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TUTORIAL 4034

# Three is a Crowd for Instrumentation Amplifiers

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*Abstract: Three-op-amp instrumentation amplifiers have long been the industry standard for precision applications that require high gains and/or high CMRR. However, these amplifiers have serious limitations when operating from the single-supply voltage rails required in many modern applications. This article explains the limitations of the conventional three-op-amp architecture for instrumentation amplifiers, and introduces Maxim's indirect current-feedback architecture that offers specific advantages for single-supply operation of instrumentation amplifiers. Detailed analysis is supported by laboratory waveforms.*

This article was also featured in [Maxim's Engineering Journal, vol. 60](#) (PDF, 386kB).

## Instrumentation Amplifier Applications

Instrumentation amplifiers amplify small differential voltages in the presence of large common-mode voltages, while offering a high input impedance. This characteristic has made them attractive to a variety of applications, such as strain-gauge bridge interfaces for pressure and temperature sensing, thermocouple temperature sensing, and a variety of low-side and high-side current-sensing applications.

## Three-Op-Amp Instrumentation Amplifiers

The classic three-op-amp instrumentation amplifier (see **Figure 1**) offers excellent common-mode rejection and accurate differential gain programmable by a single resistor. The architecture is based on a two-stage configuration: the first stage provides unity common-mode gain and all (or most) of the differential gain, while the second stage provides unity (or small) differential-mode gain and all of the common-mode rejection (see **Figure 2**).

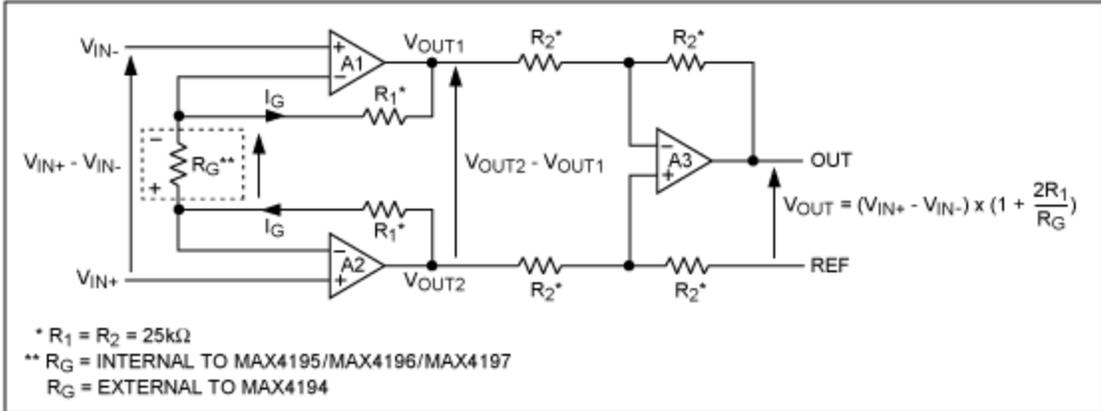


Figure 1. Internal architecture is shown for the MAX4194–MAX4197 family of three-op-amp instrumentation amplifiers.

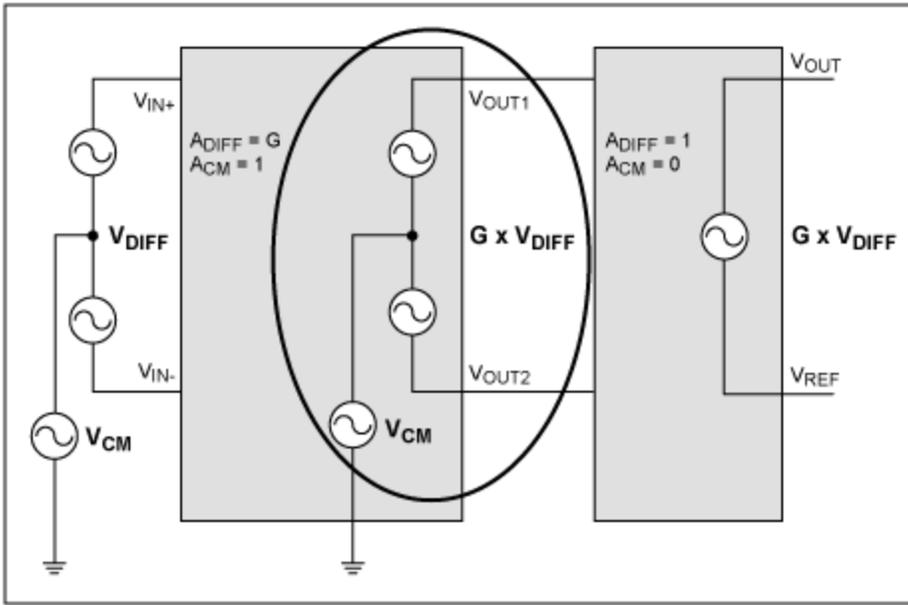


Figure 2. In this two-stage amplification of input signals, input common-mode voltage is carried through to the intermediate stage (circled).

Most low-voltage modern amplifiers have rail-to-rail output, but not necessarily rail-to-rail input. Still, let us consider an extremely high-gain, rail-to-rail input and output, three-op-amp instrumentation amplifier working from a single-supply ( $V_{CC}$ ), similar to that shown in Figure 1.

Because  $V_{OUT} = \text{gain} \times V_{DIFF} + V_{REF}$ , it follows that:

$$\begin{aligned} (V_{OUT1}, V_{OUT2}) &= V_{CM} \pm (\text{gain} \times V_{DIFF}/2) \\ &= V_{CM} \pm (V_{OUT} - V_{REF}) / 2 \end{aligned}$$

To prevent  $V_{OUT1}$  and  $V_{OUT2}$  from hitting the supply rails, it should be ensured that:

$$\begin{aligned} 0 &< (V_{OUT1}, V_{OUT2}) < V_{CC} \\ (\text{i.e., } 0 &< V_{CM} \pm (V_{OUT} - V_{REF}) / 2 < V_{CC}) \end{aligned}$$

noting that:

$$0 < V_{OUT} < V_{CC}$$

Applications often set  $V_{REF} = 0$  (for unipolar input signals) or  $V_{REF} = V_{CC}/2$  (for bipolar input signals).

With  $V_{REF} = 0$ , the inequality reduces to:

$$0 < V_{CM} \pm V_{OUT}/2 < V_{CC}$$

With  $V_{REF} = V_{CC}/2$ , the inequality reduces to:

$$0 < V_{CM} \pm V_{OUT}/2 \pm V_{CC}/4 < V_{CC}$$

These conditions are best understood graphically, as shown in **Figure 3**.

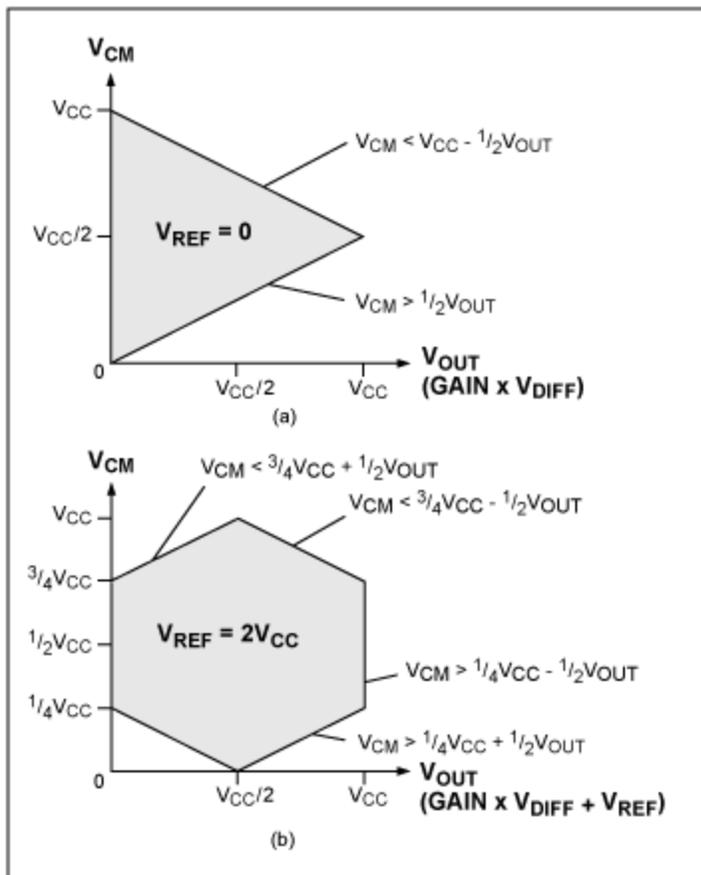


Figure 3. The usable  $V_{CM}$  at various input differential voltages for a single-supply, three-op-amp instrumentation amplifier is shown with (a)  $V_{REF} = 0$  and (b)  $V_{REF} = V_{CC}/2$ . The horizontal axis is the amplified input differential voltage ( $V_{OUT}$ ).

The grey areas in Figure 3 show the range of input common-mode voltages (in relation to input differential voltages), where the outputs of the Figure 1 amplifiers (A1, A2) will not saturate into the supply rails. This range depends on  $V_{OUT}$  and  $V_{REF}$ . Because  $V_{OUT} - V_{REF}$  is really an amplified

version of the input differential voltage, the allowed common-mode input range varies depending on the input differential voltage.

Practically, of course, it is best to make maximum use of the circuit's gain—to obtain the full output swing ( $V_{OUT}$ ) when the maximum expected differential voltages are seen by the inputs. The black areas in **Figure 4** show the range of input common-mode voltages where the instrumentation amplifier amplifies the maximum input differential voltage so that  $V_{OUT} = 0$  or  $V_{OUT} = V_{CC}$ .

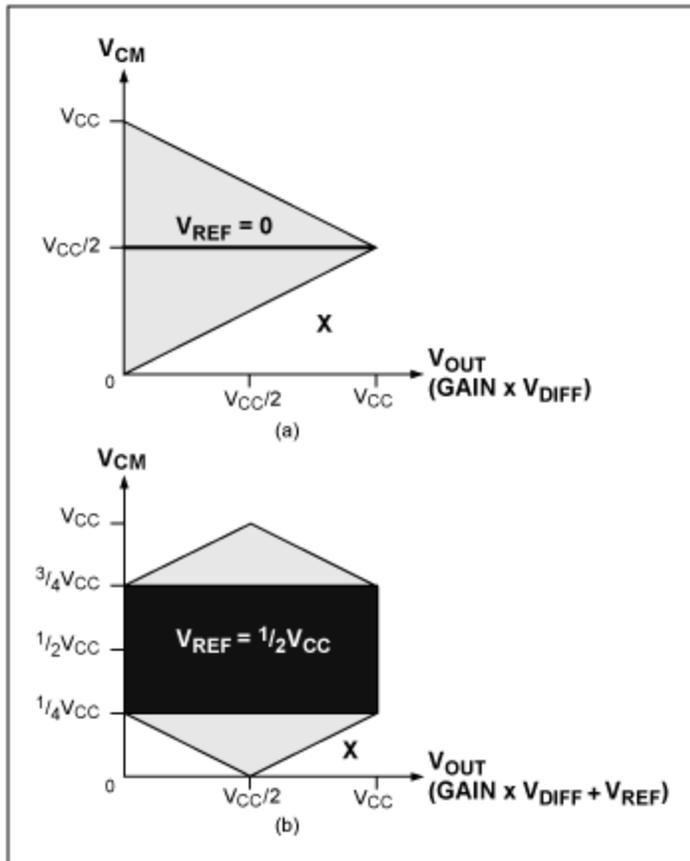


Figure 4. The black box shows the range of input common-mode voltages in which the conventional three-op-amp instrumentation amplifier uses its gain to give a maximum output voltage (i.e., at a maximum input differential voltage) with (a)  $V_{REF} = 0$  and (b)  $V_{REF} = V_{CC}/2$ .

As can be seen, the input common-mode voltage is severely restricted in both scenarios. In particular:

- If one wants to fully amplify a unipolar input-differential signal (setting  $V_{REF} = 0$  and obtaining full output swing from 0 to  $V_{CC}$ ), the signal must be present with a common-mode voltage of  $1/2 V_{CC}$ . At any other common-mode voltage, the output voltage will not reach the full swing of  $V_{CC}$  (the maximum input differential voltage is reduced). For bipolar input differential signals (with  $V_{REF} = 1/2 V_{CC}$ ), the corresponding range of input common-mode voltages, where one can achieve full output voltage swing of 0 to  $V_{CC}$ , is only between  $1/4 V_{CC}$  and  $3/4 V_{CC}$ .
- In both cases, if the input common-mode voltage were to be at or close to ground (0V), then the amplifier loses all ability to amplify input differential voltages. Therefore, assuming that the input differential (wanted) voltages are unrelated to the input common-mode (unwanted) voltages, the black areas represent design minima and maxima for  $V_{CM}$  that can be tolerated for the full range of  $V_{OUT}$ . Outside this area, certain combinations of  $V_{DIFF}$  and  $V_{CM}$  may not result in a permissible

$V_{CM}$ . Note that, in the case of the Figure 4a, if full-scale  $V_{CM}$  variation is required, the input common-mode voltage tolerance is zero. Simply put, no common-mode variation of the input signal is allowed.

As a result, three-op-amp instrumentation amplifiers find only limited applications in single-supply systems. It is worthwhile to continue this discussion to answer two questions:

1. What happens if the internal amplifiers (A1 and A2) saturate into the rails?
2. What is the effect of non-rail-to-rail-input architectures?

## Effect of Input-Amplifier Saturation

Consider the case when the output of amplifier A1 has saturated into ground. In other words,  $V_{IN+} > V_{IN-}$ , and the common-mode voltage is in the area marked X in Figure 4. ( $V_{DIFF}$  is larger than allowed by the grey area.)

Because A1 is saturated ( $V_{OUT1} = 0$ ), it transitions into a comparator (nonlinear) mode of operation, and the voltage at its inverting pin is no longer constrained to be the same as its noninverting pin ( $V_{IN-}$ ). Amplifier A2 then acts as a noninverting amplifier with a gain of  $1 + R_1 / (R_1 + R_G)$  for voltages at its noninverting pin ( $V_{IN+}$ ). For a high-gain amplifier,  $R_G \ll R_1$  and, therefore, amplifier A2 simply acts as an amplifier with a noninverting gain of 2:

$$\begin{aligned} V_{OUT2} &= 2 \times V_{IN+} = 2 \times (V_{CM} + V_{DIFF}/2) \\ &= 2 \times V_{CM} + V_{DIFF} \end{aligned}$$

The second-stage differential amplifier, A3, simply examines its inputs  $V_{OUT1}$  and  $V_{OUT2}$ , and presents the difference at its output:

$$V_{OUT} = (2 \times V_{CM} + V_{DIFF}) + V_{REF}$$

Similarly, if A2 saturates to ground:

$$V_{OUT} = -(2 \times V_{CM} - V_{DIFF}) + V_{REF}$$

This is a potentially hazardous mode of operation for the three-op-amp instrumentation amplifier. Not only has it stopped amplifying the input differential voltage, but instead of "gracefully degrading" in some fashion, the three-op-amp instrumentation amplifier transitions into a mode that amplifies the input common-mode voltage relative to the input differential voltage. This problem is exacerbated by the fact that common-mode voltages are generally uncontrolled and probably are unwanted noise that corrupts signals of interest. This is a serious issue, as the primary reason for using the instrumentation amplifier is to eliminate such noise.

## Effect of Non-Rail-to-Rail Input Architectures

As mentioned earlier, most amplifiers have rail-to-rail output, but not rail-to-rail input. Rail-to-rail input stages are especially difficult to design for precision applications, because the crossover between near- $V_{CC}$  common-mode voltage operation and near-GND common-mode voltage operation can never be perfect—during this transition, offset voltages can arise between n-type and p-type pairs in the input differential stage. A low  $V_{OS}$  and a high CMRR are key specifications for a well-designed, precision instrumentation amplifier. Because  $CMRR = \Delta V_{OS} / \Delta V_{CM}$ , the change in  $V_{OS}$  when changing common-mode voltage across the crossover region severely degrades the CMRR specification.

As a result, most precision instrumentation amplifiers tend to be non-rail-to-rail input type, though they still include the negative rail (0V) as part of the input common-mode voltage range. If we re-examine Figure 3, taking into account its input common-mode voltage limitations and redrawing the graphs, we can reason that the graphs will look like those in **Figure 5**.

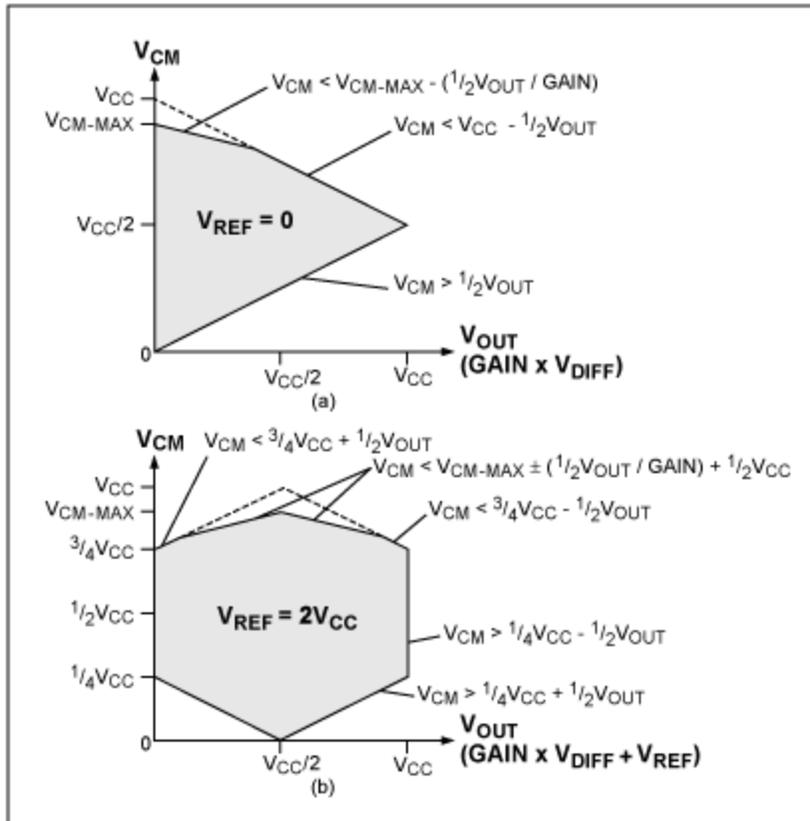


Figure 5. The usable input common-mode voltage at various input differential voltages for a single-supply, three-op-amp instrumentation amplifier accounts for a non-rail-to-rail input stage with (a)  $V_{REF} = 0$  and (b)  $V_{REF} = V_{CC}/2$ .

## The Indirect Current-Feedback Architecture

The indirect current-feedback architecture is a new approach to designing instrumentation amplifiers that has become extremely popular for its multiple benefits. **Figure 6** shows the indirect current-feedback architecture as used in the MAX4462 and MAX4209 instrumentation amplifiers.

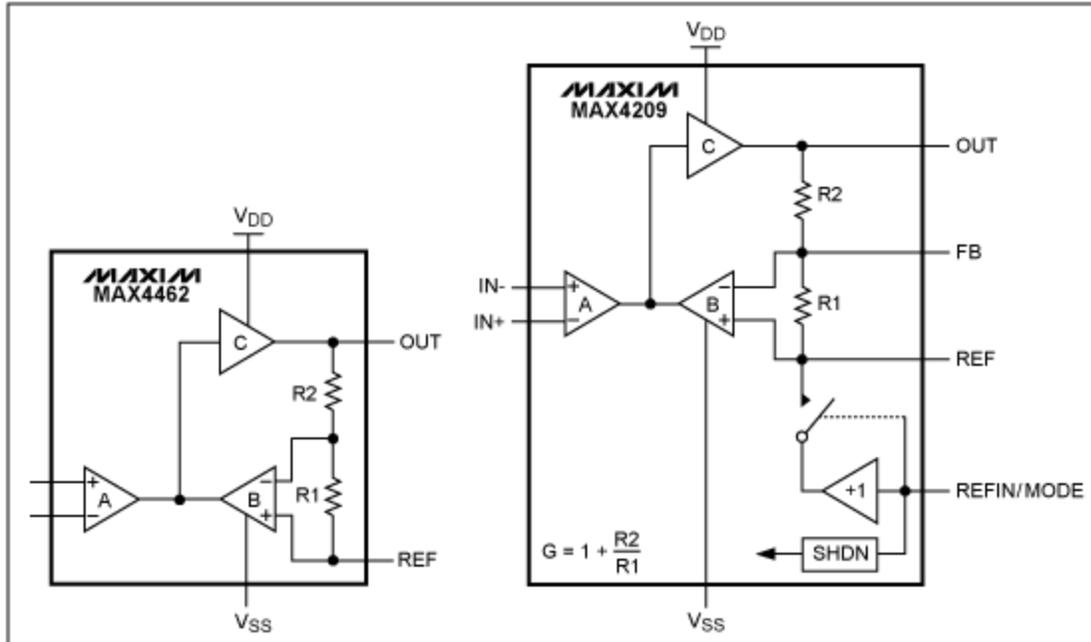


Figure 6. Indirect current-feedback architecture is used in the MAX4462 and MAX4209 instrumentation amplifiers.

This new architecture contains a high-gain amplifier (C) and two transconductance amplifiers (A and B). Each transconductance amplifier converts its input differential voltage into an output current and rejects all of its input common-mode voltage. At the stable operating point for the amplifier, the output current sourced from the  $g_M$  stage A matches the input current sunk by  $g_M$  stage B. This current matching is enabled by feedback action through high-gain amplifier C, which forces the differential voltage at the input of feedback amplifier B to be the same as the differential voltage at the inputs of amplifier A. This design then sets up a defined current in the output resistor chain (equal to  $V_{DIFF} / R1$ ), which also flows through R2. Therefore, the output voltage at OUT is simply a gained-up version of the input differential voltage (gain =  $1 + R2 / R1$ ). The output can be offset by feeding an arbitrary reference voltage at REF, much like a standard three-op-amp instrumentation amplifier.

By translating the part operation to a high-level block diagram, as in **Figure 7**, and by comparing it to Figure 2, a key advantage emerges. The intermediate signal in the three-op-amp instrumentation amplifier contains not only the gained-up differential voltage, but also the input common-mode voltage. However, the indirect current-feedback architecture contains only a recent representation of the input differential voltage. The first stage provides all the common-mode rejection. The second stage then offers all the differential gain and reinforces common-mode rejection, thereby allowing the output to be offset by a reference voltage, if necessary. As a result, the input common-mode voltage limitations that are present in the three-op-amp instrumentation amplifier simply do not exist within the indirect current-feedback architecture.

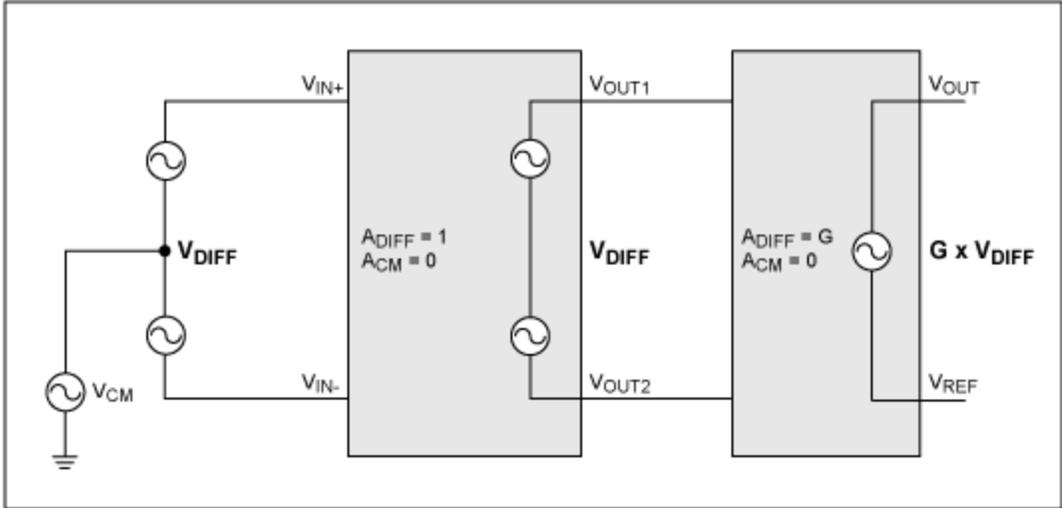


Figure 7. The operation of an indirect current-feedback instrumentation amplifier has no common-mode voltage in the output of the first stage.

Taking into account the input common-mode voltage limitations (i.e., a non-rail-to-rail input stage), the transfer characteristics then would behave similarly to that shown in **Figure 8**. The black areas show the design limit of input common-mode voltages in which the full output-voltage range is achievable. The grey areas illustrates the range of input common-mode voltages in which the instrumentation amplifier operates as expected—it outputs a voltage proportional to a gained-up version of the input differential voltage, and it rejects all input common-mode voltage.

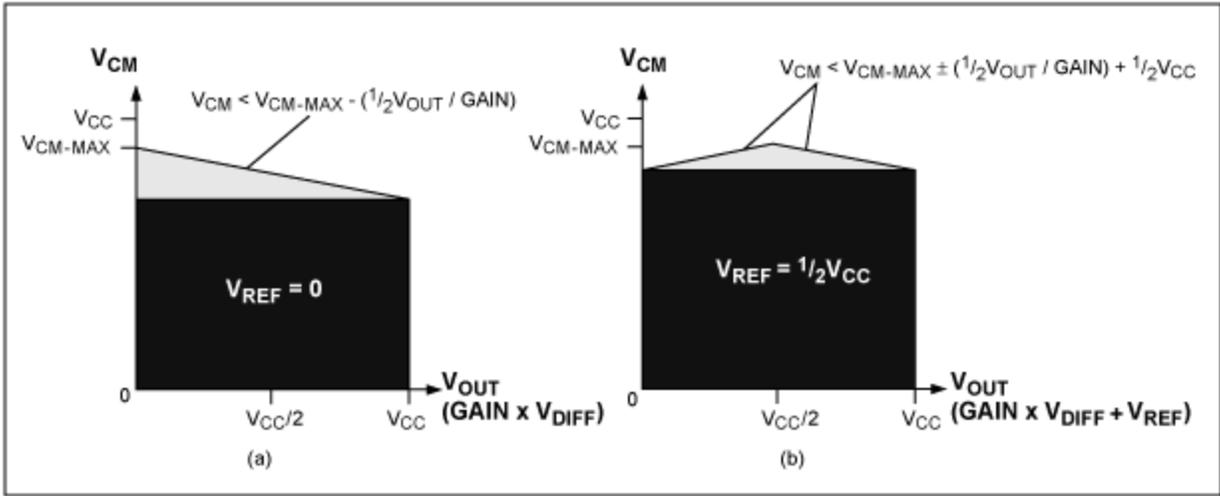


Figure 8. The usable range of input common-mode voltages for an indirect current-feedback instrumentation amplifier is shown in grey and black. In both (a) and (b), the black area, which is a subset of the grey area, shows where the full output voltage is achievable.

### Experimental Results

The following experimental results effectively support the indirect current-feedback discussion. Consider the MAX4197 and the MAX4209H. Both are instrumentation amplifiers with a gain of 100. The MAX4197 has a three-op-amp architecture, while the MAX4209H is an indirect current-feedback instrumentation amplifier. Both parts are supplied with a  $V_{CC} = 5V$  and a  $V_{REF} = 2.5V$  to offset the zero output of the device.

In this experiment, two types of waveforms are input to the instrumentation amplifier.

Case 1 has a 1kHz differential voltage in the presence of a large 100Hz common-mode voltage. The output of the instrumentation amplifier is expected to contain only a 1kHz signal with no 100Hz components. The waveforms can be approximated as:

$V_{IN+}$  = sine-wave amplitude =  $2V_{P-P}$ ,  
offset = 1V, frequency = 100Hz

$(V_{IN+} - V_{IN-})$  = sine-wave amplitude =  $30mV_{P-P}$ ,  
offset = 0, frequency = 1kHz

Case 2 has a 100Hz differential voltage in the presence of a large 1kHz common-mode voltage. The output of the instrumentation amplifier is expected to contain only a 100Hz signal with no 1kHz components. The input waveforms can be approximated as:

$V_{IN+}$  = sine-wave amplitude =  $2V_{P-P}$ ,  
offset = 1V, frequency = 1kHz

$(V_{IN+} - V_{IN-})$  = sine-wave amplitude =  $30mV_{P-P}$ ,  
offset = 0, frequency = 100Hz

The results follow, where channel 1 is  $V_{IN+}$ , channel 2 is  $V_{IN-}$ , and channel 3 is the output of the instrumentation amplifier.

## Case 1 Results

In **Figure 9a**, the MAX4209H shows the expected result. The MAX4197 gives the expected results only when the input common-mode voltage is well above ground (**Figure 9b**). The 100Hz component in the MAX4197's output voltage is obvious.

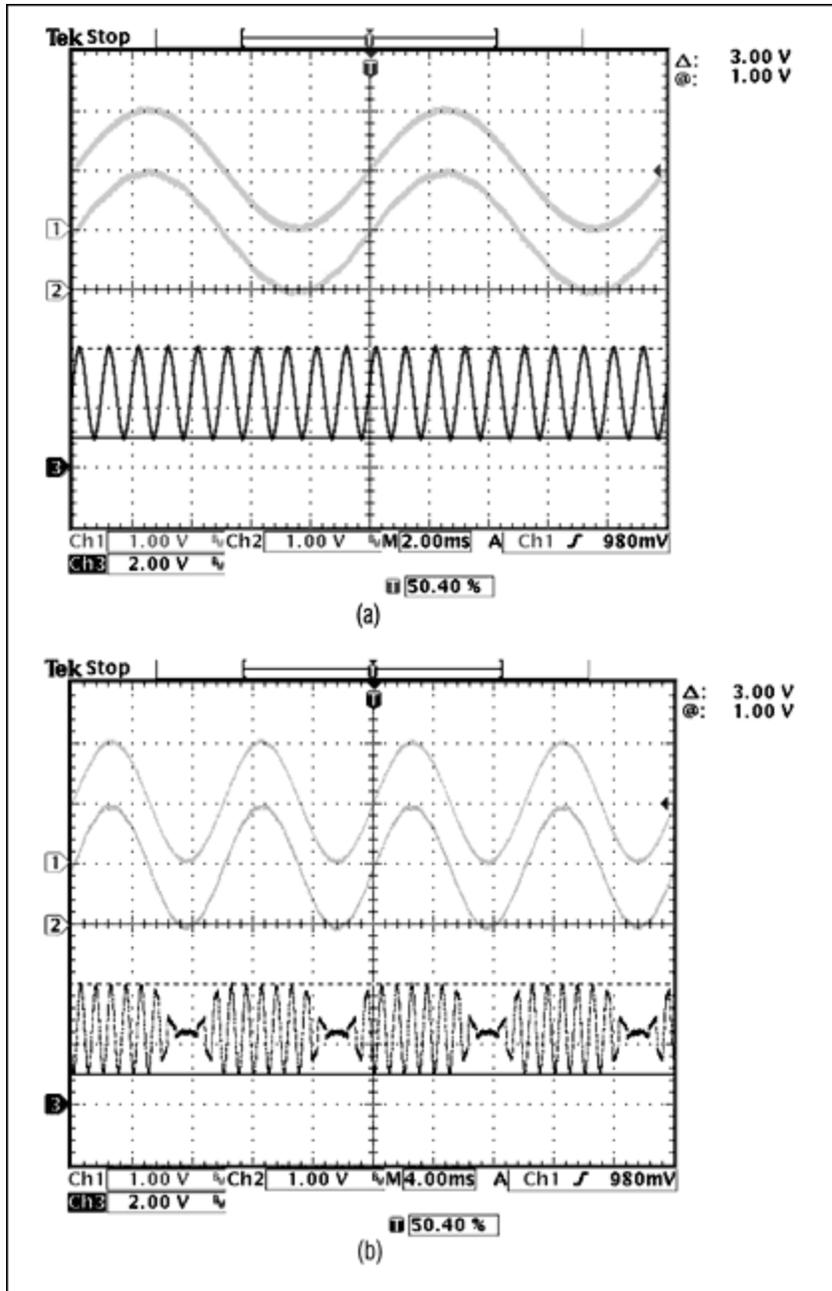


Figure 9. The results are shown for Case 1 with (a) the MAX4209H indirect current-feedback architecture and (b) the MAX4197 three-op-amp architecture. Note that the 1kHz  $V_{DIFF}$  is too small to be visible on the input 1 and input 2 traces, whereas the 100Hz  $V_{CM}$  dominates.

## Case 2 Results

Again, the MAX4209H shows the expected results (Figure 10a). The MAX4197 amplifies the input differential signal only when the common-mode voltage is well above ground (Figure 10b). When the common-mode voltage is close to ground, the output voltage either inverts the common-mode voltage or simply buffers it, depending on whether A1 or A2 saturates (as explained earlier).

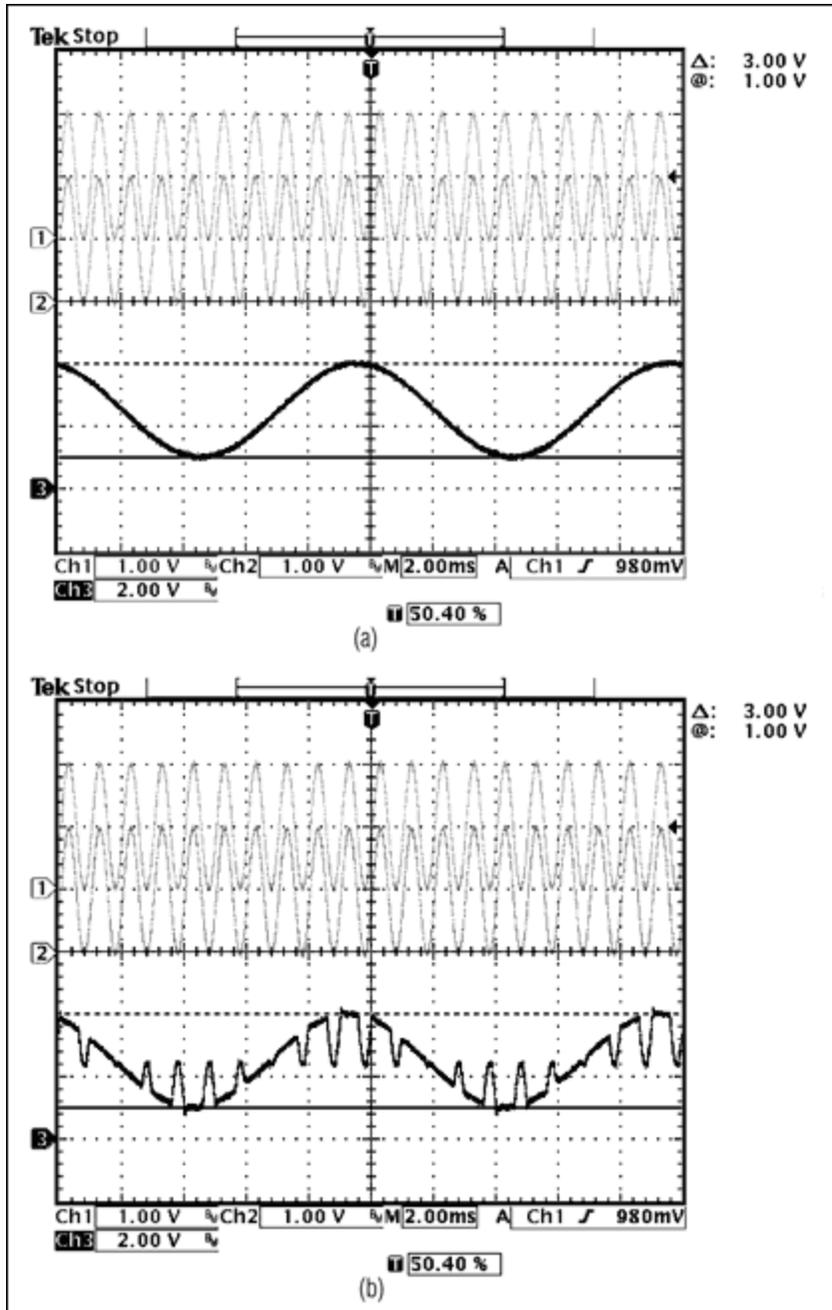


Figure 10. The results are shown for Case 2 with (a) the MAX4209H indirect current-feedback architecture and (b) the MAX4197 three-op-amp architecture. Note (as with Figure 9) the breakthrough of the 1kHz  $V_{CM}$  over the desired output for the three-op-amp instrumentation amplifiers. The indirect current-feedback architecture maintains its excellent performance.

## Conclusion

In the midst of an unprecedented era of high-performance electronic devices, today's consumers demand not only better performance, but also more intelligent power-management schemes to enable longer

battery life and energy efficiency. A transition from dual-supply analog designs to single-supply architectures is already underway that is changing the way electronics are designed and used. New, innovative architectures, such as the indirect current-feedback architecture described in this article, are making the dreams of yesterday into realities of today.

| Related Parts           |  |                              |
|-------------------------|--|------------------------------|
| <a href="#">MAX4208</a> | Ultra-Low Offset/Drift, Precision Instrumentation Amplifiers with REF Buffer | <a href="#">Free Samples</a> |
| <a href="#">MAX4209</a> | Ultra-Low Offset/Drift, Precision Instrumentation Amplifiers with REF Buffer | <a href="#">Free Samples</a> |
| <a href="#">MAX4460</a> | SOT23, 3V/5V, Single-Supply, Rail-to-Rail Instrumentation Amplifiers         | <a href="#">Free Samples</a> |
| <a href="#">MAX4461</a> | SOT23, 3V/5V, Single-Supply, Rail-to-Rail Instrumentation Amplifiers         | <a href="#">Free Samples</a> |
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