Comparator with Hysteresis Reference Design

Circuit Description

Comparators are used to differentiate between two different signal levels. For example, a comparator may differentiate between an over temperature and normal temperature condition. Noise or signal variation at the comparison threshold will cause multiple transitions. Hysteresis sets an upper and lower threshold to eliminate the multiple transitions caused by noise.

Design Resources

Design Archive
- Design Archive
- TI-TI™ SPICE Simulator
- TLV3201 Product Folder
- TLV3401 Product Folder
- TLV1702 Product Folder
- LMV7291 Product Folder
- LM397 Product Folder
- LM331 Product Folder

Ask The Analog Experts
- WEBENCH® Design Center
- TI Designs – Precision Library

Comparator without Hysteresis

Comparator with Hysteresis
1 Design Summary

The design requirements are as follows:

- Supply Voltage: +5 V
- Input: 0V to 5V

The design goals and simulated performance are summarized in Table 1.

Table 1. Comparison of Design Goals, Simulation, and Measured Performance

<table>
<thead>
<tr>
<th>Goal</th>
<th>Goal</th>
<th>Simulated</th>
<th>Measured (TLV3202)</th>
<th>Measured (TLV1702)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VL (Lower Threshold)</td>
<td>2.3V ± 0.1V</td>
<td>2.294V ± 0.001V</td>
<td>2.32V</td>
<td>2.34V</td>
</tr>
<tr>
<td>VH (Upper Threshold)</td>
<td>2.7V ± 0.1V</td>
<td>2.706V ± 0.001V</td>
<td>2.74V</td>
<td>2.76V</td>
</tr>
<tr>
<td>VH - VL</td>
<td>0.4V ± 0.1V</td>
<td>0.412V ± 0.002V</td>
<td>0.42V</td>
<td>0.42V</td>
</tr>
<tr>
<td>Total Current (per channel)</td>
<td>100µA</td>
<td>64µA (average)</td>
<td>62.5445µA (average)</td>
<td>539.3µA (average)</td>
</tr>
</tbody>
</table>

Figure 1 depicts the output for a comparator with and without hysteresis with a noisy input triangle waveform applied. The circuit without hysteresis (Vout_no_hyst) has multiple transitions at the threshold voltage whereas the circuit with hysteresis (Vout_hyst) has a single transition at the threshold.

![Figure 1: Output for a Comparator with and without Hysteresis](image-url)
2 Theory of Operation

Figure 2 shows a typical configuration for a comparator that does not use hysteresis. This configuration uses a voltage divider (Rx and Ry) to set up the threshold voltage. The comparator will compare the input signal (Vin) to the threshold voltage (Vth). The comparator input signal is applied to the inverting input, so the output will have an inverted polarity. When the Vin > Vth the output will drive to the negative supply (GND or logic low in this example). When Vin < Vth the output will drive to the positive supply (Vcc = 5V or logic high in this case). This simple method can be used to determine if a real world signal such as temperature is above some critical value. However, this method has a shortcoming. Noise on the input signal can cause the input to transition above and below the threshold causing an erratic output.

\[
\begin{align*}
\text{Vout} &= \text{GND for Vin} > \text{Vth} \\
\text{Vout} &= \text{Vcc for Vin} < \text{Vth}
\end{align*}
\]

![Comparator without Hysteresis Diagram]

Figure 2: Comparator without Hysteresis
Figure 3 shows the output of a comparator without hysteresis with a noisy input signal. As the input signal approaches the threshold ($V_{th} = 2.5V$), it transitions above and below the threshold multiple times. Consequently, the output transitions multiple times. In practical systems, the multiple transitions can create problems. For example, consider the input signal to be temperature and the output to be a critical monitor which is interpreted by a microcontroller. The multiple output transitions do not provide a consistent message to the microcontroller (e.g. whether temperature at a critical level or not).

Furthermore, consider that the comparator output could be used to control a motor or valve. This erratic transitioning near the threshold would cause the valve or motor to be turned on and off multiple times during the critical transition.

**Figure 3: Output of a Comparator without Hysteresis showing Multiple Transitions near Threshold**
A small change to the comparator circuit can be used to add hysteresis. Hysteresis uses two different threshold voltages to avoid the multiple transitions introduced in the previous circuit. The input signal must exceed the upper threshold (VH) to transition low or below the lower threshold (VL) to transition high.

Figure 4 illustrates hysteresis on a comparator. The resistor Rh sets the hysteresis level. When the output is at a logic high (5V), Rh is in parallel with Rx. This drives more current into Ry, raising the threshold voltage (VH) to 2.7V. The input signal will have to drive above VH=2.7V to cause the output to transition to logic low (0V).

When the output is at logic low (0V), Rh is in parallel with Ry. This reduces the current into Ry, reducing the threshold voltage to 2.3V. The input signal will have to drive below VL=2.3V to cause the output to transition to logic high (5V).

Vin > 2.7V causes Vout to transition to 0V

Vin < 2.3V causes Vout to transition to 5V

Figure 4: Hysteresis Creates Two Thresholds
Figure 5 illustrates the output of a comparator with hysteresis with a noisy input signal. The input must transition above the upper threshold (VH = 2.7V) for the output to transition to logic low (0V). The input must also transition below the lower threshold for the output to transition to logic high (5V). The noise in this example is ignored because of the hysteresis. However, if the noise were larger than the hysteresis range (2.7V – 2.3V) it would generate additional transitions. Thus, the hysteresis range must be wide enough to reject the noise in your application. Section 2.1 provides a method for selecting components to set the thresholds according to your application requirements.

**Figure 5: Output of a Comparator with Hysteresis Showing Single Transition**
2.1 Design of Hysteresis Comparator

Equations (1) and (2) can be used to select the resistors needed to set the hysteresis threshold voltages \( V_H \) and \( V_L \). One value (\( R_x \)) must be arbitrarily selected. In this example, \( R_x \) was set to 100k\( \Omega \) to minimize current draw. \( R_h \) was calculated to be 575k\( \Omega \), so the closest standard value 576k\( \Omega \) was used. The proof for Equations (1) and (2) is given in Appendix A.

\[
\frac{R_h}{R_x} = \frac{V_L}{V_H - V_L} = \frac{2.3V}{2.7V - 2.3V} = 5.75 \tag{1}
\]

\[
\frac{R_y}{R_x} = \frac{V_L}{V_{CC} - V_H} = \frac{2.3V}{5.0V - 2.7V} = 1 \tag{2}
\]

\[
R_h = 5.75R_x \tag{3}
\]

Let \( R_x = 100k\Omega \) \tag{4}

\[
R_y = R_x = 100k\Omega \tag{5}
\]

\[
R_h = 5.75R_x = 5.75(100k\Omega) = 575k\Omega \tag{6}
\]
3 Component Selection

3.1 Comparator Selection

This method can be used for any comparator. In this example we are optimizing for low power, so the TLV3201 was used because it has a low quiescent current (36µA).

3.2 Passive Component Selection

Standard 0.1% metal film resistors were used in simulations. Section 4.1 shows the accuracy and distribution of the hysteresis thresholds. Other tolerance can be used depending on your accuracy and cost considerations.
4 Simulation

The TINA-TI™ schematic shown in Figure 6 includes the circuit values obtained in the design process.

![Figure 6: TINA-TI™ Schematic](image)

Vin

Vnoise

Vtriangle

U2 TLV3201

Rh 576k

Rx 100k

Ry 100k

V2 5

Vout_hyst

5V

Vout_no_hyst

5V

U1 TLV3201

R4 100k

R5 100k

5V

+V
4.1 Hysteresis Thresholds

Figure 7 shows the test of the simulation verifying the threshold voltages on the comparator with hysteresis. The input is an ideal triangle waveform (no noise). Cursers were used post simulation to determine the threshold voltages. The error is primarily from the comparator offset voltage and the difference between the standard resistor value and the ideal value (i.e. Ideal Rh = 575kΩ and Standard Value Rh = 576kΩ).

![Diagram of Comparator with Hysteresis](image)

**Figure 7: Simulated Nominal Threshold Values**

- $V_L = 2.295V$
- $V_H = 2.706V$
- $V_{OUT_{hyst}}$
- $V_{IN}$
Figure 8 shows the results for a Monte Carlo analysis of the circuit from Figure 7. In this simulation the effect of resistor tolerance (0.1%) on the threshold voltages was determined.

**Figure 8: Monte Carlo Analysis of Threshold Voltage Variation vs. Resistor Tolerance**
4.2 **Current Consumption**

Figure 9 is the simulation test circuit used to confirm current flow in this circuit. This simulation was done because low current consumption is a key design consideration for this example. The voltage divider ($I_{div}$) and the comparator quiescent current ($I_{U2}$) are the primary current consumers. The output current ($I_{out}$) is minimal because $R_h$ is a large resistance ($R_h = 576k\Omega$).

![Circuit Diagram](image)

**Figure 9: Circuit for Simulation of Circuit Current Draw**
Figure 10 shows the current draw waveforms for the circuit from Figure 9. The average total current consumption is about 64µA. The current from the divider was simulated to be 23µA and 27µA (calculated = 5V / 200kΩ = 25µA). The divider current could further be reduced by choosing a larger divider resistance. The quiescent current (I_U2) simulates as 39µA (36µA from the data sheet). Note that the device draws significant transient current when the output transitions state. For this reason current consumption will increase during high speed output switching. It is also important to properly decouple the comparator so that the transient current is provided by the decoupling capacitor. Use a 0.1µF ceramic X7R capacitor connected closely to the power supply and ground connection.

![Simulated Current during Comparator Operation](image)

**Figure 10: Simulated Current during Comparator Operation**
4.3 Simulated Results Summary

Table 2 summarizes the simulated performance of the design.

Table 2. Comparison of Design Goals and Simulated Performance

<table>
<thead>
<tr>
<th></th>
<th>Goal</th>
<th>Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>VL (Lower Threshold)</td>
<td>2.3V ± 0.1V</td>
<td>2.294V ± 0.001V</td>
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<tr>
<td>Total Current (per channel)</td>
<td>100μA</td>
<td>64μA (average)</td>
</tr>
</tbody>
</table>
5 PCB Design

The PCB schematic and bill of materials can be found in the Appendix B.

5.1 PCB Layout

The PCB shown in Figure 11 is composed of two layers with all power traces and most signal traces routed on the top layer. The remainder of the top layer is poured with a solid ground plane. Minimal signal traces were routed on the bottom layer to ensure a low impedance path for any return currents on the bottom layer ground plane. Vias were placed at each components ground connection to route return currents to the bottom plane and provide the shortest possible path back to ground. General guidelines for PCB layout were followed. For example, input signal trace lengths were kept to a minimum and decoupling capacitors were placed close to the power pins of the device. This PCB can be used for different types of comparators, such as push-pull, open collector, and open drain. If a pull up resistor is not needed, resistors R1, R2, and R3 can be removed without effecting performance.

Figure 11: PCB Layout
6 Verification & Measured Performance

6.1 Functional Verifications

Figure 12-13 shows the input signal (blue), the rising edge output with no hysteresis (red) and the rising edge output with hysteresis (green) of the TLV3202 and TLV1702, respectively. With no hysteresis, there are multiple transitions at the comparison threshold due to noise on the input signal. These transitions may be the input to a microcontroller, which would not provide a consistent signal for the microcontroller to interpret. Hysteresis gives one clean transition at the upper and lower threshold, which provides a consistent signal to the microcontroller.

Figure 12: TLV3202 rising edge output with and without hysteresis

Figure 13: TLV1702 rising edge output with and without hysteresis
6.2 Measurements

Figure 14 shows a threshold level of 2.5V for the output with no hysteresis. An input signal (blue) of 5V_{pp} and a 2.5V offset was used to take this measurement. To prevent multiple transitions at the threshold level, an input signal with minimal noise was used.

![Figure 14: Threshold level with no hysteresis](image)

Measurements of the upper threshold (V\textsubscript{H}) and lower threshold (V\textsubscript{L}) of the TLV3202 and TLV1702 output with hysteresis are shown in Figures 15-16.

![Figure 15: TLV3202 upper and lower threshold with hysteresis](image)
Figure 16: TLV1702 upper and lower threshold with hysteresis

Table 3: Comparison of Calculated and Measured Performance

<table>
<thead>
<tr>
<th></th>
<th>Calculated</th>
<th>Measured (TLV3202)</th>
<th>Measured (TLV1702)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VL (Lower Threshold)</td>
<td>2.3V</td>
<td>2.32V</td>
<td>2.34V</td>
</tr>
<tr>
<td>VH (Upper Threshold)</td>
<td>2.7V</td>
<td>2.74V</td>
<td>2.76V</td>
</tr>
<tr>
<td>VH - VL</td>
<td>0.4V</td>
<td>0.42V</td>
<td>0.42V</td>
</tr>
</tbody>
</table>

While the calculated threshold limits were 2.7V and 2.3V, there are multiple factors that can affect this measurement, such as, passive element tolerances or a pull-up resistor at the output.
7 Modifications

The hysteresis circuit can be used for any comparator. Table 4 provides examples of different comparators that can be used to achieve different design objectives.

Table 4. Recommended Comparators

<table>
<thead>
<tr>
<th>Output Amplifier</th>
<th>Design Objective</th>
<th>Vs</th>
<th>Iq</th>
<th>Vos</th>
<th>$t_{pd}$ ns</th>
<th>$t_r$ ns</th>
<th>$t_f$ ns</th>
<th>Approx. Price US$ / 1ku</th>
</tr>
</thead>
<tbody>
<tr>
<td>TLV3201</td>
<td>Micro Power, Low Supply, Wide Bandwidth, Push-Pull</td>
<td>2.7V to 5.5V</td>
<td>36</td>
<td>5</td>
<td>47</td>
<td>4.8</td>
<td>5.2</td>
<td>0.40</td>
</tr>
<tr>
<td>TLV3401</td>
<td>Nano Power, Low Supply, Wide Bandwidth, Open-Drain</td>
<td>2.5V to 16V</td>
<td>0.47</td>
<td>0.25</td>
<td>175,000</td>
<td>300,000</td>
<td>5000</td>
<td>0.60</td>
</tr>
<tr>
<td>TLV1702</td>
<td>Micro Power, Low Supply, Open Collector</td>
<td>2.2V to 36V</td>
<td>55</td>
<td>3.5</td>
<td>780</td>
<td>2,000</td>
<td>400</td>
<td>0.61</td>
</tr>
<tr>
<td>LMV7291</td>
<td>Micro Power, Low Supply, Push-Pull</td>
<td>1.8V to 5.5V</td>
<td>9</td>
<td>0.3</td>
<td>-</td>
<td>2100</td>
<td>1380</td>
<td>0.35</td>
</tr>
<tr>
<td>LM397</td>
<td>General Purpose, Open Collector, Wide Supply</td>
<td>5V to 30V</td>
<td>2</td>
<td></td>
<td>-</td>
<td>900</td>
<td>940</td>
<td>0.22</td>
</tr>
<tr>
<td>LM331</td>
<td>General Purpose, Open Collector, Low Supply</td>
<td>2.7V to 5.5V</td>
<td>70</td>
<td>1.7</td>
<td>-</td>
<td>1000</td>
<td>500</td>
<td>0.26</td>
</tr>
</tbody>
</table>

The methods described in this design TI Precision Design were derived for a push-pull output stage. An open-collector output stage requires a pull-up resistor (Rp). The pull-up will create a voltage divider at the comparator output that introduces an error when the output is at logic high. This error can be minimized if $R_h > 100R_p$. Figure 17 shows the design modified for use with an open-collector output. The value of Rp was selected to minimize error ($R_h > 100R_p$). The output will need to drive 1mA for a logic low ($5V/5k\Omega = 1mA$). Additional increase in all the circuits’ resistance can reduce the output drive requirement if needed.

![Figure 17: Hysteresis Design Modified for Open-Collector](image_url)
8 About the Author

Arthur Kay is an applications engineering manager at TI where he specializes in the support of amplifiers, references, and mixed signal devices. Arthur focuses a good deal on industrial applications such as bridge sensor signal conditioning. Arthur has published a book and an article series on amplifier noise. Arthur received his MSEE from Georgia Institute of Technology, and BSEE from Cleveland State University.

Timothy Claycomb joined the Precision Linear Applications team in February 2014. Before joining the team, he was an intern in the summer of 2013. Timothy received his BSEE from Michigan State University.

9 Acknowledgements & References

9.1 Acknowledgements

The author wishes to acknowledge Collin Wells, Tim Green, and Marek Lis for technical contributions to this design.

9.2 References

1. Dave Van Ess, Comparator Hysteresis in a Nutshell, analogzone.net (out of print)
Appendix A. Proof for Equation

A.1 Proof of Equation (1)

\[ V_L = \frac{R_y R_h}{R_y + R_h} V_{cc} = \frac{R_h R_y}{R_h R_x + R_h R_y + R_x R_y} V_{cc} \tag{7} \]

\[ V_H = \frac{R_y}{R_y + R_x R_h + R_h} V_{cc} = \frac{R_h R_y + R_x R_y}{R_h R_x + R_h R_y + R_x R_y} V_{cc} \tag{8} \]

\[ V_H - V_L = \frac{R_y}{R_y + R_x R_h + R_h} V_{cc} = \frac{R_x R_y}{R_h R_x + R_h R_y + R_x R_y} V_{cc} \tag{9} \]

\[ \frac{V_L}{V_H - V_L} = \left( \frac{R_h R_y}{R_h R_x + R_h R_y + R_x R_y} \right) \left( \frac{R_h R_x + R_h R_y + R_x R_y}{R_x R_y} \right) = \frac{R_h}{R_x} \tag{10} \]

A.2 Proof of Equation (2)

\[ V_{cc} - V_H = V_{cc} - \left( \frac{R_h R_y + R_x R_y}{R_h R_x + R_h R_y + R_x R_y} \right) V_{cc} \tag{11} \]

\[ V_{cc} - V_H = \left( \frac{R_x R_h}{R_h R_x + R_h R_y + R_x R_y} \right) V_{cc} \tag{12} \]

\[ \frac{V_L}{V_{cc} - V_H} = \left( \frac{R_h R_y}{R_h R_x + R_h R_y + R_x R_y} \right) \left( \frac{R_h R_x + R_h R_y + R_x R_y}{R_h R_x V_{cc}} \right) \tag{13} \]

\[ \frac{V_L}{V_{cc} - V_H} = \frac{R_y}{R_x} \tag{14} \]
Appendix B.

B.1 Electrical Schematic

Figure B-1: Electrical Schematic

B.2 Bill of Materials

<table>
<thead>
<tr>
<th>Item Number</th>
<th>Quantity</th>
<th>Designator</th>
<th>Value</th>
<th>Description</th>
<th>Manufacturer</th>
<th>Manufacturer Part Number 1</th>
<th>Supplier Part Number 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>C1</td>
<td>10μF</td>
<td>CAP, TA, 10μF, 25V, ±10%; 0.5 ohm, SMD</td>
<td>AVX</td>
<td>TPS010K025R0000</td>
<td>478-1767-1-ND</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>C2</td>
<td>1μF</td>
<td>CAP, CERM, 1μF, 16V, ±10%; X5R, 0603</td>
<td>Kemet</td>
<td>CG063C106K54PACTU</td>
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<tr>
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<td>3</td>
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<td>C5, C7</td>
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<td>3</td>
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<td>0603541510AT2A</td>
<td>478-1365-1-ND</td>
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<td>3</td>
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<td>Vishay-Dale</td>
<td>CRCW060205010NEA</td>
<td>541-1.1KCT-ND</td>
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<td>6</td>
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<td>RES, 10kΩ ±5%, 1W, 0603</td>
<td>Vishay-Dale</td>
<td>CRCW0603100KF0E</td>
<td>541-100KCT-ND</td>
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<tr>
<td>8</td>
<td>2</td>
<td>Rh, Rh2</td>
<td>5kΩ</td>
<td>RES, 5kΩ ±5%, 1W, 0603</td>
<td>Vishay-Dale</td>
<td>CRCW0603564KF0E</td>
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<td>9</td>
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<td>Red</td>
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<td>5005K-ND</td>
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<td>Keystone</td>
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<td>5006K-ND</td>
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<td>5008K-ND</td>
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<td>White</td>
<td>Test Point, Compact, White, TH</td>
<td>Keystone</td>
<td>5007</td>
<td>5007K-ND</td>
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<tr>
<td>13</td>
<td>1</td>
<td>TP7</td>
<td>White</td>
<td>Test Point, Compact, White, TH</td>
<td>Keystone</td>
<td>5007</td>
<td>5007K-ND</td>
</tr>
<tr>
<td>14</td>
<td>1</td>
<td>TP8</td>
<td>Orange</td>
<td>Test Point, Compact, Orange, TH</td>
<td>Keystone</td>
<td>5008</td>
<td>5008K-ND</td>
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<td>TP10</td>
<td>White</td>
<td>Test Point, Compact, White, TH</td>
<td>Keystone</td>
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<td>5007K-ND</td>
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<td>Texas Instruments</td>
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<td>296-37236-2-ND</td>
<td></td>
</tr>
<tr>
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<td>U2</td>
<td>2.2-V to 36-V, microPower Comparator</td>
<td>Texas Instruments</td>
<td>TLV1701ADGKR</td>
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<td>U90, U91, U92, U93</td>
<td>STANDOFF HEX 4-40TH ALUM 1L&quot;</td>
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<td>2205</td>
<td>2205K-ND</td>
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</tr>
<tr>
<td>19</td>
<td>4</td>
<td>U94, U95, U96, U97</td>
<td>MACHINE SCREW PAN PHILLIPS 6-40</td>
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<td>M705-ND</td>
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<td>J1, J2</td>
<td>JACK NON-INSULATED 25P, KEYSTONE+</td>
<td>Keystone Electronics</td>
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<td>PCB FOR TI REF DESIGN TIP0144</td>
<td>American PCB Company</td>
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