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APPLICATION BULLETIN

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BOOST INSTRUMENT AMP CMR WITH COMMON-MODE DRIVEN SUPPLIES

By R. Mark Stitt

Ever-increasing demands are being placed on instrumentation amplifier (IA) performance. When standard IAs can not deliver the required performance, consider this enhanced version. Dramatic performance improvements can be achieved by operating the input amplifiers of a classical three-op-amp IA from common-mode driven sub-regulated power supplies.

Instrumentation amplifiers are designed to amplify low-level differential signals while rejecting unwanted common-mode signals. One of the most important specifications is common-mode rejection (CMR)—the ability to reject common mode signals. AC CMR is especially important since the common-mode signals are inevitably dynamic—commonly ranging from 60Hz power-line interference to switching-power-supply noise at tens to hundreds of kHz. With common-mode driven sub-regulated supplies, both the AC and DC CMR of the IA can be dramatically improved. Improved AC and DC power supply noise rejection is an added bonus.

At the high gains often required, input offset voltage drift can also be a critical specification. In some applications, the low input offset voltage drift of chopper stabilized op amps might provide the best solution. But, since many of these chopper stabilized op amps are built using low voltage CMOS processes, they can not be operated on standard ±15V power supplies. Operating the chopper stabilized op amps from common-mode-driven, sub-regulated ±5V supplies allows them to be used without restriction in ±15V systems.

THE THREE OP AMP IA

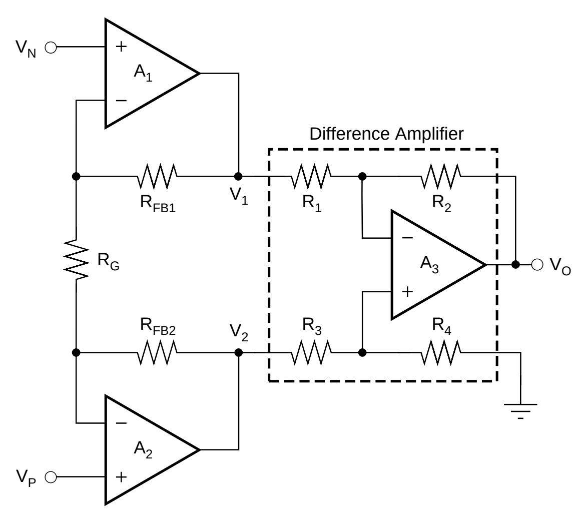
To understand how the technique works, first consider the operation of the three op amp IA shown in Figure 1A. The design consists of an input gain stage driving a difference amplifier.

The difference amplifier consists of op amp A_3 and ratio matched resistors R_1 through R_4. If the resistor ratios R_2/R_1 exactly match R_4/R_3 the difference amplifier will amplify differential signals by a gain of R_2/R_1 while rejecting common-mode signals. The CMR of the difference amplifier will almost certainly be limited by resistor mismatch when a high-performance op amp is used for A_3. A unity-gain difference amplifier requires a difficult 0.01% resistor match for CMR of 86dB.

Since the slightest input source impedance mismatch would degrade the resistor matching of the difference amplifier, a differential input, differential output gain-stage (A_1, A_2, R_{FB1}, R_{FB2}, and R_G) is used ahead of the difference amplifier. The low output-impedance of the of the gain stage preserves difference amplifier resistor matching and maintains the CMR of the difference amplifier. The input amplifiers also provide high input impedance and additional gain.

When designing a high CMR instrumentation amplifier, it is important to use a differential input, differential output amplifier using a single gain-set resistor (see Figure 1A). In the Figure 1A circuit, CMR is independent of resistor matching. Resistor mismatches degrade CMR in the two gain-set-resistor differential in/out amplifier (see Figure 1B).

To understand why CMR is independent of resistor matching in the single gain-set resistor amplifier, consider the Figure 1A circuit. With a common-mode input signal, and no differential input signal, the voltage between V_N and V_P does not change. Therefore the voltage across R_G remains constant and, since no current flows in the op amp inputs, there is no current change in R_{FB1} or R_{FB2}, and the differential output voltage, V_1-V_2, does not change. Ideally then, with a perfect difference amplifier, the common-mode gain is zero and the CMRR is ∞.



Mismatches in gain-set resistors R_{FB1} and R_{FB2} do not degrade IA CMR.

$$GAIN = (1 + [R_{FB1} + R_{FB2}]/R_G)\ (R_2/R_1)$$

If $R_{FB1} = R_{FB2} = R_{FB}$,

$$GAIN = (1 + [2 \cdot R_{FB}]/R_G)\ (R_2/R_1)$$

FIGURE 1A. The Three Op-Amp Instrumentation Amplifier.

Printed in U.S.A. June, 1997

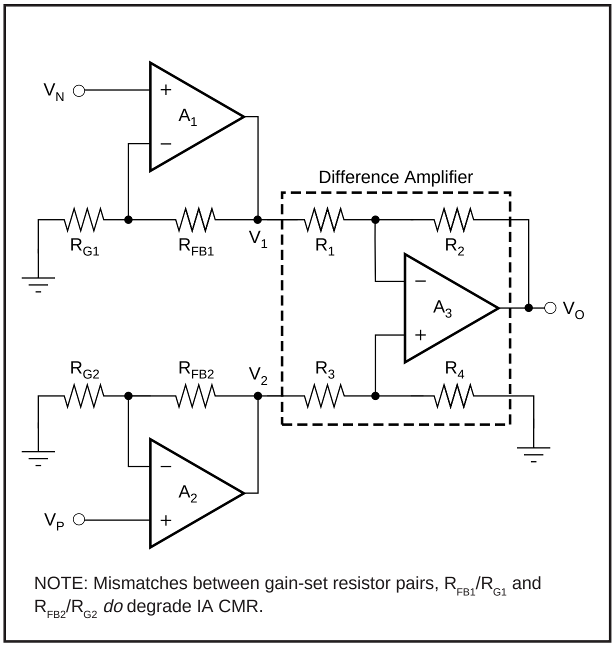


FIGURE 1B. The *Wrong* Way to Make a Three Op-Amp Instrumentation Amplifier.

In the Figure 1B circuit, CMR *does* depend on resistor matching. Common-mode signals will cause different common-mode currents to flow through R_{G1} and R_{G2} if their values are not matched. Then, if the ratio of R_{FB1}/R_{G1} is not exactly equal to the ratio of R_{FB2}/R_{G2}, there *will* be common-mode gain and the CMRR of the instrumentation amplifier *will* be degraded.

Mathematically, for the two circuits:

$$G_{DIFF} = (V_1 – V_2)/(V_N – V_P)$$
$$G_{CM} = (V_1 – V_2)/V_{CM}$$

For the single gain-set resistor circuit, Figure 1A:

$$G_{DIFF} = (R_{FB1} + R_{FB2} + R_G)/R_G$$

If $R_{FB1} = R_{FB2} = R_{FB}$, this becomes the familiar

$$G_{DIFF} = 1 + (2 \cdot R_{FB}/R_G)$$
$$G_{CM} = 0$$

For the two gain-set resistor circuit, Figure 1B:

$$G_{DIFF} = \frac{V_N \cdot (1 + (R_{FB1}/R_{G1})) – V_P \cdot (1 + (R_{FB2}/R_{G2}))}{V_N – V_P}$$
$$G_{CM} = (R_{FB1}/R_{G1}) – (R_{FB2}/R_{G2})$$

(The CMRR of the Figure 1B circuit *does* depend on buffer amplifier resistor matching.)

Where:

G_{DIFF} = Differential gain of the IA (V/V)
G_{CM} = Common-mode gain of the IA (V/V)

See Figures 1A and 1B for V_S and R_S.

Common-mode rejection ratio is the ratio of differential gain to common-mode gain. Adding gain ahead of the difference amplifier increases the CMR of the IA so long as the op amps in the gain stage have better CMR than the difference amplifier. That is why IA data sheets usually specify one CMR (e.g. 80dB) at gain = 1 and a much higher CMR at higher gains (e.g. 100dB at gain = 1000).

Most high-performance op amps have better CMR than is available from difference amplifiers. Be careful when selecting an input op amp though; the venerable “741” op amp has a minimum high-grade CMR of 80dB, and the world’s most popular op amp[(1)], the LM324, has a min high-grade CMR of only 70dB. High performance bipolar input op amps have the best CMR. The OPA177 has a min CMR of 130dB. FET input op amps usually don’t offer quite as much performance. The Burr-Brown OPA627 comes the closest with a min CMR of 106dB.

LIMITING FACTORS IN IA PERFORMANCE

The DC CMR of a standard IA can be improved by driving the power supply connections of the input op amps from sub-regulated power supplies referenced to the IA common-mode input voltage. Op amp CMR is limited by device mismatch and thermal feedback that occurs as the op amp inputs change relative to its power supplies. If the power supply rails are varied to track the common mode input signal, there is no variation of the inputs relative to the power-supply rails, errors which degrade CMR are largely eliminated, and CMR can be substantially improved.

The AC CMR of the IA is limited by the AC response of the input amplifiers. The outputs of the input amplifiers in the IA follow the common mode input signal. As the frequency of the common-mode signal increases, the loop gain of the input op amps diminishes, and CMR falls off.

For large common-mode signals, the slew rate of the input op amps can limit the ability of the IA to function altogether. This will happen when the maximum rate of change of the common-mode signal exceeds the slew rate limit of the op amp. For a sine wave, the maximum rate of change occurs at the zero crossing and can be derived as follows:

$$V = V_P \cdot \sin(2 \cdot \pi \cdot f \cdot t)$$
$$dV/dt = 2 \cdot \pi \cdot f \cdot V_P \cdot \cos(2 \cdot \pi \cdot f \cdot t)$$

At t = 0,

$$dV/dt = 2 \cdot \pi \cdot f \cdot V_P$$
$$\text{Slew rate limit} = 2 \cdot \pi \cdot f_{MAX} \cdot V_P$$

Where:

V = common-mode voltage vs time (t)
V_P = peak common-mode voltage
Slew rate limit = maximum dV/dt
f_{MAX} = maximum common-mode frequency at amplitude V_P beyond which standard IA fails to function due to slew-rate limit of input op amp.

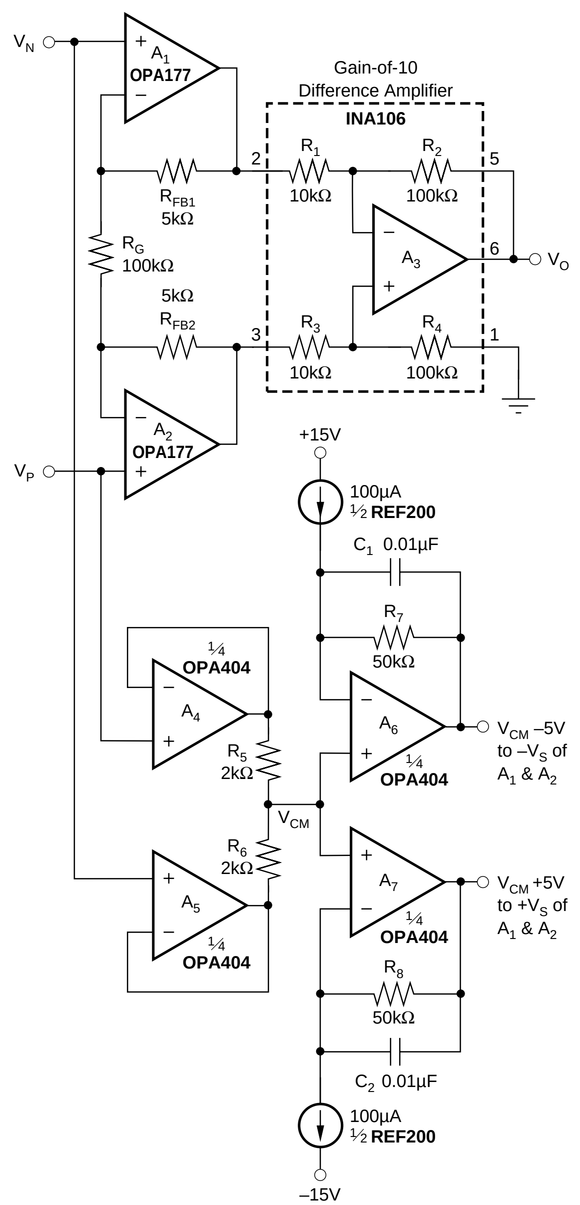
As with DC CMR, AC CMR can be improved by driving the power supply connections of the input op amps from common-mode referenced sub-regulated supplies. Since neither the inputs nor the output of the amplifier change relative to

(1) According to its designer: Frederiksen, Thomas M., *Intuitive IC Op Amps*, National Semiconductor’s Technology Series, 1984, back cover.

the power supply rails, nothing within the amplifier moves in response to the common-mode signal. No current flows in the phase compensation capacitors and the phase compensation is therefore defeated for common-mode response.

THE BOOSTED IA

The complete circuit for the enhanced IA is shown in Figure 2. In addition to the three op amp IA, it contains a buffered common-mode voltage generator, and ±5V subregulated power supplies.



NOTE: Driving the power supplies of the input amplifiers of a three op amp IA from common-mode driven supplies can dramatically improve both AC and DC CMR.

FIGURE 2. Boosted Instrumentation Amplifier.

An INA106 gain-of-10 difference amplifier is used for the difference amplifier. The INA106 contains a precision op amp and ratio matched resistors R_1 through R_4 pretrimmed for 100dB min CMR. No critical resistor matching by the user is required to build a precision IA using this approach.

The common-mode signal driving the subregulated supplies is derived from resistor divider network, R_5, R_6. The network is driven from the IA inputs through unity-gain connected op amps A_4 and A_5. These buffer amplifiers persevere the IA's high input impedance. In some applications the impedance of the R_5, R_6 network connected directly to the IA inputs is acceptable and buffer amplifiers A_4 and A_5 can be deleted as shown in Figure 3. The signal at the R_5, R_6 connection of the resistor divider is the average or common-mode voltage of the two IA inputs.

The negative subregulator consists of A_6, R_7, C_1, and a 100µA current source (1/2 of Burr-Brown REF200). Since no current flows in the op amp input, 100µA flows through the 50kΩ resistor, R_7 forcing a –5V drop from the op amp input to its output. The op amp forces the negative input to be at the same potential as its positive input. The result is a a –5V floating voltage reference relative to the op amp noninverting input terminal.

The positive subregulator is the same as the negative subregulation except for the polarity of the current source connection.

The outputs of the positive and negative subregulators are connected to the power supplies of the input op amps A_1 and A_2 only. All other op amps are connected to ±15V power supplies.

COMMON MODE RANGE OF BOOSTED IA

The common-mode input range of the boosted IA is limited by the subregulated supply voltage. The outputs of the subregulator amplifiers, A_6 and A_7 must swing the common-mode voltage plus the subregulator voltage. The smaller the subregulator voltage, the better the common-mode input range. A subregulator voltage of ±5V was chosen because it is low enough to give good input common-mode range while it is high enough to allow full performance from almost any op amp.

COMMON MODE RANGE OF BOOSTED IA IS AS GOOD AS STANDARD IA

The common-mode input range of the boosted instrumentation amplifier is as good as that of most integrated circuit IAs. It might seem that the subregulated supplies would reduce the IA's common-mode range. But because the boosted IA uses a gain-of-10 difference amplifier rather than a unity gain difference amplifier its common mode range is not limited by the input amplifiers. The common-mode input range of both the boosted IA and the standard IA is about ±7V.

That's right. With a 10V output, the common mode input range of a standard IA is only about ±7V, not ±10V as many have been incorrectly led to believe.

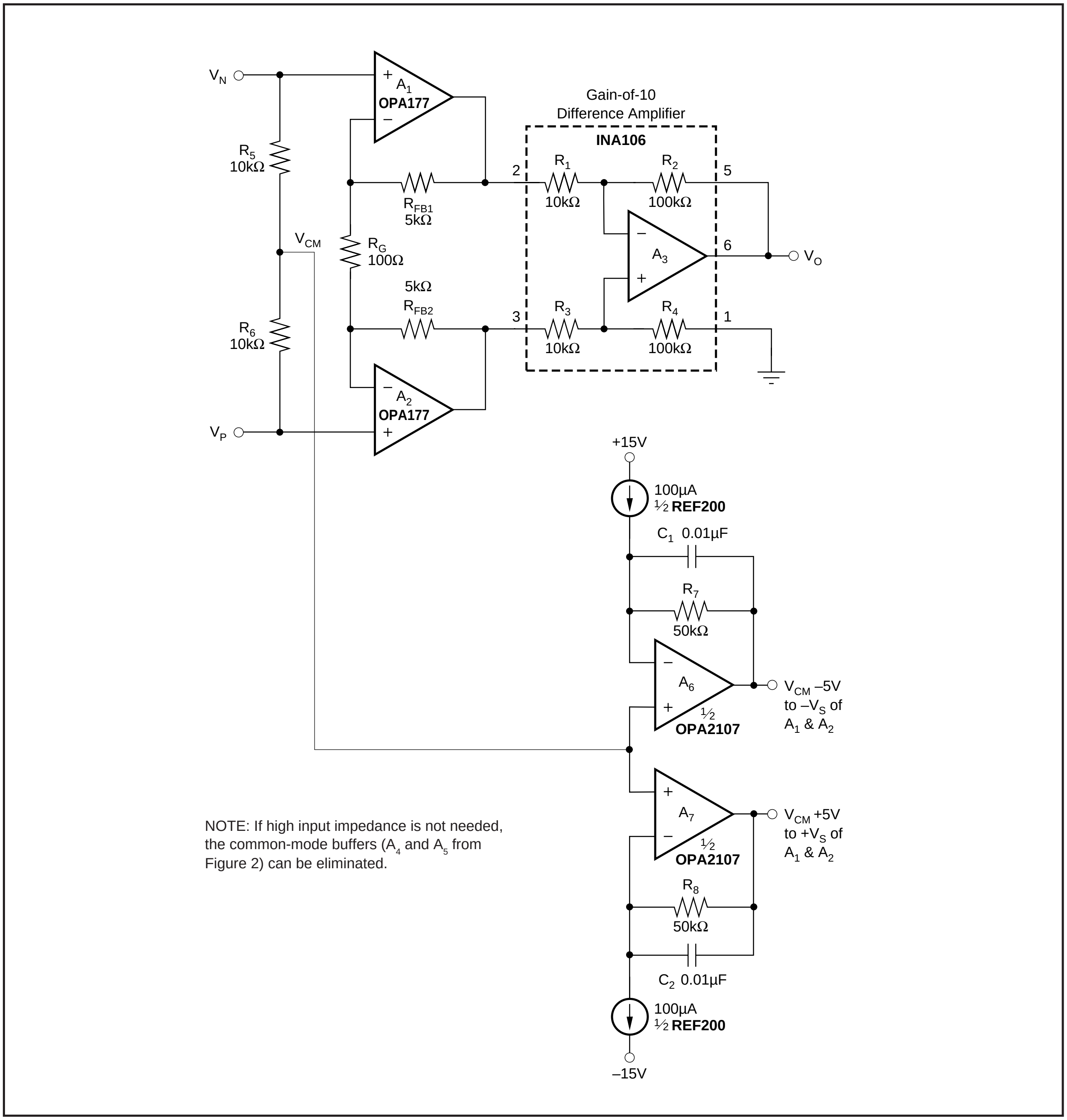


FIGURE 3. Simplified Boosted Instrumentation Amplifier.

The common-mode swing of a standard IA is limited by the output swing of the input amplifiers. The common mode range of the boosted IA is limited by the output swing of the subregulator amplifiers.

Standard IAs use unity gain difference amplifiers for practical reasons. Since standard IAs are designed for general applications, they must be adjustable to unity gain. Because it would be difficult for the user to maintain the resistor ratio matching necessary for good difference amplifier CMR, a fixed unity gain difference amplifier is provided. Gain adjustment is made with the input amplifiers, where matching is not critical for good CMR. Also, The more gain placed ahead of the difference amplifier, the better the IA CMR.

To compare the limits on input common-mode range, assume the op amps used can all swing to within 3V of their power supply rails (i.e. they can swing to ±12V when operating on ±15V power supplies).

In a standard IA, using a unity gain difference amplifier, the input amplifiers must provide a differential 10V output for a 10V IA output. With the input amplifiers in equal gains, each must deliver one half of the 10V differential signal.

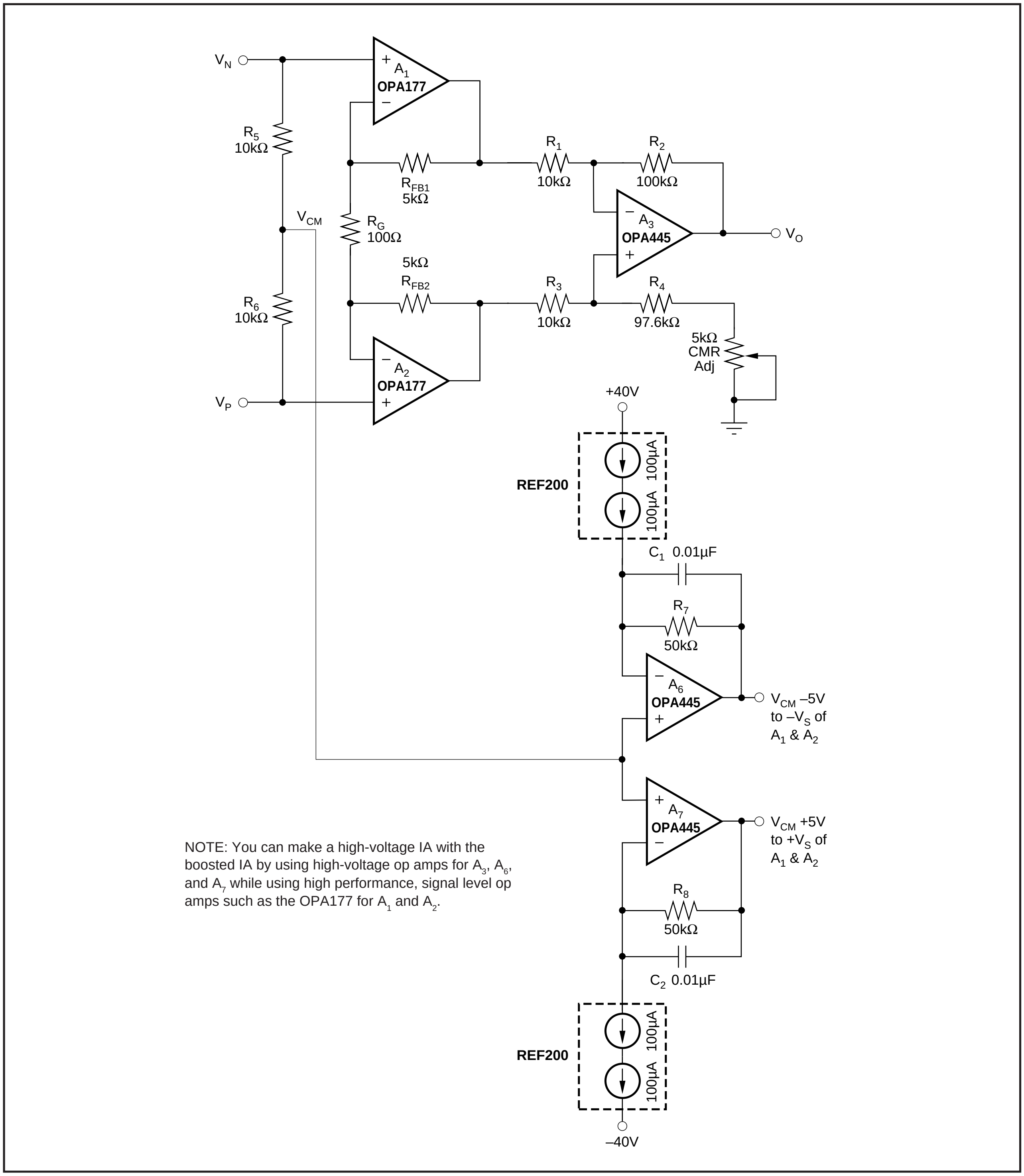
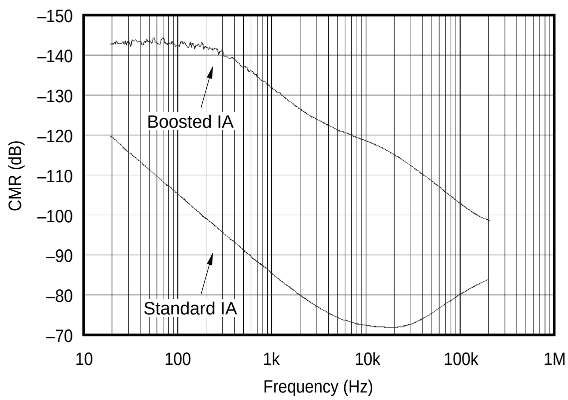


FIGURE 4. High Voltage Instrumentation Amplifier.

With a common-mode input of 7V one input amplifier must deliver 7V common-mode plus 5V differential—its 12V swing limit.

The boosted IA also has a ±7V common-mode input limit. The subregulators are set at ±5V from the input common-mode signal. With a 7V common mode input, one of the subregulator outputs is at its 12V swing limit.

In the boosted IA, using a gain-fo-10 difference amplifier, the buffer amplifiers must provide a differential output of only 1V for a 10V IA output. With the input amplifiers in equal gains, each must deliver one half of the 1V differential signal. With a common-mode input of 7V, one input amplifier must deliver 7V common-mode plus 0.5V differential for a total of 7.5V at its output which is no problem since the V_S is 12V (5V subregulated + 7V common-mode).



NOTE: Both the standard and boosted IA use OPA177s for input amplifiers. The overall gain of the IA is 1000V/V (input section gain = 100, difference gain = 10). The boosted IA gives more than 100/1 CMR improvement. Noise limits the DC CMR to slightly greater than 140dB referred to a +9dBm common-mode input signal.

FIGURE 5. CMR vs Frequency Comparison between Standard Three Op Amp IA and Boosted IA.

SUBREGULATION IMPROVES PRECISION

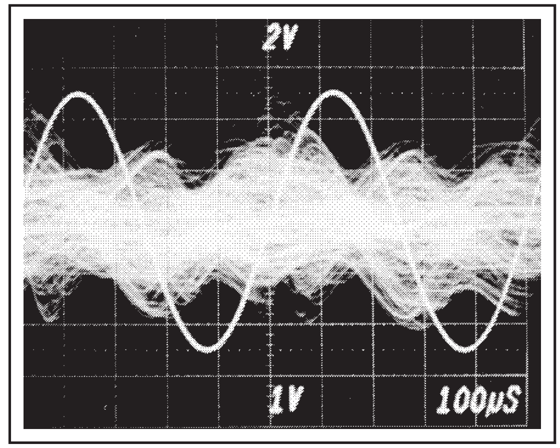
Lower power dissipation in the input op amps due to reduced power supplies can improve performance by reducing thermally induced low-frequency noise. In all semiconductor packages thermocouples are formed at various conductor interfaces. Matched-seal metal, side-braze ceramic, cerdip, and many plastic packages use Kovar leads. Significant thermocouples are formed between the lead plating and the Kovar. Thermocouples are also formed between the leads and the solder connections to the printed circuit.

If thermal gradients are properly matched (at the amplifier inputs) the thermocouple errors will cancel. In practice, mismatches occur. Even under laboratory conditions, the error produced can be several tenths of microvolts—well above the levels achievable with low-noise amplifiers. At the output of a high-gain amplifier, the error will appear as low frequency noise or short-term input offset error.

In signal op amp packages, much of the heat is conducted away through the leads. The resultant thermal gradient between the package and the printed circuit can be a major source of error. Air currents cool one lead more than another, resulting in mismatched thermal gradients. Operating the op amp on ±5V supplies (reduced from ±15V supplies) decreases quiescent power dissipation and associated temperature rise by three-to-one, providing a commensurate reduction in thermally induced errors.

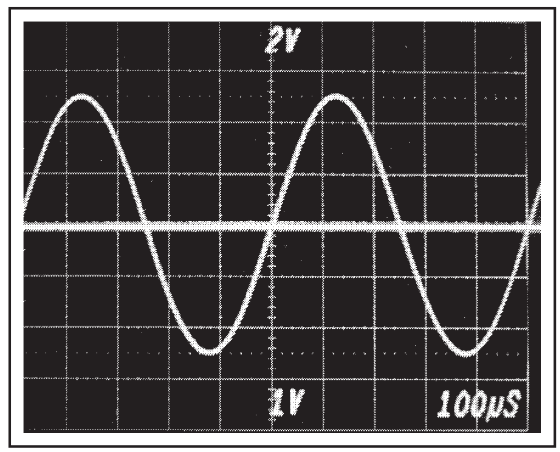
PERFORMANCE OF BOOSTED IA vs STANDARD IA

A performance comparison between the standard IA and the boosted IA in Figure 2 is shown in Figure 5. Amplifiers used for A_1 and A_2 are OPA177; A_3 is an INA106 gain-of-10 difference amplifier; and A_4 to A_7 are an OPA404 quad op amp in the boosted circuit. Overall gain of the IA is set at 1000V/V. The OPA177 is an improved version of the industry standard OP 07. It offers 10µV max V_{OS} and 0.1µV/°C max V_{OS}/dT. The OPA404 is used for speed and bias current. The FET inputs of the OPA404 do not add loading at the input of the IA. The speed is high as compared to the OPA177 giving a good improvement of CMR vs Frequency. The CMR plots were made using an HP4194A gain-phase analyzer with an input signal to the IA of +9dBm. As you can see, CMR vs Frequency is boosted dramatically. At 2kHz, for example, the CMR of the standard IA is ≈ 80dB while the CMR of the boosted IA is more than 120dB—more than a 100-to-1 improvement!



Input signal is ±2.5V, 2kHz. Output shows approximately 56dB CMR.

FIGURE 5B. Common-Mode Input and Output of Standard Gain = 1000V/V IA Using LTC1050 Chopper Stabilized Op Amp.



Input signal is ±2.5V, 2kHz. Output shows improvement over standard IA to approximately 82dB CMR.

FIGURE 5C. Common-Mode Input and Output of Boosted Gain = 1000V/V IA Using LTC1050 Chopper Stabilized Op Amp.

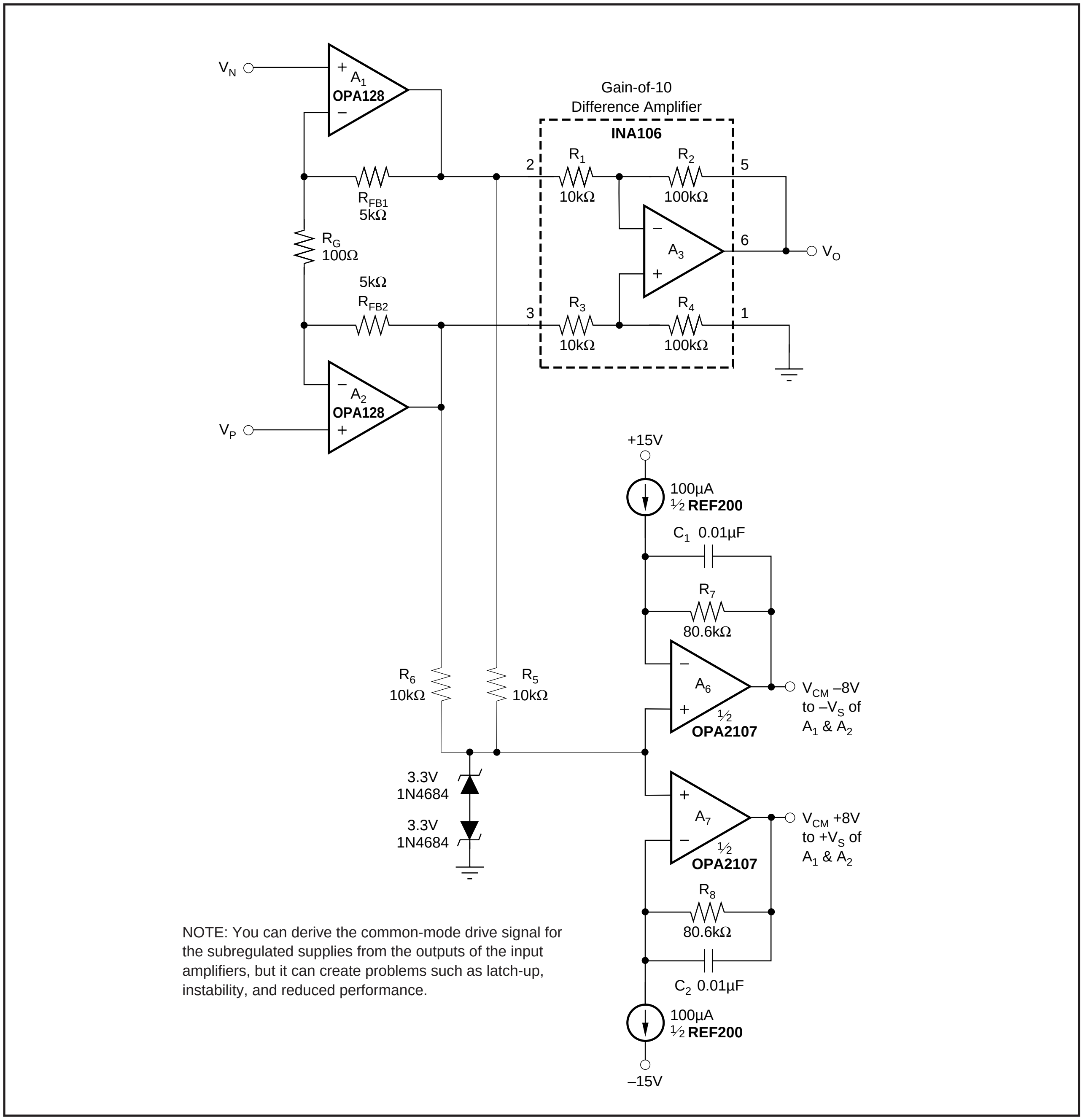


FIGURE 6. Boosted Electrometer Instrumentation Amplifier.

Another dramatic comparison is shown in the scope photos of the same IAs using LTC1050 chopper stabilized op amps for A_1 and A_2. When V_{OS}/dT is critical, chopper stabilized op amps may be the best choice—they offer 5µV max V_{OS} over temperature. As you can see, with a ±2.5V, 2kHz input signal, CMR is limited to ≈56dB by chopper noise. With the boosted circuit, CMR is a respectable ≈82dB.

The limit for CMR performance in the boosted IA is the difference amplifier. The more gain added ahead of the difference amplifier, the better the potential for improvement. For example, with a gain of 100V/V ahead of the difference amplifier an improvement in CMR of 40dB is possible. The actual performance boost will depend on matching and parasitics in the devices selected.

Of course, CMR vs Frequency depends on the dynamic performance of all amplifiers. Improvement in dynamic CMR will be most dramatic when the speed of the amplifiers used for A_4 to A_7 is much higher than the speed of A_1 and A_2.

HIGH-VOLTAGE IA

High voltage IAs can also be easily implemented using the boosted IA configuration. Standard precision signal level op amps can be used for the input amplifiers while the HV chores are taken care of by the other (less critical) op amps. The simple modifications to the Figure 3 circuit are shown in Figure 4. OPA445 op amps are used for A_6 and A_7 and for the difference amplifier, A_3. To boost the voltage rating of the current sources used in the subregulated supplies, two REF200 current source sections are placed in series. If 1% resistors are used for difference resistors R_1-R_4, a pot may be required to adjust CMR as shown. The resulting IA will provide outstanding performance on power supplies up to ±45V.

BOOSTED ELECTROMETER IA

Electrometer amps depend on the lowest possible input bias current. Connecting the input drive circuitry to the IA inputs as shown in Figure 2 may result in too much bias current. In this case you may want to take the common-mode drive signal from the outputs of the input stage as shown in Figure 6.

Taking the common-mode drive from the outputs of the input stage may seem like a good idea, but it creates problems—latch-up, instability, and reduced performance.

Driving the supplies of the input amplifiers from their outputs can cause latch-up. Many amplifiers exhibit input phase anomalies when their inputs are overloaded or overdirven relative to their power supplies. Unless precautions are taken when deriving the power supplies from the amplifier outputs, these anomalies will result in latch-up conditions. The back-to-back 3.3V zener diodes connected to the common-mode node (where R_5 and R_6 connect) prevents latch-up by keeping the common-mode drive point within 4V of ground. Also, the common-mode driven supplies are increased from 5V to 8V. In combination, this keeps 4V minimum on the power supplies of the input amps eliminating the latch-up condition when using the op amps shown.

The disadvantage of the clamp circuitry is reduced common-mode input range. The input common-mode range is limited to the clamp voltage of approximately 4V.

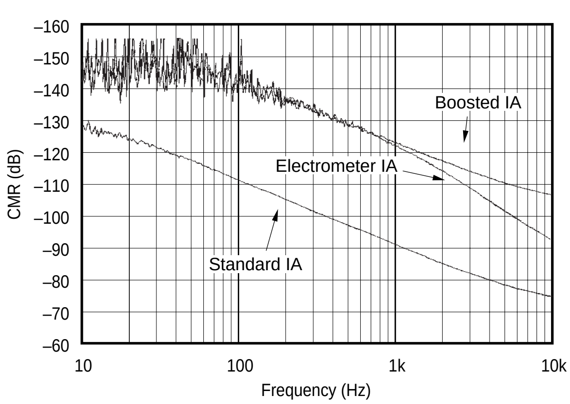
Driving the supplies of the input amplifiers from their outputs can also cause insatiably. Driving an op amp's power supply pins from the op amp output can cancel the op amp phase compensation and cause the op amp to oscillate. Driving the input op amps power supplies through the two-to-one R_5, R_6 divider does not completely cancel the compensation, but it does reduce amplifier phase margin significantly. Phase shift through A_6 and A_7 further reduces phase margin.

You might think that significantly reduced phase margin would be acceptable if the input amplifiers are used in high gain. But high gain in the differential input/output amplifier depends on virtual grounds at both ends of R_G. At the unity gain frequency of the op amp, where instability occurs, loop gain disappears and the op amps no longer approximate the ideal. At best, the op amps operate in a noise gain of two—the op amps must be stable in a gain of two. That's why you can get in trouble trying to use decompensated op amps in the front-end of an IA.

Using the faster OPA2107 for A_6 and A_7 along with the OPA128 electrometer op amp for A_1 and A_2 results in good stability. The improvement of CMR is shown in the CMR vs Frequency plot, Figure 7. The plot compares a standard IA (using the OPA128 and an INA106) to the Figure 2 and Figure 6 boosted IA circuits. The boosted circuits give a 30dB (better than 30/1) improvement in CMR up to about 1kHz. Beyond 1kHz, the CMR vs Frequency of the Figure 6 circuit begins to fall-off. At 10kHz, the Figure 6 circuit only offers about a six-to-one improvement.

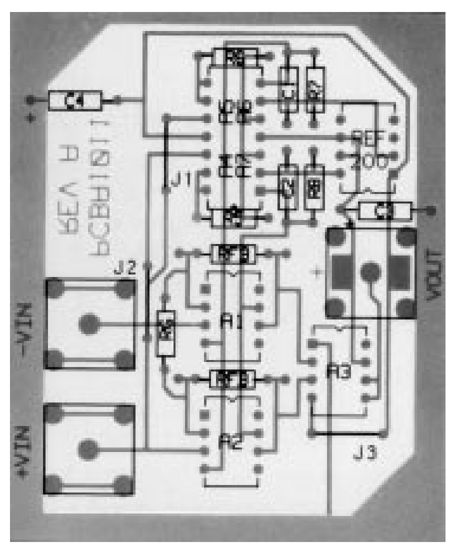
LAYOUT

To get the best performance from the boosted IA, use a good printed circuit layout. For best CMR, keep the signal-path circuitry symmetrical. A printed circuit layout of the complete boosted IA circuit, Figure 2, is shown in Figure 8. It produced the excellent results shown in this bulletin. Notice that good signal-path symmetry is achieved even though a single-sided layout is used.



NOTE: The boosted electrometer IA circuit adds CMR boost, but the boost starts to fall off beyond about 1kHz.

FIGURE 7. CMR vs Frequency Comparison between Standard Three Op Amp IA, Boosted IA, and Boosted Electrometer IA.



Best performance depends on signal-path symmetry. Notice that excellent symmetry can be maintained even with single-sided board layout. Extra pads at RFB allow *stacking* of feedback capacitors.

FIGURE 8. Printed Circuit Layout of Figure 2 Boosted IA.