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IN THIS ISSUE

Robust Industrial Sensing with the Temperature-to-Bits Family

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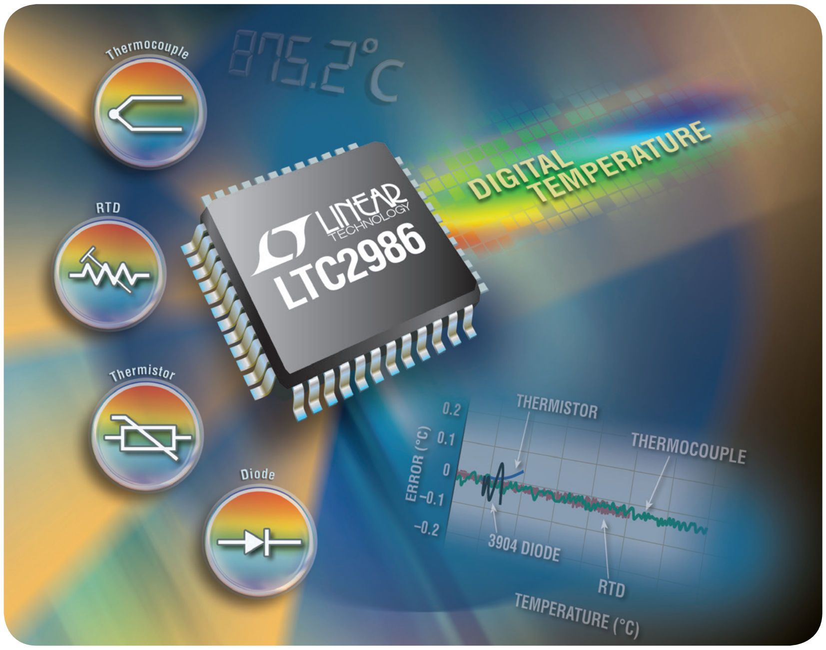
Precision temperature measurements provide important data points for industrial control systems to maximize efficiency, safety and reliability. Of course, industrial environments are challenging for performing precision measurements. High voltages, large sources of EMI and long cable runs between sensor and measurement device all conspire to deter accuracy. This article shows how to overcome these barriers, and improve the noise immunity and overvoltage tolerance of the LTC®2983, LTC2984 and LTC2986 temp-to-bits devices, without degrading measurement accuracy.



The temp-to-bits family simplifies industrial temperature measurement.

With up to 20 input channels, the temp-to-bits family is well suited for industrial temperature monitoring. Multiple sensors can be used to evaluate temperature gradients and identify anomalous behavior in time to prevent equipment failures.

Chassis wiring often exposes high voltages to sensors—the sensor wires provide a low impedance path back to the measurement circuit, which makes possible a short circuit; some cause for concern. This is especially true with bare-tip thermocouples, essentially a wire probe.

EMI in the industrial environment includes 50Hz or 60Hz line noise radiated from synchronous motors and other high current devices, as well as higher frequency noise from radio links, unshielded communications cables, and broadband noise from arcing.

(continued on page 4)

The LTC2983-6 temp-to-bits family provides numerous features that enable robust temperature measurement in industrial environments. Low input leakage permits large series resistance for overvoltage protection and RC filtering.

(LTC298x, continued from page 1)

PROTECTION

As discussed above, the industrial environment is full of hazards that must be mitigated for robust temperature measurements. Fortunately, the simple resistor can aid against the two biggest enemies: overvoltage and EMI.

The internal ESD structures in the LTC2983/4/6 family can sustain 15mA maximum, so we must ensure that an overvoltage condition from a thermocouple tip contacting the rail will not cause more than 15mA to flow into or out of the IC. A protection resistor (Figure 2) can be used to limit the current seen at the inputs in case of contact with the supply. For a 48V supply:

$$R_P = \frac{48V}{15mA}$$
$$R_P = 3.2k$$

Figure 3 shows the minimum protection resistance as a function of max fault voltage.

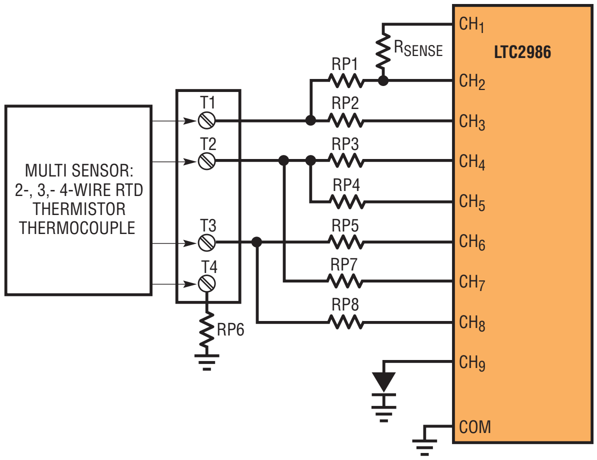


Figure 1. The LTC2986's Kelvin excitation modes support universal protected inputs for remote 2- and 3-wire sensors

The protection resistor must also be able to handle its power dissipation:

$$P_{R(P)} = 3.2k \cdot (15mA)^2$$
$$P_{R(P)} = 720mW$$

Figure 4 shows the minimum protection resistor power rating as a function of max fault voltage.

This power handling requirement can be reduced if we use a larger resistance at the cost of increased offset due to leakage currents. The LTC2983-6 inputs have less than 1nA leakage current. The minimum 3.2k protection resistors add a worst-case temperature offset of 0.16°C; 10k protection resistors could contribute up to 0.5°C error but would only need to dissipate 230mW, affording the designer a smaller protection circuit.

Figure 2. Thermocouple with 48V protection resistors

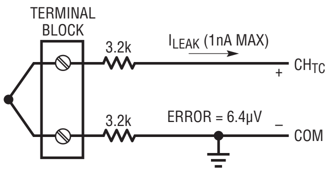


Figure 3. Maximum fault voltage vs minimum protection resistance

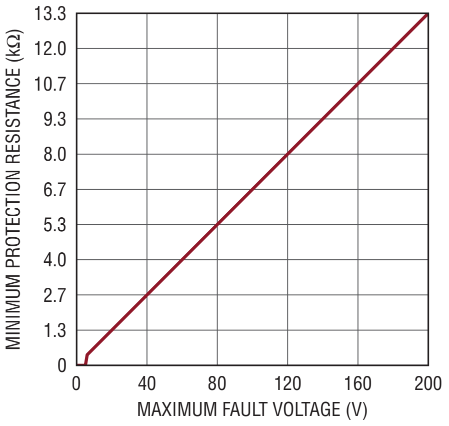
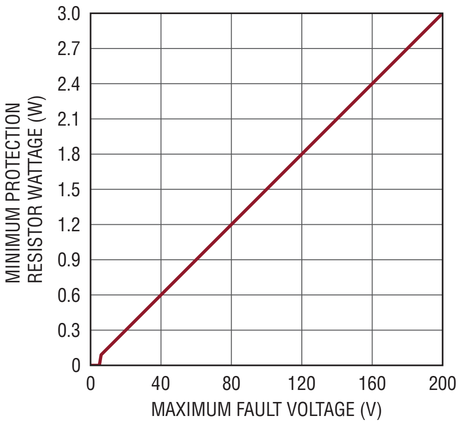


Figure 4. Maximum fault voltage vs minimum protection resistor power rating



> A major issue with remote sensors is knowing when they have failed. In many installations, the sensor has been placed remotely due to hazards encountered at the sensor location. In the case of remote thermocouples this is often a very high temperature and/or a corrosive atmosphere that can cause the thermocouple wiring to degrade over time. One solution to this problem is to apply a current through the thermocouple…

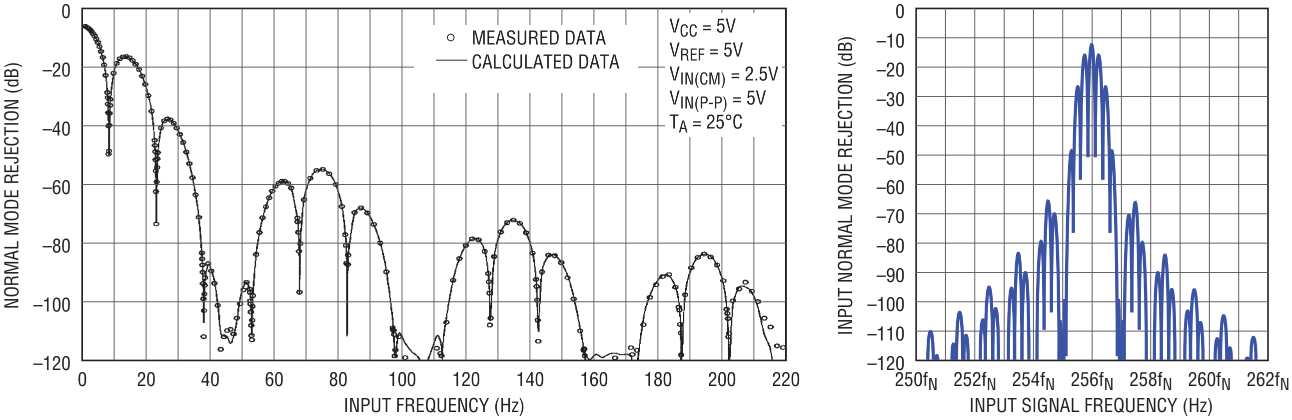


Figure 5. Input normal mode rejection at f_S = 15.36kHz

FILTERING

The LTC2983 family incorporates a sinc^4 filter that provides excellent simultaneous 50Hz/60Hz rejection and good wideband noise rejection at higher frequencies.

However, the ADC is a sampled system and there is a narrow passband at 256 times the notch frequency, as shown in Figure 5. This is where a simple RC lowpass or anti-aliasing filter on the inputs can improve the quality of the measurement in conjunction with the digital filtering.

Adding a capacitor to ground on the input side of the protection resistor forms a single pole RC filter. Since the frequencies present in the end user's environment are frequently unknown at design time, an input filter should strive to give as much attenuation at 15.36kHz as possible without causing an offset due to excessive settling time. Too large of an RC time constant will cause errors if the voltage being measured has not settled when the ADC begins sampling.

REMOTE THERMOCOUPLE BURN-OUT DETECTION

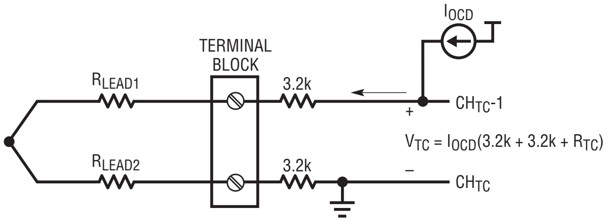
A major issue with remote sensors is knowing when they have failed. In many installations, the sensor has been placed remotely due to hazards encountered at the sensor location. Remote thermocouples are often placed in very high temperature or corrosive atmospheres that can cause the thermocouple wiring to degrade over time. As the voltages produced by the thermocouple are very small, a completely broken thermocouple could go unnoticed since the temperature reported may still be within expected limits.

One solution is to apply a current through the thermocouple, which will generate a large voltage if the thermocouple has become an open circuit as shown in Figure 6.

There is an offset voltage produced by any parasitic resistance in the leads. This offset voltage changes if either the current or the resistance changes, making it difficult to remove through calibration. Additionally, simple current sources and pull-up resistors transmit power supply noise to the thermocouple inputs, forcing stronger filtering in the measurement circuit.

Even a tiny constant current source produces a comparatively large voltage across a protection resistor. Here, two of them are in series producing an upper voltage of 64mV with only a 10μA burn-out detection current, equivalent

Figure 6. Pulsed OCD current produces detectable voltage which decays in normal use before measurement is made, eliminating offset error



> A preferred approach to thermocouple burn-out detection is to supply a pulse of current that is of sufficient amplitude and duration to create a large detectable voltage if an open circuit is present, but short enough that this voltage decays below the noise floor within a determined time if the thermocouple is healthy. This ensures no measurable offset in the reported temperature.

to an offset of approximately 1600°C for an example type K thermocouple.

A preferred approach is to supply a pulse of current of sufficient amplitude and duration to create a large detectable voltage if an open circuit is present, but short enough that this voltage decays below the noise floor within a determined time if the thermocouple is healthy. This ensures no measurable offset in the reported temperature.

In the LTC2983/4/6 family, the user can select an internally sourced excitation current from 10μA to 1mA. When open-circuit detection is enabled, this current source is applied for 8ms at the beginning of one 81ms conversion cycle, allowed to decay, and then the standard 2-conversion thermocouple measurement is made.

With an overvoltage protection resistance of 3.2k, the effective series resistance seen by the current source is over 6.4k including the resistance of the thermocouple and cabling. Therefore, our maximum selectable excitation current for a 5V-powered device would be 500μA since a larger current would exceed V_{DD}.

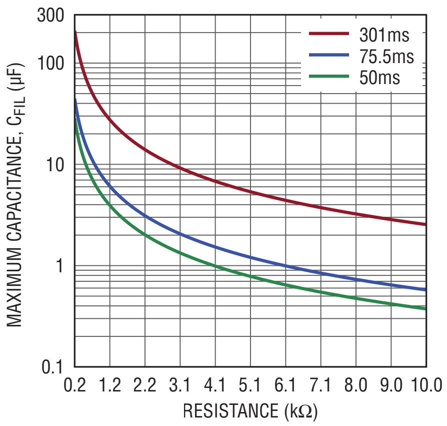


Figure 7. Thermocouple open-circuit detect settling time maximums (100μA)

FILTERING A REMOTE THERMOCOUPLE

A large RC filter reduces noise at the inputs at the cost of increased settling time from the open-circuit detection current pulse. The chart in Figure 7 shows the maximum RC combinations that settle to 1μV with various settling times.

The LTC298x provides an adjustable MUX delay of up to 25.5ms that can be used to extend the time available for settling—this is shown as the 75.5ms series in Figure 7. Very large RC filters can be supported by performing a dummy conversion after an open-circuit detection enabled conversion, extending the settling time by 160ms. Open-circuit detect disabled conversions can be used for the majority of data points, enabling open-circuit detect as needed or with a low duty cycle.

The traces in Figure 7 are maximum RC combinations for the different settling times. The graphs are based on an equation derived from the pulse response:

$$t_{SETTLE} = -\ln\left\{\frac{1\mu V}{R_{EFF} \cdot I_{OCD}\left[1-e^{\left(-8ms/RC\right)}\right]}\right\} \cdot RC$$

$$\text{where } RC = R_{EFF} \cdot C_{FIL1}$$

where R_{EFF} is the sum of the series resistance through the protection resistors and any thermocouple lead and tip resistance from CH_{TC-1} to CH_{TC} or to COM.

Using the graphs and following the line for the 50ms delay and 100μA excitation we find that for a 6.4kΩ total series resistance we can put approximately 560nF of capacitance on each input of a differential connection.

3.2k and 560nF per leg gives the RC filter an f_{3dB} of just under 90Hz. This yields over 40dB attenuation in the narrow band around our worst-case 256 • f_N frequency. Increasing the resistance can increase attenuation, but at the expense of increased thermal noise and offset voltage.

COLD JUNCTION MEASUREMENTS FOR REMOTE THERMOCOUPLES

Thermocouples are formed when two wires made of materials with different Seebeck coefficients meet. A temperature gradient along each wire generates a potential, where the potential difference between the wires is related to the temperature difference from the tip (mated end) to the (unmated) ends.

In order to calculate the absolute temperature at the thermocouple tip, the temperature at the ends must be known. The temperature at this junction of thermocouple wire and connector or circuit board is known as the cold junction. Since the absolute temperature at the tip is a function of this cold junction temperature, accurate measurement is a must.

A commonly encountered source of error in thermocouple measurement systems arises from the assumption that the temperature at the thermocouple connector is the same as that of the rest

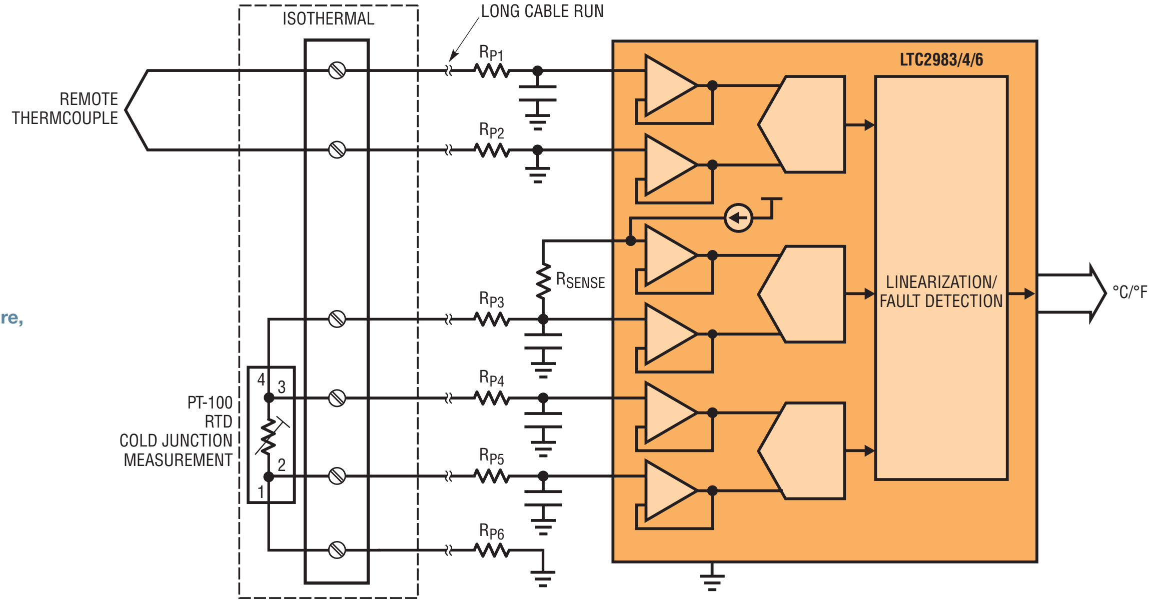


Figure 8. Remote RTD measures thermocouple cold junction temperature, improving accuracy and eliminating requirement for costly thermocouple extension wire.

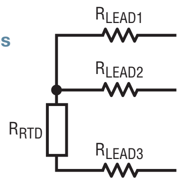
of the circuit board—many systems simply take the temperature of the measurement device as the cold junction compensation value. Errors of several degrees arise from thermal gradients across the circuit board created by power supplies or other warm objects nearby.

Filtering Resistive Sensors

Resistive sensors provide a well defined method of measuring absolute temperature and are widely used for cold junction compensation. The temp-to-bits devices make it easy to add a cold junction measurement device, which is automatically used in the remote thermocouple temp calculation (Figure 8).

Like thermocouples, it is often necessary to protect and filter inputs measuring resistive devices like RTDs and thermistors. Since they are resistors themselves, it can be difficult to separate the temperature dependent resistance from leads and other series resistance in the measurement path.

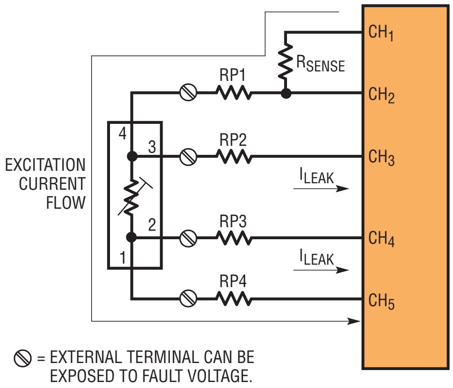
Figure 9. 3-wire RTD provides extra lead for correction



Three-wire RTDs (Figure 9) are commonly used to solve this problem. When all three leads are exactly the same length and resistance, the resistance between leads 1 and 2 can be measured to determine the lead resistance. In practice, it is difficult to ensure identical leads and the problem becomes much more difficult when additional series resistance is added to provide input protection or filtering. Any mismatch in the effective lead resistance results in a 1:1 measurement error due to mismatch.

If a fourth lead is added to the RTD, a 4-wire Kelvin measurement can be performed (Figure 10). The excitation current no longer flows through the sensed leads connected to the measurement inputs, eliminating any resistance and associated voltage drop in the leads. Additionally, the Kelvin connection allows us to rotate the direction of excitation current and remove any offsets created by parasitic thermocouples.

Figure 10. A 4-wire RTD is an ideal choice for a remote cold junction sensor as the 4-wire connection eliminates the effects of parasitic resistance from the long cable.

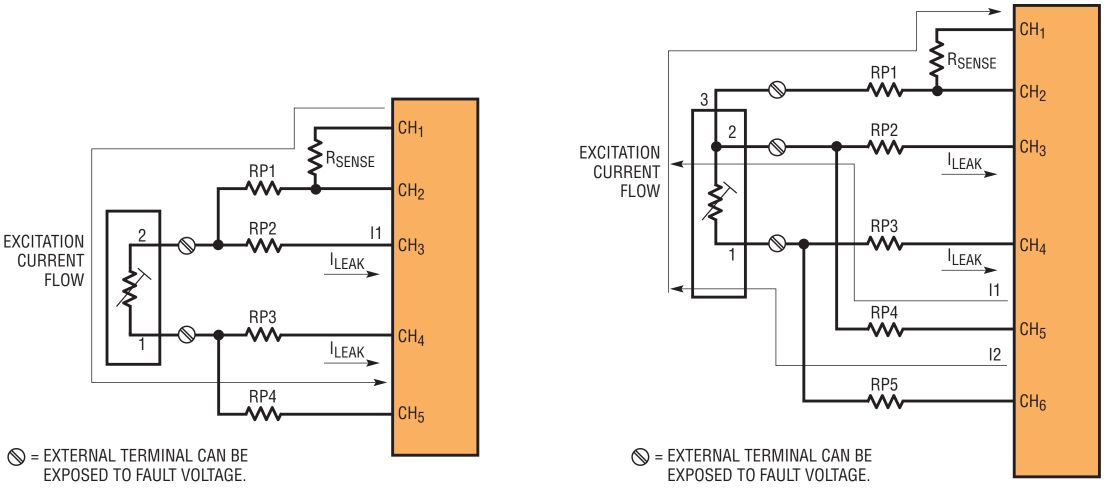


The LTC2986 and LTC2986-1 provide special modes for achieving low error measurements with 2- and 3-wire RTDs and thermistors. The LTC2986 achieves this accuracy by using additional connections to Kelvin sense the sensor element and provide excitation current from separate channels. In this way, the filtering and protection resistances are removed from the current path and their mismatch removed from the measured resistance.

Filtering the Cold Junction Sensor

Unlike a thermocouple, which may have an exposed tip, a cold junction sensor can be physically protected within a housing and does not require overvoltage protection.

Settling time for a resistive measurement is an important consideration, as too much RC delay leads to an effectively reduced resistance value. Unlike the



(a)

(b)

Figure 11. The LTC2986 enables the use of remote sensing with 2- or 3-wire RTDs. Shown are Kelvin current sourcing modes for (a) 2-wire and (b) 3-wire RTDs.

open-circuit detect pulse for a thermocouple, the excitation current for RTDs and thermistors is applied just prior to the start of a conversion cycle. The RC network should settle to required accuracy within a few milliseconds.

A 4-wire RTD is an ideal choice for a remote cold junction sensor as the 4-wire connection eliminates the effects of parasitic resistance from the long cable. With the LTC2986 we also have the option of using a remote thermistor or 2- or 3-wire RTDs, as the Kelvin current sourcing modes allow us to eliminate the cable resistance from the measurement in the same way (Figure 11).

A PT-100 RTD excited by a 250μA current has a temperature coefficient of about 96μV/°C. To keep offset error to less than 0.1°C the RC circuit should settle to within 9.6μV in approximately 3ms.

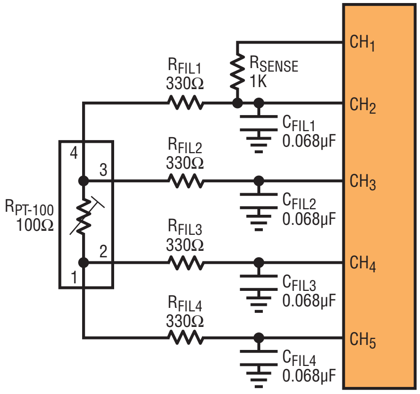
To ensure we do not exceed our current source compliance limits, calculate the steady state voltage at the sourcing channel with a 250μA excitation:

$$V_{CS} = I_{EXC}(R_{SENSE} + R_{FIL1} + R_{PT\text{-}100} + R_{FIL4})$$

Since we cannot exceed 4V, R_{FIL1} and R_{FIL4} must be less than 1.5k each. To maximize noise performance with the 250μA excitation source, use a smaller series resistor here, ideally less than 500Ω. Note that the resistances on the sensed leads (R_{FIL1} and R_{FIL3}) are not in series with the excitation current and do not factor in the steady state calculation. This is important because they do not contribute an offset in the 4-wire case. As a result, precision matching of these resistors is not necessary, as in the 3-wire RTD case.

A combination of R_{FIL} = 330Ω and C_{FIL} = 68nF (Figure 12) was found to settle to within 10μV in 3ms when all four leads from the RTD are filtered. The first and fourth connections do not factor in the measurement and are directly connected to either GND or the current source during measurement, giving us the possibility of reducing or eliminating the filter on these leads. It is good practice to provide some filtering, as noise on these leads could couple into the signal inputs.

Figure 12. RC filters for RTD should settle to within 9.6μs in approximately 3ms



INCREASING THE CHANNEL COUNT WITH KELVIN CONNECTIONS

One limitation of the Kelvin sensing scheme is the number of channels in use by each sensor. While the LTC2986 trades channels for current sourcing flexibility, an external multiplexer can be used to increase the number of Kelvin-connected sensors, as shown in Figure 13.

Here we show how to Kelvin-connect nine thermistors on an LTC2983 or LTC2984 20-channel part. Each thermistor requires only two channels and the input protection resistors are removed from the current path.

The system controller connects each sensor's ground through the multiplexer just prior to initiating a conversion. In this way, the excitation current flows from the sense resistor through R_{P1}, across the thermistor and to ground through the analog MUX. Assuming the MUX has low channel-to-channel leakage, this technique should isolate the protection/filtering resistance from the measurement result.

Kelvin modes of the LTC2986 remove offsets due to extra series resistance when protecting and filtering 2- and 3-wire RTDs and thermistors. The Kelvin sensing technique implemented internally in the LTC2986 can be extended to larger numbers of sensors by using an external switch.

It is important to note that settling time will be a factor here, as the chain of potentially large valued thermistors with parallel protection resistors and filter caps creates a structure not unlike a lumped element transmission line.

CONCLUSION

The LTC2983-6 temp-to-bits family provides numerous features that enable robust temperature measurement in industrial environments. Low input leakage permits large series resistance for overvoltage protection and RC filtering. Kelvin modes of the LTC2986 remove offsets due to extra series resistance when protecting and filtering 2- and 3-wire RTDs and thermistors. The Kelvin sensing technique implemented internally in the LTC2986 can be extended to larger numbers of sensors by using an external switch. ■

Figure 13. Using an analog MUX to Kelvin-connect nine thermistors to an LTC2983 or LTC2984 20-channel part.

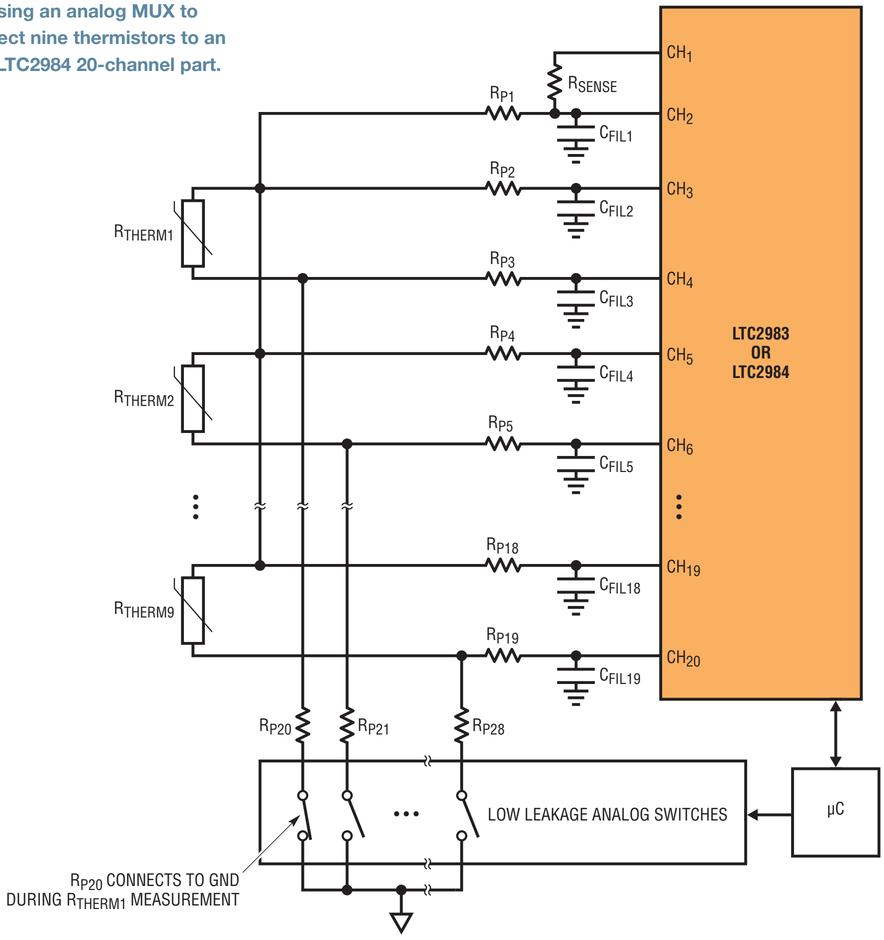


Table 1. Temp-to-bits converters for industrial applications

	LTC2983	LTC2984	LTC2986	LTC2986-1
Channel count	20	20	10	10
Any sensor any input	✓	✓	✓	✓
Automatic burnout and fault detection	✓	✓	✓	✓
Built-in and custom sensor coefficients	✓	✓	✓	✓
Automatic cold junction compensation—uses any sensor	✓	✓	✓	✓
Universal protected inputs (2- 3- and 4-wire)			✓	✓
Custom table lookup for analog voltage sensors			✓	✓
EEPROM		✓		✓
Package	7mm × 7mm LQFP-48			