Ratiometric Resistance Measurement of PT100 and PT1000 Sensors: Two-, Three- and Four-Wire Connections

Technical note

14 October 2026

1 Scope

This note describes how the resistance of a platinum RTD is measured with a delta-sigma ADC in a ratiometric configuration, and how that resistance is converted to temperature. Three connection methods are treated: two-wire, three-wire and four-wire.

The note is arranged in the order in which a measurement is built up. Section 2 gives the sensor characteristic, and Section 3 shows how a resistance value is converted to temperature. A temperature measurement is therefore a resistance measurement. Section 4 explains why the resistance is measured ratiometrically and how the ADC output relates to it. Sections 5 to 7 apply this to the three connections. For each one the circuit is given first, the node voltages are written from the circuit, the measurement equation is derived, and a numerical example is worked through from the ADC output word to the temperature. Section 8 compares the connections, and Section 9 covers the error sources they have in common. Section 10 relates the method to commercial practice. It covers two-wire sensors with a fixed cable, sensors with individual calibration data, and what happens inside a reader that displays temperature directly.

2 Sensor characteristic

The resistance of an industrial platinum RTD is defined by IEC 60751 [1] through the Callendar–Van Dusen equation,

$$R(T) = R_0\left(1 + AT + BT^2\right), \qquad T \geq 0\,^\circ\mathrm{C}, \tag{1}$$

$$R(T) = R_0\left(1 + AT + BT^2 + C(T-100)T^3\right), \qquad T < 0\,^\circ\mathrm{C}, \tag{2}$$

with T in °C and

$$A = 3.9083 \times 10^{-3}\ ^\circ\mathrm{C}^{-1}, \qquad B = -5.775 \times 10^{-7}\ ^\circ\mathrm{C}^{-2}, \qquad C = -4.183 \times 10^{-12}\ ^\circ\mathrm{C}^{-4}.$$

R_0 is the resistance at 0 °C: 100 Ω for a PT100 and 1 000 Ω for a PT1000. Table 1 lists values used later in this note.

The sensitivity near 0 °C is 0.391 Ω °C^{-1} for a PT100. A fractional resistance error ε therefore produces a temperature error

$$\Delta T \approx \varepsilon \, \frac{R(T)}{\mathrm{d}R/\mathrm{d}T}, \tag{3}$$

which at 0 °C is $\Delta T \approx 256\,^\circ\mathrm{C} \times \varepsilon$. A resistance error of 100 ppm corresponds to about 0.026 °C. This figure sets the accuracy the electronics must reach.

Table 1: PT100 resistance and sensitivity at selected temperatures. PT1000 values are ten times larger.

T (°C)	$R(T)$ (Ω)	$\mathrm{d}R/\mathrm{d}T$ (Ω °C^{-1})
−200	18.5201	0.4323
−100	60.2558	0.4053
0	100.0000	0.3908
100	138.5055	0.3793
850	390.4811	0.2927

3 Conversion of resistance to temperature

Each connection in Sections 5 to 7 ends with a measured value of R_{RTD}. The temperature is found from it by inverting (1) or (2). This step is the same for all connections. It is also the standard method in commercial instruments, which perform it in firmware and display only the result (Section 10.3).

3.1 Range $T \geq 0\,^{\circ}\mathrm{C}$

Equation (1) is quadratic in T. Solving for the root that lies in the physical range,

$$T = \frac{-A + \sqrt{A^2 - 4B\left(1 - R_{\mathrm{RTD}}/R_0\right)}}{2B}. \tag{4}$$

This expression is exact. It applies when $R_{\mathrm{RTD}} \geq R_0$. As a check, $R_{\mathrm{RTD}} = R_0$ gives $T = 0$.

3.2 Range $T < 0\,^{\circ}\mathrm{C}$

When $R_{\mathrm{RTD}} < R_0$, Eq. (2) is a quartic and is solved numerically. Define

$$f(T) = R_0\left[1 + AT + BT^2 + C(T - 100)T^3\right] - R_{\mathrm{RTD}}, \tag{5}$$

$$f'(T) = R_0\left[A + 2BT + C\left(4T^3 - 300T^2\right)\right]. \tag{6}$$

The value from (4) is used as the starting point T_0, and the Newton iteration

$$T_{k+1} = T_k - \frac{f(T_k)}{f'(T_k)} \tag{7}$$

is applied. The starting value is close because the C term is small. Its error is largest at the bottom of the range, $-2.42\,^{\circ}\mathrm{C}$ at $-200\,^{\circ}\mathrm{C}$. Over the whole interval from $-200\,^{\circ}\mathrm{C}$ to $0\,^{\circ}\mathrm{C}$, three iterations reduce the error below $1 \times 10^{-13}\,^{\circ}\mathrm{C}$, which is far below any other error in the measurement. A lookup table with linear interpolation, or a polynomial fitted to $T(R_{\mathrm{RTD}})$, are alternatives where computation must be minimised.

Example. For a PT100 with $R_{\mathrm{RTD}} = 60.2558\,\Omega$, Eq. (4) gives $T_0 = -100.2079\,^{\circ}\mathrm{C}$. The first Newton step gives $-100.00001\,^{\circ}\mathrm{C}$ and the second gives $-100.00000\,^{\circ}\mathrm{C}$, which agrees with Table 1.

4 Measurement principle

4.1 Direct measurement and its limitation

The simplest way to measure the sensor resistance is to pass a known current I through it and measure the voltage IR_{RTD} with an ADC that uses its own internal reference voltage V_{int}. The ADC reports the voltage

as a fraction k of its reference, $V = k V_{\text{int}}$, and the resistance is calculated as

$$R_{\text{RTD}} = \frac{V}{I} = \frac{k V_{\text{int}}}{I}. \tag{8}$$

The result depends on I and V_{int} as directly as on R_{RTD}. A current source integrated in an ADC typically has an initial tolerance of the order of 1 % and a temperature drift of several tens of ppm/K. By (3), a 1 % error in I gives 2.6 °C at 0 °C.

The initial error could be removed by a one-time calibration, but the drift cannot, because it continues after calibration as the ambient temperature changes. A drift of 50 ppm/K over a 40 K ambient change is 0.2 %, or 0.51 °C. This is more than the class A tolerance of the sensor itself, which is 0.15 °C at 0 °C. The drift of V_{int} adds to it.

Measuring the current separately does not solve this. A current measurement needs a shunt resistor and a voltage reference, so its accuracy is again limited by a reference voltage. The error is moved to another component rather than removed.

4.2 Ratiometric measurement

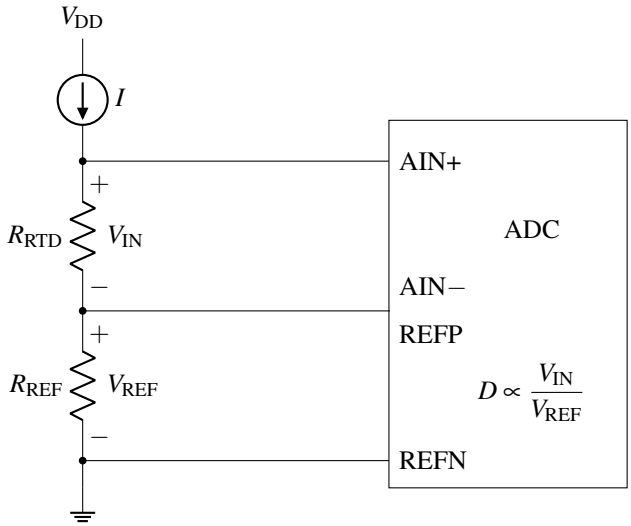


Figure 1: Ratiometric principle. The same current I flows through the sensor and the reference resistor. The voltage across R_{REF} is used as the ADC reference, so the ADC output depends only on $R_{\text{RTD}}/R_{\text{REF}}$.

In the ratiometric method a precision reference resistor R_{REF} is placed in series with the sensor, so that the same current flows through both (Fig. 1). The voltage across R_{REF} is connected to the reference input of the ADC in place of the internal reference. The two voltages are

$$V_{\text{IN}} = I R_{\text{RTD}}, \qquad V_{\text{REF}} = I R_{\text{REF}}. \tag{9}$$

An ADC output is always proportional to the ratio of its input voltage to its reference voltage. Here that ratio is

$$\frac{V_{\text{IN}}}{V_{\text{REF}}} = \frac{I R_{\text{RTD}}}{I R_{\text{REF}}} = \frac{R_{\text{RTD}}}{R_{\text{REF}}}. \tag{10}$$

The current cancels, and the internal reference is not used at all. Neither the tolerance nor the drift of I or V_{int} affects the result. The accuracy now depends on R_{REF}, which is available with a tolerance of 0.01 % and a temperature coefficient of a few ppm/K. With 5 ppm/K, the same 40 K ambient change gives 0.05 °C instead of 0.51 °C.

The reference resistor acts as the current sensor. The difference from a separate current measurement is that its voltage is not compared with another reference. It is itself the reference. Short-term fluctuations of I also cancel, because the converter processes V_{IN} and V_{REF} at the same instants.

4.3 ADC transfer function

The ADC considered here is a delta-sigma converter with a differential signal input (AIN+, AIN−), a differential external reference input (REFP, REFN), a programmable gain amplifier of gain G, and N-bit two's-complement output coding. Its input range is $-V_{\mathrm{REF}}/G \le V_{\mathrm{IN}} < +V_{\mathrm{REF}}/G$, where

$$V_{\mathrm{IN}} = V_{\mathrm{AIN+}} - V_{\mathrm{AIN-}}, \qquad V_{\mathrm{REF}} = V_{\mathrm{REFP}} - V_{\mathrm{REFN}}.$$

The span $2V_{\mathrm{REF}}/G$ is divided into 2^N steps. One half of the codes represent negative inputs and the other half positive inputs, so the output word D is

$$D = \mathrm{round}\left(\frac{G V_{\mathrm{IN}}}{V_{\mathrm{REF}}} 2^{N-1} \right), \qquad -2^{N-1} \le D \le 2^{N-1} - 1. \tag{11}$$

It is convenient to define the normalised reading

$$\rho = \frac{D}{G 2^{N-1}} \approx \frac{V_{\mathrm{IN}}}{V_{\mathrm{REF}}}. \tag{12}$$

In the circuit of Fig. 1, $\rho = R_{\mathrm{RTD}}/R_{\mathrm{REF}}$ by (10), so the resistance follows directly from the output word as $R_{\mathrm{RTD}} = R_{\mathrm{REF}}\,\rho$.

The three connections in the following sections apply this principle. They differ in how the cable between sensor and board is wired, and therefore in how the lead resistances enter V_{IN}. In each of them V_{REF} is taken across R_{REF}, which carries the excitation current. The examples use $N = 24$ ($2^{N-1} = 8\,388\,608$) and $R_{\mathrm{REF}} = 1.62\,\mathrm{k\Omega}$.

5 Two-wire connection

5.1 Circuit

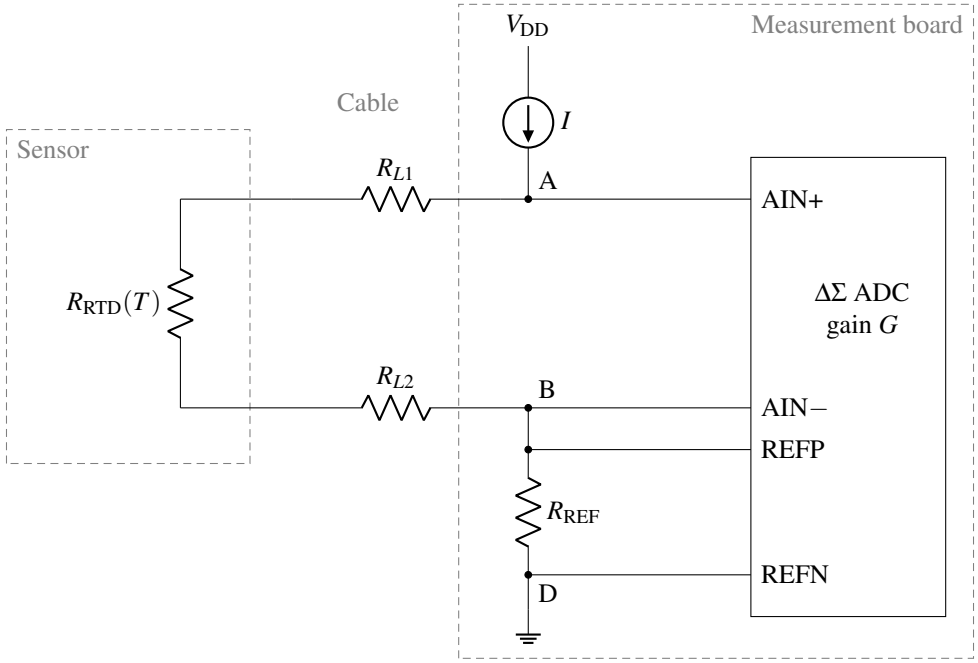


Figure 2: Two-wire connection with a low-side reference resistor. The ADC input is taken at the board end of the cable, so both lead resistances lie inside the measured voltage.

A single current source I drives the series loop R_{L1}, R_{RTD}, R_{L2}, R_{REF} to ground (Fig. 2). AIN+ is connected to node A and AIN− to node B. REFP is connected to node B and REFN to node D, so the reference voltage is the drop across R_{REF}.

This is the circuit of Fig. 1 with the cable added. R_{REF} is placed on the low side, between the sensor and ground. This raises both ADC inputs to at least $IR_{\mathrm{REF}} \approx 1.6\,\mathrm{V}$, which keeps them inside the common-mode range of the input amplifier. The same arrangement is used for all three connections.

5.2 Node voltages and measurement equation

With node D at ground potential,

$$V_{\mathrm{B}} = I R_{\mathrm{REF}}, \tag{13}$$

$$V_{\mathrm{A}} = I\,(R_{L1} + R_{\mathrm{RTD}} + R_{L2} + R_{\mathrm{REF}})\,. \tag{14}$$

The ADC input and reference voltages are

$$V_{\mathrm{IN}} = V_{\mathrm{A}} - V_{\mathrm{B}} = I\,(R_{\mathrm{RTD}} + R_{L1} + R_{L2})\,, \tag{15}$$

$$V_{\mathrm{REF}} = V_{\mathrm{B}} - V_{\mathrm{D}} = I R_{\mathrm{REF}}. \tag{16}$$

Substituting into (12), the current cancels:

$$\rho = \frac{R_{\mathrm{RTD}} + R_{L1} + R_{L2}}{R_{\mathrm{REF}}}. \tag{17}$$

The quantity obtained from the ADC is therefore the loop resistance

$$R_{\mathrm{meas}} = R_{\mathrm{REF}}\,\rho = R_{\mathrm{REF}}\,\frac{D}{G\,2^{N-1}} = R_{\mathrm{RTD}} + R_{L1} + R_{L2}. \tag{18}$$

The excitation current has no influence on the result, but the two lead resistances are added to the sensor resistance.

5.3 Lead correction

The lead contribution can be measured once at installation. The sensor is replaced by a short circuit at its terminals and a reading D_0 is taken. From (18) with $R_{\mathrm{RTD}} = 0$,

$$R_{L1} + R_{L2} = R_{\mathrm{REF}}\,\rho_0, \qquad \rho_0 = \frac{D_0}{G\,2^{N-1}}. \tag{19}$$

In service the sensor resistance is then

$$R_{\mathrm{RTD}} = R_{\mathrm{REF}}\,(\rho - \rho_0) = R_{\mathrm{REF}}\,\frac{D - D_0}{G\,2^{N-1}}. \tag{20}$$

The correction is valid only while the cable stays at the temperature it had when D_0 was recorded. Copper has a temperature coefficient of about $0.393\,\%\,\mathrm{K}^{-1}$, so the lead resistance changes with the cable temperature and this change is not removed. Section 10.1 estimates the size of this effect and shows when a corrected two-wire connection is adequate.

5.4 Measurement procedure

1. Set the IDAC to I, connect it to node A, and select AIN+ = A, AIN− = B, REFP = B, REFN = D.
2. Wait for the RC input filters and the digital filter to settle, then read D.
3. Compute $\rho = D/(G\,2^{N-1})$ and $R_{\mathrm{RTD}} = R_{\mathrm{REF}}(\rho - \rho_0)$ from (20), or $R_{\mathrm{meas}} = R_{\mathrm{REF}}\,\rho$ if no lead correction is applied.
4. Convert R_{RTD} to temperature as described in Section 3.

5.5 Design values for a PT100

With $I = 1\,\mathrm{mA}$ and $R_{\mathrm{REF}} = 1.62\,\mathrm{k\Omega}$, $V_{\mathrm{REF}} = 1.62\,\mathrm{V}$. At $850\,^{\circ}\mathrm{C}$ with $1\,\Omega$ of total lead resistance, $V_{\mathrm{IN}} = 0.3915\,\mathrm{V}$. A gain $G = 4$ gives $GV_{\mathrm{IN}} = 1.566\,\mathrm{V}$, which is 97 % of the positive full scale. The voltage at the current source output is $V_{\mathrm{A}} = 2.01\,\mathrm{V}$ at the top of the range. This must be lower than the IDAC compliance limit, which is typically a few hundred millivolts below the analogue supply. The self-heating power at $850\,^{\circ}\mathrm{C}$ is $I^2 R_{\mathrm{RTD}} = 0.39\,\mathrm{mW}$.

5.6 Example

Let the sensor be at $100.00\,^{\circ}\mathrm{C}$ ($R_{\mathrm{RTD}} = 138.5055\,\Omega$) and let $R_{L1} = R_{L2} = 0.50\,\Omega$.

- From (11), $D = 2\,889\,523$. Without correction, $R_{\mathrm{meas}} = 139.5055\,\Omega$, which converts to $102.64\,^{\circ}\mathrm{C}$. The error of $+2.64\,^{\circ}\mathrm{C}$ is caused entirely by the leads.
- The installation reading with the sensor shorted is $D_0 = 20\,713$, giving $R_{L1} + R_{L2} = 1.0000\,\Omega$.
- With (20), $R_{\mathrm{RTD}} = 138.5055\,\Omega$, which converts to $99.9999\,^{\circ}\mathrm{C}$.
- If the cable later warms by 20 K, the lead resistance rises to $1.0786\,\Omega$. The uncorrected change of $0.079\,\Omega$ gives an error of $+0.21\,^{\circ}\mathrm{C}$.

For a PT1000 the same leads produce one tenth of these errors, which is why the two-wire connection is more often used with PT1000 sensors.

6 Three-wire connection

6.1 Circuit

The sensor has one wire on its upper terminal and two wires on its lower terminal N (Fig. 3). Current I_1 flows from node A through R_{L1} into the upper terminal and through the sensor to N. Current I_2 flows from node C through R_{L2} directly into N. The sum $I_1 + I_2$ returns from N through R_{L3} and R_{REF} to ground. AIN+ is connected to A, AIN− to C, REFP to B and REFN to D.

6.2 Node voltages and measurement equation

With D at ground,

$$V_{\mathrm{B}} = (I_1 + I_2)\,R_{\mathrm{REF}}, \tag{21}$$

$$V_{\mathrm{N}} = (I_1 + I_2)\,(R_{L3} + R_{\mathrm{REF}}), \tag{22}$$

$$V_{\mathrm{A}} = V_{\mathrm{N}} + I_1\,(R_{\mathrm{RTD}} + R_{L1}), \tag{23}$$

$$V_{\mathrm{C}} = V_{\mathrm{N}} + I_2\,R_{L2}. \tag{24}$$

The common term V_{N}, which contains R_{L3}, cancels in the difference $V_{\mathrm{A}} - V_{\mathrm{C}}$:

$$V_{\mathrm{IN}} = I_1\,(R_{\mathrm{RTD}} + R_{L1}) - I_2\,R_{L2}, \tag{25}$$

$$V_{\mathrm{REF}} = (I_1 + I_2)\,R_{\mathrm{REF}}. \tag{26}$$

Matched case. If $I_1 = I_2 = I$ and $R_{L1} = R_{L2}$, then $V_{\mathrm{IN}} = IR_{\mathrm{RTD}}$ and $V_{\mathrm{REF}} = 2IR_{\mathrm{REF}}$. Both the current and the lead resistances cancel, and

$$\rho = \frac{R_{\mathrm{RTD}}}{2R_{\mathrm{REF}}}, \qquad R_{\mathrm{RTD}} = 2R_{\mathrm{REF}}\,\rho = 2R_{\mathrm{REF}}\,\frac{D}{G\,2^{N-1}}. \tag{27}$$

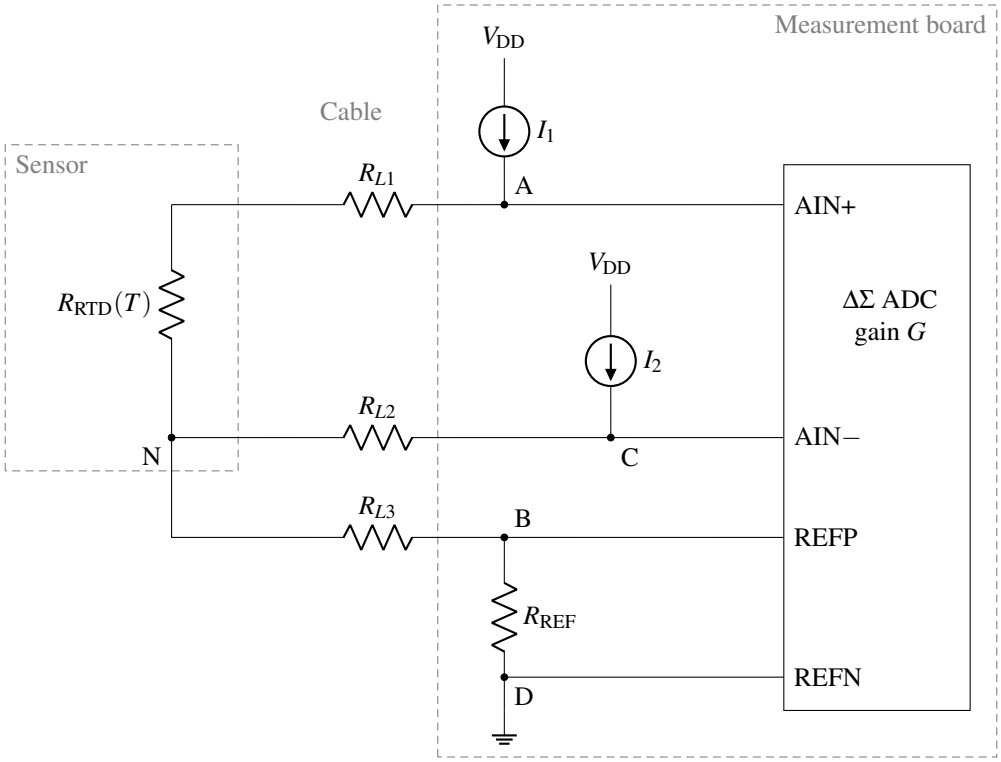


Figure 3: Three-wire connection with two current sources and a low-side reference resistor. The lower sensor terminal N has two wires. I_1 and I_2 both return through R_{L3} and R_{REF}.

Current mismatch. Two on-chip current sources never match exactly. Let $I_2 = I_1(1+\varepsilon)$. Equations (25) and (26) give

$$\rho_1 = \frac{R_{\mathrm{RTD}} + R_{L1} - (1+\varepsilon)\,R_{L2}}{(2+\varepsilon)\,R_{\mathrm{REF}}}. \tag{28}$$

Evaluating (27) with this reading leaves two errors: a lead term εR_{L2} in the numerator and a scale error from the factor $(2+\varepsilon)$ in the denominator.

Swapped second conversion. A second conversion is made with the two current sources exchanged, so that the source of value $I_1(1+\varepsilon)$ drives R_{L1} and the source of value I_1 drives R_{L2}. The analogue input and reference connections are unchanged. The total current through R_{REF} is still $(2+\varepsilon)I_1$, and

$$\rho_2 = \frac{(1+\varepsilon)(R_{\mathrm{RTD}} + R_{L1}) - R_{L2}}{(2+\varepsilon)\,R_{\mathrm{REF}}}. \tag{29}$$

Adding (28) and (29),

$$\rho_1 + \rho_2 = \frac{(2+\varepsilon)\,(R_{\mathrm{RTD}} + R_{L1} - R_{L2})}{(2+\varepsilon)\,R_{\mathrm{REF}}} = \frac{R_{\mathrm{RTD}} + R_{L1} - R_{L2}}{R_{\mathrm{REF}}}. \tag{30}$$

The mismatch ε cancels exactly, and the sensor resistance is

$$R_{\mathrm{RTD}} = R_{\mathrm{REF}}\,(\rho_1 + \rho_2) - (R_{L1} - R_{L2}) = R_{\mathrm{REF}}\,\frac{D_1 + D_2}{G\,2^{N-1}} - \Delta R_L. \tag{31}$$

The only remaining lead term is the difference $\Delta R_L = R_{L1} - R_{L2}$ between the two leads that carry the separate currents. When both are cores of the same cable and of equal length, ΔR_L is small and is normally neglected.

6.3 Measurement procedure

1. Route IDAC 1 to node A and IDAC 2 to node C, both set to the nominal current I. Select AIN+ = A, AIN− = C, REFP = B, REFN = D.
2. Wait for settling and read D_1.
3. Exchange the IDAC output pins (IDAC 1 to C, IDAC 2 to A). Leave the input and reference selection unchanged.
4. Wait for settling and read D_2.
5. Compute $R_{\mathrm{RTD}} = R_{\mathrm{REF}}(D_1 + D_2)/(G\,2^{N-1})$ from (31).
6. Convert R_{RTD} to temperature as described in Section 3.

6.4 Design values for a PT100

With $I_1 \approx I_2 \approx 500\,\mu\mathrm{A}$ and $R_{\mathrm{REF}} = 1.62\,\mathrm{k}\Omega$, the reference voltage is $V_{\mathrm{REF}} \approx 1.62\,\mathrm{V}$, the same as in the two-wire design. At 850 °C, $V_{\mathrm{IN}} \approx 0.195\,\mathrm{V}$, and $G = 8$ gives $GV_{\mathrm{IN}} = 1.56\,\mathrm{V}$. The highest pin voltage is at node A and is about 1.82 V. Each current is half that of the two-wire design, so the self-heating at 850 °C falls to 0.10 mW.

6.5 Example

Let the sensor be at 100.00 °C ($R_{\mathrm{RTD}} = 138.5055\,\Omega$), $I_1 = 500\,\mu\mathrm{A}$, $I_2 = 502.5\,\mu\mathrm{A}$ ($\varepsilon = 0.5\,\%$), $R_{L1} = R_{L3} = 0.50\,\Omega$, $R_{L2} = 0.52\,\Omega$ and $G = 8$. Then $V_{\mathrm{REF}} = 1.62405\,\mathrm{V}$.

- First conversion: $V_{\mathrm{IN}} = 69.2414\,\mathrm{mV}$, $D_1 = 2\,861\,190$. Using (27) alone gives 138.1376 Ω and 99.03 °C.
- Second conversion: $V_{\mathrm{IN}} = 69.5903\,\mathrm{mV}$, $D_2 = 2\,875\,603$. Equation (27) alone gives 138.8334 Ω and 100.86 °C.
- Combined with (31) and ΔR_L neglected: $R_{\mathrm{REF}}(\rho_1 + \rho_2) = 138.4855\,\Omega$, which converts to 99.947 °C.

The single readings are in error by about one degree in opposite directions. The combined reading has a residual of −0.053 °C, which is exactly the effect of the $-0.02\,\Omega$ lead difference ΔR_L. The 0.5 % current mismatch has no effect on the combined result.

7 Four-wire connection

7.1 Circuit

Each sensor terminal has two wires (Fig. 4). The excitation current I flows from node A through the force lead R_{L1}, the sensor, the force lead R_{L4} and R_{REF} to ground. The sense leads R_{L2} and R_{L3} connect the sensor terminals S_1 and S_2 to AIN+ and AIN−. REFP is connected to B and REFN to D.

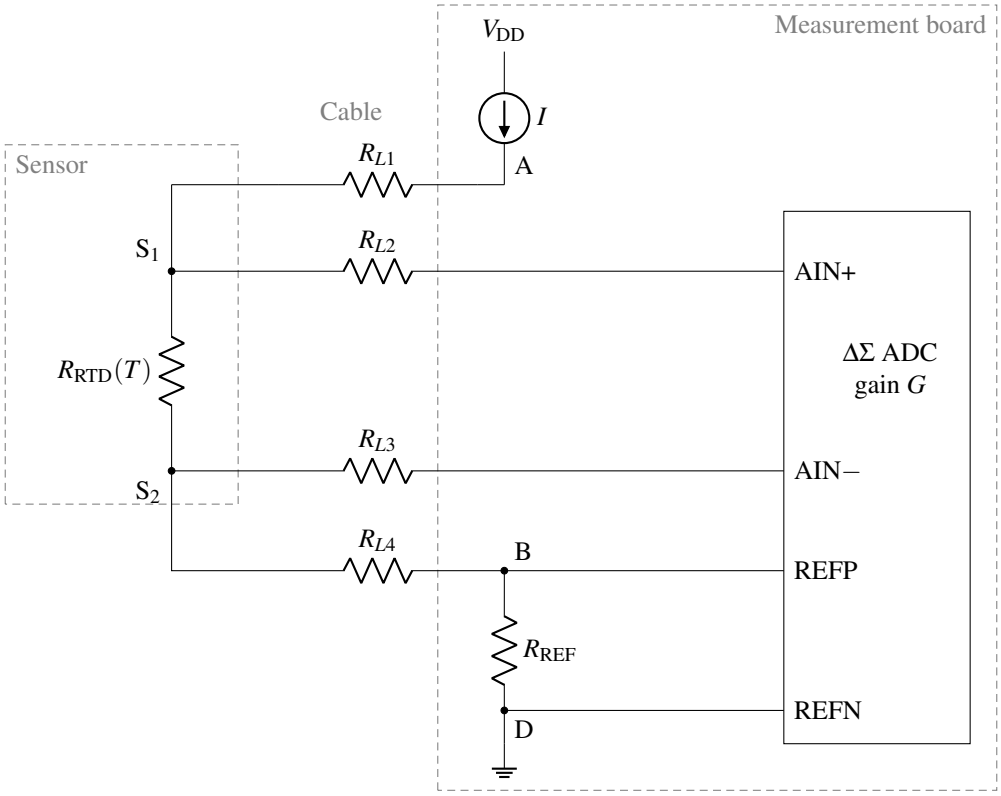


Figure 4: Four-wire connection with a low-side reference resistor. R_{L1} and R_{L4} carry the excitation current. R_{L2} and R_{L3} connect the sensor terminals S_1 and S_2 to the ADC inputs and carry only the ADC input current.

7.2 Node voltages and measurement equation

The ADC inputs draw a leakage current I_{lk}, typically of the order of 1 nA. The voltage drop across a sense lead is $I_{\mathrm{lk}}R_L$, about 1 nV for a 1 Ω lead, and is neglected. With D at ground,

$$V_{\mathrm{B}} = I\,R_{\mathrm{REF}}, \tag{32}$$

$$V_{\mathrm{S2}} = I\,(R_{L4} + R_{\mathrm{REF}}), \tag{33}$$

$$V_{\mathrm{S1}} = I\,(R_{\mathrm{RTD}} + R_{L4} + R_{\mathrm{REF}}), \tag{34}$$

$$V_{\mathrm{AIN+}} = V_{\mathrm{S1}}, \qquad V_{\mathrm{AIN-}} = V_{\mathrm{S2}}. \tag{35}$$

Hence

$$V_{\mathrm{IN}} = V_{\mathrm{S1}} - V_{\mathrm{S2}} = I\,R_{\mathrm{RTD}}, \tag{36}$$

$$V_{\mathrm{REF}} = I\,R_{\mathrm{REF}}, \tag{37}$$

and

$$\rho = \frac{R_{\mathrm{RTD}}}{R_{\mathrm{REF}}}, \qquad R_{\mathrm{RTD}} = R_{\mathrm{REF}}\,\rho = R_{\mathrm{REF}}\,\frac{D}{G\,2^{N-1}}. \tag{38}$$

No lead resistance appears in (38). The force leads R_{L1} and R_{L4} only raise the voltage at node A and so use up some of the current source compliance range. A single current source is used, so there is no matching requirement.

7.3 Thermoelectric offset

Junctions between dissimilar metals in the signal path (sensor wire to cable, cable to connector, connector to copper track) produce small thermoelectric voltages. Their net value E_{th} adds to (36), so that $V_{\mathrm{IN}} =$

$IR_{\mathrm{RTD}} + E_{\mathrm{th}}$. If the excitation direction through the sensor can be reversed, for example by exchanging the two force connections with a switch matrix while R_{REF} remains in the return path, a second reading gives $V'_{\mathrm{IN}} = -IR_{\mathrm{RTD}} + E_{\mathrm{th}}$ with the same V_{REF}. Then

$$R_{\mathrm{RTD}} = R_{\mathrm{REF}} \frac{\rho_+ - \rho_-}{2}, \tag{39}$$

and E_{th} cancels. With $I = 1\,\mathrm{mA}$, an uncorrected offset of $10\,\mu\mathrm{V}$ corresponds to $0.01\,\Omega$, or about $0.026\,^{\circ}\mathrm{C}$ for a PT100. Whether the reversal is needed depends on the accuracy target. The same offset is present in the two- and three-wire connections. It is treated here because the four-wire connection is the one used when errors of this size matter.

7.4 Measurement procedure

1. Route the IDAC to node A, set it to I, and select AIN+ = S_1 sense line, AIN− = S_2 sense line, REFP = B, REFN = D.
2. Wait for settling and read D.
3. Compute $R_{\mathrm{RTD}} = R_{\mathrm{REF}} D/(G\,2^{N-1})$ from (38).
4. Convert R_{RTD} to temperature as described in Section 3.

7.5 Design values for a PT100

The values are those of the two-wire design: $I = 1\,\mathrm{mA}$, $R_{\mathrm{REF}} = 1.62\,\mathrm{k}\Omega$, $V_{\mathrm{REF}} = 1.62\,\mathrm{V}$ and $G = 4$. At $850\,^{\circ}\mathrm{C}$, $GV_{\mathrm{IN}} = 1.562\,\mathrm{V}$. The voltage at node A is about 2.01 V with $0.5\,\Omega$ force leads. One ADC count corresponds to $R_{\mathrm{REF}}/(G\,2^{N-1}) = 4.83 \times 10^{-5}\,\Omega$, or $0.13\,\mathrm{m}^{\circ}\mathrm{C}$ near $100\,^{\circ}\mathrm{C}$. In practice the converter noise, not the quantisation step, limits the resolution.

For a PT1000, the sensor and reference resistances are scaled by ten and the current by one tenth: $I = 100\,\mu\mathrm{A}$, $R_{\mathrm{REF}} = 16.2\,\mathrm{k}\Omega$, $G = 4$. The node voltages are unchanged.

7.6 Example

Let the sensor be at $100.00\,^{\circ}\mathrm{C}$ ($R_{\mathrm{RTD}} = 138.5055\,\Omega$). With $G = 4$, (11) gives $D = 2\,868\,811$, and (38) gives $R_{\mathrm{RTD}} = 138.50551\,\Omega$, which converts to $100.00003\,^{\circ}\mathrm{C}$. The difference from the true value is the quantisation step of the ADC. The lead resistances do not enter the calculation.

8 Comparison of the three connections

Table 2 brings together the measurement equation and the remaining lead error of each connection. Table 3 collects the results of the examples, all for a PT100 at $100.00\,^{\circ}\mathrm{C}$.

Table 2: Measurement equations and residual lead errors. $\rho = D/(G\,2^{N-1})$.

Connection	Conversions	Resistance	Residual lead error
Two-wire	1	$R_{\mathrm{REF}}\,\rho = R_{\mathrm{RTD}} + R_{L1} + R_{L2}$	$R_{L1} + R_{L2}$; after correction, its drift
Three-wire	2 (swapped)	$R_{\mathrm{REF}}(\rho_1 + \rho_2) = R_{\mathrm{RTD}} + R_{L1} - R_{L2}$	$R_{L1} - R_{L2}$
Four-wire	1	$R_{\mathrm{REF}}\,\rho = R_{\mathrm{RTD}}$	none ($I_{\mathrm{lk}} R_L$ only)

Table 3: Worked examples for a PT100 at 100.00 °C ($R_{\mathrm{RTD}} = 138.5055\,\Omega$), $N = 24$, $R_{\mathrm{REF}} = 1.62\,\mathrm{k}\Omega$.

Case	G	I (µA)	D	R (Ω)	T (°C)
Two-wire, uncorrected	4	1000	2 889 523	139.5055	102.638
Two-wire, lead-corrected	4	1000	2 868 810[a]	138.5055	99.9999
Three-wire, first conversion	8	500 / 502.5	2 861 190	138.1376	99.030
Three-wire, second conversion	8	502.5 / 500	2 875 603	138.8334	100.865
Three-wire, combined	8	–	–	138.4855	99.947
Four-wire	4	1000	2 868 811	138.5055	100.000

[a] $D - D_0$ with $D_0 = 20\,713$.

8.1 Advantages and limitations

Table 4 lists the main advantages and limitations of each connection. The lead error figures are for a PT100 and 0.5 Ω per lead.

Table 4: Advantages and limitations of the three connections.

Connection	Advantages	Limitations
Two-wire	• Fewest wires, terminals and cable cost. • One current source and one conversion. • Simplest circuit and firmware.	• Lead resistance adds directly to the reading: +2.6 °C for 1 Ω in total. • Lead correction holds only at the cable temperature at which D_0 was taken. • Suitable only for short leads or PT1000.
Three-wire	• Lead resistance cancels when $R_{L1} = R_{L2}$. • One wire fewer than four-wire. • Common industrial standard; many sensors and transmitters are made for it.	• Needs two current sources; their mismatch causes an error unless they are swapped. • The swap needs two conversions, which halves the output rate. • Residual error from $R_{L1} - R_{L2}$: 0.05 °C for 0.02 Ω.
Four-wire	• Lead resistance is removed completely, whatever the cable length or temperature. • One current source and one conversion. • Highest accuracy of the three.	• Four wires: highest cable and connector cost. • Force leads still use part of the current source compliance range. • Thermoelectric offsets remain unless the current is reversed.

In short, the two-wire connection suits PT1000 sensors with short leads and low-cost designs, particularly when the cable is fixed and its resistance is corrected (Section 10.1). The three-wire connection is the usual choice for industrial PT100 installations with moderate cable lengths. The four-wire connection is used for laboratory, calibration and other high-accuracy work, and wherever the cable is long or its temperature varies.

9 Remaining error sources common to all connections

Once the current has cancelled, the accuracy depends on the following.

Reference resistor.
Its tolerance enters directly as a gain error, and its temperature coefficient as a gain drift. By (3), a 0.1 % tolerance gives 0.26 °C at 0 °C, and a coefficient of 5 ppm/K over a 40 K ambient change gives 0.05 °C.

PGA gain error.
It scales ρ in the same way as an error in R_{REF} and is removed by the calibration described below.

Offset.
An input offset V_{os} appears as a resistance error V_{os}/I. It is reduced by input chopping or by an offset calibration with the inputs shorted.

Input and reference filters.
Both differential pairs normally have RC filters. The filters should have similar corner frequencies so that noise on the excitation current is filtered equally in V_{IN} and V_{REF} and continues to cancel. The settling time after a channel change or an IDAC swap must be allowed before a reading is taken.

Reference input loading.
If the reference input of the ADC is not buffered, its sampling current flows in R_{REF} and causes a gain error. The reference buffer should be enabled when R_{REF} is large.

Self-heating.
The power $I^2 R_{\mathrm{RTD}}$ raises the sensor above the medium temperature by an amount set by the self-heating coefficient of the sensor and its mounting. It is reduced by lowering I or by exciting the sensor only during conversions.

A two-point system calibration removes the reference resistor tolerance, the gain error and the offset together. Two precision resistors R_a and R_b (for example $100.000\,\Omega$ and $300.000\,\Omega$) are connected in place of the sensor and the readings ρ_a and ρ_b are recorded. Here ρ is the reading defined for the connection in use, for example $\rho_1 + \rho_2$ for the three-wire connection. The corrected resistance is then obtained from any later reading by linear interpolation,

$$R_{\mathrm{RTD}} = R_a + (R_b - R_a)\,\frac{\rho - \rho_a}{\rho_b - \rho_a}. \tag{40}$$

What remains after calibration is the drift of R_{REF} since the calibration and the tolerance of the sensor itself, which for IEC 60751 class A is $\pm(0.15 + 0.002\,|T|)\,^{\circ}\mathrm{C}$.

10 Practice in commercial sensors and instruments

The preceding sections build the measurement from first principles. This section relates them to equipment that is bought ready-made. It covers two-wire sensors supplied with a fixed cable, sensors supplied with individual calibration data, and readers that display temperature directly.

10.1 Two-wire sensors with a fixed cable

Many PT1000 sensors are sold as two-wire assemblies with a moulded cable that the user is not expected to shorten. Because the cable is fixed, its resistance $R_{L1} + R_{L2}$ is a constant of that assembly. It can be measured once, by the manufacturer or at installation, and subtracted from every reading. This is the lead correction of Section 5.3. Temperature transmitters provide for it directly. The Rosemount 644, for example, has a two-wire offset parameter into which the lead resistance is entered [2]. For the constant part of the lead resistance, therefore, the number of wires does not matter.

The correction removes only the part of the lead resistance that does not change. Three effects remain.

Cable temperature.
Copper has a temperature coefficient of about $0.393\,\%\,\mathrm{K}^{-1}$. When the cable warms after the correction was made, the increase in its resistance appears as a temperature error. Table 5 gives its size for typical cables.

Conductors inside the probe.
The wires inside the probe sheath are at the process temperature, not at the ambient temperature. Their resistance therefore changes with the quantity being measured. This behaves as a gain error rather than an offset, and a correction made at room temperature does not remove it. If an internal loop of $0.2\,\Omega$ were entirely at 300 °C, its resistance would rise by $0.22\,\Omega$, which is 0.62 °C for a PT100. In practice only part of the internal wiring is that hot, so this figure is an upper bound.

Connections and replacement.
The contact resistance of terminals and connectors increases with ageing and corrosion. The stored correction also becomes wrong when the sensor is replaced or the cable is extended.

Table 5: Two-wire lead resistance before and after correction. Copper cable, $0.0842\,\Omega\,\mathrm{m}^{-1}$ per conductor (24 AWG). The offset is removed by the correction. The remaining error is caused by the change of cable temperature after the correction. Sensitivities are taken at 0 °C.

Sensor	Cable length	Cable ΔT	$R_{L1}+R_{L2}$	Offset removed	Remaining error
PT1000	2 m	50 K	$0.34\,\Omega$	0.09 °C	0.02 °C
PT100	2 m	50 K	$0.34\,\Omega$	0.86 °C	0.17 °C
PT1000	50 m	30 K	$8.42\,\Omega$	2.15 °C	0.25 °C
PT100	50 m	30 K	$8.42\,\Omega$	21.5 °C	2.54 °C

With a PT1000 and a short fixed cable, the remaining error of 0.02 °C is well below the class A tolerance. A corrected two-wire sensor is then adequate for most purposes. With a PT100 the remaining error is 0.17 °C even for a 2 m cable. This is already comparable with the class A tolerance of 0.15 °C at 0 °C, and long cables make it much larger. Three- and four-wire connections remove the lead resistance at every conversion, so none of the three effects above enter the result. The number of wires therefore matters little for a PT1000 with short fixed leads, and matters a great deal for a PT100, for long cables and for high accuracy.

10.2 Calibration of the sensor and sensor matching

What a manufacturer specifies for a standard sensor is not its lead resistance but its conformity to the curve of Section 2. Standard sensors are sold to a tolerance class of IEC 60751 [1], for example class A, $\pm(0.15+0.002\,|T|)$ °C, or class B, $\pm(0.3+0.005\,|T|)$ °C. They are not calibrated individually.

When better accuracy is needed, a sensor can be calibrated at several temperatures and supplied with its own coefficients, either R_0, A, B and C or the equivalent Callendar–Van Dusen constants α, δ and β. These replace the standard values in (1) and (2), and the conversion of Section 3 is carried out with them. Transmitters that accept such coefficients call this sensor matching [2]. Sensor matching improves the conversion from resistance to temperature. It does not change how the lead resistance is handled, which is still decided by the connection or by the correction of Section 10.1.

10.3 Inside a temperature reader

A finished instrument, such as a panel meter, a transmitter or a data logger, displays temperature and does not normally show resistance. Internally it follows the same chain as this note:

1. An excitation current flows through the sensor and an internal reference resistor.
2. The ADC measures $V_{\mathrm{IN}}/V_{\mathrm{REF}} = R_{\mathrm{RTD}}/R_{\mathrm{REF}}$ (Section 4).
3. The lead resistance is compensated according to the configured wiring (Sections 5 to 7).

4. The resistance is converted to temperature with the IEC 60751 curve, by the Callendar–Van Dusen equation or a lookup table in firmware (Section 3).
5. The temperature is sent to the display, a 4 mA to 20 mA output or a digital interface.

The user configures the sensor type (PT100 or PT1000), the curve and the wiring mode. Where the instrument allows it, the user also enters the two-wire lead resistance and the sensor-matching coefficients. The IEC 60751 curve ($\alpha = 0.00385\,^{\circ}\mathrm{C}^{-1}$) is the usual choice, and some instruments also offer older national curves.

Whether the user has to perform the conversion depends on how much of this chain the purchased part contains.

Complete instruments.
All five steps are internal, and the output is a temperature.

Converters with built-in linearisation.
The LTC2983 measures the RTD ratiometrically against a sense resistor. It converts the result with built-in tables for the European, American, Japanese and ITS-90 curves, or with a user-defined table, and reports the temperature in °C [3].

Front-end converters.
The MAX31865 returns only the ratio $R_{\mathrm{RTD}}/R_{\mathrm{REF}}$ as a 15-bit number. The conversion to temperature is done in the host firmware, as in Section 3 [4].

Discrete designs.
A design built from an ADC, as described in this note, performs every step in its own firmware.

The conversion from resistance to temperature is therefore always present. The only question is whether it runs inside the purchased part or in the user's own code.

References

[1] IEC 60751, *Industrial platinum resistance thermometers and platinum temperature sensors*. International Electrotechnical Commission, Geneva.

[2] Emerson Process Management, *Rosemount 644 Temperature Transmitter*, user manual and quick start guide. `https://manualmachine.com/emerson/644r/1269719-user-manual/`

[3] Analog Devices, *Temperature-to-Bits: One IC for All Sensor Types, 0.1 °C Conformity*, technical article. `https://www.analog.com/en/resources/technical-articles/temperature-to-bits-one-ic-for-all-sensor-types.html`

[4] Analog Devices (Maxim Integrated), *MAX31865 RTD-to-Digital Converter*, data sheet.