

# Low-side bidirectional current sensing circuit with MSP430™ smart analog combo

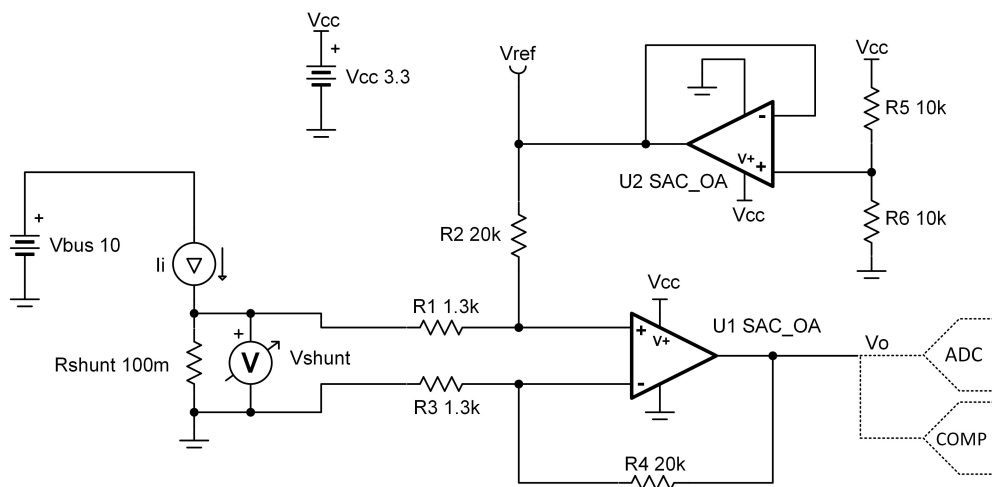
## Design Goals

Input		Output		Supply	
$I_{iMin}$	$I_{iMax}$	$V_{oMin}$	$V_{oMax}$	$V_{cc}$	$V_{ref}$
-1 A	1 A	100 mV	3.2 V	3.3 V	1.65 V

## Design Description

Some MSP430™ microcontrollers (MCUs) contain configurable integrated signal chain elements such as op-amps, DACs, and programmable gain stages. These elements make up a peripheral called the Smart Analog Combo (SAC). For information on the different types of SACs and how to leverage their configurable analog signal chain capabilities, visit [MSP430 MCUs Smart Analog Combo Training](#). To get started with your design, download the [Low-side Bidirectional Current Sensing Design Files](#).

This single-supply low-side, bidirectional current sensing solution can accurately detect load currents from -1 A to 1 A. The linear range of the output is from 100 mV to 3.2 V. Low-side current sensing keeps the common-mode voltage near ground, and is thus most useful in applications with large bus voltages. This design leverages two of the four integrated op-amp blocks (SACs) in the [MSP430FR2355](#) MCU. One SAC\_L3 peripheral is configured as a general purpose op-amp to amplify the voltage across the shunt resistor, while the other is configured as a buffer to provide the bias voltage ( $V_{ref}$ ). The latter SAC\_L3 block can also be configured in DAC buffer mode to provide  $V_{ref}$ , replacing the external voltage divider circuit. The output of the circuit can be internally or externally connected to other integrated peripherals in the [MSP430FR2355](#) MCU. For example, the analog-to-digital converter (ADC) window comparator can sample this output periodically (with no CPU intervention) and trigger an interrupt when the signal crosses a threshold.



## Design Notes

- To minimize errors, set  $R_3 = R_1$  and  $R_4 = R_2$ .
- Use precision resistors for higher accuracy.
- Set output range based on linear output swing (see  $A_{oI}$  specification).
- Low-side sensing should not be used in applications where the system load cannot withstand small ground disturbances or in applications that need to detect load shorts.
- In the schematic above, the first SAC\_L3 peripheral in the MSP430FR2355 MCU (U1) is configured in general purpose mode. The second SAC\_L3 peripheral (U2) is also configured in general purpose mode, but with an external voltage divider.
- It is recommended to use the DAC buffer configuration for U2 (as seen in the code examples in the [Low-side Bidirectional Current Sensing Design Files](#)) to provide  $V_{ref}$  instead of using the external voltage divider circuit.
- This solution can also be implemented using the MSP430FR2311 device by using the internal transimpedance amplifier for U1, and the SAC\_L1 op-amp for U2.
- The [Low-side Bidirectional Current Sensing Design Files](#) include code examples showing how to properly initialize the SAC peripherals.

## Design Steps

1. Determine the transfer equation given  $R_4 = R_2$  and  $R_1 = R_3$ .

$$V_o = (I_i \times R_{shunt} \times \frac{R_4}{R_3}) + V_{ref}$$

$$V_{ref} = V_{cc} \times (\frac{R_6}{R_5 + R_6})$$

2. Determine the maximum shunt resistance.

$$R_{shunt} = \frac{V_{shunt}}{I_{imax}} = \frac{100mV}{1 A} = 100m\Omega$$

3. Set reference voltage.

- a. Because the input current range is symmetric, the reference should be set to mid supply. Therefore, make  $R_5$  and  $R_6$  equal.

$$R_5 = R_6 = 10k\Omega$$

4. Set the difference amplifier gain based on the op amp output swing. The op amp output can swing from 100 mV to 3.2 V, given a 3.3-V supply.

$$Gain = \frac{V_{oMax} - V_{oMin}}{R_{shunt} \times (I_{imax} - I_{iMin})} = \frac{3.2V - 100mV}{100m\Omega \times (1 A - (-1 A))} = 15.5 \frac{V}{V}$$

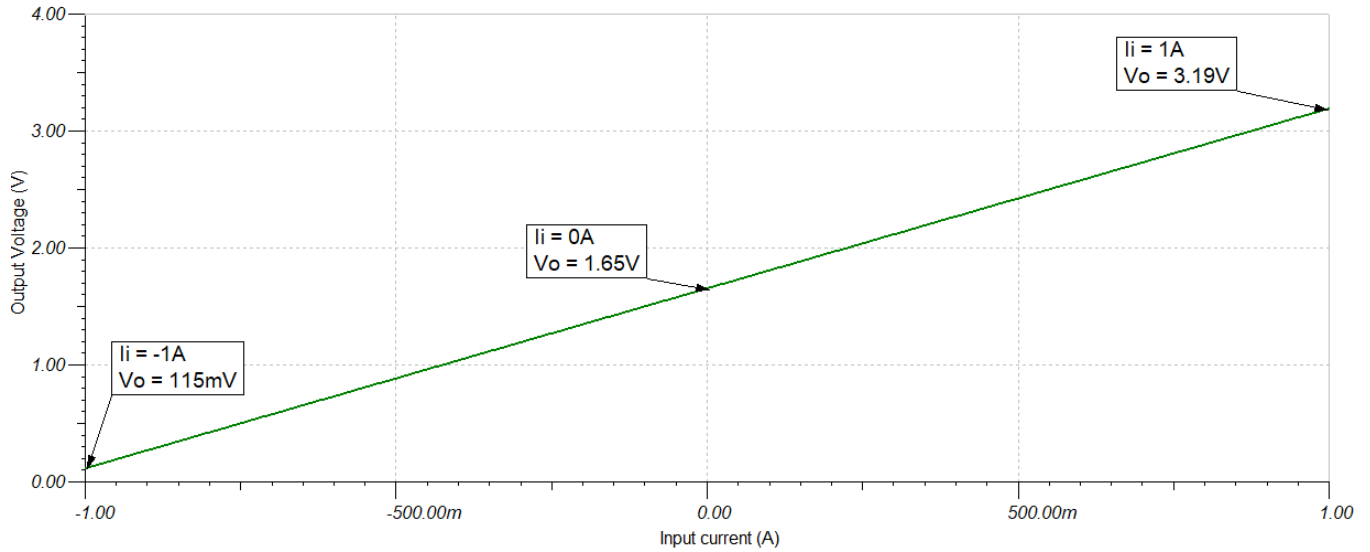
$$Gain = \frac{R_4}{R_3} = 15.5 \frac{V}{V}$$

Choose  $R_1 = R_3 = 1.3k\Omega$  (Standard Value)

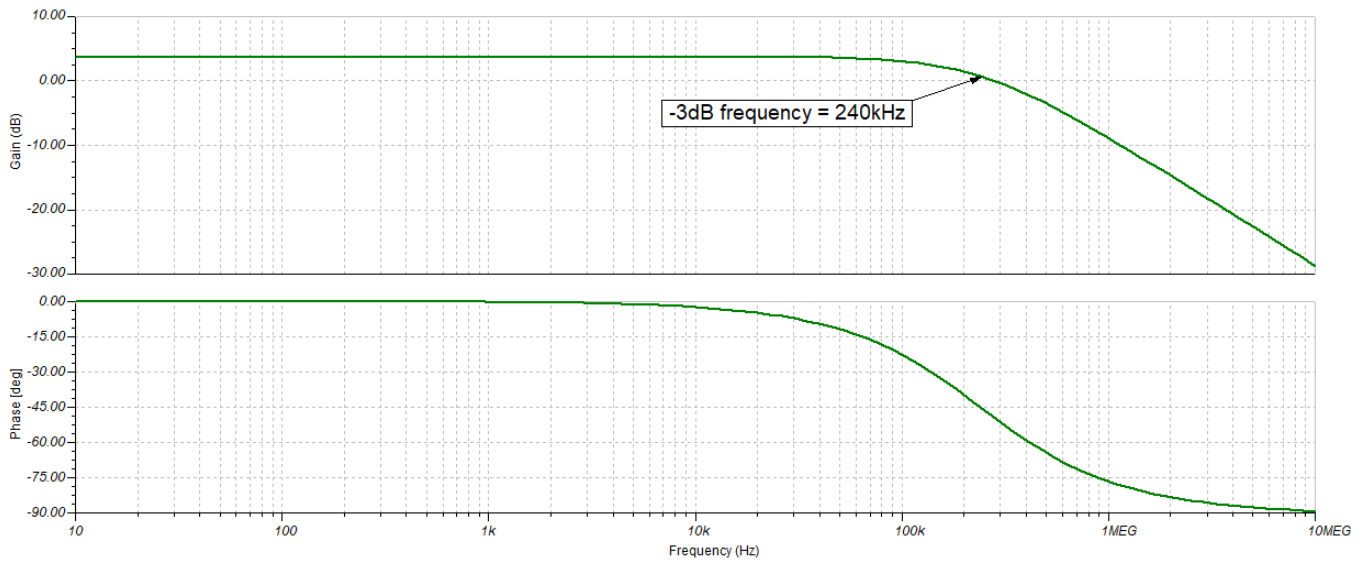
$$R_2 = R_4 = 15.5 \frac{V}{V} \times 1.3k\Omega = 20.15 k\Omega \approx 20k\Omega \text{ (Standard Value)}$$

**Design Simulations**

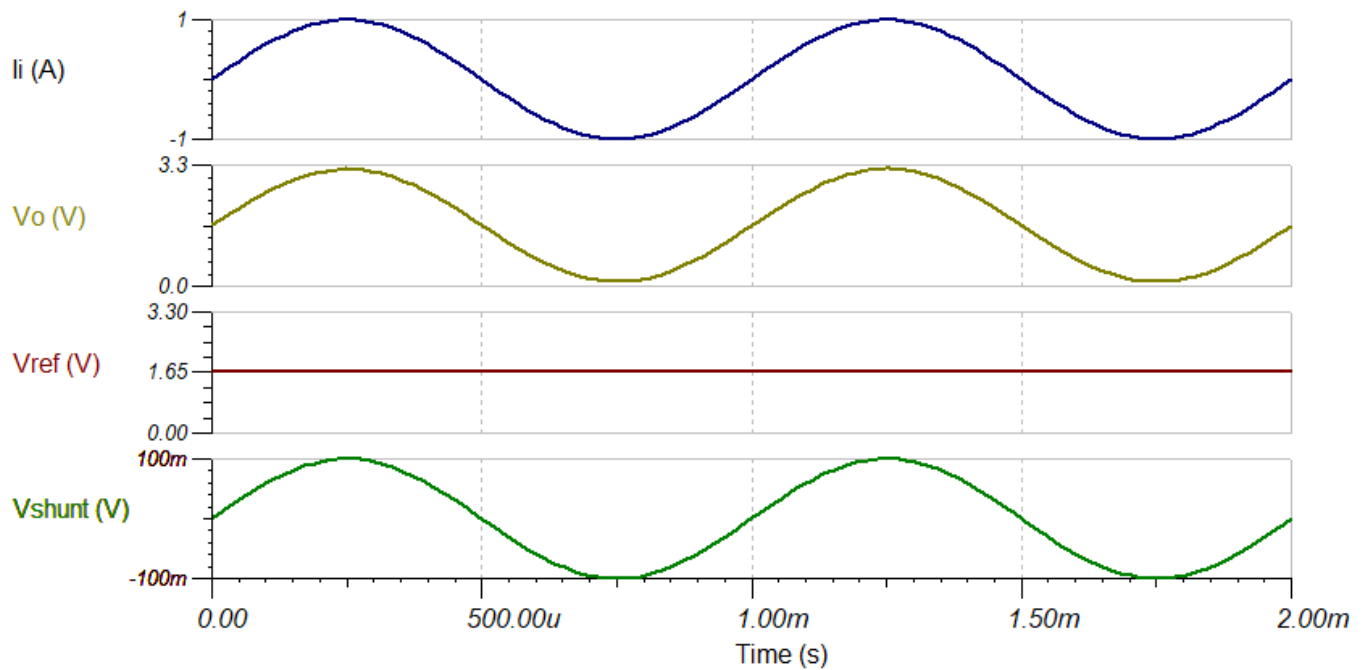
**DC Simulation Results**



**Closed Loop AC Simulation Results**



## Transient Simulation Results



### Target Applications

[Motor Drives](#)

[Servo Drive Functional Safety Module](#)

[Merchant Battery Charger](#)

[Battery Pack: Cordless Power Tool](#)

[Battery Pack: E-Bike/E-Scooter/Light Electric Vehicle \(LEV\)](#)

### Design References

- [1. MSP430 Low-side Bidirectional Current Sensing Circuit Code Examples and SPICE Simulation File](#)
- [2. Analog Engineer's Circuit Cookbooks](#)
- [3. MSP430FR2311 TINA-TI Spice Model](#)
- [4. MSP430 MCUs Smart Analog Combo Training](#)

## Design Featured Op Amp

MSP430FRxx Smart Analog Combo		
	MSP430FR2311 SAC_L1	MSP430FR2355 SAC_L3
$V_{CC}$	2.0 V to 3.6 V	
$V_{CM}$	-0.1 V to $V_{CC} + 0.1$ V	
$V_{out}$	Rail-to-rail	
$V_{os}$	$\pm 5$ mV	
$A_{OL}$	100 dB	
$I_q$	350 $\mu$ A (high-speed mode)	
	120 $\mu$ A (low-power mode)	
$I_b$	50 pA	
UGBW	4 MHz (high-speed mode)	2.8 MHz (high-speed mode)
	1.4 MHz (low-power mode)	1 MHz (low-power mode)
SR	3 V/ $\mu$ s (high-speed mode)	
	1 V/ $\mu$ s (low-power mode)	
Number of channels	1	4
<a href="http://www.ti.com/product/MSP430FR2311">http://www.ti.com/product/MSP430FR2311</a>		
<a href="http://www.ti.com/product/MSP430FR2355">http://www.ti.com/product/MSP430FR2355</a>		

## Design Alternate Op Amp

MSP430FR2311 Transimpedance Amplifier	
$V_{CC}$	2.0 V to 3.6 V
$V_{CM}$	-0.1 V to $V_{CC}/2$ V
$V_{out}$	Rail-to-rail
$V_{os}$	$\pm 5$ mV
$A_{OL}$	100 dB
$I_q$	350 $\mu$ A (high-speed mode)
	120 $\mu$ A (low-power mode)
$I_b$	5 pA (TSSOP-16 with OA-dedicated pin input)
	50 pA (TSSOP-20 and VQFN-16)
UGBW	5 MHz (high-speed mode)
	1.8 MHz (low-power mode)
SR	4 V/ $\mu$ s (high-speed mode)
	1 V/ $\mu$ s (low-power mode)
Number of channels	1
<a href="http://www.ti.com/product/MSP430FR2311">http://www.ti.com/product/MSP430FR2311</a>	

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