Analog linearization of resistance temperature detectors

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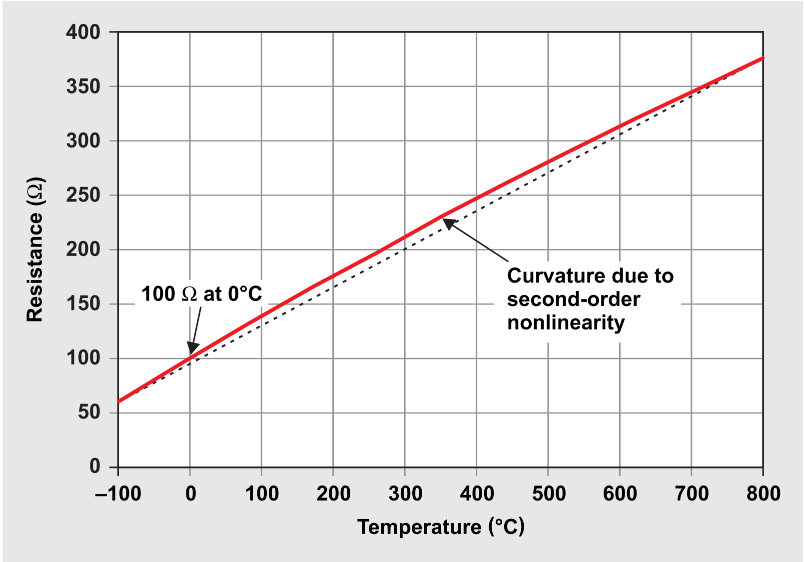
Resistance temperature detectors (RTDs) are commonly used in industrial and scientific temperature measurements. The most common types are pure platinum (Pt) formed into wire or evaporated in a thin film on a substrate. They rely on the fundamental temperature-dependent resistance properties of this noble metal. They are very stable and useful at temperatures ranging from cryogenic to over 800°C. A wide range of physical configurations, resistance ranges and accuracies is available.[1] The commonly used notation "Pt100" indicates a 100-Ω resistance at 0°C. The relationship between the RTD's resistance and temperature is described by the Callendar-Van Dusen equation,

Figure 1. Resistance of Pt100 RTD versus temperature



$$R_{RTD} = R_0[1 + AT + BT^2 + C(T - 100)T^3],$$

whose values are defined as follows:

R_0 is a 100-Ω resistance at 0°C (Pt100)
$A = 3.9083 \times 10^{-3}$
$B = -5.775 \times 10^{-7}$
$C = 0$ for $T > 0°C$, or $C = -4.23225 \times 10^{-12}$ for $T < 0°C$.

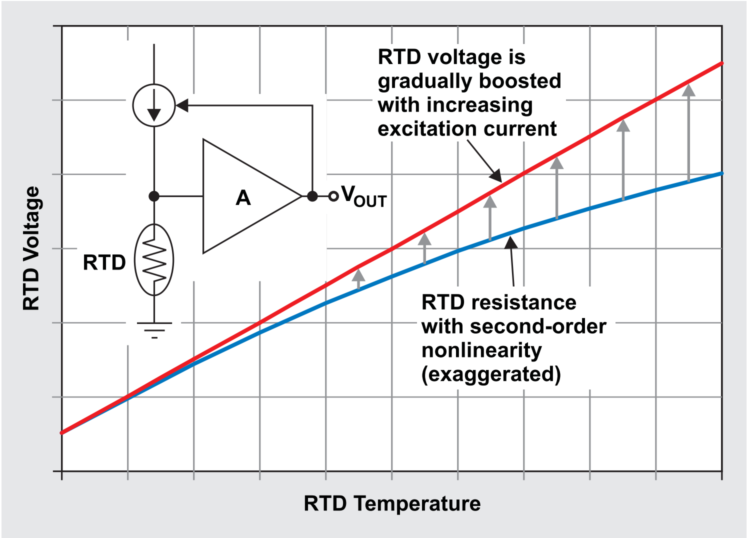
The resistance of a Pt100 RTD increases with temperature at approximately 0.39%/°C. While they are far more linear than thermocouples, RTDs have a significant second-order nonlinearity of approximately 0.38% per 100°C measurement range (see Figure 1). This nonlinearity is often corrected digitally, but there are many applications for purely analog processing and linearization of the RTD.

This article explains an analog technique for linearization of the RTD. The same technique is also used with bridge sensors such as pressure and load cells. The principles can be applied to other ratiometric devices with primarily second-order nonlinearity; i.e., any sensor or system with an output that is proportional to an excitation voltage or current.

The exaggerated graph in Figure 2 shows that the temperature coefficient decreases with increasing temperature, producing an upward bow in the middle. Above 0°C, standardized data for the Pt100 has a purely second-order or parabolic function. Assuming calibration at two endpoint temperatures, this produces an error that is greatest at the midpoint temperature.

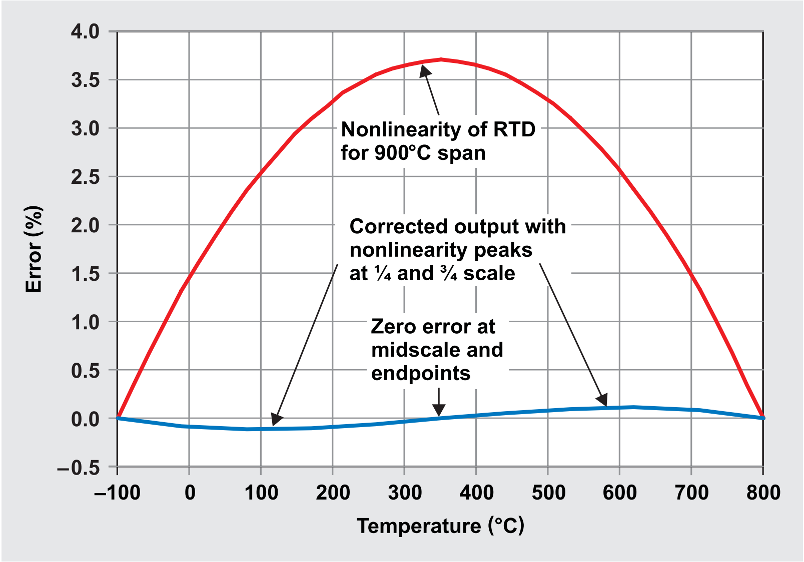
When the RTD is excited with a current source, the resulting RTD voltage is directly proportional to the resistance, yielding the same nonlinearity. If, however, the excitation current is gradually increased as the RTD temperature

Figure 2. RTD voltage versus temperature



is increased, the nonlinearity can be greatly reduced. Figure 2 shows an increasing excitation current derived from the output of the amplified RTD voltage. This current is, in effect, a controlled amount of positive feedback. It yields an interesting "chicken-or-egg" dichotomy: The RTD voltage at the input of the amplifier is linearized when the output of the amplifier is linearized—and vice versa. The correct amount of positive feedback results in both.

Figure 3. Percentage of RTD error versus temperature



When positive feedback is optimized, a much smaller s-shaped error remains with nearly equal negative and positive values, reaching maximums at ¼ and ¾ full scale (see Figure 3). This primarily third-order nonlinearity does not come from the RTD but is an artifact of the linearization technique. Its magnitude depends on the temperature range chosen for linearization. Figure 3 shows the initial nonlinearity error for a –100°C to +800°C temperature range—a 900°C span. The 3.7% RTD nonlinearity at midscale is reduced to approximately ±0.11%, a 33:1 improvement. The improvement is even greater for narrow temperature ranges, approaching 150:1 for a 200°C range.

The use of positive feedback might raise the concern of possible circuit instability. The magnitude of this feedback is small enough, however, to have negligible effect on the stability of commonly used circuits.

Figure 4. Typical RTD configuration with error compensation

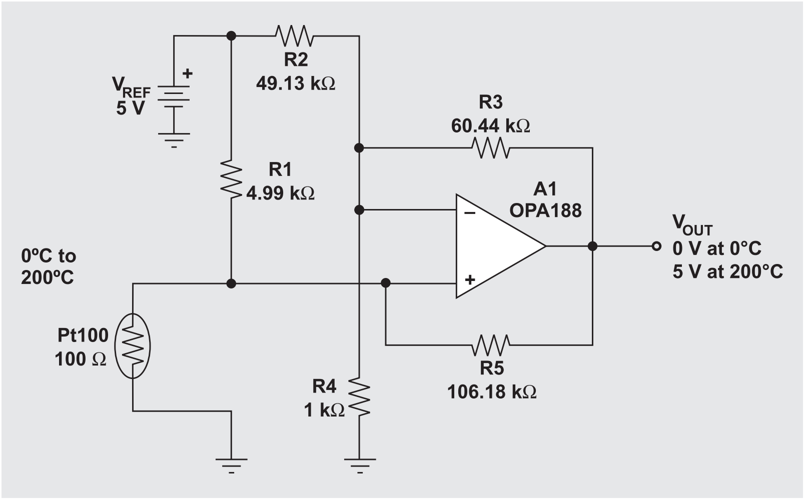


Figure 4 shows a practical implementation of an RTD. R1 provides the primary excitation current from V_{REF}, a stable voltage reference. R5 provides the temperature-varying component of excitation current from the output of A1. R2, R3, and R4 set the required amplifier gain and offset to produce the desired output-voltage range. The Texas Instruments (TI) OPA188* shown in this example is a new low-noise, chopper-stabilized operational amplifier that contributes negligible error to the circuit. Its very low and stable offset voltage makes it a possible upgrade to TI's OPA277 precision industrial amplifier.

The resistor values to achieve best correction can be calculated with iterative techniques. Many designers might optimize this type of circuit by using creative calculations or approximations. A closed-form solution is possible by solving the nodal equation that relates the RTD voltage, RTD resistance, V_{REF}, R1, R5, and V_{OUT}:

$$V_{RTD} = V_{REF} \times \frac{\dfrac{R_{RTD} \times R5}{R_{RTD} + R5}}{\dfrac{R_{RTD} \times R5}{R_{RTD} + R5} + R1} + V_{OUT} \times \frac{\dfrac{R_{RTD} \times R1}{R_{RTD} + R1}}{\dfrac{R_{RTD} \times R1}{R_{RTD} + R1} + R5}$$

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*The OPA188 is expected to be available in early 2012. For general specifications, please refer to the dual version, OPA2188, at www.ti.com/product/OPA2188

Three conditions must be met to achieve zero error at the calibration endpoint temperatures and the midpoint temperature. Three separate variations of the preceding equation are written to describe the three zero-error conditions and are solved simultaneously for the only unknown variable, R5. The resistance of the RTD at the midpoint temperature is not halfway between the endpoint resistances. This midpoint condition holds the key to the solution for best linearity correction.

The math yields three results for R5; only one is a positive resistance. The expression for R5 is very long and impractical to present here. To download an Excel® worksheet that provides the calculations, go to http://www.ti.com/lit/zip/SLYT442 and click Open to view the WinZip® directory online (or click Save to download the WinZip file for offline use). Then open the file RTD_Linearization_v7.xls to view the calculation worksheet. This closed-form solution is intellectually satisfying and avoids possible problems with convergence, but the results are no better than those produced with iterative calculations. Practical implementations often require trimming of resistors for calibration because accurate, nonstandard values are often required. SPICE simulation can help determine actual performance with the nearest standard values. The WinZip file download listed above also includes two RTD simulation examples in TINA-TI™ SPICE files. One file implements an RTD linearization circuit based on an operational amplifier, and the other file is based on an instrumentation amplifier. Please see Reference 2 for more information on an RTD simulator for SPICE.

Figure 5. Correlation of excitation current to RTD error

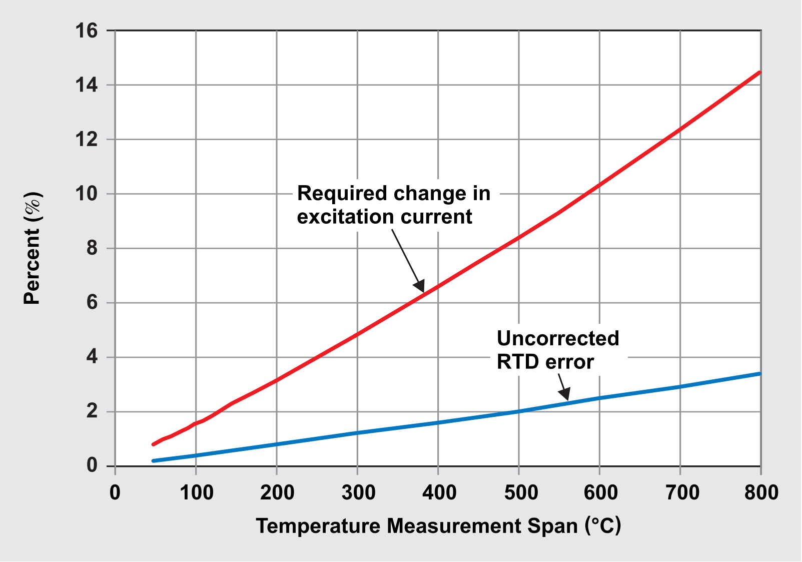

Figure 6. Amplifier with three-wire RTD connection

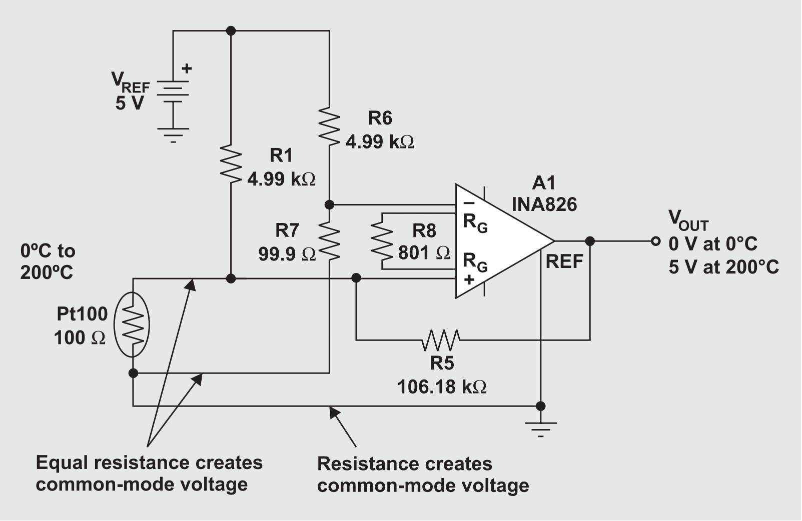

Figure 5 shows that uncorrected nonlinearity of the RTD increases as the calibrated temperature range is increased, reaching approximately 2% for a 500°C span. The variation in the RTD's excitation current to compensate for this nonlinearity is approximately four times the nonlinearity. Thus, for a 500°C measurement span, the excitation current increases by approximately 8% from low-scale temperature to full scale.

Low-resistance connections to the RTD are crucial in maintaining accuracy with this circuit. For this reason, high-resistance RTDs such as Pt1000 or Pt5000 may be most practical. With a four-wire (or Kelvin) connection to the RTD and an additional operational amplifier, errors induced by wire resistance can be eliminated.

An integrated instrumentation amplifier with a three-wire RTD connection can provide an alternative solution (see Figure 6). In the three-wire connection, two connections are used on the ground side of the RTD. Equal currents flowing in equal line resistances create a common-mode input voltage that is rejected by the instrumentation amplifier. Current flowing in the ground-wire connection also creates a common-mode voltage. Note that the currents in signal connections are not precisely equal. They differ due to the varying linearity correction current from R5. Nevertheless, this configuration removes most of the error that is due to line resistance.

Table 1. Partial listing of TI's integrated circuits for RTDs and bridge sensors

PRODUCT	SENSOR TYPE	EXCITATION	OUTPUT	FEATURES
XTR105	RTD	Dual 1-mA current	4 to 20 mA	Resistor-programmed range and linearization
XTR106	Pressure bridge	Voltage	4 to 20 mA	Corrects positive or negative second-order nonlinearity
XTR108	RTD	Dual programmable current	4 to 20 mA or voltage	Programmable excitation current and linearization
XTR112	High-impedance RTD	Dual 100-µA current	4 to 20 mA	Excitation for Pt1000 RTD
XTR114	High-impedance RTD	Dual 250-µA current	4 to 20 mA	Excitation for Pt5000 RTD
PGA309	Pressure bridge	Programmable voltage	Voltage	Digitally controlled analog-signal path with linearization

Other sensor types

Bridge sensors such as strain gauges and load cells frequently require linearization with similar techniques. Voltage excitation is generally used for these applications, but the concept is the same. Excitation voltage is varied with amplifier output voltage. These sensors can have a downward bowing nonlinearity requiring that the excitation voltage decrease as pressure increases. Furthermore, nonlinearity may vary significantly from unit to unit, so individual calibration may be required.

Integrated solutions

TI uses variable excitation for linearization in several integrated circuits intended for RTDs and bridge sensors (see Table 1). Some circuits are designed specifically for remote sensors with two-wire, 4- to 20-mA current-loop output. XTR106 and PGA309 provide voltage excitation, which is preferred for many strain-gauge bridge-sensor applications. Though designed for specific sensor types, these devices have been successfully adapted to a variety of sensor applications, with and without variable excitation for linearization.

References

1. Resistance thermometer. *Wikipedia* [Online]. Available: http://en.wikipedia.org/wiki/Resistance_thermometer
2. Thomas Kuehl. (2007, May 28). Developing a precise Pt100 RTD simulator for SPICE. *EN-Genius Network: analogZONE: acquisitionZONE* [Online]. Available: http://www.analogzone.com/acqt_052807.pdf
3. Bruce C. Trump. (1994, March 3). Pressure gauge responds linearly to altitude. *EDN* [Online]. Available: http://www.edn.com/archives/1994/030394/05di5.htm

Related Web sites

www.ti.com/product/*partnumber*
Replace *partnumber* with INA826, OPA277, OPA2188, PGA309, XTR105, XTR106, XTR108, XTR112, or XTR114

Support files with Excel spreadsheet and TINA-TI™ simulation examples:
www.ti.com/lit/zip/SLYT442