Error analysis for ratiometric and absolute methods of temperature sensing

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Introduction

A thermistor is designed as a two-terminal solid state (thermally) sensitive transducer in which its resistivity changes with temperature. Using different semiconductor (SC) materials and fabrication processes, thermistors are available with a negative temperature coefficient (NTC) or a positive temperature coefficient (PTC). According to Ohm's law, a current passing through a resistive component will produce a voltage drop across that component. This voltage is proportional to the magnitude of the component resistance and the flowing current. Hence, thermistors require an external excitation signal for their biasing and operation. This is normally done with the use of a constant voltage or current source. Although voltage and current sources are designed to be constant, they undergo some variations under different operating conditions. These variations may cause erroneous readings in the sensors measurement.

It is crucial that the power supply interference does not impact the actual measurement. To negate the effect of power supply variation, ratiometricity[1,2] is a common measurement approach. In ratiometricity, the quantity under measurement is proportional to the ratio of two signals rather than an absolute reference signal. In other words, the signal of interest is measured with respect to another signal (i.e., voltage or current source) to which it has a proportion relationship. This article presents the comparison between the ratiometric and absolute methods in temperature sensing using NTC and Si-based PTC thermistors. Also included is a fundamental theory discussion about PTC and NTC thermistors with a comparison between the two measurement methods. Moreover, the application of ratiometricity in rejecting external supply voltage/current variations is also explained via mathematical calculations.

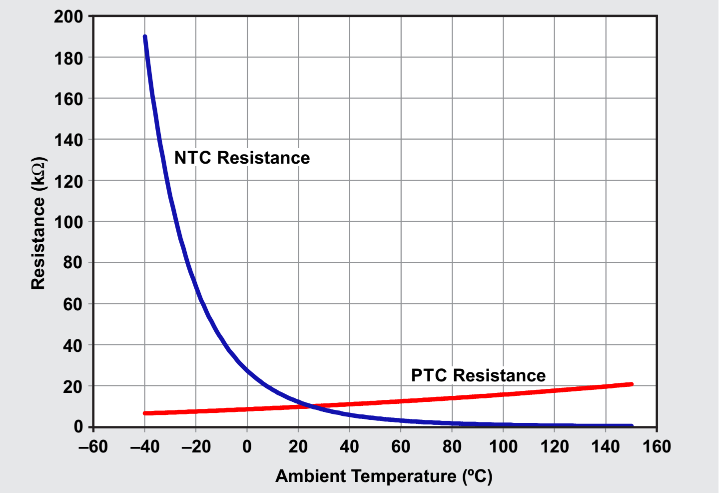
Operating principles of thermistors

The design and fabrication of NTC and PTC thermistors is basically feasible because of band-gap engineering and conductivity modification of the SC materials.[3] In a doped semiconductor, as temperature rises, one effect is that more charge carriers are produced and contribute to the electrical conduction, hence the resistivity drops. This is also interpreted as the reduction in the energy bandgap against temperature. On the other hand, the mobility of a particle in a semiconductor is expected to be small if the time between scattering events is small. In a solid-state temperature sensing device, there is a second effect to be considered for higher doping concentration, where the mean free path is reduced due to increased atomic vibrations, so electrons get less time to accelerate between collisions. This shorter time tends to increase the device resistivity as temperature goes higher. In the case of low-doped semiconductors, the first effect is predominant, so they are NTC. Alternatively, in heavily doped semiconductors, the second effect is predominant, which results in a PTC thermistor. Due to the predominant second effect, Si-based PTC devices show more of a linear-like behavior as opposed to NTCs, which are usually nonlinear.

Figure 1 depicts the comparison between NTC and Si-based PTC thermistors used throughout this study in the temperature range from –40 to 150°C. Note that one can get intrinsic behavior in silicon if it is operated at high enough temperature (~250°C and above). This would also put a limit on the silicon—PTC maximum operating temperature (150°C used in this study). Figure 1 shows that at lower temperatures, the NTC thermistor has a very large resistance. As temperature increases, it substantially loses its resistance value. More importantly, the resistance-vs.-temperature slope (sensitivity) of the NTC thermistor also becomes very small for higher temperatures.

Conversely, the Si-based PTC device in Figure 1 has somewhat linear shape with roughly constant sensitivity response. This is considered to be an advantage for PTC over NTC thermistors for some applications. In the following section, the concept of ratiometricity is discussed through a design example.

Figure 1. Thermistor resistance vs. ambient temperature



Absolute versus ratiometric measurement

For high-precision applications, the sensor's accuracy is of main concern. Hence, much attention is paid to reducing the sensor reading errors. These errors are generated by a variety of internal and external sources. As mentioned before, power supply variation is one root cause of erroneous temperature readings in thermistor-based devices. One popular method to negate this effect and improve a sensor's accuracy is ratiometricity. In this method, the measured quantity sought after is the ratio of two quantities that typically exhibit interference. This section explains how the ratiometric value is independent of the supply voltage. For example, Figure 2 shows simplified schematic views of utilizing thermistors for temperature measurements. Figure 2a represents one simple and commonly used method of using thermistor as part of a potential divider. In this configuration, a constant voltage source (V_{DD}) is applied across the thermistor in series with a current-limiting resistor (R_S) and the output voltage measured across the thermistor (V_{OUT}). The magnitude of V_{OUT} is proportionally related to the ratio of the resistive divider formed by R_S and the thermistor's effective resistance ($R_{NTC/PTC}$). Thus the potential divider circuit in Figure 2a is an example of a simple resistance-to-voltage converter where the resistance of the thermistor is controlled by temperature with the output voltage produced being proportional to the temperature. This output signal is then fed into an analog-to-digital converter (ADC) for signal conditioning and data communication. Although this seems to be a simple method of biasing the thermistor, it can suffer from power supply variations and potentially cause measurement errors. The measurement accuracy of the circuit in Figure 2a can be affected from three different sources:

- The power supply voltage (V_{DD}) variations,
- The error caused by the ADC's reference voltage (V_{SS}) interferences, and
- The error due to the tolerance variations of the current limiting resistor (R_S).

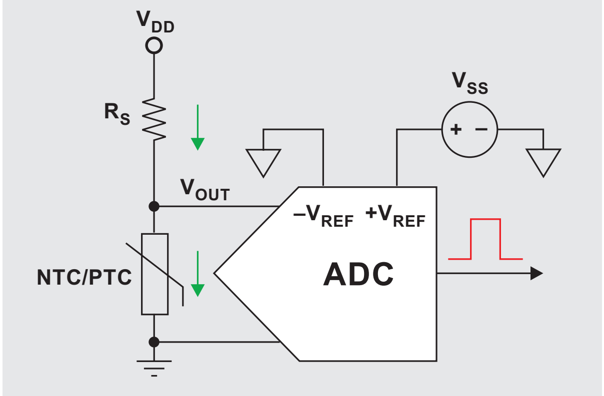
The following equations describe the relationship between the signal under measurement and the ADC's output result.

$$\text{ADC Output Result} = \frac{V_{OUT}}{V_{SS}} \times (2^N - 1) \tag{1}$$

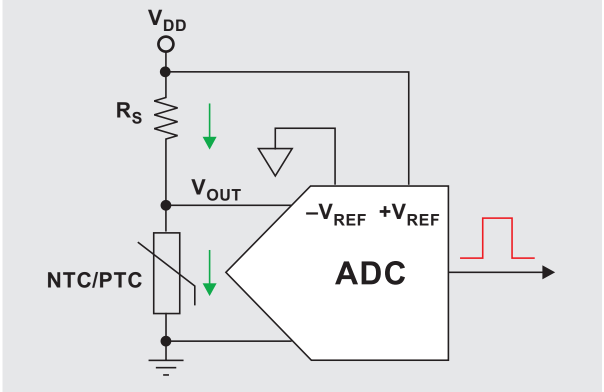
where N denotes to the ADC's resolution bit and V_{SS} is the independent reference voltage. Also, the temperature-dependent signal across the thermistor (V_{OUT}) can be expressed as

$$V_{OUT} = \frac{R_{Therm}}{R_{Therm} + R_S} \quad V_{DD} \tag{2}$$

Figure 2. Circuit comparison for absolute and ratiometric temperature sensing



(a) Absolute temperature sensing



(b) Ratiometric temperature sensing

Substituting for the V_{OUT} with the actual term given by Equation 2 from the voltage divider of Figure 2a yields:

$$\text{ADC Output Result} = \frac{R_{Therm}}{R_{Therm} + R_S} \times \frac{V_{DD}}{V_{SS}} \times \left(2^N - 1\right) \tag{3}$$

From Equation 3, observe that the ADC's output result is proportional to the V_{DD}, V_{SS} and R_S values. For an ideal situation, constant values are desired for these parameters to avoid measurement error. Unfortunately, a power supply with zero tolerance at a reasonable cost is very hard to design, if not impossible. Also, extremely low-tolerance resistors (R_S, for this example) are usually costly and not economically reasonable to use. To rectify these issues, ratiometric technique can be employed as a practical solution. Figure 2b represents the schematic of the same network given by Figure 2a, except with a ratiometric configuration. In this method, instead of using an independent (external) voltage source (V_{SS}), the reference voltage is also picked from the main supply voltage, V_{DD}.

Assuming the wires connecting V_{DD} to the reference input and ground terminals ($\pm V_{REF}$) have minimum impedance effect, the reference voltage of the ADC in Figure 2b is expressed by Equation 4.

$$+V_{REF} - V_{REF} = V_{DD} \tag{4}$$

Substituting the new reference voltage from Equation 4 into Equation 3, the ADC output result can be simplified to Equation 5.

$$\text{ADC Output Result} = \frac{R_{Therm}}{R_{Therm} + R_S} \times \left(2^N - 1\right) \tag{5}$$

From Equation 5, observe that when using the ratiometric technique, the dependency of ADC output result on the V_{DD} and V_{SS} voltage sources is completely eliminated. This will result in a substantial improvement in the sensor's reading accuracy. Note that for some applications, the ratiometric technique is not a feasible option and the absolute method is still preferred. For example, in remote sensing where the temperature sensor (thermistor) is located far away from the host microcontroller or microprocessor, the need for an independent reference voltage seems to be inevitable.

Conclusion

Temperature sensors constructed with semiconductor materials are available with either NTC or PTC resistance characteristics. A comparison of two measurement techniques commonly used for temperature sensing demonstrated that the use of external voltage sources and biasing resistor (with some tolerances) could potentially impact system measurement accuracy. For some applications, the ratiometric technique is a possible alternative to negate the impact of external component variations.

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