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High Accuracy (±1°C) Temperature Sensors Improve System Performance and Reliability

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The march toward increasingly dense computing power has amplified the challenges related to heat. In many systems, the capabilities of the cooling system are a significant limitation to overall performance. Standard cooling components—bulky heat sinks and power-hungry noisy fans (or expensive quiet ones)—impose size limitations on tightly packed electronics. The only way to maximize performance, minimize cooling requirements, and ensure the health of the electronics is with accurate, precise and comprehensive temperature monitoring throughout the system.

With this in mind, Linear Technology has developed a family of highly accurate temperature monitors that can be easily distributed throughout a system. Included in this family:

- The LTC®2997 accurately measures either its own temperature or the temperature of an external diode.
- The LTC2996 adds monitoring functionality by comparing the measured temperature with a high and a low temperature threshold and communicating any temperature excess via open drain alert outputs.
- The LTC2995 combines the LTC2996 with a dual supply voltage monitor, allowing it to measure temperature, compare temperature to configurable thresholds, and supervise two supply voltages.

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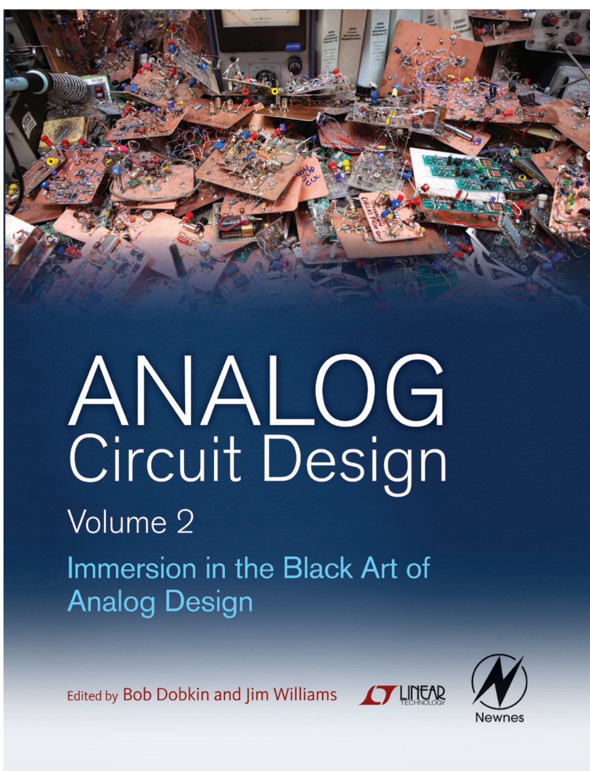

Analog Circuit Design, Volume 2 now available. See page 3.

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THE LTC2997 IS A TINY HIGH PRECISION TEMPERATURE SENSOR

The LTC2997 in a 2mm × 3mm 6-pin DFN package is perfectly suited to measure temperature of an FPGA or microprocessor as shown in Figure 1.

To this end, the LTC2997 sends measurement currents to the temperature monitoring diode of the FPGA or microprocessor and generates a voltage proportional to the temperature of the diode on its V_{PTAT} output. LTC2997 also provides a 1.8V reference voltage at the V_{REF} output, which can be used as reference voltage for the onboard ADC in the FPGA or microprocessor. The measurement error in this configuration with external sensor element is *guaranteed* to ±1°C over the wide temperature range from 0°C to 100°C and to ±1.5°C from –40°C to 125°C; *typical* temperature measurement error is far better, as shown in Figure 2.

Tying the D^+ pin to V_{CC} configures the LTC2997 to use its own internal temperature sensor. The V_{PTAT} voltage has a slope of 4mV/K and is updated every 3.5ms.

OPERATING PRINCIPLES

The LTC2997 achieves impressive accuracy by measuring the diode voltage at multiple test currents and using the measurements to remove any process-dependent errors and series resistance errors.

The diode equation can be solved for T, where T is temperature in Kelvin, I_S is a process dependent factor on the order of 10^{-13}A, η is the diode ideality factor, k is the Boltzmann constant and q is the electron charge:

$$T = \frac{q}{\eta \bullet k} \bullet \frac{V_D}{\ln\left(\frac{I_D}{I_S}\right)}$$

This equation has a relationship between temperature and voltage, dependent on the process-dependent variable I_S. Measuring the same diode (with the same value I_S) at two different currents yields an expression that is independent of

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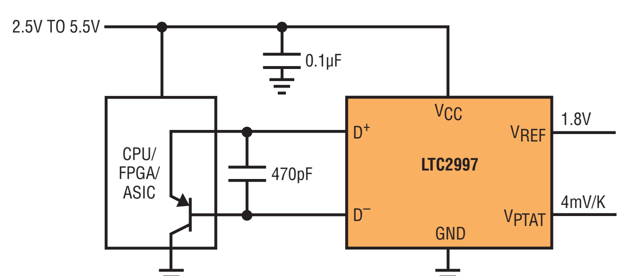
Figure 1. Remote CPU temperature sensor



The LTC2997 in a 2mm × 3mm 6-Pin DFN package is perfectly suited to measure temperature of an FPGA or microprocessor via the processor's temperature measuring diode. The measurement error in this configuration is *guaranteed* to ±1°C over the temperature range from 0°C to 100°C and to ±1.5°C from –40°C to 125°C.

(LTC299x continued from page 2)

I_S. The value in the natural logarithm term becomes the ratio of the two currents, which is process independent:

$$T = \frac{q}{\eta \bullet k} \bullet \frac{V_{D2} - V_{D1}}{\ln\left(\frac{I_{D2}}{I_{D1}}\right)}$$

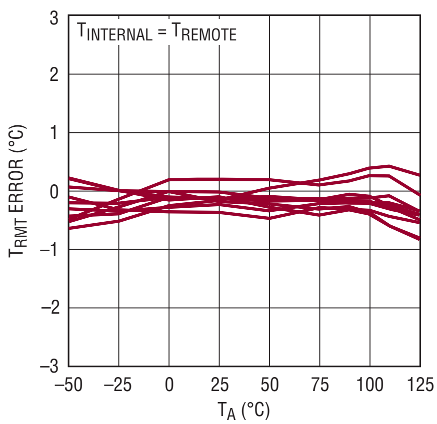
Resistance in series with the remote diode causes a positive temperature error by increasing the measured voltage at each test current. The composite voltage equals:

$$V_D + V_{ERROR} = \eta \frac{kT}{q} \bullet \ln\left(\frac{I_D}{I_S}\right) + R_S \bullet I_D$$

where R_S is the series resistance.

The LTC2997 removes this error term from the sensor signal by subtracting a cancellation voltage (see Figure 3a). A resistance extraction circuit uses one additional measurement current (I_3) to determine the series resistance in the measurement path. Once the correct value of the resistor is determined V_{CANCEL} equals V_{ERROR}. Now the temperature to voltage converter's input signal is free from errors due to series

Figure 2. Temperature error vs temperature (LTC2997 at same temperature as remote diode)



resistance and the sensor temperature can be determined using currents I_1 and I_2.

Series resistance up to 1k typically causes less than 1°C of temperature error as indicated in Figure 3b, which makes LTC2997 the ideal device to read out diode sensors that are several meters away from the temperature management system. Indeed, the maximum distance is limited more by the line capacitance than by the line resistance.

Capacitances larger than 1nF start to impact the settling of the sensor voltage at the various sense currents and therefore introduce additional temperature reading errors. For example, a 10m long CAT 6 cable has about 500pF of capacitance.

Unlike many remote diode sensors, the LTC2997 accurately tracks fast changing temperatures due to its short update time (3.5ms) and its robust temperature measurement algorithm in the face of temperature variations, even during a measurement interval. Figure 4 shows the step response of the LTC2997's internal sensor when the entire device is dipped into boiling water immediately after sitting in ice water.

The LTC2997 has many advantages over its digital counterparts when applied in temperature regulation loops. Its fast response time and analog output temperature eliminate much of the complexity required by digital systems. For example, Figure 5 shows the LTC2997 in a heater that regulates at 75°C. In this application, the

Figure 3. Series resistance cancellation

a. Simplified block diagram

b. Temperature error vs series resistance

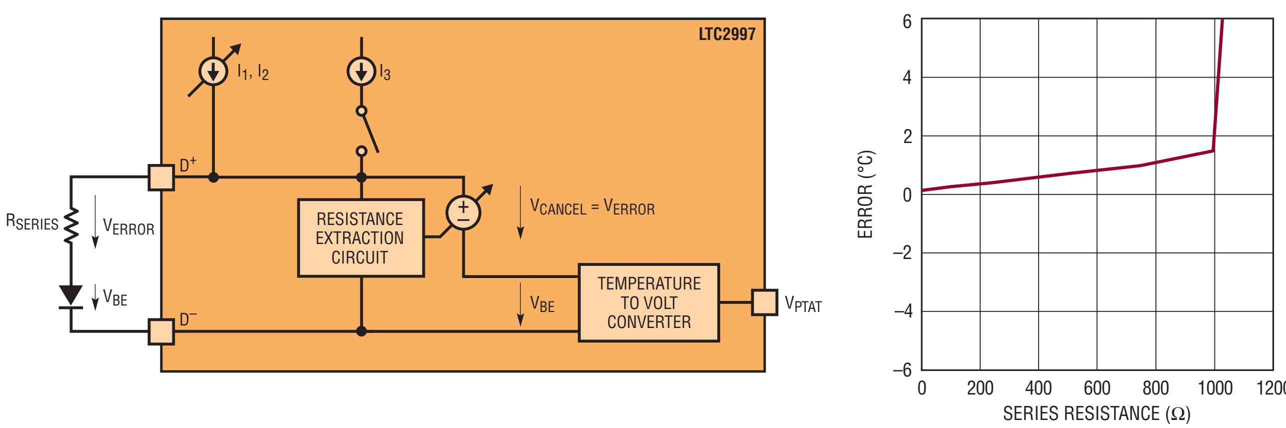


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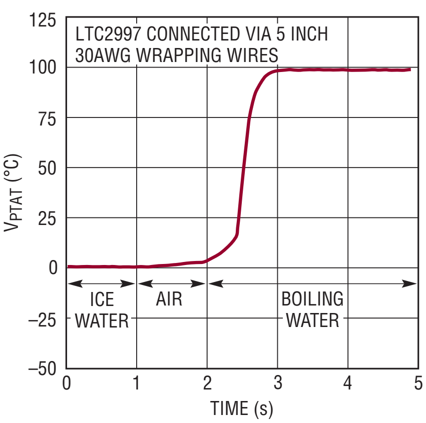
Figure 4. LTC2997 internal sensor thermal step response



reference voltage is used to generate—by means of a resistive divider—a target voltage of 1.392V (= [75 + 273.15]K • 4mV/K).

The first micropower rail-to-rail amplifier, the LTC6079, integrates the difference between the V_{PTAT} output of the LTC2997 and the target voltage. The integrated error signal is converted to a pulse width modulated signal by the PWM oscillator, which in turn drives the switch of the PMOS, controlling the current through the heating resistor.

The LTC2997 can also be used to build a Celsius thermometer (Figure 6), a Fahrenheit thermometer (Figure 7), a thermocouple thermometer with cold junction compensation (Figure 8), or in countless other applications where accurate and fast temperature measurements are required.

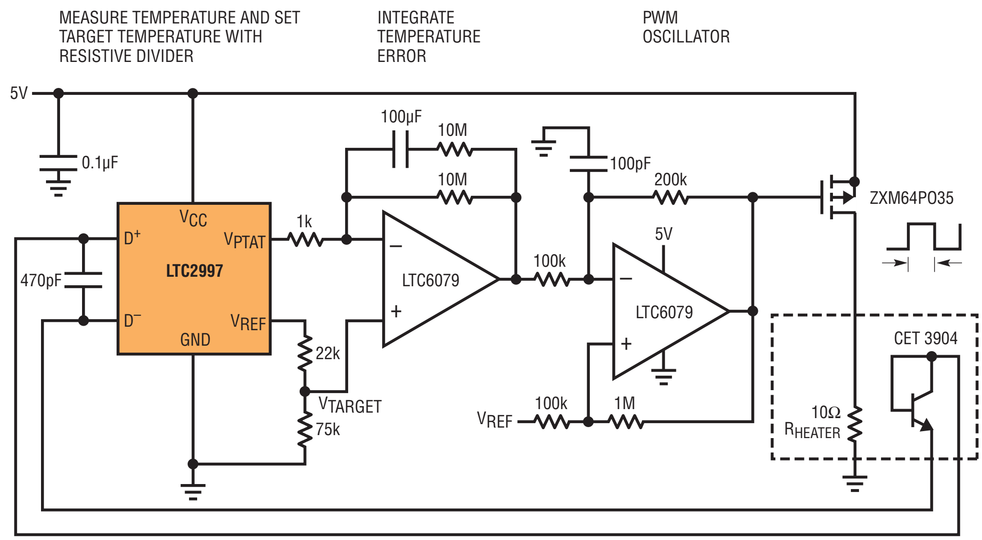


Figure 5. 75°C analog PWM heater controller

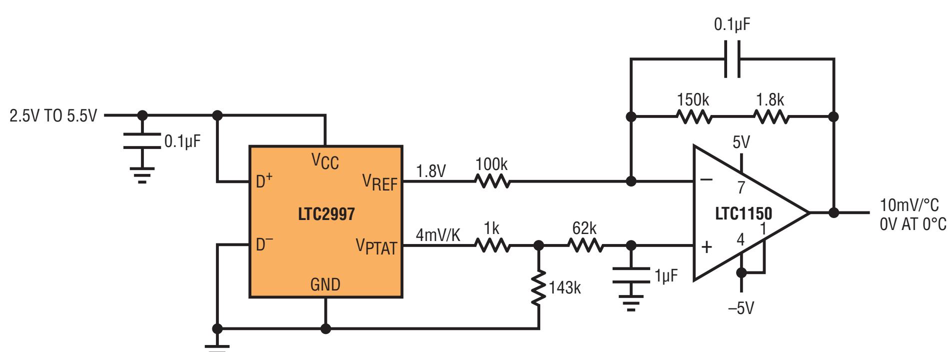


Figure 6. Celsius thermometer

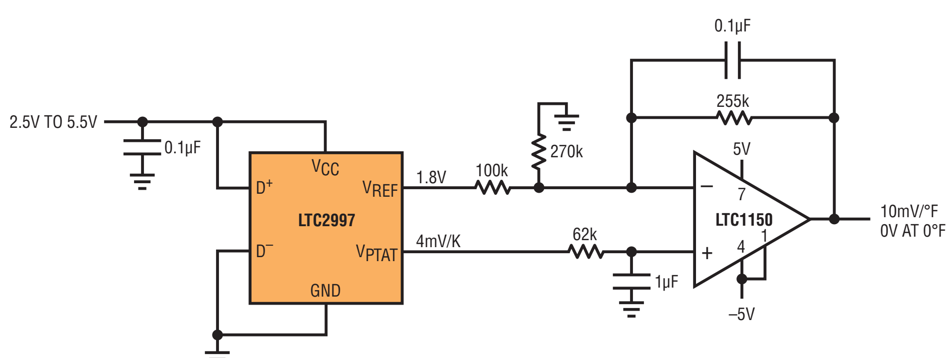


Figure 7. Fahrenheit thermometer

Unlike many remote diode sensors, the LTC2997 accurately tracks fast changing temperatures due to its short update time (3.5ms) and its robust temperature measurement algorithm in the face of temperature variations, even during a measurement interval.

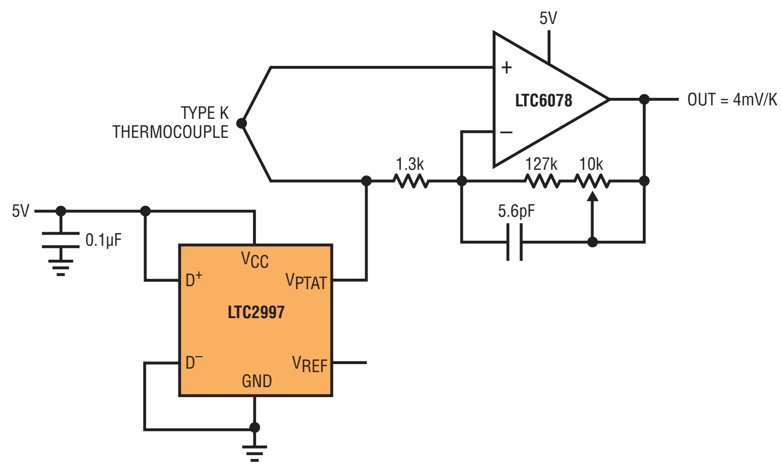


Figure 8. Thermocouple thermometer with cold junction compensation

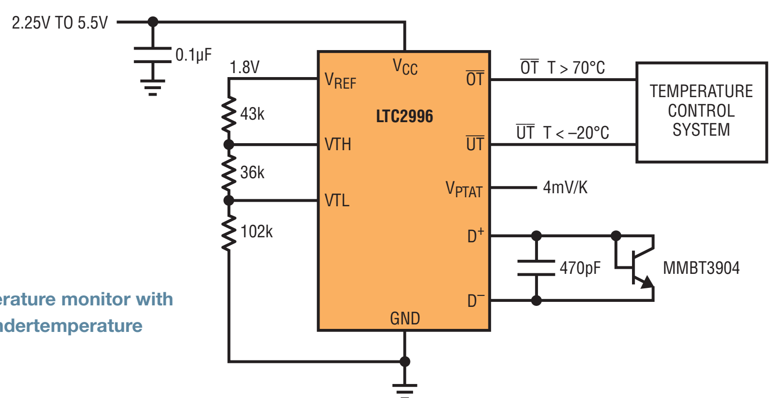


Figure 9. Remote temperature monitor with overtemperature and undertemperature thresholds

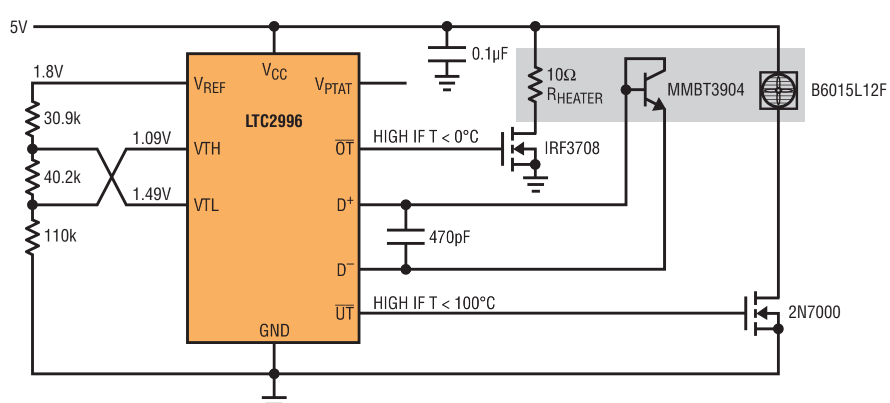


Figure 10. Bang-bang controller maintains temperature between 0°C and 100°C

THE LTC2996 TEMPERATURE MONITOR

The LTC2996 adds threshold inputs VTH and VTL to the LTC2997 and continuously compares V_{PTAT} to these thresholds to detect overtemperature (OT) or undertemperature (UT) conditions. The threshold input voltages can be conveniently set by resistive dividers from the built-in reference voltage, as depicted in Figure 9.

If the temperature of the remote diode in Figure 9 increases above 70°C, the V_{PTAT} voltage exceeds the high temperature threshold at VTH. The LTC2996 detects this overtemperature condition and alerts the temperature control system by pulling the OT pin low. In the same way, a temperature falling below –20°C is communicated via the UT pin. Note that the LTC2996 pulls on the open drain alert outputs only if the temperature exceeds the corresponding threshold for five consecutive update intervals of 3.5ms each. The OT and the UT pin have internal weak 400k pull-up resistors to V_{CC}—no external resistors are required in many applications.

The LTC2996 can be used to implement a bang-bang controller, keeping the temperature of a sensitive device (e.g., a battery) in a certain desirable temperature range, as shown in Figure 10.

In this application, the undertemperature input threshold is set to 100°C, whereas the overtemperature input threshold input is set to 0°C. This seemingly upside down arrangement is linked to the fact that OT und UT are pulled low when a threshold is exceeded. Therefore, in this

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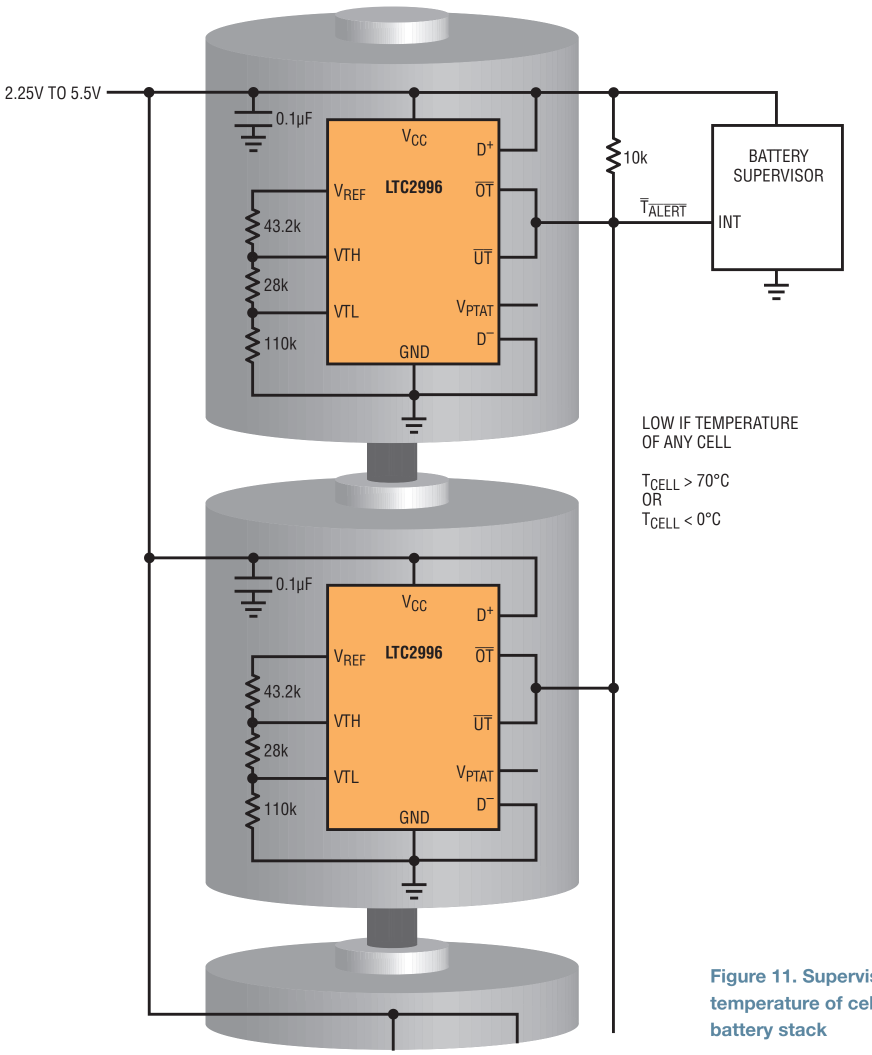


Figure 11. Supervising temperature of cells in a battery stack

configuration, UT and OT both pull the gates of the NMOS transistors low while the temperature remains within the desired range (over the overtemp and under the undertemp), and the heating resistor and the cooling fan are turned off. If the temperature rises above 100°C, the undertemperature open drain output UT is released high and the fan is switched on. Similarly, a temperature below 0°C turns on the heater.

In the context of batteries, the LTC2996 can also be used to supervise the temperature of a large battery composed of several different cells. A damaged, shorted or worn out cell typically heats up, and can, in worst case, catch fire. The LTC2996 supervises the temperature of each cell individually with minimal additional wiring, as shown in Figure 11.

In fact, if the cells are connected in series (battery stack) only three additional lines—V_{CC}, GND and an alert output—are required to monitor whether the temperature of any cell leaves the desired operating range. If the cells are connected in parallel, and a battery with a terminal voltage between 2.25V and 5.5V (e.g., Li-ion) is monitored, even a single additional line—the alert output—is sufficient to supervise the temperature of each cell.

THE LTC2995 COMBINES A TEMPERATURE AND A DUAL VOLTAGE MONITOR / SUPERVISOR

In addition to temperature monitoring, nearly every electronic system requires multisupply voltage supervision. To serve this need, the LTC2995 combines the LTC2996 with a dual voltage supervisor, monitoring two supply lines for overvoltage and undervoltage conditions as shown in Figure 12.

The LTC2995 adds two additional high and low voltage inputs per channel, which are continuously compared to an internal 500mV reference. As soon as the voltage at either VH1 or VH2 falls below 500mV, the LTC2995 flags an undervoltage condition by pulling the UV output pin low. Similarly, an overvoltage condition is indicated by pulling the OV pin low if either VL1 or VL2 rise above 500mV.

To prevent spurious resets due to noise on the monitored supply voltages, the LTC2995's lowpass filter causes the

To prevent spurious resets due to noise on the monitored supply voltages, the LTC2995's lowpass filter causes the output of the comparator to be integrated before asserting UV or OV. Any transient at the input of the comparator must be of sufficient magnitude and duration before the comparator triggers the output logic.

output of the comparator to be integrated before asserting UV or OV. Any transient at the input of the comparator must be of sufficient magnitude and duration before the comparator triggers the output logic. Furthermore, the LTC2995 has an adjustable timeout period (t_{UOTO}) that holds UV and OV asserted after any faults have cleared. This delay minimizes the effect of input noise with a frequency above $1/t_{UOTO}$. The timeout period (t_{UOTO}) is adjustable by connecting a capacitor, C_{TMR}, between the TMR pin and ground in order to accommodate a variety of applications.

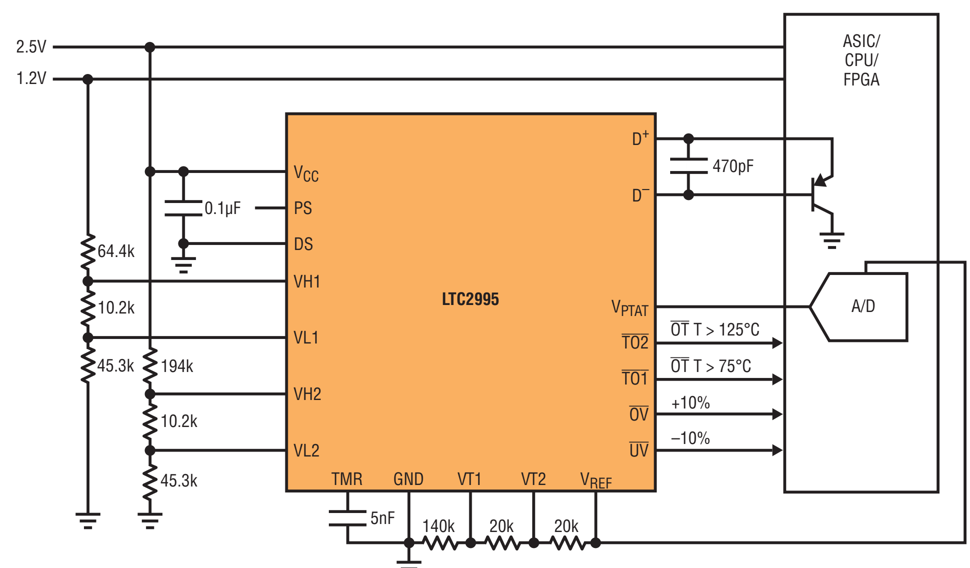
The LTC2995 includes temperature measuring and monitoring features that provide more flexibility than the LTC2997 and LTC2996. While the latter devices always switch to external mode if an external diode is connected, requiring D^+ to be connected to V_{CC} to measure the internal diode, the LTC2995 provides an additional diode select (DS) pin, allowing switching between the internal and an external diode on the fly. If the DS pin is left floating, the LTC2995 goes into "ping-pong" mode, where it alternates between internal and external diode measurement with a period of about 20ms.

Finally, the LTC2995 can configure its two temperature thresholds both as overtemperature or both as undertemperature limits using the polarity select (PS) pin. This feature allows systems to react in levels to changes in temperature. As an example you might want to get a warning if the temperature rises above 75°C (e.g., to switch on a fan) and an alert if it increases above 125°C (e.g., to switch off the system) as depicted in Figure 12.

CONCLUSION

Linear Technology's new family of accurate temperature sensors/monitors can use an internal or external diode as a sensor and produce analog outputs proportional to measured temperature. The family ranges from a tiny temperature sensor to a combined temperature and dual voltage supervisor that can signal out-of-range conditions. These devices make it easy to build analog temperature control loops or to monitor temperatures (and voltages) with minimum complexity. ■

Figure 12. Dual OV/UV ±10% supply and 75°C/125°C OT/OT remote temperature monitor



If You Need Digital Output

The LTC2990 and the LTC2991 feature digital I^2C output and control as well as voltage and current monitoring functions. For more information, go to www.linear.com/2990 or www.linear.com/2991.