Beyond Op-Amps

How to use special-purpose op-amps in practical and exotic circuits.

By Joseph J. Carr

The operational amplifier revolutionized analog computer design in what seems eons ago, but early models were not well-suited to general use in analog circuits owing to its bulk and high power drain. In the mid-sixties, when the μA-709 integrated-circuit operational amplifier was developed, it became possible to use this wonderful invention for a wide range of applications.

Figure 1 shows the four basic forms of op-amp circuit: inverting follower (Fig. 1A), noninverting follower with gain (Fig. 1B), unity gain noninverting follower (Fig. 1C), and dc differential amplifier (Fig. 1D).

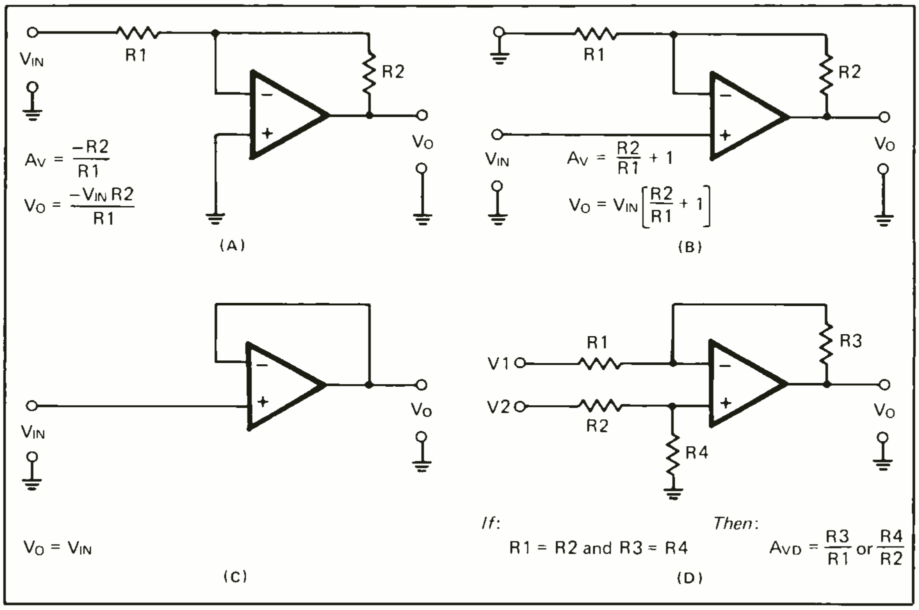


Fig. 1. Four basic op-amp circuits: (A) inverting follower, (B) noninverting follower, (C) unity-gain noninverting follower, and (D) differential amplifier.

The inverting follower circuit shown in Figure 1A produces an output signal that is 180 degrees out of phase with the input signal—which is where it gets its name, "inverting" follower. The gain of the inverting follower is simple: $-R2/R1$, where the minus sign indicates the inversion. Thus, when a circuit like that in Fig. 1A has an input resistor ($R1$) of 10 kohms, and a feedback resistor ($R2$) of 100 kohms, the gain is (−100 k)/10 k, or −10. The input impedance of this circuit is equal to $R1$.

The noninverting follower with gain (Fig. 1B) provides no phase reversal between input and output. The input impedance of this circuit is very high, and is not related to the value of any resistors in the circuit. The gain of the circuit is $[(R2/R1)+1]$, so in the example above, the gain where $R1 = 10$ kohm and $R2 = 100$ kohm will be 101.

The unity gain noninverting follower (Fig. 1C) is a special case of Fig. 1B in which the feedback resistor is zero ohms: the output is connected directly to the inverting input. This circuit provides a voltage gain of one ("unity gain"). There are two main purposes for the unity gain noninverting follower: buffering and impedance transformation. "Buffering" means that the circuit provides isolation between input and output. Thus, variations in load will not affect the input circuit, an ideal situation where oscillators and other such sensitive circuits must drive unstable loads. Impedance transformation is high-to-low: a high input impedance reduces to a low output impedance. Since the voltage remains the same, and the impedance drops at the output, we can see that the unity gain noninverting amplifer provides a power gain greater than unity while providing a voltage gain of one.

Finally, we have the dc differential amplifier (Fig. 1D). This type of amplifier is used to provide a single-ended (that is, unbalanced) output from a differential (that is, balanced) input signal source. Output voltage V_o is proportional to the differential voltage (A_{vd}) and the difference between input voltages V1 and V2 (V1 − V2):

$$V_o = A_{vd} \times (V1 - V2).$$

The gain is calculated in much the same mananer as for the inverting amplifier, and is equal to either $R3/R1$ or $R4/R2$, provided that $R1 = R2$ and $R3 = R4$ (these equalities are important).

The foregoing circuits are based on single op-amps. When we use two or more op-amps, however, even more complex circuits are possible. In the remainder of this article we will deal with IC versions of the Instrumenta-

"The op-amp truly revolutionized analog circuit design."

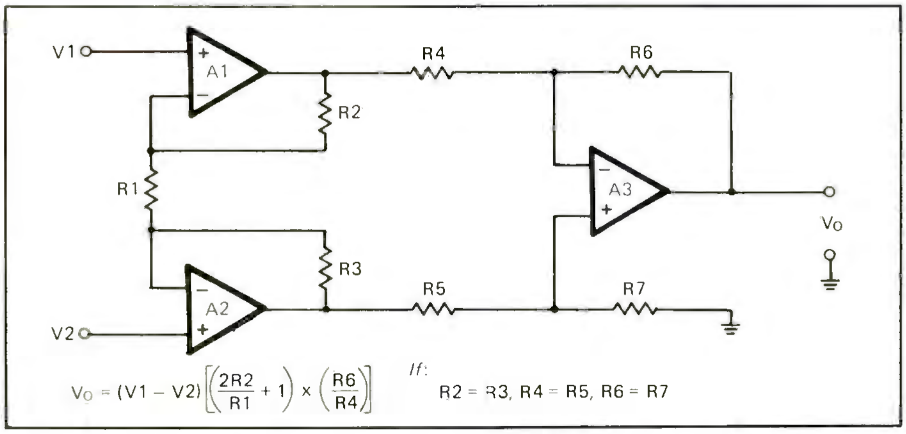


Fig. 2. The instrumentation amplifier provides an extremely high input impedance, high possible gain, and easy design. The gain equation is shown at bottom.

tion Amplifier (IA) circuit shown in Fig. 2. The IA provides an extremely high input impedance (similar to the noninverting follower circuits), a high possible gain, and easy design. The gain equation for this circuit is shown in Fig. 2.

The IA circuit shown in Fig. 2 consists of two sections: A1 – A2 and A3. Amplifier A3 forms a simple dc differential amplifier such as shown in Fig. 2, and obeys the same rules. The A1 – A2 amplifier is a differential-noninverting-input-with-differential-output stage. By cascading these two forms of amplifier we obtain the instrumentation amplifier.

In many cases, where variable or adjustable gain is required, we leave all resistors constant except *R1*. We must be careful, however, because *R1* appears in the denominator of the equation in Fig. 2. This location means that the gain can be very, very large when the resistance of *R1* drops close to zero. In some cases, the designer will place a small-value fixed resistor in series with a variable resistor (potentiometer) to adjust gain, but limit it to a maximum.

IC Operational Amplifiers

The operational amplifier truely revolutionized analog circuit design. For a long time, the only additional advances were that op-amps became better and better (they became nearer the ideal op-amp of textbooks). While that was an exciting development, it was not a really new device. The big breakthrough came when the analog device designers made an integrated-circuit version of Fig. 2, the integrated-circuit instrumentation amplifier (ICIA).

Figure 3 illustrates one popular ICIA, Precision Monolithics, Inc.'s AMP-01 device. The AMP-01 is housed in an 18-pin dual-inline-pin (DIP) package (Fig. 3A).

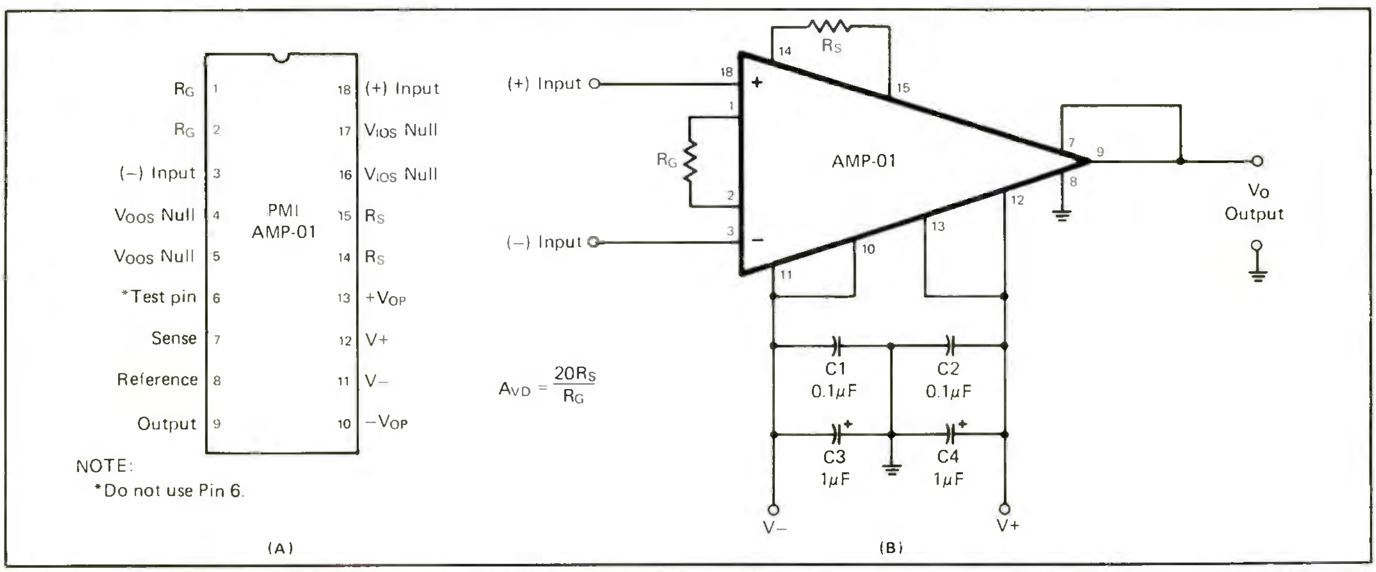
The basic circuit for the AMP-01 is shown in Fig. 3B. Notice how simple the circuit is! There are few connections: differential inputs, dc power supply (V – and V +), output, ground and two gain-setting resistors. The voltage gain of this circuit is given by:

$$V_{vd} = 20\ R_s/R_g.$$

Suppose we want to make a differential voltage amplifier with a gain of ×1000. We need to make a resistor ratio of 1000/20, or 50:1. Thus, if R_s is set to 100 kohms, and R_g is 2 kohms, we will have the required gain of 1000. The permissable gain range is 0.1 to 10,000.

The dc power supply voltages are up to ± 18-volts dc. Notice in Fig. 3B

Fig. 3. Pin designations and basic circuit of Precision Monolithic's IC instrumentation amplifier.



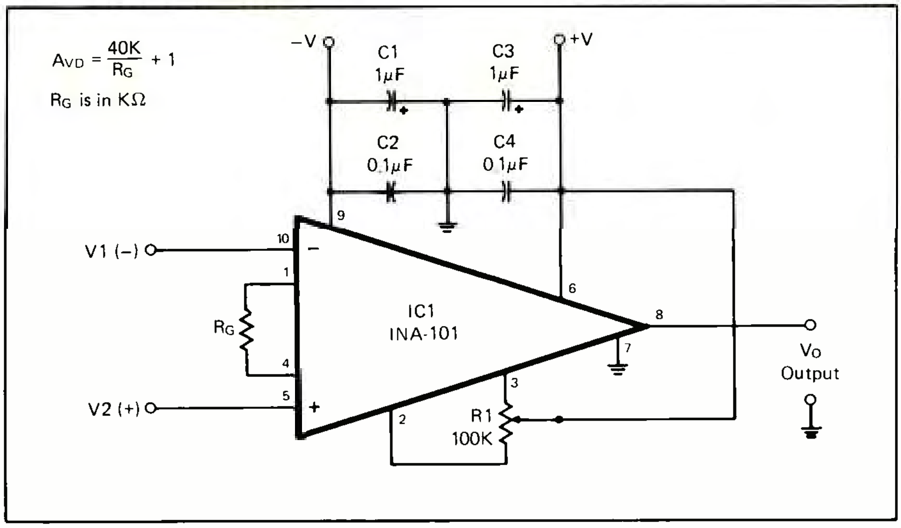


Fig. 4. Simplified Burr-Brown INA-101 ICIA circuit and its gain equation.

that the dc power supply lines are heavily bypassed. The 0.1-μF units are used to bypass high frequencies, while the 1-μF units are for low frequencies. The 0.1-μF units must be mounted as close as possible to the body of the amplifier.

The maximum operating frequency depends upon the gain. At a gain of 1, the maximum small-signal input frequency is 570 kHz, while at a gain of 1000 it reduces to 26 kHz.

The Burr-Brown INA-101 is another new ICIA device. This amplifier is similarly simple to connect. There are only dc power connections, differential input connections, offset adjust connections, ground and an output. Gain of the circuit is set by:

$$A_{vd} = (4\ k/R_g) + 1$$

The INA-101 is basically a low-noise, low-input bias current integrated circuit version of the IA of Fig. 2. The resistors labeled *R2* and *R3* in Fig. 2 are 20 kohms, hence the "40k" term in Fig. 4.

Potentiometer *R1* in Fig. 4 is used to null the offset voltages appearing at the output. An offset voltage is a voltage that exists on the output at a time when it should be zero (that is, when V1 = V2, so that V1 − V2 = 0). The offset voltage might be internal to the amplifier or a component of the input signal. Dc offsets in signals are common, especially in biopotential amplifiers such as ECG and EEG used to measure electrical impulses from the heart and brain.

Still another ICIA is National Semiconductors' LM-363 device shown in Fig. 5; the miniDIP version is shown in Fig. 5A (an 8-pin metal can is also available), while a typical circuit is illustrated in Fig. 5B. The LM-363 device is a fixed-gain ICIA. There are three versions:

Designation	Gain
LM-363-10	10
LM-363-100	100
LM-363-500	500

The LM-363-xx is useful in places where one of the standard gains is required and there is minimal space available. Two examples spring to mind. We could use the LM-363-x as a transducer preamplifier, especially in noisy signal areas; the LM-363-x can be built onto (or into) the transducer to build up its signal before sending it to the main instrument or signal acquisition computer. The other example is in bioamplifiers. The biopotentials are typically very small, especially in lab animals. The LM-363-x can be mounted on the subject and a higher-level signal sent to the main instrument; a little exotic, but nonetheless useful.

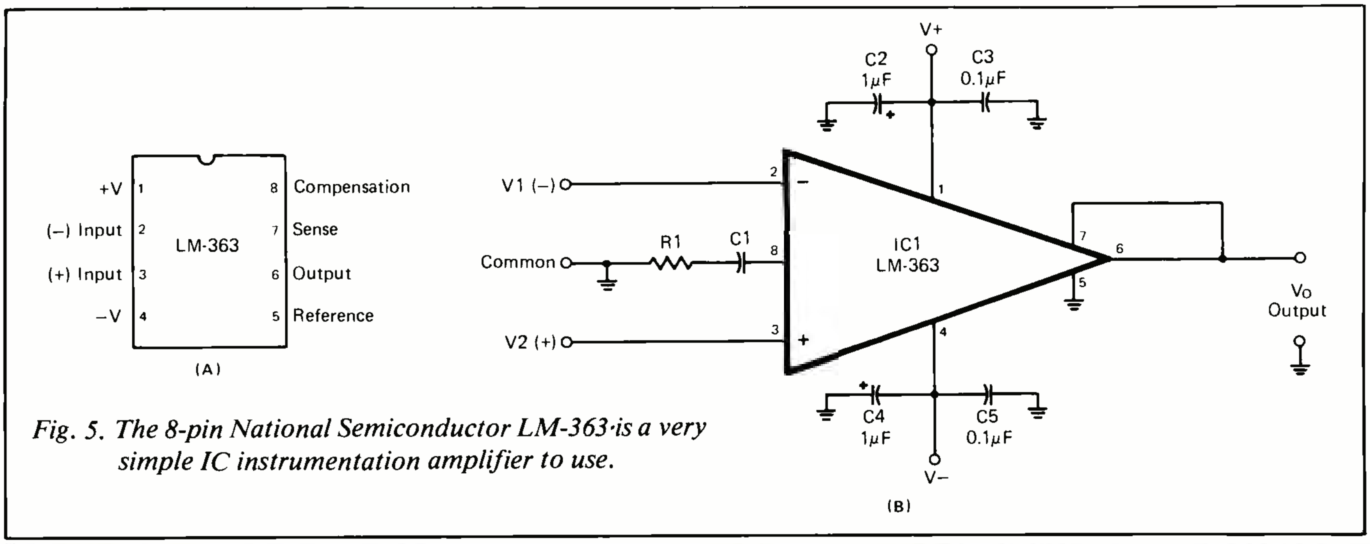


Fig. 5. The 8-pin National Semiconductor LM-363 is a very simple IC instrumentation amplifier to use.

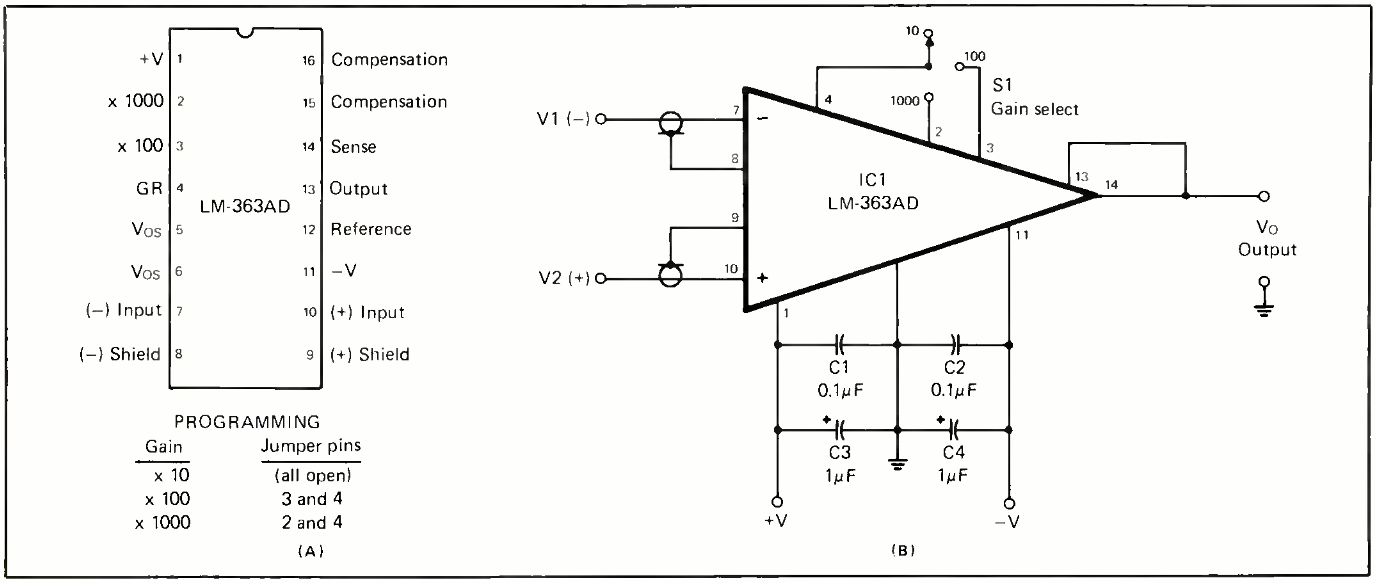


Fig. 6. The LM-363AD is a selectable-gain version of the National Semiconductor LM-363 ICIA.

A selectable-gain version of the LM-363 device is shown in Fig. 6; the 16-pin DIP package is shown in Fig. 6A, while a typical circuit is shown in Fig. 6B. The type number of this device is LM-363-AD, which distinguishes it from the LM-363-x devices. The gain can be ×10, ×100 or ×1000, depending upon the programming of the gain-setting pins (2, 3 and 4). The programming protocol is as follows:

Gain Desired	Jumper Pins
×10	(All Open)
×100	3 & 4
×1000	2 & 4

Switch *S1* in Fig. 6B is the GAIN SELECT switch. This switch should be mounted close to the IC device, but is quite flexible in mechanical form. The switch could also be made from a combination of CMOS electronic switches (for example, 4066).

The dc power supply terminals are treated in a manner similar to the other amplifiers. Again, the 0.1-μF capacitors need to be mounted as close as possible to the body of the LM-363-AD integrated circuit.

Pins 8 and 9 are guard shield outputs. These pins are a feature that makes the LM-363-AD more useful for many instrumentation problems than other models. By outputting a signal sample back to the shield of the input lines, we can increase the common-mode rejection ratio. This feature is used a lot in bipotential amplifiers and in other applications where a low-level signal must pass through a strong interference (high-noise) environment.

The LM-363 devices will operate with dc supply voltages of ± 5 volts to ± 18 volts dc, with a common-mode rejection ratio (CMRR) of 130 dB. The 7 nV/[SQR(Hz)] noise figure makes the device useful for low-noise applications (a 0.5 nV model is available at premium cost).

Isolation Amplifiers

There are many applications for instrumentation amplifiers that present a danger to the user. In biomedical applications, for example, the issue is patient safety. There are numerous signal acquisition needs in biomedical instrumentation where the patient is at risk. Even the simple ECG machine, which measures and records the heart's electrical activity, was once implicated in patient safety problems. Another problem area in biomedical applications is catherization instruments. There are several tests where physicians insert an electrode or transducer into the body, and then measure the resulting signal: the intracardiac ECG places an electrode inside the heart by way of a blood vein; the cardiac output computer uses a signal from a thermistor inside a catheter placed in the heart (also through a vein), and simple electronic blood pressure monitors use a transducer that connects to an artery. In all of these cases we do not want the patient exposed to small differences of potential due to current leakage from the 60-Hz ac power lines. The solution is use of an isolation amplifier.

Another application is signal acquisition in high voltage circuits. We do not want to mix high-voltage sources with low-voltage electronics because we don't want the low-voltage circuits to blow out. Again, the solution is the isolation amplifier.

Figure 7 shows the basic symbol for the isolation amplifier. The break in the triangle used to represent any amplifier denotes that there is an extremely high impedance (typically 10^{12} ohms) between the inputs and output of the isolation amplifier.

Notice that there are two sets of dc power supply terminals. The V − and V + terminals are the same as found on all ICIA or op-amp devices. These

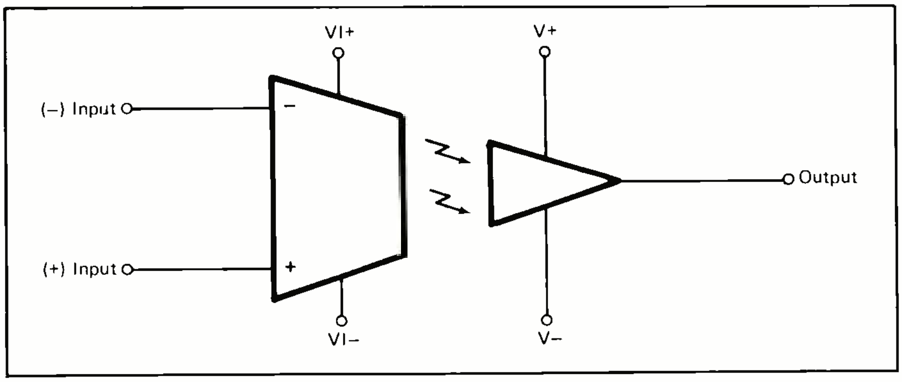


Fig. 7. Shown here is the basic symbol for the isolation operational amplifier.

dc power supply terminals are connected to the regular dc supply of the equipment where the device is used. Such a power supply derives its dc potentials from the ac power source by way of a 60-Hz transformer. The isolated dc power supply inputs (VI – and VI +) are used to power the input amplifier stages, and must be isolated form the main dc power supply of the equipment. The VI – and VI + terminals are usually either battery powered or powered from a dc-to-dc converter that produces a dc output from the main power supply by using a high frequency (50- to 500-kHz) oscillator. The high-frequency "power supply" transformer does not pass 60-Hz signals well, so the isolation is maintained.

Figure 8 pictures the circuit of an isolation amplifier based on the Burr-Brown 3652 device. This isolation amplifier is not generally available to hobbyists, but would be used even in small "one-of-a-kind" professional labs.

The dc power for both the isolated and nonisolated sections of the 3652 is provided by the 722 dual dc-to-dc converter. This device produces two independent ± 15 V dc supplies that are each isolated from the 60-Hz ac power source and from each other. The 722 device is powered from a + 12-V dc source that is derived from the ac power source. In some cases, the nonisolated section (which is connected to the output terminal) is powered from a bipolar dc power supply that is derived from the 60-Hz ac source, such as a ± 12 VDC or ± 15 V dc supply. In no instance, however, should the isolated dc power supplies be derived from the ac power source.

There are two separate ground systems in this circuit, symbolized by the small triangle and the regular three-bar "chassis" ground symbol. The isolated ground is not connected to either the dc power supply ground/common, or the chassis ground. It is kept floating at all times, and becomes the signal common for the input signal source.

Circuit gain is approximately:

$$\text{GAIN} = \frac{1{,}000{,}000}{R1 + R2 + 115}$$

In most design cases, the issue is the unknown values of the gain setting resistors. We can rearrange the equation above to solve for $(R1 + R2)$:

$$(R1 + R2) = \frac{1{,}000{,}000 - (115 \times \text{GAIN})}{\text{GAIN}}$$

Where: $R1$ and $R2$ are in ohms and GAIN is the voltage gain desired

Let's work an example. Suppose we need a differential voltage gain of

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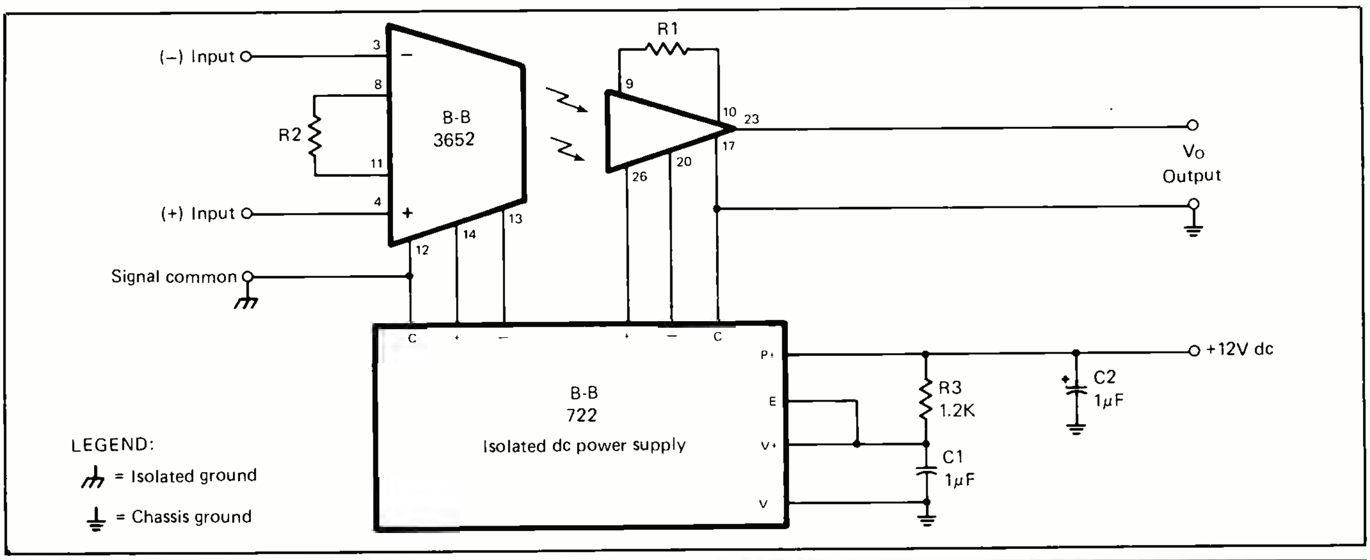
Fig. 8. This is the circuit of an isolation amplifier based on the Burr-Brown 3652 device.



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1,000. What combination of *R1* and *R2* will provide that gain figure?

If GAIN = 1000

$$(R1 + R2) = \frac{1{,}000{,}000 - (115 \times 1000)}{1000}$$

$$(R1 + R2) = \frac{1{,}000{,}000 - (115{,}000)}{1000}$$

$$(R1 + R2) = \frac{885{,}000}{1000}$$

$$(R1 + R2) = 885 \text{ ohms}$$

In this case, we need some combination of *R1* and *R2* that adds to 885 ohms. The value 440 ohms is "standard," and will result in only a tiny gain error if used.

Conclusion

The IC instrumentation amplifier and the isolation amplifier open new applications that the simple op-amp cannot match. Digital electronics fans should be aware that linear circuits are not dead. They live in more sophisticated manifestations than ever before. **ME**

452.95, and 452.975 MHz.

These frequencies contain communications of train dispatchers, yardmasters, and conversations between train crew members. There's something very gutsy and rugged about the people who work on the railroads; they offer a unique brand of chatter which sounds different than anything else you're liable to hear on a scanner. These frequencies are active in most areas of the nation. In urban areas you'll find the activities of the railway police to be pretty grisly as they wage a constant battle against the vandals and vagrants who frequent track, yard and station areas.

You are invited to explore the many exciting areas you can access via a scanner. Actually, there are many more than are described here. A scanner puts you on the inside of what's going on, and gives you a glimpse of events you'd otherwise never have known about. The nicest part about it is that you can add these potentials to your scanner without giving up the ability to monitor the neighborhood police or fire departments you like to hear.