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

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 (RSET). 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 (ROUT). Additionally, multiple circuits can be summed together to determine total current from multiple sources.

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
<th>Error</th>
<th>Supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILOAD_MIN</td>
<td>ILOAD_MAX</td>
<td>VCM</td>
<td>IOUT_MIN</td>
</tr>
<tr>
<td>1A</td>
<td>10A</td>
<td>12V</td>
<td>88.3µA</td>
</tr>
</tbody>
</table>
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:

\[
I_{OUT\_MAX\_Worst\_Case} = \frac{V_{SET\_MAX}}{R_{SET} \cdot (1 - \text{Tolerance} \cdot \text{R}_{\text{Res}})}
\]

\[
I_{OUT\_MAX\_Worst\_Case} = \frac{\text{Gain}_{\text{INA}185} \cdot (1 + \text{GainError}) \cdot (V_{SHUNT\_MIN} + V_{OS\_INA185}) + V_{OS\_TLV9061}}{R_{SET} \cdot (1 - \text{Tolerance} \cdot \text{R}_{\text{Res}})}
\]

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:

\[
V_{SHUNT\_MIN} > \left( \frac{1}{2.2\%} \right) \cdot \left( V_{OS\_INA185} + \frac{V_{OS\_TLV9061}}{\text{Gain}_{\text{INA185}}} \right)
\]

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 \( V_{OUT\_MIN} > 50 \text{ mV} \) will provide sufficient \( A_{OL} \) when circuit sensing minimum load current.

\[
V_{OUT\_TLV9061} = V_{CM\_TLV9061} = V_{OUT}
\]

\[
V_{OUT\_MIN} > 50 \text{ mV} \text{ for good TLV9061 A}_{OL}
\]
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 lose 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 $I_{OUT\_MAX} = 900\mu A$
   c. Choose $R_{OUT} = 1k \Omega$

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.
   \[
   V_{OUT\_MAX} = I_{OUT\_MAX} \cdot R_{OUT} = 900\text{mV} \\
   V_{SET\_MAX} = V_{O\_MAX} - V_{OUT\_MAX} = 4V \\
   V_{IN\_MAX} = \frac{V_{SET\_MAX}}{Gain_{INA185A2}} = \frac{4V}{50} = 80\text{mV} \\
   R_{SHUNT} = \frac{V_{IN\_MAX}}{I_{LOAD\_MAX}} = \frac{80\text{mV}}{10 \text{A}} \\
   R_{SHUNT} = 8\text{m}\Omega
   \]

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.
   \[
   V_{SHUNT\_MIN} > \left(\frac{1}{2.2\%}\right) \cdot \left\{V_{OS\_INA185A2} + \frac{V_{OS\_TLV9061}}{Gain_{INA185A2}}\right\} = 45.45 \cdot \left\{130\mu V + \frac{2\text{mV}}{50V}\right\} = 7.73\text{mV} \\
   V_{SHUNT\_MIN} = 1A \cdot 8\text{m}\Omega = 8\text{mV} > 7.73\text{mV} \\
   V_{OUT\_MIN} = V_{SHUNT\_MIN} \cdot Gain_{INA185A2} \cdot \frac{R_{OUT}}{R_{SET}} \\
   V_{OUT\_MIN} = 8\text{mV} \cdot \frac{50V}{1k \Omega} = \frac{88\text{mV}}{4.53k \Omega} = 88\text{mV} > 50\text{mV}
   \]
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 SBOMA16.

Getting Started with Current Sense Amplifiers video series
https://training.ti.com/getting-started-current-sense-amplifiers

Current Sense Amplifiers on TI.com

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

<table>
<thead>
<tr>
<th>INA185A2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_S$</td>
<td>2.7V to 5.5V (operational)</td>
</tr>
<tr>
<td>$V_{CM}$</td>
<td>0V to 26V</td>
</tr>
<tr>
<td>Swing to $V_S$ ($V_{SP}$)</td>
<td>$V_S - 0.02V$</td>
</tr>
<tr>
<td>$V_{OS}$</td>
<td>±25µV to ±130µV at 12V $V_{CM}$</td>
</tr>
<tr>
<td>$I_Q$</td>
<td>200µA to 260µA</td>
</tr>
<tr>
<td>$I_B$</td>
<td>75µA at 12V</td>
</tr>
<tr>
<td>BW</td>
<td>210kHz at 50V/V (A2 gain variant)</td>
</tr>
<tr>
<td># of channels</td>
<td>1</td>
</tr>
<tr>
<td>Body size (including pins)</td>
<td>1.60 mm × 1.60 mm</td>
</tr>
</tbody>
</table>

http://www.ti.com/product/ina185

Design Featured Operational Amplifier

<table>
<thead>
<tr>
<th>TLV9061 (TLV9061S is shutdown version)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_S$</td>
<td>1.8V to 5.5V</td>
</tr>
<tr>
<td>$V_{CM}$</td>
<td>($V_-$) − 0.1V &lt; $V_{CM}$ &lt; ($V_+$) + 0.1V</td>
</tr>
<tr>
<td>CMRR</td>
<td>103dB</td>
</tr>
<tr>
<td>$A_{OL}$</td>
<td>130dB</td>
</tr>
<tr>
<td>$V_{OS}$</td>
<td>±1.6mV maximum</td>
</tr>
<tr>
<td>$I_Q$</td>
<td>750µA maximum</td>
</tr>
<tr>
<td>$I_B$ (input bias current)</td>
<td>± 0.5pA</td>
</tr>
<tr>
<td>GBP (gain bandwidth product)</td>
<td>10MHz</td>
</tr>
<tr>
<td># of channels</td>
<td>1 (2 and 4 channel packages available)</td>
</tr>
<tr>
<td>Body size (including pins)</td>
<td>0.80 mm × 0.80 mm</td>
</tr>
</tbody>
</table>

http://www.ti.com/product/tlv9061