Application Report
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Low-Cost Bidirectional Current Sensing Using INA181

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ABSTRACT

In applications like home inverter and UPS where high currents are measured using general-purpose op amps, measuring the current accurately is often challenging. Because low-resistance resistors are used to improve efficiency, the input offset of an op amp significantly contributes to the error in measured voltages. The INA181 device can help overcome this problem. This application note demonstrates current sensing using the INA181 to replace the traditional current sensing using general-purpose op amps. The INA181 has lower input offset voltage and is a low-cost device. The device can also operate at the high common-mode voltage of 26 V and can be used in low-side and high-side sensing. Because the INA181 can sense bidirectional current with the reference voltage, a single-channel device can replace the conventional way of using inverting and noninverting topology with general-purpose op amps. This application note also lists error calculations of the solution with reference voltage generated from the TL431 and TLV431 devices.

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1 Introduction

1.1 High-Side and Low-Side Current Sensing

In high-side current sensing, the sense resistor is placed between the positive supply and load. In low-side current sensing, the sense resistor is placed between load and common ground. Figure 1 and Figure 2 show the high-side and low-side current sensors, respectively.

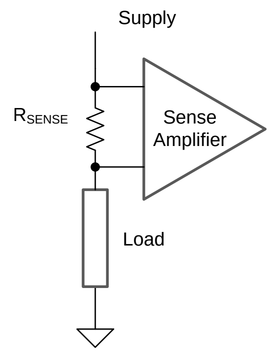

Figure 1. High-Side Current Sensor

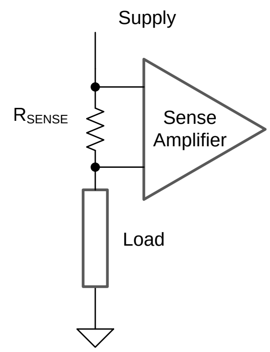

Figure 2. Low-Side Current Sensor

Susceptibility to ground disturbance, parasitic error, and the inability to detect load shorts are major drawbacks in low-side current sensing. To implement high-side current sensing, op amps must have high CMRR and high common-mode voltage ranges. Unlike the low-side method, the high-side method provides protection against the load short.

1.2 Differential Current Sensing Approach

The errors caused by ground disturbance and parasitic resistance are avoided using a difference amplifier for current sensing. This approach can be used for low-side and high-side methods.

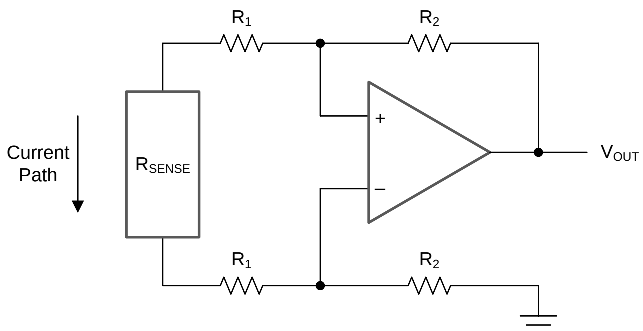

Figure 3. Difference Amplifier

1.3 Conventional Method

Figure 4 shows the conventional method using general-purpose op amps for bidirectional current sensing. This method is low-side current sensing, and the ground disturbance causes an error in the measured current value.

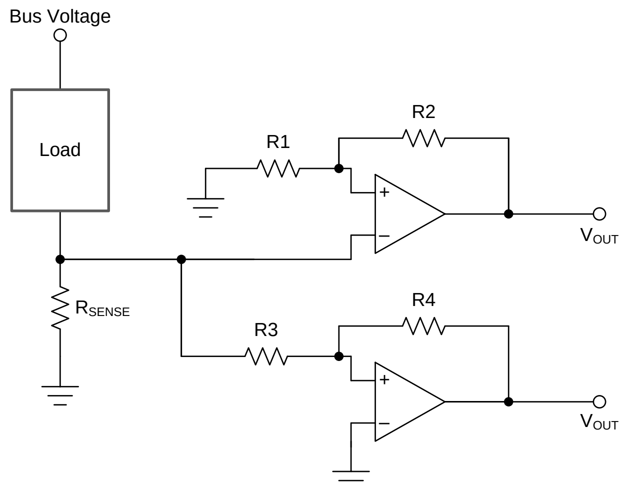

Figure 4. Conventional Method of Current Sensing

Other than ground disturbance and parasitic resistance errors, general-purpose op amps have an offset voltage in mV. Using the example of inverter application, if a general-purpose op amp has a 5-mV offset voltage, it causes an error of 5 A for a sense resistance of 1 mΩ. As a result, the wattage error is approximately 10%. In addition, ground disturbance and parasitic resistance add more error.

2 Current Sensing Using INA181

2.1 INA181

Important features of the INA181 device follow:

- Cost-optimized, bidirectional current-sense amplifier with accurate internal resistors
- Single-rail supply range: 2.7 V to 5.5 V
- Output swing to the supply voltage: V_{SUPPLY} – 0.02 V
- Common-mode voltage range: –0.2 V to 26 V
- Offset voltage:
  - 150 µV at V_{CM} = 0 V
  - 500 µV at V_{CM} = 12 V
- Accuracy:
  - Maximum gain error of 1%
  - Maximum offset drift of 1 µV/°C

  Gain options: 20 V/V, 50 V/V, 100 V/V, and 200 V/V

2.2 *Design Calculations of Sensing With INA181*

2.2.1 Design for the System With a 5-V Supply Bus

Figure 5 shows the design where the INA181 device is used for bidirectional current sensing, whereas the TL431 device is used to provide an accurate reference of 2.5 V. The major advantage of this design is that it has the least number of external components, resulting in a minimum error and low cost. The 250-Ω series resistor connected between the supply and cathode of TL431 limits the current to 10 mA. The output of the circuit is given by Equation 1

$$V_{OUT} = V_{REF} + (V_{SENSE} \times Gain) \tag{1}$$

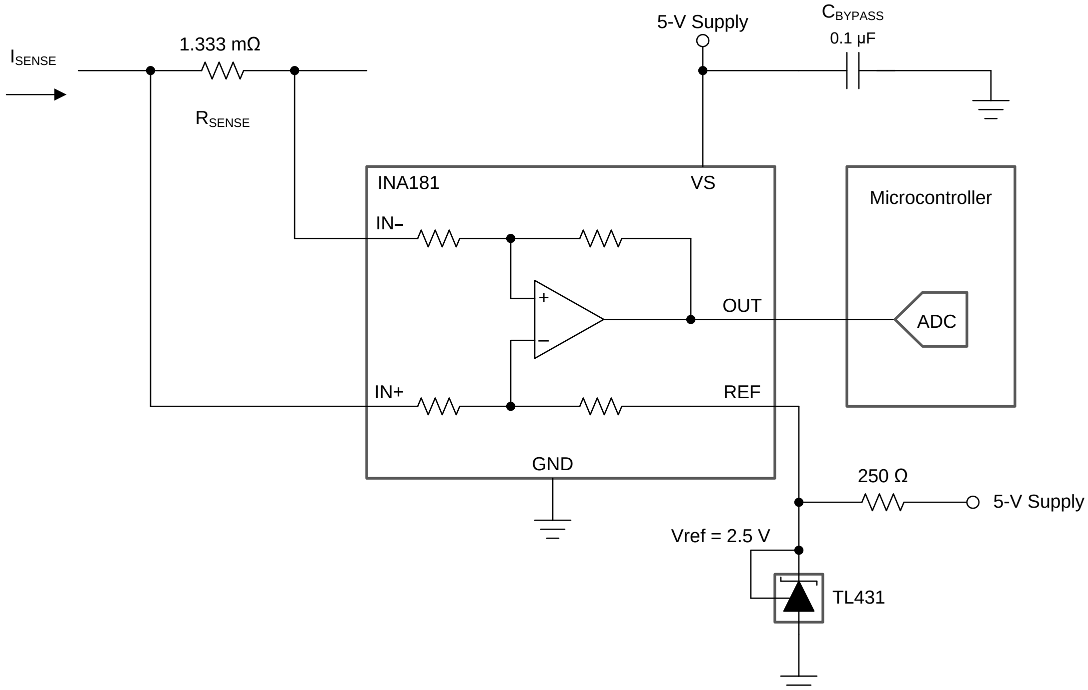

Figure 5. Bidirectional Current Sensing Using INA181 and TL431

For a system with a maximum current limit of 90 A, calculations follow.

- Limitation on negative voltage at input IN+ in low-side sensing in case of negative current. INA181 can operate until V_{CM} = –0.2 V, thus for Gain = 20 V/V.

$$-0.2 = 2.5 - \left(\frac{500}{525}\right) \times (2.5 + V_{IN+}) \tag{2}$$

  Thus, V_{IN+} can go up to –0.3352 V without violating the VCM limit of the op amp.

- Limitation of V_{SENSE}:

  The output swing can be obtained from 2.5 V to 5 V as well as from 2.5 V to 0 V. Thus, the maximum value of Gain × $V_{SENSE(MAX)}$ can go to 2.5 V. Selecting Gain × $V_{SENSE(MAX)}$ = 2.4 V and Gain = 20 V/V, then $V_{SENSE(MAX)}$ = 0.12 V.

  Because V_{SENSE} = I_{SENSE} × R_{SENSE}, and $I_{SENSE(MAX)}$ = 90 A, then R_{SENSE} = 1.3 mΩ. Thus, in inverter applications with a maximum discharging current of 90 A and maximum charging current of 60 A:

  – When I_{SENSE} = 90 A, V_{OUT} = 2.5 + (0.12 × 20) = 4.9 V

  – When I_{SENSE} = –60 A, V_{OUT} = 2.5 – (0.08 × 20) = 0.9 V

  Thus, overcurrent limits can be set as 4.9 V for I_{SENSE} = 90 A, and as 0.9 V for I_{SENSE} = –60 A.

2.2.2 Design for the System With a 3.3-V Supply Bus

The TLV431 has a 1.24-V reference in this design, which is the only change. This design can also be modified for systems with a 5-V bus. Figure 6 shows the circuit.

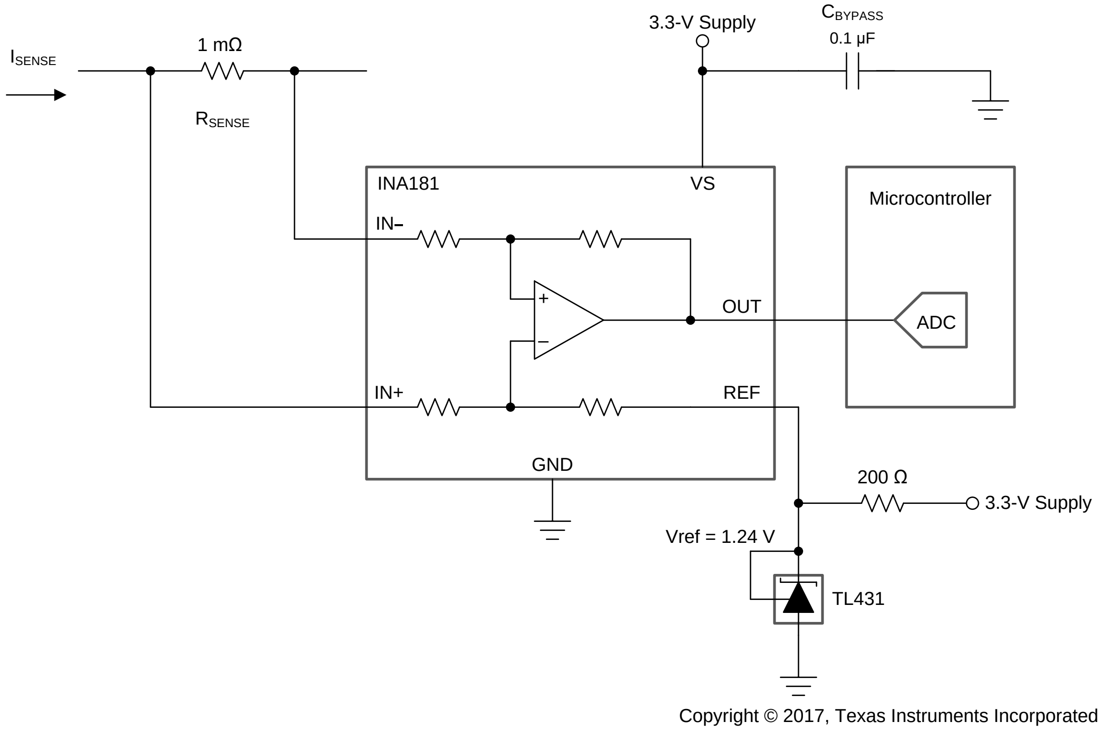

Figure 6. Bidirectional Current Sensing Using INA181 and TLV431

For a system with a maximum current limit of 90 A, calculations follow.

- Limitation on negative voltage at input IN+ in low-side sensing in case of –ve current:

  INA181 can operate up to VCM = –0.2 V, thus for Gain = 20 V/V.

$$-0.2 = 1.24 - \left(\frac{500}{525}\right) \times (1.24 + V_{IN+}) \quad (3)$$

  Thus, V_{IN+} can go up to –0.2721 V without violating the VCM limit of the op amp.

- Limitation of V_{SENSE}:

  For negative current, output can go from 1.24 V to 0 V. Thus, V_{SENSE} is limited by the maximum value of negative current.

  Selecting gain × $V_{SENSE(MAX)}$ = 1.2 V.

  Gain = 20 V/V, thus, $V_{SENSE(MAX)}$ = 0.06 V.

  For an inverter application, charging current is typically 2/3 of the charging current. Thus, taking the maximum negative current of 60 A:

  – $V_{SENSE} = I_{SENSE} \times R_{SENSE}$ and $I_{SENSE(MAX)}$ = –60 A → R_{SENSE} = 1 mΩ

  – When I_{SENSE} = 90 A, V_{OUT} = 1.24 + (0.09 × 20) = 3.04 V

  – When I_{SENSE} = –60 A, V_{OUT} = 1.24 – (0.06 × 20) = 0.04 V

  Thus, the overcurrent limits can be set as 3.04 V for I_{SENSE} = 90 A, and as 0.04 V for I_{SENSE} = –60 A.

2.3 Error Calculations

2.3.1 Worst-Case Error in Current Sensing Using General-Purpose Op Amps

2.3.1.1 Input Offset Error

Assuming the R_{SENSE} equals 1 mΩ for a 90-A current application, the worst-case V_{OS}, including temperature drift, is approximately 6 mV, resulting in:

$$\% \text{ Offset Error} = 7\% \tag{4}$$

2.3.1.2 Gain Error

Assuming the 2% tolerance error of external resistors used, the worst-case gain error is 4%.

$$\text{Total \% error} = \sqrt{\left((7)^2 + (4)^2\right)} = 8.1\% \tag{5}$$

For a 720-W inverter application, it results into approximately 58 W. This calculation does not include other errors (such as input bias current error or error due to input offset current).

2.3.2 Worst-Case Error in Bidirectional Current Sensing Using INA181 and TL431

2.3.2.1 Errors Due to INA181

2.3.2.1.1 Offset Error

The input offset voltage in the INA181 device is 150 µV. Including the temperature drift for an application operating up to 55°C maximum, the input offset voltage is 180 µV. Thus:

$$\% \text{ Offset Error} = \frac{\text{Offset Voltage}}{V_{SENSE}} \tag{6}$$

The maximum value of V_{SENSE} is 120 mV. Thus, the offset error is 0.15%.

2.3.2.1.2 Gain Error

The INA181 device has a maximum gain error of 1%.

2.3.2.2 Error in the Reference TL431

The typical deviation in V_{REF} value over its full operating temperature range is 14 mV. It can also have ΔV_{REF} of 12 mV in the worst case. Thus, the maximum V_{REF} error is 26 mV.

$$\% V_{REF} \text{ Error} = \frac{26}{20 \times (V_{SENSE})} \tag{7}$$

Maximum V_{SENSE} is 120 mV, meaning $\% V_{REF}$ = 1.1%.

$$\% \text{ Total Error} = \sqrt{(1)^2 + (0.15)^2 + (1.1)^2} = 1.1\% \tag{8}$$

Thus, this design has a maximum calculated error of 1.494%. In an example of a 720-W inverter, the worst-case wattage error is 10.75 W.

2.3.3 Worst-Case Error in Bidirectional Current Sensing Using INA181 and TL431 Devices

2.3.3.1 Errors Due to INA181

2.3.3.1.1 Offset Error

The input offset voltage in the INA181 device is 150 µV. Including temperature drift for an application operating up to 55°C maximum, the input offset voltage is 180 µV. Thus:

$$\%\text{ Offset Error} = \frac{\text{Offset Voltage}}{V_{SENSE}} \tag{9}$$

Maximum value of V_{SENSE} is 0.09 mV. Thus, the offset error is 0.20%.

2.3.3.1.2 Gain Error

The INA181 device has a maximum gain error of 1%.

2.3.4 Error in the Reference TL431

The typical deviation in V_{REF} value over its full operating temperature range is 6 mV. It can also have ΔV_{REF} of 4 mV in the worst case. Thus, maximum V_{REF} error is 10 mV.

$$\%V_{REF}\text{ Error} = \frac{10}{20 \times (V_{SENSE})} \tag{10}$$

Maximum V_{SENSE} is 90 mV, meaning $\%V_{REF}$ = 0.55%.

$$\%\text{ Total Error} = \sqrt{(1)^2 + (0.2)^2 + (0.55)^2} = 1.26\% \tag{11}$$

Thus, this design has a maximum calculated error of 1.26%. In an example of a 720-W inverter, the worst-case wattage error is 9 W.

3 Test Results

Table 1 and Table 2 list the output of bidirectional current-sensing circuits using INA181 and TL431 devices for positive and negative currents.

Table 1. Positive Current

V_{SENSE} (mV)	V_{REF} (V)	V_{OUT} (V)	$V_{OUT} - V_{REF}$ (V)	GAIN
28.2	2.5	3.066	0.566	20.07
32.7	2.5	3.154	0.654	20
38.9	2.5	3.28	0.78	20.05
48	2.5	3.462	0.962	20
62.8	2.5	3.758	1.258	20.03
64.8	2.5	3.798	1.298	20.03
95.1	2.5	4.406	1.906	20.04
118.5	2.5	4.906	2.406	20.03

Table 2. Negative Current

V_{SENSE} (mV)	V_{REF} (V)	V_{OUT} (V)	$V_{OUT} - V_{REF}$ (V)	GAIN
–15.9	2.5	2.177	0.323	20.31
–27.9	2.5	1.941	0.559	20.03
–50.6	2.5	1.488	1.012	20
–92.1	2.5	0.647	1.853	20.11
–117.4	2.5	0.143	2.357	20.07

4 References

- *INAx181 Bidirectional, Low- and High-Side Voltage Output, Current-Sense Amplifier* (SBOS793)
- *TL43xx Precision Programmable Reference* (SLVS543)
- *TLV431x Low-Voltage Adjustable Precision Shunt Regulator* (SLVS139)
- *Setting the Shunt Voltage on an Adjustable Shunt Regulator* (SLVA445)
- *800VA Pure Sine Wave Inverter's Reference Design* (SLAA602)
- *Low-Side Current Sense Circuit Integration* (SBOA190)
- *https://e2e.ti.com/blogs_/b/analogwire/archive/2017/06/01/system-trade-offs-for-high-and-low-side-current-measurements*

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