Application Note

Driving Voltage Reference Pins of Current-Sensing Amplifiers

Guang Zhou *Current and Magnetic Sensing*

ABSTRACT

Bidirectional Current Sense Amplifiers (CSA) are capable of measuring current flowing in either direction. The quiescent output level corresponds to zero current. One, sometimes two output reference pins are available for configuring the zero current voltage. A bidirectional CSA can function in unidirectional mode by setting the quiescent output at or close to either of the supply rails. There are many ways of driving the reference pins. The most common methods include using a reference IC, a voltage divider, or a voltage divider followed by a buffer. Output impedance of the driving source impacts the CSA output and may cause significant error if not designed properly. A voltage divider has the advantage of being versatile and inexpensive. It also tends to occupy less area. As a result, it finds adoption in many applications.

Table of Contents

1 Introduction......3
2 One, Versus Two Reference Pins......4
3 Bidirectional Current Sense Amplifier Topologies......5
3.1 Single-Stage Difference Amplifier......5
3.2 Difference Amplifier Input Followed by Noninverting Output Buffer......5
3.3 Voltage Feedback Multi-Stage Difference Amplifier......6
3.4 Single-Stage Current Feedback......6
3.5 Current Feedback Multi-Stage Difference Amplifier......7
3.6 Isolated Bidirectional Current Sensors......7
4 Options for Driving Reference Pins and Input Referred Reference Error......8
5 Resistor Divider as Reference......10
5.1 Resistor Divider and Equivalent Circuit......10
5.2 Reference Source Impedance Error in Difference Amplifier......10
5.3 Reference Source Impedance Error in Voltage Feedback Multi-Stage CSA......11
5.4 Reference Source Impedance Error in Current Feedback Multi-Stage CSA......12
5.5 Reference Source Impedance Error in Difference Amplifier with Output Buffer......13
6 Examples......13
6.1 Calculating Reference Source Impedance Error in Difference Amplifier......14
6.2 Calculating Reference Source Impedance Error in Voltage Feedback Multi-Stage CSA......14
6.3 Calculating Reference Source Impedance Error in Current Feedback Multi-Stage CSA......15
7 Summary......16

List of Figures

Figure 1-1. Unidirectional Response......3
Figure 1-2. Bidirectional Response......3
Figure 2-1. Simplified Block Diagram of a Bidirectional Current Sense Amplifier......4
Figure 2-2. Bidirectional CSA With Two Reference Pins......4
Figure 2-3. Reference by Splitting the Supply......5
Figure 3-1. Single-stage Difference Amplifier......5
Figure 3-2. Difference Amplifier Followed by Noninverting Output Buffer......6
Figure 3-3. Two-Stage Voltage Feedback CSA......6
Figure 3-4. Single-Stage Current Feedback......7
Figure 3-5. Two-Stage Current Feedback CSA......7
Figure 3-6. Bidirectional TMCS1100......8

Figure 4-1. Options Driving Reference Pin....8
Figure 4-2. Refer Reference Voltage Error to Device Input....9
Figure 5-1. Resistor Divider and its Equivalent....10
Figure 5-2. Difference Amplifier Output Error Due to Reference Source Impedance....10
Figure 5-3. Differential Measurement....11
Figure 5-4. Voltage Feedback Multi-Stage CSA Output Error....12
Figure 5-5. Current Feedback Multi-Stage CSA Output Error....13
Figure 5-6. Output Error of Difference Amplifier With Output Buffer....13
Figure 6-1. INAx181 Input Resistance....14

List of Tables

Table 4-1. Comparison of Reference-setting Methods....9
Table 6-1. Reference Source Impedance Error for INA181A2....14
Table 6-2. Reference Source Impedance Error for INA240A2....14
Table 6-3. Reference Source Impedance Error for INA186A2....15
Table 6-4. Reference Source Impedance Error for INA241A3....15

Trademarks

All trademarks are the property of their respective owners.

1 Introduction

One way to classify a Current Sense Amplifier (CSA) is based on whether it is able to measure current in both directions. Then it can be put into one of two categories - unidirectional or bidirectional. A unidirectional device only linearly responds to current flowing in one direction, with its 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 illustrates such a scenario.

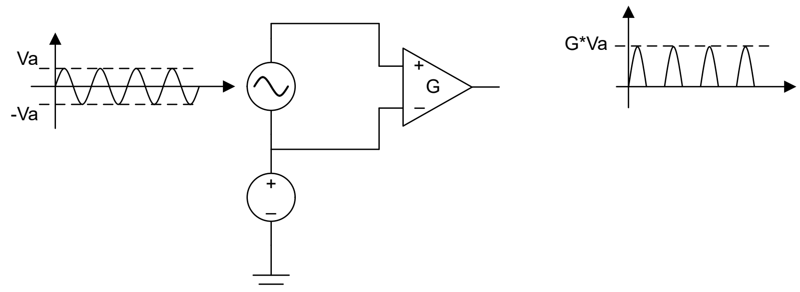

Figure 1-1. Unidirectional Response

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 is typically one or two output reference pins. The output is level-shifted by driving the reference pins with a suitable source. Figure 1-2 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.

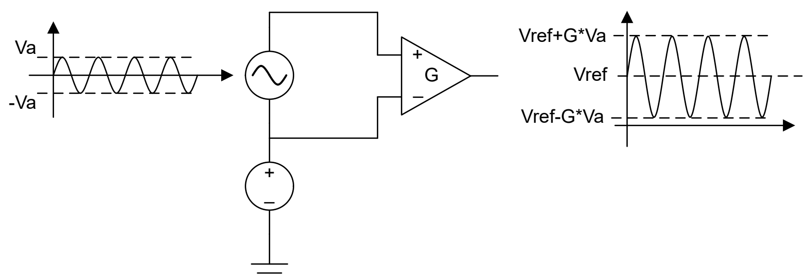

Figure 1-2. Bidirectional Response

This report reviews TI's bidirectional CSA then examines different ways of configuring the output reference, associated performance tradeoffs, and the reasons behind these tradeoffs. Next, the impact of the resistor divider driving reference pins in common CSA architectures is explored. The goal is to help designers make an informed decision when choosing a reference driving circuit that meets performance requirements, and is economical at the same time.

2 One, Versus Two Reference Pins

A CSA measures target current by deriving a small differential signal (voltage or current) that is proportional to the magnitude of the current. Signal conditioning circuitry then turns this small differential signal into a stable and noise-free output for further processing down the signal chain. For shunt-based current sensors, either non-isolated or isolated, the input differential signal is created by inserting a shunt resistor in the path of the target current. Magnetic sensors work without making physical contact between the sensor IC and the target current. For example, the magnetic field generated by the load current can be sensed by a Hall sensor, which is then conditioned and amplified by a low-noise amplifier.

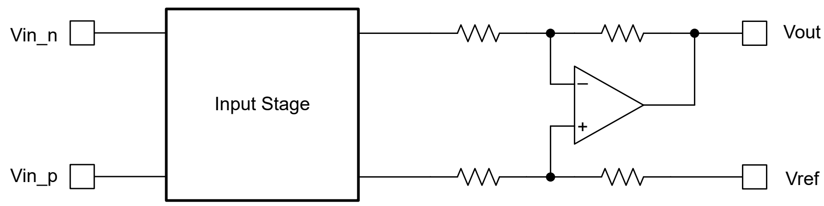

Figure 2-1. Simplified Block Diagram of a Bidirectional Current Sense Amplifier

Figure 2-1 shows a block diagram of a typical bidirectional CSA with a single reference pin. The input stage is responsible for extracting the differential input signal while rejecting the typically very high input common-mode voltage. The input stage can take on many forms, including but not limited to, voltage feedback, current feedback, and isolated technology. The output stage takes care of output drive capabilities to interface effectively with downstream circuitry.

The output stage is typically a classic difference amplifier. To enable bidirectional measurement capability, the output stage is equipped with a reference pin. By providing a positive reference voltage to the reference pin, the output is level shifted to a desired quiescent output voltage. Typically, when a positive differential input is applied, the output moves away from the quiescent voltage, toward the supply. Conversely, when a negative differential input is applied, the output moves away from the quiescent voltage toward ground.

Matching of the resistor network is important. One of the parameters that reflect how well the resistors match is Reference Voltage Rejection Ratio (RVRR). This parameter measures net change (relative to V_{ref}) in output voltage for a given amount of change in reference voltage. If RVRR is listed in the data sheet and is input referred, the device gain should be used as a multiplier in calculating the corresponding change in output.

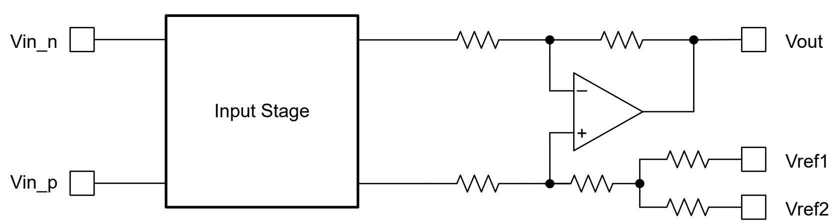

Figure 2-2. Bidirectional CSA With Two Reference Pins

Some bidirectional devices come with two reference pins which are connected internally to form a voltage divider. Figure 2-2 shows such an arrangement.

As an example, for INA240, the reference divider is made up of two equal-value resistors. Real-world differences directly influence the reference voltage. For this reason, the divider accuracy is specified in the data sheet, However, if the two reference pins are shorted together and driven with a voltage source, then the divider function is not used. The divider accuracy specification is not a concern in this situation.

A common scheme of creating a reference voltage, called splitting the supply, is shown in Figure 2-3. One of the reference pins is connected to the device power supply, while the other connected to ground. This results in a reference voltage that is half of the supply. In similar fashion, this scheme can be used to create customized references, with voltage rails at different potentials.

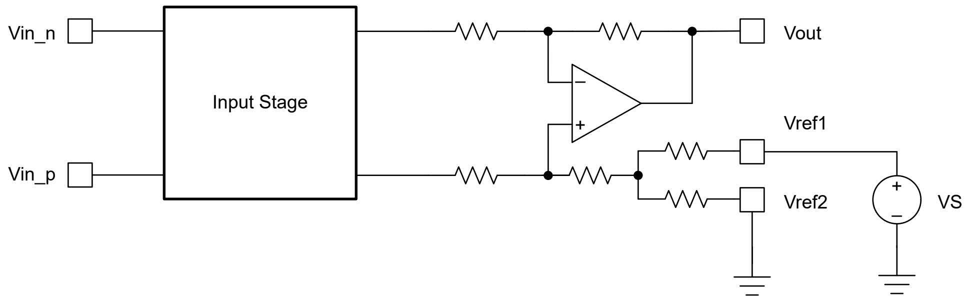

Figure 2-3. Reference by Splitting the Supply

The two-pin arrangement brings flexibility without incurring additional error compared with external resistor dividers. When the two reference pins are shorted together, they function exactly the same as a single pin and can be treated as such.

3 Bidirectional Current Sense Amplifier Topologies

More often than not, a high-performance CSA is made up of multiple gain stages. These stages could include input, output, and possibly intermediate stages in between. Even though bidirectional functionality is achieved in the output stage, it is necessary to be aware of the overall topology including the input. This knowledge is needed to estimate the impact of the external reference driving circuitry.

3.1 Single-Stage Difference Amplifier

Based on conventional difference amplifiers, this topology achieves input and output functionalities in a single stage. Compared with a conventional difference amplifiers, the most significant distinction is the capability to withstand common-mode input voltage that is significantly higher than device supply voltage while maintaining high gain. For example, the working input common-mode voltage could be 28 V while the device supply is only 3.3 V. Shown in Figure 3-1 is the simplified diagram of such a device. In this diagram, R_i and R_f represent the ideal values of the input and feedback resistors respectively.

The resistor network must be closely matched to achieve good Common Mode Rejection Ratio (CMRR) and Gain Error (GE) performance. The resistor network is often trimmed for matching. Although sometimes it is possible to meet relaxed design goals by optimizing circuit design and layout without trim.

When driving the reference pin of a single-stage difference amplifier, ideally the voltage source should have zero impedance to maintain the balance of the resistor network.

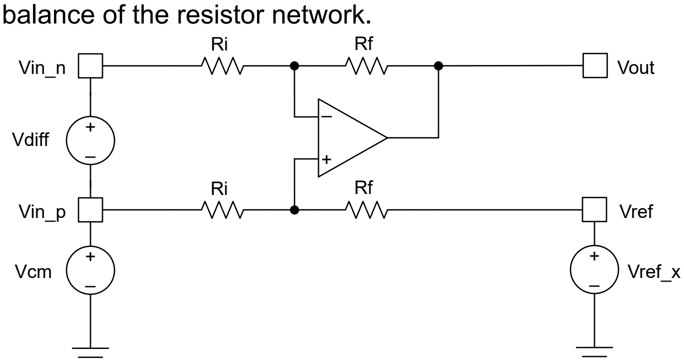

Figure 3-1. Single-stage Difference Amplifier

The difference amplifier transfer function is the familiar equation:

$$V_{out\_ideal} = \frac{R_f}{R_i} V_{diff} + V_{ref\_x} \quad (1)$$

3.2 Difference Amplifier Input Followed by Noninverting Output Buffer

As Figure 3-2 shows, by attaching a noninverting output stage to the single-stage difference amplifier, a two-stage CSA with potentially very high gain is developed. Aside from flexibility in gain configuration, the intermediate output can be brought out as an optional output pin. The overall performance is dominated by the first stage, therefore much of the same performance limitations remain as with single-stage difference amplifier. Compared with other multistage alternatives discussed in the next sections, the added output stage does not significantly improve critical electrical performance.

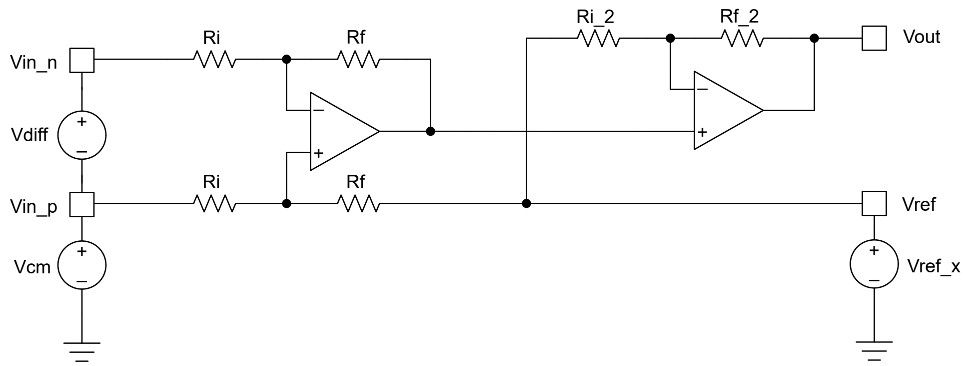

Figure 3-2. Difference Amplifier Followed by Noninverting Output Buffer

The device gain is the product of the gains of all stages, and the transfer function is written as:

$$V_{out\_ideal} = \frac{R_f}{R_i}\left(1 + \frac{R_{f\_2}}{R_{i\_2}}\right)V_{diff} + V_{ref\_x} \quad (2)$$

3.3 Voltage Feedback Multi-Stage Difference Amplifier

The front stage is usually a fully differential amplifier dedicated to rejecting high input common-mode voltage so that a clean and gained-up version of the differential input is passed to the output stage, which is effectively isolated from the high input common-mode voltage. This is a huge advantage in achieving exceptional CMRR.

Matching resistor networks is important in both stages to achieve excellent CMRR and GE performance. This is especially true for the input stage, where the resistor network is sometimes in-package trimmed at final production. The output of the input stage is fully differential, and the common-mode voltage is defined by the Common Mode Feed Back (CMFB) circuitry. It is worth noting that this common-mode output voltage is the same as the common-mode input voltage of the output stage. For compliance, the common-mode voltage is set between ground and supply voltage. It is normally set to somewhere close to mid-supply. With this arrangement, the output stage is decoupled from the high input common-mode voltage seen at input of the device.

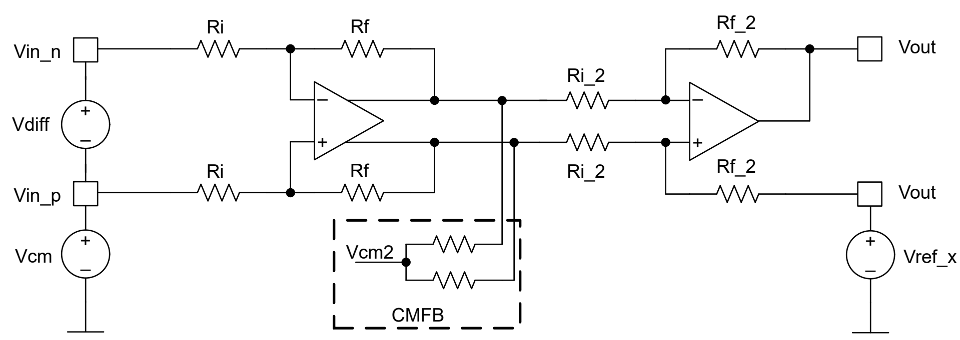

Figure 3-3. Two-Stage Voltage Feedback CSA

The transfer function of the amplifier shown in Figure 3-3 can be written as:

$$V_{out\_ideal} = \frac{R_f}{R_i}\frac{R_{f\_2}}{R_{i\_2}}V_{diff} + V_{ref\_x} \quad (3)$$

3.4 Single-Stage Current Feedback

Figure 3-4 shows the block diagram of the INA170. Bidirectional current measurement is accomplished by output offsetting through amplifier A2. The offset voltage level is defined by an external resistor and voltage reference. This setup permits measurement of a bidirectional shunt current while using a single supply. Applying a positive reference voltage to reference (pin 3) causes a current to flow through R_{OS}, forcing output current to be offset from zero. The transfer function is written as Equation 4.

$$V_{out\_ideal} = \frac{I_S R_S R_L}{R_G} + \frac{V_{REF} R_L}{R_{OS}} \tag{4}$$

Driving the reference pin is straightforward. A simple voltage divider will suffice due to the high input impedance of amplifier A2. A filtering cap close to the reference pin may help limit noise contribution. Resistor sizing and V_{REF}Vref voltage should fit the operating range of amplifier A2.

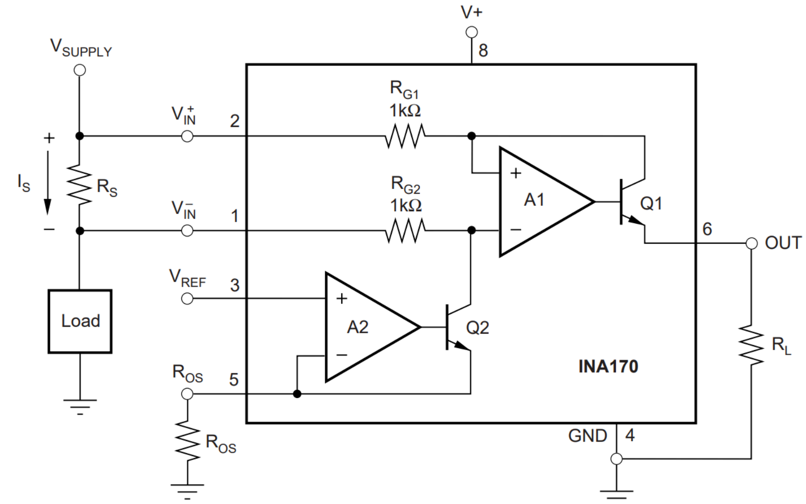

Figure 3-4. Single-Stage Current Feedback

3.5 Current Feedback Multi-Stage Difference Amplifier

Current feedback topology decouples the common-mode input voltage from input bias current and has the potential for high CMRR without precision manufacturing. The current feedback also provides higher bandwidth than its voltage counterpart. As shown in Figure 3-5, the input stage isolates the rest of the circuits from the high input common-mode voltage with high-breakdown MOSFETs. The output stage amplifier common-mode voltage is defined by the first stage load resistors, which converts current into voltage.

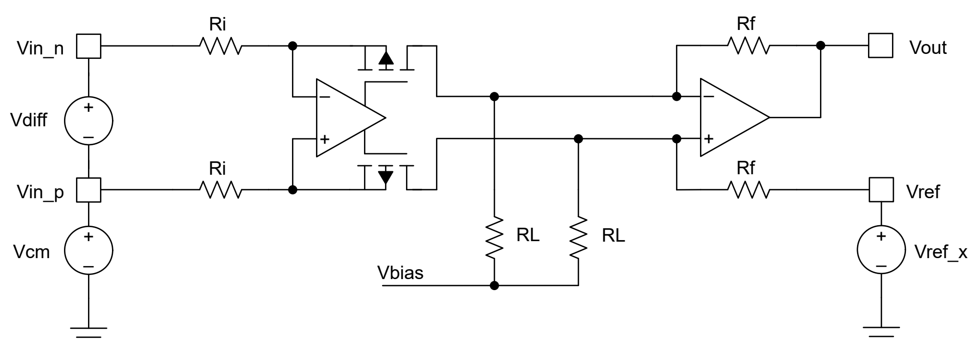

Figure 3-5. Two-Stage Current Feedback CSA

The transfer function of the amplifier can be written as:

$$V_{out\_ideal} = \frac{R_f}{R_i} V_{diff} + V_{ref\_x} \tag{5}$$

3.6 Isolated Bidirectional Current Sensors

An example of in-package Hall sensors is the TMCS1100 family, shown in Figure 3-6. Within the device, the high-voltage side load current passes through the low-ohmic leadframe path. No external components, isolated supplies, or control signals are required on the high-voltage side. At the low-voltage side, the magnetic field generated by the input current is sensed by a Hall sensor and amplified by a precision signal chain.

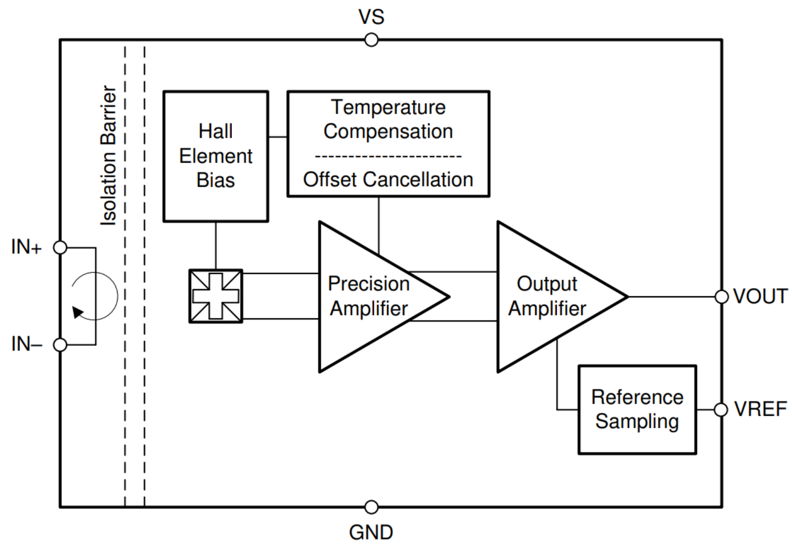

Figure 3-6. Bidirectional TMCS1100

The transfer function can be written as:

$$V_{out\_ideal} = S \times I_{in} + V_{ref\_x} \quad (6)$$

where

- S is the sensitivity
- I_{in} is the target current being measured
- V_{ref_x} is the reference voltage at the VREF pin

The reference voltage determines the zero-current output voltage. This zero-current output level along with sensitivity determine the measurable input current range of the device, and allows for unidirectional or bidirectional sensing. By shifting the zero current output voltage of the device, the dynamic range of measurable input current can be modified.

The input voltage on Vref pin can be provided by any external voltage source, such as a precision reference IC. The VREF pin is sampled by the internal circuitry at approximately 1 MHz, then buffered and provided to the signal chain of the device. An apparent DC load of approximately 1 µA is observed by the external reference. To prevent errors due to sampling settling, keep the source impedance below 5 kΩ, the level specified in the electrical characteristics table.

4 Options for Driving Reference Pins and Input Referred Reference Error

Three methods are commonly used to drive the reference pin, namely with a reference voltage IC, with a supply divider, or with a supply divider followed by a buffer. These options are illustrated in Figure 4-1.

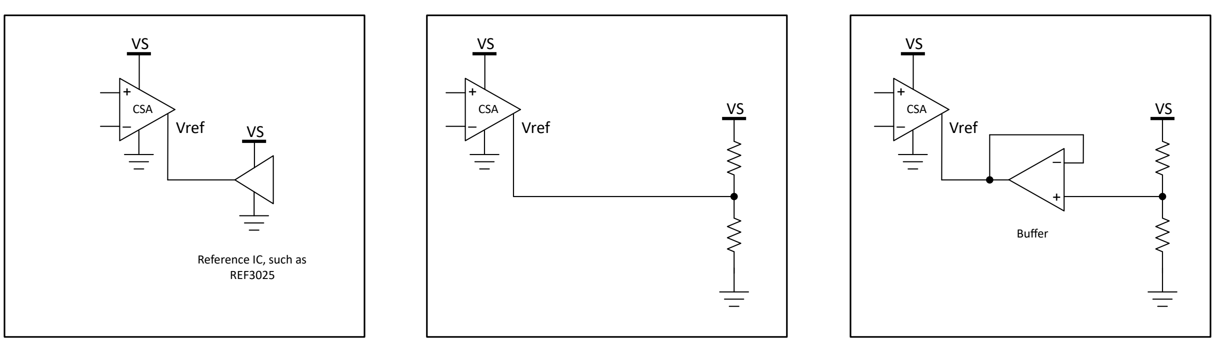

Figure 4-1. Options Driving Reference Pin

Each of these has its own pros and cons. A high-level comparison is show in Table 4-1.

Table 4-1. Comparison of Reference-setting Methods

Reference Source	Accuracy	Power Dissipation	Cost
Reference IC	High	Low	High
Divider	Low	High	Low
Divider + buffer	Medium	Medium	Medium

From a performance perspective, a reference IC is the best choice. The electrical characteristics of a reference are well defined and production tested. Key parameters such as offset, drift, and noise are excellent. Such reference provides a stable, clean output voltage that is ideal for data acquisition. Sometimes a reference already exists because it is required by other components such as ADC. It might be possible to use the existing reference without incurring additional cost.

The most affordable reference is the supply divider, where the reference voltage is derived from the device power supply with a resistor divider. Any value in between 0 V and supply is possible. It is a natural tendency to use large resistors so that power dissipation is kept to a minimum. However, a large divider adds to the internal resistor of the reference pin and breaks the balance of the resistor network. To reduce such impact, The Thevenin's equivalent resistance should be kept as small as possible. But it may become impractical if the resistance values get too low and consequently the power dissipation becomes too great. In theory, an ideal point between the two extremes is possible, which may be suitable for certain applications. The following sections look deeper into the performance impact of such dividers. Another aspect that should not be ignored is the quality of the power supply itself.

For applications that are power sensitive, the third approach might be a good option. A large resistor divider followed by a general-purpose buffer can provide a good reference at a reasonable cost. The buffer isolates the divider from the internal resistor network and provides a virtual ground for the reference pin. The buffer amplifier does not have to be high performance. Because its non-idealities are added to the CSA output, they get divided down by the CSA gain when referred to input. Figure 4-2 illustrates the idea of referring reference error to equivalent input error.

Regardless of the method chosen, in reality there is going to be some error introduced by the reference source. It may be necessary to account for this error if it is not negligible. To do this, it is important to keep the calculation consistent with that for the rest of the error sources. In other words, either input referred or output referred calculation can be used. But the two methods should not be mixed.

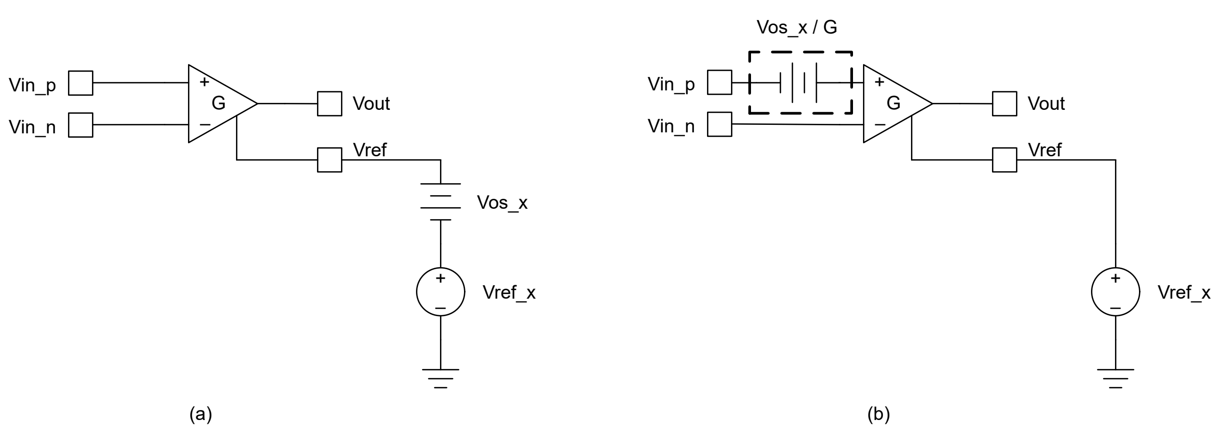

Figure 4-2. Refer Reference Voltage Error to Device Input

Reference source errors are directly added to the output. To compare or combine with other error sources, the reference errors are normally referred to input. As an example, the external reference source in Figure 4-2(a) has an offset V_{os_x} in addition to its ideal value of V_{ref_x}. when calculating input referred error contribution, V_{os_x} needs to be divided by the CSA gain. Figure 4-2(b) shows the equivalent circuit after V_{os_x} is referred to input.

Even though offset of the reference source is used as an example, the same principle applies to other non-idealities, including gain error, temperature drift, and noise, to name a few.

5 Resistor Divider as Reference

This section quantifies the impact on a single-stage CSA performance and accuracy when a voltage divider is used to drive the reference pin. The same findings will subsequently be adapted for multi-stage, where the output is a difference amplifier.

5.1 Resistor Divider and Equivalent Circuit

Figure 5-1(a) shows a resistor divider is used to generate the reference voltage, which is defined by Equation 7 when the contribution from VS is considered:

$$\boldsymbol{V_{ref}} = \frac{R_b//\left(R_i + R_f\right)}{R_a + R_b//\left(R_i + R_f\right)} V_S \qquad (7)$$

Figure 5-1(b) shows the Thevenin's equivalent with the following parameters:

$$\boldsymbol{V_{ref\_x}} = \frac{R_b}{R_a + R_b} V_s \qquad (8)$$

$$\boldsymbol{R_x} = R_a//R_b \qquad (9)$$

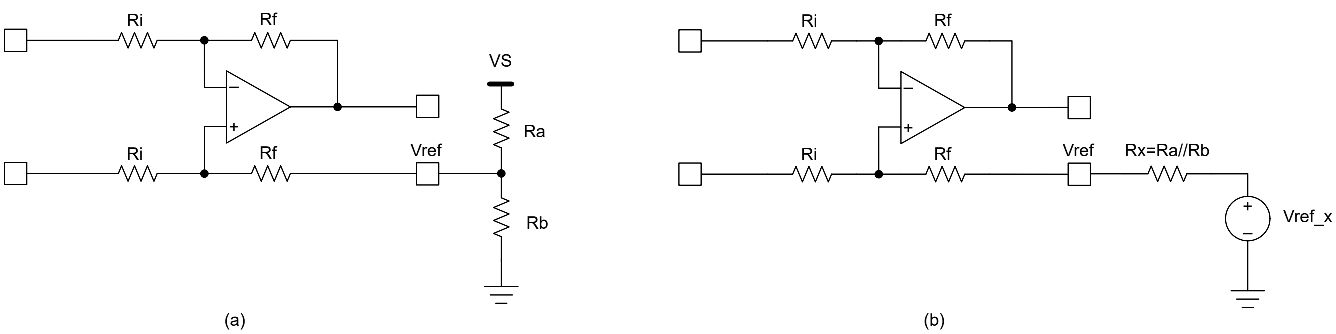

Figure 5-1. Resistor Divider and its Equivalent

The Thevenin's equivalent circuit also represents situations where the reference voltage source has finite output impedance. This circuit is used in the next sections.

5.2 Reference Source Impedance Error in Difference Amplifier

Figure 5-2 shows a non-ideal voltage source, V_{ref_x}, driving the reference pin of a difference amplifier. The output impedance of V_{ref_x} is represented by R_x. The difference amplifier input is connected to common-mode voltage source V_{cm}, as well as differential voltage source V_{diff}.

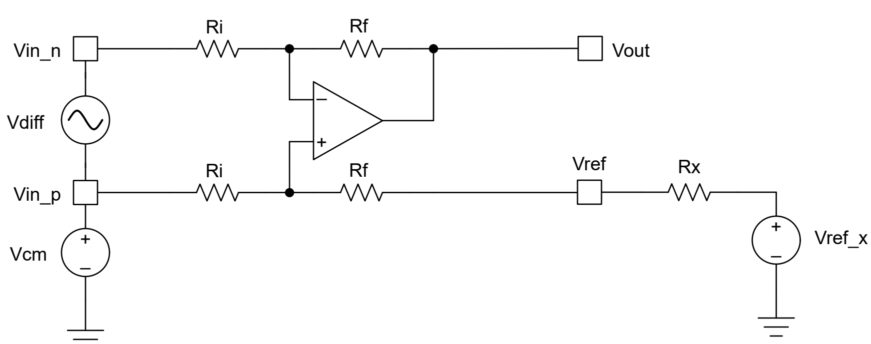

Figure 5-2. Difference Amplifier Output Error Due to Reference Source Impedance

The following expression can be derived for the output:

$$\boldsymbol{V_{out}} = \frac{R_i + R_f}{R_i + R_f + R_x} V_{ref\_x} + \frac{R_x}{R_i + R_f + R_x} V_{cm} + \frac{R_f}{R_i} V_{diff} + \frac{R_x}{R_i + R_f + R_x} \frac{V_{diff}}{2} \qquad (10)$$

For ideal V_{ref_x}, its output impedance equals to zero. Therefore, setting R_x = 0 yields the familiar ideal output equation:

$$V_{out\_ideal} = V_{ref\_x} + \frac{R_f}{R_i} V_{diff} \tag{11}$$

Note that V_{ref} = V_{ref_x} for ideal voltage source. Taking the difference of the two previous equations gives the equation for output error due to reference source impedance:

$$V_{out\_error} = V_{out} - V_{out\_ideal} = \frac{\frac{R_x}{R_i + R_f}}{1 + \frac{R_x}{R_i + R_f}} \left(-V_{ref\_x} + V_{cm} + \frac{V_{diff}}{2} \right) \tag{12}$$

Upon inspection, the following observations are made:

1. The first two terms are due to V_{ref_x} and V_{cm} respectively and have opposite signs. Combined together, it represents an equivalent output offset. The third term represents a gain error that is proportional to the differential input voltage.
2. The differential input is normally under a couple hundred millivolts considering the input range for common gain options and supply voltage range, while common-mode input could be many tens of volts. As a result, the offset term is normally much larger than the gain error term.
3. Both the offset and gain error terms are proportional to the ratio R_x / (R_i+R_f), when R_x << (R_i+R_f). This coefficient can be used as an indicator of the output error magnitude.
4. When referred to input, all terms in the output error are divided by the gain of the difference amplifier.

So far, it is assumed that the output is measured single-end relative to ground. The reference voltage V_{ref_x} is then subtracted from the measured results. If differential measurement is made with respect to the reference pin, the output error cancels. In this situation, the finite source impedance, R_x, has no impact on accuracy. Figure 5-3 shows the preferred measurement setup when using a voltage divider to drive the reference, or when output impedance of the driving source is not negligible.

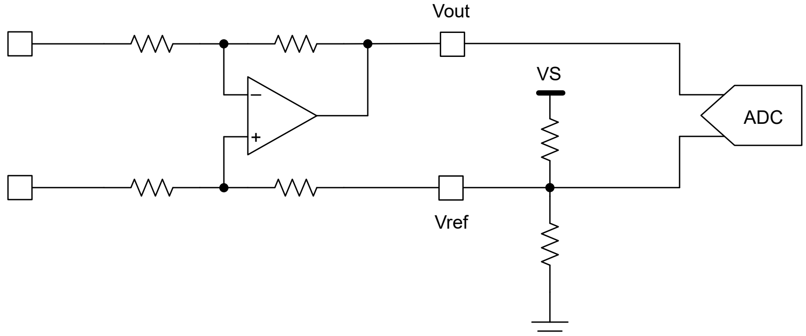

Figure 5-3. Differential Measurement

Comparing with single-ended measurement, differential measurement is a great improvement. However, it does not mean that the source impedance has no impact on performance at all. The price to pay is output dynamic range. Because the error voltage is still added to the output and reduces its effective swing range that is otherwise available to respond to differential input.

5.3 Reference Source Impedance Error in Voltage Feedback Multi-Stage CSA

High-performance CSAs are often found to be multi-stage. In between input and output, there could be additional gain stages for signal enhancement. If such a device is bidirectional, it generally comes with an output stage that is based on difference amplifier which accomplishes differential to single-ended conversion. This section builds upon what has previously been explored from single-stage difference amplifiers, and extrapolates that information to multi-stage CSAs.

Since the output stage is a difference amplifier, the output error Equation 12 still applies. Similar to the single-stage case, the external reference voltage is known, as well as the source impedance. However, for multi-stage, the input to the output difference amplifier is an internal node. Internal operating condition is generally not published in product data sheets. Both the common-mode and differential input voltages must be found to utilize the error equation.

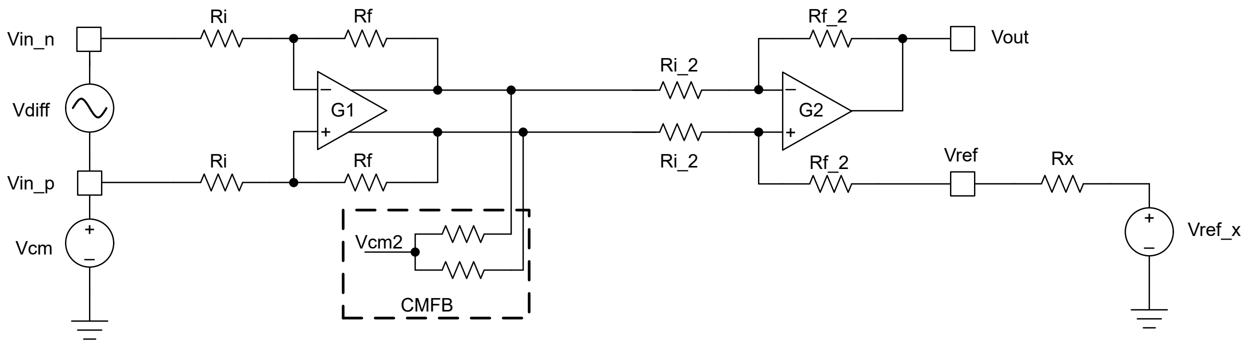

Figure 5-4. Voltage Feedback Multi-Stage CSA Output Error

Figure 5-4 shows a two-stage voltage feedback CSA. The differential input is easy to calculate if the gain of each stage is known. This particular example is made up of two stages with gain of G_1 and G_2, respectively. The overall gain equals to the product of all gains:

$$\boldsymbol{G} = \boldsymbol{G}_1 \times \boldsymbol{G}_2 \tag{13}$$

The differential input to the output stage equals to the differential output of the input stage:

$$\boldsymbol{V_{diff\_2}} = V_{diff} \times \boldsymbol{G}_1 \tag{14}$$

The common-mode input is a value determined by design and is unique to the individual device. It is bound between ground and power supply for voltage compliance. Practical choices often put the common-mode voltage near mid supply. It should be noted that the common-mode operating point is independent of the input common-mode voltage of the device, which is the reason behind very high CMRR specifications of such devices.

Rewriting the output error equation, with V_{cm2} being the common-mode voltage:

$$\boldsymbol{V_{out\_error}} = \frac{\frac{R_x}{R_{i\_2} + R_{f\_2}}}{1 + \frac{R_x}{R_{i\_2} + R_{f\_2}}} \left(-V_{ref\_x} + V_{cm2} + \frac{V_{diff}\boldsymbol{G}_1}{2} \right) \tag{15}$$

5.4 Reference Source Impedance Error in Current Feedback Multi-Stage CSA

Figure 3-5 is redrawn and shown in Figure 5-5. The two current sources are shown for illustration only and are not independent stimuli. They represent the differential small signal current due to input shunt voltage, V_{diff}. The relationship can be rewritten as:

$$\frac{\Delta \boldsymbol{I}}{2} = \frac{V_{diff}}{2} \times \frac{1}{Ri} \tag{16}$$

Comparing with Figure 5-2, the only difference in Figure 5-5 is that current now acts as differential input instead of voltage. Similar to voltage feedback, the input to the difference amplifier is an internal node of the CSA. Vbias is the common-mode voltage of the difference amplifier. Since knowledge of its value is not essential for an end user, it may not be listed in product data sheets.

It can be derived that the differential term of the output error equation is:

$$\boldsymbol{V_{o\_err\_diff}} = \frac{\frac{R_x}{R_L + R_f}}{1 + \frac{R_x}{R_L + R_f}} \frac{V_{diff}}{2} \frac{R_L}{R_i} \tag{17}$$

Rewriting the output error equation for two stage CSA, with V_{bias} being the common-mode voltage:

$$V_{out\_error} = \frac{\frac{R_x}{R_L + R_f}}{1 + \frac{R_x}{R_L + R_f}} \left(-V_{ref\_x} + V_{bias} + \frac{V_{diff}}{2} \frac{R_L}{R_i} \right) \tag{18}$$

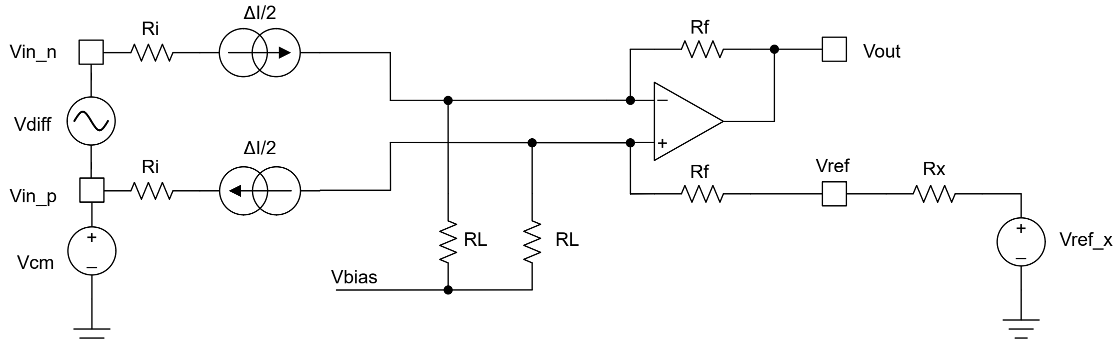

Figure 5-5. Current Feedback Multi-Stage CSA Output Error

5.5 Reference Source Impedance Error in Difference Amplifier with Output Buffer

Even though it is multi-stage, the device shown in Figure 5-6 is similar to single-stage difference amplifier. As long as the nominal resistor values are known, the derivation of the output error is relatively straightforward:

$$V_{out\_error} = \frac{\frac{R_x}{R_i + R_f}}{1 + \frac{R_x}{R_i + R_f}} \left\{ -V_{ref\_x} + V_{cm} + \left[1 + 2\left(1 + \frac{R_f}{R_i} \right) \frac{R_f}{R_{i\_2}} \right] \frac{V_{diff}}{2} \right\} \tag{19}$$

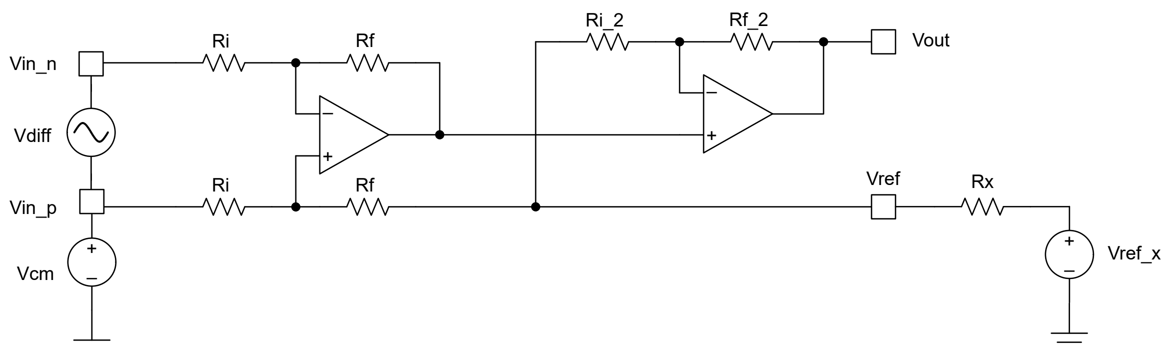

Figure 5-6. Output Error of Difference Amplifier With Output Buffer

6 Examples

This section provides several example calculations using error equations found in previous sections. Bench verification was performed to corroborate the validity of this data. Calculations are based on typical device information, including resistor values, gain of each stage, and common-mode input voltage if the example is multi-stage.

Resistor value is influenced by process variation and vary from lot to lot. Within the same lot, different units will have different resistor values. With multi-stage, the output stage common mode is determined by CMFB circuitry if the front end is fully differential, which is true for the vast majority of CSA. Gain of each stage is not fixed, it can vary within a small range for production trim.

Due to these variations, the calculations should only be treated as guidelines in visualizing the impact of the source impedance on accuracy for typically manufactured devices. Such calculations should not be used to compensate for system error.

6.1 Calculating Reference Source Impedance Error in Difference Amplifier

For the single-stage difference amplifier, all that is needed is the values of the internal resistors. Sometimes these values are either partially or entirely listed in data sheets. For example, Figure 6-1 is listed in the INAx181 data sheet.

PRODUCT	GAIN	R_{INT} (kΩ)
INA181A1	20	25
INA181A2	50	10
INA181A3	100	5
INA181A4	200	2.5

Figure 6-1. INAx181 Input Resistance

"$\boldsymbol{R_{INT}}$" in this table represents the input resistors, and corresponds to R_i in Figure 3-1 and Figure 5-2. The feedback resistor is not listed. However, inferences can be based on the information available. For example, the feedback resistor, R_f, in INAx181A2 can be found:

$$\boldsymbol{R_f} = R_i \times 50 = 500\ k\Omega \tag{20}$$

Alternatively, the combined resistance of R_i + R_f can be measured. In case no resistance information is given in the data sheet, this method can be used to find the values of R_i and R_f. As an example, the total resistance turns out to be 494 kΩ for a sample INA181A2. Since the ratio of the two resistors equals to the gain, the resistance values can be calculated:

$$\boldsymbol{R_i} = \frac{494\ k\Omega}{51} = 9.7\ k\Omega \quad \text{and} \quad \boldsymbol{R_f} = \frac{50 \times 494\ k\Omega}{51} = 484.3\ k\Omega \tag{21}$$

Table 6-1 shows calculated output error terms (columns titled "***Err_V****ref*", "***Err_V****cm*", and "***Err_V****diff*") due to finite source impedance R_x, using these measured resistance values. The external condition is: V_{ref_x} = 2.5 V; V_{cm} = 25 V; V_{diff} = 50 mV. The last column, "***Err_Total***" is the sum of all three error terms.

Table 6-1. Reference Source Impedance Error for INA181A2

R_x (kΩ)	C = R_x / (R_i + R_f)	m = C / (1 + C)	Err_V_{ref} (mV)	Err_V_{cm} (mV)	Err_V_{diff} (mV)	Err_Total (mV)
1	0.0020	0.0020	–5.05	50.54	0.10	45.59
5	0.0101	0.0100	–25.07	250.66	0.50	226.10
10	0.0203	0.0199	–49.63	496.35	0.99	447.70
20	0.0405	0.0389	–97.34	973.37	1.95	877.98
30	0.0608	0.0573	–143.22	1432.17	2.86	1291.82
40	0.0810	0.0750	–187.38	1873.78	3.75	1690.15
50	0.1013	0.0920	–229.91	2299.15	4.60	2073.83

6.2 Calculating Reference Source Impedance Error in Voltage Feedback Multi-Stage CSA

Table 6-2. Reference Source Impedance Error for INA240A2

R_x (kΩ)	C = R_x / (R_{i_2} + R_{f_2})	m = C / (1 + C)	Err_V_{ref} (mV)	Err_V_{cm} (mV)	Err_V_{diff} (mV)	Err_Total (mV)
1	0.0057	0.0057	–5.68	14.20	2.84	11.36
5	0.0286	0.0278	–27.78	69.44	27.03	55.56
10	0.0571	0.0541	–54.05	135.14	13.89	108.11
20	0.1143	0.1026	–102.56	256.41	51.28	205.13
30	0.1714	0.1463	–146.34	365.85	73.17	292.68
40	0.2286	0.1860	–186.05	465.12	93.02	372.09
50	0.2857	0.2222	–222.22	555.56	111.11	444.44

Referring to Figure 5-4 output stage, and using INA240A2 as an example, the design values for input (R_{i_2}) and feedback (R_{f_2}) resistors are 50 kΩ and 125 kΩ respectively. Use these nominal values in the calculations shown in Table 6-2. It is known that the common-mode voltage is set at half supply.

Table 6-2 is under the condition of: V_s = 5 V; V_{ref_x} = 1 V; V_{diff} = 50 mV.

The common-mode voltage of the output stage is set at half-supply and is independent of the potentially high input common-mode voltage seen at the input of the device. Therefore, the output error term is decoupled from the common-mode voltage of the device. As a result, if the reference voltage is also set at half supply, the two error terms cancel, regardless of the source impedance. However, the term due to differential input still remains. In this table, a 50-mV input to the device input is used as an example, because the front stage is in a gain of 20, the output stage sees and effective differential input of 20 × 50 mV = 1 V.

The second example is INAx191 and INA186. The INA186A2 is used to illustrate. Although the input stage is different from that of INA240, the output stage is very similar. The design values for input (R_{i_2}) and feedback (R_{f_2}) resistors are 400 kΩ and 1 MΩ respectively. The common-mode voltage is set at one-third of supply. Again, the nominal values are used in the following calculation.

This information can be used to generate Table 6-3 for the output error terms, under the condition of: V_s = 5 V; V_{ref_x} = 2.5 V; V_{diff} = 50 mV.

Table 6-3. Reference Source Impedance Error for INA186A2

R_x (kΩ)	C = R_x / (R_{i_2} + R_{f_2})	m = C / (1 + C)	Err_V_{ref} (mV)	Err_V_{cm} (mV)	Err_V_{diff} (mV)	Err_Total (mV)
1	0.0007	0.0007	–1.78	1.19	0.36	–0.24
5	0.0036	0.0036	–8.90	5.93	1.78	–1.19
10	0.0143	0.0071	–17.73	11.82	3.55	–2.36
20	0.0071	0.0141	–35.21	23.47	7.04	–4.69
30	0.0214	0.0210	–52.45	34.97	10.49	–6.99
40	0.0286	0.0278	–69.44	46.30	13.89	–9.26
50	0.0357	0.0345	–86.21	57.47	17.24	–11.49

6.3 Calculating Reference Source Impedance Error in Current Feedback Multi-Stage CSA

The INA241 and INA296 family of devices take advantage of the current feedback front end and isolates the rest of the circuits from the high input common-mode voltage. The following relevant design parameters are known (refer to Figure 5-5): R_i = 10 kΩ; R_L = 106 kΩ; R_f = 500 kΩ; V_{bias} = –9 V which is achieved through negative charge pump for V_s = 5 V.

The output error terms are calculated for the following condition: V_s = 5 V; V_{ref_x} = 2.5 V; V_{diff} = 50 mV. The results are shown in Table 6-4.

Table 6-4. Reference Source Impedance Error for INA241A3

R_x (kΩ)	C = R_x / (R_L + R_f)	m = C / (1 + C)	Err_V_{ref} (mV)	Err_V_{cm} (mV)	Err_V_{diff} (mV)	Err_Total (mV)
1	0.0017	0.0016	–4.12	–14.83	0.44	–18.51
5	0.0083	0.0079	–20.46	–73.65	2.17	–91.94
10	0.0165	0.0157	–40.58	–146.10	4.30	–182.39
20	0.0330	0.0310	–79.87	–287.54	8.47	–358.95
30	0.0495	0.0458	–117.92	–424.53	12.50	–529.95
40	0.0660	0.0602	–154.80	–557.28	16.41	–695.67
50	0.0825	0.0741	–190.55	–685.98	20.20	–856.33

7 Summary

For high accuracy measurement, the resistor divider should be avoided. Instead, consider using either a reference IC or buffered voltage source.

When a resistor divider is used to set the reference voltage for a bidirectional CSA, differential measurements with respect to the reference pin should be taken when possible. With differential measurement, the output error due to reference source impedance is canceled.

When differential measurement is not an option, the equivalent source impedance can cause both common-mode error and gain error. The coefficients of the error terms are approximately proportional to the ratio of the equivalent source impedance to the difference amplifier total resistance (for example, $R_i + R_f$). Larger output error can be expected with larger source impedance, except for the special situations where V_{cm} and V_{ref} are equal in magnitude, then their resulting errors cancel.

It should be noted that regardless of how the measurement is taken – differentially or single-ended, the encroachment on output dynamic range is present. The issue can be quite serious with large source impedance.

The output error can be estimated. It is straightforward if the CSA takes on single-stage difference amplifier topology. Sometimes the resistance values are not listed in the data sheet, but an inference can be made from a simple bench measurement. For multi-stage topologies, bench measurement is not straightforward, some background information about the design of the chip is necessary. Such information may include the gain of each stage, the common-mode voltage of the output stage, as well as the resistor network value.

Spice simulation must be used with care. For single-stage difference amplifier, it is generally not an issue. However for multi-stage CSA, the source impedance effect is typically not modeled.

Some may ask - Should I use a large divider to drive the reference pin directly, then calculate and subtract its errors based on the error equations? The answer is “no”, and here are the reasons why, even if the loss of output dynamic range is not an issue:

- The internal resistor values can be different by up to 15% among devices due to process variation
- For multi-stage topologies, the gain of each stage may not be constant even though the overall gain is
- The input common-mode voltage of the output stage is not strictly, accurately defined. Variation from the nominal value is expected.

Therefore, this error estimate should only be used as a guideline, helping system designers choose a proper reference driving method in the early design stage. It should not be used to subtract from actual measurements, in an attempt to cancel the error.