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TI Designs – Precision: Verified Design

Comparator with Hysteresis Reference Design

TEXAS INSTRUMENTS

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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	All Design files
TINA-TI™	SPICE Simulator
TLV3201	Product Folder
TLV3401	Product Folder
TLV1702	Product Folder
LMV7291	Product Folder
LM397	Product Folder
LM331	Product Folder

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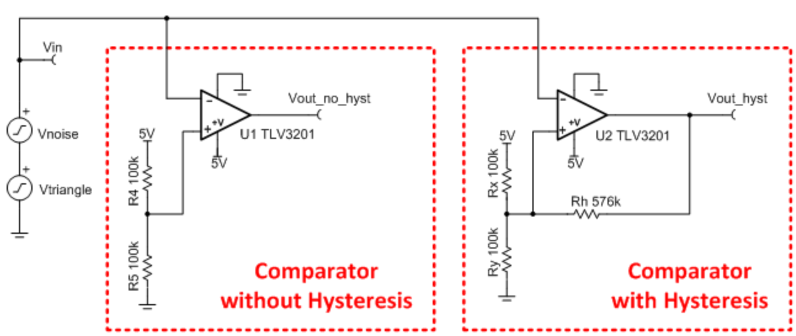

1 Design Summary

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

	Goal	Simulated	Measured (TLV3202)	Measured (TLV1702)
VL (Lower Threshold)	2.3V ± 0.1V	2.294V ± 0.001V	2.32V	2.34V
VH (Upper Threshold)	2.7V ± 0.1V	2.706V ± 0.001V	2.74V	2.76V
VH - VL	0.4V± 0.1V	0.412V ± 0.002V	0.42V	0.42V
Total Current (per channel)	100µA	64µA (average)	62.5445uA (average)	539.3uA (average)

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.

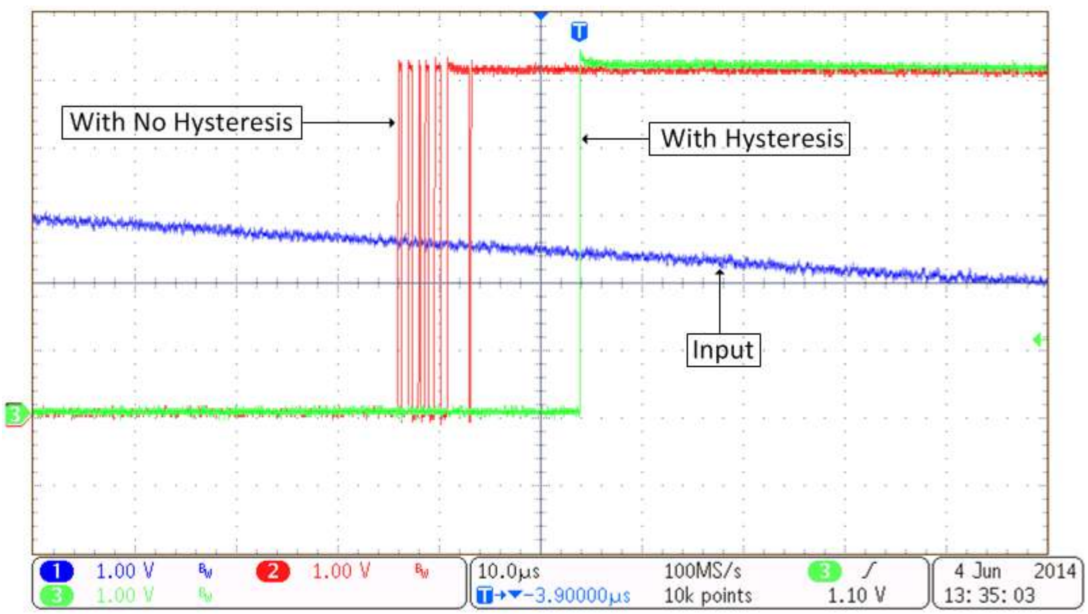

Figure 1: Output for a Comparator with and without Hysteresis

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.

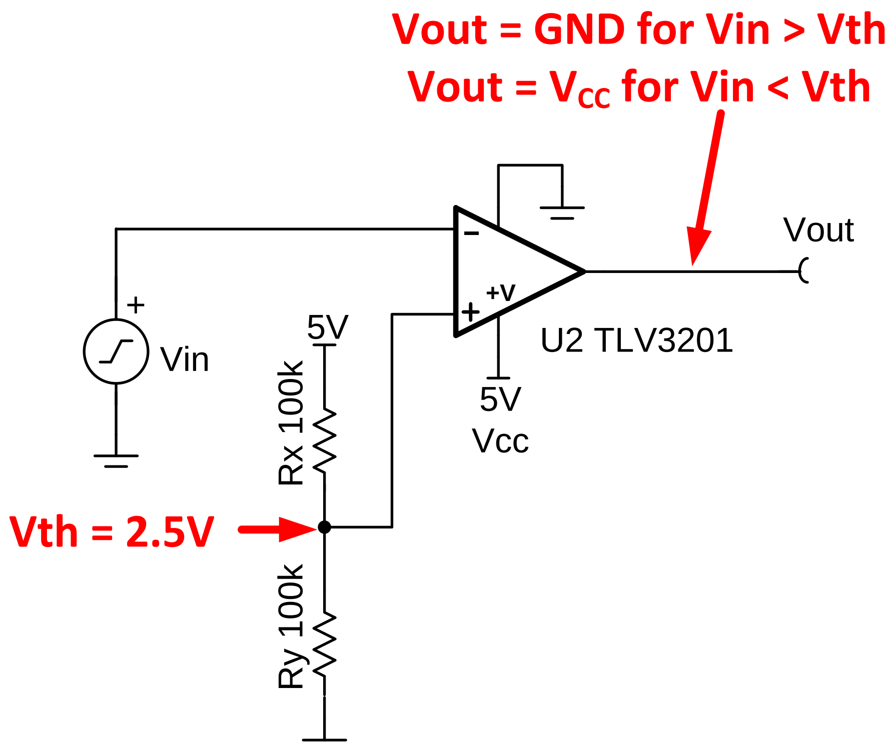

Figure 2: Comparator without Hysteresis

Figure 3 shows the output of a comparator without hysteresis with a noisy input signal. As the input signal approaches the threshold (Vth = 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.

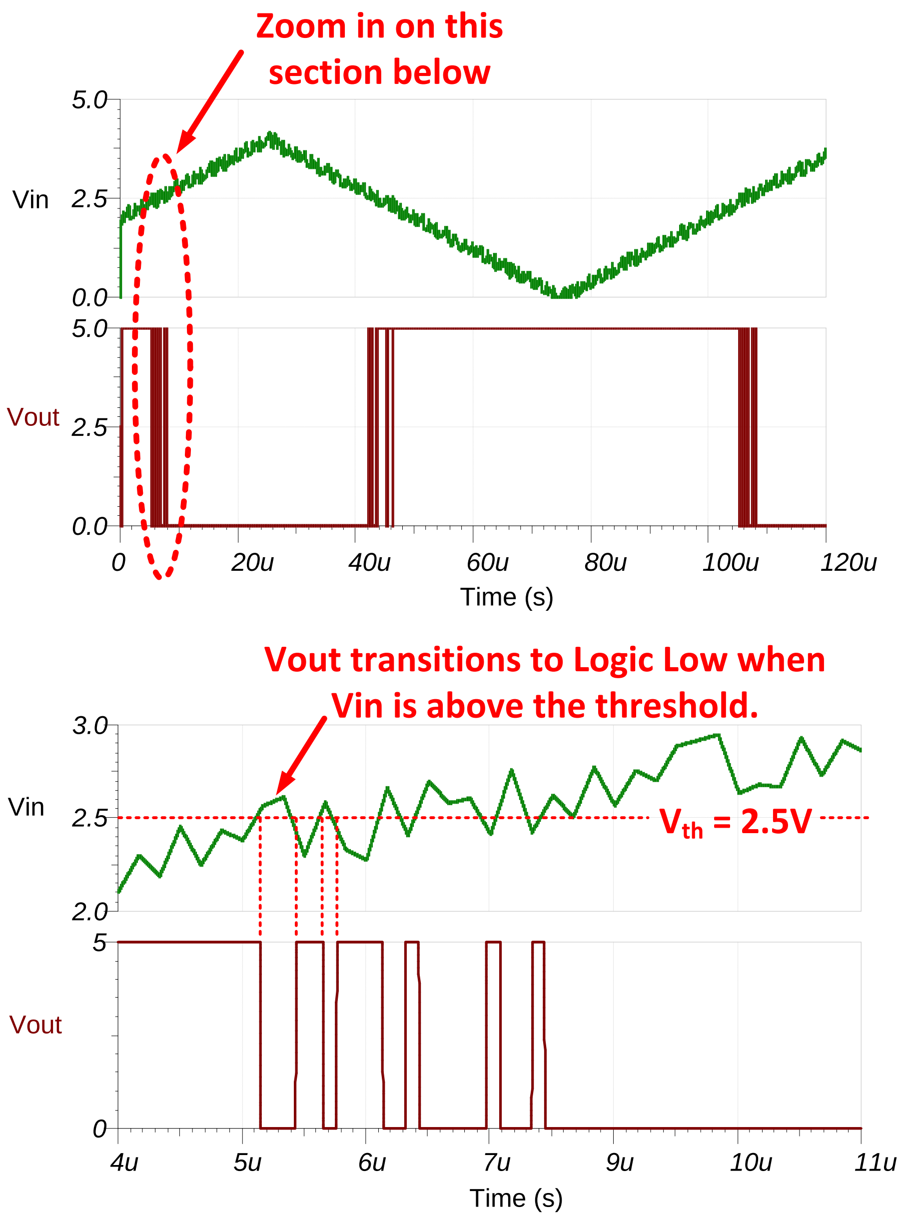

Figure 3: Output of a Comparator without Hysteresis showing Multiple Transitions near Threshold

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).

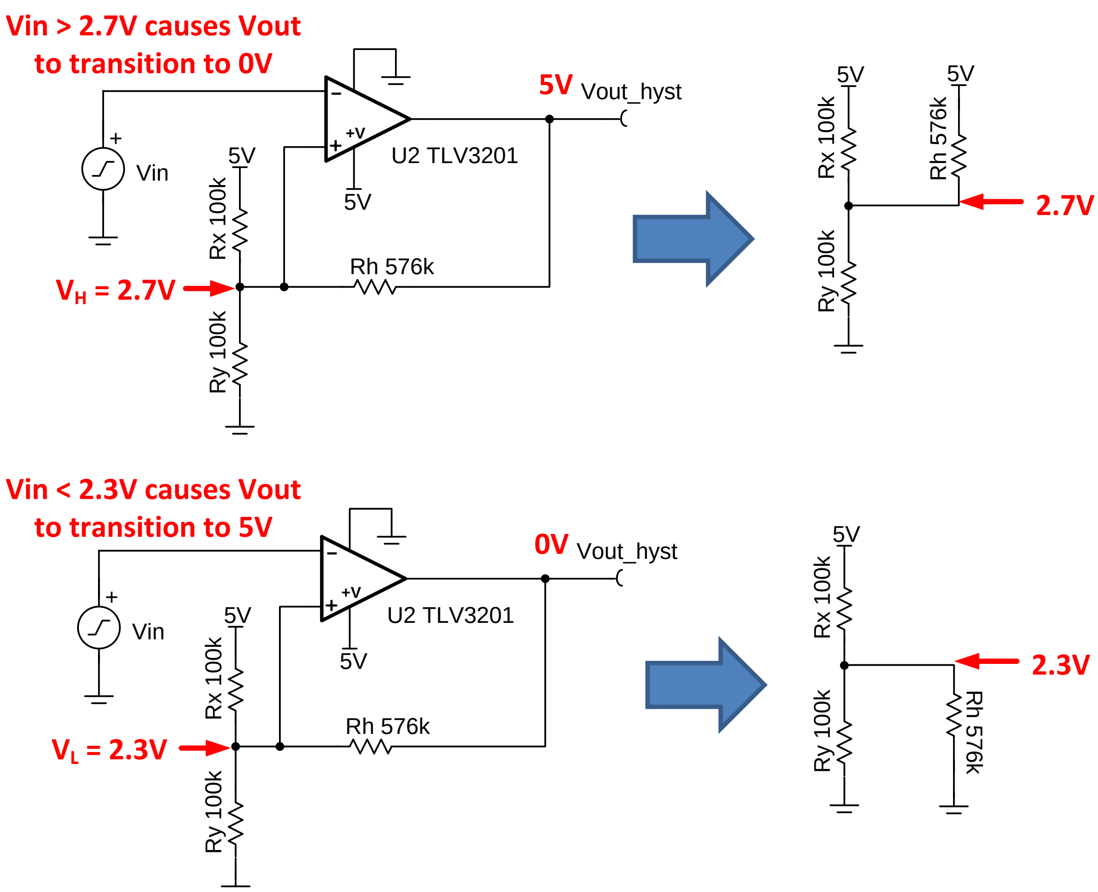

Figure 4: Hysteresis Creates Two Thresholds

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.

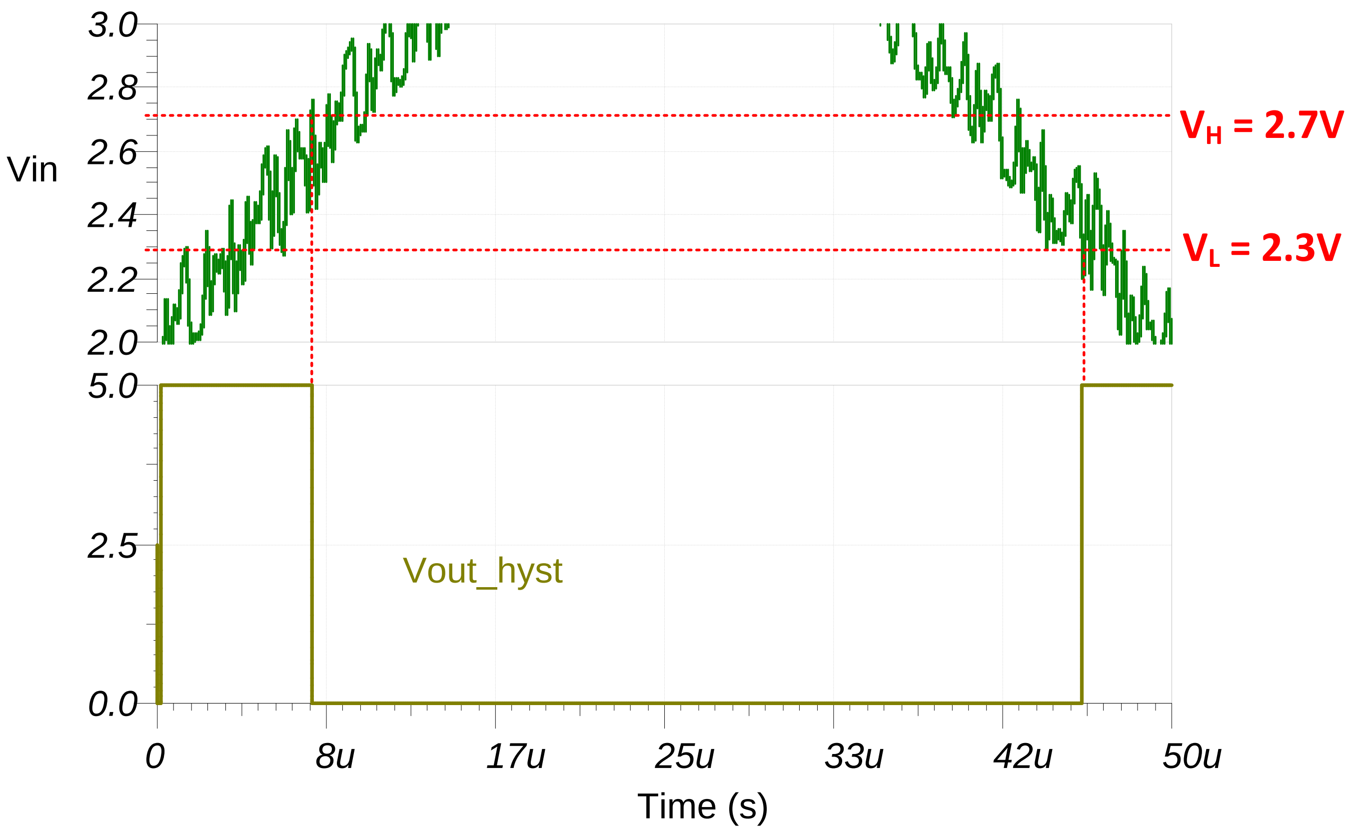

Figure 5: Output of a Comparator with Hysteresis Showing Single Transition

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 100kΩ to minimize current draw. R_h was calculated to be 575kΩ, so the closest standard value 576kΩ was used. The proof for Equations (1) and (2) is given in Appendix A.

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

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

$$R_h = 5.75R_x \tag{3}$$

$$\text{Let } R_x = 100k\Omega \tag{4}$$

$$R_y = R_x = 100k\Omega \tag{5}$$

$$R_h = 5.75R_x = 5.75(100k\Omega) = 575k\Omega \tag{6}$$

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 la 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.

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4 Simulation

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

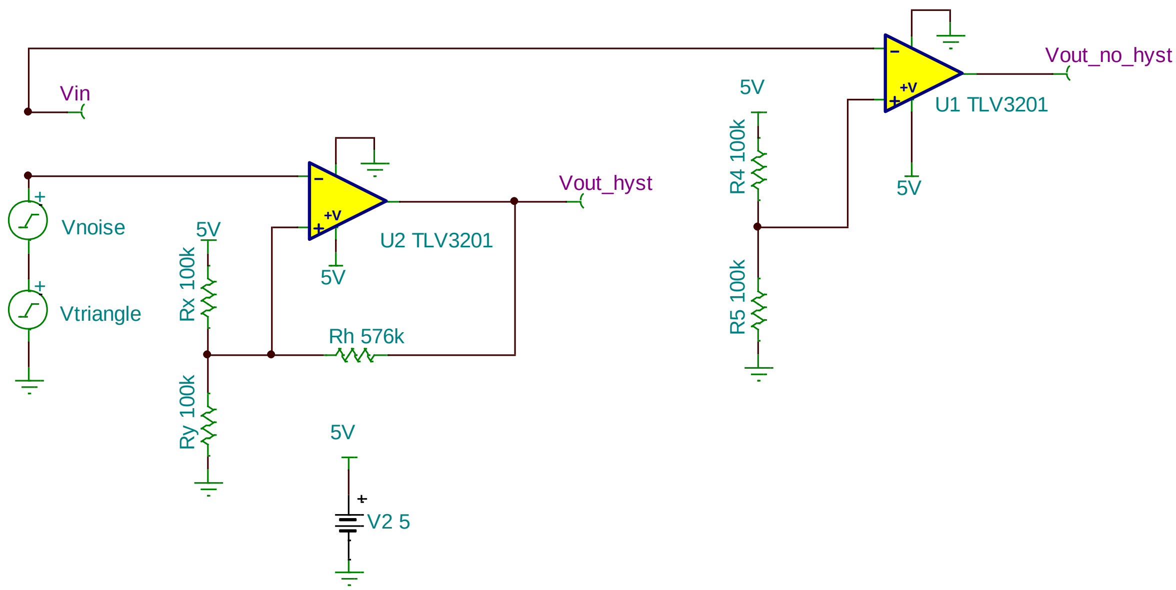

Figure 6: TINA-TI™ Schematic

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).

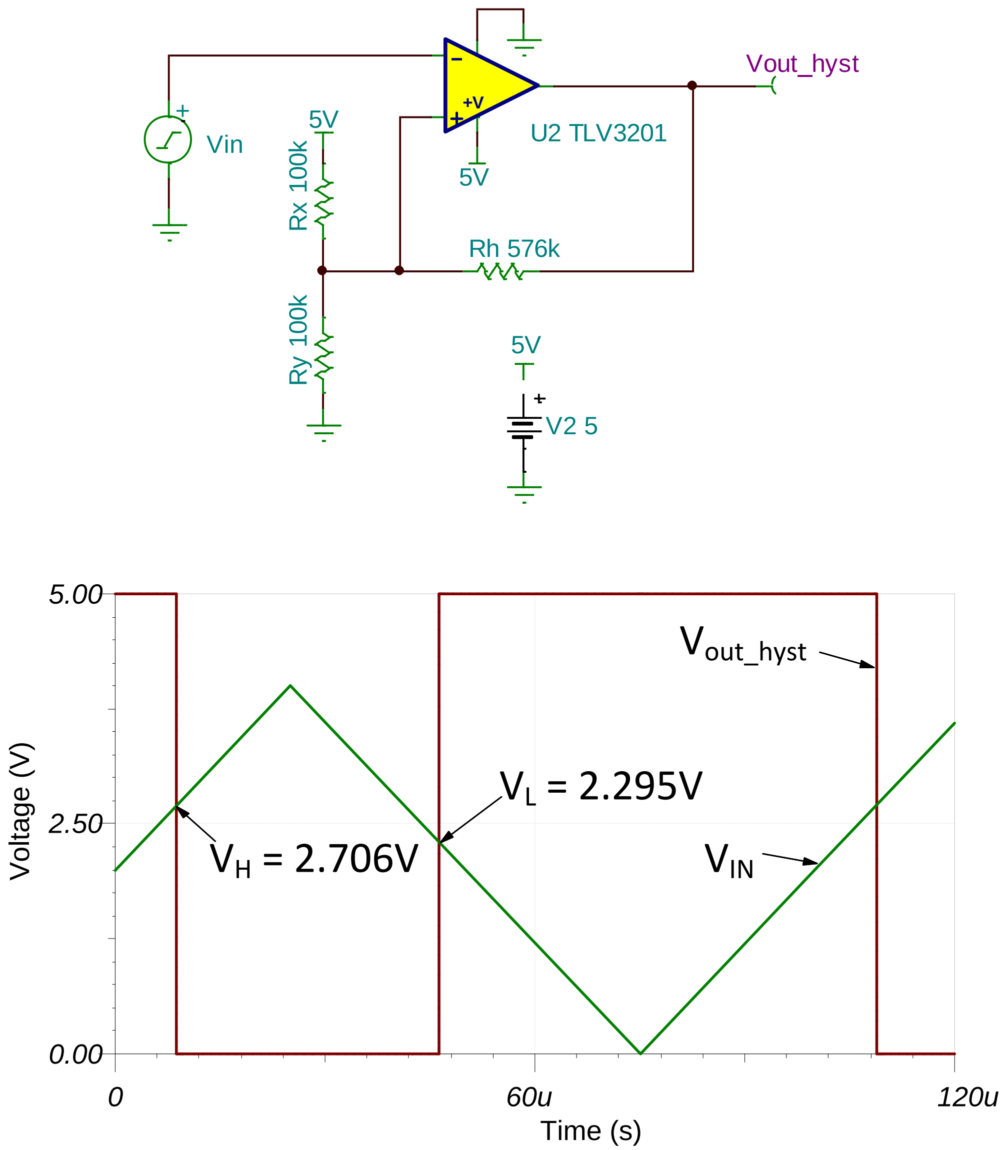

Figure 7: Simulated Nominal Threshold Values

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.

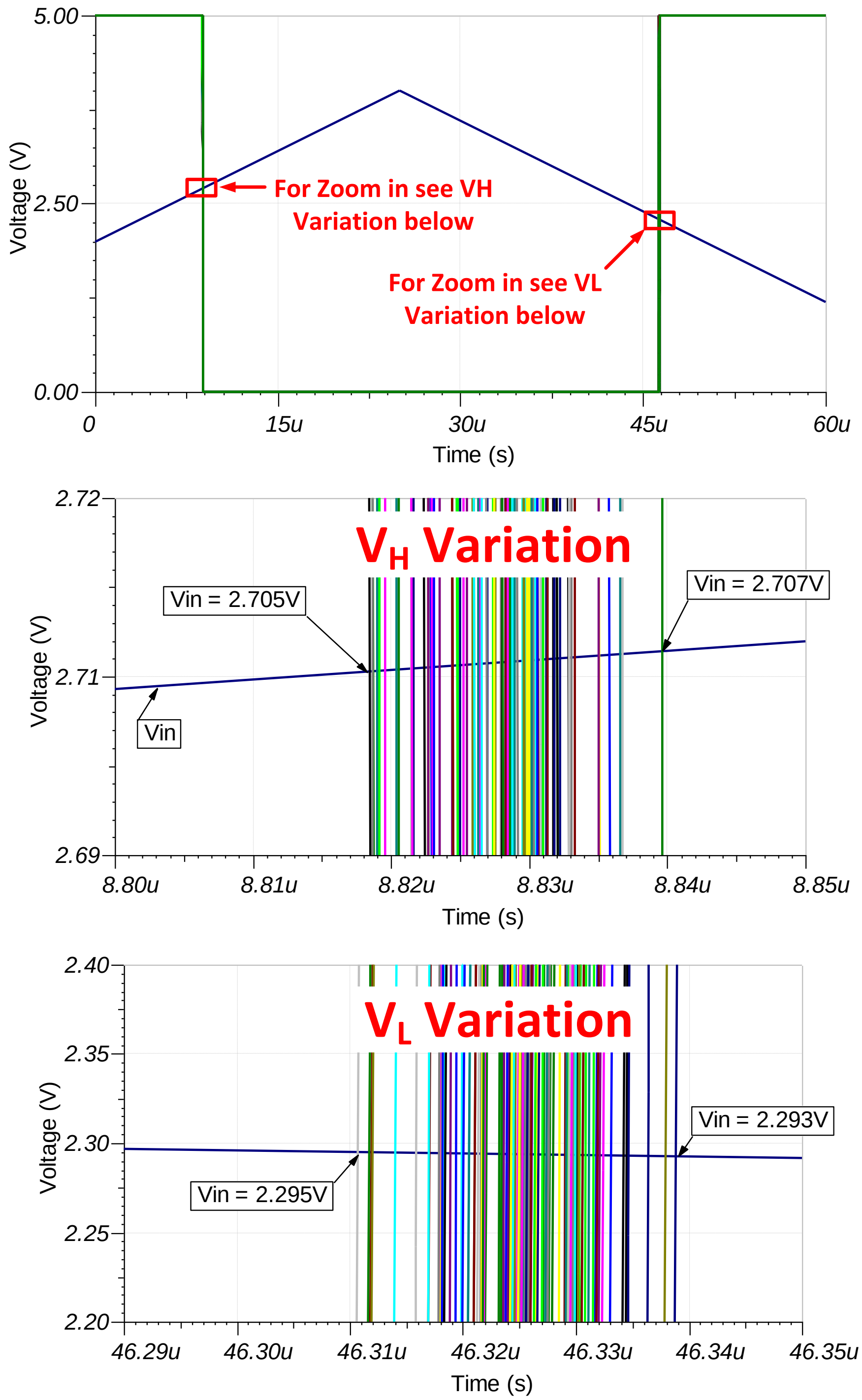

Figure 8: Monte Carlo Analysis of Threshold Voltage Variation vs. Resistor Tolerance

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 (Idiv) and the comparator quiescent current (I_U2) are the primary current consumers. The output current (Iout) is minimal because Rh is a large resistance (Rh = 576kΩ).

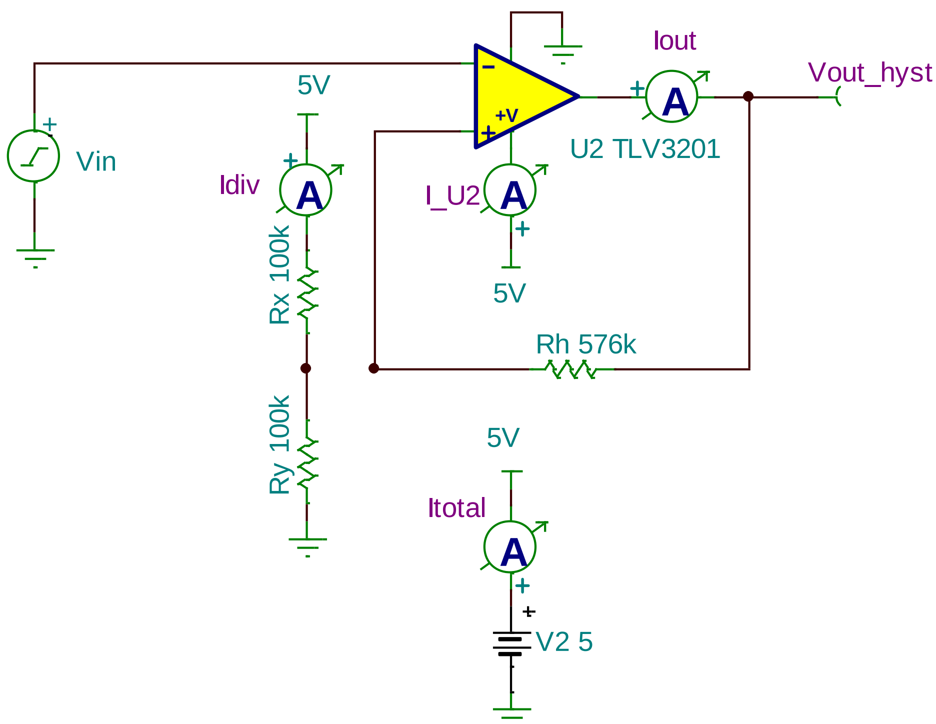

Figure 9: Circuit for Simulation of Circuit Current Draw

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.

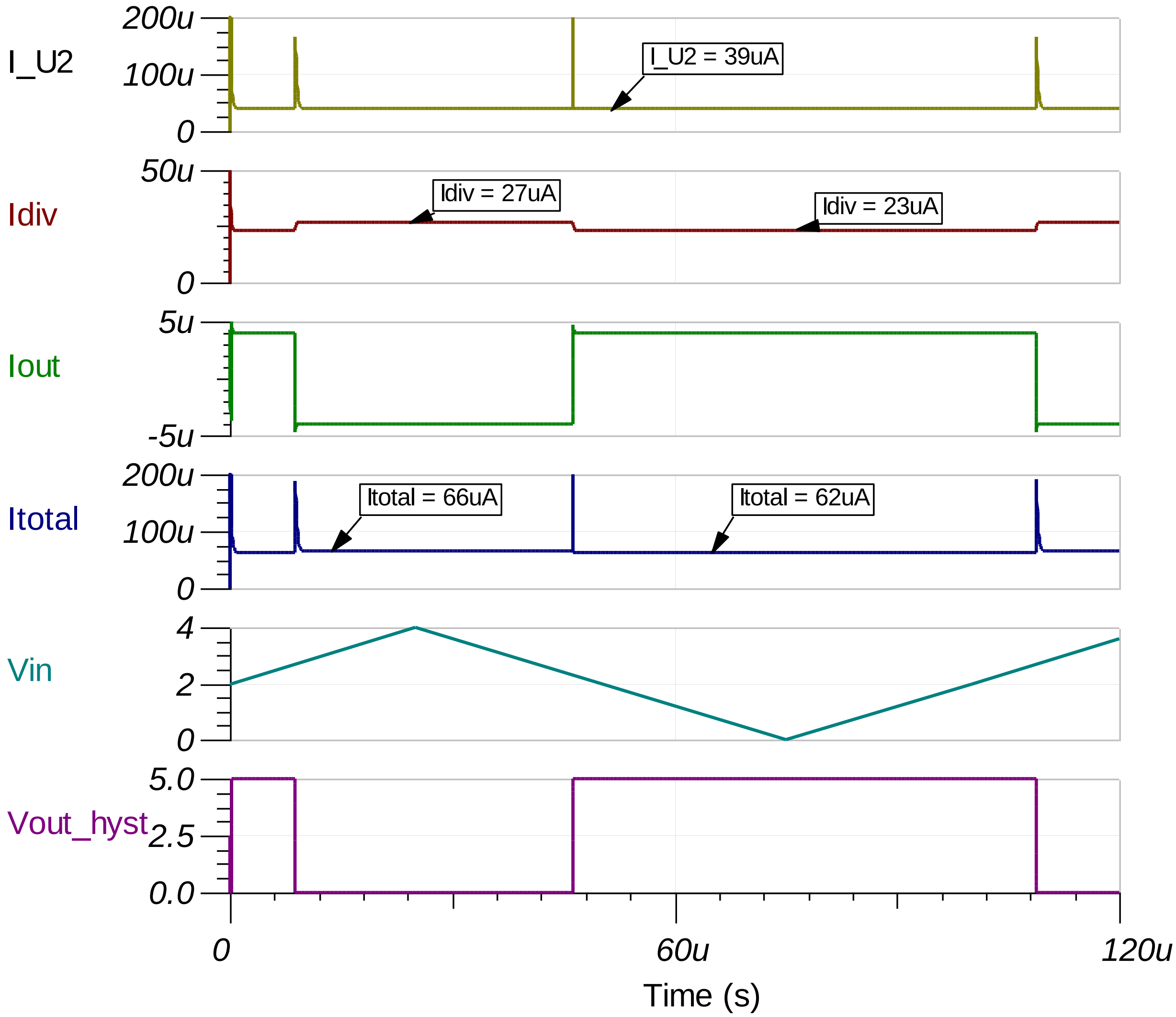

Figure 10: Simulated Current during Comparator Operation

4.3 Simulated Results Summary

Table 2 summarizes the simulated performance of the design.

Table 2. Comparison of Design Goals and Simulated Performance

	Goal	Simulated
VL (Lower Threshold)	2.3V ± 0.1V	2.294V ± 0.001V
VH (Lower Threshold)	2.7V ± 0.1V	2.706V ± 0.001V
VH - VL	0.4V± 0.1V	0.412V ± 0.002V
Total Current (per channel)	100µA	64µA (average)

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.

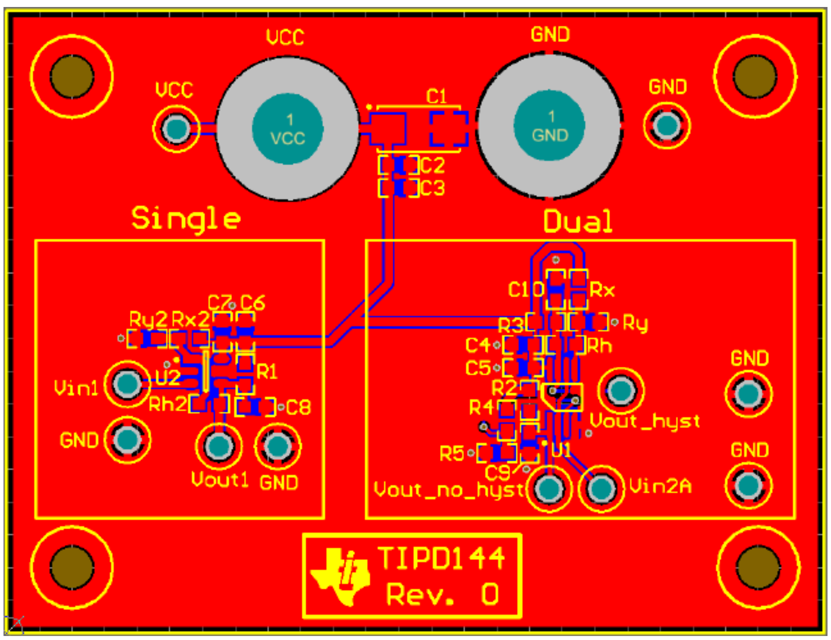

Figure 11: PCB Layout

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 theTLV3202 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.

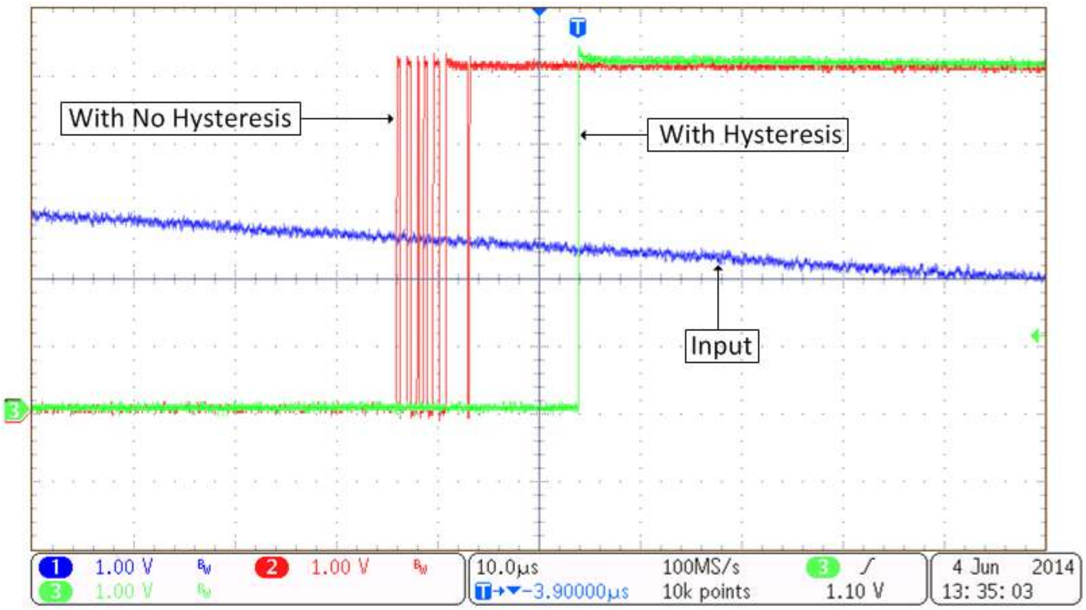

Figure 12: TLV3202 rising edge output with and without hysteresis

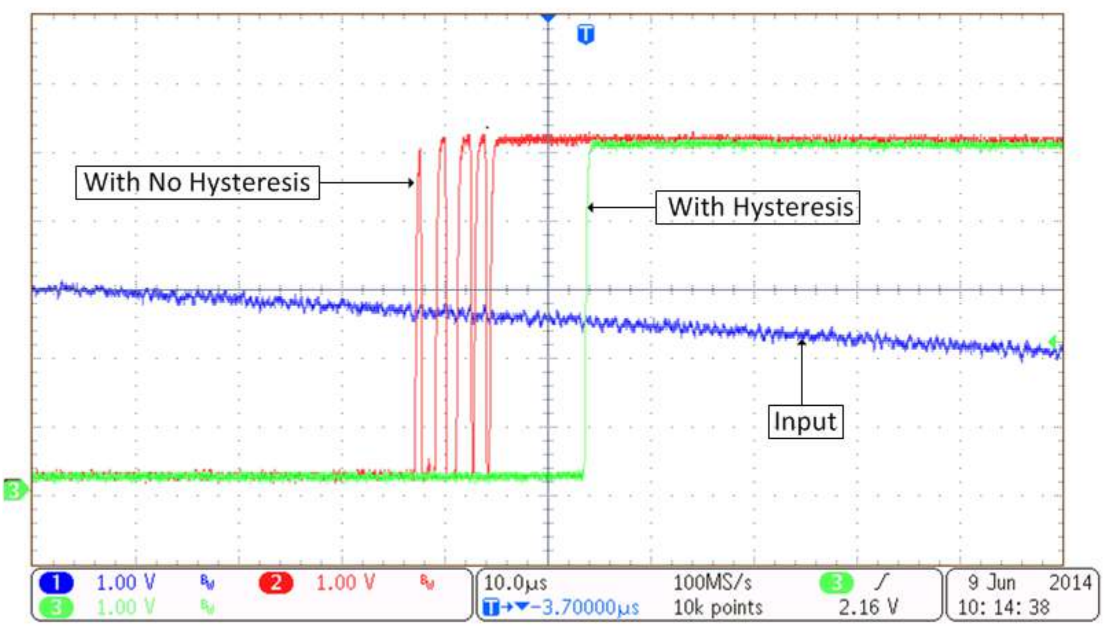

Figure 13:TLV1702 rising edge output with and without hysteresis

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.

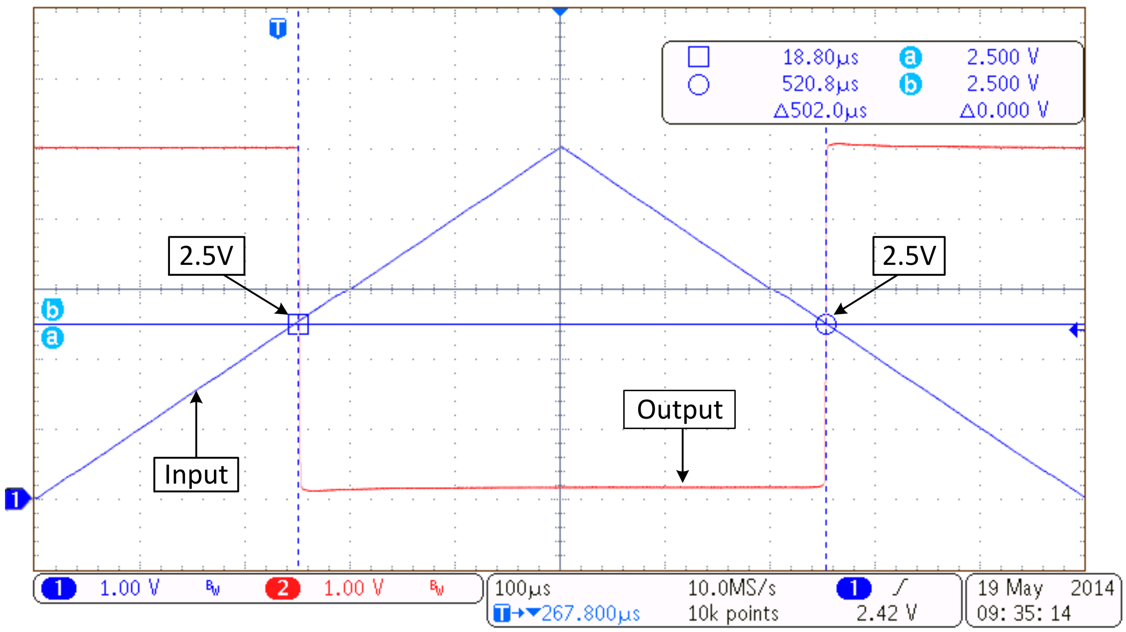

Figure 14: Threshold level with no hysteresis

Measurements of the upper threshold (VH) and lower threshold (VL) of the TLV3202 and TLV1702 output with hysteresis are shown in Figures 15-16.

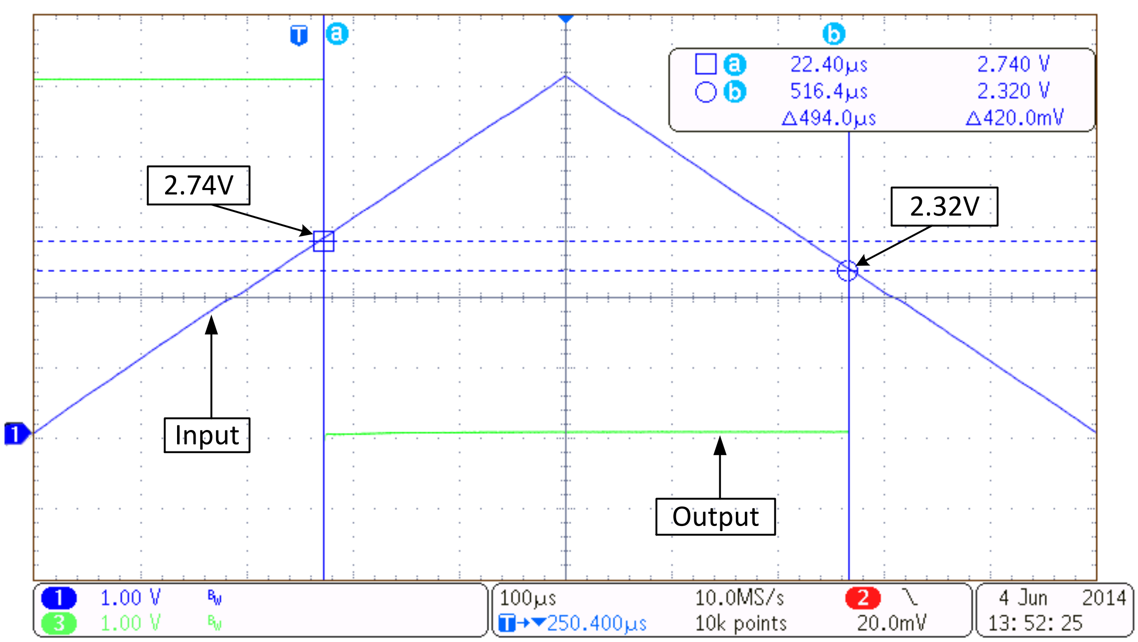

Figure 15: TLV3202 upper and lower threshold with hysteresis

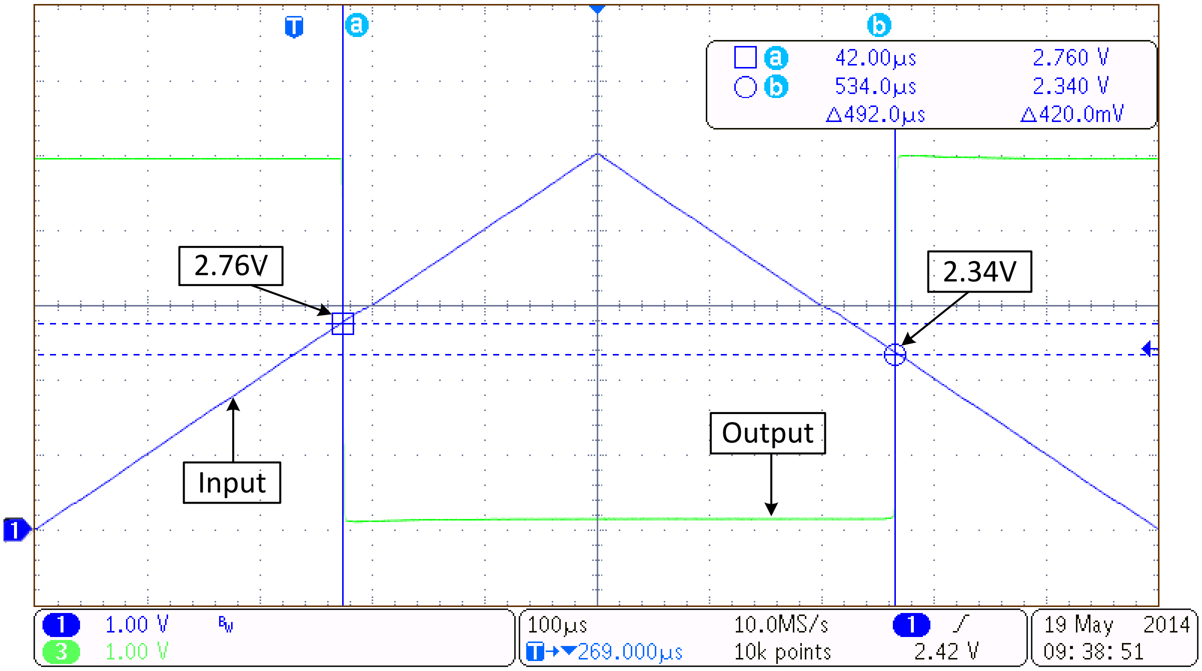

Figure 16: TLV1702 upper and lower threshold with hysteresis

Table 3: Comparison of Calculated and Measured Performance

	Calculated	Measured (TLV3202)	Measured (TLV1702)
VL (Lower Threshold)	2.3V	2.32V	2.34V
VH (Upper Threshold)	2.7V	2.74V	2.76V
VH - VL	0.4V	0.42V	0.42V

While the calculated threshold limits were 2.7V and 2.3V, there are multiple factors that can effect 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

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

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 Rh > 100Rp. Figure 17 shows the design modified for use with an open-collector output. The value of Rp was selected to minimize error (Rh > 100Rp). The output will need to drive 1mA for a logic low (5V/5kΩ = 1mA). Additional increase in all the circuits' resistance can reduce the output drive requirement if needed.

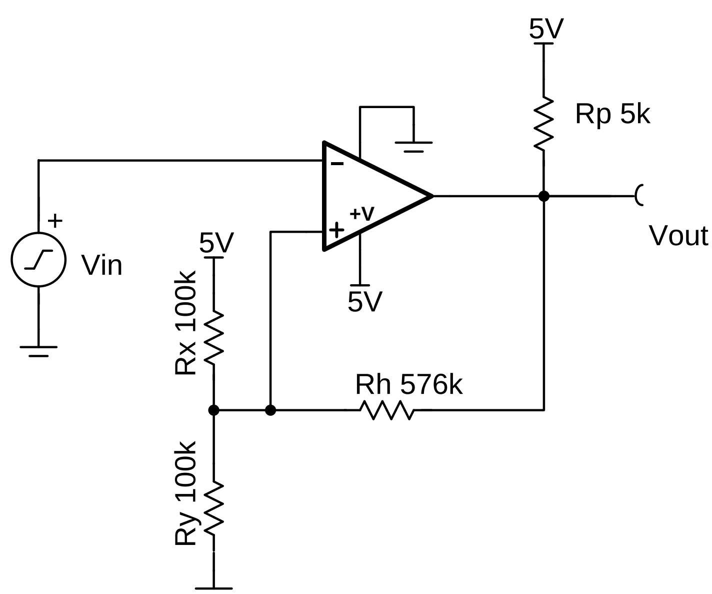

Figure 17: Hysteresis Design Modified for Open-Collector

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)

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

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

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

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

A.2 Proof of Equation (2)

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

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

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

$$\frac{V_L}{V_{cc} - V_H} = \frac{R_y}{R_x} \tag{14}$$

Appendix B.

B.1 Electrical Schematic

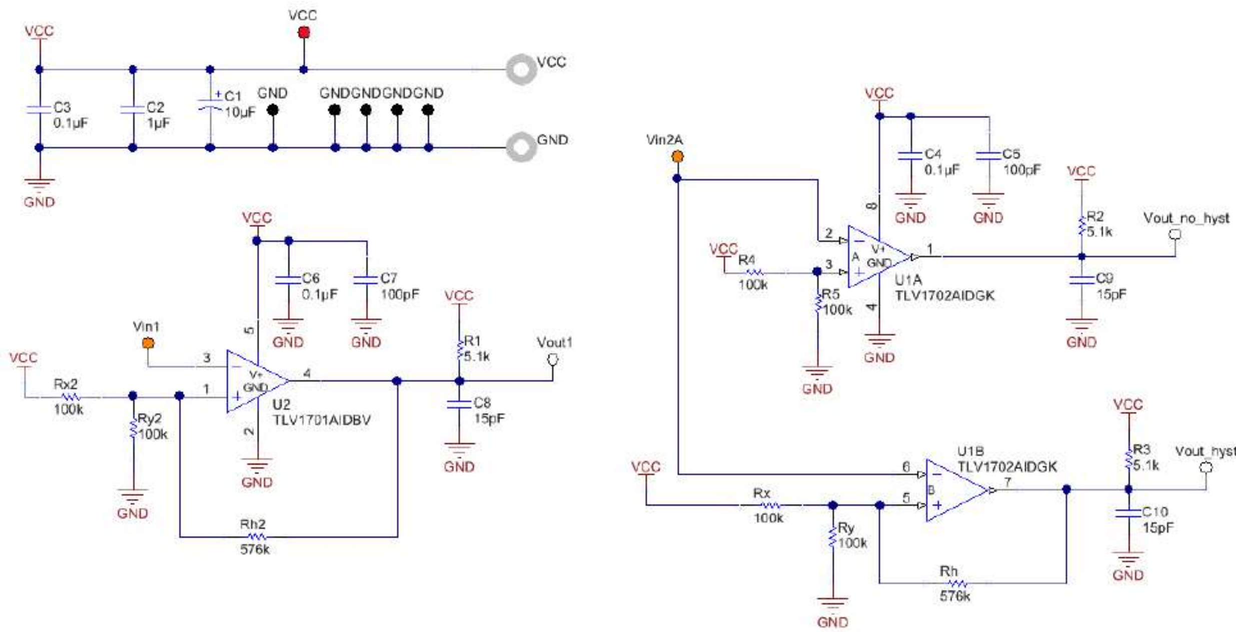

Figure B-1: Electrical Schematic

B.2 Bill of Materials

Item Number	Quantity	Designator	Value	Description	Manufacturer	Manufacturer Part Number 1	Supplier Part Number 1
1	1	C1	10uF	CAP, TA, 10uF, 25V, +/-10%, 0.5 ohm, SMD	AVX	TPSC106K025R0500	478-1762-1-ND
2	1	C2	1uF	CAP, CERM, 1uF, 16V, +/-10%, X5R, 0603	Kemet	C0603C105K4PACTU	399-5090-1-ND
3	3	C3, C4, C6	0.1uF	CAP, CERM, 0.1uF, 25V, +/-10%, X7R, 0603	AVX	06033C104KAT2A	478-3714-1-ND
4	2	C5, C7	100pF	CAP, CERM, 100pF, 50V, +/-5%, C0G/NP0, 0603	AVX	06035A101JAT2A	478-1175-1-ND
5	3	C8, C9, C10	15pF	CAP, CERM, 15pF, 50V, +/-5%, C0G/NP0, 0603	AVX	06035A150JAT2A	478-1165-1-ND
6	3	R1, R2, R3	5.1k	RES, 5.1k ohm, 5%, 0.1W, 0603	Vishay-Dale	CRCW06035K10JNEA	541-5.1KGCT-ND
7	6	R4, R5, Rx, Rx2, Ry, Ry2	100k	RES, 100k ohm, 1%, 0.1W, 0603	Vishay-Dale	CRCW0603100KFKEA	541-100KHCT-ND
8	2	Rh, Rh2	576k	RES, 576k ohm, 1%, 0.1W, 0603	Vishay-Dale	CRCW0603576KFKEA	541-576KHCT-ND
9	1	TP1	Red	Test Point, TH, Compact, Red	Keystone	5005	5005K-ND
10	5	TP2, TP4, TP11, TP12, TP13	Black	Test Point, TH, Compact, Black	Keystone	5006	5006K-ND
11	1	TP5	Orange	Test Point, Compact, Orange, TH	Keystone	5008	5008K-ND
12	1	TP6	White	Test Point, Compact, White, TH	Keystone	5007	5007K-ND
13	1	TP8	White	Test Point, Compact, White, TH	Keystone	5007	5007K-ND
14	1	TP9	Orange	Test Point, Compact, Orange, TH	Keystone	5008	5008K-ND
15	1	TP10	White	Test Point, Compact, White, TH	Keystone	5007	5007K-ND
16	1	U1		2.2-V to 36-V, microPower Comparator	Texas Instruments	TLV1702AIDGKR	296-37236-2-ND
17	1	U2		2.2-V to 36-V, microPower Comparator	Texas Instruments	TLV1701AIDGKR	
18	4	U90, U91, U92, U93		STANDOFF HEX 4-40THR ALUM 1L"	Keystone	2205	2205K-ND
19	4	U94, U95, U96, U97		MACHINE SCREW PAN PHILLIPS 4-40	B&F Fastener Supply	PMSSS 440 0025 PH	H703-ND
20	2	J1, J2		JACK NON-INSULATED .218",Keystone"	Keystone Electronics	575-4	575-4K-ND
21	1	N/A		PCB FOR TI REF DESIGN TIPD144	American PCB Company	TIPD144	

Figure B-2: Bill of Materials

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