Current Sensing with Low-Voltage Precision Op-Amps

Sensing and controlling current flow is a fundamental requirement in electronics systems. This application note explains the design of low-side and high-side current sensing circuits using the ISL28x3x family of low-voltage precision op-amps in combination with current sense resistors.

Contents

1. Current Sensing Techniques

This section introduces two basic techniques for current sensing applications, low-side current sensing and high-side current sensing. Each technique has its own advantages and disadvantages, discussed in detail in the following topics.

1.1 Low-Side Current Sensing

As shown in Figure 1, low-side current sensing connects the sensing resistor between the load and ground. Commonly, the current flow is in one direction (unidirectional). The sensed voltage signal ($V_{SENSE} = I_{LOAD} \times R_{SENSE}$) is so small that it needs to be amplified by a subsequent op-amp circuit, such as a non-inverting amplifier, to obtain the measurable output voltage (V_{OUT}).

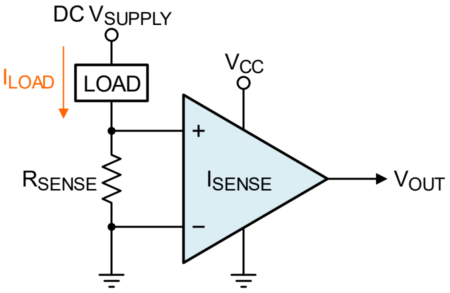


Figure 1. Low-Side Current Sensing

In a single-supply configuration, the most important aspect of low-side current sensing is that the input common mode voltage range (V_{ICM}) of the op-amp must include ground. The ISL2813x op-amps are a good choice since their V_{ICM} includes both supply rails.

Low-Side Sensing Advantages

- Low input common-mode voltage
- Low-voltage amplifiers possible
- Ground referenced output voltage
- Simple single-supply design and low cost

Low-Side Sensing Disadvantages

- Load lifted from direct ground connection as R_{SENSE} adds undesirable resistance to the ground path
- Load could be activated by accidental short to ground
- High load current caused by accidental short is not detected

Considering the advantages, choose low-side current sensing where short-circuit detection is not required, and ground disturbances can be tolerated.

1.2 High-Side Current Sensing

As shown in Figure 2, high-side current sensing connects the sensing resistor between the power supply and load. The sensed voltage signal is amplified by subsequent op-amp circuits to obtain the measurable V_{OUT}.

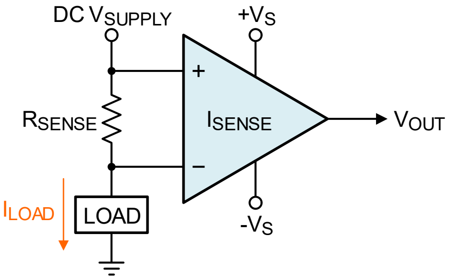


Figure 2. High-Side Current Sensing

High-Side Sensing Advantages

- Load is grounded
- Load not activated by accidental short at power connection
- High load current caused by short is detected

High-Side Sensing Disadvantages

- High input common mode voltages (often very high)
- Output needs to be level shifted down to system operating voltage levels
- Higher complexity and cost

In a single-supply configuration with low-voltage op-amps, the important aspects of high-side current sensing are:

- The V_{ICM} range of the op-amp must include the upper supply rail to withstand high common-mode input voltages.
- In a high-voltage application, the op-amp supply rails must be level-shifted towards the system supply.

The ISL2813x op-amps are a good fit for this type of high-side current sensing, which is discussed in the later sections.

1.3 Current-Sensing Resistor

A current-sensing resistor is a current-to-voltage converter that wen inserted into the current path converts the current into voltage in a linear way of V = I × R. The main advantages and disadvantages of current sensing resistors include.

Advantages:

- Low cost
- High measurement accuracy
- Measurable current ranges from very low to medium
- Capability to measure DC or AC current

Disadvantages:

- Introduces additional resistance into the measured circuit path, which may increase source output resistance and result in undesirable loading effect
- Power loss since power dissipation $P = I^2 \times R$. Therefore, current-sensing resistors are rarely used beyond the low and medium current-sensing applications

The disadvantages can be reduced by using low-value sensing resistors. To allow for low voltage drops across the sense resistor, auto-zero op-amps such as ISL28134, ISL28133, and ISL28130 are recommended to avoid compromising the measurement accuracy.

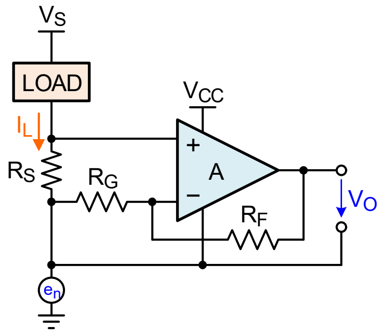
Also, resistance tolerance, temperature coefficient, temperature rating, and power rating are important parameters of the current-sense resistor when high measurement accuracy is required.

The selection of the current-sensing resistor is vital for designing any kind of current monitor. so use the following criteria as a guide::

- Low resistance with tight tolerance, to create a balance between accuracy and power dissipation.
- High current capability and high peak power rating to handle short duration and transient peak current.
- Low temperature coefficient, low thermal EMF and high temperature capability, if there is a wide temperature variation.

2. Low-Side Current Sensing Implementation

The simple non-inverting amplifier in Figure 3 requires that the circuit inputs and output, and the op-amp ground terminals are in close proximity to the sense resistor.



Parameter	Low-/High-Voltage Application
V_S	5V/40V
V_{CC}	3.3V
R_S	5mΩ
R_F	11.8k
R_G	200
I_L	0 – 10A
V_O	0 – 3V

Figure 3. Low-Side Current Sensing with Non-inverting Amplifier

This ensures the noise voltage, created by noise currents in the ground plane, appears as common-mode noise to all these terminals. Therefore, the entire circuit rides on the ground + noise potential, causing the output voltage to be:

(EQ. 1) $$V_O = I_L \times R_S\left(1+\frac{R_F}{R_G}\right)$$

Non-precision op-amps introduce an error because of their input offset voltage, therefore making the output voltage:

(EQ. 2) $$V_O = I_L \times R_S\left(1+\frac{R_F}{R_G}\right)+V_{OS}\left(1+\frac{R_F}{R_G}\right)$$

To limit this error to 1% maximum, the voltage across R_S must be 100-times larger than the input offset:$I_L \times R_S \geq 100V_{OS}$. This requirement limits the minimum value for the sense resistor, which is calculated using Equation 3:

(EQ. 3) $$R_S \geq \frac{100V_{OS}}{I_L}$$

Equation 3 shows that the smaller V_{OS}, the lower the required minimum for R_S. Therefore, for a given power rating, the smaller the value of R_S, the higher the maximum possible load current.

In the case of the ISL28134 with a maximum input offset of 2.5µV over a temperature range at 25°C, the voltage across R_S could be as small as 250µV. Therefore, with a 1mΩ sense resistor, you could measure currents as small as 250mA before reaching the minimum sense voltage and up to 31A without exceeding 1W of power consumption.

3. High-Side Current Sensing Implementation

As shown in Figure 4, high-side current sensing makes use of an output transistor. For low-voltage applications, two circuit configurations are available, one using an NPN transistor and the other one a PNP transistor.

The operating principle is simple. The op-amp input connected to the low end of R_S causes the op-amp to create the same potential at the other input by means of an output transistor. The op-amp output causes the transistor to conduct to allow for enough output current to flow until $v_p = v_n$, that is: $V_S - I_L \times R_S = V_S - I_O \times R_I$.

Because both potentials are referenced to V_S, the voltage drop across the sense resistor must equal the voltage drop across the input resistor:

(EQ. 4) $$I_L \times R_S = I_O \times R_I$$

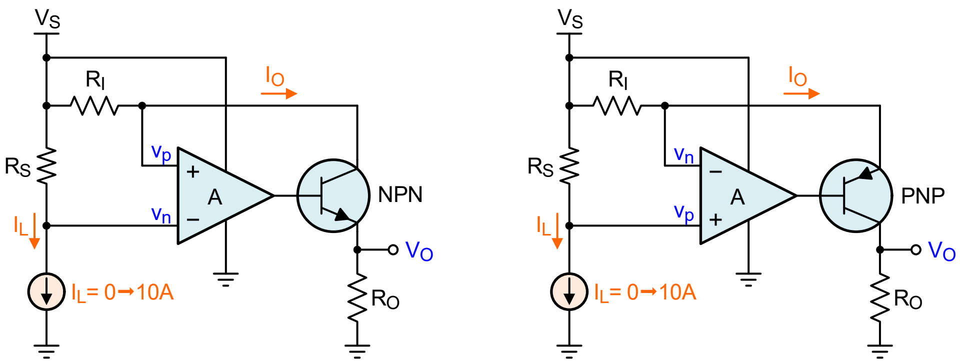


Figure 4. High-Side Current Sensing in Low-Voltage Application with NPN and PNP Transistors

Because $I_O = V_O/R_O$, substituting I_O in Equation 4 and solving for I_L, the load current can be expressed through the measured output voltage and the applied resistor values:

(EQ. 5) $$I_L = \frac{V_O}{R_O} \times \frac{R_I}{R_S}$$

Note: Besides the resistor tolerances, the finite current gain of the bipolar transistor adds a small gain error. Again, the ultra-low input offset of the ISL2813x family of auto-zero amplifiers allows for the use of small sense resistor values and therefore significantly lower power loss. With the circuit parameters listed in Figure 5, the circuit gain for both circuits is V_O/I_L = 250mV/A.

Parameter	Value
V_S	3.3V
R_S	5mΩ
R_I	200Ω
R_O	10kΩ
NPN	MMBT3904
PNP	MMBT3906
I_L	0 – 10A
V_O	0 – 2.5V

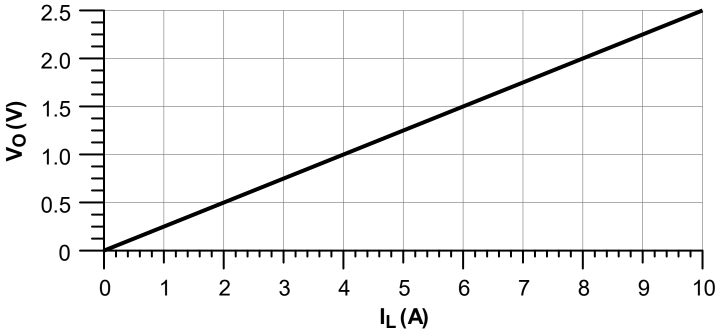


Figure 5. Circuit Parameters and Transfer Characteristic of the Circuits in Figure 3 and Figure 4

For high-voltage applications, the circuit of Figure 4 can be applied, albeit with a minor change in the supply voltage connections. As the op-amp is a low-voltage device, its supply rails must be level shifted to the high common-mode voltage, V_S. This is accomplished with a Zener diode, D_Z, and a biasing resistor, R_B (Figure 6). The Zener voltage must cover the supply range of the op-amp; therefore, a 4.7V to 5.1V Zener diode is required.

In this case, the positive supply terminal of the op-amp remains connected to the system supply, V_S. However, the ground or negative supply terminal of the op-amp is connected to the anode of the Zener diode.

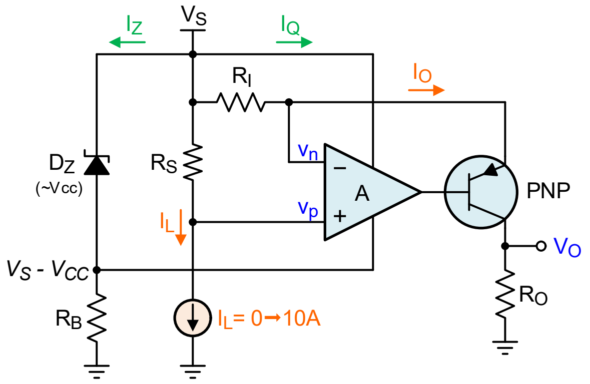


Figure 6. High-Side Current Sensing in High-Voltage Application

Because the Zener current, I_Z, and the quiescent current, I_Q, flow from V_S into R_B, the value of R_B is calculated using Equation 6:

(EQ. 6) $$R_B = \frac{V_S - V_Z}{I_Z + I_Q}$$

Note: With the circuit parameters listed in Figure 7, the circuit gain is V_O/I_L = 250mV/A.

Parameter	Value
V_S	80V
R_S	5mΩ
R_I	200Ω
R_O	10kΩ
R_B	10kΩ
D_Z	BZV55B4V7
PNP	MMBT3906
I_L	0 – 10A
V_O	0 – 2.5V

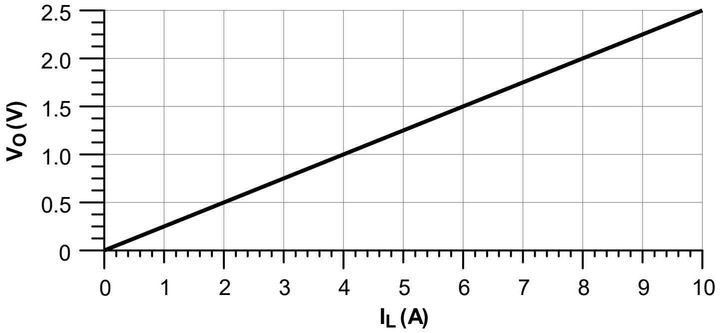


Figure 7. Circuit Parameters and Transfer Characteristic of the Circuits in Figure 6

4. Conclusion

The ISL28x3x family of precision op-amps are chopper-stabilized, zero drift operational amplifiers optimized for single and dual supply operation. These devices use auto-correction circuitry to provide low input offset voltage and, drift and a reduction of the 1/f noise corner below 0.1Hz.

The ISL28134 has a 9-times higher gain-bandwidth than the ISL28x33 and ISL28x30 amplifiers. These op-amps devices provide stable ultra-low offset across the full industrial temperature range of -40°C to +125° (Figure 8).

All amplifiers have rail-to-rail input capability, meaning they can measure down to below 0V and above the V_{CC} level, both of which are necessary for low-and high-side current sensing. They also possess high common-mode rejection ratios at DC and low frequencies, mainly important for high-side current sensing (Figure 9).

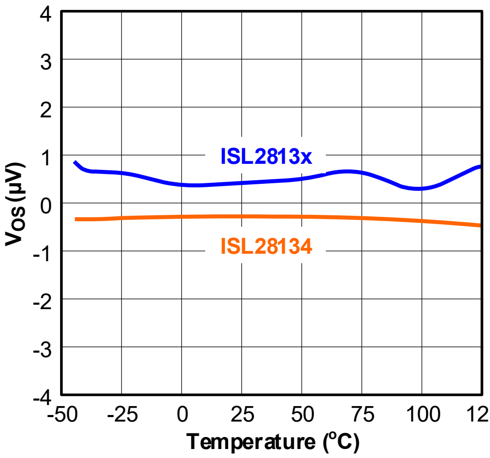


Figure 8. Input Offset Stability Across Temperature

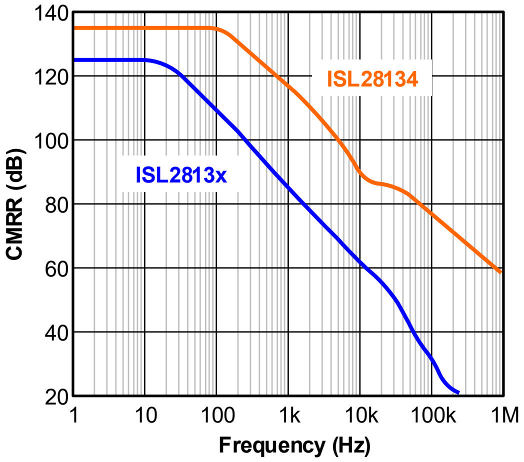


Figure 9. Common-Mode Rejection Ratio

Summarizing, the ISL28134, ISL28x30, and ISL28x33 families of precision amplifiers allow for precise current sensing in space constraint applications while keeping design cost and time at a minimum. They are also ideal for amplifying the sensor signals of other analog front-ends that include pressure, temperature, medical, strain gauge, and inertial sensors down to the µV levels.

Table 1 lists the key parameters of the auto-zeroing amplifiers, and Table 2 lists the wide variety of available package options including SOIC, MSOP, SOT-23, and DFN packages.

Table 1. Key Performance Parameters of Auto-Zeroing Amplifiers

Part Number	Channel (#)	V_{CC} Range (V)	V_{OS} (max) (µV)	TCV_{OS} (nV/°C)	I_B (pA)	I_Q (µA)	GBW (MHz)	Slew Rate (V/µs)	Rail-to-Rail	AOL (dB)	CMRR (dB)	PSRR (dB)
ISL28134	1	2.25 - 6	2.5	15	120	675	3.5	1.5	In/Out	174	135	135
ISL28x33	x = 1, 2, 4	1.8 - 5.5	6	50	30	18	0.4	0.2	In/Out	174	125	138
ISL28x30	x = 1, 2, 4	1.8 - 5.5	40	150	250	20	0.4	0.2	In/Out	150	125	138

Table 2. List of Available Device Packages

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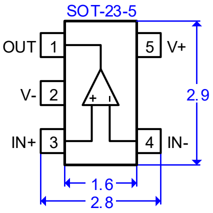
<td>
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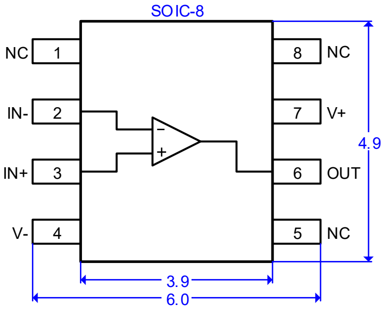
<td>
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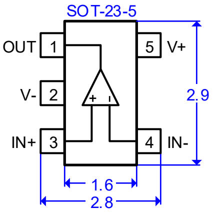
<td>
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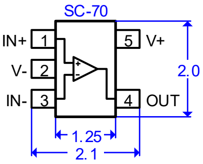
<td>
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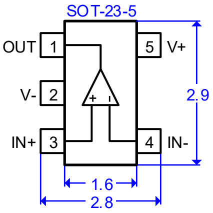
<td>
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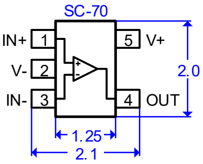
<td>
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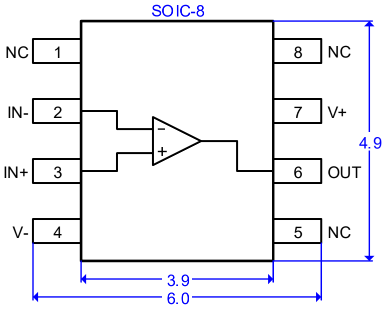
<td>
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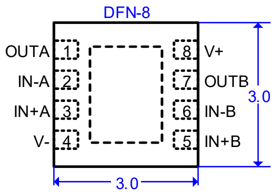
<td>
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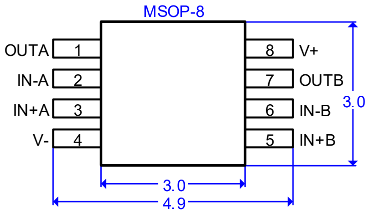
<td>
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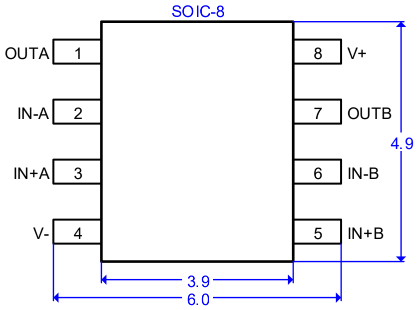
<td>
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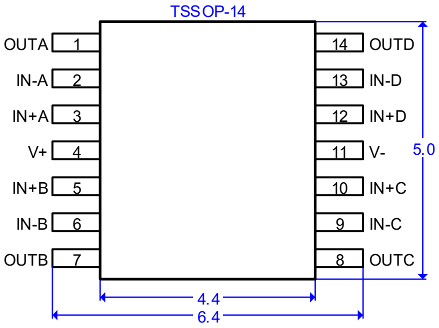
<td colspan="2">
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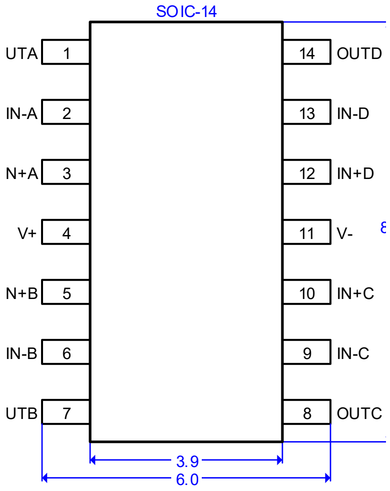
<td>
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5. Revision History

Revision	Date	Description
1.01	Feb 7, 2022	Updated Figures 4 and 6. Updated VS value in Figure 7 table from 3.3V to 80V.
1.00	Jan 21, 2022	Initial release.

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