Application Note

Using Current Sense Amplifiers at Near-Zero V_{sense}

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Current Sensing

ABSTRACT

When operating a Current Sense Amplifier (CSA) with differential input V_{sense} that is near-zero, we must make sure that the amplifier output stays within linear range. One method to avoid swing limitations is output biasing or level shifting. As a result, zero V_{sense} is included in the linear input range. Bidirectional CSA provides a convenient option for output biasing. Further, at near-zero V_{sense}, the offset of the amplifier starts to dominate, resulting in high percentage output error. Offset calibration is effective in improving system accuracy at near-zero V_{sense}. Some legacy products exhibit large output error at low V_{sense} levels. This limitation is a tradeoff to accommodate wide input common mode range. Recent development addresses this issue and the low V_{sense} limitation is eliminated in newly released devices.

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1 Introduction

Current sense amplifiers are typically powered with a single supply and designed to function with an input common-mode range that far exceeds supply voltage. At the same time, differential input voltage, V_{sense}, needs to be precisely amplified without distortion. Ideally, the range of V_{sense} is only limited by supply voltage, and extends all the way down to and including ground.

A unidirectional CSA only linearly responds to current flowing in one direction, with the output moving in one direction in proportion to the input differential signal. A current flowing in the opposite direction causes the output to collapse to one of the supply rails, normally ground.

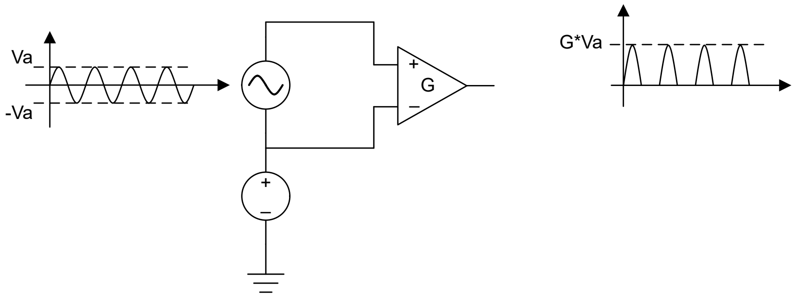

Figure 1-1. Unidirectional Response

Figure 1-1 illustrates the best output response of a unidirectional CSA with bipolar differential voltage input. The CSA precisely amplifies the input signal without any distortion or delay when V_{sense} is positive. When V_{sense} is negative, the output collapses to ground or 0 V.

Figure 1-2 depicts the DC input-output transfer function of the unidirectional CSA. Assuming a power supply voltage V_s, the best transfer function is shown by the solid black piecewise linear curve. When V_{sense} is within the range of ground and V_s/Gain, where Gain stands for the CSA gain, the input-output transfer curve is a straight line that pass through (0, 0) and (V_s/Gain, V_s). When V_{sense} is below 0 V, the output is stuck at ground; when V_{sense} is greater than V_s/Gain, the output is stuck at V_s.

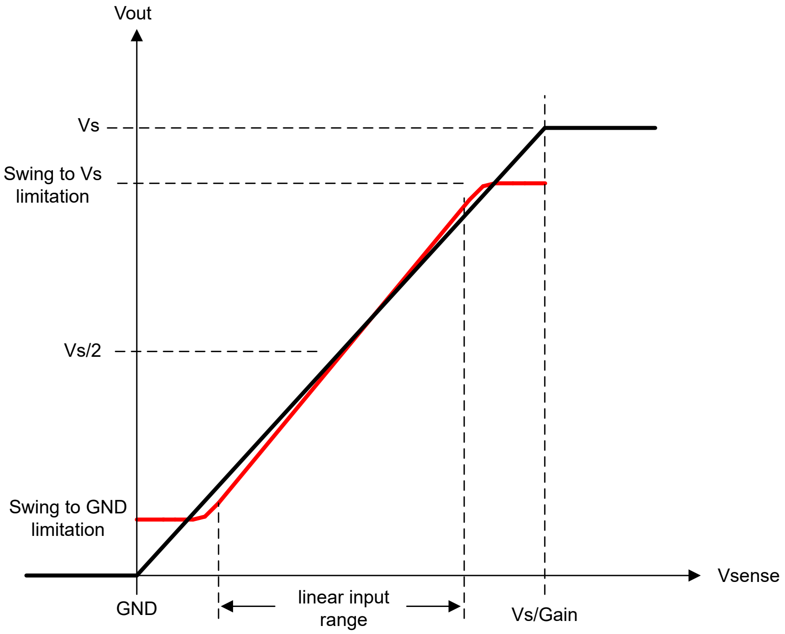

Figure 1-2. Unidirectional CSA Transfer Function

Unless special circuits are involved, such as charge pumps, there is normally a limit to the smallest V_{sense} possible which does not include 0 V, due to practical implementations. Below the limit of the smallest V_{sense}, the amplifier output can no longer be regarded as a reliable representation of input.

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Typical CSA output is not capable of swing rail-to-rail. A more realistic input-output transfer function is depicted by the red curve, which is exaggerated to show the deviation from the ideal curve.

When V_{sense} approaches zero, the output encounters swing to ground limit. The continued decrease in V_{sense} can no longer cause the output voltage to decrease in proportion, which eventually stops at a level that is higher than ground. The output swing to ground characteristic imposes a limit on how low V_{sense} can be. Similarly at the high end, swing to power supply imposes an upper limit on V_{sense}.

For a bidirectional CSA, current flowing in either direction is allowed. The output of the device moves off of a quiescent output level, in proportion to the input differential signal. The fact that bidirectional CSA output is able to move up toward supply or down toward ground implies that the quiescent output level corresponds to zero current. In these devices, there are typically one or two output reference pins. The output is level-shifted by driving the reference pins with a suitable source. Figure 1-3 shows the same bidirectional input is accurately reproduced. A bidirectional CSA can be configured as unidirectional by setting the quiescent output at or close to either supply rail.

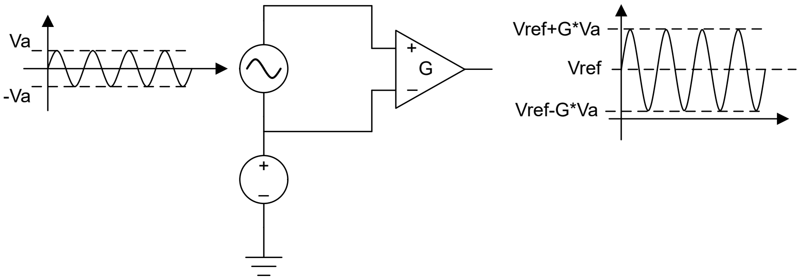

Figure 1-3. Bidirectional Response

It is customary to configure a bidirectional CSA quiescent output level to be midway between ground and V_s. A V_{ref} at mid-supply allows symmetric bidirectional input with respect to ground. Taking the CSA of Figure 1-2 and configuring it as bidirectional while keeping all other characteristics unchanged, the transfer function as shown in Figure 1-4 is attained. The linear input range now includes 0 V.

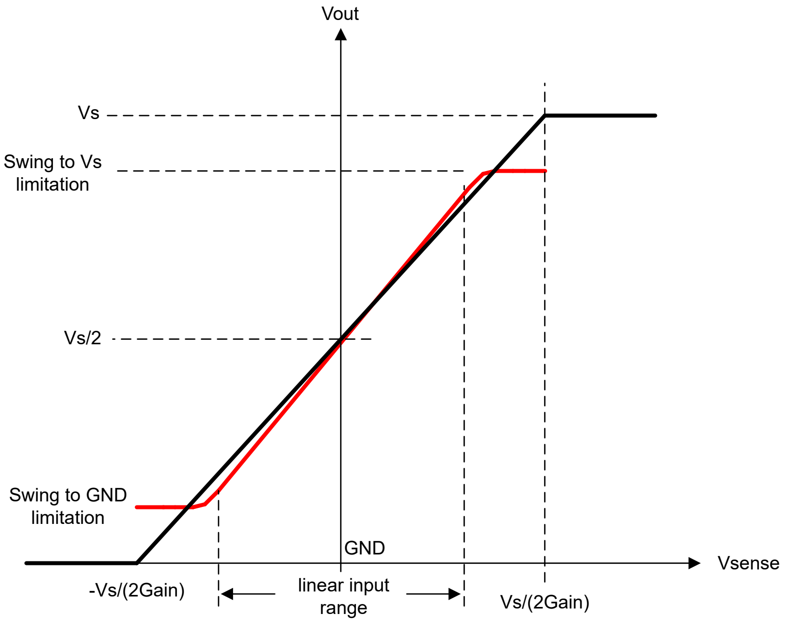

Figure 1-4. Bidirectional CSA Transfer Function

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2 Total Output Error of CSA at Near-Zero V_{sense}

To include zero V_{sense} in the linear input range, use the bidirectional CSA. A bidirectional CSA is equipped with one or two reference pins. The output of such CSA can be biased such that the output is no longer masked by the swing to rails limitation. As a result, as soon as the differential input changes by a small amount, the output changes by the same amount, multiplied by the device gain.

As illustrated by Figure 1-4, the real transfer curve deviates from theoretical due to device errors such as offset, gain error, and nonlinearity. One figure of merit commonly used in evaluating the accuracy of a system is total output percentage error, and is defined as the amount of deviation of actual output relative to the theoretical output.

$$Total\ Output\ Error\ (\%) = \frac{Actual\ Output - Ideal\ Output}{Ideal\ Output} \times 100 \tag{1}$$

Figure 2-1 shows the typical error versus current plot of a CSA. Since V_{sense} equals to the product of current and shunt resistance, the x-axis can be changed to V_{sense} and the curve maintains shape.

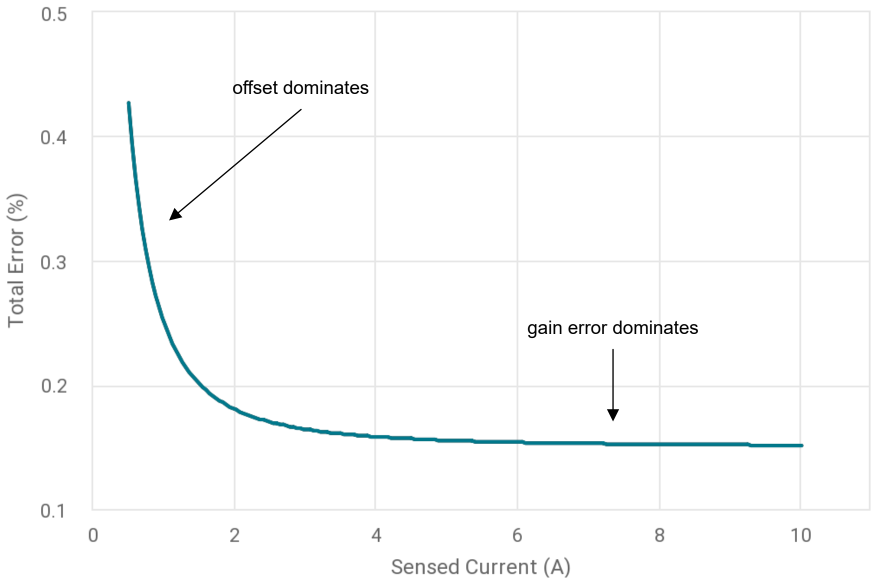

Figure 2-1. Total Output Error of CSA

In the higher current range (for example, > 2 A) of this particular example, the percentage error is near flat and is dominated by gain error; in the lower current range, offset has an out-sized impact as current decreases toward zero while offset itself remains constant. At zero current, the percentage error approaches infinity, and the effect from device imperfections becomes more pronounced.

The total error plot reflects the CSA specification only, and does not consider other components at the system level. For example, shunt resistor tolerance has an impact on total error that is similar to gain error. This plot also assumes worst-case device specification. Individual device performance is likely to be much better, due to the fact that device parameters typically follow normal distribution. The likelihood of running into samples with the worst performance for all parameters is low.

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3 Calibration-Enabled Near-Zero V_{sense} Measurement

In some applications, relying on the data sheet specification of an otherwise well-fitting CSA is not enough to satisfy the accuracy requirement. If this is the case, calibration can provide a path forward by improving system accuracy.

Offset calibration can be adopted to improve the accuracy of a current sensing system at near-zero V_{sense} During offset calibration, individual system's offset is measured and stored, which is then subtracted from future measurements. A block diagram of CSA offset calibration is shown in Figure 3-1. The voltage source V_{os} stands for the input referred offset voltage of the device.

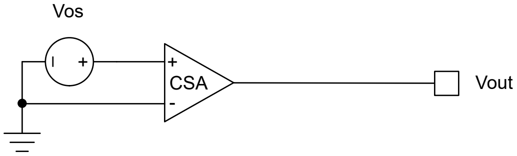

Figure 3-1. Offset Calibration

One of the key considerations in offset calibration is to keep the calibration path and the normal signal path overlap as much as possible. By including the complete signal measurement path in the calibration path, all error contributors are taken into account. The cumulative effect of all the error contributors can be subtracted with one calibration operation. When additional components are introduced to enable calibration, the tolerance of such components must be taken into consideration; the effect on normal signal measurement must be considered as well, so that any adverse effect is minimized.

Another consideration is to keep the system in linear operation range. For example, if the CSA output is clipped to either power supply rails, the calibration results are invalid.

In Figure 3-1, the inputs are shorted together to perform offset calibration. However, the swing limitations of the CSA very likely causes the output of the CSA to stuck to ground, masking the effect of V_{os}. The correct setup is to configure the CSA so that the output can move freely with zero input.

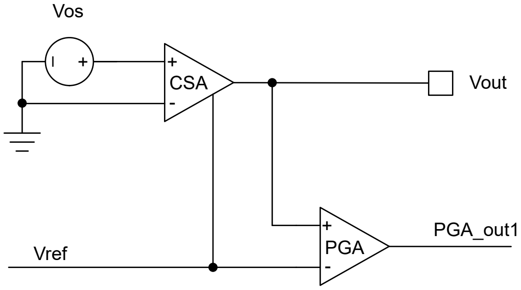

Figure 3-2. Offset Calibration for Bidirectional CSA

Biasing the output to higher than ground gets away from swing limitation. In the setup shown in Figure 3-2, a bidirectional CSA is configured with a reference voltage equal to half supply. With inputs shorted, the CSA output is compared with the reference voltage by the PGA. The difference equals to the output offset. To calculate input referred offset, use Equation 2.

$$V_{os} = \frac{PGA\_out1}{PGA_{Gain} \times CSA_{Gain}} \tag{2}$$

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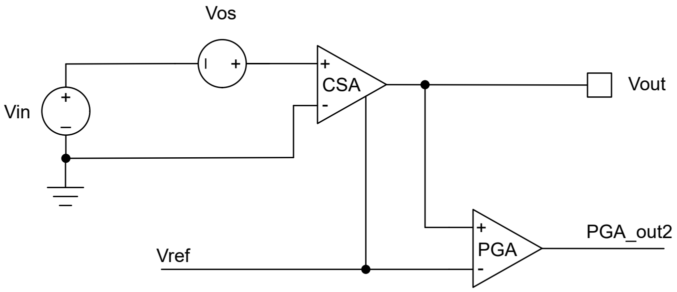

Figure 3-3. Gain Calibration

To build upon offset calibration, gain error can be calibrated with at least one additional data point. Figure 3-3 shows the CSA driven with a nonzero input V_{in}. The corresponding output is PGA_Out2, and the CSA gain can be calculated as shown in Equation 3.

$$Gain = \frac{PGA\_out2 - PGA\_out1}{PGA_{Gain} \times V_{in}} \tag{3}$$

The nonzero input is assumed to be a known accurate value. In practice, the input is either measured with a precision meter, or is provided by a precision source. In either case the true magnitude of the input must be available, otherwise uncertainties in the input value negatively impact the accuracy and defeat the purpose of calculation.

These are some of the basic calibration schemes. More elaborate ones are possible to achieve higher levels of accuracy.

4 Near-Zero V_{sense} Operating Mode in Some Legacy CSA

The INA193-INA198 devices use a unique circuit topology that provides common-mode range extending from −16 V to 80 V while operating from a single power supply. As shown in Figure 4-1, when the common-mode voltage is positive, amplifier A_2 is active. The differential input voltage, $(V_{IN+}) - (V_{IN-})$ applied across R_S, is converted to a current through a resistor. This current is converted back to a voltage through R_L, and then amplified by the output buffer amplifier. When the common-mode voltage is negative, amplifier A_1 is active. The differential input voltage, $(V_{IN+}) - (V_{IN-})$ applied across R_S, is converted to a current through a resistor. This current is sourced from a precision current mirror whose output is directed into R_L converting the signal back into a voltage and amplified by the output buffer amplifier.

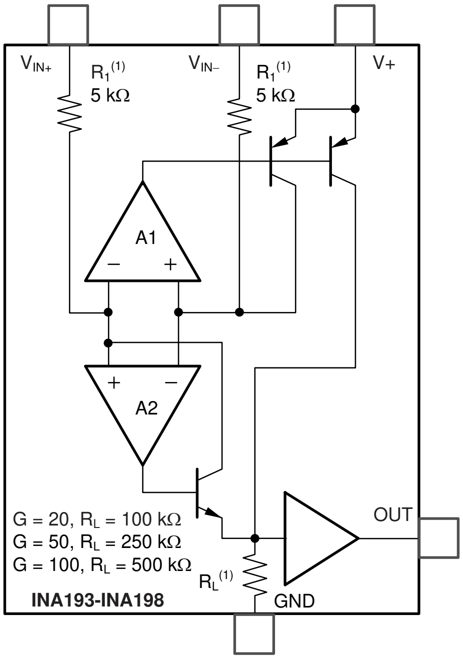

Figure 4-1. INA193-INA198 Block Diagram

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At near-zero V_{sense}, the output current is very low, the collector-base (or Emitter-base) leakage of the output transistor becomes prominent and can effectively shut down the transistors driving the output transistor. Consequently, the output cannot continue to swing toward ground in proportion to the decreasing input voltage. The lowest output level appears as a floor that is higher than the expected output voltage. This is the reason why 20 mV and below is considered low V_{sense} for this family of devices, where the output deviation becomes noticeable.

Another factor affecting output accuracy is common mode voltage, V_{cm}. Normally one of the two amplifiers, A_1 or A_2, is active and dominates. However, when common mode input voltage is between ground and supply voltage, both A_1 and A_2 can be active but neither is dominating. The deviation from linear operation becomes greatest the closer V_{sense} approaches zero, making this region the least accurate.

INA200 through INA208 are a family of nine devices based on the INA193-INA198. Comparators and references are included to these devices, which makes overcurrent protection (OCP) convenient. Because the analog core remains the same, take care when operating these devices with near-zero V_{sense}. Similar to the INA193-INA198, the least accurate region of operation is when V_{cm} is between ground and supply voltage.

5 Recent Development in High-Voltage CSA

The INA193-INA198 family of high-voltage current sensors has been very successful, providing customers with high-voltage current sensing and OCP for over a decade. As discussed in Section 4, these devices have limitations in terms of precision and transient performance due to the two-stage setup, especially at near-zero V_{sense} and in the transition range of common-mode input voltage where both op amps are active.

The INA293 family of devices are designed specifically to solve this issue, as well as to improve performance on all key electrical parameters. The INA293 is the latest ultra-precise high-voltage current sense amplifier with common-mode range from –4 V to 110 V (−20 V to +120 V survival).

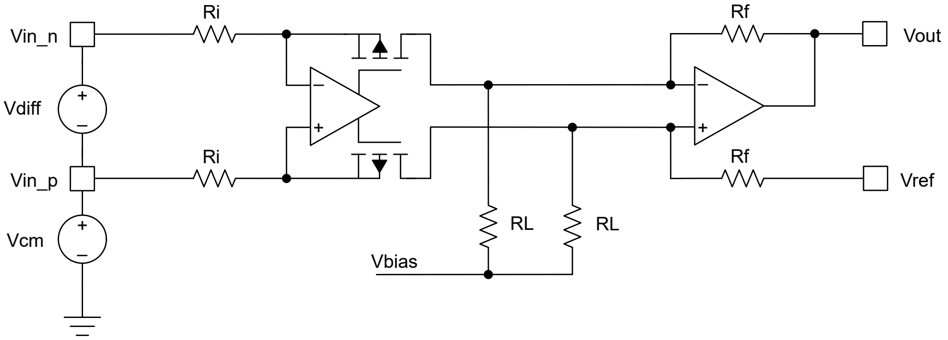

Figure 5-1. INA293 Block Diagram

The INA293 uses a two-stage topology as shown in Figure 5-1. In the front is a current feedback amplifier powered by drawing a fixed amount of current from the common-mode source attached to the inputs. This effectively creates a floating power supply for the first stage amplifier that is independent of device power supply.

The INA293 output stage is a voltage feedback amplifier that accomplishes differential to single-ended conversion. This two stage structure allows for high bandwidth. V_{bias} is used as ground reference for the front stage and the inputs of output stage looking into common-mode outputs on R_L. A negative charge pump is used to create V_{bias} to accommodate input common-mode voltages below ground.

The INA310 is based on the INA293, and incorporates an open-drain comparator with internal reference voltage. Similar to the INA200-INA208, the INA310 comparator can be configured in either transparent or latch mode. The trip point is set with an external resistor divider. One major improvement of INA310 over INA200-INA208 is there is no longer the near-zero V_{sense} limitation.

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6 Summary

Current sense amplifiers are typically powered by a single power supply. Swing to ground limitation can mask the output at zero V_{sense}. Bidirectional CSA provides a convenient way to include zero V_{sense} in the linear input range. Percentage output error typically increases with decreasing V_{sense} and becomes infinite at zero V_{sense}. One way to improve accuracy of a current measurement system is through calibration. Recent development at TI introduced a series of high-voltage ultra-precise CSA that solve the issue of output limitation found on certain legacy products.

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