A Miniature In-Head Transmitter with Linear Response for Resistance Temperature Detectors

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Abstract

This paper describes a miniature in-head two-wire current loop transmitter that was developed to compete in the temperature measurement market with mandatory specifications of low-cost and intrinsic linearity for Resistance Temperature Detectors (RTD). A solution was devised to meet these requirements, which resulted from a suitable combination of a linear transconductor and a few external thick-film resistors to make up a current-feedback structure that linearizes the RTD's resistance versus temperature relationship.

Measurements of the miniature in-head transmitter, which incorporates the novel linearization technique, have shown an accuracy of 0.1% in production, thus proofing that the technical competitiveness was accomplished. The low-cost requirement was also accomplished due to the simplicity of its implementation and efficiency of the linearization technique.

1. Introduction

The development of the miniature in-head transmitter that is focused in this paper was motivated by the need of a new industrial assembly for temperature sensors, which, differently from existing types, should dispense with the usual connection head by moving the whole sensor's signal conditioning electronics from the head into the protection tube where the sensing element is inserted. A typical industrial assembly with the connection head is shown in Fig-1 right above the image of the targeted head-less assembly.

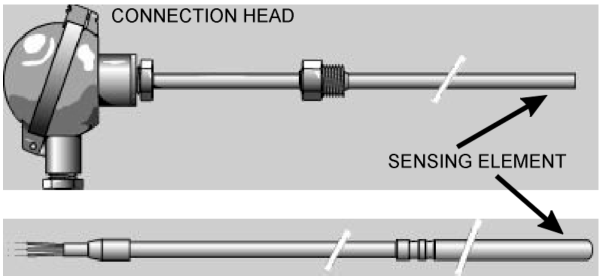

Fig. 1: Industrial assemblies for temperature sensors. With connection head (upper image). Head-less assembly (lower image)

The design of a full custom integrated circuit was readily considered as a solution for accomplishing the specifications. However, due to constraints in production volumes an alternative implementation was adopted, which is based on an off-the-shelf monolithic micro-system that comprises a pair of precision current sources and an accurate voltage-to-current converter. In order to differentiate the new device from existing rivals, a distinguished feature was added, other than the new type of assembly, which made it unique. This new feature was the intrinsic linearization of RTD's implemented at a very low cost.

2. Linearization Technique

The linearization of sensors is a long existing and studied topic in the literature [1]. Diverse techniques have been developed and some of them were applied to products similar to the one that is addressed in this paper [2,3]. More recently, cost-effective microprocessors and micro-controllers have become the preferred component for implementing the linearization of sensors [4], which are based on well-known techniques like the interpolation of values from a table or the straightforward calculation of the value of the function that represents the relationship between the signal produced by the sensor and the variable it measures. More sophisticated linearization techniques have recently appeared, which are based on neural networks [5].

If in one hand the microprocessor-based linearization solution is attractive because of its simplicity and reduced development time, on the other hand it may not be appropriate in many other cases, which are constrained by power consumption and/or cost. The analog linearization solution unveiled in this paper [6], by using only a few resistors and a reference diode, has proved to be more effective than the digital solution.

A. Linearization Circuit

Fig.2 shows a simplified diagram of a temperature measuring setup that uses a Resistance Temperature Detector, represented by resistor R_T, as temperature sensing element in the circuit of a current-loop transmitter. This temperature sensor is connected in series with a constant voltage V_R to allow offset voltage adjustment. The reference voltage is added to the voltage drop across the sensor to produce the voltage E, which is linearly converted by transconductor G into the current that circulates in the loop. Notice that the excitation current, Ix, for R_T is not constant. A feedback component I_F, whose amplitude depends on the amplitude of the loop current, is subtracted from the reference current I_R to impose a near linear relationship between the excitation current and the temperature.

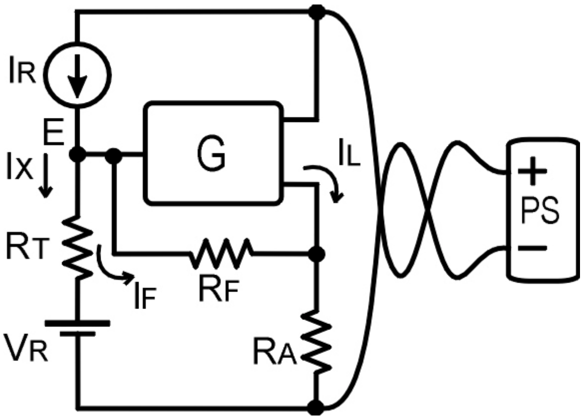

Fig. 2: Simplified diagram of a two-wire transmitter for a RTD

B. Principle

The transfer function of the linear transconductor G can be written as:

$$I_L = Io + G.E \tag{1}$$

Where Io is an offset current and G is the voltage to current conversion factor in amp/volt.

This output current is split into two fractions, one of which flows through R_A and the other, I_F , which flows through the feedback resistance R_F. As a result, the excitation current will be:

$$I_X = I_R - I_F \tag{2}$$

Current I_R is constant while I_F is given by:

$$I_F = \left(\frac{1}{R_A + R_F}\right).\left[E.(1 - G.R_A) - R_A.Io\right] \tag{3}$$

Where $E = V_R + R_T.I_X$ (4)

The resistance of the temperature sensitive element R_T is related to the temperature by the relationship:

$$R_T = R_{To}.(1 + \alpha.t + \beta.t^2) \tag{5}$$

Where R_{To} is the resistance value at zero degrees Celsius, $\alpha=3.9.10^{-3}K^{-1}$ and $\beta=-5.8.10^{-7}K^{-2}$.

By substituting (2), (3) and (5) in (4), the following relationship for the voltage E at the input of the voltage-to-current converter can be established:

$$\frac{E}{E_R} = \frac{(b + c) + \alpha.b.t + \beta.b.t^2}{(a + 1) + \alpha.a.t + \beta.a.t^2} \tag{6}$$

Where $E_R = R_{To}.I_R$ (7)

$$a = \left[\frac{1 - G.R_A}{R_A + R_F}\right].R_{To} \tag{8}$$

$$b = 1 + \left[\frac{R_A.Io}{R_A + R_F}\right].\frac{1}{I_R} \tag{9}$$

$$c = \frac{V_R}{I_R.R_{To}} \tag{10}$$

The relationship (6), which is a rational polynomial, can be rewritten as:

$$\frac{E}{E_R} \cong r_0 + r_1.t + r_2.t^2 \tag{11}$$

Where:

$$r_0 = \frac{b + c}{a + 1} \tag{12}$$

$$r_1 = \alpha.(b - a.c) \tag{13}$$

$$r_2 = (b - a.c).\left[\beta - (a + 1).a.\alpha^2\right] \tag{14}$$

Since the output current of transconductor G is linearly related to the input voltage E, it is necessary to cancel the second-order term in (11) to achieve linearization of this parameter. That is:

$$\frac{\beta}{\alpha^2} = a.(a + 1) \tag{15}$$

By substituting (8) in (15) an expression for the feedback resistance R_F can be established:

$$R_F = \frac{-B - \sqrt{B^2 - 4.A.C}}{2.A} \tag{16}$$

Being:

$$A = \frac{\beta}{\alpha^2}$$

$$B = 2.R_A.A - R_{T0}(1 - G.R_A))$$

$$C = A.R_A{}^2 - R_{To}.R_A.(1 - G.R_A) - R_{To}{}^2.(1 - G.R_A)^2$$

Therefore, given a voltage-to-current conversion factor G, a resistance value R_A and the zero Celsius degree value of R_T, the feedback resistance R_F is calculated from (15) to establish the linearization of the output current.

For example: G = 0.175 A/V, R_{To} = 100Ω and R_A =50Ω results in R_F = 19.5 KΩ.

3. System Level Simulation

In order to verify the validity of the linearization technique, extensive simulations were performed at both the system level and circuit level with the RTD operating in different temperature ranges.

For the sake of illustration, the simulation results of a system similar to the one shown in Fig.1, in which the RTD is a Pt100 operating in the range of $0^oC - 100^oC$, are shown: Fig.3, shows the intrinsic nonlinearity of the Pt100 that accounts for an error of approximately 0.4% of the full scale.

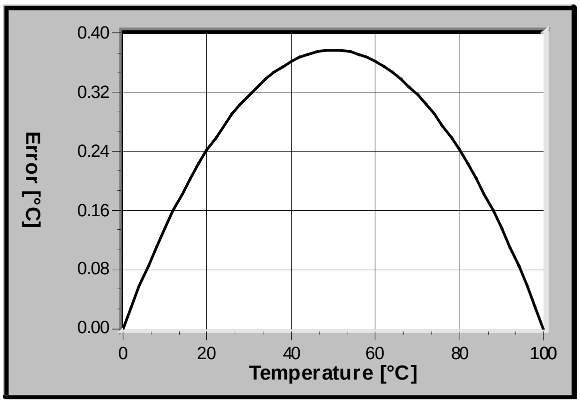

Fig. 3: Intrinsic nonlinearity of a Pt100 RTD

The result of linearization is in Fig.4 showing that the error is reduced to approximately 0.002% of the full scale

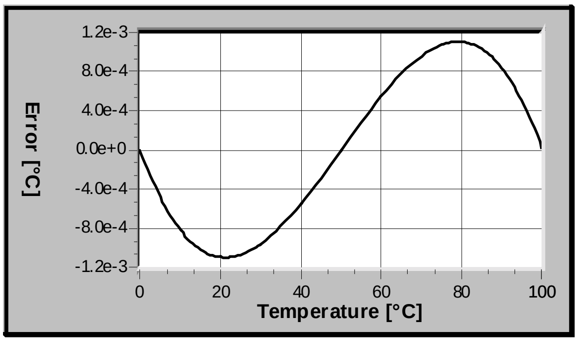

Fig. 4: Effect of the linearization of a Pt100

4. Other Configurations

Alternative configurations of the system can be used according to the required application. In Fig.5, the reference voltage V_R, which in the original system can be implemented by either using a temperature compensated diode or a two-terminal reference voltage source, has been replaced by a resistor R_R. Since the current that flows across this resistor is not constant, the same expressions found for the original configuration can not be applied in this case. However, following the same procedure used to derive the expressions in Session III will easily lead to the corresponding equations. By replacing the reference diode with a resistor the cost of this diode is reduced at the expense of adjusting the right value of R_R.

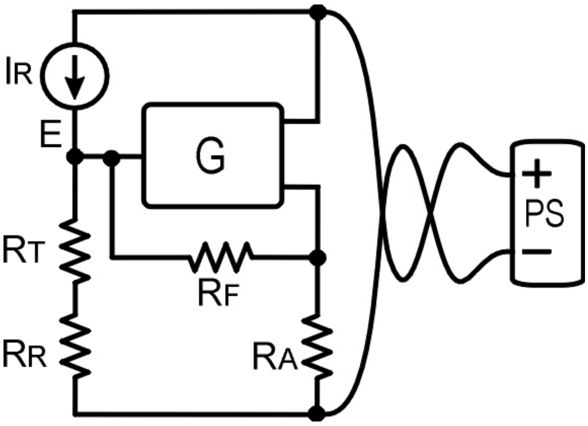

Fig. 5:Simplest configuration

The preferred configuration, the one adopted for commercial production, uses a differential Voltage-to-Current converter and a second reference current source, as shown in Fig.6.

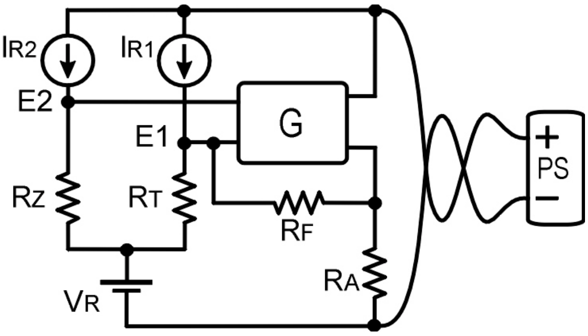

Fig. 6: Preferred configuration

In the above case, zero adjustment is achieved by trimming the value of resistor R_Z. A wide variety of temperature ranges can be covered by selecting the pertinent values of R_F and R_A.

5. Results

The resulting miniature in-head transmitter for Resistance Temperature Detectors, shown in Fig.7, is built on a ceramic substrate measuring 5mm X 50mm with thick-film resistors that are actively trimmed to the specified temperature range of operation.

Fig. 7:Photograph of the in-head transmitter

The commercial versions of this device are in-factory calibrated with guaranteed ASTM Class B accuracy.
For the sake of illustration, the effects of linearization for two different temperature ranges are shown in the two figures below: In both cases, the circle points are measurements with the sensor without linearization and the square points are the measurements with linearization.

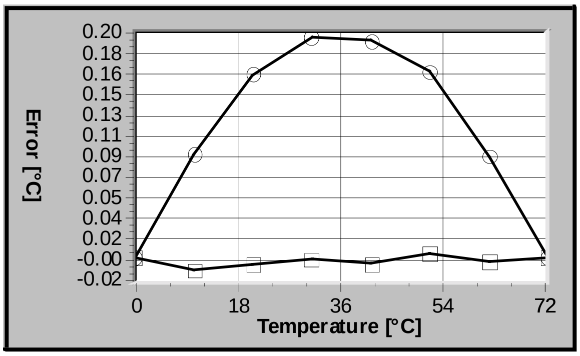

Fig. 8: Measurements in the range 0-72°C.

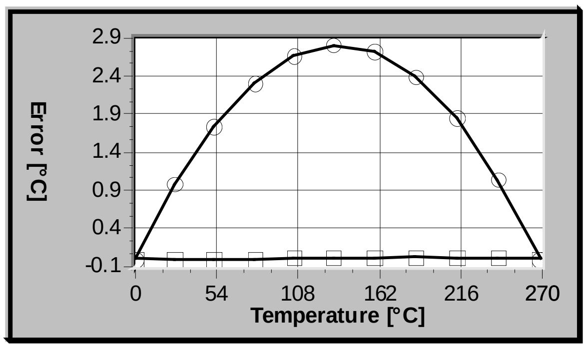

Fig. 9: Measurements in the range 0-270°C

6. Conclusions

This paper described a technique to linearize Resistance Temperature Detectors that allows the implementation of linearized in-head two-wire current loop transmitters without adding expensive extra devices. Instead of using instrumentation amplifiers and other expensive devices as usual in analog similar existing solutions, the presented technique is based on a linear transconductor with a local current feedback. The technique has been applied to the production of miniature in-head transmitters featuring Class B accuracy. Results have shown that the developed analog solution is more effective than a microprocessor based solution.

References

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