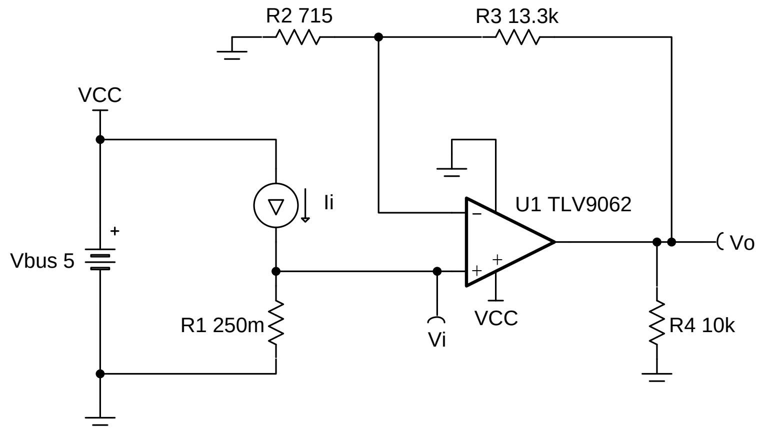
Single-supply, low-side, unidirectional current-sensing circuit

Design Goals

Input		Output		Supply		Full–Scale Range Error
I_{iMax}	V_{iMax}	V_{oMin}	V_{oMax}	V_{cc}	V_{ee}	FSR_{Error}
1A	250mV	50mV	4.9V	5V	0V	0.2%

Design Description

This single–supply, low–side, current sensing solution accurately detects load current up to 1A and converts it to a voltage between 50mV and 4.9V. The input current range and output voltage range can be scaled as necessary and larger supplies can be used to accommodate larger swings.



Design Notes

1. Use the op amp linear output operating range, which is usually specified under the test conditions.
2. The common–mode voltage is equal to the input voltage.
3. Tolerance of the shunt resistor and feedback resistors will determine the gain error of the circuit.
4. Avoid placing capacitive loads directly on the output of the amplifier to minimize stability issues.
5. If trying to detect zero current with output swing to GND, a negative charge pump (such as LM7705) can be used as the negative supply in this design to maintain linearity for output signals near 0V. [5]
6. Using high–value resistors can degrade the phase margin of the circuit and introduce additional noise in the circuit.
7. The small–signal bandwidth of this circuit depends on the gain of the circuit and gain bandwidth product (GBP) of the amplifier.
8. Filtering can be accomplished by adding a capacitor in parallel with R_3 . Adding a capacitor in parallel with R_3 will also improve stability of the circuit if high–value resistors are used.
9. For more information on op amp linear operating region, stability, capacitive load drive, driving ADCs, and bandwidth please see the Design References section.

Design Steps

The transfer function for this circuit is given below.

$$V_o = I_i \times R_1 \times \left(1 + \frac{R_3}{R_2}\right)$$

1. Define the full–scale shunt voltage and calculate the maximum shunt resistance.

$$V_{iMax} = 250\ mV \quad at \quad I_{iMax} = 1\ A$$

$$R_1 = \frac{V_{iMax}}{I_{iMax}} = \frac{250\ mV}{1\ A} = 250\ m\Omega$$

2. Calculate the gain required for maximum linear output voltage.

$$V_{iMax} = 250\ mV \quad and \quad V_{oMax} = 4.9\ V$$

$$Gain = \frac{V_{oMax}}{V_{iMin}} = \frac{4.9\ V}{250\ mV} = 19.6\ \frac{V}{V}$$

3. Select standard values for R_2 and R_3.

   From Analog Engineer's calculator, use "Find Amplifier Gain" and get resistor values by inputting gain ratio of 19.6.

   R_2 = 715 Ω (0.1% Standard Value)

   R_3 = 13.3 kΩ (0.1% Standard Value)

4. Calculate minimum input current before hitting output swing–to–rail limit. I_{iMin} represents the minimum accurately detectable input current.

$$V_{oMin} = 50\ mV; \quad R_1 = 250\ m\Omega$$

$$V_{iMin} = \frac{V_{oMin}}{Gain} = \frac{50\ mV}{19.6\ \frac{V}{V}} = 2.55\ mV$$

$$I_{iMin} = \frac{V_{iMin}}{R_1} = \frac{2.55\ mV}{250\ m\Omega} = 10.2\ mA$$

5. Calculate Full scale range error and relative error. V_{os} is the typical offset voltage found in datasheet.

$$FSR_{error} = \left(\frac{V_{os}}{V_{iMax} - V_{iMin}}\right) \times 100 = \left(\frac{0.3\ mV}{247.45\ mV}\right) \times 100 = 0.121\ \%$$

$$\text{Relative Error at } I_{iMax} = \left(\frac{V_{os}}{V_{iMax}}\right) \times 100 = \left(\frac{0.3\ mV}{250\ mV}\right) \times 100 = 0.12\ \%$$

$$\text{Relative Error at } I_{iMin} = \left(\frac{V_{os}}{V_{iMin}}\right) \times 100 = \left(\frac{0.3\ mV}{2.5\ mV}\right) \times 100 = 12\ \%$$

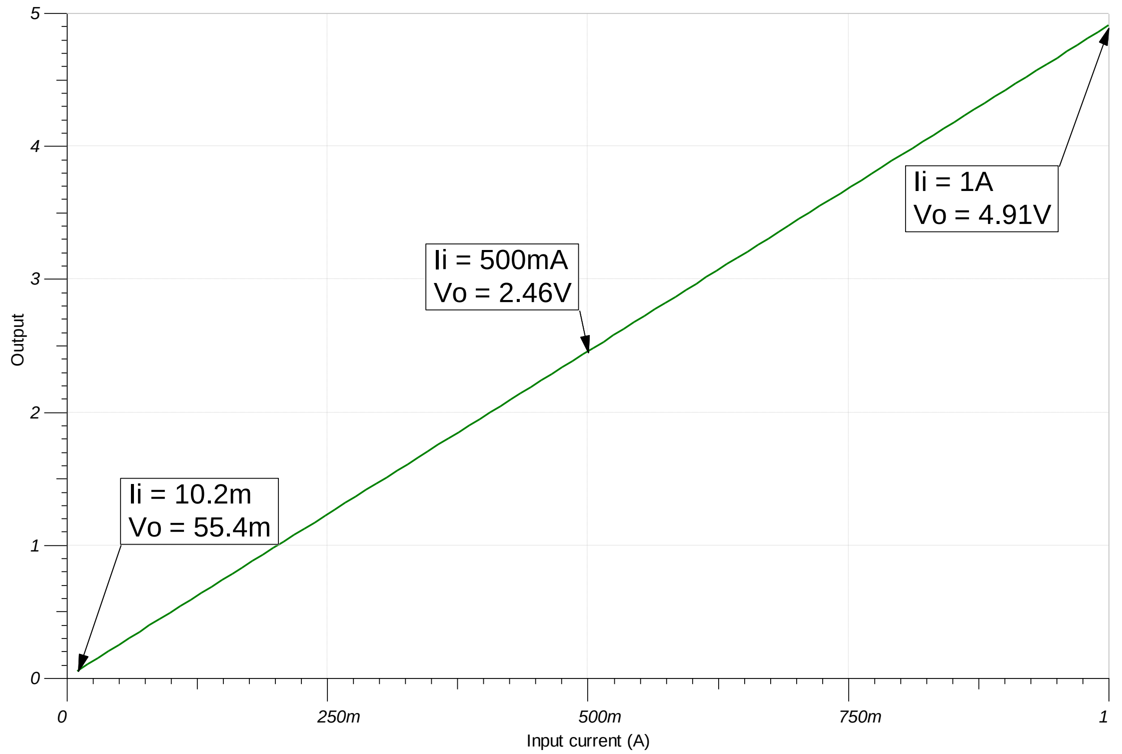
6. To maintain sufficient phase margin, ensure that the zero created by the gain setting resistors and input capacitance of the device is greater than the bandwidth of the circuit

$$\frac{1}{2 \times \pi \times (C_{cm} + C_{diff}) \times (R_2 \| R_3)} > \frac{GBP}{G}$$

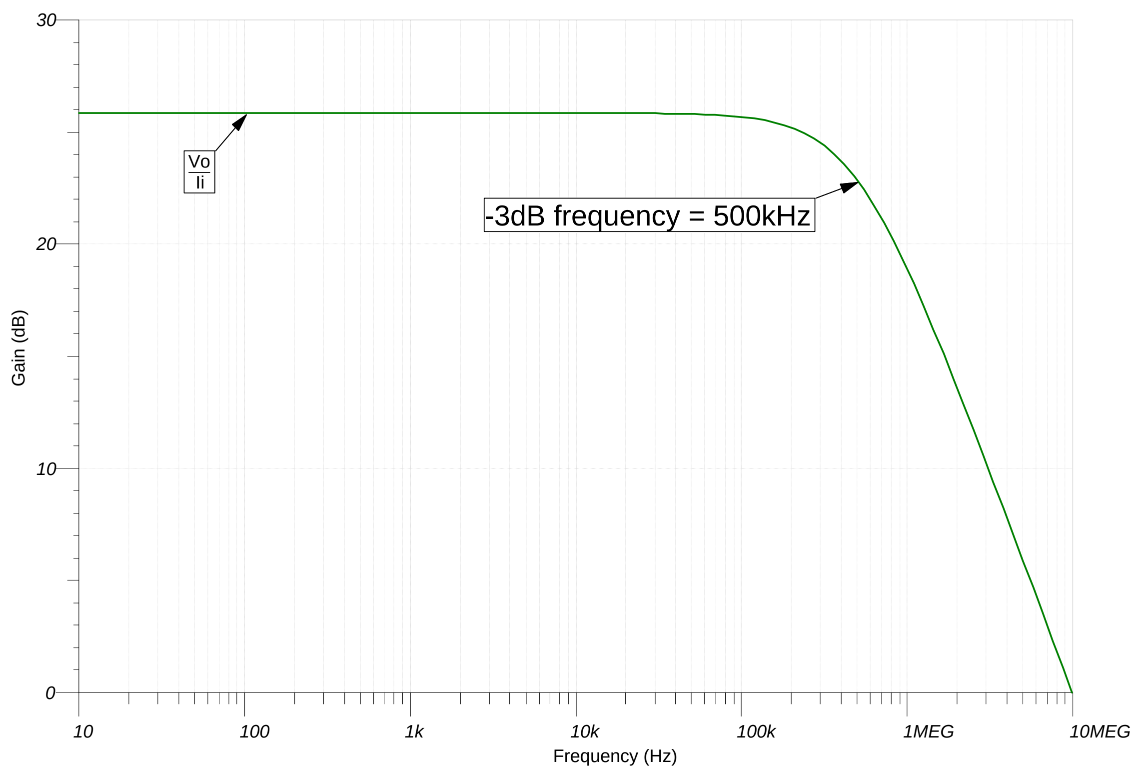
$$\frac{1}{2 \times \pi \times (3pF + 3pF) \times \left(\frac{715\ \Omega \times 13.3\ k\Omega}{715\ \Omega + 13.3\ k\Omega}\right)} > \frac{10\ MHz}{19.6\ \frac{V}{V}} = 39.1\ MHz > 510\ kHz$$

Design Simulations

DC Simulation Results



AC Simulation Results



References:

1. Analog Engineer's Circuit Cookbooks
2. SPICE Simulation File SBOC523
3. TI Precision Designs TIPD129, TIPD104
4. TI Precision Labs
5. Single-Supply, Low-Side, Unidirectional Current-Sensing Solution with Output Swing to GND Circuit

Design Featured Op Amp

TLV9061	
V_{ss}	1.8V to 5.5V
V_{inCM}	Rail–to–rail
V_{out}	Rail–to–rail
V_{os}	0.3mV
I_q	538µA
I_b	0.5pA
UGBW	10MHz
SR	6.5V/µs
#Channels	1,2,4
www.ti.com/product/tlv9061	

Design Alternate Op Amp

OPA375	
V_{cc}	2.25V to 5.5V
V_{inCM}	(V–) to ((V+)–1.2V)
V_{out}	Rail–to–rail
V_{os}	0.15mV
I_q	890µA
I_b	10pA
UGBW	10MHz
SR	4.75V/µs
#Channels	1
www.ti.com/product/OPA375	

For battery operated or power conscious designs, outside of the original design goals described earlier, where lowering total system power is desired.

LPV821	
V_{cc}	1.7V to 3.6V
V_{inCM}	Rail–to–rail
V_{out}	Rail–to–rail
V_{os}	1.5µV
I_q	650nA/Ch
I_b	7pA
UGBW	8kHz
SR	3.3V/ms
#Channels	1
www.ti.com/product/LPV821	

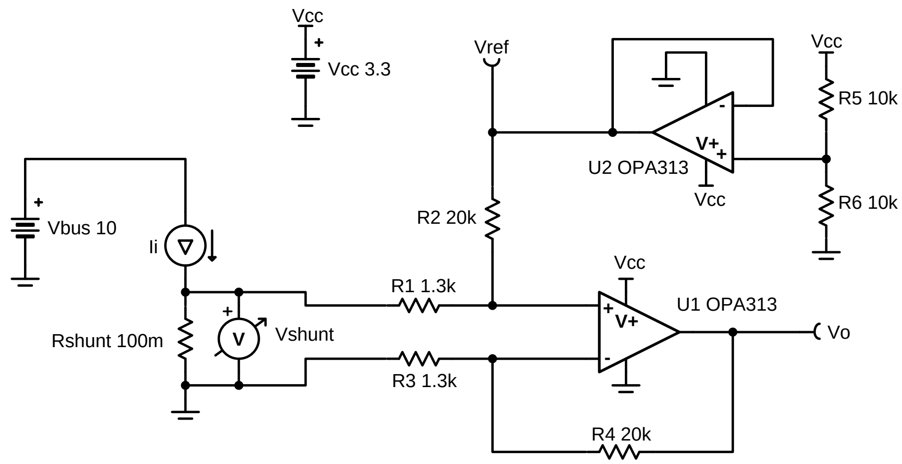
Low-side, bidirectional current sensing circuit

Design Goals

Input		Output		Supply		
I_{iMin}	I_{iMax}	V_{oMin}	V_{oMax}	V_{cc}	V_{ee}	V_{ref}
–1A	1A	110mV	3.19V	3.3V	0V	1.65V

Design Description

This single-supply low-side, bidirectional current sensing solution can accurately detect load currents from –1A to 1A. The linear range of the output is from 110mV to 3.19V. Low-side current sensing keeps the common-mode voltage near ground, and is thus most useful in applications with large bus voltages.



Design Notes

1. To minimize errors, set $R_3 = R_1$ and $R_4 = R_2$.
2. Use precision resistors for higher accuracy.
3. Set output range based on linear output swing (see A_{ol} specification).
4. 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.

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. Since 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 100mV to 3.2V, given a 3.3-V supply.

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

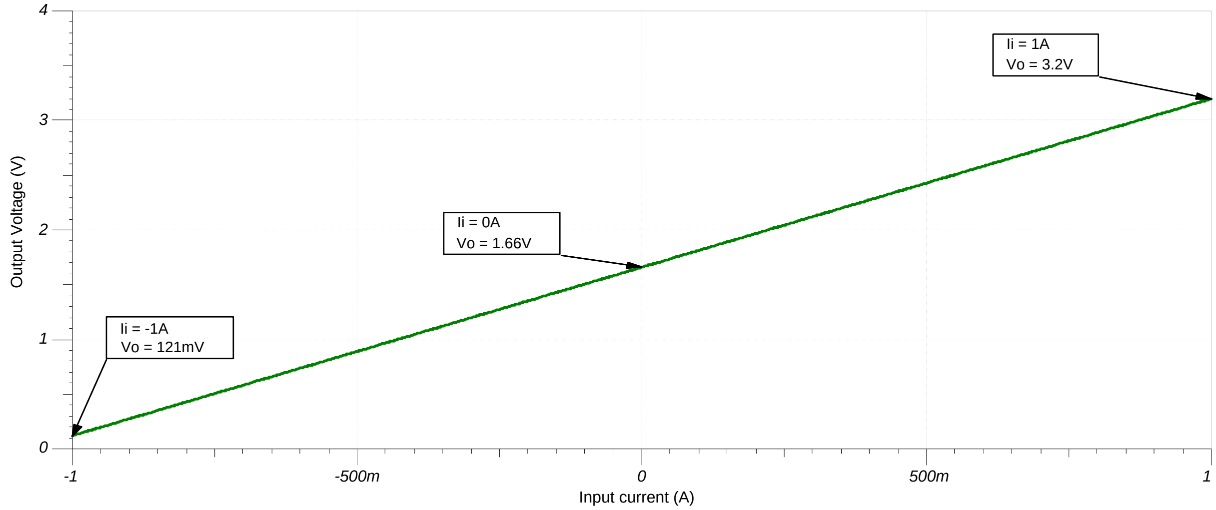
$$Gain = \frac{R_4}{R_3} = 15.5\ \frac{V}{V}$$

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

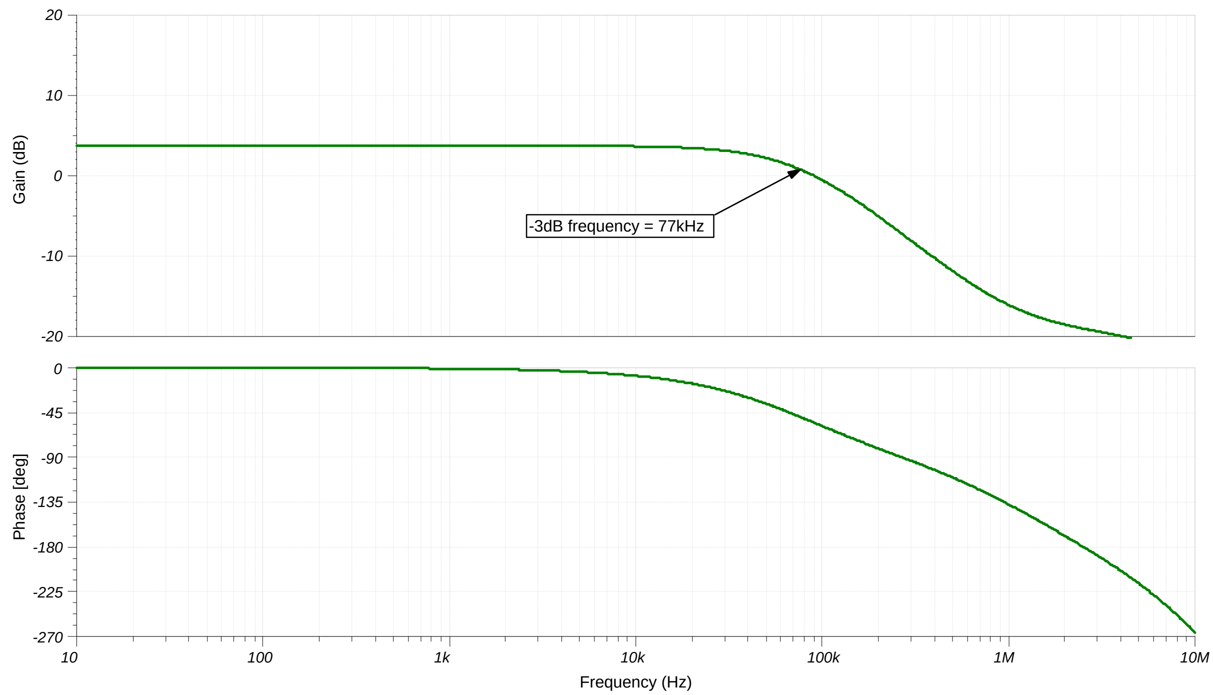
$$R_2 = R_4 = 15.5\frac{V}{V} \times 1.3k\Omega = 20.15\ k\Omega \approx 20k\Omega \text{ (Standard Value)}$$

Design Simulations

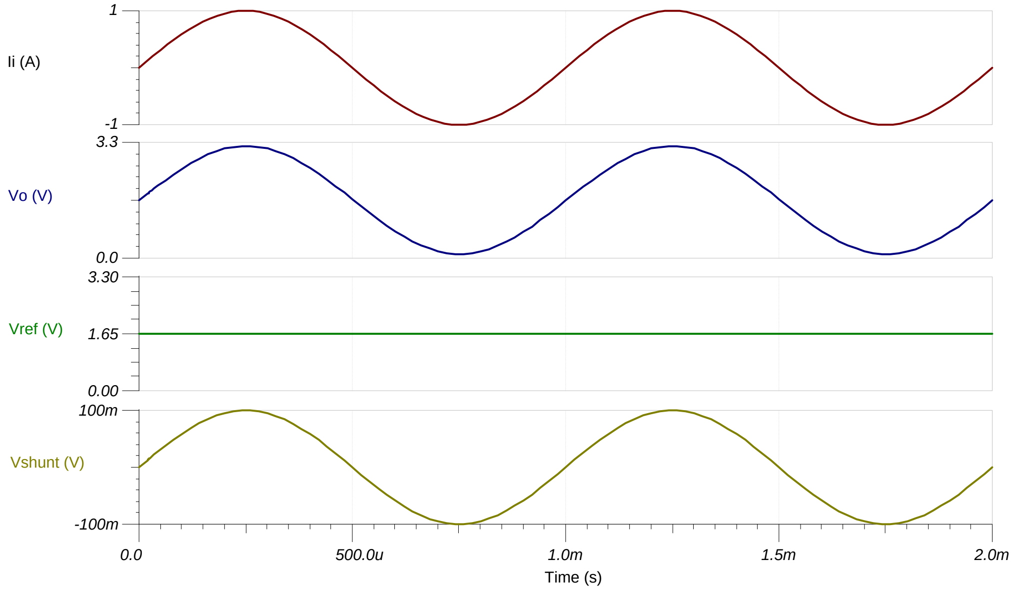
DC Simulation Results



Closed Loop AC Simulation Results



Transient Simulation Results



Design References

See Analog Engineer's Circuit Cookbooks for TI's comprehensive circuit library.

See circuit SPICE simulation file SBOC500.

See TIPD175, www.ti.com/tipd175.

Design Featured Op Amp

OPA313	
V_{cc}	1.8V to 5.5V
V_{inCM}	Rail-to-rail
V_{out}	Rail-to-rail
V_{os}	500µV
I_q	50µA/Ch
I_b	0.2pA
UGBW	1MHz
SR	0.5V/µs
#Channels	1, 2, 4
www.ti.com/product/opa313	

Design Alternate Op Amp

	TLV9062	OPA376
V_{cc}	1.8V to 5.5V	2.2V to 5.5V
V_{inCM}	Rail-to-rail	Rail-to-rail
V_{out}	Rail-to-rail	Rail-to-rail
V_{os}	300µV	5µV
I_q	538µA/Ch	760µA/Ch
I_b	0.5pA	0.2pA
UGBW	10MHz	5.5MHz
SR	6.5V/µs	2V/µs
#Channels	1, 2, 4	1, 2, 4
	www.ti.com/product/tlv9062	www.ti.com/product/opa376

For battery-operated or power-conscious designs, outside of the original design goals described earlier, where lowering total system power is desired.

LPV821	
V_{cc}	1.7V to 3.6V
V_{inCM}	Rail-to-rail
V_{out}	Rail-to-rail
V_{os}	1.5µV
I_q	650nA/Ch
I_b	7pA
UGBW	8KHz
SR	3.3V/ms
#Channels	1
www.ti.com/product/lpv821	

Revision History

Revision	Date	Change
B	January 2019	Downscale the title. Added link to circuit cookbook landing page.
A	May 2018	Changed title role to 'Amplifiers'. Added SPICE simulation file link. Added LPV821 as a Design Alternate Op Amp for battery-operated or power-conscious designs.