Analog Engineer's Circuit

High-Side Current-Sensing Circuit Design with MSP430™ Smart Analog Combo

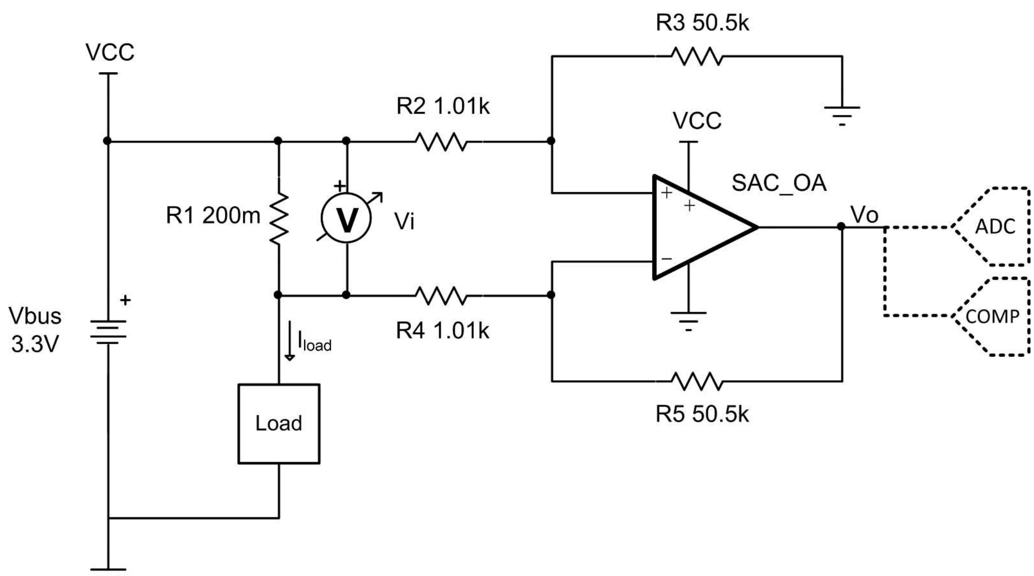
Design Goals

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.

$$V_o = I_{in} \times R_1 \times \frac{R_5}{R_4}$$
$$\text{Given} \quad R_2 = R_4 \quad \text{and} \quad R_3 = R_5$$

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

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

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

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

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

$$\text{Choose} \quad R_2 = R_4 = 1.01k\ \Omega \quad (\text{Standard value})$$
$$R_3 = R_5 = R_2 \times Gain = 1.01k\ \Omega \times 50\frac{V}{V} = 50.5k\ \Omega\ (\text{Standard value})$$

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

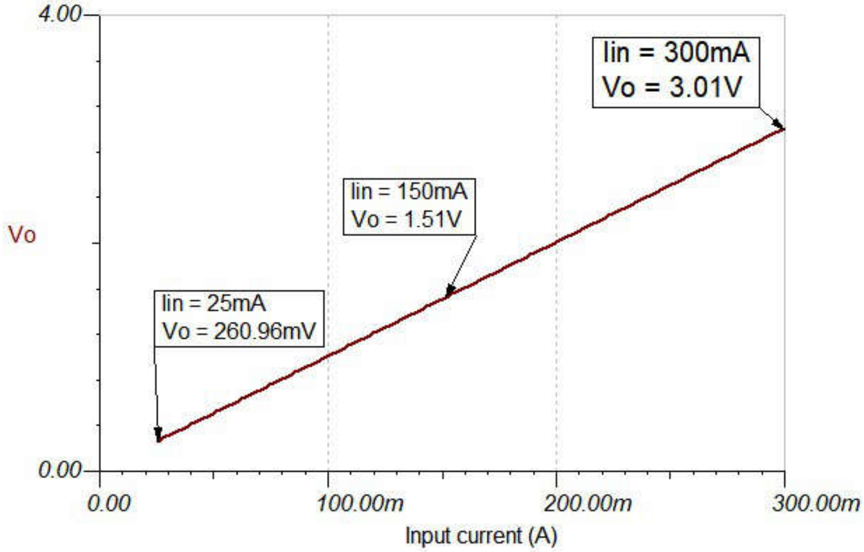
$$V_{cm} = V_{CC} \times \frac{R_3}{R_2 + R_3} = 3.3V \times \frac{50.5k}{1.01k + 50.5k} = 3.235V$$

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.

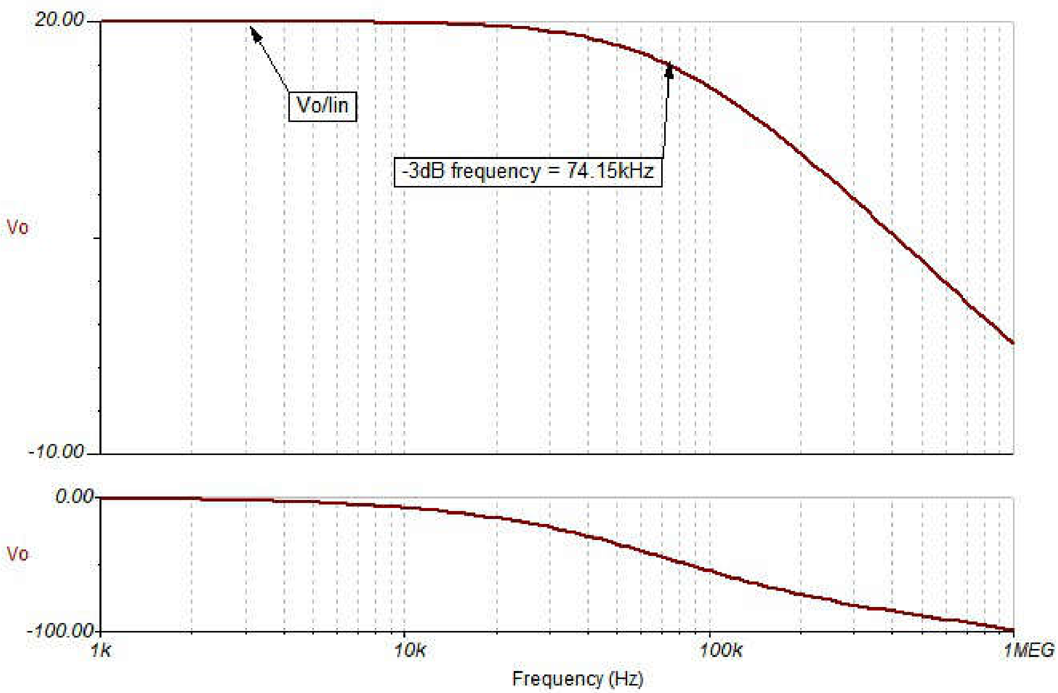
$$f_H = \frac{GBW}{\text{Noise Gain}} = \frac{4MHz}{51\frac{V}{V}} = 78.43 \quad kHz$$

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

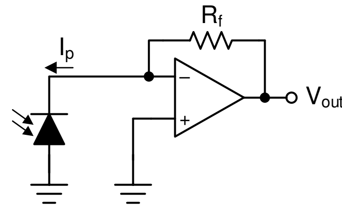
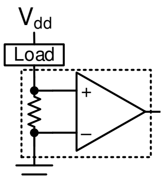
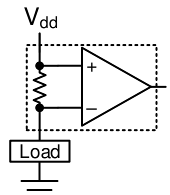
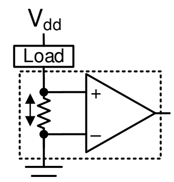
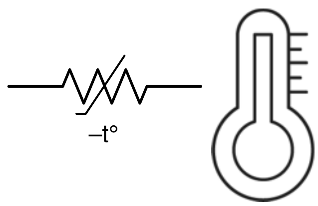
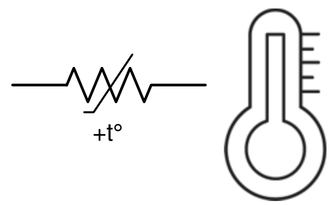
Design Featured Op Amp

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}	±5 mV	
A_{OL}	100 dB	
I_q	350 µA (high-speed mode)	
	120 µA (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/µs (high-speed mode)	
	1 V/µs (low-power mode)	
Number of channels	1	4
	MSP430FR2311	MSP430FR2355

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}	±5 mV
A_{OL}	100 dB
I_q	350 µA (high-speed mode)
	120 µA (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/µs (high-speed mode)
	1 V/µs (low-power mode)
Number of channels	1
	MSP430FR2311

Related MSP430 Circuits

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

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 *Related MSP430 Circuits* section	1