Temperature Accuracy Considerations for RTD Measurement Techniques

Temperature is a critical parameter of many processes. Optimum process control and efficiency necessitate accurate temperature measurements. The platinum RTD (Resistance Temperature Detector) is considered among the most accurate of temperature sensing devices, using a resistive element of platinum that changes with temperature in a very predictable and repeatable manner. There are three RTD leadwire configurations: 2-wire, 3-wire, and 4-wire, each with corresponding resistance measurement techniques. This paper examines several resistance measurement techniques, and derives the potential temperature error introduced by each technique. Although it is clearly shown that 4-wire resistance measurement is the most accurate, extenuating circumstances may preclude the use of 4-wire RTD sensors for a specific application. For such instances, suggestions are given to minimize the errors in 2-wire and 3-wire configurations, including the incorporation of temperature transmitters.

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Table of Contents

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Introduction

AS TECHNOLOGY AND AUTOMATION BECOME INCREASINGLY ADVANCED AND ABUNDANT, THE HUNGER FOR SENSORS GROWS.

Whether it's oil refinement, launching a communication satellite in orbit, or simply getting the weekend weather forecast on your smart phone, a myriad of sensors are necessary for successful and accurate results: Pressure, temperature, humidity, flow, level, acceleration, position, and a variety of optical sensors provide critical information to the control system. The temperature sensor was deemed the "most useful sensor" in an EDN reader poll.[1] This shouldn't come as a big surprise, since temperature affects chemical reactions, volume, pressure, dimensions, state (solid/liquid/gas), and even our comfort level. Accurate temperature measurements, therefore, are important – even imperative.

Temperature Measurement Techniques

Since temperature affects so many physical parameters, it follows that measuring temperature can b e done by monitoring one of those physical parameters in a controlled environment. For example, mercury expands in volume with increasing temperature. If the mercury is contained in a transparent material that does not expand significantly with temperature, the height of the mercury can indicate temperature. This is the principle behind mercury-in-glass thermometers (*Figure 1*).

Another mechanical device bonds dissimilar metals together. Their differences in thermal expansion result in a temperature dependent deflection of a needle (indicator). Before the digital age, virtually every house in North America was adorned by a bimetal thermometer (*Figure 2*).

FIGURE 1

FIGURE 2

The previous examples provide adequate local indication, but what about measuring temperature in areas that aren't visually accessible? Fortunately, in addition to affecting many physical parameters, temperature also affects several electrical properties. A voltage is produced by a thermocouple that is proportional to the temperature gradient along the wires. The electrical resistances of metal oxides (thermistors) and conductive metals (Resistance Temperature Detectors or RTDs) are likewise proportional to temperature, and are often used for critical, high-accuracy temperature measurements. Specifically, platinum possesses many characteristics that make it a perfect candidate for RTD element material: it's chemically and thermally stable and has both a high melting point and relatively high resistivity (compared to copper, silver, nickel, etc.).

Due to its propensity for high accuracy applications, platinum is the RTD on which we will focus our attention concerning measurement techniques. For the sake of demonstration, we'll use Pt100 (Platinum, 100 ohms at 0°C, 0.00385 ohms/ohm/°C) – the most widely used RTD – for calculation examples.

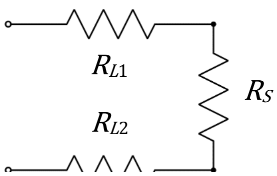
Resistance Measurement Techniques

The heart of an RTD is the sensing element – a wire-wound or thin-film resistor. Electrical access to the sensing element is created with leadwires or circuit traces. Resistance can be measured using two, three, or four conductors (hereafter designated as 2-wire, 3-wire, or 4-wire). Each resistance measurement technique has advantages and disadvantages which must be carefully weighed against the application, installation, and accuracy requirements. If the measurement instrumentation is already in place, you may not have a choice but to select an RTD with the number of leads for which the instrumentation is designed.

Although the leadwires or circuit traces are typically composed of excellent electrical conductors (like copper or plated copper), they still have inherent resistance. A key factor in making accurate temperature measurements is compensating for the circuit resistance between the sensing element and the measurement device.

2-Wire

The simplest form of RTD is a 2-wire configuration, where a single conductor (leadwire or circuit trace) is attached to either side of a resistive sensing element as shown in *Figure 3*.



Meaured resistance $= R_{L1} + R_S + R_{L2}$
where $R_S =$ *resistance of the temperature sensing element,*
$R_{L1} =$ *resistance of one leadwire,*
$R_{L2} =$ *resistance of the other leadwire.*

FIGURE 3

The error is the difference between measured resistance and the sensing element resistance:

$$Error = Measured\ resistance - R_S = R_{L1} + R_{L2} \qquad \text{(equation 1)}$$

The only resistance of interest is R_S, since it indicates the temperature of the object being measured. Mathematically, it is obvious that we can determine R_S by simply subtracting the leadwire resistances R_{L1} and R_{L2}. In practice however, measuring R_{L1} and R_{L2} is usually impossible, because there is no electrical access to the leadwire end that's connected to the sensing element. In addition, many sensor designs internally transition the leadwires to conductors of different size and/or material to accommodate high temperature and/or size demands. The resistance of the transition conductors is seldom known – their mere existence may be part of a proprietary sensor design. Lead resistance estimates are further complicated by the unavoidable yet unpredictable temperature gradients along the leads. Leadwire material is typically copper, silver-plated copper, nickel-plated copper, or nickel, all of which exhibit temperature dependent resistance. (In fact, copper and nickel are used as RTD element materials.) Therefore, it is generally difficult to achieve high accuracy by subtracting leadwire resistance in a 2-lead sensor configuration.

Minimizing the error by minimizing R_{L1} and R_{L2} is often not practical due to:

- Logistics: shortening leadwires is not practical because the measurement instrumentation can't be located right next to every temperature sensor
- Size: increasing leadwire diameter lowers resistance, but a pair of 12AWG leads will not fit into a 0.125" diameter case, no matter how hard you try
- Physics: leadwires have resistance, and insulated superconductors of zero resistance at room temperature aren't currently known to exist

3-Wire

The most common method to improve temperature measurement accuracy in industrial applications is by using 3-wire RTDs, where an extra leadwire is attached to one side of the sensing element as shown in Figure 4.

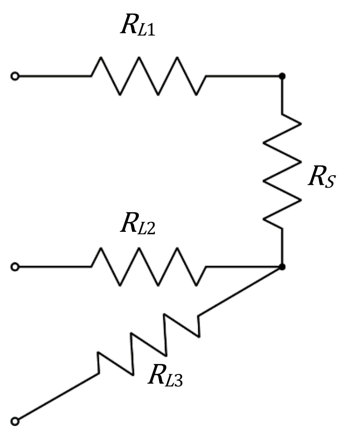


FIGURE 4

There are a number of different resistance measurement circuit designs for 3-wire configurations that attempt to reduce or eliminate any error attributable to leadwire resistance. Some designs are more effective than others. This paper will examine a single current source design, matched current source design, differential design, and Wheatstone bridge. To determine which 3-wire resistance measurement technique is used in your application, a detailed description or schematic of the measurement instrumentation is required. Unfortunately, these are rarely available for purchased equipment.

Single Current Source

In the 3-wire resistance measurement technique shown in *Figure 5*, the excitation current I_M from the measurement instrumentation passes through R_{L1}, R_S, and R_{L3}.

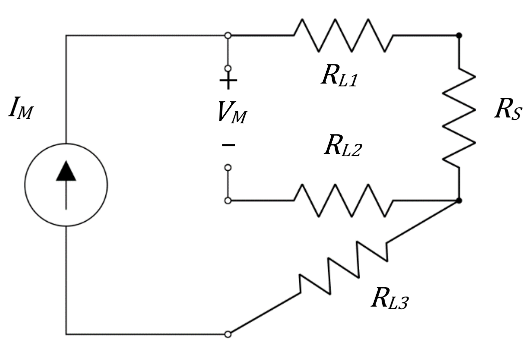


FIGURE 5

$$V_M = I_M (R_{L1} + R_S)$$

where V_M *= measured voltage (by measurement instrumentation),*
I_M *= excitation current (from the measurement instrumentation),*
R_S *= resistance of the temperature sensing element,*
R_{L1}, R_{L2}, *and* R_{L3} *= resistances of corresponding leadwires.*

Theoretically, there is no voltage drop across R_{L2}, since there is no current going through it. This is a reasonable approximation, since a voltmeter with 10M ohm input impedance[2] would typically limit the current through R_{L2} to less than 0.1 µA.

Solving for measured resistance:

$$Measured\ resistance = \frac{V_M}{I_M} = R_S + R_{L1}$$

The error is the difference between measured resistance and the sensing element resistance:

$$Error = Measured\ resistance - R_S = R_{L1} \qquad \textit{(equation 2)}$$

If we assume all the leads are equivalent in resistance, the error for the single source circuit of *Figure 5* is half that of a 2-wire resistance measurement circuit.

Matched Current Sources

The error for the single source circuit in the previous example can be virtually eliminated by adding a second current source as shown in *Figure 6*.

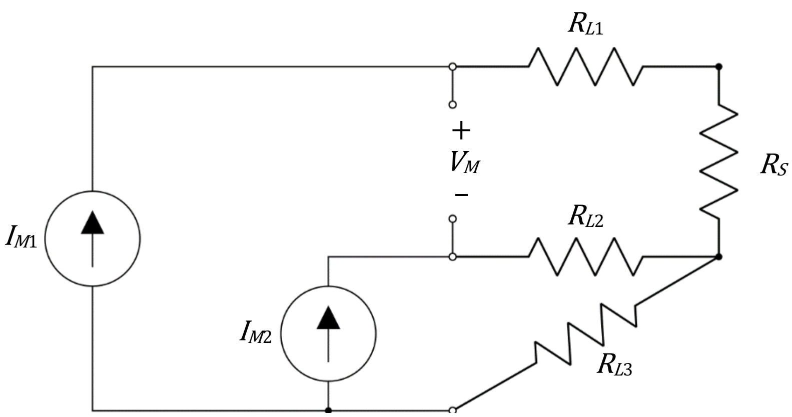


FIGURE 6

$$V_M = [I_{M1}(R_{L1} + R_S) + (I_{M1} + I_{M2})R_{L3})] - [I_{M2}R_{L2} + (I_{M1} + I_{M2})R_{L3}] \qquad \textit{(equation 3)}$$

If the constant current sources I_{M1} and I_{M2} are balanced ($I_{M1} = I_{M2} = I_M$) and we assume the leadwire resistances are equivalent ($R_{L1} = R_{L2} = R_{L3}$), *equation 3* simplifies to:

$$Measured\ resistance = \frac{V_M}{I_M} = R_S$$

Theoretically, the leadwire resistances have been completely eliminated.

However, recall that there were 2 assumptions made that greatly simplified the expression:

- The constant current sources are balanced ($I_{M1} = I_{M2} = I_M$)
- The leadwire resistances are equivalent ($R_{L1} = R_{L2} = R_{L3}$)

There are several ways to achieve the first assumption – high precision current sources, match calibration, or electronically "swapping" the current sources and averaging the results.

The second assumption however, poses a greater challenge – especially for small diameter and/or long leads. A consequence of process variances in the manufacture of leadwire is inconsistent resistance. The inconsistencies tend to be greater for small diameter wires (i.e. 26AWG or smaller). Empirical data has shown that inconsistency can even exist within a single spool (same process lot/batch).

R_L will represent the average resistance of all three leadwires:

$$R_L = \frac{R_{L1} + R_{L2} + R_{L3}}{3}$$

If the individual leadwire resistances are represented by the average leadwire resistance (R_L) and a unique factor (α, β, δ), *equation 3* exposes the potential error introduced by unequal leadwire resistances.

$$R_{L1} = \alpha R_L \text{ and } R_{L2} = \beta R_L \text{ and } R_{L3} = \delta R_L$$

If the current sources are balanced $(I_{M1} = I_{M2} = I_M)$ then *equation 3* becomes:

$$V_M = I_M(\alpha R_L + R_S) - I_M \beta R_L$$

$$Error = Measured\ resistance - R_S = R_L(\alpha - \beta) \qquad \textit{(equation 4)}$$

This reveals a "double jeopardy" for small diameter leadwires, since inconsistency in leadwire resistance (α, β, δ) tends to be greater, and average leadwire resistance (R_L) is also greater.

Differential

In the next example, two consecutive measurements are made. The schematic in *Figure 7* uses a single pole double throw (SPDT) switch for purposes of illustration, but it is far more likely that an actual circuit would use a multiplexer (MUX) or relay.

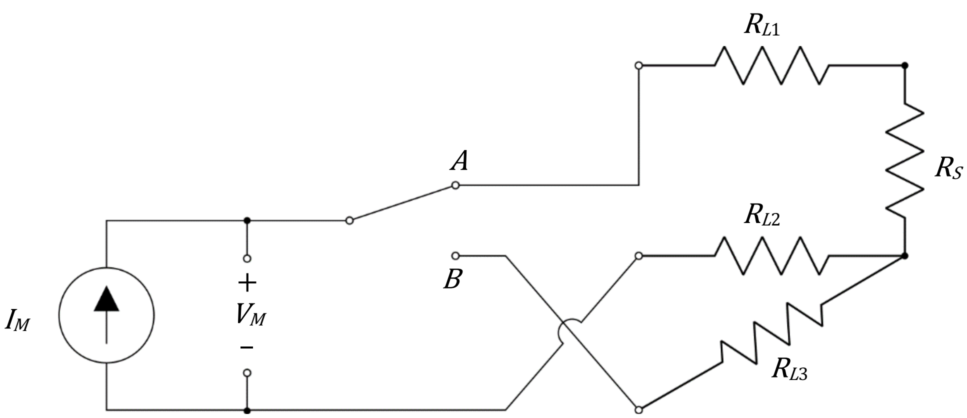


FIGURE 7

The first measurement is made with the switch in position A:

$$Measurement\ \#1 = \frac{V_{M1}}{I_M} = R_{L1} + R_S + R_{L2}$$

The second measurement is made with the switch in position B:

$$Measurement\ \#2 = \frac{V_{M2}}{I_M} = R_{L3} + R_{L2}$$

If we assume the leadwire resistances are equivalent ($R_{L1} = R_{L2} = R_{L3}$), and subtract the second measurement from the first:

$$Measurement\ \#1 - Measurement\ \#2 = (R_{L1} + R_S + R_{L2}) - (R_{L3} + R_{L2}) = R_S$$

Theoretically, the leadwire resistances have been completely eliminated.

Once again, we assumed that the leadwire resistances are equivalent ($R_{L1} = R_{L2} = R_{L3}$). If the individual leadwire resistances are represented by the average leadwire resistance (R_L) and a unique factor (α, β, δ), the potential error introduced by unequal leadwire resistances is again revealed:

$$R_{L1} = \alpha R_L\ and\ R_{L2} = \beta R_L\ and\ R_{L3} = \delta R_L$$
$$Measurement\ \#1 - Measurement\ \#2 = (\alpha R_L + R_S + \beta R_L) - (\delta R_L + \beta R_L)$$
$$Error = (Measurement\ \#1 - Measurement\ \#2) - R_S = R_L(\alpha - \delta) \qquad \textit{(equation 5)}$$

Wheatstone Bridge

The Wheatstone bridge (*Figure 8*) is a network of resistors, arranged into 2 "legs" of voltage dividers. It uses a voltage source and 3 known resistances to determine a single unknown resistance.

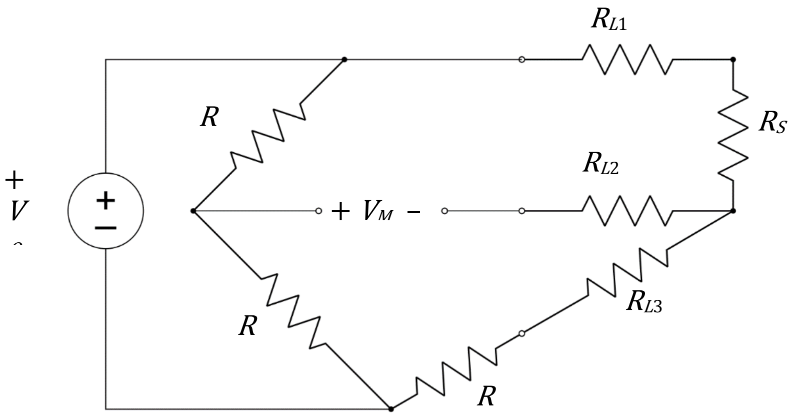


FIGURE 8

$$V_M = \frac{V_O R_2}{(R_1 + R_2)} - \frac{V_O(R_{L3} + R_3)}{(R_{L1} + R_S + R_{L3} + R_3)}$$

If the bridge is designed such that $R_1 = R_2$, and R_3 is a known resistance, adjusted such that $V_M = 0$, then the bridge is considered "balanced", and there is no voltage drop across R_{L2}:

$$\frac{(R_{L3} + R_3)}{(R_{L1} + R_S + R_{L3} + R_3)} = \frac{1}{2}$$

If we assume the leadwire resistances are equivalent ($R_{L1} = R_{L3} = R_L$), the above expression becomes:

$$R_S + R_3 + R_L + R_L = 2R_3 + 2R_L$$

which simplifies to: $R_S = R_3$

Theoretically, the leadwire resistances have been completely eliminated.

Again, we assumed that the leadwire resistances are equivalent ($R_{L1} = R_{L2} = R_{L3}$), and again, representing the individual leadwire resistances by the average leadwire resistance (R_L) and a unique factor (α, β, δ), the potential error introduced by unequal leadwire resistances can be quantified:

$$R_{L1} = \alpha R_L \text{ and } R_{L2} = \beta R_L \text{ and } R_{L3} = \delta R_L$$

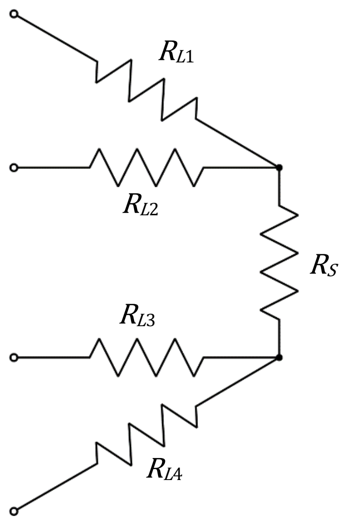
$$\frac{(\delta R_L + R_3)}{(\alpha R_L + R_S + \delta R_L + R_3)} = \frac{1}{2}$$

$$R_3 = R_S + R_L(\alpha - \delta)$$

Since R_3 is a known (albeit adjustable) resistance, it is considered the measured resistance:

$$Error = Measured\ resistance - R_S = R_L(\alpha - \delta) \qquad \textit{(equation 6)}$$

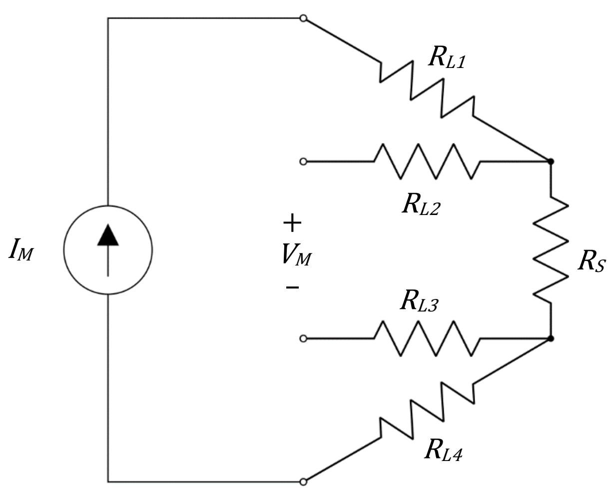
4-Wire



The 4-wire resistance measurement technique is the most effective method of eliminating leadwire resistance, and therefore offers the highest accuracy when measuring temperature with an RTD. A 4-wire RTD is manufactured with two leadwires attached to either side of the sensing element as shown in *Figure 9*:

FIGURE 9

Now, consider the resistance measurement circuit in *Figure 10*, where two of the leadwires deliver the excitation current from the measurement instrumentation to the sensing element, and the other two leadwires measure the resulting voltage drop:



$$V_M = I_M R_S$$

The only assumption we've made is that there is no current going through R_{L2} or R_{L3}, and therefore, no voltage drop across them. As in a previous example, this is a reasonable approximation, since a voltmeter with 10M ohm input impedance[2] would typically limit the current to less than 0.1 µA.

FIGURE 10

$$Measured\ resistance = \frac{V_M}{I_M} = R_S$$

Since the measured resistance has no dependence on any R_L, the leadwire resistance has no effect on the measured resistance, nor do unequal leadwire resistances.

Translating Resistance Error into Temperature Error

We've done the math, and derived expressions that define measurement error introduced by leadwire resistance. But who cares? It's resistance. You're trying to measure temperature.

According to international standard IEC 60751 for industrial platinum resistance thermometers[3], the mathematical relationship between resistance and temperature is defined as follows:

$$R_S = R_0[1 + At + Bt^2 + Ct^3(t - 100)] \qquad \textit{for} \text{ -200°C} \leq t \leq \text{0°C}$$

$$R_S = R_0(1 + At + Bt^2) \qquad \textit{for} \text{ 0°C} \leq t \leq \text{850°C}$$

where R_S *= resistance of the temperature sensing element at temperature t (in °C),*
R_0 *= resistance of the temperature sensing element at* 0°C,
$A = 3.9083 \times 10^{-3}$,
$B = -5.775 \times 10^{-7}$,
$C = -4.183 \times 10^{-12}$.

It follows then, that the sensitivity (change in resistance per unit change in temperature) can be represented by the first derivative of the resistance-temperature characteristic curves with respect to temperature:

$$Sensitivity = \frac{dR_S}{dt} = R_0[A + 2Bt + 4Ct^2(t - 75)] \qquad \textit{for} \text{ -200°C} \leq t \leq \text{0°C}$$

$$Sensitivity = \frac{dR_S}{dt} = R_0(A + 2Bt) \qquad \textit{for} \text{ 0°C} \leq t \leq \text{850°C}$$

Recall the calculated errors in equations 4, 5, and 6 are the product of the average leadwire resistance (R_L) and the difference in the corresponding factors (α, β, δ) for two of the leadwires. Statistically, the leadwire resistance inconsistency follows a normal distribution, and the rules of probability state that:

$$\sigma_{X-Y} = \pm\sqrt{\sigma_x^2 + \sigma_y^2}$$

where σ_x *= standard deviation of resistance for one of the leads,*
σ_y *= standard deviation of resistance for another lead,*
$\sigma_{X\text{-}Y}$ *= standard deviation of the difference between the 2 corresponding factors.*

$$Temperature\ error\ (°C) = \frac{Resistance\ error\ (ohms)}{Sensitivity\ (ohms/°C)} \qquad \textit{(equation 7)}$$

Since the temperature error is inversely proportional to the sensitivity (per *equation 7*), for a given resistance error, the temperature error can be minimized by maximizing sensitivity. And since sensitivity (above and below 0°C) is directly proportional to R_0, a sensor with higher resistance is less vulnerable to temperature error from leadwire resistance inconsistency than a sensor with lower resistance.

Let's dispense with the variables and use some real numbers. In this example, a Pt100 RTD with 12 feet of 28AWG leadwires is monitoring a process at 80°C.

$R_S = 130.90$ ohms,
$Sensitivity = 0.38$ ohms/°C,
$R_L = 0.80$ ohms,
$(\alpha - \beta) = (\alpha - \delta) = \pm 0.071$ (leadwire resistances match to $\pm 5\%$ of their average).

Table 1 compares the relative temperature errors for the different resistance measurement techniques examined herein, based on the example application above. Resistance errors are calculated with equations 1, 2, 4, 5, and 6. The resistance errors are translated into temperature errors using equation 7.

Resistance measurement technique	**Temperature error (R_0 = 100.00 ohms)**	**Temperature error (R_0 = 1000.0 ohms)**
2-Wire	+4.21°C	+0.42°C
3-Wire (Single Current Source)	+2.11°C	+0.21°C
3-Wire (Matched Current Sources)	±0.15°C	±0.01°C
3-Wire (Differential)	±0.15°C	±0.01°C
3-Wire (Wheatstone Bridge)	±0.15°C	±0.01°C
4-Wire	none	none

TABLE 1.

Transmitters or Signal Conditioners

Another solution for eliminating errors due to leadwire resistance is incorporating a temperature transmitter. A temperature transmitter measures the sensor resistance and converts it to a current signal proportional to temperature. The current signal travels over two wires to the measurement instrumentation. Unlike voltage or resistance, which can vary over the length of the connecting wires, a loop current is the same throughout the entire circuit. This means that temperature signals can be sent thousands of feet over two wires with no loss of accuracy from leadwire resistance.

Standard transmitters produce a signal between 4 and 20 mA that is linearly proportional to temperature over a specified temperature range. The same two wires that provide power for the transmitter's electronics are also the signal wires. The signal is at least four times the signal strength of a typical resistance measurement circuit, dramatically improving the signal-to-noise ratio. Electromagnetic interference can be reduced simply by twisting the wires together, which equally distributes EMI across both wires. Any induced current occurs in both wires in opposite directions, effectively "cancelling out".

Temperature transmitters are portable devices and are typically installed in close proximity to the sensor, thereby minimizing leadwire resistance errors between the sensor and transmitter. Temperature error can be further reduced by "tuning" (match calibrating) the transmitter to the output of a specific sensor. The obvious disadvantage to a matched set is that the entire set requires replacement if either component fails.

For example, consider a transmitter specified for use with a Pt100 RTD to output 4 mA at 0°C and 20 mA at 250°C. Under "nominal" calibration (not matched), the transmitter would be adjusted to output 4 mA with an input resistance of 100.00 ohms output 20 mA with an input of 194.10 ohms (per IEC 60751). But what if the RTD's actual resistance was 100.11 ohms at 0°C, and 194.62 ohms at 250°C?

At 4 mA output – which is supposed to represent 0°C – the actual temperature would be just under 0.3°C. At 20 mA output – which is supposed to represent 250°C – the actual temperature would be over 251.4°C. By "tuning" (match calibrating) the transmitter to the actual RTD resistance, the temperature errors attributable to imperfect RTD calibration can be virtually eliminated.

Conclusion

Platinum RTDs (Resistance Temperature Detectors) are very popular temperature measurement devices due to their stability and accuracy. However, resistance measurement techniques can introduce significant temperature error from leadwire resistance. Of the three resistance measurement techniques (2-wire, 3-wire, and 4-wire), the 4-wire resistance measurement technique is the only one that effectively eliminates leadwire resistance errors. It is often impractical to expect IEC 60751 Class A or even Class B accuracy with 2-lead or 3-lead measurement techniques. This is especially true for small-diameter or low-profile RTDs that require small diameter leadwires. Although the errors can be minimized with high resistance RTD elements, the application, sensor design, and budgeted cost may not allow it. The end user should take the potential temperature errors into consideration and adjust their expectations and system accuracy calculations.

Start Measuring With More Confidence.

Contact our RTD and match calibration experts to begin identifying a winning match calibration solution that promotes system safety, operational efficiency, and optimal performance.

Call Minco at 763.571.3121 or visit Minco.com to get started.

References

[1]Mannion, Patrick. "The most useful sensors, according to you." *EDN.com.* UBM Communities, 15 June 2016. Web. 19 August 2016.

[2]Keysight 34465A Datasheet. 24 April 2020. Keysight Technologies.; and Fluke 115 Users Manual. March 2020. Fluke Corporation. (Both references, one benchtop and one handheld, specify ≥10M ohm input impedance for voltage measurements.)

[3]International Electrotechnical Commission (IEC). *Industrial platinum resistance thermometers and platinum temperature sensors.* IEC 60751 Edition 3.0: 2022-01.

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