Application Note

RTD Alternative Measurement Methods in Real-Time Control Applications

ABSTRACT

The purpose of this document is to familiarize the reader with the resistance temperature detector (RTD) as a method of temperature measurement in real-time control applications, as well to introduce possible sources of error and how to correct them. There is an extensive portfolio of semiconductor sensing technologies that allow for new capabilities in efficiency, performance, and low-latency response in real-time control systems. Therefore, alternative temperature measurement methods and their corresponding advantages are discussed in this document.

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1 RTD Introduction

A resistance temperature detector is a passive circuit element whose resistance increases as temperature increases. They are generally constructed using platinum, copper, or nickel, and one major advantage of RTDs is that they support a wide span of temperature, ranging from –200°C to +850°C. The accuracy limits of an RTD are defined by the class, or grade, of the RTD. The characteristics of platinum, copper, or nickel determine the linear approximation of resistance versus temperature within the 0°C to 100°C temperature range. The platinum RTD is known for its strong linearity and repeatability characteristic.

DIN/IEC 60751 is considered the worldwide standard for platinum RTDs. For a PT100 RTD, the standard requires the sensing element to have an electrical resistance of 100.00 Ω at 0°C and a temperature coefficient of resistance (TCR) of 0.00385 Ω/Ω/°C between 0°C and 100°C.

Equation 1 and Equation 2 define the resistance-to-temperature relation for temperature ranges above and below 0°C.

$$R_T = R_0\left[(1 + \mathrm{AT}) + \mathrm{BT}^2\right] \text{ for T } \geq 0°\mathrm{C} \quad (1)$$

$$R_T = R_0\left[(1 + \mathrm{AT}) + \mathrm{BT}^2 + \mathrm{CT}^3(100 - T)\right] \text{ for T} < 0°\mathrm{C} \quad (2)$$

with:
- $A = 3.9083 \times 10^{-3}$
- $B = -5.775 \times 10^{-7}$
- $C = -4.183 \times 10^{-12}$

1.1 Common Wiring Configurations

RTDs are typically designed with three common configurations: two-wire, three-wire, and four-wire. In the two-wire configuration, as shown in Figure 1-1 below, the RTD is connected with two wires to either end of the RTD. In this configuration, the lead wire resistances cannot be separated from the RTD resistance, adding an error that cannot be separated from the RTD measurement. Two-wire RTDs yield the least accurate RTD measurements and are used when accuracy is not critical or when lead lengths are short. Two-wire RTDs are the least expensive RTD configuration.

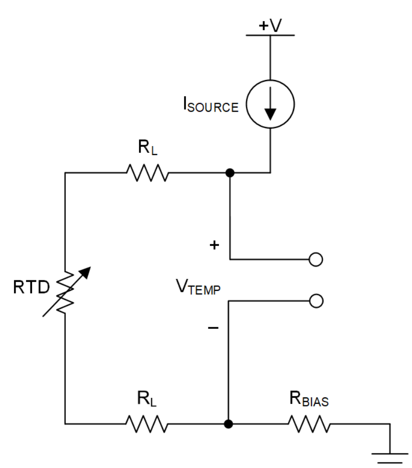

Figure 1-1. Two-Wire RTD Configuration

In the three-wire configuration, as shown in Figure 1-2, the RTD is connected to a single lead wire on one end and two lead wires on the opposite end. Using different circuit topologies and measurements, lead resistance effects can effectively be cancelled, reducing the error in three-wire RTD measurements. Compensation for lead wire resistance assumes that the lead resistances match.

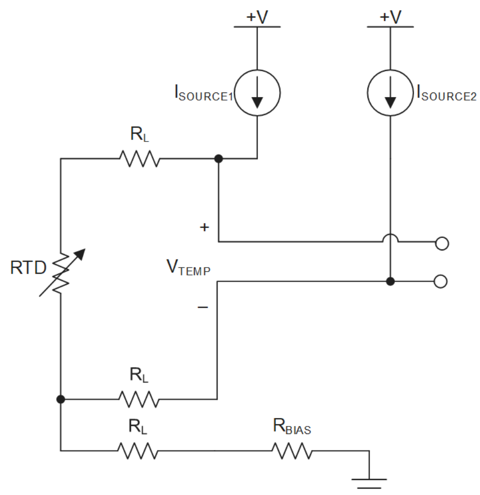

Figure 1-2. Three-Wire RTD Configuration

In the four-wire configuration, as shown in Figure 1-3, two lead wires are connected to either end of the RTD. In this configuration, the RTD resistance may be measured with a four-wire resistive measurement with superior accuracy. The RTD excitation is driven through one lead on either end, while the RTD resistance is measured with the other lead on either end. In this measurement, the RTD resistance is sensed without error contributed from the lead wire reacting with the sensor excitation. Four-wire RTDs yield the most accurate measurements, but are the most expensive RTD configuration.

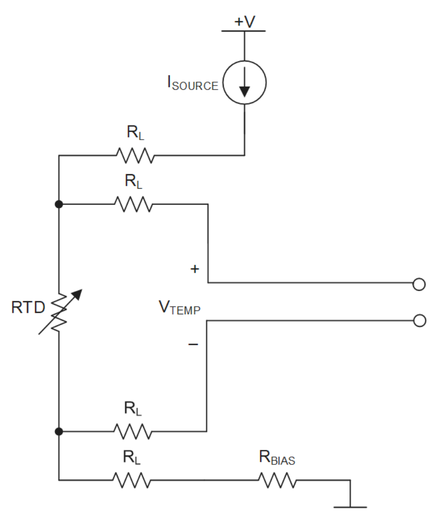

Figure 1-3. Four-Wire RTD Configuration

1.2 RTD Tolerances and Accuracy

There are four tolerance classes specified in DIN/IEC751:

Class	Tolerance
AA	± (0.1 + 0.0017·|T|)
A	± (0.15 + 0.002·|T|)
B	± (0.3 + 0.005·|T|)
C	± (1.2 + 0.005·|T|)

These tolerance classes also represent the interchangeability of a detector. Should a detector become damaged, good interchangeability assures that the replacement sensor delivers the same readings under the same conditions as the predecessor. Another important criterion for selecting a temperature sensor is the long-term stability. Great stability produces little output signal drift over time, thus reducing the frequency of costly calibrations. Depending on the application requirement, today's RTDs can provide long-term drifts from as little as 0.003°C/year up to 0.01 and 0.05°C/year.

RTDs are considered to be amongst the most accurate temperature sensors available. In addition to high accuracy, they offer excellent stability, repeatability, and high immunity to electrical noise. However, for each class, the accuracy varies as the temperature changes. Figure 1-4 shows the accuracy of different classes of RTDs.

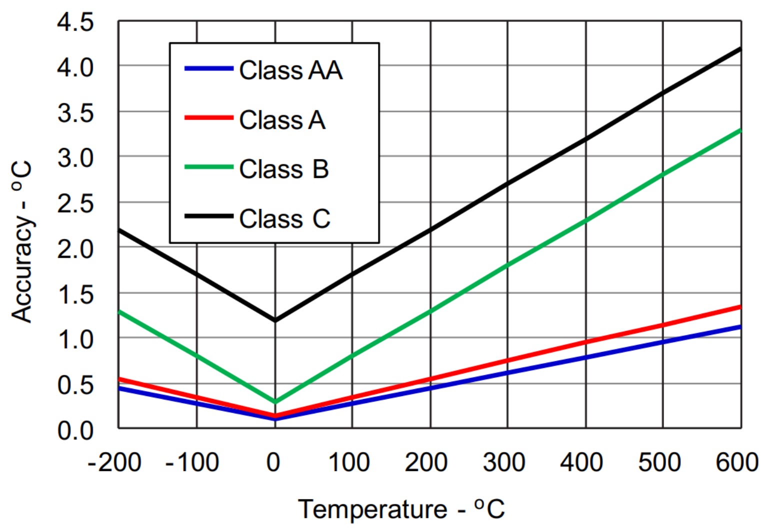

Figure 1-4. Accuracy Classes for RTDs

1.3 Error Sources of RTD Systems

To convert the change in resistance of an RTD into a sensible output signal, a current source that drives a constant current through the sensing element is commonly used, thus creating a temperature dependent voltage across the RTD. This method creates two sources of measurement errors.

First, the current through the RTD causes a certain amount of self-heat that adds to the sensing elements temperature, thus falsifying the actual measurement reading. Therefore, TI recommends currents in the range of 500 μA to 1 mA maximum to minimize the impact of self-heating.

The second error source is the voltage drop across long measurement leads as is expected in PT100 applications. The voltage division between the lead resistance and the RTD can significantly reduce the measured output voltage at the signal amplifier input, yielding a false temperature reading. To minimize the impact of lead resistance, the leads must either be short when using a 2-wire RTD, or the RTD itself must accommodate lead-compensation wires, as provided in 3-wire and 4-wire RTD designs.

1.3.1 Error Minimization Circuitry

The circuitry in Figure 1-5 is designed to take advantage of the four-wire RTD, which is the most accurate configuration to use. The two wires (W1 and W4) are the force leads and connect the RTD to the constant current source. The other two wires (W2 and W3) are the sense leads and connect voltage across the RTD to the amplifier. This arrangement separates the constant-current source driving the RTD from the measurement circuit. The voltage drop in wires W1 and W4 is removed from the measurement of the voltage across the RTD.

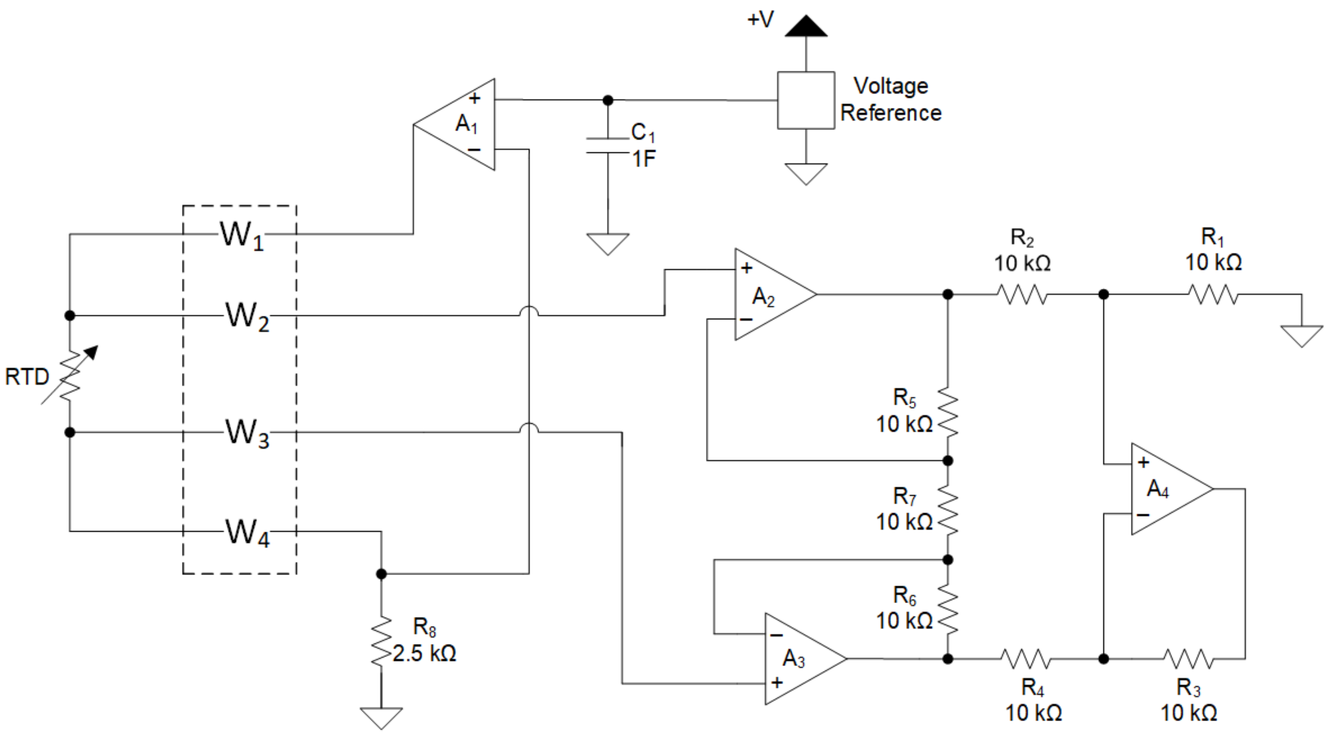

Figure 1-5. Example of RTD Error Minimization Circuitry

2 RTD Alternatives

Semiconductor temperature sensors are manufactured using technology that allows these devices to be produced efficiently and inexpensively. As a result, these devices have properties designed to easily interface with many other types of semiconductor devices, such as amplifiers, power regulators, buffer output amplifiers, and microcontrollers.

The fast thermal response time of these sensors enables fast error correction in real-time digital control loops, which can help maximize control speed for higher productivity and safety. This also allows for faster adaptation to control motor position and velocity with a low-latency response. The high accuracy of these sensors helps reduce maintenance costs and system downtime, as systems become more reliable and control is more efficient. The ability to operate systems closer to the thermal limits increases system efficiency and allows for immediate failure detection and reaction.

2.1 TMP116 and TMP117

The TMP116 has significantly better accuracy than the Class B RTD. In addition, when compared to the Class A RTD, the TMP116 accuracy is better over most of the –55°C to +125°C operating temperature range. This improvement in accuracy is in addition to lower cost and simplified designs when compared with RTDs.

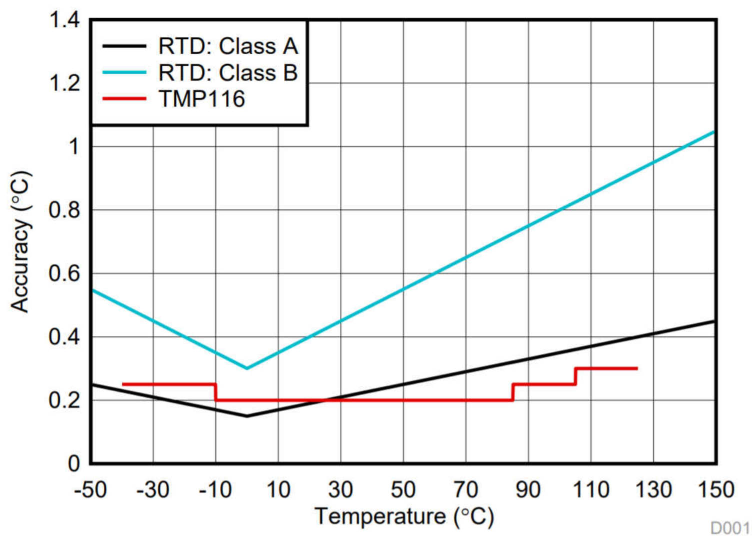

Figure 2-1. Comparing the Accuracy of an RTD to the TMP116

The TMP117 is another semiconductor temperature sensor that can replace RTDs. It is a high-precision digital temperature sensor which provides a 16-bit result with a resolution of 0.0078°C and an accuracy of up to ±0.1°C across the –20°C to +50°C temperature range with no calibration. The TMP117 is I2C- and SMBus™ interface-compatible, has a programmable alert function, and can allow up to four devices on a single bus. Table 2-1 shows the overall accuracy of the TMP117 across its operating range.

Table 2-1. TMP117 Accuracy Across Temperature Range

Temperature Range	Accuracy
–20°C to +50°C	±0.1°C
–40°C to +100°C	±0.2°C
–55°C to +150°C	±0.3°C

Figure 2-2 shows the accuracy of the TMP117 versus an RTD across the operating temperature range of –55°C to +150°C. It is evident looking at Figure 2-2 that the TMP117 with no calibration has the same or better accuracy as an RTD Class-AA sensor. Note that this is the raw accuracy of the two devices and that the final system layout has a minor effect on the TMP117 and a major effect on the accuracy of an RTD sensor due to a number of parameters such as the choice of ADC, layout of signal traces, and component tolerances.

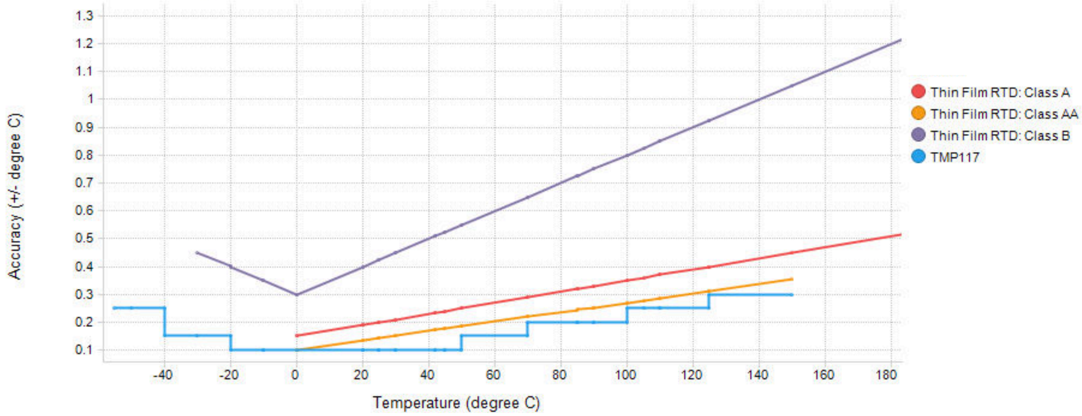

Figure 2-2. Accuracy Chart for TMP117 and RTD

The TMP117 is comparable in accuracy to the Class AA thin-film RTD and consumes a fraction of the power of a PT100 RTD. The systems using the TMP117 require less components, such as delta-sigma ADCs, programmable gain amplifiers, and RC filters, than the systems using RTD elements.

2.2 TMP1826

The TMP1826 is a high-accuracy, single-wire compatible digital output temperature sensor. The typical accuracy of this device is ±0.1°C across the temperature range of –20°C to +85°C. Figure 2-3 shows the bus-powered mode where the TMP1826 only requires a single connection and a ground return, which helps to simplify design and reduce cost by limiting the number of wires in the system. Alternatively, the V_{DD} pin gives users the option to use a dedicated power supply for certain applications that may require it. This is seen in Figure 2-4. The TMP1826 also has integrated 8-kV IEC-61000-4-2 ESD protection on the data pin, which removes the need for any external protection components.

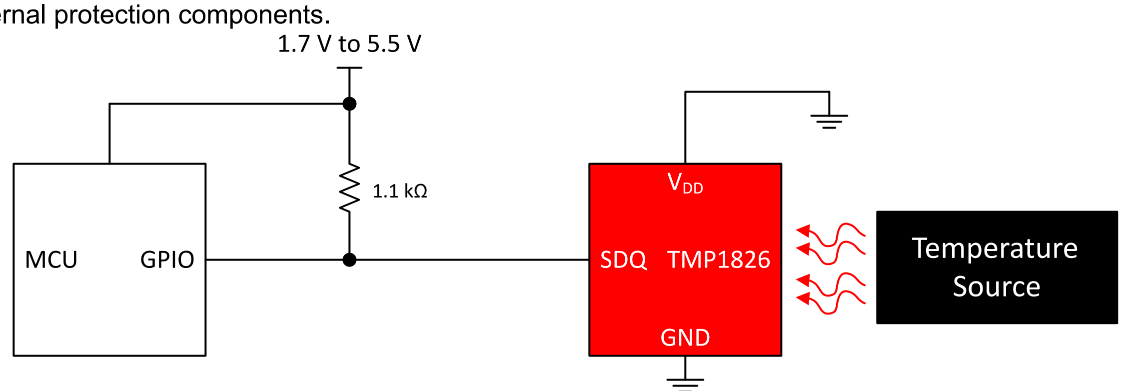

Figure 2-3. TMP1826 Bus Powered Application

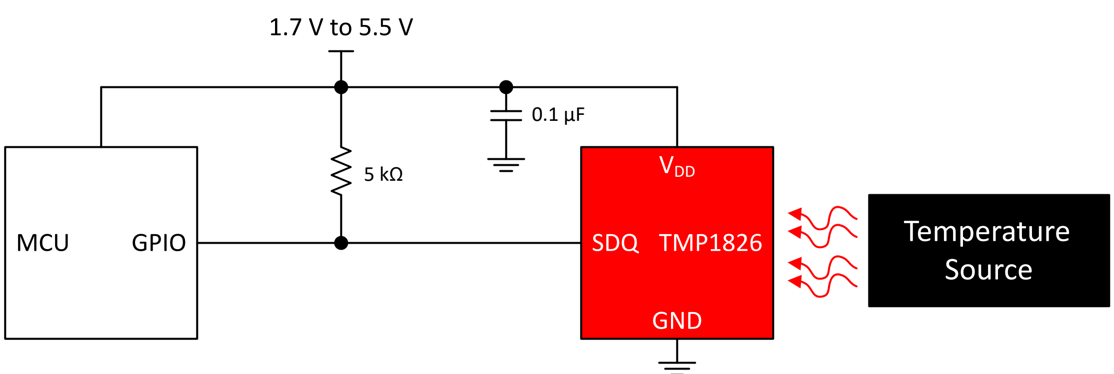

Figure 2-4. TMP1826 Supply Powered Application

Figure 2-5 shows the accuracy of the TMP1826 across temperature. The data sheet minimum and maximum temperature error specifications are identified by the red lines on the graph, while the typical performance of the TMP1826 is shown in black. This device can provide another high-accuracy alternative to complicated RTD circuits.

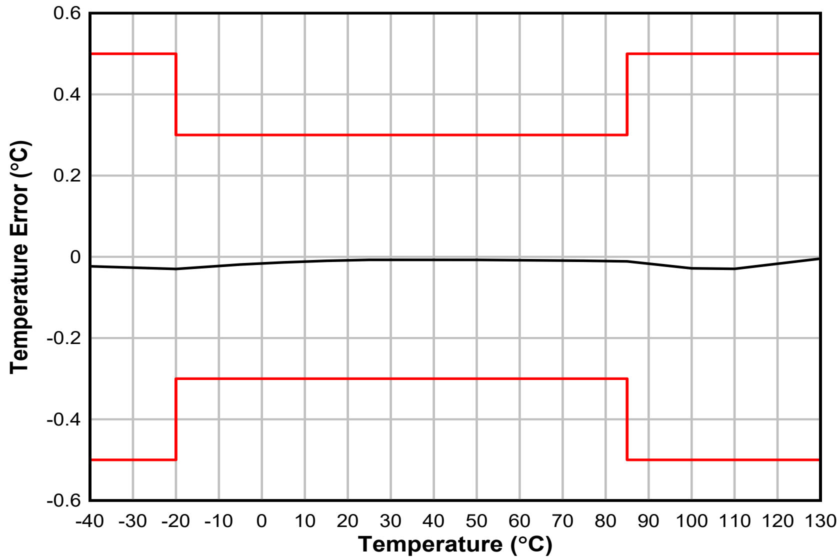

Figure 2-5. TMP1826 Temperature Error vs Temperature

Table 2-2. TMP1826 Accuracy Across Temperature Range

Temperature Range	Accuracy
–20°C to +85°C	±0.3°C
–40°C to +125°C	±0.5°C

2.3 TMP6x

Most RTD applications use a current source to excite the RTD element and create a voltage difference. The TMP61 is a linear silicon-based thermistor that has consistent sensitivity across temperature. Using the TMP61 in a current biasing circuit such as Figure 2-6 can offer a method of temperature monitoring to replace the expense and complexity of RTDs. The TMP61 has a positive temperature slope and a temperature measurement range of –40°C to 125°C. The TMP61 can also be used in a voltage biasing circuit, seen in Figure 2-7. The output voltage that corresponds to the measured temperature, V_{TEMP} , is measured across R_{BIAS}.

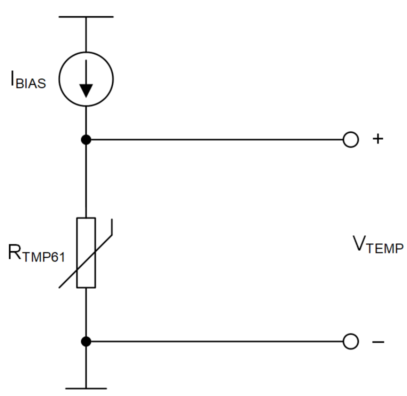

Figure 2-6. TMP61 Current Biasing Circuit

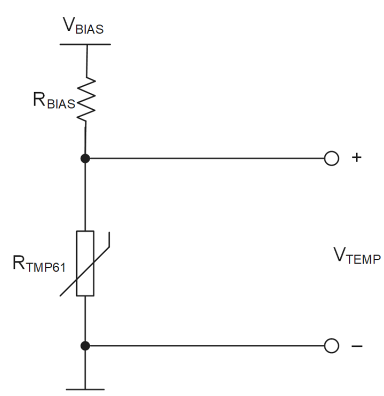

Figure 2-7. TMP61 Voltage Biasing Circuit

Note

For additional design resources TI provides the Thermistor Design Tool, which offers resistance versus temperature table computation, alternative methods for deriving temperature, and example C-code.

3 Conclusion

There are a variety of replacement options for RTD applications. Depending on specific system needs, a digital temperature sensor such as the TMP116, TMP117, or TMP1826 can increase accuracy while keeping printed circuit board costs and complexity low. For other systems, the TMP61 silicon-based linear thermistor can be easily integrated using a current or voltage biasing source from an already-existing RTD design.
The high accuracy and fast response time of these semiconductor temperature sensors are key performance differentiators that allow these devices to replace expensive RTD systems in real-time control applications. In applications where milliseconds can make or break system stability, TI enables the sensing, processing, control and communication necessary to implement and optimize real-time control.

4 References

- Texas Instruments, *Replacing Resistance Temperature Detectors with the TMP116 Temp Sensor* application note
- Texas Instruments, *Analog linearization of resistance temperature detectors* analog design journal
- Texas Instruments, *A Basic Guide to RTD Measurements* application note
- Texas Instruments, *Thermistor Design Tool*
- Texas Instruments, *Measuring an RTD Sensor with the TDC1000 and TDC7200 for Ultrasonic Sensing* application note
- Texas Instruments, *RTD Class-AA Replacement With High-Accuracy Digital Temperature Sensors in Field Transmitters* application note
- Texas Instruments, *RTD Replacement in High Accuracy Sensing and Compensation Systems Using Digital Temperature Sensors* application brief
- Texas Instruments, *Semiconductor Temperature Sensors Challenge Precision RTDs and Thermistors in Building Automation* application note

5 Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision * (May 2021) to Revision A (June 2022) **Page**

- Expanded the *Abstract* 1
- Updated the *RTD Alternatives* section, including expanding the discussion on the *TMP116 and TMP117*, and adding sections for the *TMP1826* and *TMP6x*.. 6

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