WHITE PAPER

Thermistors—A Closer Look

DR. DEBASHIS SARKAR
Sr. Engineering Manager

RAHUL BBHASKAR
Sr. Engineer, Product Design

molex

INTRODUCTION

Temperature monitoring and control are fundamental requirements for a vast array of equipment in an equally vast number of applications and represent a $6 billion global market that is growing about 5% per year. Yet even though they perform a critical function for this equipment, these tiny devices are taken for granted by many engineers and are often misunderstood. To help solve the problem, this white paper describes the major types of temperature sensors and focuses on negative temperature coefficient (NTC) thermistors, as they are the most widely used for temperature sensing.

Temperature sensors measure heat to ensure that a process or piece of equipment is remaining within its specific range, ensuring it is safe to continue operating, or meeting a mandatory condition. And these sensors must do so in extreme heat, with the presence of hazards and where there are inaccessible measuring points. Three types of temperature sensors, thermocouples, NTC thermistors and resistance temperature detectors (RTDs) account for most of the market, and each has its own advantages and disadvantages for use in specific applications. The temperature sensors and their characteristics are described in Table 1.

Sensor type	Thermocouple	NTC or PTC* thermistor	RTD
Measurement range (°C)	-250 to + 4,200	-100 to +500	-250 to +1,200
Response time (sec)	0.2 to 20	0.12 to 10	1 to 50
Linearity	Non-linear	Requires linearization	May require linearization
Accuracy (°C)	0.5 to 5	0.05 to 1.5	0.5 to 5
EMI resistance	Very high	Very low	Very low
Lead effect	High	Medium	Low
Stability	Fair	Fair	Good
Power required	None	Any constant voltage/ current source	Any constant voltage/current source
Cost	Low	Low to medium	High
Size	Small to large	Small to medium	Small to medium
Advantages	Simple, inexpensive, high temperatures, point sensing	High-voltage output, fast, inexpensive, point temperature sensing	Very stable and accurate, most repeatable
Disadvantages	Non-linear, low-voltage output, least stable, least sensitive	Non-linear, limited range, requires power source, self-heating	Requires power source, has slow response time, is insensitive to small temperature changes, self-heating

* Positive temperature coefficient

Thermocouple: The First Temperature Sensor

The thermocouple is the simplest of these sensors, and it has been in use since the late 1800s, after a discovery by Italian scientist Allesandro Volta and later a “rediscovery” by German physicist Thomas Johann Seebeck. Collectively, their research showed that a magnetic field is created when two wires made of different metals are joined at the ends when a temperature difference exists between the joints. As the temperature changes, the voltage rises and falls (called the Seebeck effect). In a thermocouple, this relationship between voltage and temperature is calculated using reference tables.

The major benefits of a thermocouple are its very low cost, high temperature range, durability and ability to function without a power source. Its disadvantages are that there must not be heat flow between the object to be measured and the thermocouples, and as they age so does their accuracy, especially if the wires are affected by moisture, exposure to chemicals or mechanical interference. Thermocouples also produce a very low-output voltage that must be amplified and are susceptible to external noise over long wires, and a "cold junction" can occur when the thermocouple wires meet copper traces of signal circuitry.

Thermistors

The thermistor (thermally sensitive resistor)—and specifically the NTC thermistor—was first described by Michael Faraday in 1833, who found that the resistance of silver sulfide decreased with increases in temperature. However, as the thermistor was difficult to produce and applications were few, commercial production began a century later when Samuel Ruben patented the thermistor in 1930.

Thermistors have continued to be popular because their higher resistance change per degree of temperature provides greater resolution, they are highly repeatable and stable, and they have excellent interchangeability (described later). They have low thermal mass, so their response to temperature changes is quite fast.

NTC thermistors are made from a pressed disc, rod, plate, bead or cast chip of semiconducting material, such as sintered metal oxides. NTC thermistors are used primarily for precise temperature control because they can be manufactured to very tight resistance tolerances and temperature accuracy.

They are also used as an inrush current limiter in power supplies, where they present a high initial resistance that prevents high current levels from flowing when a host device is turned on. After they heat up, this resistance decreases and allows more current to flow and the host device to function without damage. NTC thermistors for this application are larger than those used for temperature measurement and are designed specifically for this application.

In contrast, PTC thermistors are used as self-resettable fuses and heaters. As this discussion concerns temperature measurement and control, it focuses on NTC thermistors. However, it is important to recognize how different the PTC is from its counterpart, and why it is so useful in specific applications.

When little or no power is applied, a PTC is in its low-resistance state and the atoms in the ceramic are arranged in a specific pattern that allows some electrons to flow freely. When sufficient voltage is applied, the PTC almost instantaneously reaches a "transition temperature" of around 180°C, and its resistance increases about 1,000-fold, inhibiting the voltage from flowing to the host device, making it a simple and effective self-resettable fuse. When the voltage is removed, the thermistor returns to its low-resistance state. PTC's are used as heaters because they self-regulate at a constant temperature once the transition temperature is exceeded. This property allows PTC's to operate at nearly the same temperature regardless of variations in voltage and ambient temperature.

Thermistors are nonlinear devices, which means that the points on a graph representing the relationship between resistance and temperature do not form a straight line. As a result, they require the data to be corrected by a circuit such as a thermistor combined with a fixed-value resistor to form a voltage divider whose output is digitized by an ADC. By selecting an appropriate value for the resistor, the temperature range for which the curve is most linear can be shifted to meet the needs of the application.

NTC thermistors are usually specified by their resistance at room temperature (typically 25°C), although the temperature can also be that of the thermistor body when at "zero-power" resistance. Zero-power resistance refers to a thermistor's resistance value measured at a specific temperature when the thermistor's power dissipation is low. An additional decrease in power will be equal to no more than 0.1% in resistance change (or 1/10 of the tolerance, whichever is smaller).

Relatively low-temperature applications, such as -55 to 70°C, generally use lower-resistance thermistors of 200 to 10,000 Ohms and higher-temperature applications generally use thermistors with resistance above 10,000 Ohms to optimize the resistance change per degree at the required temperature.

Thermistors come in a variety of shapes, such as disk, chip, bead or rod, and can be surface mounted or embedded in a system. They can be encapsulated in epoxy resin, glass, or baked-on phenolic, or they can be painted. The best shape often depends on what material is being monitored, such as a solid, liquid or gas.

They can also be connected to a cable when the device to be measured is inaccessible or difficult to reach. In this case, the NTC thermistor is housed in a ring terminal connected to the device, and the other end has a connector for attachment to the controller. The cables used for these assemblies are designed specifically for this application. Cable lengths can be specified from 100 to 9,999 mm, and a variety of beta and resistance values from 1 kohm to 100 kohms can be specified as well.

Thermistors vary in cost, depending in part on their accuracy. Very low-cost thermistors are guaranteed only at a single temperature and provide a basic indication within a few degrees of actual value (at the guaranteed temperature). More expensive thermistors have accuracy guaranteed to a fraction of a degree over a wide range of temperatures.

In a typical application, a controller monitors the temperature of the thermistor. The tiny bias current running through the device is sent to the controller which uses a current source to apply a bias current across the thermistor, resulting in a control voltage. When the measured temperature falls below or above a specified range (the setpoint), the controller will perform a function such as turning off or on a fan or other device.

The RTD

RTDs use a resistor whose resistive value changes with temperature. Accurate, repeatable and stable, RTDs can be used for temperatures ranging from -50 to 500°C for the thin film type and -200 to 850°C for the wire-wound variety. Thin-film RTD elements have a thin layer of platinum on a substrate and a pattern is created that provides an electrical circuit that is trimmed to yield a specific resistance. The assembly is coated to protect the film and connections. In comparison, wire-wound elements are either coils of wire packaged in a ceramic or glass tube or wound around glass or a ceramic material.

RTD elements have higher thermal mass, so they are slower to detect changes in temperature than thermocouples and thermistors are. Although only two copper wires are necessary to connect an RTD to an electrical circuit, they are subject to small changes in resistance based on surrounding temperature, so a third wire is built into most RTDs to allow the controller to correct for these variations.

The most accurate RTDs use platinum and are available with resistance from 100 to 1,000 Ohms, referred to as PT100 and PT1000 types. Platinum RTDs have nearly linear response to temperature changes, are stable and very accurate, are repeatable, and cover a broad temperature range. As they are more expensive, they are used when the highest precision is required.

The Beta and Steinhart-Hart Equations for Representing the Resistance vs. Temperature Relationship in NTC Thermistor Materials

A fundamental value for specifying thermistors is called "beta" (β), which indicates the shape of a curve that varies with the thermistor's relationship between resistance and temperature and is a critical factor when specifying a specific type. It is measured in degrees Kelvin (K) and follows the rule defined in the following equation:

$\Delta R = k*\Delta T$

where

ΔR = change in resistance
ΔT = change in temperature
k = first-order temperature coefficient of resistance

If the value of k is positive, the resistance increases with increasing temperature, so the thermistor would be called positive temperature coefficient (PTC) thermistor. If the value of k is negative, the resistance decreases with increasing temperature, and the device is called an NTC thermistor. By specifying the beta value, it is possible to achieve the proper thermistor characteristic at a given temperature versus the resistance required for the application. That is, it determines what the thermistor's resistance must be at a specific temperature.

There are two ways to determine the value of beta for an NTC thermistor. The first is calculated using the four components below:

$$\beta = \frac{\ln(\frac{R_{T1}}{R_{T2}})}{(\frac{1}{T_1} - \frac{1}{T_2})}$$

where:

R_{T1} = Resistance (Ohms) at temperature 1
R_{T2} = Resistance (Ohms) at temperature 2
T_1 = Temperature 1 (K)
T_2 = Temperature 2 (K).

Using this method, the beta value of an NTC thermistor is calculated using two temperatures (R_{T1} and R_{T2}), but it is accurate over only a narrow temperature range. A more accurate method is the Steinhart–Hart Equation, which results in a value closer to the actual temperature and is useful over the entire working temperature range of the thermistor. If Steinhart–Hart coefficients are not available on a thermistor manufacturer's data sheet, they can be derived by measuring three resistances at precise temperatures and deriving the coefficients by solving three simultaneous equations (solved together). The process is as follows:

$1/T = A + B(\mathrm{LnR}) + C3*(\mathrm{LnR})^3$

where

T = Temperature (K)
LnR is the log of the measured resistance of the thermistor
and
A, B and C are the Steinhart–Hart coefficients that vary with the type and model of a thermistor and the desired temperature range.

As noted above, the coefficients A, B and C are found by taking the resistance of the thermistor at three temperatures and solving three simultaneous equations. For example:

T_1 = 0°C when the resistance of a 10-kohm thermistor R_1 is 32,803 Ohms.
T_2 = 50°C when the resistance of a 10-kohm thermistor R_2 is 36,03 Ohms.
T_3 = 100°C when the resistance of a 10-kohm thermistor R_3 is 685.7 Ohms.

$1/T_1 = A + B(\mathrm{LnR}\ ) + C(\mathrm{LnR})$
$1/T_2 = A + B(\mathrm{LnR}\ ) + C(\mathrm{LnR})$
$1/T_3 = A + B(\mathrm{LnR}\ ) + C(\mathrm{LnR})$

The value of constants A, B and C are:

A = 0.001100669397
B = 0.000238957307
C = 0.00000006722278769

The errors from this calculation are shown in the table for a 10-kohm thermistor at 25ºC.

Resistance of 10-kohm Thermistor	Calculated Temperature (ºC)	Actual Temperature (ºC)	Error (ºC)
180,591	-29.9719569	-30	-0.028
98,374	-19.9851009	-20	-0.0149
55,780	-9.9942298	-10	-0.0058
32,803	0.0014642	0	-0.0015
19,943	9.9974991	10	0.0025
12,499	19.9950337	20	0.0050
8,054	29.9961911	30	0.004
5,324	39.9980346	40	0.002
3,603	50.000003	50	0.000003
2,492	59.9975092	60	0.0025
1,758	69.9992256	70	0.0008

Another factor called beta tolerance describes how closely a part's actual curve tracks the nominal curve defined by its beta value and is used when describing point-matched parts. Point-matched thermistors are used in applications that require a specific resistance value matched to a specific temperature.

Beta is in part determined by the composition and structure of the various metal oxides being used in the device as well as variables in the manufacturing process. As a result, there will be a variation from unit to unit within a production lot as well as from lot to lot. For bead-type thermistors, beta tolerances are usually on the order of ± 1% to ± 3% (up to +/-5% is achievable with some materials). For metalized-surface contact-type thermistors, beta tolerances will range from ±0.5% up to ± 3%.

NTC thermistor manufacturers provide tables of either resistance or resistance-ratio versus temperature for each of the products they offer. There are a great many material systems in use, and each one has certain limitations with respect to the type of thermistor that can be manufactured, the size of the thermistor, and temperature ranges for operation and storage, as well as the range of available nominal resistance values.

Interchangeability in a thermistor is an important consideration and is defined as how closely a thermistor tracks a published resistance curve over a span of temperatures. The published resistance curve is considered absolute accuracy, so interchangeability is the deviation from this point.

The more closely a thermistor adheres to this determines how a part can be interchanged for another with no degradation in performance and without needing to calibrate each sensor assembly in the circuit after replacement. Note that interchangeable thermistors include beta tolerance within their specifications so there is no beta tolerance on an interchangeable part as its accuracy is established by its interchangeability to the absolute nominal curve.

Summary

At first, the selection of the proper temperature monitoring and control devices for end-user needs might seem quite simple, requiring little knowledge before one is selected and installed into a system. As this white paper illustrates, there is far more to specifying a thermistor, and failure to evaluate the device with reference to its intended use can result in failure, destruction of the system it's designed to serve, and possibly even fire and/or danger to people around the product or system. Becoming familiar with these essential temperature-managing devices does not require a lot of time, and the results are worth the effort.

Order No. 987652-2251 USA/0K/GF/2020.05