

# Bidirectional Current Sensing with a Window Comparator Circuit

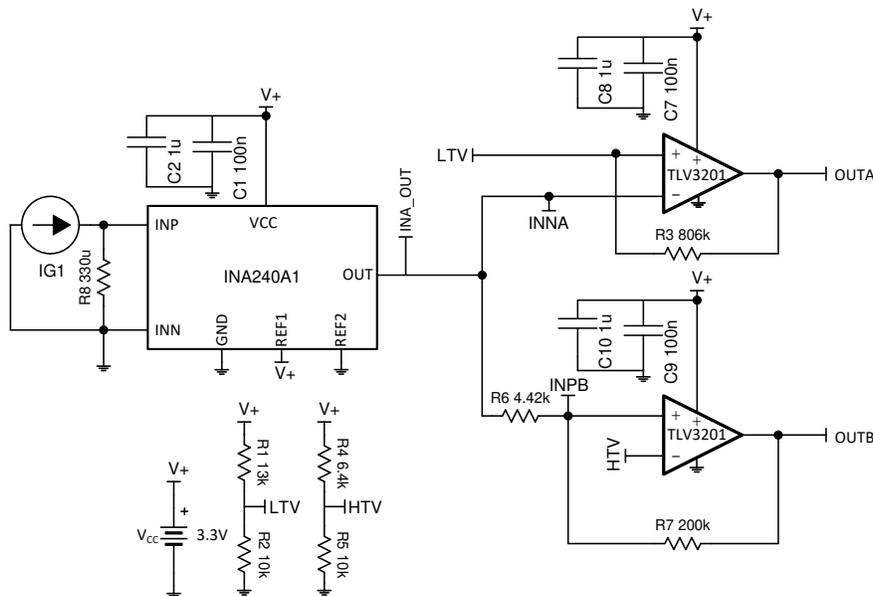


## Design Goals

SYSTEM CURRENT LEVELS				SUPPLY	
Falling OC Threshold	Falling OC Recovery	Rising OC Threshold	Rising OC Recovery	V+	V-
IG1 < -35 A	IG1 > -31 A	IG1 > 100 A	IG1 < 90 A	3.3 V	0 V

## Design Description

This bidirectional current sensing solution uses a current-sense amplifier and a high speed dual comparator with a rail-to-rail input common mode range to create over-current (OC) alert signals at the comparator outputs (OUTA and OUTB) if the input current (IG1) rises above 100 A or falls below -35 A. In this implementation, both over-current alert signals are active high, so when the 100 A or -35 A thresholds are crossed, the comparator outputs will go high. External hysteresis is implemented on both comparators so that the comparator outputs will return to logic low states when the current reduces by 10% (90 A and -31 A). While the circuit below has shunt resistor R8 connected to ground, the same circuit is applicable for high side current sensing up to the common mode voltage range of the INA.



## Design Notes

1. Select a comparator with rail-to-rail input common mode range.
2. Select a current sense amplifier with low offset voltage and a common mode input range that matches the requirements of the system.

## Design Steps

- To determine the comparator threshold voltages, first calculate the INA240A1 output voltages that correspond to the desired current thresholds. The calculations depend on the gain of the INA240 (20, 50, 100, 200 for A1, A2, A3, A4, respectively), the input current (IG1) and sense resistor (R8), and the reference voltage when the input current is 0 (VREF). Per section 8.3.2 in the INA240 data sheet, R8 is a function of the differential input voltage and the maximum input current to the INA240. Given that the input current in this system swings above 100 A, by keeping R8 small, the power dissipation across R8 will be lessened.

$$\text{INA\_OUT} = \text{VREF} + G \times (\text{INP} - \text{INN})$$

$$\text{INP} - \text{INN} = \text{IG1} \times \text{R8}$$

$$\text{VREF} = \frac{(\text{V}_+) - 0}{2} = \frac{3.3\text{V}}{2} = 1.65\text{V}$$

Using these equations and the desired current thresholds, the following table is generated:

DESCRIPTION		IG1	INA-OUT
V <sub>H, CHB</sub>	Overcurrent threshold in forward direction	100 A	1.65 V + 20 x (100 A x 0.33 mΩ) = 2.31 V
V <sub>L, CHB</sub>	<i>Recovery threshold</i> in forward direction	90 A	1.65 V + 20 x (90 A x 0.33 mΩ) = 2.244 V
V <sub>H, CHA</sub>	Overcurrent threshold in reverse direction	-35 A	1.65 V + 20 x (-35 A x 0.33 mΩ) = 1.419 V
V <sub>L, CHA</sub>	<i>Recovery threshold</i> in reverse direction	-31.5 A	1.65 V + 20 x (-31.5 A x 0.33 mΩ) = 1.4421 V

First, focus on the top comparator (channel A), which is in an inverting comparator configuration. This comparator will swing to a logic high when the current in the reverse direction exceeds -35 A, and will return to a logic low when the current in the reverse direction recovers to -31.5 A. These current levels correspond to voltage levels of 1.419 V and 1.4421 V, respectively.

- Assume a value for R2 (the bottom resistor in the resistor divider). In this circuit, 10 kΩ is chosen.
- Derive two equations for R1 in terms of V<sub>+</sub>, V<sub>L</sub>, V<sub>H</sub>, R<sub>2</sub>, R<sub>3</sub> by analyzing the circuit when INNA = V<sub>L</sub> and when INNA = V<sub>H</sub>:

$$R_1 = \left( \frac{V_+}{V_L} - 1 \right) \left( \frac{R_2 R_3}{R_2 + R_3} \right)$$

$$R_1 = \frac{V_+ - V_H}{\frac{V_H}{R_2} - \frac{V_+ - V_H}{R_3}}$$

- Set these two equations equal to each other and then solve for R<sub>3</sub>.

$$\left( \frac{V_+ - V_H}{V_L} - V_H \right) R_3^2 + \left( \frac{V_+ - V_H}{V_L} + V_+ - V_H \right) R_2 R_3 = 0$$

$$\left( \frac{3.3 - 1.4421}{1.419} - 1.4421 \right) R_3^2 + \left( \frac{3.3 - 1.4421}{1.419} + 3.3 - 1.4421 \right) (10\text{k}) R_3 = 0$$

$$R_3 = 0, \quad R_3 = 804.29\text{k}\Omega$$

The standard 1% resistor value closest to this is 806 kΩ.

5. Solve for  $R_1$  using any of the two equations derived in 3:

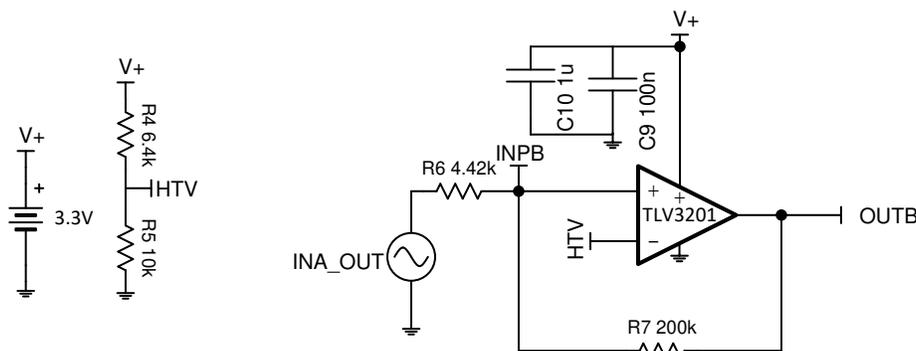
$$R_1 = \left( \frac{V_+}{V_L} - 1 \right) \left( \frac{R_2 R_3}{R_2 + R_3} \right)$$

$$R_1 = \left( \frac{3.3}{1.419} - 1 \right) \left( \frac{(10 \text{ k}\Omega)(806 \text{ k}\Omega)}{10 \text{ k}\Omega + 806 \text{ k}\Omega} \right)$$

$$R_1 = 13.093 \text{ k}\Omega$$

The standard 1% resistor value closest to this is 13 k $\Omega$ .

The next step is to focus on the bottom comparator (channel B), which is in a non-inverting configuration. This comparator will swing to a logic high when the current in the forward direction exceeds 100A, and will return to a logic low when the current in the forward direction recovers to 90A. These current levels correspond to voltage levels of 2.31 V and 2.244 V, respectively.



**Figure 1-1.**

SBOA306 (*High-side current sensing with comparator circuit*) derives two equations for  $V_{TH}$  (the voltage on the non-inverting pin) when the comparator output is in a logic low state and a high-impedance state (SBOA306 uses an open-drain comparator). These equations are then set equal to each other creating a quadratic equation to solve for  $R_6$ . Since TLV3202 is a push-pull device, the output will go to a logic high state instead of a high-impedance state. Thus, the pull-up resistor value is 0 and  $V_{PU}$  is  $V_+$ .

6. Rewrite the quadratic equation to match this circuit:

$$0 = V_+ \times R_6^2 + (V_+ \times R_7 + V_L \times (R_7) - V_H \times R_7) \times R_6 + (V_L - V_H) \times (R_7^2)$$

$$0 = 3.3 \times R_6^2 + (3.3 \times R_7 + 2.244 \times (R_7) - 2.31 \times R_7) \times R_6 + (2.244 - 2.31) \times (R_7^2)$$

7. Choose a value for  $R_7$ . This resistor dictates the load current of the comparator, and should thus be large. For this circuit,  $R_7$  is assumed to be 200 k $\Omega$ .

$$0 = 3.3 \times R_6^2 + (3.3 \times 200\text{k} + 2.244 \times (200\text{k}) - 2.31 \times 200\text{k}) \times R_6 + (2.244 - 2.31) \times (200\text{k})^2$$

$$R_6 = 4.47 \text{ k}\Omega$$

The standard 1% resistor value closest to this is 4.42k $\Omega$ .

8. Calculate  $V_{TH}$  using  $R_6$ .

$$V_{TH} = V_H \times \left( \frac{R_7}{R_6 + R_7} \right) = 2.31 \times \frac{200\text{k}}{4.42\text{k} + 200\text{k}} = 2.26\text{V}$$

9. Choose a value for  $R_5$ . In this case,  $R_5$  is chosen to be 10 k $\Omega$ .

$$V_{TH} = V_H \times \left( \frac{R_2}{R_1 + R_2} \right) = 9.802\text{V}$$

10. Solve for  $R_4$ .

$$R_4 = \frac{R_5 \times (V_S - V_{TH})}{V_{TH}} = \frac{10\text{k} \times (3.3 - 2.6)}{2.26} = 4.602 \text{ k}\Omega$$

The standard 1% resistor value closest to this is 4.64 k $\Omega$ .

## Design Simulations

### Transient Simulation Results

The below simulation results use a -70A to 130A, 100Hz sine wave for IG1.

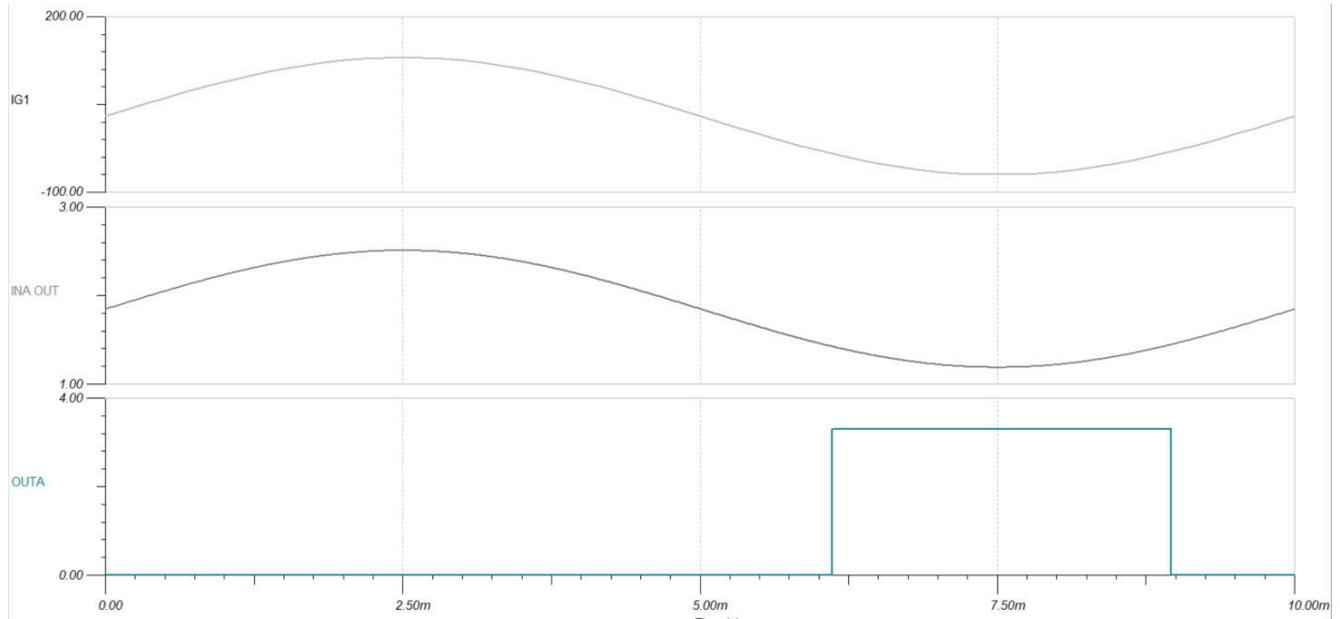


Figure 1-2. Channel A

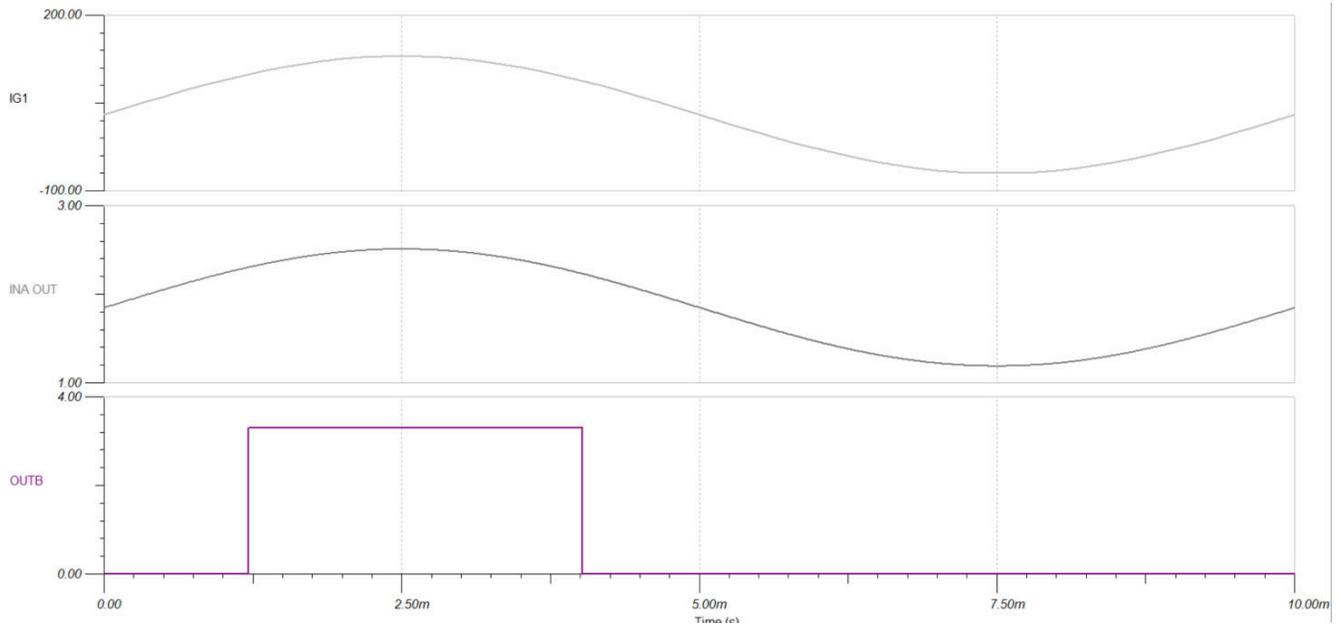


Figure 1-3. Channel B

## Design References

See [Analog Engineer's Circuit Cookbooks](#) for TI's comprehensive circuit library.

See Circuit SPICE Simulation File [SBOMB05](#).

## Design Featured Comparator

TLV320x	
$V_S$	2.7 V to 5.5 V
$V_{inCM}$	200 mV beyond either rail
$V_{OUT}$	Push-Pull, Rail-to-rail
$V_{OS}$	1 mV
$I_Q$	40 $\mu$ A/channel
$t_{PD(HL)}$	40 ns
#Channels	1, 2
<a href="#">TLV3201-Q1 and TLV3202-Q1</a>	

## Design Featured Op Amp

INA240	
$V_S$	1.6 V to 5.5 V
$V_{inCM}$	-4 V to 80 V
$V_{OUT}$	Rail-to-rail
$V_{OS}$	5 $\mu$ V
$V_{OS}$ Drift	50 nV/ $^{\circ}$ C
$I_Q$	260 ns
Gain Options	20 V/V, 50 V/V, 100 V/V, 200 V/V
<a href="#">INA240</a>	

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