Vol 55, No 3—September 2021

A Precision Temperature Measurement Solution with High EMC Performance Using an RTD

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Introduction

Have you wondered how to design a precision temperature measurement system with high electromagnetic compatibility (EMC) performance? This article will discuss design considerations for a precision temperature measurement system and how to improve the system's EMC performance while maintaining measurement accuracy. We will present the test results and data analysis that allow us to easily move from concept to prototype and from concept to market using an RTD temperature measurement as an example.

Precision Temperature Measurement and EMC Challenges

Temperature measurement is one of the most commonly used sensing technologies known in the analog world. Many measurement technologies are available to sense ambient temperature. A thermistor is a small, simple 2-wire implementation with a fast response time, but its nonlinearity and limited temperature range limit its precision and application. An RTD is the most stable and most accurate temperature measurement method. The difficulty of RTD design is that it requires an external stimulus, complex circuits, and calibration work. Engineers without experience in developing temperature measurement systems may be discouraged. A thermocouple (TC) can provide a rugged, inexpensive solution with varying ranges, but cold junction compensation (CJC) is necessary for a complete system. Compared to the thermistor, TC, and RTD, a newly developed digital temperature sensor can provide calibrated temperature data directly through a digital interface. Precision temperature measurement requires high accuracy temperature sensors and a precision signal chain to form a temperature measurement system. TC, RTD, and digital temperature sensors have the highest accuracy. Precision signal chain devices are available and can be used to collect these sensor signals and convert them into absolute temperature. In the industrial sector, reaching 0.1°C accuracy is our target. This accuracy measurement does not include sensor errors. Table 1 shows a comparison of different temperature sensor types.

Table 1. A Comparison of Different Temperature Sensor Types

Temperature Sensor Type	Pros	Cons
Thermistor	Simple 2-wire implementation, fast response time, small size	Nonlinear, limited temperature range, not as rugged as TCs and RTDs, requires stimulus, inaccuracies occur due to self-heating
RTD	Most stable, most accurate, rugged, easy to connect and implement	Requires external stimulus, nonlinear, inaccuracies occur due to self-heating
Thermocouple	Rugged, self-powered, inexpensive, supports varying ranges (J, K, T, E, R, S, B, N), good for distance	Nonlinear, requires cold junction compensation (CJC), low output ranges requiring low noise/low drift electronics, accuracy 1% to 3%
IC Temperature Sensor	Fully calibrated, linear, stable, analog and digital output	Limited temperature range

When creating a digital temperature measurement system, especially for applications in harsh environments such as industrial and railway, not only is accuracy and design difficulty of concern, but EMC performance is a key feature to keep the system stable. The system needs additional circuitry and discrete components to increase EMC performance. However, more protection components mean more error sources. Therefore, it is very challenging to design a temperature measurement system with high sensing accuracy and high EMC performance. The EMC performance of a temperature measurement system determines if it can work normally in the specified electromagnetic environment.

ADI offers a variety of temperature measurement solutions, such as precision analog-to-digital converters (ADCs), analog front ends (AFEs), IC temperature sensors, and more. ADI AFE solutions provide a multisensor high accuracy digital temperature measurement system for direct TC measurement, direct RTD measurement, direct thermistor measurement, and support for custom sensor applications. Some special configurations can help maintain high measurement accuracy while adding EMC protection components. Figure 1 shows the classic ratiometric temperature measurement circuit and equation.

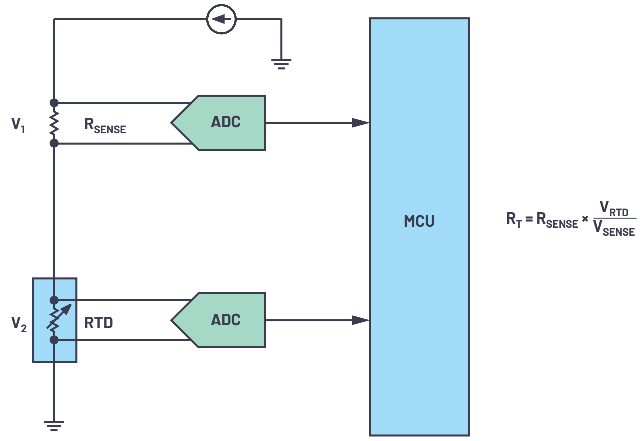

Figure 1. Classic ratiometric temperature measurement circuit and equation.

The following sections describe temperature sensing solutions for system designers to achieve the best EMC performance.

RTD Temperature Measurement Solutions

Take the LTC2983 temperature measurement AFE as an example. The system controller can read the calibrated temperature data from the LTC2983 directly via the SPI interface with an accuracy of 0.1°C and a resolution of 0.001°C. When a 4-wire RTD is connected, the excitation current rotation function can automatically eliminate the parasitic effect of the thermocouple and reduce the effect of the signal circuit leakage current. Based on these features, the LTC2983 can accelerate the design of multichannel precision temperature measurement systems and achieve high EMC performance without complex circuit design, giving you and your customers more confidence. Figure 2 shows the EMC-protected LTC2983 temperature measurement system block diagram.

An RTD is undoubtedly the best choice for high accuracy temperature measurement and can measure temperature in the range of –200°C to +800°C. 100 Ω and 1000 Ω platinum RTDs are the most common, but they can also be made of nickel or copper.

The simplest RTD temperature measurement system is a 2-wire configuration, but the lead resistance introduces additional system temperature errors. A 3-wire configuration can eliminate the lead resistance errors by applying two matched current sources to the RTD, but the lead resistance should be equal. A Kelvin configuration or 4-wire configuration can remove the balanced or unbalanced lead resistance by measuring directly across the sensor using high impedance Kelvin sensing. However, the cost will be the main constraint for the 4-wire configuration as it needs more cables, especially for remote temperature measurement. Figure 3 shows the different RTD wire configurations.[1] Considering real customer use cases, this article chooses a 3-wire RTD configuration and tests its EMC performance.

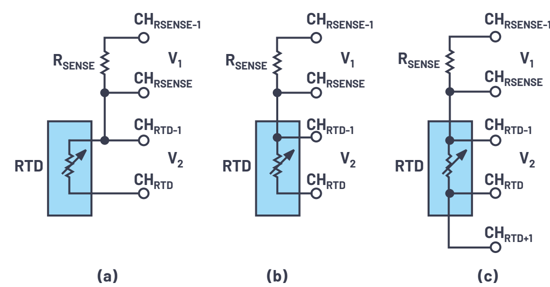

Figure 3. Different RTD wire configurations: (a) 2-wire, (b) 3-wire, and (c) 4-wire.

The 2-wire and 3-wire RTD sensors can also use a Kelvin configuration on a PCB. When we need to add current limiting resistors and an RC filter to the signal link to protect the device's analog input pins, these additional resistances will introduce a large system offset. For example, replacing a 2-wire protection circuit with a 4-wire Kelvin configuration can help remove this offset, because the excitation current does not flow through these limiting resistors and RC filter, and the error caused by the protection resistance is negligible (see Figure 4). See the LTC2986 data sheet for more details.

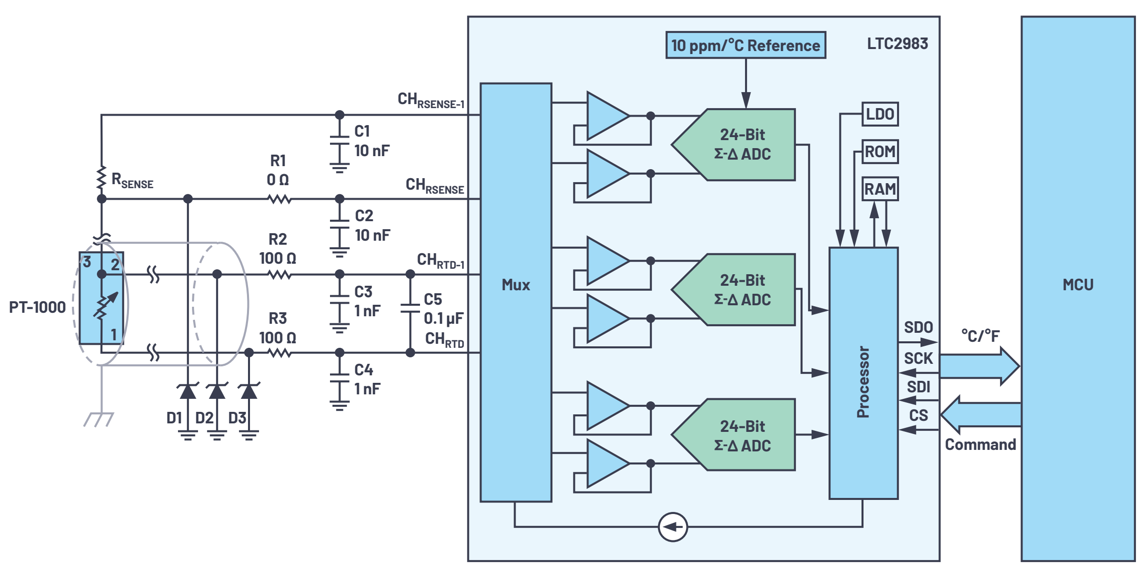

Figure 2. EMC-protected LTC2983 temperature measurement system.

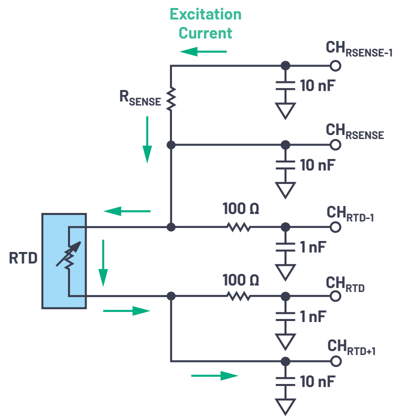

Figure 4. A 4-wire configuration removes additional resistor errors.

What Are the Robustness Challenges for Temperature Measurement Systems?

Like most temperature measurement ICs, the LTC2983 can tolerate over the 2 kV HBM ESD level. But in industrial automation, railway, and other harsh electromagnetic environments, electronic devices need to face higher interference levels and more complicated EMC events, such as electrostatic discharge (ESD), electrical fast transients (EFT), radiated susceptibility (RS), conducted susceptibility (CS), and surges.

Additional discrete protection components are necessary to reduce the risk of damage to the downstream devices and improve the system's robustness.

The three elements of EMC events are the noise source, the coupling path, and the receiver. As shown in Figure 5, in this temperature measurement system, the noise source comes from the ambient environment. The coupling path is a sensor cable and the LTC2983 is the receiver. Industrial automation and railway applications always use long sensor cables to sense the temperature of remote devices. The length of the sensor cable may be several meters or even tens of meters. Longer cables will result in larger coupling paths, and the temperature measurement system will face more severe EMI challenges.

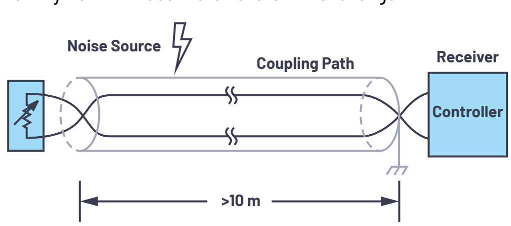

Figure 5. The three elements of a temperature measurement system's EMI events.

System-Level Protection Solution with a TVS

Transient voltage suppressors (TVSs) and current limiting resistors are the most common protection components. Choosing the appropriate TVS and current limiting resistor can not only improve the system robustness but also maintains the high measurement performance of the system. Table 2 shows the key parameters of the TVS device, including the working peak reverse voltage, the breakdown voltage, the maximum clamping voltage, and the maximum reverse leakage. The working peak reverse voltage must be above the maximum sensor signal to ensure proper operation of the system. The breakdown voltage should not be much greater than the signal voltage to avoid creating wide, unprotected voltage ranges. The maximum clamping voltage determines the maximum interference signal voltage that the TVS can suppress. The reverse leakage will contribute a lot to the measurement error of the system, so the TVS with the smallest possible reverse leakage should be selected.

Table 2. TVS Key Parameters

Parameters	Description
Working peak reverse voltage	The voltage below which no significant conduction occurs
Breakdown voltage	The voltage where the specified conduction is triggered
Maximum clamping voltage	The maximum voltage across the device when conducting the specified maximum current
Maximum reverse leakage	The leakage current when the maximum voltage is applied to the TVS before triggering conduction

Under normal operating conditions, the TVS device appears to have a high impedance to ground. When a transient voltage greater than the TVS breakdown voltage is applied to the input of the system, the voltage at the input is clamped as soon as the TVS breaks down and provides a low impedance path to ground, diverting the transient current from the input to ground.

As Figure 2 shows, this is a 3-wire PT-1000 protected circuit. A 3-wire PT-1000 is connected to the LTC2983 by three adjacent channels, which are protected by an SMAJ5.0A TVS and a 100 Ω current limiting resistor. The current limiting resistor and the downstream capacitor form a low-pass filter to remove as many RF components from the input lines as possible, to keep the AC signal balance between each line and ground, and to maintain a high enough input impedance over the measurement bandwidth to avoid loading the signal source.[2] The differential-mode filter –3 dB bandwidth is 7.9 kHz, and the common-mode filter –3 dB bandwidth is 1.6 MHz.

This temperature measurement system was tested to IEC 61000-4-2, IEC 61000-4-3, IEC 61000-4-4, IEC 61000-4-5, and IEC 61000-4-6 standards. Under these tests the system must work normally and provide precise temperature measurement. The sensor under test is a Class B 3-wire PT-1000, which uses a shielded wire of about 10 m length.

Table 3 lists the IEC 61000-4-x immunity test items, the test levels, and the temperature fluctuations when the system is disturbed by EMI events. Figure 6 displays the output temperature data curve when testing, which corresponds to the max temperature fluctuation in Table 3.

Table 3. EMI Test Results

IEC 61000-4 Transient	Protection Level	Max Temperature Fluctuation (°C)
RS	10 V/m, 80 MHz to ~1 GHz, and 1.4 GHz to ~2 GHz	<0.5
CS	10 V, 0.15 MHz to ~80 MHz	<0.2
ESD	±8 kV, conducted; ±15 kV, air	<0.15
EFT	±4 kV, 5 kHz	<0.15
Surge	±4 kV, 1.2/50 (8/20) µs	<0.2

Temperature Measurement Accuracy After Being Protected

The TVS and the current limiting resistor help protect the temperature measurement system from EMC. The TVS with the lowest possible clamp voltage can better protect the sensitive circuits. But they can in turn produce errors to the system. To counter this, we have to use a TVS with a higher breakdown voltage because the higher breakdown voltage means there is less leakage current at the normal operating voltage. The lower current leakage of a TVS results in fewer errors added to the system.

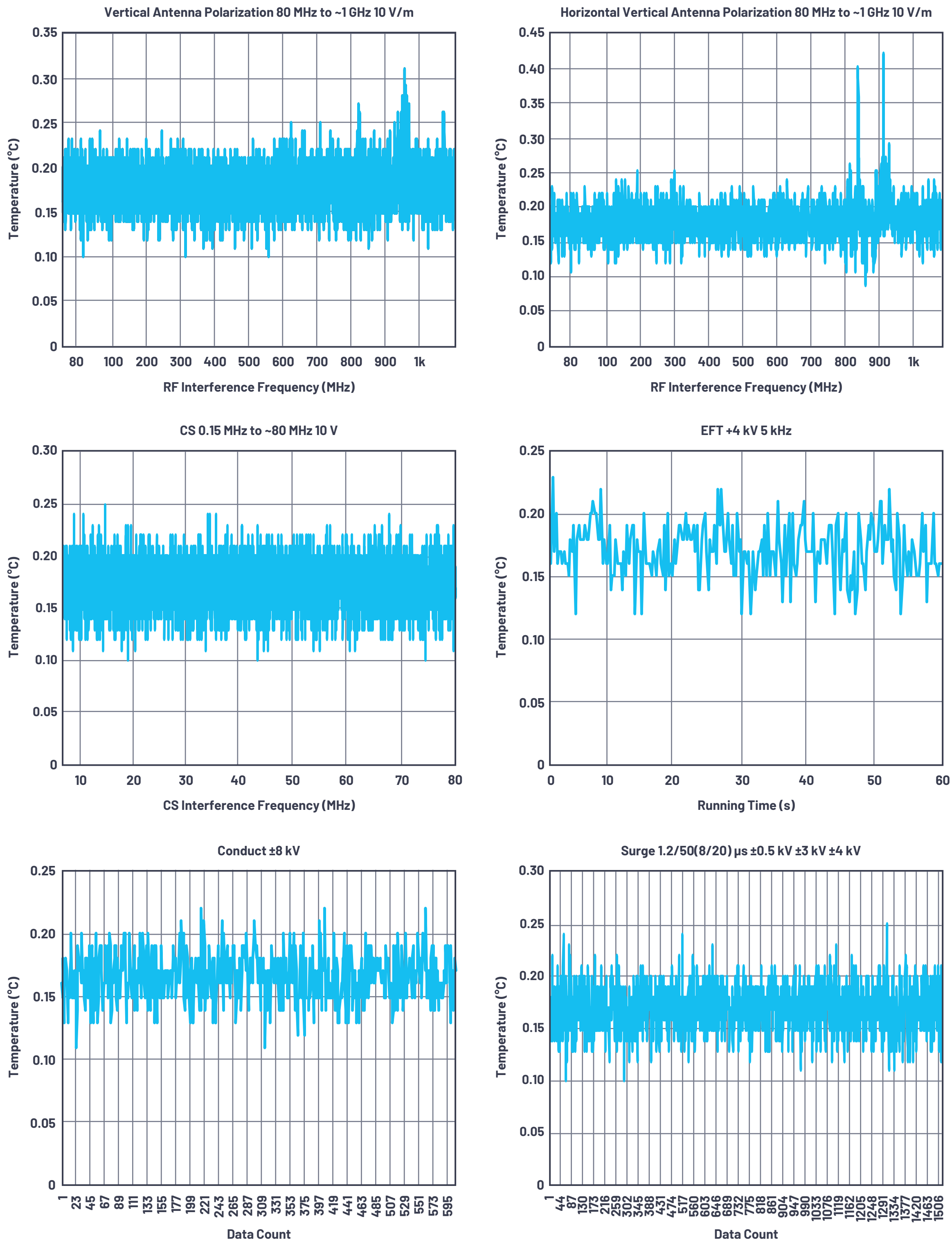

Figure 6. Output temperature data curve when testing.

Table 4. Electrical Characteristics of the Littelfuse SMAJ5.0A TVS

Electrical Characteristics (T_A = 25°C Unless Otherwise Noted)

Part Number (Uni)	Part Number (Bi)	Marking		Reverse Stand-Off Voltage V_R (V)	Breakdown Voltage V_{BR} @ I_T (V)		Test Current I_T (mA)	Maximum Clamping Voltage V_C @ I_{pp} (V)	Maximum Peak Pulse Current I_{pp} (A)	Maximum Reverse Leakage I_R @ V_R (µA)	Agency Approval
		Uni	Bi		Min	Max					
SMAJ5.0A	SMAJ5.0CA	AE	WE	5.0	6.40	7.00	10	9.2	43.5	800	X

Taking these considerations into account, we used a Littelfuse SMAJ5.0A TVS, which can be bought at most electronic component distributors, and a 100 Ω current limiting resistor with ±0.1% accuracy to protect the system and avoid inserting any remarkable measurement errors.

To achieve high measurement accuracy, we use a precision resistance matrix to replace the PT-1000 sensor and simulate changes in temperature. This precision resistance matrix has been calibrated with a Keysight Technologies 3458A multimeter.

To ease the difficulty of removing matched lead resistance errors, we use a 4-wire configuration to evaluate the system's accuracy performance. This is more conducive to eliminating sensor errors.

To calculate the system error more accurately, we need to convert the resistance values to temperature using the same standard as the LTC2983. The temperature lookup table published by the sensor manufacturer is the most accurate conversion method. However, it would be unwise to write every temperature point into the processor's memory. Therefore, we use the following formula to compute the temperature results.[3]

When T > 0°C, the equation is:

$$R_{RTD}(T) = R_0\,(1 + A \times T + B \times T^2) \tag{1}$$

Calculate the temperature corresponding to the resistance value:

$$T = \frac{-A + \sqrt{A^2 - 4B\left(1 - \dfrac{R_{RTD}(T)}{R_0}\right)}}{2B} \tag{2}$$

When T ≤ 0°C, the equation is:

$$R_{RTD}(T) = R_0\,(1 + A \times T + B \times T^2 + C \times (T - 1000°C) \times T^3) \tag{3}$$

The temperature is obtained by polynomial fitting:

$$T = -242 + 0.2222 \times R_{RTD} + 2.61^{-5} \times R_{RTD}^2 - 5.257^{-9} \times R_{RTD}^3 - 2.457^{-12} \times R_{RTD}^4 + 1.409^{-15} \times R_{RTD}^5 \tag{4}$$

where:

T is the RTD temperature, °C.
$R_{RTD}(T)$ is the RTD resistance, Ω.
R_0 is the RTD resistance at 0°C, R_0 = 1000 Ω.
$A = 3.9083 \times 10^{-3}$
$B = -5.775 \times 10^{-7}$
$C = -4.183 \times 10^{-12}$

Figure 7 shows that the total system error does not exceed ±0.4°C over the temperature range of –134°C to +607°C. Compared to Figure 9, which shows the error contribution of the LTC2983 to the RTD temperature measurement, the additional protection component adds approximately ±0.3°C to the system error, especially the TVS leakage current. We can see that as the temperature rises, the system error increases. This is where the TVS's I-V curve characteristics come in.

System error can be calculated by:

$$T_{error} = T_{cal} - T_{LTC2983} \tag{5}$$

where:

T_{error} is the total LTC2983 temperature measurement system output error, °C.

T_{cal} is the computed temperatures by precision resistor, which has been calibrated with a Keysight Technologies 3458A, °C.

$T_{LTC2983}$ is the LTC2983 output temperature, °C.

Figure 8 tells us that the total system peak-to-peak noise does not exceed ±0.01°C. This result corresponds with the data sheet.

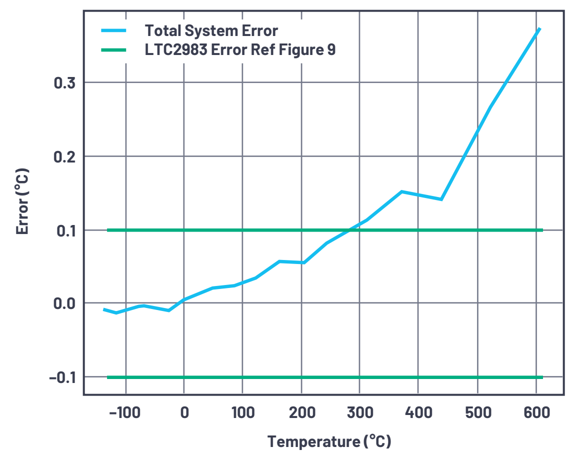

Figure 7. System error vs. temperature.

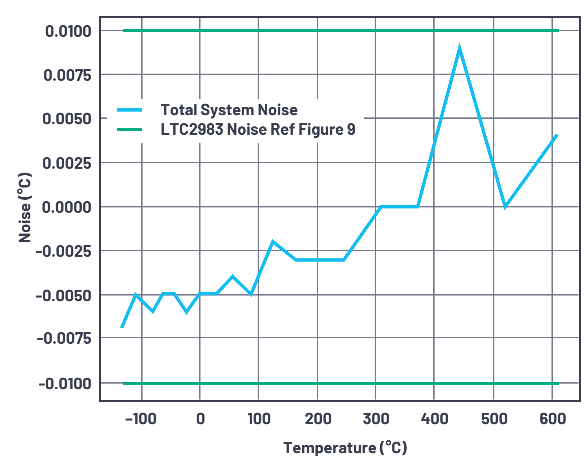

Figure 8. System peak-to-peak noise vs. temperature.

Table 1. LTC2983 Error Contribution and Peak Noise Errors

SENSOR TYPE	TEMPERATURE RANGE	ERROR CONTRIBUTION	PEAK-TO-PEAK NOISE
Platinum RTD - PT-10, R_{SENSE} = 1kΩ	–200 °C to 800 °C	±0.1 °C	±0.05 °C
Platinum RTD - PT-100, R_{SENSE} = 2kΩ	–200 °C to 800 °C	±0.1 °C	±0.05 °C
Platinum RTD - PT-500, R_{SENSE} = 2kΩ	–200 °C to 800 °C	±0.1 °C	±0.02 °C
Platinum RTD - PT-1000, R_{SENSE} = 2kΩ	–200 °C to 800 °C	±0.1 °C	±0.01 °C
Thermistor, R_{SENSE} = 10kΩ	–40 °C to 85 °C	±0.1 °C	±0.01 °C

Figure 9. LTC2983 error contribution to RTD temperature measurement.

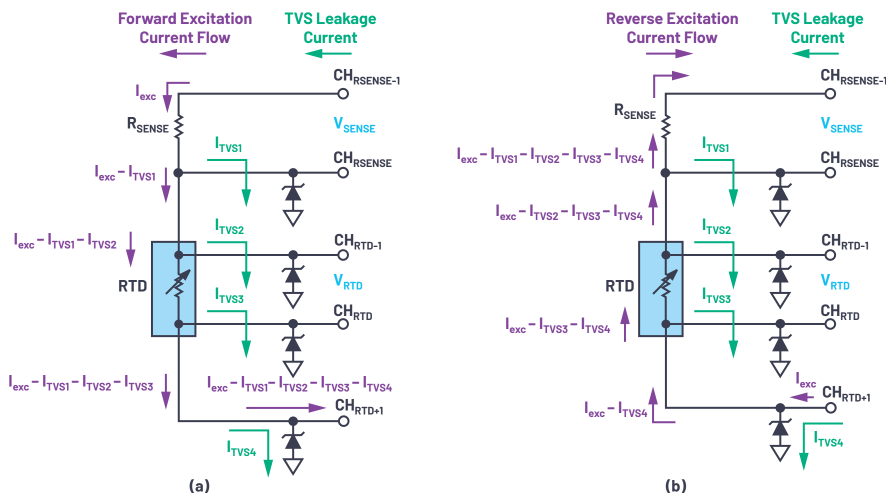

Figure 10. Excitation current rotation configurations: (a) the forward excitation flow and (b) the reverse excitation flow.

TVS Error Contribution and Optimized Configuration

You can find the I-V curve characteristics of a TVS from the device's data sheet. However, most TVS manufacturers only provide typical values for the device's parameters—not all the I-V data you may need to calculate the error contribution of the TVS at a particular voltage, especially the leakage current error.

A Littelfuse SMAJ5.0A TVS is used in this application. After testing some samples, we found the leakage current to be about 1 µA at 1 V reverse voltage, far less than the TVS data sheet maximum reverse leakage. This leakage current contributes significant error to the system. But if the excitation current rotation of the LTC2983 is enabled, the leakage error effect will be greatly reduced. Figure 10 shows the excitation current rotation configuration and TVS leakage current flow.

When the current flowing through R_{sense} is the same as the excitation current flowing through the RTD, the resistance of the RTD, R_T, can be expressed by[4]:

$$R_T = R_{sense} \times \frac{V_{RTD}}{V_{sense}} \tag{6}$$

When using the excitation current rotation configuration for forward excitation flow (shown in Figure 10(a)), the RTD resistance R_{RTD1} is calculated by:

$$V_{sense1} = R_{sense} \times I_{exc} \tag{7}$$

$$V_{RTD1} = R_{RTD} \times (I_{exc} - I_{TVS1} - I_{TVS2}) \tag{8}$$

$$R_{RTD1} = R_{sense} \times \frac{V_{RTD1}}{V_{sense1}} = R_{RTD} \times \frac{I_{exc} - I_{TVS1} - I_{TVS2}}{I_{exc}} \tag{9}$$

Where:

R_{sense} is the real resistance value of sense resistor

R_{RTD} is the real resistance value of RTD in measurement cycle

V_{sense1} is the measured voltage value at sense resistor

V_{RTD1} is the measured voltage value at RTD in forward excitation flow cycle, as Figure 10(a) shows.

R_{RTD1} is the calculated value of RTD in forward excitation flow cycle

When using the excitation current rotation configuration for reverse excitation flow (shown in Figure 10(b)), the RTD resistance R_{RTD2} is calculated by:

$$V_{sense2} = R_{sense} \times (I_{exc} - I_{TVS1} - I_{TVS2} - I_{TVS3} - I_{TVS4}) \tag{10}$$

$$V_{RTD2} = R_{RTD} \times (I_{exc} - I_{TVS3} - I_{TVS4}) \tag{11}$$

$$R_{RTD2} = R_{sense} \times \frac{V_{RTD2}}{V_{sense2}} = R_{RTD} \times \frac{I_{exc} - I_{TVS3} - I_{TVS4}}{I_{exc} - I_{TVS1} - I_{TVS2} - I_{TVS3} - I_{TVS4}} \tag{12}$$

Where:

V_{sense2} is the measured voltage value of sense resistor.

V_{RTD2} is the measured voltage value of the RTD in a reverse excitation flow cycle, as shown in Figure 10(b).

R_{RTD2} is the calculated value of the RTD in a reverse excitation flow cycle.

According to the TVS measured data, at 2 V reverse voltage, the difference between the maximum leakage current and minimum leakage current is about 10% on average. The position and matching degree of the four TVSs can cause systematic error to a significant extent. To show where the error is the largest, we can assume that I_{TVS} is the average leakage current and that $I_{TVS1} = I_{TVS2} = 0.9 \times I_{TVS}$, while $I_{TVS3} = I_{TVS4} = 1.1 \times I_{TVS}$.

$$R_{RTD1} = R_{RTD} \times \frac{I_{exc} - 1.8 \times I_{TVS}}{I_{exc}} \tag{13}$$

$$R_{RTD2} = R_{RTD} \times \frac{I_{exc} - 2.2 \times I_{TVS}}{I_{exc} - 4 \times I_{TVS}} \tag{14}$$

If you are not using the excitation current rotation configuration, R_{RTD1} or R_{RTD2} will include the maximum TVS error contribution. $\frac{I_{exc} - 1.8 \times I_{TVS}}{I_{exc}}$ or $\frac{I_{exc} - 2.2 \times I_{TVS}}{I_{exc} - 4 \times I_{TVS}}$ are the error factors.

When using the excitation current rotation configuration, the final calculated results are

$$R_{RTDROT} = \frac{R_{RTD1} + R_{RTD2}}{2} \tag{15}$$

$$Error(R_{RTDROT}) = R_{RTDROT} - R_{RTD} \tag{16}$$

$$Error(R_{RTD1}) = R_{RTD1} - R_{RTD} \tag{17}$$

$$Error(R_{RTD2}) = R_{RTD2} - R_{RTD} \tag{18}$$

When the Error(R_{RTDROT}) = min {Error(R_{RTD1}), Error(R_{RTD2})}, then Error (R_{RTDROT}) will be equal to Error (R_{RTD1}) or Error(R_{RTDROT}) will be equal to Error(R_{RTD2}). According to Equation 13 through Equation 18, when $I_{exc} = 6 \times I_{TVS}$, the Error ($R_{RTDROT}$) will be equal to min {Error(R_{RTD1}), Error(R_{RTD2})}. When $I_{exc} = 6 \times I_{TVS}$, the accuracy of the system will be reduced by 16.7% due to the TVS leakage current.

According to the configuration and test result, $I_{exc} > 6 \times I_{TVS}$, so

$$Error(R_{RTDROT}) < \min\{Error(R_{RTD1}), Error(R_{RTD2})\}$$

Usually, $I_{exc} > 100 \times I_{TVS}$. Figure 11 shows the system error, where:

R_{RTDROT} is the final RTD resistance calculated result with the excitation current rotation.

Error(R_{RTDROT}) is the TVS error contribution when using the excitation current rotation configuration, with units in °C.

Error(R_{RTD1}) and Error(R_{RTD2}) are the TVS error contribution when not using the rotation configuration, with units in °C.

The derivation above tells us that the excitation current rotation configuration can reduce the TVS leakage current error contribution. The following test results confirm our assertion.

Figure 11 shows the system errors in different excitation current modes and TVS configurations. As shown in the figure, the system accuracy is about the same for both rotating and nonrotating configurations when a TVS is not used. However, enabling excitation current rotation automatically eliminates the parasitic thermocouple effect, a more detailed description of which can be found in the LTC2983 data sheet. When using a TVS to protect the system, the total system error increases. But excitation current rotation configuration can significantly reduce the error impact of the TVS leakage current, thus helping to achieve a similar level of accuracy to non-TVS protected systems over most of the temperature measurement range. Compared to the system without a TVS, the additional error was contributed by the TVS device-to-device variation.

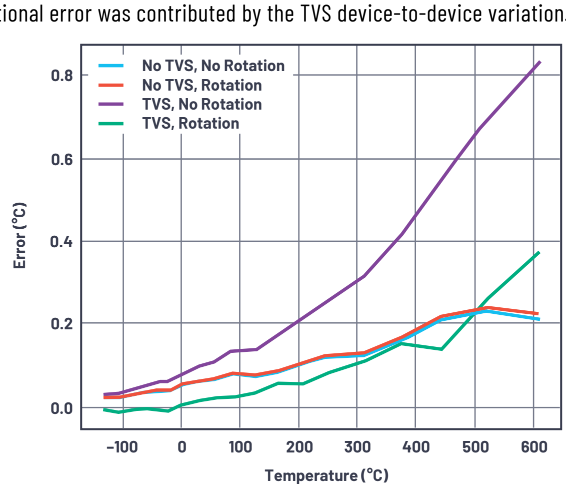

Figure 11. System error vs. different hardware and software configurations.

Conclusion

Temperature measurement system design is not often considered to be a difficult task. However, for most system designers, developing a highly accurate and robust temperature measurement system is a challenge. The LTC2983 intelligent digital temperature sensor can help you overcome this challenge and create a product that can be brought to market quickly.

- This protected LTC2983 temperature measurement system has ±0.4°C system accuracy. Measurement errors include the LTC2983 error, the TVS/current limiting resistor error, and the PCB error contributions.
- The LTC2983 rotation excitation current configuration can significantly reduce the protection components' leakage current error effect.
- The LTC2983 temperature measurement system provides high EMC performance despite the most common protection measures. See Table 3 for EMI test results.

This article presents the accuracy and EMC performance test results for some specific configurations. You can choose different TVS devices and current limiting resistors to obtain different measurement accuracy and EMC performance to meet your production requirements.

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