

# High-side current-sensing circuit design with MSP430™ smart analog combo

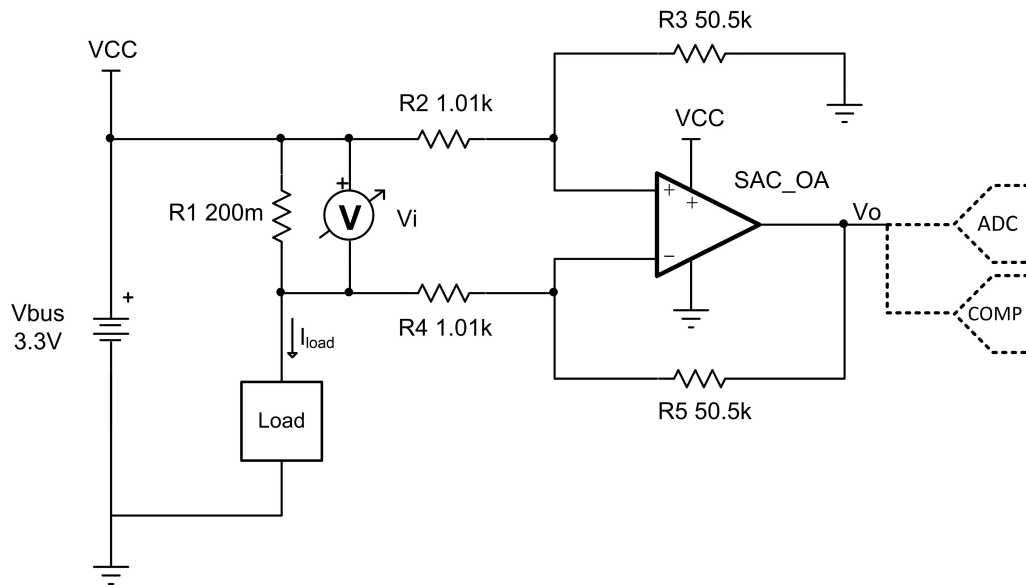
## Design Goals

Input		Output		Supply	
$I_{iMin}$	$I_{iMax}$	$V_{oMin}$	$V_{oMax}$	$V_{cc}$	$V_{ee}$
25 mA	300 mA	0.25 V	3 V	3.3 V	0 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 [High-Side Current Sensing Circuit Design Files](#).

This single-supply, high-side, low-cost current sensing solution detects load current between 25 mA and 300 mA and converts it to an output voltage from 0.25 V to 3 V. High-side sensing allows for the system to identify ground shorts and does not create a ground disturbance on the load. The circuit uses the [MSP430FR2311](#) SAC\_L1 op-amp in general-purpose (GP) mode with OAx+ and OAx- dedicated as noninverting and inverting inputs. The same approach can be implemented with the [MSP430FR2355](#), featuring four SAC\_L3 peripherals with additional built-in DAC and PGA capabilities. The output of the integrated SAC op-amp can be sampled directly by the on-board ADC or monitored by the on-board comparator for further processing inside the MCU.



## Design Notes

- DC common-mode rejection ratio (CMRR) performance is dependent on the matching of the gain setting resistors,  $R_2$ - $R_5$ .
- Increasing the shunt resistor increases power dissipation.
- Ensure that the common-mode voltage is within the linear input operating region of the amplifier. The common-mode voltage is set by the resistor divider formed by  $R_2$ ,  $R_3$ , and the bus voltage. Depending on the common-mode voltage determined by the resistor divider a rail-to-rail input (RRI) amplifier may not be required for this application.
- An op amp that does not have a common-mode voltage range that extends to  $V_{cc}$  may be used in low-gain or an attenuating configuration.
- A capacitor placed in parallel with the feedback resistor will limit bandwidth, improve stability, and help reduce noise.
- Use the op amp in a linear output operating region. Linear output swing is usually specified under the  $A_{OL}$  test conditions.
- If the solution is implemented with the MSP430FR2311 SAC\_L1 or with the MSP430FR2355 SAC\_L3, the op-amp is configured in general-purpose mode.
- If the solution is implemented using the MSP430FR2311 TIA, the input voltage range is limited to  $V_{CC}/2$ , so the gain or range must be adjusted accordingly.
- The [High-Side Current Sensing Circuit Design Files](#) include code examples showing how to properly initialize the SAC peripherals.

## Design Steps

1. The full transfer function of the circuit is provided below.

$$V_o = I_{in} \times R_1 \times \frac{R_5}{R_4}$$

Given  $R_2 = R_4$  and  $R_3 = R_5$

2. Calculate the maximum shunt resistance. Set the maximum voltage across the shunt to 60 mV.

$$R_1 = \frac{V_{I_{Max}}}{I_{I_{Max}}} = \frac{60\text{mV}}{300\text{mA}} = 200\text{m}\Omega$$

3. Calculate the gain to set the maximum output swing range.

$$\text{Gain} = \frac{V_{oMax} - V_{oMin}}{(I_{I_{Max}} - I_{I_{Min}}) \times R_1} = \frac{3\text{V} - 0.25\text{V}}{(0.3\text{A} - 0.025\text{A}) \times 200\text{m}\Omega} = 50\frac{\text{V}}{\text{V}}$$

4. Calculate the gain setting resistors to set the gain calculated in step 3.

$$\text{Choose } R_2 = R_4 = 1.01\text{k}\Omega \text{ (Standard value)}$$

$$R_3 = R_5 = R_2 \times \text{Gain} = 1.01\text{k}\Omega \times 50\frac{\text{V}}{\text{V}} = 50.5\text{k}\Omega \text{ (Standard value)}$$

5. Calculate the common-mode voltage of the amplifier to ensure linear operation.

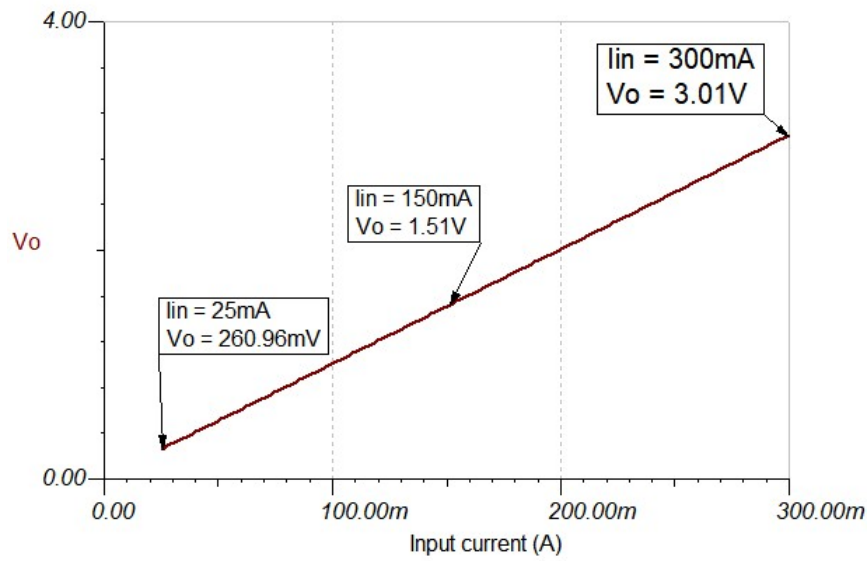
$$V_{cm} = V_{CC} \times \frac{R_3}{R_2 + R_3} = 3.3\text{V} \times \frac{50.5\text{k}}{1.01\text{k} + 50.5\text{k}} = 3.235\text{V}$$

6. The upper cutoff frequency ( $f_H$ ) is set by the non-inverting gain (noise gain) of the circuit and the gain bandwidth (GBW) of the op amp.

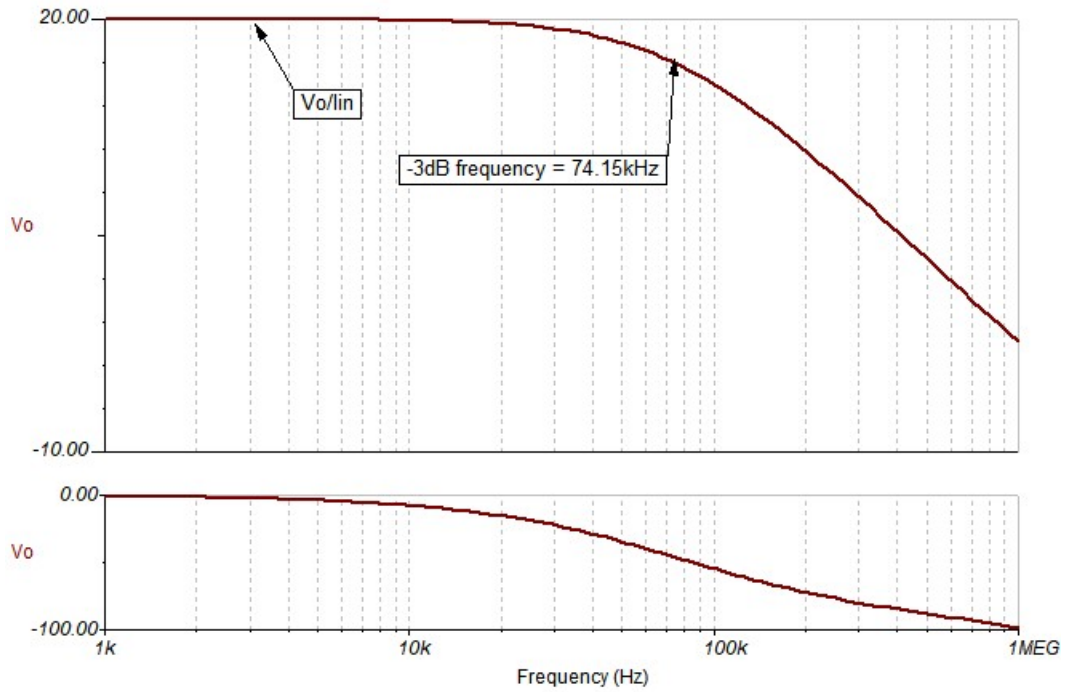
$$f_H = \frac{\text{GBW}}{\text{Noise Gain}} = \frac{4\text{MHz}}{51\frac{\text{V}}{\text{V}}} = 78.43 \text{ kHz}$$

**Design Simulations**

**DC Simulation Results**



**AC Simulation Results**



### Target Applications

- Cordless power tool battery pack
- E-bike, e-scooter battery pack
- Motor drives
- LED luminaire
- Grid infrastructure

### References

1. [High-Side Current Sensing Circuit Design Files](#)
2. [Analog Engineer's Circuit Cookbooks](#)
3. [MSP430FR2311 TINA-TI Spice Model](#)
4. [MSP430 MCUs Smart Analog Combo Training](#)



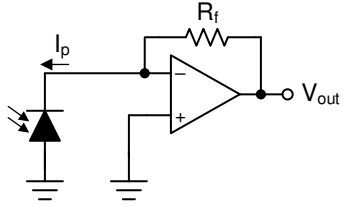
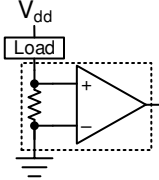
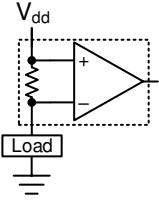
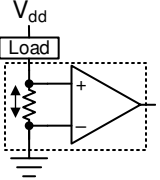

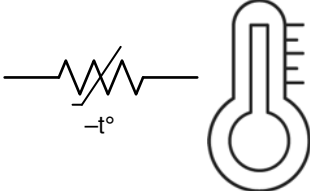
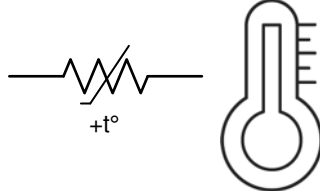
### Design Featured Op Amp

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>	

**Related MSP430 Circuits**

<p>Low-noise and long-range PIR sensor conditioner circuit</p> 	<p>Bridge amplifier circuit</p> 	<p>Transimpedance amplifier circuit</p> 
<p>Single-supply, low-side, unidirectional current-sensing circuit</p> 	<p>High-side current sensing with discrete difference amplifier circuit</p> 	<p>Low-side, bidirectional current-sensing circuit</p> 
<p>Half-wave rectifier circuit</p> 	<p>Temperature sensing with NTC thermistor circuit</p> 	<p>Temperature sensing with PTC thermistor circuit</p> 

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## Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from November 26, 2019 to March 6, 2020	Page
• Added <i>Related MSP430 Circuits</i> section.....	5

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