

# **Methods to Reduce Thermistor Linearization Error, Memory, and Power Requirements Over Wide Operating Temperature Ranges**

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## **ABSTRACT**

Most thermistors are highly non-linear over a wide operating temperature range. In many cases, thermistor linearization over a wide temperature range proves to be a challenge. For example, in some automotive applications, the operating temperature can vary from  $-40^{\circ}\text{C}$  to  $150^{\circ}\text{C}$ . Linearization in this range is not without significant system tradeoffs. This ultimately affects system requirements such as temperature accuracy, power, and memory size. Understanding how linearity affects these key system tradeoffs can help system designers take advantage of the linear TMP61 thermistor for wide-operating-temperature applications.

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## 1 The Thermistor Family

Traditionally known for its low cost and versatility, thermistors are widely used in many applications. Some example applications of thermistors include inrush current limiters, temperature monitors, thermal protection, and thermal compensation. These thermistors are available in a wide number of form factors including leaded packages, surface mount packages, or even preassembled probes.

Within the thermistor family, there are two basic types: Negative Temperature Coefficient (NTC) and Positive Temperature Coefficient (PTC). The NTC type has resistance decreasing with temperature and the PTC type has resistance increasing with temperature. PTC thermistors can be further divided into two subclasses: linear and switching. TMP61 falls under the linear PTC type. The thermistor family tree is summarized in Figure 1. While most NTC thermistors are made from ceramic, PTC thermistors are made from a variety of materials such as silicon, metal, ceramic, or polymer. This speaks to the diversity of the thermistor family.

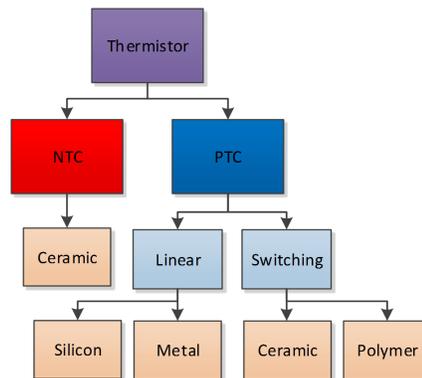


Figure 1. Generalized Thermistor Family Tree

### 1.1 PTC Thermistors

The silicon-based PTC thermistors, also known as silistors, are much more linear than the switching PTC or NTC thermistors. The linear PTC temperature coefficient (also known as  $\alpha$ ) ranges from 0.6%/K to 0.8%/K. As shown in Figure 2, the switching PTC's resistance increases exponentially at the Curie temperature. Generally, the linear PTC type is used for temperature sensing and thermal compensation. In contrast, the switching PTC type is typically used for current limiting (for example, soft start, failsafe) and thermal protection.

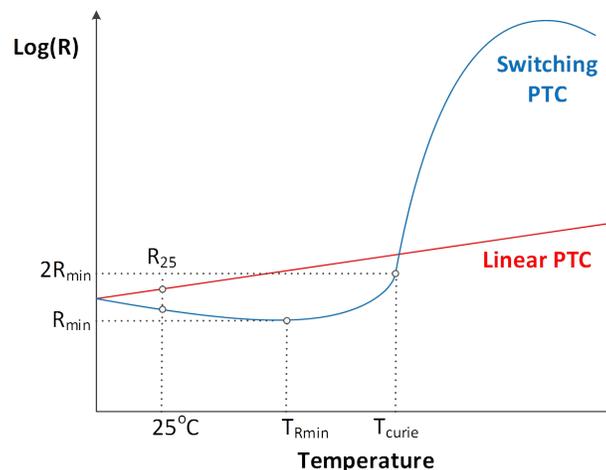


Figure 2. Comparison Between Linear Versus Switching PTC Thermistors

### 1.2 NTC Thermistors

In many applications, the most widely used thermistor type is NTC. NTC thermistors can be used for inrush current limiters, temperature monitors, and thermal protection. The NTC resistance versus temperature profile is distinctly less linear compared to the linear PTC TMP61 as shown in Figure 3.

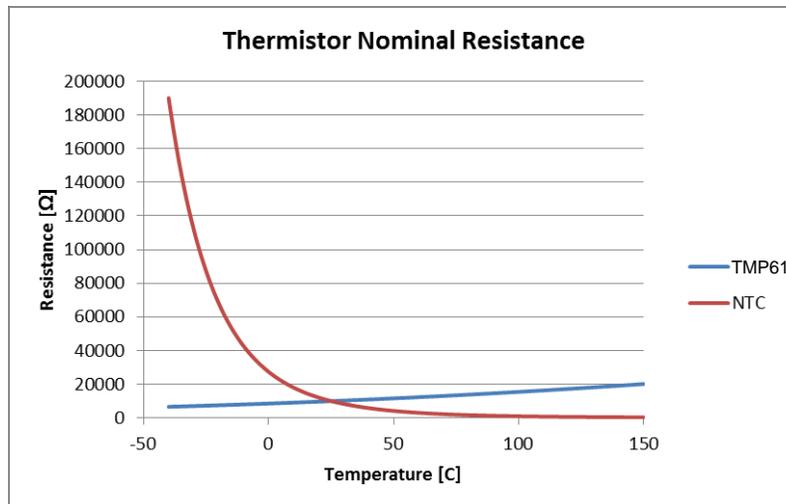


Figure 3. Resistance Versus Temperature Profile of NTC and TMP61

### 1.3 Thermistor Application for Temperature Monitor and Protection

Thermistors are commonly used in a voltage divider circuit to interface with either a comparator or an analog-to-digital converter (ADC). The former case is used for thermal protection as shown in Figure 4. The latter case is used for temperature monitor as shown in Figure 5. Note that most thermistor applications employ the ratiometric method. A circuit is ratiometric when the ADC Vref and the divider circuit Vbias share a common voltage source. This effectively eliminates Vbias and Vref from the ADC result. In other words, the ADC readout is just a function of the ratio of the divider circuit resistances (Rt and Rbias) and ADC resolution (N-bit ADC resolution) as shown in Equation 1.

$$\text{ADC Code} = \text{Round}\left(\frac{R_t}{R_t + R_b} 2^N\right) \tag{1}$$

In the comparator case, if both the inputs are generated from the same voltage supply as shown in Figure 4, the circuit is also considered ratiometric.

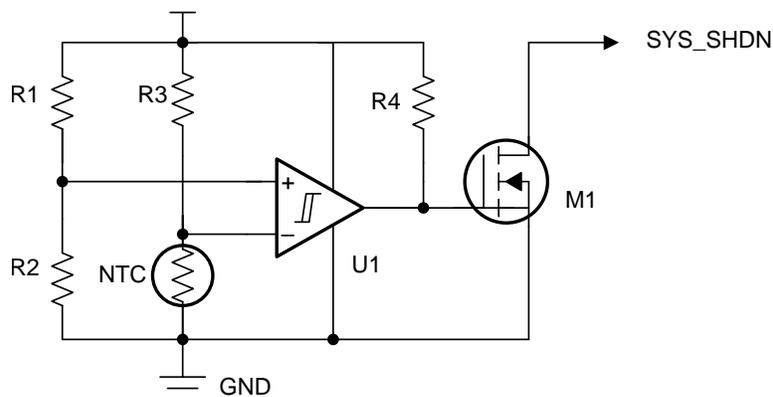
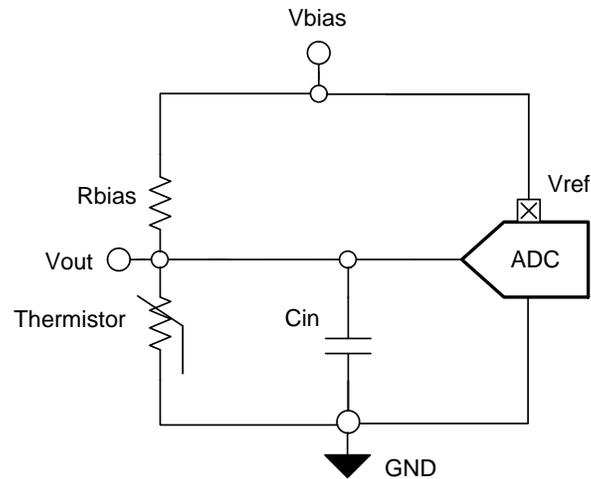


Figure 4. Thermal Switch Circuit

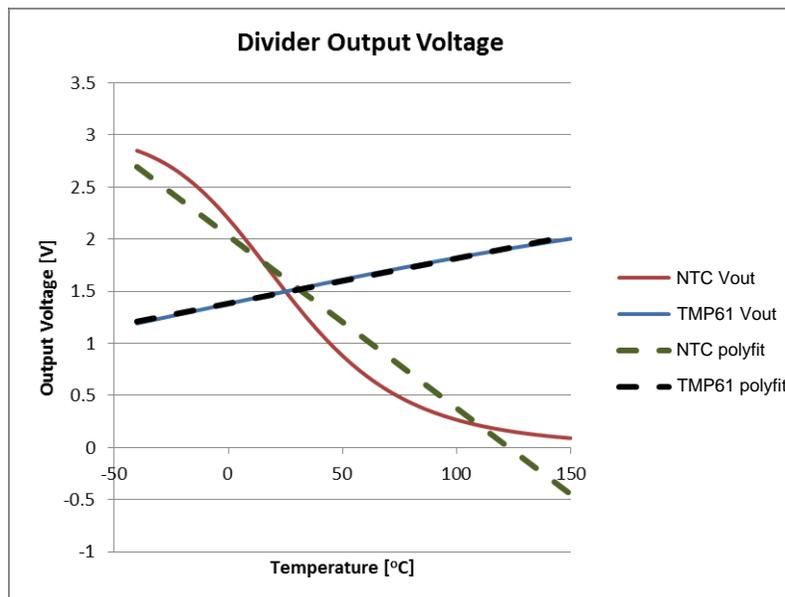
Employing the ratiometric measurement method does reduce many ADC error sources including ADC reference and bias voltage variation. However, it does not reduce software linearization error. In the temperature monitor case, an additional software linearization step is required in order to convert the ADC readings into actual temperature values. As described in the next section, the thermistor's linearity can have a significant impact on the system accuracy, memory, and power requirements.



**Figure 5. Ratiometric Temperature Monitor Circuit**

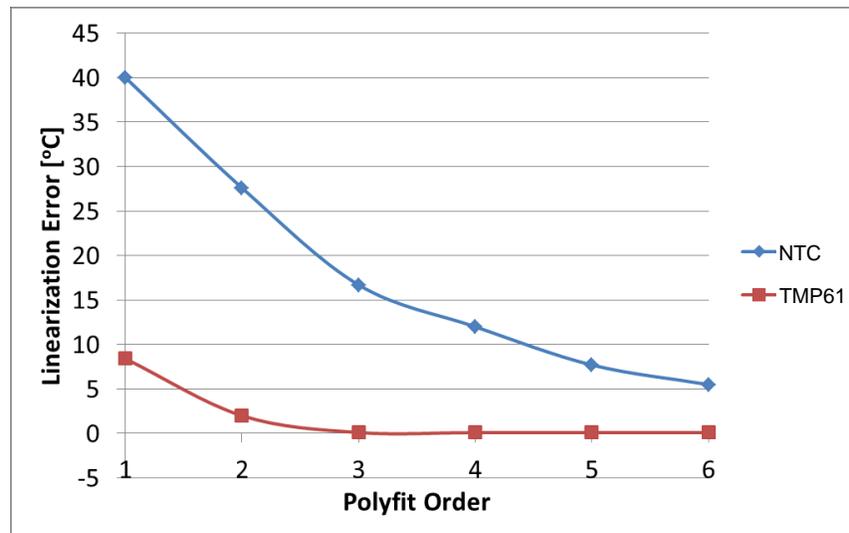
## 2 Linearization

There are two basic ways to linearize thermistors in software: polynomial fitting (polyfit) and look-up-table (LUT). When using polyfit, the linearization error is reduced with a higher polynomial fit order (that is, more fit coefficients). However, this is at the expense of increasing power consumption due to increasing processing requirements. Alternatively, some applications employ the Steinhart and Hart empirical equation for curve fitting. Unfortunately, the Steinhart and Hart equation requires the use of natural logarithmic operations, which may not be the most efficient implementation in fixed-point microcontroller architectures compared to polynomial operations. The second linearization method is with a LUT. When using a LUT, the linearization error is reduced with a deeper LUT. However, this is at the expense of increasing memory size. Note that there are a number of LUT algorithms available and some are quite computational efficient. However, LUT algorithms are beyond the scope of this application report. In the following section, specific linearization tradeoffs are discussed in detail.

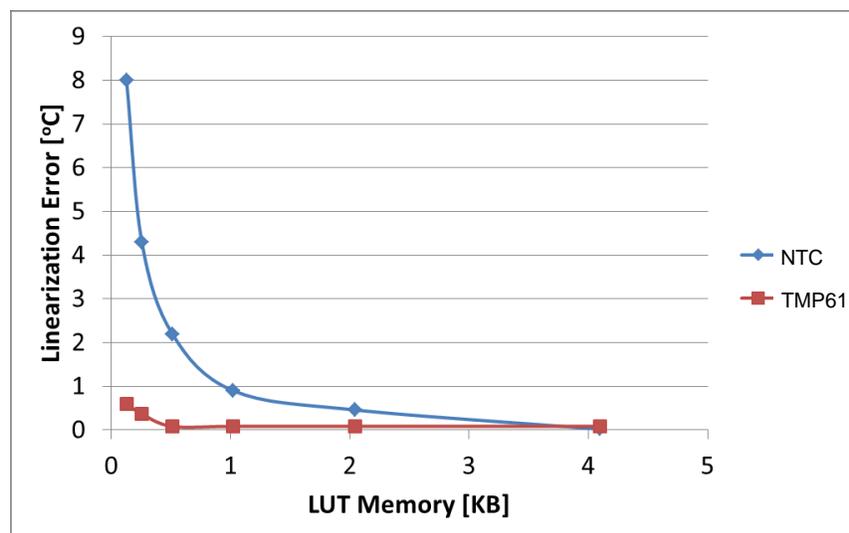


**Figure 6. Example Voltage Divider Output and 1<sup>st</sup> Order Polyfit Linearization**

Based on the voltage divider circuit from [Figure 5](#), the voltage outputs and its 1<sup>st</sup> order linearization curves are shown in [Figure 6](#) for both the NTC and TMP61 devices. In this example, the operating temperature is from  $-40^{\circ}\text{C}$  to  $150^{\circ}\text{C}$ . Notice how the linearity of the thermistor affects its linearization error. [Figure 7](#) and [Figure 8](#) show the tradeoff between linearization error versus polyfit order and LUT memory, respectively. In both cases, due to its higher linearity, the TMP61 requires less fit order and memory to linearize than the NTC. Given a second-order polyfit or 1 kB of LUT memory, the linearization error is roughly ten times better with TMP61 compared to NTC. Up to this point, it has been shown that given a wide temperature range, there are two methods to reduce the linearization error: higher polynomial order and more LUT memory. An alternative way to reduce linearization error is by reducing the operating temperature range as NTC becomes more linear with smaller operating temperature ranges.



**Figure 7. Linearization Error Versus Polyfit Order**



**Figure 8. Linearization Error Versus LUT Memory**

Note that it is also common to see thermistor linearized in hardware with series and parallel resistors combinations. An example thermistor linearization circuit is shown in [Figure 9](#) and its equivalent resistance versus temperature profile is shown in [Figure 10](#). In this example, the linearized NTC R25 is 10 k $\Omega$ , R<sub>s</sub> is 5 k $\Omega$ , and R<sub>p</sub> is 10 k $\Omega$ . There are two basic ways to linearize a thermistor in hardware: voltage mode and resistance mode. For example, placing the thermistor in a voltage divider is considered as voltage-mode linearization because the divider output voltage is directly used. Regardless, to translate voltage reading to temperature, an additional software linearization step is required. Sometimes, a thermistor is linearized to be used as a temperature-compensation resistor such as for LCD temperature compensation. This approach is called resistance mode linearization. However, improving thermistor linearity with series and parallel resistor combinations is at the expense of sensitivity. In these compensation applications, TMP61 may be a better alternative to NTC since TMP61 is already linear and sensitivity is more uniform across temperature compared to the linearized NTC.

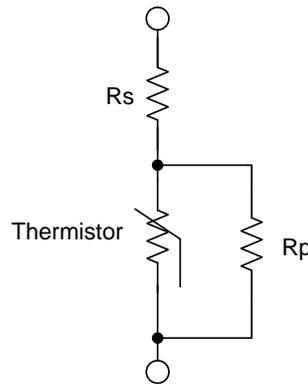


Figure 9. Example Thermistor Linearization Circuit

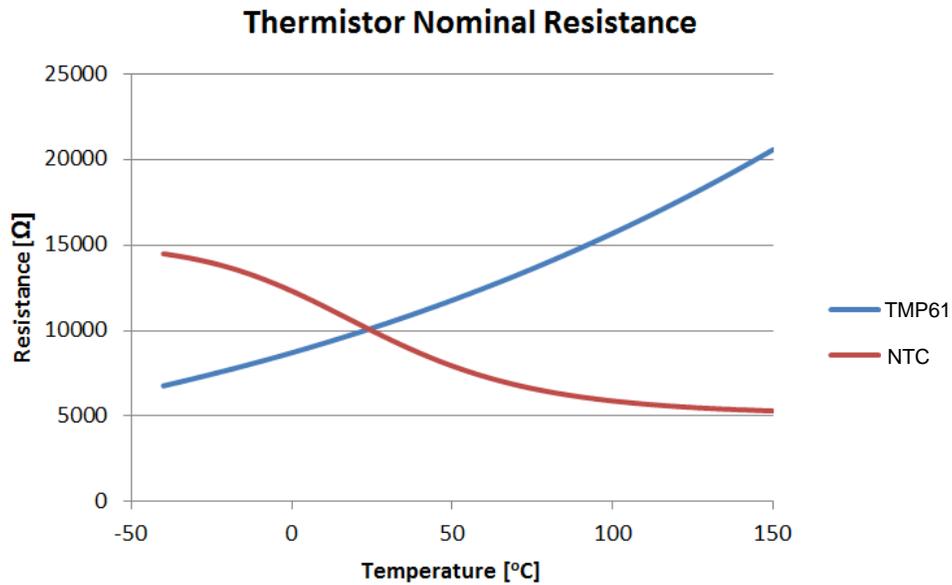


Figure 10. Resistance Versus Temperature Profile of a Linearized NTC Compared to TMP61

### 3 Other Design Considerations

For wide temperature operation, linearization error can be the dominant source of error. However, there are a number of other error sources that can contribute to the total system error including component tolerances, component temperature drift, noise, and ADC-related errors. Note that using ratiometric will mitigate most of these ADC errors except for non-linearity errors. TI recommends use of the *TMP61 System Parameter Simulator* tool to determine the appropriate design tradeoffs.

TI provides a broad portfolio of temperature sensors including linear silicon TMP61 thermistors. The TMP61 thermistor family offers a typical temperature sensitivity of 0.6%/K at 25°C. The TMP61 is available in a small 2-pin SMD package (0.6 mm × 1 mm) and a 2-pin TO-92s (4 mm × 3.15 mm) through-hole package.

For alternative device recommendations, refer to [Table 1](#). The TMP235 is a linear analog IC temperature sensor that provides a positive slope output of 10 mV/°C over the full –40°C to +150°C temperature range, which greatly simplifies linearization requirements. A higher gain version, TMP236, is also available. For thermal protection applications requiring ensured accuracy, the TMP302 IC temperature switch is a good alternative to discrete thermistor implementations. The TMP302 offers pin-programmability and hysteresis. For applications requiring high system accuracy, the digital TMP117 temperature sensor provides a maximum accuracy of ±0.1°C without additional calibration or linearization. These IC sensors minimize self-heating due to the low quiescent supply current across the operating temperature range. To learn more about thermal monitor and protection, refer to the references in [Table 2](#).

**Table 1. Alternative Device Recommendations**

Device	Optimized Parameters	Performance Trade-Off
<a href="#">TMP235</a>	Analog IC Temperature Sensor, linearity	Pin-count, not ratiometric
<a href="#">TMP302</a>	Pin-programmable temperature switch, system simplicity	Pin-count
<a href="#">TMP117</a>	Digital IC Temperature Sensor, system accuracy and simplicity	Pin-count

**Table 2. Related Documentation**

Literature Number	Title
<a href="#">SNOA996</a>	Protecting Control Systems From Thermal Damage
<a href="#">SNOA966</a>	Design Considerations for Measuring Ambient Air Temperature

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