^2}{3747\Omega} = 6.67\,mW \quad (6)$$

$$P = I^2 R_T = (1.334 mA)^2 \times 3747\Omega = 6.67 mW \quad (7)$$

The *Self-Heating Error,* or the temperature rise ΔT of the thermistor due to the self-heating effect can be determined by applying Equation (3):

$$SH\ Error = \Delta T_{1(20°)} = \frac{P}{P_D} = \frac{6.67\,mW}{5\,mW/°C} = 1.33°C \quad (8)$$

Hence the thermistor will operate not at T = 20°C, but rather at its real temperature:

$$T_{REAL} = T + \Delta T_{1(20°)} = 20°C + 1.33°C = 21.33°C, \quad (9)$$

That corresponds to a new real value of the thermistor resistance:

$$\left.\begin{aligned} R_{T\,REAL} &= R_T - \Delta T_{1(20^\circ)} SR_T \\ &= 3747\Omega - 1.33^\circ C \times 0.035 / C^\circ \times 3747\Omega \\ &= 3572.577\Omega \end{aligned}\right\} \quad (10)$$

Further V, P, ΔT and $R_{T\,REAL}$ should be recalculated in order to determine their even more accurate values. It is obvious that the *Self-Heating Error* can be reduced if the current through a thermistor is reduced.

III. Instrumentation System for Improvement of the Themistor Performance

The developed instrumentation system, shown in Figure 2, considerably improves the performance of thermistors as temperature sensors. This is achieved by employing a modified thermistor circuit that is imbedded in a Wheatstone-bridge configuration.

Instead of only one thermistor, the temperature sensor is built by two thermistors R_{T1} *and* R_{T2}. The two thermistors R_{T1} *and* R_{T2} connected in a specific circuit involving the resistors R_3 and R_5 [8], [9]. The equivalent resistance of the circuit R_{T1}, R_{T2}, R_3 and R_5 is operating as the variable resistive arm R_{TEQ} of a Wheatstone bridge, that changes with temperature as shown in Figure 3. Its reciprocal value can be determined from the following relationship:

$$\frac{1}{R_{TEQ}} = \frac{1}{R_{T1}} + \frac{1}{R_{T2} + R_5} + \frac{1}{R_3} \quad (11)$$

The Wheatstone bridge consists of the resistors R_1, R_2, R_4 and R_{TEQ} and is balanced when the thermistor sensor measures a temperature of 0°C. Then the thermistor resistances are R_{T1} = R_{T2} = 9795Ω, as seen from the graph at Figure 3. This corresponds to R_{TEQ} = 3958Ω and output voltage of the Wheatstone bridge of 0V. The Wheatstone bridge output voltage is further subjected to proper signal conditioning [3], [9], [10], provided by the operational amplifiers OA1 to OA4. If the Wheatstone bridge is balanced at 0°C, the output voltage of the total instrumentation system is also 0V.

As seen from the graph at Figure 3, at temperature T = 20°C, the values of the thermistor resistances are R_{T1} = R_{T2} = 3747Ω. At this condition, the Wheatstone bridge is unbalanced and the output voltage of the instrumentation system is V = 1.722V, as shown in Figure 2.

The function of the signal conditioning is to buffer the signal obtained from the Wheatstone bridge and to provide a proper signal amplification [9], [10]. The operational amplifiers OA1 and OA2 are voltage followers with very high input resistances protecting the exact resistor settings of the Wheatstone bridge.

The amplifier OA3 operates as a difference amplifier, while OA4 is a Zero and Span converter. Depending on its settings, the output voltage of the instrumentation system can be adjusted within a required range. For the discussed case, the output voltage changes from 0V to 10V.

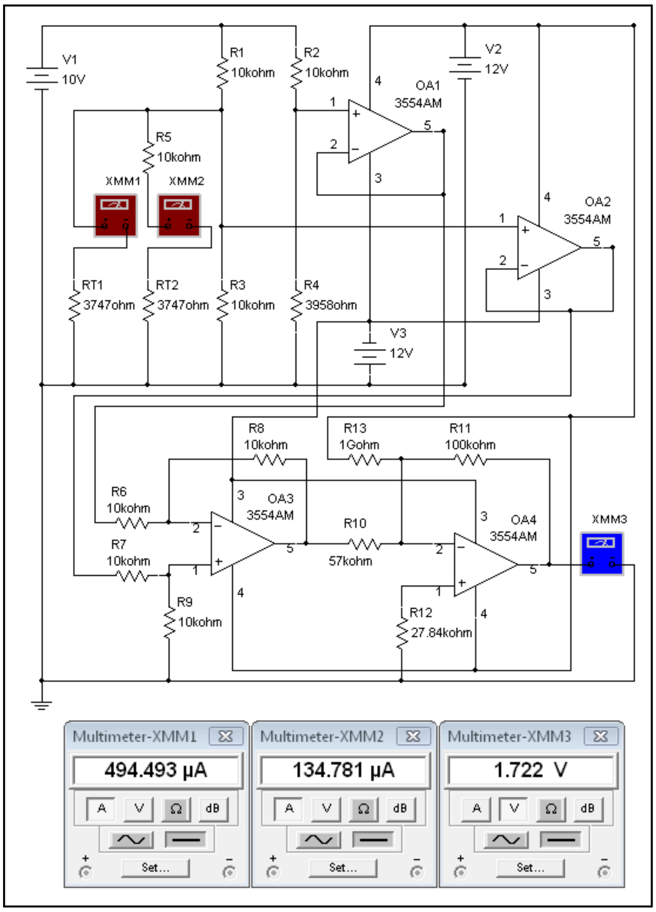

Figure 2. Instrumentation System for Improvement of the Thermistors Performance as Temperature Sensors

One of the purposes of the two-thermistor sensor instrumentation system is to reduce the *Self-Heating Error*. This error is significantly reduced, due to the decreased currents throgh the thermistors, in comparison with the case of single-thermistor sensor.

The current through the single-thermistor sensor is I = 1.334mA, as seen from From Figure 1.

The currents through the thermistors of the two-thermistor sensor bridge arrangement, are much smaller and are accordingly I_1 ≈ 0.494mA and I_2 ≈ 0.135mA, as shown in Figure 2. Their average value will determine the much smaller *Self-Heating Error* in this case.

Another purpose of the two-thermistor sensor instrumentation system is to improve the sensor *Sensitivity* for the full measurement range. The *Sensitivity* of the total instrumentation system becomes better in terms of consistency within the full measurement range and also in terms of the much larger ouput signal, as seen from Figure 4. The improved total *Sensitivity* is due to the termistor sensor-bridge arrangement and the applied signal conditioning in the instrumentation system as well.

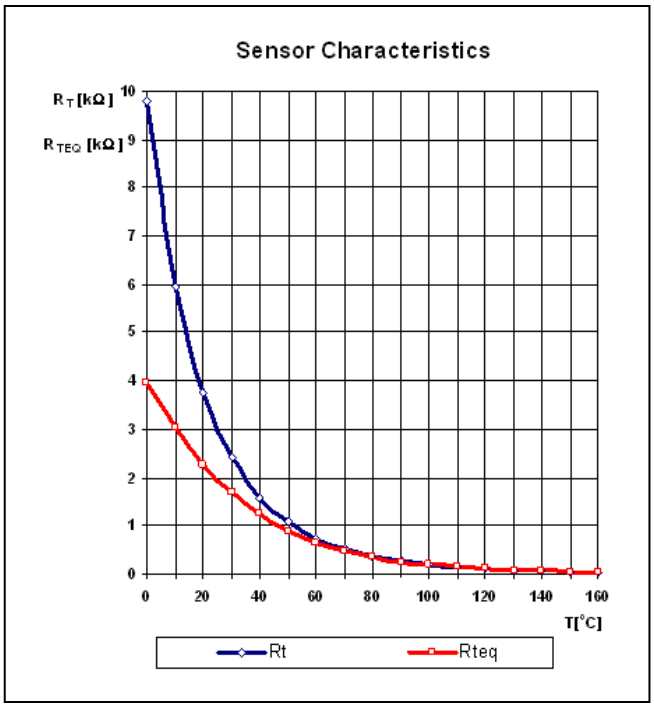

Figure 3. Thermistor Sensor Characteristics before and after the Application of the Two-Thermistor Instrumentation System

In the case of thermistor connection as shown in Figure 1, the *Self-Heating Error* of the explored thermistor is determined from equation (8). At *T* = 20°C, it is $\Delta T_{1(20°)} = 1.33°C$.

If the two-thermistor sensor instrumentation system of Figure 2 is used to measure the same temperature *T* = 20°C, the average thermistor *Self-Heating Error* can be determined as:

$$\left.\begin{aligned} &SH\ Error = \Delta T_{2(20^{\circ})} = \\ &= \frac{\left[\frac{(I_1 + I_2)}{2}\right]^2 R_T}{P_D} \\ &= \frac{\left[\frac{0.495mA + 0.135mA}{2}\right]^2 3747\Omega}{5\,mW/°C} \approx 0.074°C \end{aligned}\right\} \quad (12)$$

The improved sensor performance and accuracy of measurement is obvious from comparing the results of equations (8) and (12). In the second case, the *Self-Heating Error* is considerably reduced, as demonstrated in equation (13).

$$\Delta T_{1(20°)} = 1.33°C > \Delta T_{2(20°)} = 0.074°C \quad (13)$$

To determine the sensor *Sensitivity* for the cases of Figure 1 and Figure 2, the data are considered from the characteristics shown in Figure 4.

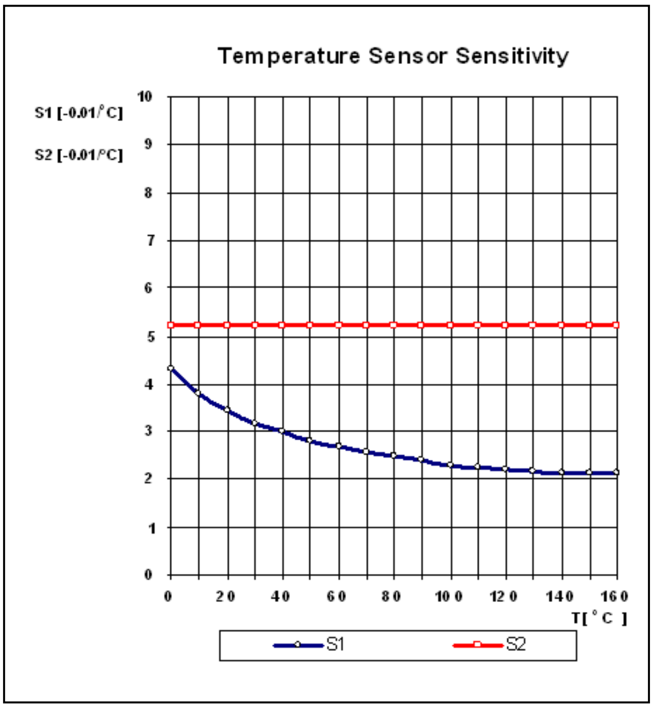

Figure 4. Sensitivity Characteristics before and after the Application of the Two-Thermistor Instrumentation System

These characteristics are obtained experimentally and they completely match the results received from the computer simulation of the circuits.

The *Sensitivity* of the explored thermistor at base temperature *T* = 20°C, using the simple voltage divider connection as shown in Figure 1, can be determined from equation (14).

$$\left.\begin{aligned} &S_{1(20^{\circ})} = \frac{\Delta R / R_T}{\Delta T} \\ &= \frac{(3.747 - 2.417)k\Omega / 3.747k\Omega}{20°C - 30°C} = \frac{0.354923}{-10°} \\ &\approx -0.035/°C \end{aligned}\right\} \quad (14)$$

Using a single thermistor in the voltage divider connection of Figure 1, but at higher base temperature, for instance at *T* = 120°C, the *Sensitivity* is reduced as seen from equation (15). Even less *Sensitivity* will be observed, as temperature is further increased.

$$\left.\begin{aligned} &S_{1(120^{\circ})} = \frac{\Delta R / R_T}{\Delta T} \\ &= \frac{(0.1168 - 0.0903)k\Omega / 0.1168k\Omega}{120°C - 130°C} \\ &= \frac{0.22688}{-10°} \approx -0.023/°C \end{aligned}\right\} \quad (15)$$

When the instrumentation system of Figure 2 is implemented, the *Sensitivity* of the two-thermistor-sensor is improved within the full measurement range.

If the sensor is placed at a temperature T = 20°C, its *Sensitivity* can be determined as:

$$\left.\begin{aligned} S_{2(20^{o})} &= \frac{\Delta R_{EQ}/R_{T\,EQ}}{\Delta T} \times \frac{V_{U4\,OUT}}{V_{U4\,IN}} \\ &= \frac{(2.274-1.686)k\Omega/2.274k\Omega}{20°C-30°C} \times \frac{1.716V}{0.86V} \\ &\approx -0.052/°C \end{aligned}\right\} \quad (16)$$

When the two-thermistor-sensor system is measuring a temperature T = 120°C, the *Sensitivity* is:

$$\left.\begin{aligned} S_{2(120^{o})} &= \frac{\Delta R_{EQ}/R_{T\,EQ}}{\Delta T} \times \frac{V_{U4\,OUT}}{V_{U4\,IN}} \\ &= \frac{(0.114-0.0905)k\Omega/0.0905k\Omega}{120°C-130°C} \times \frac{8.7V}{4.36V} \\ &\approx -0.052/°C \end{aligned}\right\} \quad (17)$$

Comparison between the results of equations (14) and (15) and equations (16) and (17) shows that the implementation of the two-thermistor sensor system increases the *Sensitivity,* which becomes almost constant in the complete measurement range. This is achieved due to the implementation of the Wheatstone bridge, as well as the additional signal amplification in the final stage of the system. The *Sensitivity* can be even further increased if a larger gain is used.

The increased temperature senser *Sensitivity*, as well as the applied signal conditioning, causes considerable system output variation from V = 0V to V = 10V, reflecting the temperature change from T = 0°C to T = 160°C, as demonstrated in Figure 5.

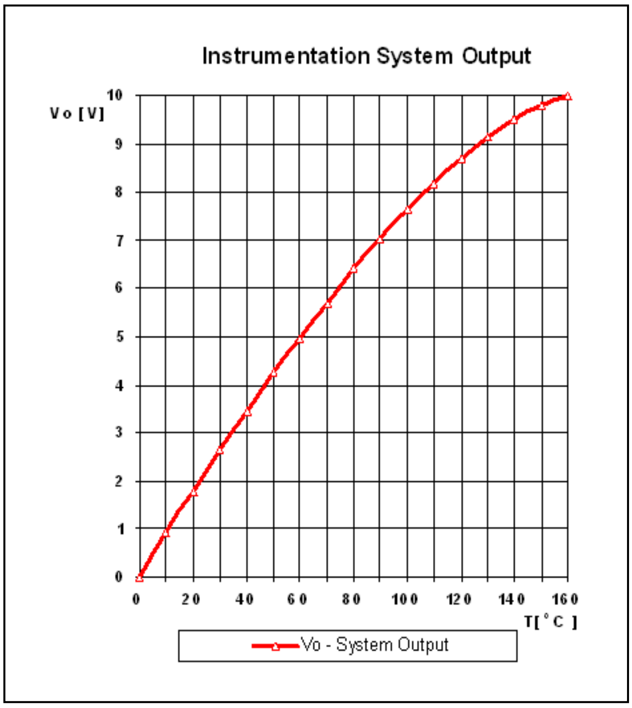

Figure 4. Output of the Two-Thermistor Instrumentation System

IV. CONCLUSION

The suggested two-thermistor configuration imbedded in a Wheatstone bridge, together with the proper signal conditioning, improves considerably the performance and the accuracy of temperature measurement. As seen from the characteristic of Figure 5, the output voltage signal of the instrumentation system has quite improved *Linearity* within the full temperature range. Due to this, the *Sensitivity* of the improved the two-thermistor sensor system remains constant and is also larger, compared with the one of the stand-alone thermistor circuit.

The additional resistances connected in the two-thermistor configuration sensor, decrease the thermistor currents and this reduces considerably the *Self-Heating Error* making it almost negligible. As a result, the accuracy of measurement is significantly improved.

The designed instrumentation system can operate successfully with different thermistor types. It can be employed successfully in a variety of industrial and domestic applications: monitoring temperatures and control in chemical and mining industry, control of air-conditioning, monitoring temperature of electrical machines and drives, precise electronic thermometry.

The two-thermistor sensor instrumentation system is actually dismissing the major disadvantages of thermistors, making them a perfect choice as transducers for measurements within the temperature range from –80°C to +300°C.

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