



Thermistors in Single Supply Temperature Sensing Circuits

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INTRODUCTION

There is a variety of temperature sensors on the market all of which meet specific application needs. The most common sensors that are used to solve these application problems include the thermocouple, Resistive Temperature Detector (RTD) thermistor, and silicon-based sensors. For an overview and comparison of these sensors, refer to Microchip's AN679, "Temperature Sensing Technologies".

This application note focuses on circuit solutions that use Negative Temperature Coefficient (NTC) thermistors in the design. The Thermistor has a non-linear resistance change-over temperature. The degree of this non-linearity will be discussed in the "Hardware Linearization Solutions" section of this application note. From this discussion, various linearization resistor networks will be shown with error analysis included. Finally, the signal conditioning path for the thermistor system will be covered with complete application circuits from sensor or microprocessor.

THERMISTOR OVERVIEW

The term "thermistor" originated from the descriptor THERMally Sensitive RESISTOR. The two basic types of thermistors are the Negative Temperature Coefficient (NTC) and Positive Temperature Coefficient (PTC). The NTC thermistor is best suited for precision temperature measurement. The PTC is best suited for switching applications. This application note will only discuss NTC applications.

The NTC thermistor is used in three different modes of operation which services a variety of applications. One of the modes exploits the resistance-versus-temperature characteristics of the thermistor. The other two modes take advantage of the voltage-versus-current and current-over-time characteristics of the thermistor.

Voltage-Versus-Current Mode

Voltage-versus-current applications use one or more thermistors that are operated in a self-heated, steady-state condition. An application example for an NTC thermistor in this state of operation would be using a flow meter. In this type of circuit, the thermistor would be in an ambient self-heated condition. The thermistor's resistance is changed by the amount of heat

generated by the power dissipated by the element. Any change in the flow of the liquid or gas across the device changes the power dissipation factor of the thermistor element. In this manner, the resistance of the thermistor is changed, relative to the degree of cooling provided by the flow of liquid or gas. A useful thermistor graph for this phenomena is shown in Figure 1. The small size of the thermistor allows for this type of application to be implemented with minimal interference to the system. Applications such as vacuum manometers, anemometers, liquid level control, fluid velocity and gas detection are used with the thermistors in voltage-versus-current mode.

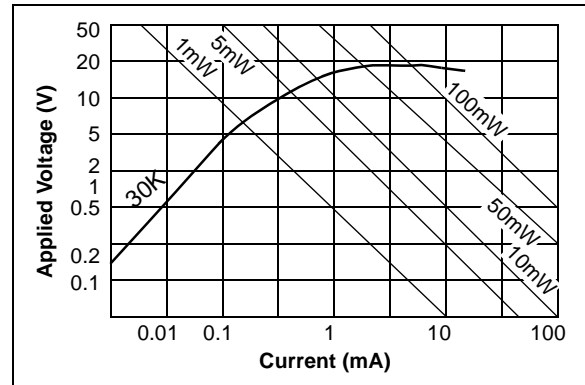


FIGURE 1: When a thermistor is overheated by its own power, the device operates in the voltage-versus-current mode. In this mode, the thermistor is best suited to sense changes in the ambient conditions, such as changes in the velocity of air flow across the sensor.

Current-Over-Time Mode

The current-over-time characteristics of a thermistor also depends on the dissipation constant of the thermistor package as well as element's heat capacity. As current is applied to a thermistor, the package will begin to self-heat. If the current is continuous, the resistance of the thermistor will start to lessen. The thermistor current-time characteristics can be used to slow down the affects of a high voltage spike, which could be for a short duration. In this manner, a time delay from the thermistor is used to prevent false triggering of relays.

The effect of the thermistor current-over-time delay is shown in Figure 2. This type of time response is relatively fast as compared to diodes or silicon based temperature sensors. The diode and silicon based sensors require several minutes to reach their steady state temperature. In contrast, thermocouples and RTDs are equally as fast as the thermistor, but they don't have the equivalent high level outputs. Applications based on current-over-time characteristics include time delay devices, sequential switching, surge suppression or inrush current limiting.

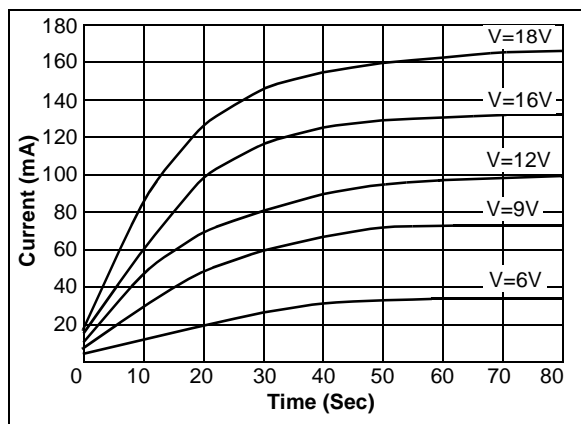


FIGURE 2: The time constant of the thermal mass of the thermistor sensor can be used to time delay a reaction to changes in conditions in a circuit. If a thermistor is overdriven, the thermal mass time constant of the sensor eventually causes the thermistor to overheat, reducing its resistance.

Resistance-Versus-Temperature Mode

By far, applications using the first mode, resistance-versus-temperature, NTC Thermistor configurations, are the most prevalent. These circuits perform precision temperature measurement, control and compensation. Unlike applications that are based on the voltage-versus-current and current-over-time characteristics of the thermistor, the resistance-versus-temperature circuits depend on the thermistor being operated in a "zero-power" condition. This condition implies that there is no self-heating of the thermistor as a consequence of current or voltage excitation. The resistance-versus-temperature response of a 10kΩ, NTC thermistor is shown in Figure 3.

The resistance across the thermistor is relatively high in comparison to the RTD element which is usually in the hundreds of ohms range. Typically, the 25°C rating for thermistors is from 1kΩ up to 10MΩ. The housing of the thermistor varies as the requirements for hermeticity and ruggedness vary, but in all cases, there are only two wires going to the element. This is possible because of the resistance of the wiring over temperature is considerably lower than the thermistor element. Consequently, a four wire configuration is not necessary, as it is with the RTD element. (Refer to AN687, "RTD Temperature Sensing Circuits" for details.)

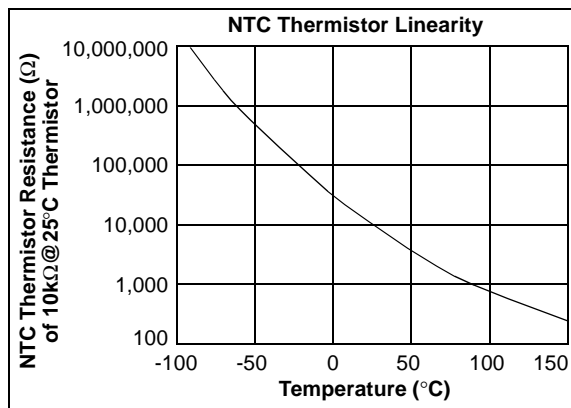


FIGURE 3: In precision temperature measurement environments, the thermistor is used in a "zero power" condition. In this condition, the power consumption of the thermistor has a negligible affect on the elements resistance. This is a graph of an NTC 10kΩ thermistor resistance-versus-temperature.

Since the thermistor is a resistive element, current excitation is required. The current can originate from a voltage or current reference, as will be shown in the "Hardware Linearization Solutions" section of this application note. The performance of the thermistor in Figure 3 is fairly repeatable as long as the power across the device does not exceed the power dissipation capability of the package. Once this condition is violated, the thermistor will self-heat and artificially decrease in resistance, giving a higher than actual temperature reading.

Figure 3 illustrates the high degree of non-linearity of the thermistor element. Although the thermistor has considerably better linearity than the thermocouple linearity, the thermistor still requires linearization in most temperature sensing circuits. The non-linear response of the thermistor can be corrected in software with an empirical third-order polynomial or a look-up table. There are also easy hardware linearization techniques that can be applied prior to digitalization of the output of the thermistor. These techniques will be discussed later in this application note. The third-order polynomial is also called the Steinhart-Hart Thermistor equation. This equation is an approximation and can replace the exponential expression for a thermistor. Wide industry acceptance makes it the most useful equation for precise thermistor computation.

The Steinhart-Hart equation is:

$$T = 1/(A_0 + A_1(\ln R_T) + A_3(\ln R_T)^3)$$

$$\ln R_T = B_0 + B_1/T + B_3/T^3$$

where:

T is the temperature of the thermistor in Kelvin.

$A_0, A_1, A_3, B_0, B_1,$ and $B_3,$ are contents provided by the thermistor manufacturer.

R_T is the thermocouple resistance at temperature, T .

With a typical thermistor, this third-order linearization formula provides $\pm 0.1^\circ\text{C}$ accuracy over the full temperature range. This is usually better than the accuracy of individual elements from part to part.

Although the temperature range of the thermistor is a little better than the diode or silicon-based temperature sensor (-55°C to $+175^\circ\text{C}$), it is still limited to a practical range of -100°C to $+175^\circ\text{C}$. This can also be compared to the temperature sensing range of the RTD (-200°C to 600°C) or the thermocouple which ranges up to 1820°C .

The advantages versus disadvantages of the thermistor are summarized in Table 1.

ADVANTAGES	DISADVANTAGES
Fast	Non-Linear
Small	Excitation Required
Two-Wire	Limited Temperature Range
Inexpensive	Self-Heating
	Fragile

TABLE 1: Summary of Thermistor Advantages and Disadvantages.

Thermistors are manufactured by a large variety of vendors. Each vendor carefully specifies their thermistor characteristics with temperature, depending on their manufacturing process. Of all of the temperature sensors, the thermistor is the least expensive sensing element on the market. Prices start at \$0.10 with some vendors and range up to \$25.

The thermistor is used in a large variety of applications such as automotive monitor and control exhaust emissions, ice detection, skin sensors, blood and urine analyzers, refrigerators, freezers, mobile phones, base stations laser drives, and battery pack charging. In the precision instrumentation applications, thermistors are used in hand-held meters and temperature gauges.

THE TEMPERATURE- RESISTIVE MODE OF THE THERMISTOR

An electrical configuration for the thermistor is shown in Figure 4. This illustrates a seemingly obvious way to excite the thermistor and measure the change in resistance where the sensing element is excited with a current source.

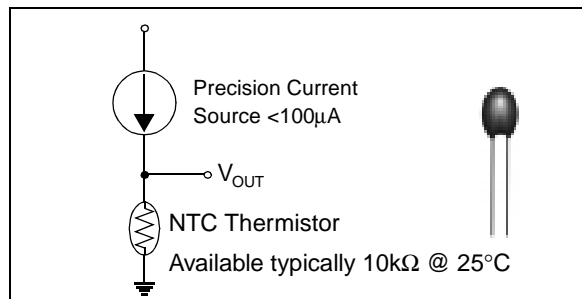


FIGURE 4: Common sense would dictate that the thermistor be excited by a precision constant current source as shown in this figure. A picture of an NTC Thermistor is shown on the right.

With this style of excitation, the magnitude of the current source is typically below $100\mu\text{A}$, preferably $20\mu\text{A}$. Lower currents prevent the thermistor from entering a self-heating condition as described previously. This style of excitation is effective for sensing a limited range of temperatures. Larger ranges of temperature have deltas in resistance that are too high to accurately convert the resistance to voltage without bumping into the noise limitations of the analog signal path.

As an example, the temperature range of a typical thermistor from BetaTHERM is -80°C to 150°C . The change in resistance for a $10\text{k}\Omega$ @ 25°C thermistor from BetaTHERM over its temperature range is shown in Table 2.

It is useful to note that the differential resistance for a 10°C delta at high temperature is significantly smaller than a 10°C delta at low temperatures. For instance, the change in resistance of the device in Table 2 from 125°C to 135°C is 76.28Ω ($340.82\Omega - 264.54\Omega$). The change in resistance of the same thermistor from -25°C to -15°C is $58.148\text{k}\Omega$. This diversity in the ratio of resistance to temperature over the range of thermistor creates an awkward analog problem. If the thermistor in this example is excited with a $20\mu\text{A}$ current source, the analog circuit must discriminate between 0.015V deltas at high temperatures and 1.16V deltas at low temperatures for $\Delta 10^{\circ}\text{C}$ of resolution. This forces the LSB size in a linear digitizing system to be $1/2$ of 0.015V . This would require a 9.57-bit system to achieve 10°C accuracy from the system over a temperature span of -25°C to 135°C (delta of 160°C).

Temp (°C)	R Value (Ω)	Temp (°C)	R Value (Ω)	Temp (°C)	R Value (Ω)
-80	7296874	0	32650.8	75	1480.12
-75	4713762	5	253985.5	80	1256.17
-70	3095611	10	19903.5	85	1070.58
-65	2064919	15	15714.0	90	916.11
-60	1397935	20	12493.7	95	786.99
-55	959789	25	10000	100	678.63
-50	667828	30	8056.0	105	587.31
-45	470609	35	6530.1	110	510.06
-40	335671	40	5324.9	115	44.48
-35	242195	45	4366.9	120	388.59
-30	176683	50	3601.0	125	340.82
-25	130243	55	2985.1	130	299.82
-20	96974	60	2487.1	135	264.54
-15	72895	65	2082.3	140	234.08
-10	55298	70	1751.6	145	207.70
-5	42314.6			150	184.79

TABLE 2: Resistive changes with temperature of a BetaTHERM, $10\text{k}\Omega$ @ 25°C (10K3A1) NTC Thermistor in its "zero power" mode.

LINEARIZATION SOLUTIONS

It is obvious in this example that the conversion process is inefficient if a linear response is required. It is also obvious that the digital output word will require a look-up table to linearize the response. Additionally, temperature accuracy is usually required for most systems. These problems can be solved to a small degree by using a high resolution Analog-To-Digital (A/D) Converting device. In this scenario, bits will still be thrown away, but the LSB size is smaller. An alternative is to implement linearization with the analog hardware.

A simple approach to a first level linearization of the thermistor output is to use one of the three circuits shown in Figure 5. In Figure 5a. the thermistor is placed in series with a standard resistor (1%, metal film) and a voltage source. The temperature response and linearity of the system shown in Figure 5a. is shown in Figure 6. In this figure, the series thermistor system responds to temperature in a linear manner over a limited temperature range. The linearization resistor's value (R_{SER}) should be equal to magnitude of the thermistor at the mid-point of the temperature range of interest. This creates a response where the output

slope of the resistive network is at its steepest at this mid-point temperature. If high precision is required, this range is typically $\pm 25^{\circ}\text{C}$ around the nominal temperature of the thermistor at the R_{SER} value.

In Figure 5b., the thermistor is placed in parallel with a standard resistor (R_{PAR}), which creates a composite resistor element. This type of resistive configuration is typically used in system feedback loops and used for automatic gain control circuits.

The resistance to temperature response along with the linearization error of this circuit configuration is shown in Figure 7. Once again, the optimum linearity response of this resistive network is obtained at the point where the thermistor resistance and R_{PAR} are equal.

A third linearization approach is shown in Figure 5c. This circuit combines the parallel configuration in Figure 5b. with an additional reference resistor and a capacitor. The switchable reference is used to charge and discharge the parallel NTC resistance and the reference resistor against the integrating capacitor, C_{INT} . With this circuit, the NTC resistance is biased to a voltage reference and the integrating capacitor charges.

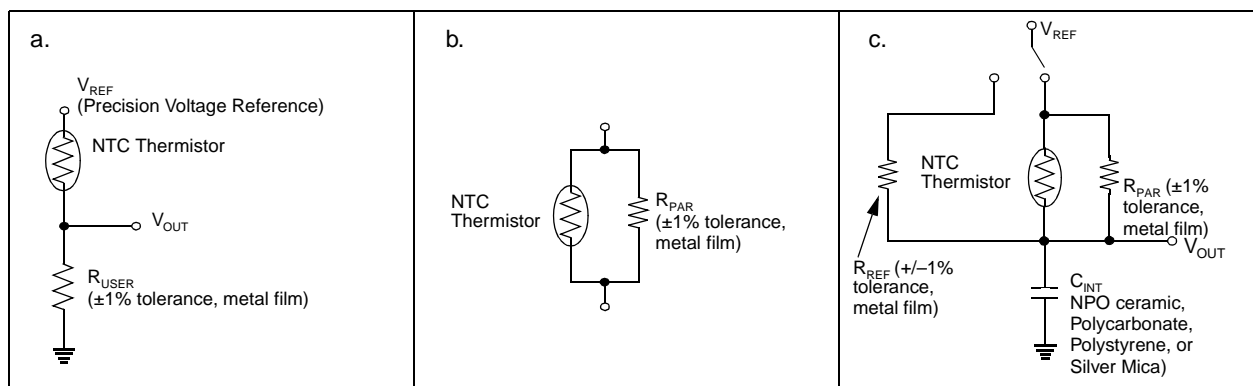


FIGURE 5: The series configuration (a) requires a voltage excitation. The parallel configuration (b) can be used in the feedback loop of an amplifier and does not require a precision source. The parallel configuration can be combined with a capacitor (c) which provides a linear circuit response with time.

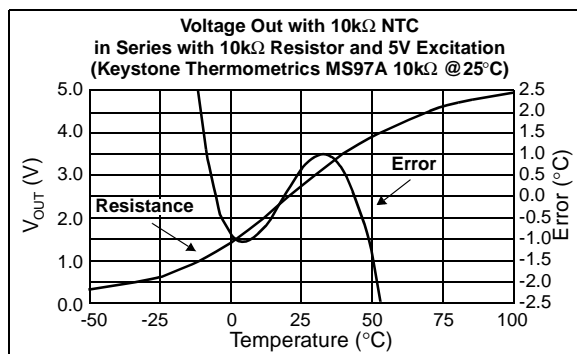


FIGURE 6: The series configuration response of the circuit shown in Figure 5a. has good linear response in a $\pm 25^{\circ}\text{C}$ range surrounding the temperature where both resistors (NTC and R_{SER}) are equal. The error in this range is typically within $\pm 1\%$. $V_{REF} = 5\text{V}$.

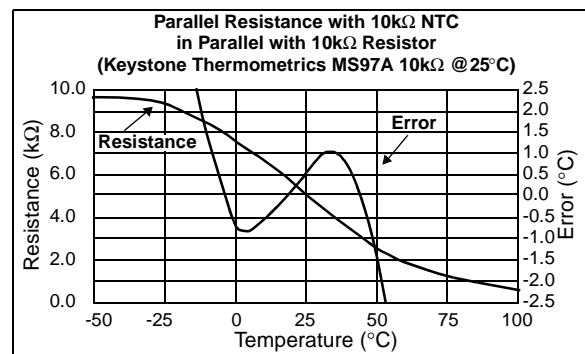


FIGURE 7: The parallel configuration response of the circuit shown in Figure 5c. allows for a counter to be used to determine the relative resistance of the NTC element.

Once the voltage at the top of the integrating capacitor reaches a threshold value V_{TH} (Figure 8), the integration time is recorded and the switching voltage reference is set to zero which discharges the integrating capacitor.

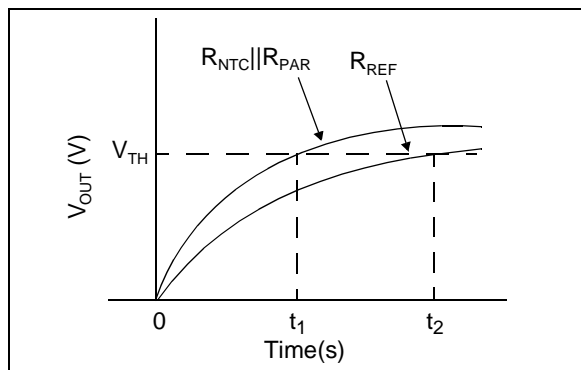


FIGURE 8: The RC time response of the circuit shown in Figure 5c. allows for the microcontroller counter to be used to determine the relative resistance of the NTC element.

Once the integrating capacitor is discharged, the reference voltage is applied to the reference resistor R_{REF} . This circuit is allowed to integrate until V_{OUT} reaches V_{TH} and the time of that integration period is recorded.

The integration time of this circuit can be calculated using:

$$V_{OUT} = V_{REF} (1 - e^{-t/RC}) \text{ or}$$

$$t = RC \ln (1 - V_{TH}/V_{REF})$$

If the ratio of $V_{TH} \cdot V_{REF}$ is kept constant, the unknown resistance of the $R_{NTC} \parallel R_{PAR}$ can be determined with:

$$R_{NTC} \parallel R_{PAR} = (t_2/t_1) \times R_{REF}$$

In this configuration, the resistance calculation of the parallel combination of $R_{NTC} \parallel R_{PAR}$ is independent of C_{INT} .

The implementation of this linearization circuit will be discussed with further detail in the "Thermistor Signal Conditioning Circuits" of this application note.

The circuits in Figure 5, along with the other configurations shown in Figure 9 linearize the thermistor to various ways. Figure 9a. uses the combination of the parallel and serial configurations shown in Figure 5 to extend the linear temperature response beyond 50°C. Figure 9b. demonstrates a way that the initial DC voltage of a thermistor linearization circuit can be removed by employing a bridge configuration. The circuit in Figure 9c. uses a switching network to adjust the linearization range of the of the NTC Thermistor. Additionally, there is a resistor divider added that implements a bridge configuration in order to reduce DC errors. The response of all of these networks can easily be modeled in an excel spreadsheet or mathcad which can be used to generate the appropriate look-up tables.

The next section of this application note will use the networks in Figure 5 to implement complete application circuits.

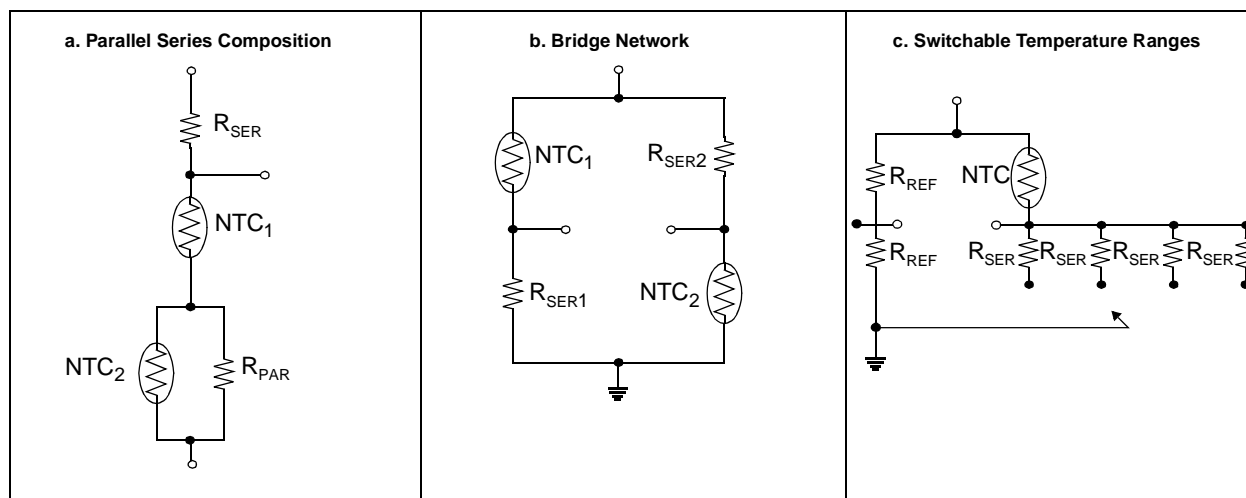


FIGURE 9: Other Thermistor Linearization Circuits.

THERMISTOR SIGNAL CONDITIONING CIRCUITS

There is a large variety of application circuits where the thermistor can be utilized. The three circuits in this application note use the thermistor to implement the cold junction compensation portion of a thermocouple circuit, a linear variable gain versus temperature circuit and an integrated scheme which achieves high accuracy.

Thermocouple Cold Junction Compensation

Although thermocouples can sense temperatures accurately at extreme temperatures or in ambient hostile conditions, a reference temperature is required, if an absolute temperature measurement is desired. (See Microchip's AN684, "Single Supply Temperature Sensing with Thermocouples" for details concerning thermocouple circuit requirements.)

The circuit in Figure 10 is designed to sense the temperature at the isothermal block location with a thermistor. The linearized temperature response of the thermistor is divided down to appropriate levels in order to minimize the EMF voltage errors introduced to the circuit by the parasitic thermocouples on the isothermal block. This style of compensation is done in hardware, requiring no supportive firmware compensation schemes.

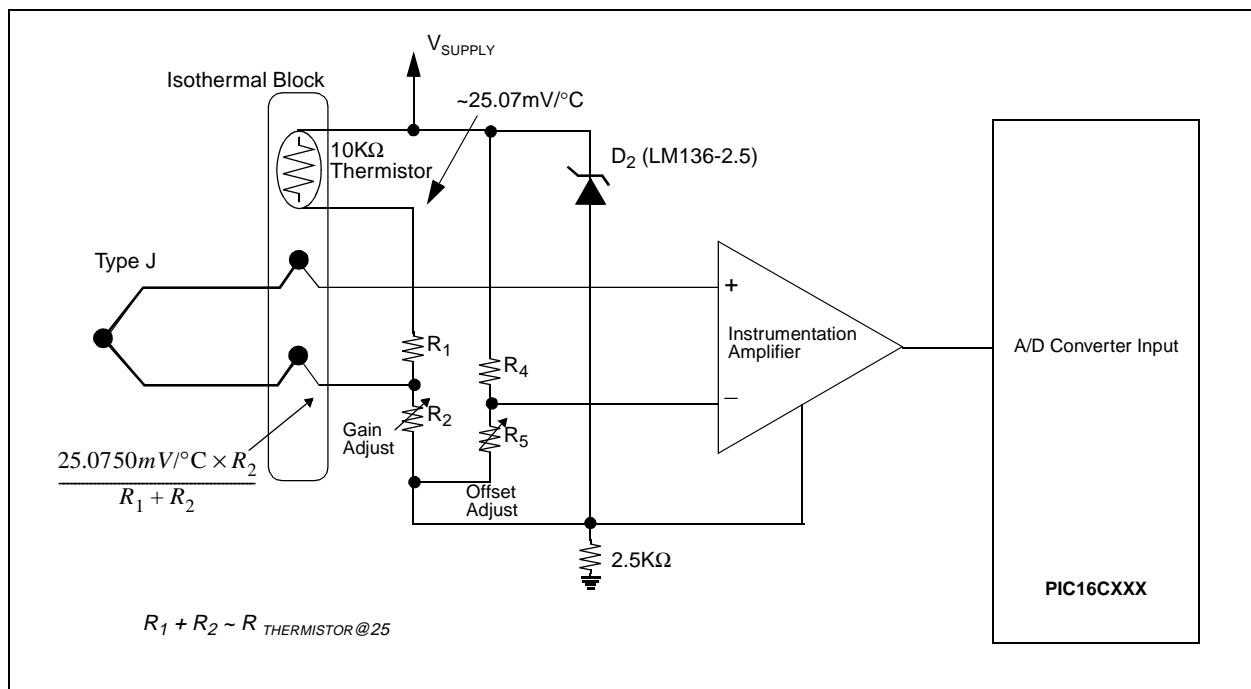


FIGURE 10: A thermistor is used to sense the temperature of the isothermal block in a thermocouple temperature sensing application.

The drift with temperature of the parasitic thermocouples on the isothermal block is approximately $-51 \mu\text{V}/^\circ\text{C}$. The thermistor circuit changes by $25.07 \text{ mV}/^\circ\text{C}$ over the 0 to 50°C linear range given the resistor configuration and the 2.5V excitation voltage. The thermistor drift is divided down using the resistor divider formed with R_1 and R_2 . Appropriate resistor values for R_1 and R_2 with a Type J thermocouple is 100Ω and $49.9 \text{ k}\Omega$, inclusive. The R_4 and R_5 resistor divider is used to zero offsets in the system as well as implement any required level shifts.

An instrumentation amplifier is used to differentiate the offset error correction circuitry and the Type J thermocouple EMF voltage. (For more details about instru-

mentation amplifiers, see Microchip's AN682, "Using Operational Amplifiers for Analog Gain in Embedded System Design".)

With the thermistor linearization circuitry in place, the voltage changes at the input to the instrumentation amplifier in accordance with temperature changes at the Type J thermocouple measurement site.

The instrumentation amplifier is configured in the appropriate gain for the expected temperature excursions of the Type J thermocouple. The output of the gained analog signal is digitized and used by the microcontroller. With this circuit implementation, the microcontroller is only required to linearize the thermocouple output response.

Temperature Dependent Reference

A temperature dependent reference voltage can be constructed using thermistor/resistive parallel combination illustrated in Figure 5b. as the feedback element in an operational amplifier circuit. The implementation of this type of circuit configuration is shown in Figure 11. In this circuit, a precision reference is used to drive the inverting input of an operational amplifier. The gain of the amplifier portion of the circuit is:

$$V_{OUT:AMP} = V_{IN:AMP} (1 + (R_{NTC} // R_{PAR}) / R_1)$$

where:

$V_{OUT:AMP}$ is the voltage at the output of the operational amplifier

$V_{IN:AMP}$ is the voltage presented to the non-inverting input of the amplifier

A 2.5V precision voltage reference is used to generate the 0.276 voltage at the input to the operational amplifier. When the temperature of the NTC thermistor is equal to 0°C, the resistance of the thermistor is approximately 32,650.8Ω. The value of the parallel combination of this resistor and the 10kΩ metal film resistor (R_{PAR}) is equal to 7655.38Ω. This gives an operational amplifier gain of 14.94 V/V or an output voltage ($V_{OUT:AMP}$) of 4.093V.

When the temperature of the NTC thermistor is 50°C, the resistance of the thermistor is approximately 3601Ω. Following the same calculations above, the operational amplifier gain becomes 5.8226V/V, giving a 1.595V at the output of the amplifier.

The voltage at the output of the amplifier is used as the voltage reference of a 12-bit A/D Converter. Over the reference range of 4.093V to 1.595V the converter provides 11.75-bit accurate conversions. The converter digitizes the input signal in accordance with the transfer function:

$$DIGITAL\ OUT = \left(\frac{V_{IN:ADS}}{V_{OUT:AMP}} \right) (2^{12} - 1)$$

(to the nearest integer value)

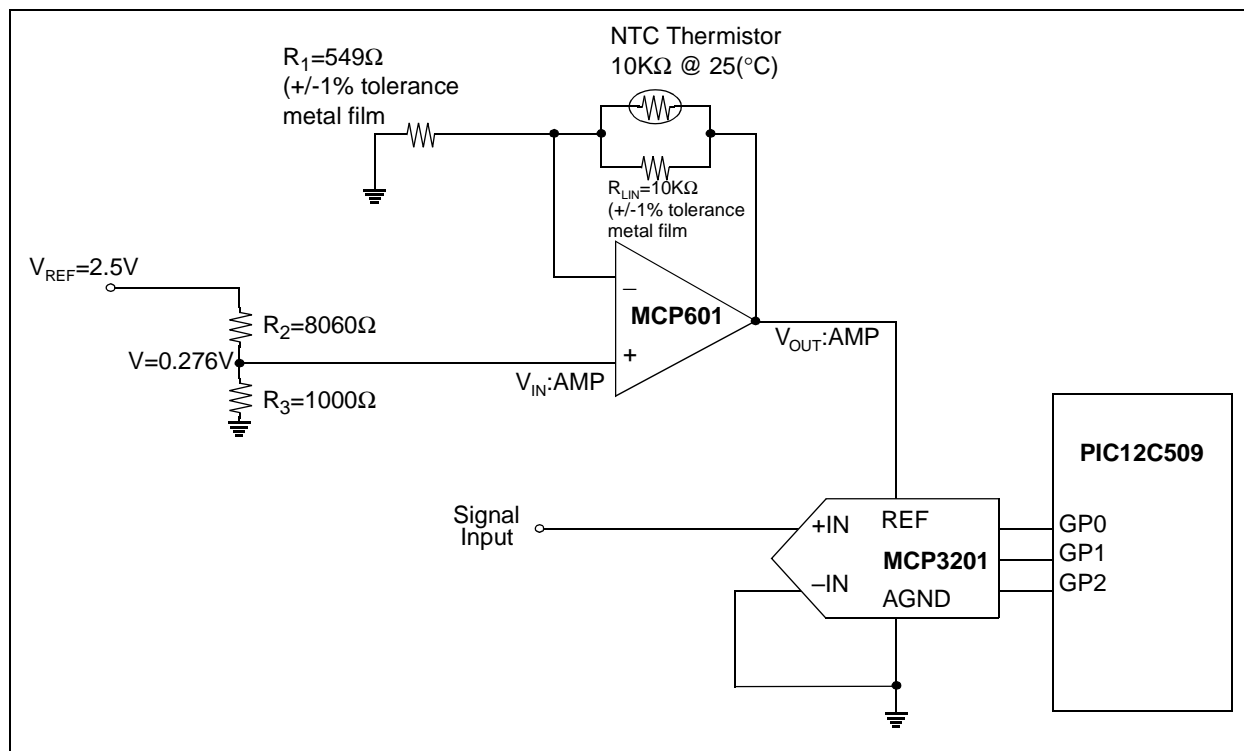


FIGURE 11: A thermistor is used to change the gain of an amplifier circuit with respect to temperature.

Temperature Sensing Using an Integrator

The linearization circuit in Figure 5c. is simply implemented with one microcontroller in the signal path as shown in Figure 12.

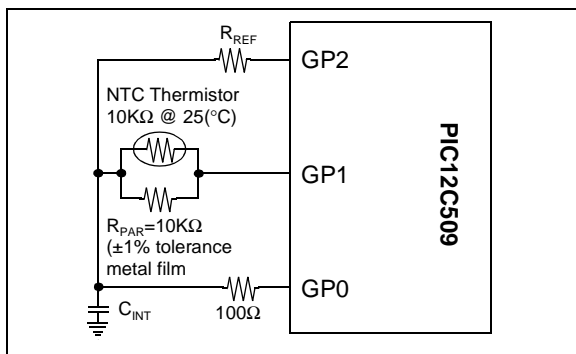


FIGURE 12: This circuit switches the voltage reference on and off at GP1 and GP2. In this manner, the time constant of the NTC Thermistor ($R_{NTC} \parallel R_{PAR}$) and integrating capacitor (C_{INT}) is compared to the time constant of the reference resistor (R_{REF}) and integrating capacitor.

This sensing circuit is implemented by setting GP1 and GP2 of the PIC12C509 as inputs. Additionally, GP0 is set low to discharge the capacitor, C_{INT} . Once C_{INT} is discharged, the configuration of GP0 is changed to an input and GP1 is set to a high output. A timer counts the amount of time before GP0 changes to 1, giving the time, t_1 per Figure 8.

At this point, GP1 and GP2 are again set as inputs and GP0 as an output low. Once the integrating capacitor C_{INT} has time to discharge, GP2 is set to a high output and GP0 as an input. A timer counts the amount of time before GP0 changes to 1, giving the time, t_2 , per Figure 8.

For more details concerning the implementation of this type of integrating circuit, refer to Microchip's AN512, "Implementing Ohmmeter/Temperature Sensor", and AN611, "Resistance and Capacitance Meter Using a PIC16C622".

CONCLUSION

Although the thermistor is non-linear, it can be tamed for a limited temperature range. This allows the design of an inexpensive temperature sensing device which can be used in a variety of Analog-to-Digital Converter applications.

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AN685

NOTES:

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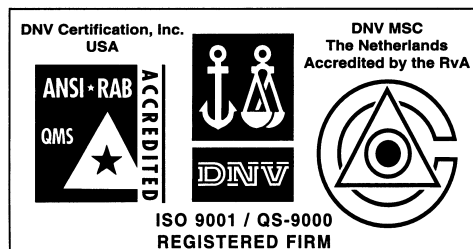
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