Analog Engineer's Circuit

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

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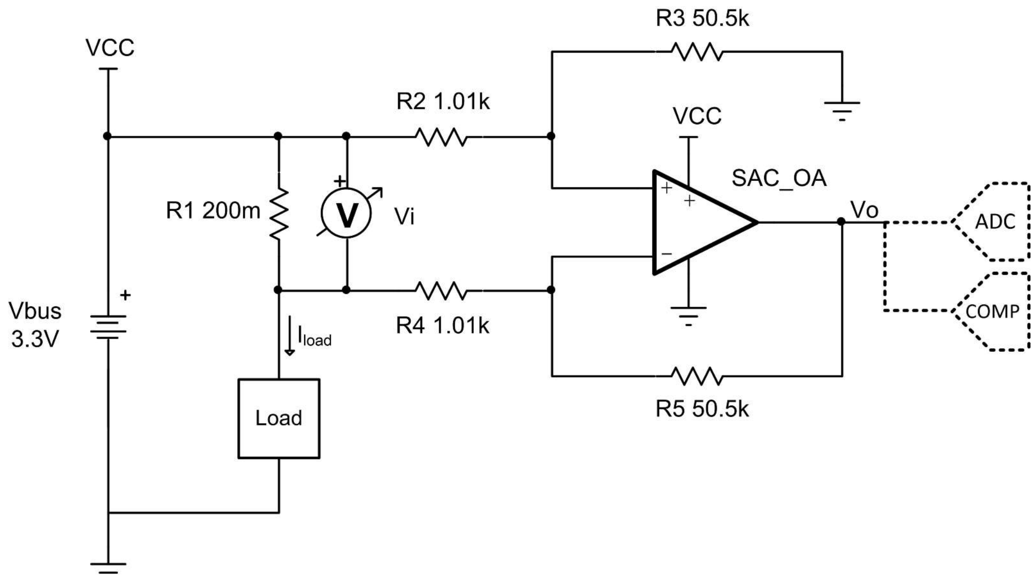
Design Goals

Input		Output		Supply	
I_{iMin}	I_{iMax}	V_{oMin}	V_{oMax}	V_{cc}	V_{ee}
25mA	300mA	0.25V	3V	3.3V	0V

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 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 option detects load current between 25mA and 300mA and converts it to an output voltage from 0.25V to 3V. 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.
- Verify 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} can be used in low-gain or an attenuating configuration.
- A capacitor placed in parallel with the feedback resistor limits bandwidth, improves stability, and reduces 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 process is implemented with the MSP430FR2311 SAC_L1 or with the MSP430FR2355 SAC_L3, the op-amp is configured in general-purpose mode.
- If the process 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 60mV.

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

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

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

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

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

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

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

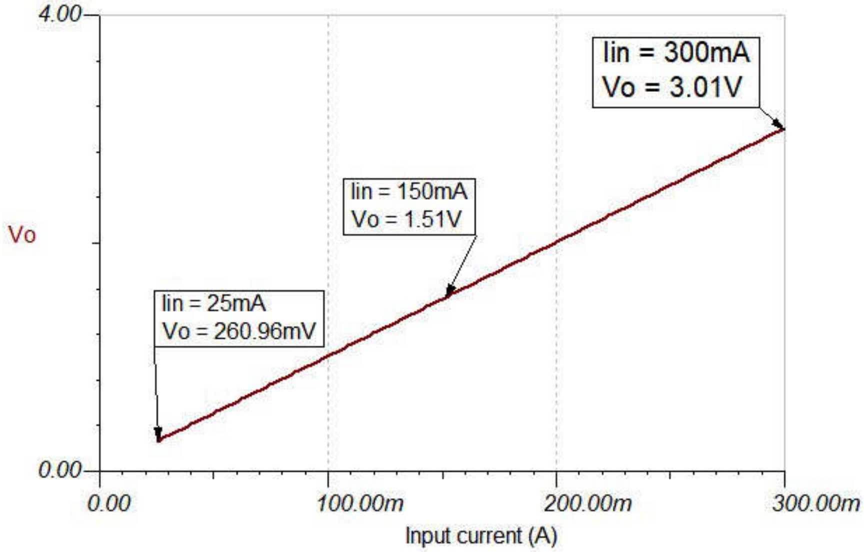
$$V_{cm} = V_{CC} \times \frac{R_3}{R_2 + R_3} = 3.3\text{V} \times \frac{50.5\text{k}}{1.01\text{k} + 50.5\text{k}} = 3.235\text{V}$$

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.

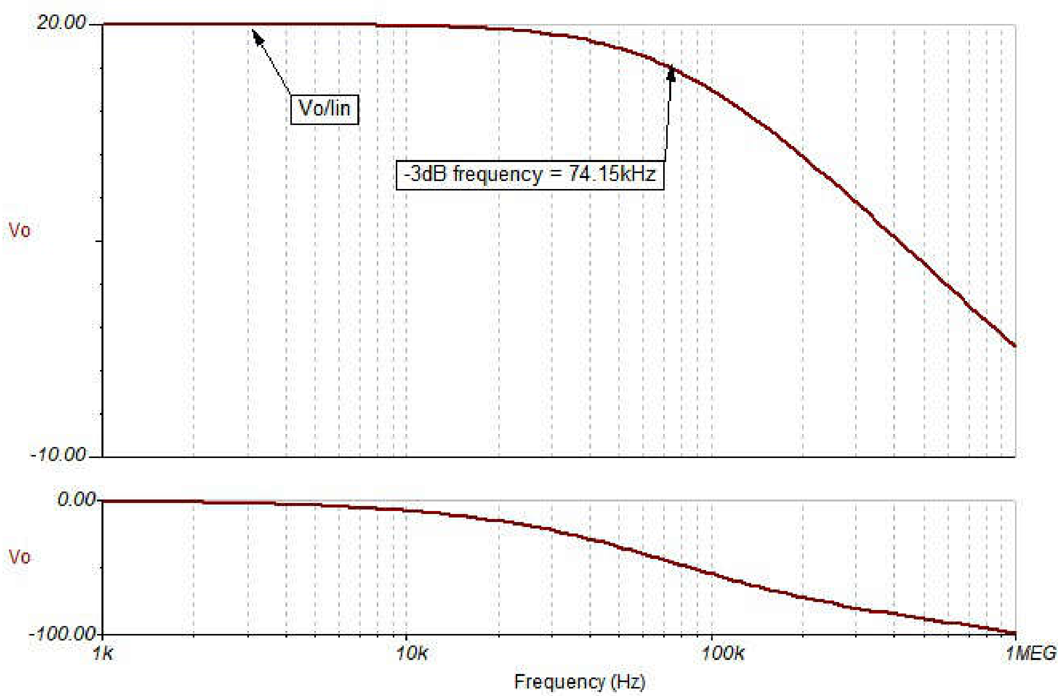
$$f_H = \frac{\text{GBW}}{\text{Noise Gain}} = \frac{4\text{MHz}}{51\frac{\text{V}}{\text{V}}} = 78.43 \quad \text{kHz}$$

Design Simulations

DC Simulation Results



AC Simulation Results



Target Applications

- *Battery pack: cordless power tool*
- *HEV/EV battery-management system (BMS)*
- *Motor drives*
- *Lighting*
- *Energy infrastructure*

References

1. Texas Instruments, *High-Side Current Sensing Circuit*, design files
2. Texas Instruments, *MSP430FR2311 TINA-TI Spice Model*, file download
3. Texas Instruments, *MSP430 MCUs Smart Analog Combo*, training video

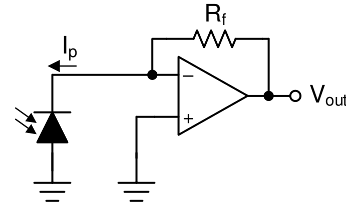
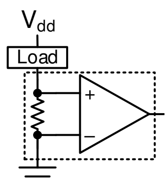
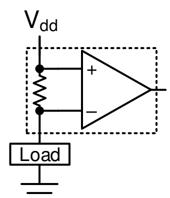
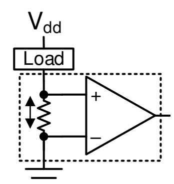
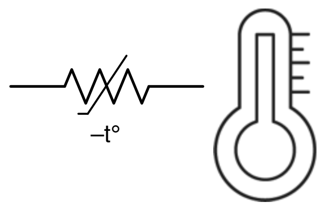
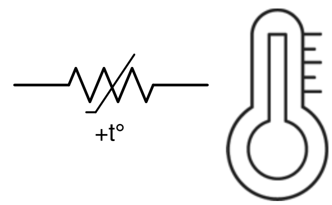
Design Featured Op Amp

MSP430FRxx Smart Analog Combo		
	MSP430FR2311 SAC_L1	MSP430FR2355 SAC_L3
V_{cc}	2.0V to 3.6V	
V_{CM}	-0.1V to V_{CC} + 0.1V	
V_{out}	Rail-to-rail	
V_{os}	±5mV	
A_{OL}	100dB	
I_q	350µA (high-speed mode)	
	120µA (low-power mode)	
I_b	50pA	
UGBW	4MHz (high-speed mode)	2.8MHz (high-speed mode)
	1.4MHz (low-power mode)	1MHz (low-power mode)
SR	3V/µs (high-speed mode)	
	1V/µs (low-power mode)	
Number of channels	1	4
	MSP430FR2311	MSP430FR2355

Design Alternate Op Amp

MSP430FR2311 Transimpedance Amplifier	
V_{cc}	2.0V to 3.6V
V_{CM}	-0.1V to V_{CC}/2V
V_{out}	Rail-to-rail
V_{os}	±5mV
A_{OL}	100dB
I_q	350µA (high-speed mode)
	120µA (low-power mode)
I_b	5pA (TSSOP-16 with OA-dedicated pin input)
	50pA (TSSOP-20 and VQFN-16)
UGBW	5MHz (high-speed mode)
	1.8MHz (low-power mode)
SR	4V/µs (high-speed mode)
	1V/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 

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Revision History

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

Changes from Revision B (March 2020) to Revision C (October 2024)	Page
• Updated the format for tables, figures, and cross-references throughout the document	1

Changes from Revision A (November 2019) to Revision B (March 2020)	Page
• Added *Related MSP430 Circuits* section	1

Changes from Revision * (November 2019) to Revision A (November 2019)	Page
• Removed mention of thermistor circuit in Design Notes	1

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