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Semiconductor Sensors Provide a Hot Temperature Sensing Solution at a Cool Price

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INTRODUCTION

Silicon temperature sensors with precise temperature accuracy and linear output are required in many automotive, consumer, and industrial temperature monitoring and control applications (e.g., air conditioning, rice cooker, oven, washing machine, refrigerator, and weather data electronics systems). Most of these applications require a very low–cost temperature sensing solution. Motorola's solid–state temperature sensor MTS102/103/105 series has an output which is guaranteed to within 2°C, 3°C, and 5°C, respectively. The MTS series sensors are small–signal bipolar transistors that have been optimized and characterized for excellent performance over temperature. The main performance parameter is a linear change in the base–emitter voltage with temperature. The MTS series is packaged in low–cost TO–92 transistor packages, making them economical for even disposable applications. This paper presents two examples of interface circuits which may be employed to signal condition the output of the MTS temperature sensor in many temperature monitoring and control applications. The first circuit is intended for applications in which a continuous analog range of temperature is to be sensed, while the second circuit is designed for temperature switch applications (i.e., the temperature relative to a specific temperature threshold or temperature range is the only information of interest).

ANALOG TEMPERATURE SENSING

The system block diagram in Figure 1 represents a typical temperature monitoring system. The system consists of a temperature sensor, an amplification stage, an A/D converter (typically on–board the MCU), a microcontroller, and an LCD display or control circuitry stage.

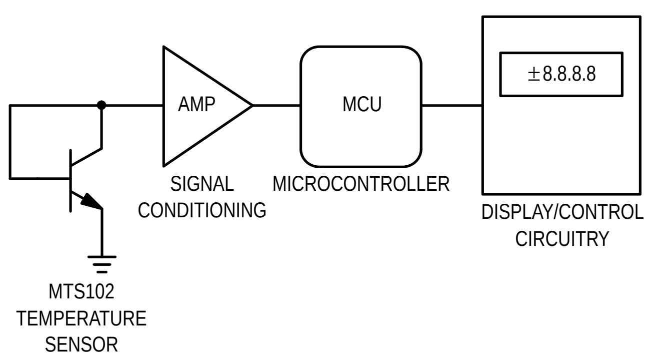

Figure 1. System Block Diagram

AMPLIFIER DESIGN CONSIDERATIONS

Figure 2 shows a simple amplifier interface circuit for signal conditioning the output of the MTS102. With a 5 V supply, a 44 kΩ collector resistor is used to bias the temperature sensor to its nominal room temperature V_{BE} of 650 mV with a collector current of 100 µA. Figure 3 shows the V_{BE} characteristic versus ambient temperature. The temperature coefficient (TC_{VBE}) of a MTS102 is typically equal to –2.0 mV/°C. Assuming a system resolution of 0.5°C per A/D step and an operation temperature range of 0°C to 100°C is desired, the number of A/D steps required is:

0.5°C/step = (100 – 0)°C/(# of A/D steps)
# of A/D steps = 100/0.5 = 200 steps

Using V_{RH} = 5.0 V, V_{RL} = 0 V,

A/D resolution = 5.0 V/255 steps = 19.6 (mV/steps)
Span = 200 steps * 19.6 (mV/steps) = 3.92 V ≈ 4 V

Using TC_{VBE} = –2.0 mV/°C and a temperature range of 0°C to 100°C,

ΔV_{BE} = (100°C – 0°C) * (–2 mV/°C) = –200 mV
Gain = 4 V/ΔV_{BE} = 4000 mV/200 mV = 20

Choose R1 = 1 kΩ, R2 = Gain * R1 = 20 kΩ

CIRCUIT OPERATION

The base and collector pins of the MTS102 should be connected together since they are not internally connected. The variable resistor Rcal is used to adjust the temperature output signal to a desired analog voltage input to the A/D converter. At 25°C, the MTS102 has a V_{BE} output of 0.65 V. The base–emitter voltage is buffered. This gives an output of 0.65 V at the output pin of U1A. Assume an amplified temperature signal of 2.5 V is desired at 50°C, which corresponds to 1.5 V at 25°C with an amplified TC of (20 * –2 mV/°C = –40 mV/°C), the offset voltage, *x*, at the positive pin of U1B can be obtained by the following equation:

(x – 0.65 V)/1 kΩ = (1.5 – x)/20 kΩ

Solve for *x*

x = (1.5/20 + 0.65)/(1 + 1/20) = 0.69 V (at 25°C)

In this example, the variable resistor Rcal of voltage divider provides a dynamic range from 0 to 1.667 V (one–third of the supply voltage of the divider) at the positive input pin of U1B and also provides calibration to compensate the room temperature V_{BE} deviations between devices. Figure 4 shows the output signal of the temperature sensor versus different temperatures.

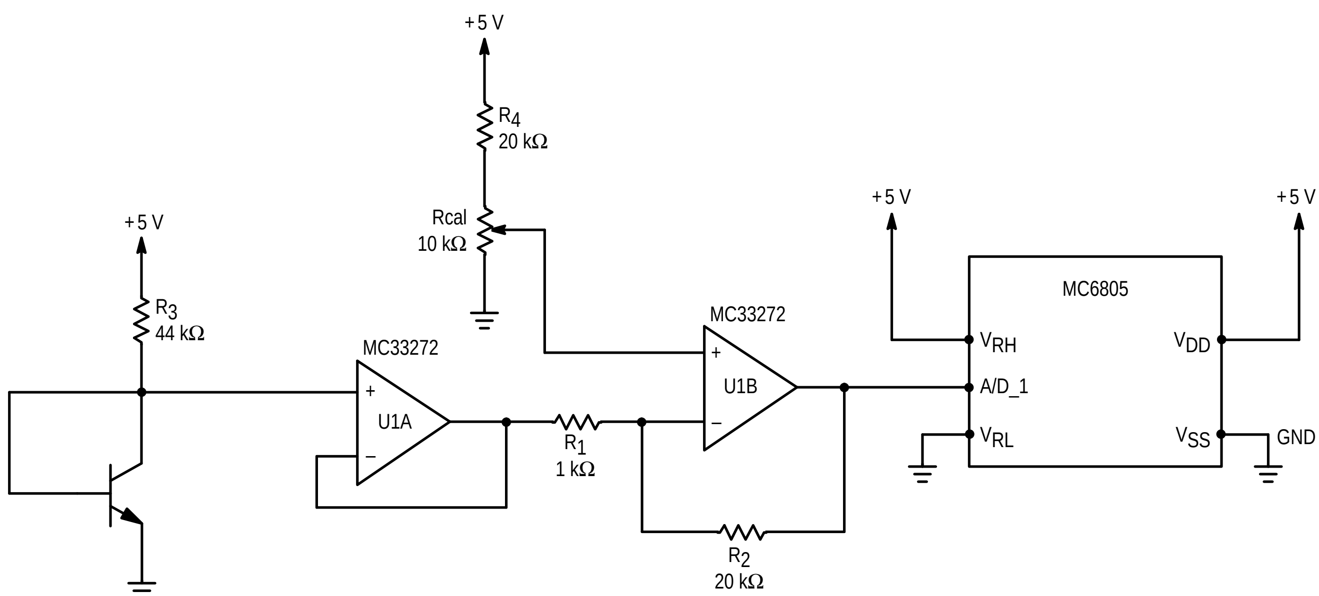

Figure 2. Analog Temperature Sensing Circuit

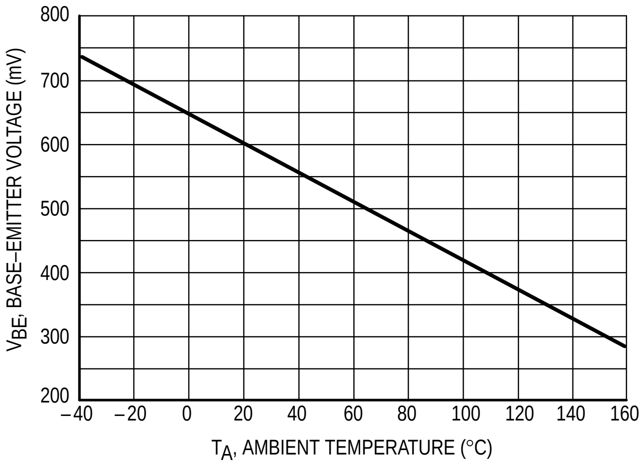

Figure 3. V_{BE} versus Ambient Temperature Characteristic

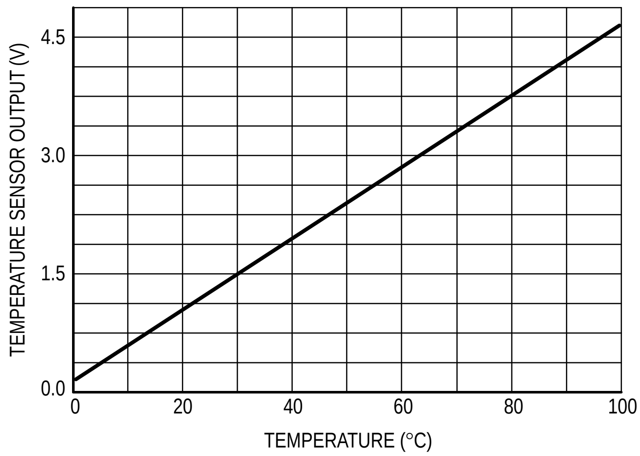

Figure 4. Temperature Sensor Output versus Temperature

TEMPERATURE SWITCH APPLICATIONS

Many times, a temperature sensing application only requires information about the current temperature compared to a set threshold. To detect when the temperature has exceeded or fallen below a specified threshold, a logic–level transition can serve as the circuit output. This logic signal is typically an input to a microcontroller I/O pin which can detect such a logic–level transition. The interface circuit that can provide this additional functionality is very similar to the analog amplifier interface presented above. In fact, the identical circuit topology will be employed, with the addition of a comparison stage for setting the temperature threshold and providing a “clean” logic–level output. Several comparator circuit topologies which use comparator IC’s and/or operational amplifiers will be presented. A window comparator design (high and low thresholds) is also included. The following sections describe the characteristics and design criteria for each comparator circuit, while evaluating them in overall performance (i.e., switching speed, logic–level voltages, etc.).

DESIGN CONSIDERATIONS

Since the output of the sensor is only on the order of millivolts per degree Celsius (mV/°C), amplification of the temperature signal is still necessary for this design. Thus, the circuit in Figure 2 will be used to provide the signal–conditioning function in this temperature switch design (see the section on Amplifier Design Considerations). Now that the sensor signal has been amplified to a usable voltage level, it can be compared to a user–programmable threshold voltage that is set at the comparison stage. Depending on the logic chosen, the comparison stage output can be either a low–to–high or high–to–low transition when exceeding or falling below the given threshold, i.e., positive logic when ouput goes high to a temperature that exceeds threshold, etc.

The Comparison Stage

The comparison stage is the “heart” of the temperature switch design. This stage converts the analog voltage output to a digital output, as dictated by the comparator’s threshold. The comparison stage has a few design issues which must be addressed (component names and values reference Figure 5):

- The threshold for which the output switches must be programmable. In Figure 5, the threshold is easily set by dividing the regulated 5 V supply voltage with resistors R_1 and R_2. In Figure 5, the threshold is set at 2.5 V for $R_1 = R_2 = 10\ k\Omega$.
- A method for providing an appropriate amount of hysteresis should be available. Hysteresis prevents multiple transitions from occurring when slow varying signal inputs oscillate about the threshold. The hysteresis can be set by applying positive feedback. The amount of hysteresis is determined by the value of the feedback resistor, R_H (refer to equations in the following section).
- It is ideal for the comparator’s logic level output to swing from one supply rail to the other. In practice, this is not possible. Thus, the goal is to swing as high and low as possible for a given set of supply voltages. This offers the greatest difference between logic states and will avoid having a microcontroller read the switch level as being in an indeterminate state.
- In order to be compatible with CMOS circuitry and to avoid microcontroller timing delay errors, the comparator must switch sufficiently fast.
- By using two comparators (or op–amps configured as comparators), a window comparator may be implemented. The window comparator may be used to monitor when the current temperature is within a set range. By adjusting the input thresholds, the window width can be customized for a given application. As with the single threshold design, positive feedback can be used to provide hysteresis for both switching points. The window comparator and the other comparator circuits will be explained in the following section.

EXAMPLE COMPARATOR CIRCUITS

Several comparator circuits were built and evaluated. Comparator stages using the LM311 comparator, LM358 Op–Amp (with and without an output transistor stage), and LM339 were examined. Each comparator circuit was evaluated regarding its output voltage levels (dynamic range) and the output transition time, as shown in Table 1.

The LM311 Used in a Comparator Circuit

The LM311 chip is designed specifically for use as a comparator and thus has short delay times, high slew rate, and an open collector output. A pull–up resistor at the output is all that is needed to obtain a "rail–to–rail" output. Additionally, the LM311 is a reverse logic circuit; that is, for an input lower than the reference voltage, the output is high. Likewise, when the input voltage is higher than the reference voltage, the output is low. Figure 5 shows a schematic of the LM311 stage with threshold setting resistor divider, hysteresis resistor, and the open–collector pull–up resistor. Table 1 shows the comparator's performance. Based on its performance, this circuit can be used in many types of applications, including interface to microprocessors.

The amount of hysteresis can be calculated by the following equations:

$$V_{REF} = \frac{R_2}{R_1 + R_2} V_{CC}, \text{ neglecting the effect of } R_H$$

$$V_{REFH} = \frac{R_1R_2 + R_2R_H}{R_1R_2 + R_1R_H + R_2R_H} V_{CC}$$

$$V_{REFL} = \frac{R_2R_H}{R_1R_2 + R_1R_H + R_2R_H} V_{CC}$$

HYSTERESIS = $V_{REF} - V_{REFL}$ when the normal state is below V_{REF}, or

HYSTERESIS = $V_{REFH} - V_{REF}$ when the normal state is above V_{REF}

An illustration of hysteresis and the relationship between these voltages is shown in Figure 6.

Table 1. The comparator circuits' performance characteristics.

Characteristic	LM311	LM358	LM358 with Transistor	Unit
Switching Speeds				
Rise Time	1.40	5.58	2.20	µs
Fall Time	0.04	6.28	1.30	µs
Output Levels				
V_{OH}	4.91	3.64	5.00	V
V_{OL}	61.1	38.0	66.0	mV
Circuit Logic Type	NEGATIVE	NEGATIVE	POSITIVE	

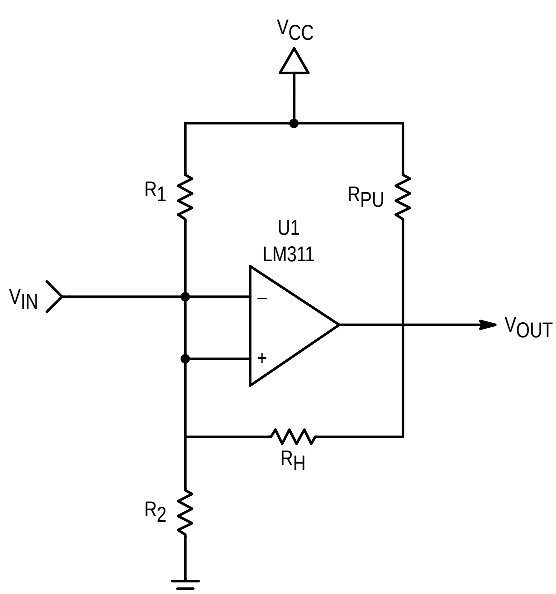

Figure 5. The LM311 Comparator Circuit Schematic

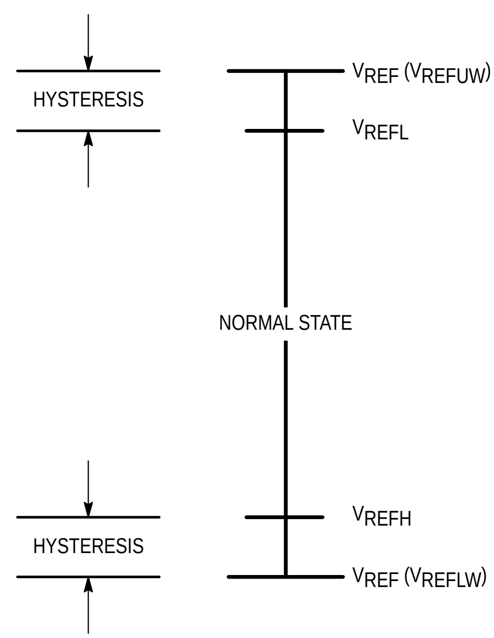

Figure 6. Setting the Reference Voltages

The initial calculation for V_{REF} will be slightly in error due to neglecting the effect of R_H. To establish a precise value for V_{REF} (including R_H in the circuit), recompute R_1 taking into account that V_{REF} depends on R_1, R_2, and R_H. It turns out that when the normal state is below V_{REF}, R_H is in parallel with R_1:

$$V_{REF} = \frac{R_2}{R_1 || R_H + R_2} V_{CC}$$ (which is identical to the equation for V_{REFH})

Alternately, when the normal state is above V_{REF}, R_H is in parallel with R_2:

$$V_{REF} = \frac{R_2 || R_H}{R_1 + R_2 || R_H} V_{CC}$$ (which is identical to the equation for V_{REFL})

These two additional equations for V_{REF} can be used to calculate a more precise value for V_{REF}.

The user should be aware that V_{REF}, V_{REFH}, and V_{REFL} are chosen for each application, depending on the desired switching point and hysteresis values. Also, the user must specify which range (either above or below the reference voltage) is the desired normal state (see Figure 6). Referring to Figure 6, if the normal state is below the reference voltage, then V_{REFL} (V_{REFH} is only used to calculate a more precise value for V_{REF} as explained before) is below V_{REF} by the desired amount of hysteresis (use V_{REFL} to calculate R_H). Alternately, if the normal state is above the reference voltage, then V_{REFH} (V_{REFL} is only used to calculate a more precise value for V_{REF}) is above V_{REF} by the desired amount of hysteresis (use V_{REFH} to calculate R_H).

The LM358 Op–Amp Used in a Comparator Circuit

Figure 7 shows the schematic for the LM358 op–amp comparator stage, and Table 1 shows its performance. Since the LM358 is an operational amplifier, it does not have the fast slew–rate of a comparator IC nor the open collector output. Comparing the LM358 and the LM311 (Table 1), the LM311 is better for logic/switching applications since its output nearly extends from rail to rail and has a sufficiently high switching speed. The LM358 will perform well in applications where the switching speed and logic–state levels are not critical (LED output, etc.). The design of the LM358 comparator is accomplished by using the same equations and procedure presented for the LM311. This circuit is also reverse logic.

The LM358 Op–Amp with a Transistor Output Stage

The LM358 with a transistor output stage is shown in Figure 8. This circuit has similar performance to the LM311 comparator; its output reaches the upper rail and its switching speed is comparable to the LM311's. This enhanced performance does, however, require an additional transistor and base resistor.

Like the other two circuits, this comparator circuit can be designed with the same equations and procedure. The values for R_B and R_{PU} are chosen to give a 5:1 ratio in Q_1's collector current to its base current, in order to ensure that Q_1 is well–saturated (V_{OUT} can pull down very close to ground when Q_1 is on). Once the 5:1 ratio is chosen, the actual resistance values determine the desired switching speed for turning Q_1 on and off. Also, R_{PU} limits the collector current to be within the maximum specification for the given transistor. Unlike the other two circuits, this circuit is positive logic due to the additional inversion created at the output transistor stage.

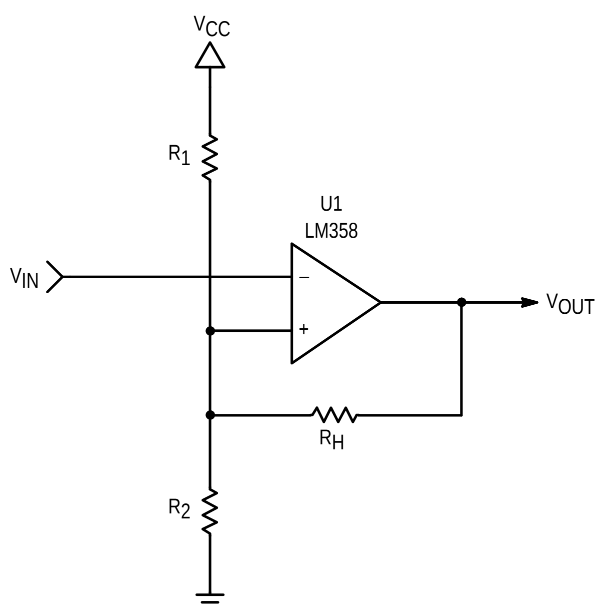

Figure 7. The LM358 Comparator Circuit Schematic

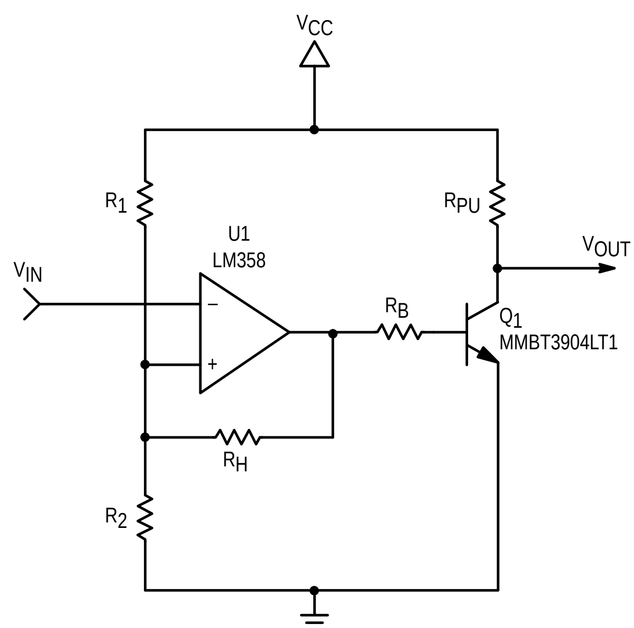

Figure 8. The LM358 with a Transistor Output Stage Comparator Circuit

The LM339 Used in a Window Comparator Circuit

Using two voltage references to detect when the input is within a certain range is another possibility for the temperature switch design. The window comparator's schematic is shown in Figure 9. The LM339 is a quad comparator IC (it has open collector outputs), and its performance will be similar to that of the LM311.

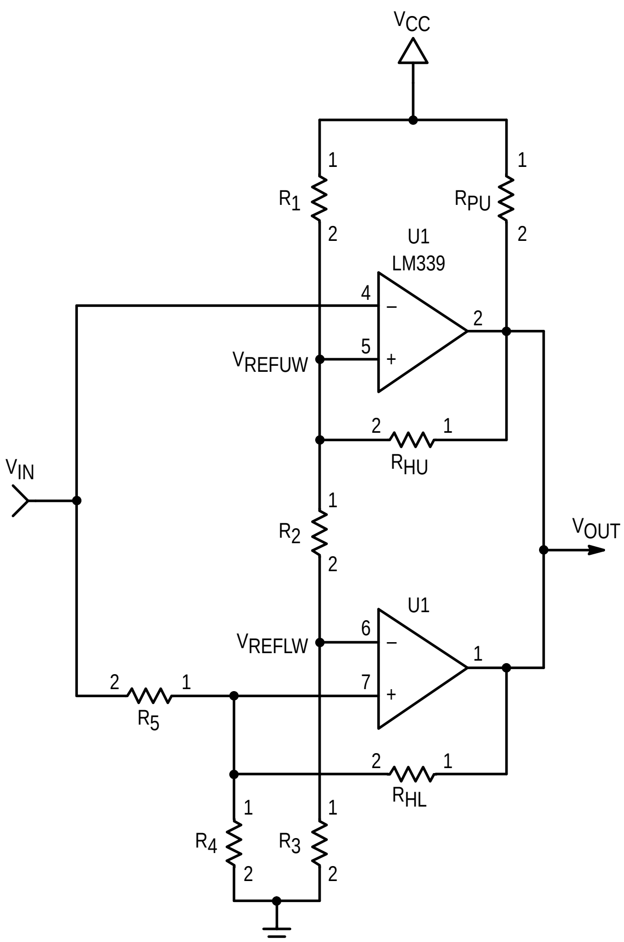

Figure 9. The LM339 Window Comparator Circuit

Obtaining the correct amount of hysteresis and the input reference voltages is slightly different than with the other circuits. The following equations are used to calculate the hysteresis and reference voltages. Referring to Figure 9, V_{REFUW} is the upper window reference voltage, and V_{REFLW} is the lower window reference voltage. Remember that reference voltage and threshold voltage are interchangeable terms.

For the upper window threshold:

Choose the value for V_{REFUW} and R1 (e.g., 10 kΩ). Then, by voltage division, calculate the total resistance of the combination of R_2 and R_3 (named R_{23} for identification) to obtain the desired value for V_{REFUW}, neglecting the effect of R_{HU}:

$$V_{REFUW} = \frac{R_{23}}{R_1 + R_{23}} V_{CC}$$

The amount of hysteresis can be calculated by the following equation:

$$V_{REFL} = \frac{R_{23}R_{HU}}{R_1R_{23} + R_1R_{HU} + R_{23}R_{HU}} V_{CC}$$

Notice that the upper window reference voltage, V_{REFUW}, is now equal to its V_{REFL} value, since at this moment, the input voltage is above the normal state.

$$\text{HYSTERESIS} = V_{REFUW} - V_{REFL},$$

where V_{REFL} is chosen to give the desired amount of hysteresis for the application.

The initial calculation for V_{REFUW} will be slightly in error due to neglecting the effect of R_{HU}. To establish a precise value for V_{REFUW} (including R_{HU} in the circuit), recompute R_1 taking into account that V_{REFUW} depends on R_2 and R_3 and the parallel combination of R_1 and R_{HU}. This more precise value is calculated with the following equation:

$$V_{REFUW} = \frac{R_{23}}{R_1 \parallel R_{HU} + R_{23}} V_{CC}$$

For the lower window threshold:

Choose the value for V_{REFLW}.

$$\text{Set } V_{REFLW} = \frac{R_3}{R_1 \parallel R_{HU} + R_2 + R_3} V_{CC},$$

where $R_2 + R_3 = R_{23}$ from above calculation.

To calculate the value of the hysteresis resistor:

The input to the lower comparator is one–half V_{IN} (since $R_4 = R_5$), when in the normal state. When V_{REFLW} is above one–half of V_{IN} (i.e., the input voltage has fallen below the window), R_{HL} parallels R_4, thus loading down V_{IN}. The resulting input to the comparator can be referred to as V_{INL} (a lower input voltage). To summarize, when the input is within the window, the output is high, and only R_4 is connected to ground from the comparator's positive terminal. This establishes one–half of V_{IN} to be compared with V_{REFLW}. When the input voltage is below V_{REFLW}, the output is low, and R_{HL} is effectively in parallel with R_4. By voltage division, less of the input voltage will fall across the parallel combination of R_4 and R_{HL}, demanding that a higher input voltage at V_{IN} be required to make the noninverting input exceed V_{REFLW}. Therefore, the following equations are established:

$$\text{HYSTERESIS} = V_{REFLW} - V_{INL},$$

Choose $R_4 = R_5$ to simplify the design.

$$R_{HL} = \frac{R_4R_5(V_{REFLW} - V_{INL} - V_{CC})}{(R_4 + R_5)(V_{INL} - V_{REFLW})}$$

Important Note: As explained above, because the input voltage is divided in half by R_4 and R_5, all calculations are done relative to the one–half value of V_{IN}. Therefore, for a hysteresis of 200 mV (relative to V_{IN}), the preceding equations must use one–half this hysteresis value (100 mV). Also, if a V_{REFLW} value of 2 V is desired (relative to V_{IN}), then 1 V for its value should be used in the preceding equations. The value for V_{INL} should be scaled by one–half also.

The window comparator design can also be designed using operational amplifiers and the same equations as for the LM339 comparator circuit. For the best performance, however, a transistor output stage should be included in the design.

CONCLUSION

The circuits that have been described herein are intended to demonstrate relatively simple and cost effective ways of interfacing the MTS102/103/105 series of solid–state temperature sensors to digital systems. Several examples of simple signal conditioning the temperature sensor's output have been given for both analog temperature measurements, as well as logic–level switch applications. A means of amplifying and level–shifting the sensor's millivolt–level output to a 4 V signal swing (symmetrical with respect to A/D converter range) is demonstrated. The same basic signal conditioning (amplifier) design is used in both types of sensor interfaces. However, the temperature switch design uses an additional comparator stage to create a logic–level output, by comparing the temperature sensor's amplified output voltage to a user–defined reference voltage. The flexibility of the switch design makes it compatible with many different applications. The principal design presented here uses an op–amp with a transistor output stage, yielding excellent logic–level outputs and output transition speeds for many applications. Finally, several other comparison stage designs, including a window comparator, are evaluated and compared for overall performance.

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