Analog Engineer’s Circuit Amplifiers

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

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
<th>Error</th>
<th>Supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{LOAD, Min}$</td>
<td>$I_{LOAD, Max}$</td>
<td>$V_{CM}$</td>
<td>$I_{OUT, Min}$</td>
</tr>
<tr>
<td>1A</td>
<td>10A</td>
<td>12V</td>
<td>88.3µA</td>
</tr>
</tbody>
</table>

**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:

$$I_{OUT_{Max, Worst-Case}} = \frac{V_{SET_{Max}}}{R_{SET} \cdot (1 - \text{Tolerance}_{Rset})}$$

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:

$$V_{SHUNT_{MIN}} > \left\{ \frac{1}{2.2\%} \right\} \cdot \left\{ \frac{V_{OS_{INA185}}}{\text{Gain}_{INA185}} + \frac{V_{OS_{TLV9061}}}{\text{Gain}_{INA185}} \right\}$$

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.

$$V_{OUT_{TLV9061}} = V_{CM_{TLV9061}} = V_{OUT}$$

$$V_{OUT_{MIN}} > 50$ mV for good TLV9061 $A_{OL}$$

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 $V_{O_{MAX}} = 4.9$ V
   b. Choose $I_{OUT_{MAX}} = 900$ µA
c. Choose $R_{\text{OUT}} = 1\,\text{k}\Omega$

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

\[
\begin{align*}
V_{\text{SET\_MAX}} &= I_{\text{OUT\_MAX}} \cdot R_{\text{SET}} \\
V_{\text{OUT\_MAX}} &= I_{\text{OUT\_MAX}} \cdot R_{\text{OUT}} \\
V_{\text{OUT\_MAX}} &= V_{\text{O\_MAX}} - V_{\text{SET\_MAX}} \\
R_{\text{SET}} &= \frac{V_{\text{O\_MAX}} - I_{\text{OUT\_MAX}} \cdot R_{\text{OUT}}}{I_{\text{OUT\_MAX}}} = 4444.3\,\Omega \\
R_{\text{SET}} &= 4530\,\Omega, \ 1\%
\end{align*}
\]

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

\[
\begin{align*}
V_{\text{OUT\_MAX}} &= I_{\text{OUT\_MAX}} \cdot R_{\text{OUT}} = 900\,\text{mV} \\
V_{\text{SET\_MAX}} &= V_{\text{O\_MAX}} - V_{\text{OUT\_MAX}} = 4\,\text{V} \\
V_{\text{IN\_MAX}} &= \frac{V_{\text{SET\_MAX}}}{\text{Gain}_{\text{INA185A2}}} = \frac{4\,\text{V}}{50\,\text{V}} = 80\,\text{mV} \\
R_{\text{SHUNT}} &= \frac{V_{\text{IN\_MAX}}}{I_{\text{LOAD\_MAX}}} = \frac{80\,\text{mV}}{10\,\text{A}} \\
R_{\text{SHUNT}} &= 8\,\text{m}\Omega
\end{align*}
\]

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

\[
V_{\text{SHUNT\_MIN}} > \left( 1 - 2.2\% \right) \left( V_{\text{OS\_INA185A2}} + \frac{V_{\text{OS\_TLV9061}}}{\text{Gain}_{\text{INA185A2}}} \right) = 45.45 \cdot \left( 130\,\mu\text{V} + \frac{2\,\text{mV}}{50\,\text{V}} \right) = 7.73\,\text{mV}
\]

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

\[
V_{\text{OUT\_MIN}} = V_{\text{SHUNT\_MIN}} \cdot \text{Gain}_{\text{INA185A2}} \cdot \frac{R_{\text{OUT}}}{R_{\text{SET}}}
\]

\[
V_{\text{OUT\_MIN}} = 8\,\text{mV} \cdot 50\,\text{V} \cdot \frac{1\,\text{k}\Omega}{4.53\,\text{k}\Omega} = 88\,\text{mV} > 50\,\text{mV}
\]
8. Run a simulation in TINA-TI software using available models. Note that these models use typical specifications. Calculate \textit{Error} in the TINA-TI \textit{Post-processor} window.
Design Simulations

DC Simulation Results

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

![Graph showing linear output response for load currents from 1A to 10A.]

AC Simulation Result – I\textsubscript{LOAD} to I\textsubscript{OUT} (V\textsubscript{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](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](http://www.ti.com/analog/docs/litabsmultiplefilelist.tsp?literatureNumber=snoa474a&docCategoryId=1&familyId=78)

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[http://e2e.ti.com](http://e2e.ti.com)

**Design Featured Current Sense Amplifier**

<table>
<thead>
<tr>
<th>INA185A2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>V&lt;sub&gt;S&lt;/sub&gt;</strong></td>
<td>2.7V to 5.5V (operational)</td>
</tr>
<tr>
<td><strong>V&lt;sub&gt;CM&lt;/sub&gt;</strong></td>
<td>0V to 26V</td>
</tr>
<tr>
<td>Swing to <strong>V&lt;sub&gt;S&lt;/sub&gt;</strong> (<strong>V&lt;sub&gt;SP&lt;/sub&gt;</strong>)</td>
<td><strong>V&lt;sub&gt;S&lt;/sub&gt;</strong> − 0.02V</td>
</tr>
<tr>
<td><strong>V&lt;sub&gt;OS&lt;/sub&gt;</strong></td>
<td>±25μV to ±130μV at 12V <strong>V&lt;sub&gt;CM&lt;/sub&gt;</strong></td>
</tr>
<tr>
<td><strong>I&lt;sub&gt;Q&lt;/sub&gt;</strong></td>
<td>200μA to 260μA</td>
</tr>
<tr>
<td><strong>I&lt;sub&gt;B&lt;/sub&gt;</strong></td>
<td>75μA at 12V</td>
</tr>
<tr>
<td><strong>BW</strong></td>
<td>210kHz at 50V/V (A2 gain variant)</td>
</tr>
<tr>
<td><strong># of channels</strong></td>
<td>1</td>
</tr>
<tr>
<td><strong>Body size (including pins)</strong></td>
<td>1.60 mm × 1.60 mm</td>
</tr>
</tbody>
</table>


**Design Featured Operational Amplifier**

<table>
<thead>
<tr>
<th>TLV9061 (TLV9061S is shutdown version)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>V&lt;sub&gt;S&lt;/sub&gt;</strong></td>
<td>1.8V to 5.5V</td>
</tr>
<tr>
<td><strong>V&lt;sub&gt;CM&lt;/sub&gt;</strong></td>
<td>(V−) – 0.1V &lt; <strong>V&lt;sub&gt;CM&lt;/sub&gt;</strong> &lt; (V+) + 0.1V</td>
</tr>
<tr>
<td><strong>CMRR</strong></td>
<td>103dB</td>
</tr>
<tr>
<td><strong>A&lt;sub&gt;OL&lt;/sub&gt;</strong></td>
<td>130dB</td>
</tr>
<tr>
<td><strong>V&lt;sub&gt;OS&lt;/sub&gt;</strong></td>
<td>±1.6mV maximum</td>
</tr>
<tr>
<td><strong>I&lt;sub&gt;Q&lt;/sub&gt;</strong></td>
<td>750μA maximum</td>
</tr>
<tr>
<td><strong>I&lt;sub&gt;B&lt;/sub&gt;</strong> (input bias current)</td>
<td>± 0.5pA</td>
</tr>
<tr>
<td><strong>GBP</strong> (gain bandwidth product)</td>
<td>10MHz</td>
</tr>
<tr>
<td><strong># of channels</strong></td>
<td>1 (2 and 4 channel packages available)</td>
</tr>
<tr>
<td><strong>Body size (including pins)</strong></td>
<td>0.80 mm × 0.80 mm</td>
</tr>
</tbody>
</table>

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