Analog Engineer's Circuit

Low-Side Bidirectional Current Sensing Circuit with MSP430™ Smart Analog Combo

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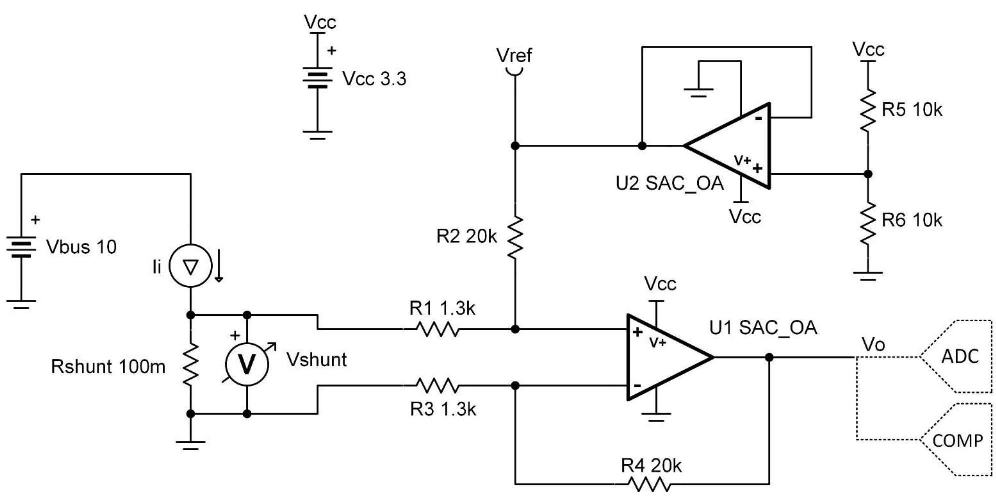
Design Goals

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

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 *Low-side Bidirectional Current Sensing Design Files*.

This single-supply low-side, bidirectional current sensing method accurately detects load currents from –1A to 1A. The linear range of the output is from 100mV to 3.2V. 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 (Vref). The latter SAC_L3 block can also be configured in DAC buffer mode to provide Vref, 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_{ol} specification).
- Do not use low-side sensing 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.
- Use the DAC buffer configuration for U2 (as seen in the code examples in the *Low-side Bidirectional Current Sensing Design Files*) to provide Vref instead of using the external voltage divider circuit.
- This option 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 $R_1 = R_3$.

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

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

2. Determine the maximum shunt resistance.

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

3. Set reference voltage. Because the input current range is symmetric, set the reference 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 is able to swing from 100mV to 3.2V, given a 3.3-V supply.

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

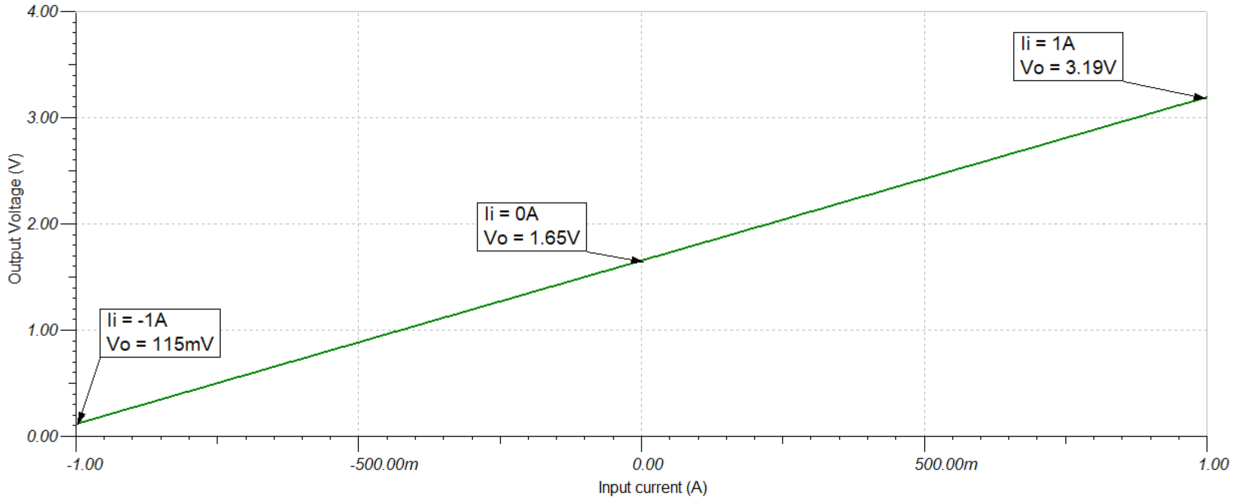
$$\text{Gain} = \frac{R_4}{R_3} = 15.5\ \frac{V}{V}$$

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

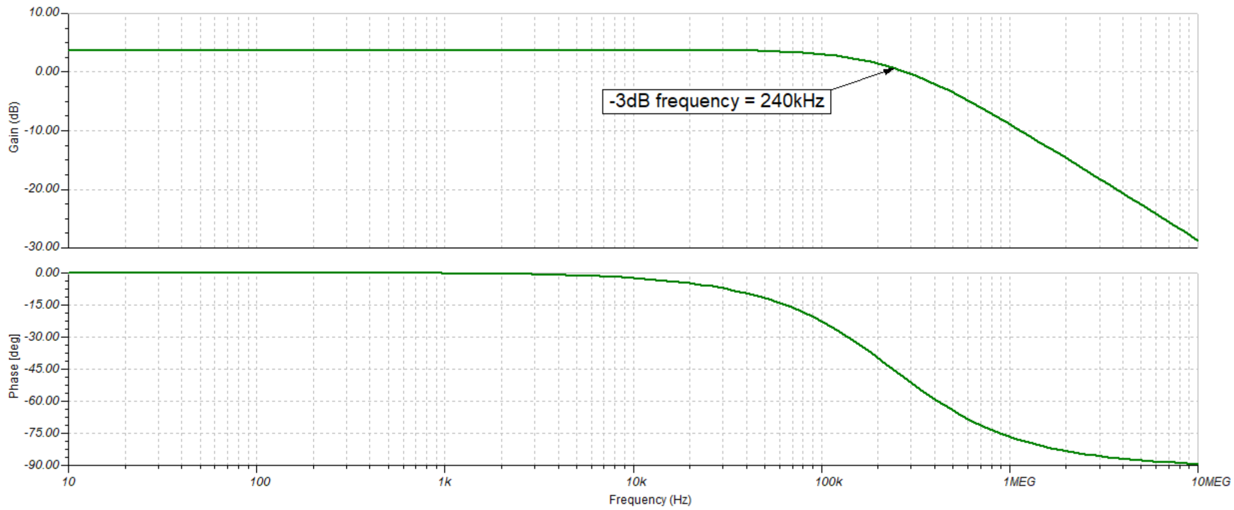
$$R_2 = R_4 = 15.5\frac{V}{V} \times 1.3k\Omega = 20.15\ k\Omega \approx 20k\Omega \text{ (Standard Value)}$$

Design Simulations

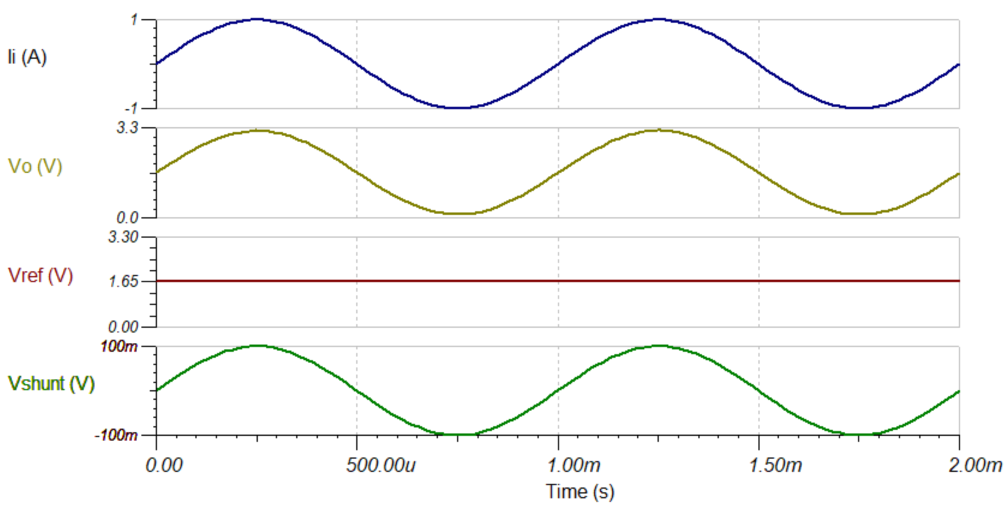
DC Simulation Results



Closed Loop AC Simulation Results



Transient Simulation Results



Target Applications

- *Motor Drives*
- *Servo Drive Functional Safety Module*
- *Battery Charger*
- *Battery Pack: Cordless Power Tool*
- *HEV/EV battery-management system (BMS)*

Design References

1. Texas Instruments, *MSP430 Low-side Bidirectional Current Sensing Circuit*, code examples and SPICE simulation file
2. Texas Instruments, *16MHz integrated analog microcontroller with 3.75-KB FRAM, Op Amp, TIA, comparator with DAC, 10-bit ADC*, product page
3. Texas Instruments, *MSP430 MCUs Smart Analog Combo Training*, video

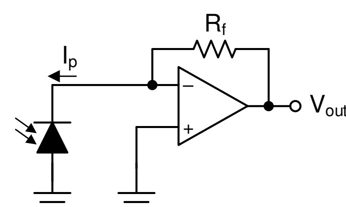
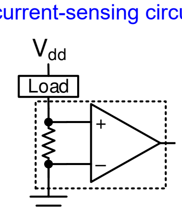
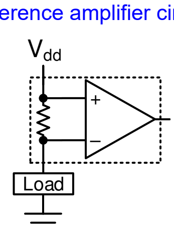
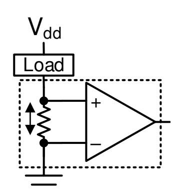
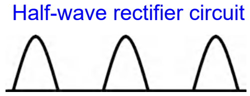
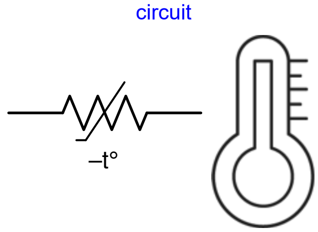
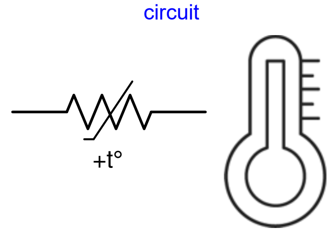
Design Featured Op Amp

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

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