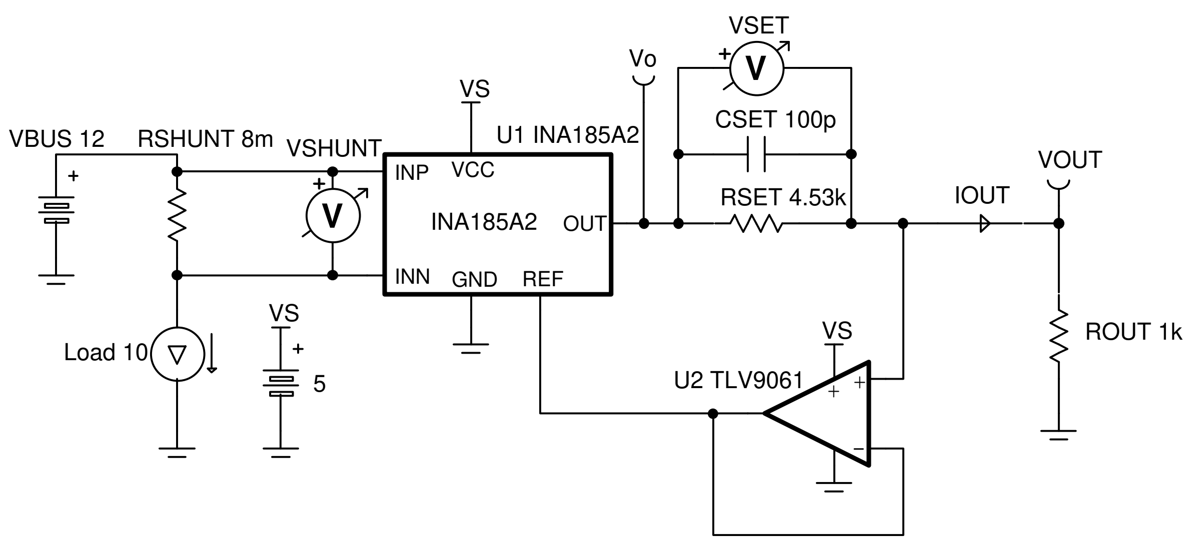
Analog Engineer's Circuit Amplifiers

Adjustable-gain, current-output, high-side current-sensing circuit

Input			Output			Error	Supply		
$I_{LOAD\ Min}$	$I_{LOAD\ Max}$	V_{CM}	$I_{OUT\ Min}$	$I_{OUT\ Max}$	Bandwidth	at $I_{LOAD\ Min}$	$I_{Q\ Max}$	V_S	V_{ee}
1A	10A	12V	88.3µA	883µA	200kHz	2.2% maximum, 0.3% typical	260 + 750µA	5V	GND (0V)

Design Description

This circuit demonstrates how to convert a voltage-output, current-sense amplifier (CSA) into a current-output circuit using an operational amplifier (op amp) and a current-setting resistor (R_{SET}). Taking advantage of the matched internal resistor gain network of the current-sense amplifier, this circuit utilizes the Howland Current Pump method to create a current source that is proportional to the sense current. The overall circuit gain is adjustable by changing the load resistor value (R_{OUT}). Additionally, multiple circuits can be summed together to determine total current from multiple sources.



Design Notes

1. The *Getting Started with Current Sense Amplifiers* video series introduces implementation, error sources, and advanced topics for using current sense amplifiers.
2. Choose precision 0.1% resistors to limit gain error at higher currents.
3. The output current (I_{OUT}) is sourced from the VS supply, which adds to the I_Q of the current sense amplifier.
4. Use the V_{OUT} versus I_{OUT} curve ("claw-curve") of the CSA (U1) to set the I_{OUT} limit during I_{LOAD_Max}. If a higher amount of current is needed, then consider adding a buffer to the output of the current sense amplifier. A buffer on the output allows for smaller R_{OUT}.
5. For applications with higher bus voltages, simply substitute in a bidirectional current sense amplifier with a higher rated input voltage.
6. The V_{OUT} voltage is the input common-mode voltage (V_{CM}) for the op amp.
7. Offset errors can be calibrated out with one-point calibration given that a known sense current is applied and the circuit is operating in the linear region. Gain error calibration requires a two-point calibration.
8. Include a small feed-forward capacitor (C_{SET}) to increase BW and decrease V_{OUT} settling time to a step response in current. Increasing C_{SET} too much introduces gain peaking in the system gain curve, which results in output overshoot to a step response.
9. Multiple circuits can sum their current outputs into a single load resistor, but note that the headroom voltage for each individual circuit will decrease. The INA2181 and INA4181 devices are multi-channel CSAs that have similar performance to the INA185 device.
10. Follow best practices for printed-circuit board (PCB) layout according to the data sheet: decoupling capacitor close to the VS pin, routing the input traces for IN+ and IN– as a differential pair, and so forth.

Design Steps

1. To satisfy system requirements, the minimum shunt (V_{SHUNT_MIN}) voltage value must be sufficiently greater than the known offsets of the amplifiers. Here is the equation for the worst-case maximum output current:

$$I_{OUT\_MAX\_Worst-Case} = \frac{V_{SET\_MAX}}{R_{SET} \cdot (1 - Tolerance_{Rset})}$$

$$I_{OUT\_MAX\_Worst-Case} = \frac{Gain_{INA185} \cdot (1 + GainError) \cdot \left[V_{SHUNT\_MIN} + V_{OS\_INA185}\right] + V_{OS\_TLV9061}}{R_{SET} \cdot (1 - Tolerance_{Rset})}$$

2. Since offset errors dominate at the low currents, negate resistor tolerance and gain error for establishing V_{SHUNT_MIN}. Set the error of V_{SET} to 2.2% to determine the following condition:

$$V_{SHUNT\_MIN} > \left(\frac{1}{2.2\%}\right) \cdot \left\{V_{OS\_INA185} + \frac{V_{OS\_TLV9061}}{Gain_{INA185}}\right\}$$

3. V_{OUT_MIN} also needs to be large enough so the common-mode voltage (V_{CM}) and output voltage ($V_{OUT\_TLV9061}$) of the TLV9061 device are in the optimal operating region. The TLV9061 device is a rail-to-rail-input-output (RRIO) op amp so it can operate with very small V_{CM} and output voltages, but A_{OL} will vary. Testing conditions for data sheet CMRR and A_{OL} show that choosing V_{OUT_MIN} > 50 mV will provide sufficient A_{OL} when circuit sensing minimum load current.

$$V_{OUT\_TLV9061} = V_{CM\_TLV9061} = V_{OUT}$$

$$V_{OUT\_MIN} > 50\,\text{mV for good TLV9061 } A_{OL}$$

4. The scaling of R_{OUT} and R_{SET} can be determined by setting three parameters: V_{O_MAX}, I_{OUT_MAX}, and R_{OUT}. It is critical that I_{OUT_MAX} does not exceed the driving capability of the CSA or else V_{O_MAX} will droop and the circuit will loose headroom voltage. Use the swing-to-rail specification and the V_{OUT} versus I_{OUT} data sheet curve to determine optimal values.
   a. Choose V_{O_MAX} = 4.9V
   b. Choose I_{OUT_MAX} = 900μA

c. Choose R_{OUT} = 1kΩ

5. Using the system of equations for V_{OUT}, solve for R_{SET}. Choose the closest larger 1% resistor value. Note that rounding up the R_{SET} value will decrease the I_{OUT_MAX} from initially chosen 900µA.

$$V_{SET\_MAX} = I_{OUT\_MAX} \cdot R_{SET}$$

$$V_{OUT\_MAX} = I_{OUT\_MAX} \cdot R_{OUT}$$

$$V_{OUT\_MAX} = V_{O\_MAX} - V_{SET\_MAX}$$

$$R_{SET} = \frac{V_{O\_MAX} - I_{OUT\_MAX} \cdot R_{OUT}}{I_{OUT\_MAX}} = 4444.3\Omega$$

$$R_{SET} = 4530\Omega,\ 1\%$$

6. Now choose an INA185 gain variant and solve for R_{SHUNT}. Choose a 1% resistor value. Note that R_{SET} is independent of gain and R_{SHUNT} can be calculated for each gain variant.

$$V_{OUT\_MAX} = I_{OUT\_MAX} \cdot R_{OUT} = 900\,mV$$

$$V_{SET\_MAX} = V_{O\_MAX} - V_{OUT\_MAX} = 4V$$

$$V_{IN\_MAX} = \frac{V_{SET\_MAX}}{Gain_{INA185A2}} = \frac{4V}{50\frac{V}{V}} = 80\,mV$$

$$R_{SHUNT} = \frac{V_{IN\_MAX}}{I_{LOAD\_MAX}} = \frac{80\,mV}{10\,A}$$

$$R_{SHUNT} = 8\,m\Omega$$

7. Now check if V_{OUT_MIN} and V_{SHUNT_MIN} are large enough to achieve 2% error at 1A with updated values. Use the maximum offset specifications of the devices when calculating error.

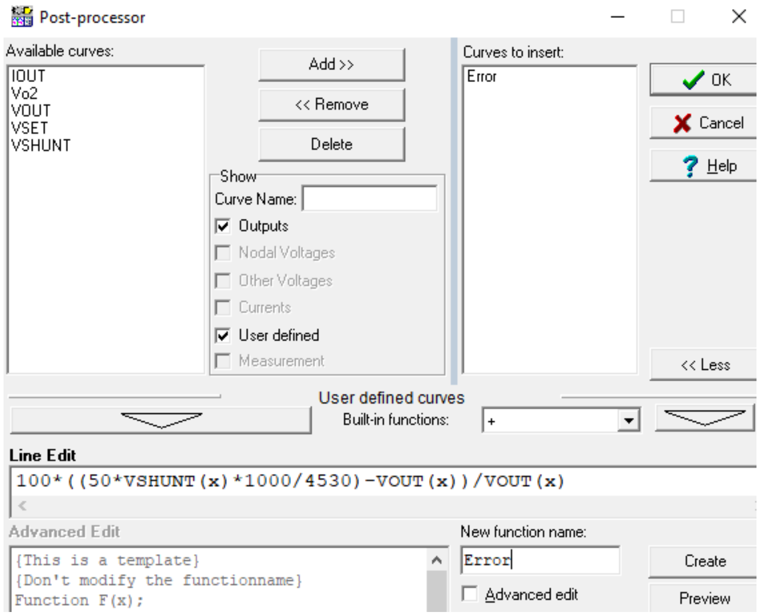
$$V_{SHUNT\_MIN} > \left(\frac{1}{2.2\%}\right) \cdot \left\{V_{OS\_INA185A2} + \frac{V_{OS\_TLV9061}}{GAIN_{INA185A2}}\right\} = 45.45 \cdot \left\{130\mu V + \frac{2mV}{50\frac{V}{V}}\right\} = 7.73\,mV$$

$$V_{SHUNT\_MIN} = 1A \cdot 8m\Omega = 8mV > 7.73\,mV$$

$$V_{OUT\_MIN} = V_{SHUNT\_MIN} \cdot Gain_{INA185A2} \cdot \frac{R_{OUT}}{R_{SET}}$$

$$V_{OUT\_MIN} = 8mV \cdot 50\frac{V}{V} \cdot \frac{1k\Omega}{4.53k\Omega} = 88mV > 50\,mV$$

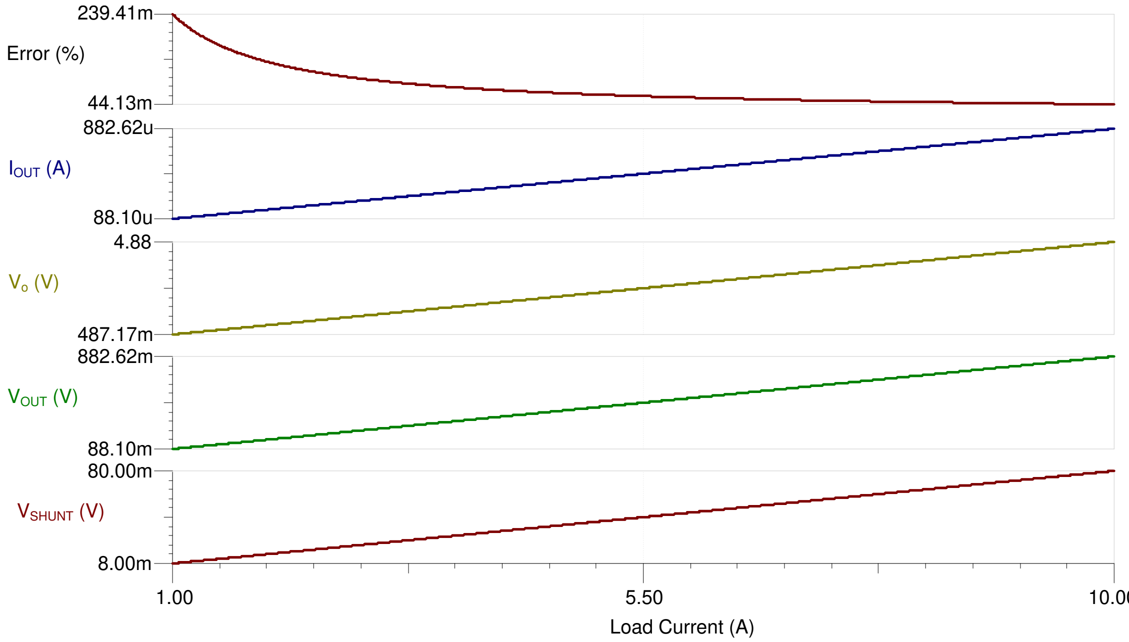
8. Run a simulation in TINA-TI software using available models. Note that these models use typical specifications. Calculate *Error* in the TINA-TI *Post-processor* window.



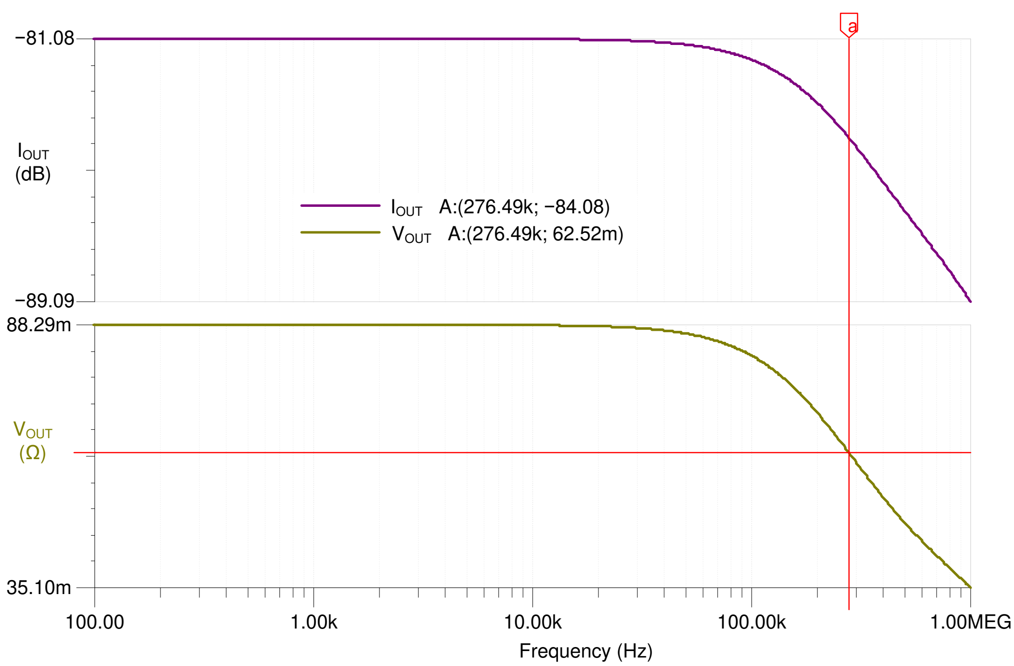
Design Simulations

DC Simulation Results

The following graph shows a linear output response for load currents from 1A to 10A.



AC Simulation Result – I_{LOAD} to I_{OUT} (V_{OUT}) circuit gain



Design References

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

See the circuit SPICE simulation file SBOMAI6.

Getting Started with Current Sense Amplifiers video series

https://training.ti.com/getting-started-current-sense-amplifiers

Current Sense Amplifiers on TI.com

http://www.ti.com/amplifier-circuit/current-sense/products.html

Comprehensive Study of the Howland Current Pump

http://www.ti.com/analog/docs/litabsmultiplefilelist.tsp?literatureNumber=snoa474a&docCategoryId=1&familyId=78

For direct support from TI Engineers use the E2E community

http://e2e.ti.com

Design Featured Current Sense Amplifier

INA185A2	
V_S	2.7V to 5.5V (operational)
V_{CM}	0V to 26V
Swing to V_S (V_{SP})	V_S – 0.02V
V_{OS}	±25μV to ±130μV at 12V V_{CM}
I_Q	200μA to 260μA
I_{IB}	75μA at 12V
BW	210kHz at 50V/V (A2 gain variant)
# of channels	1
Body size (including pins)	1.60 mm × 1.60 mm
http://www.ti.com/product/ina185	

Design Featured Operational Amplifier

TLV9061 (TLV9061S is shutdown version)	
V_S	1.8V to 5.5V
V_{CM}	(V–) – 0.1V < V_{CM} < (V+) + 0.1V
CMRR	103dB
A_{OL}	130dB
V_{OS}	±1.6mV maximum
I_Q	750μA maximum
I_B (input bias current)	± 0.5pA
GBP (gain bandwidth product)	10MHz
# of channels	1 (2 and 4 channel packages available)
Body size (including pins)	0.80 mm × 0.80 mm
http://www.ti.com/product/tlv9061	