

# So many amplifiers to choose from: Matching amplifiers to applications

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## Introduction

Amplifier selection is confusing because there are many different amplifier types to choose from and many of the amplifiers seem to do identical jobs. Various amplifier types include op amps, instrumentation amps, audio amps, differential amps, current feedback amps, high-frequency amps, buffers, and several kinds of power amps. Selecting amplifiers by name is complicated because an amplifier name often stems from the initial rather than present application. “Op amp” is an abbreviation for operational amplifier, an application where the op amp performed mathematical functions in an analog computer.

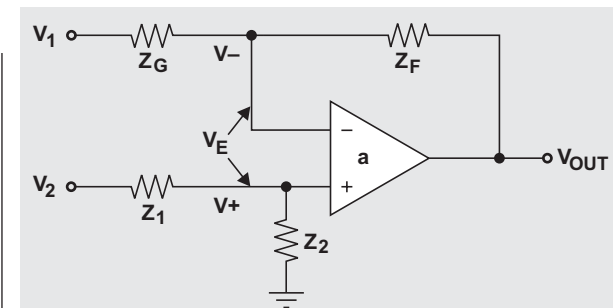
One sure thing about a semiconductor amplifier (the only kind discussed here) is that it involves either internal or external feedback. The basic building blocks of amplifiers are transistors, and the characteristics of transistors are that their base-emitter voltage and current gain vary with manufacturing tolerances, temperature, stress, and time. Without feedback, the amplifier gain becomes uncontrollable, often varying by a factor of 10 or more.

The best method to control gain variations is with feedback, but there is no free lunch because along with feedback comes the possibility of overshoot, ringing, and eventual oscillation.<sup>1</sup> Internal feedback, or internal compensation (a more popular name), compensates for the amplifier's tendency to overshoot, ring, or oscillate. Internal compensation is transparent to the user, and the amplifier is stable in the recommended application and conditions; but any amplifier with gains greater than one can oscillate under certain conditions. You must supply external compensation components for amplifiers requiring external feedback (externally compensated amplifiers) or they will oscillate or saturate. Always investigate the compensation situation when selecting an amplifier, because it is exasperating to complete a design only to discover that you have built an oscillator rather than an amplifier.

## Operational amplifiers (op amps)

Op amps are versatile and within their limitations can replace any other amplifier. The key to good design is to find the op amp limits and then know where to go when you reach these limits. Often the limits are not the op amp; rather the external components impose the limits. Figure 1 shows a generalized schematic for the op amp circuit. Table 1 shows some of the many options available for the circuit performance as a function of the external components. Notice that replacing impedances with capacitors yields functions that are frequency-dependent, and that the placement of the input signal changes the transfer function. There are many specialty amplifiers that replace op amps because general-purpose op amps have limitations, but the separating line has become so gray that in many cases the designer has a choice between an op amp or a specialty amp because both will do the job. This discussion moves on to the types of specialty amps, but it always refers back to the op amp because some deficiency in the op amp has resulted in a specialty amp being designed for a specific purpose.

**Figure 1. This op amp configuration produces many different circuits**



**Table 1. Changing component values yields many op amp circuits**

CIRCUIT TYPE	V <sub>1</sub>	V <sub>2</sub>	Z <sub>G</sub>	Z <sub>F</sub>	Z <sub>1</sub>	Z <sub>2</sub>
Inverting amp	Input signal	Ground	Determined by gain	Determined by gain	Open	Z <sub>G</sub>    Z <sub>F</sub>
Noninverting amp	Ground	Input signal	Determined by gain	Determined by gain	Z <sub>G</sub>    Z <sub>F</sub>	Open
Inverting integrator	Input signal	Ground	R <sub>G</sub>	C <sub>G</sub>	Open	Z <sub>G</sub>    Z <sub>F</sub>
Buffer	Ground	Input signal	Open	Short	Short	Open
Subtractor	Input signal –	Input signal +	R <sub>G</sub>	R <sub>F</sub>	R <sub>G</sub>	R <sub>F</sub>

## Buffer amplifiers

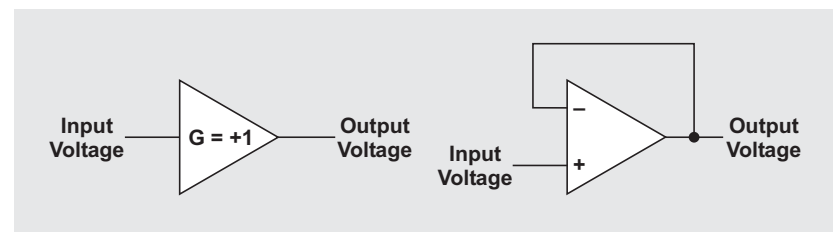
This discussion is limited to voltage buffer amps (see Figure 2) because we enclose current buffer amps inside feedback loops. Voltage buffers have a gain of one, exceptionally high input impedance, and very low output impedance. In an op amp, the input voltage sees an impedance load composed of the input components and the op amp input impedance. In the buffer circuit, the impedance load is due solely to the op amp. This is the first limitation of the op amp; the external components always load the input signal, and this situation is detrimental to good performance when the signal source has significant resistance. The key to solving the input impedance problem is to use buffer amplifiers or possibly instrumentation amplifiers.

Op amps exhibit output impedance characteristics like all other amplifiers, but the op amp output impedance is a complex function because feedback modifies the output impedance. The first component of output impedance is the resistance of the output stage. The output stage is usually an emitter-follower type configuration that has low inherent output impedance, usually  $r_{ib} + R_B/\beta$  on the order of 25  $\Omega$ . The emitter-follower output impedance increases as frequency increases, causing moving poles (poles are points where the frequency response changes sharply) and errors at high frequencies. Worse yet, the output stage of a rail-to-rail op amp is common-collector; and the total impedance depends on the load and can be quite large, often in the kilohm range. The saving grace is the circuit loop gain that divides into the output stage impedance, lowering the overall output impedance dramatically.

The final result is that at low frequencies op amps generally have very low output impedances (fractional ohm values) at dc or low frequencies. Their output impedance rises as frequency increases because the op amp gain decreases as frequency increases. High output impedance causes two problems: dc errors caused by load currents, and stability problems caused by output capacitors creating poles. The best solution for high load currents is to buy an op amp designed to drive the output load in question. A few years ago, a buffer was required to drive several hundred milliamps into a back-terminated cable, but now there are op amps specifically designed to drive these cables without incurring any errors. The buffer always has an advantage over the op amp when it comes to low output impedance because its loop gain is always maximum and the output stage is designed for low impedance.

Some op amps become unstable when they drive capacitive loads, and some op amps drive any capacitive load with no problem. Those op amps designed to drive large capacitive loads have very low resistance output stages, but they sacrifice some speed because of the large structures the output transistors require. In summary, output impedance may cause you to migrate to a buffer, select a very application-specific op amp, or select a power amp.

**Figure 2. Either of these symbols represents a buffer**



## Subtractor or difference amplifiers

Building an op amp circuit requires external resistors and capacitors. We see from Table 1 that when all the external impedances are resistive and equal, the circuit is a subtractor. Equation 1 is the general subtractor equation.

$$V_{OUT} = V_2 \frac{R_2}{R_1 + R_2} \left( \frac{R_F + R_G}{R_G} \right) - V_1 \frac{R_F}{R_G} \quad (1)$$

When  $R_2 = R_F$  and  $R_1 = R_G$ , Equation 1 reduces to Equation 2.

$$V_{OUT} = (V_2 - V_1) \frac{R_F}{R_G} \quad (2)$$

If the designer is after common-mode voltage rejection—i.e., where  $V_2 = V_{2Signal} + V_{CM}$  and  $V_1 = V_{1Signal} + V_{CM}$ —the conditions to get to Equation 2 demand excellent matching between the resistors. The designer implements Equation 2 with op amps and discrete resistors or with an integrated circuit (IC). The op amp approach is more general because there are ICs with multiple op amps in the package, op amps are inexpensive, and the discrete resistor values are easy to change for gain changes. The down side of the op amp discrete resistor approach is that the resistors don't match well. A designer using 1% tolerance resistors hopes for a 40-dB common-mode rejection, but the discrete circuit yields a worst-case common-mode rejection of 24.17 dB.<sup>2</sup>

Integrated circuit subtractors obtain common-mode rejection ratios greater than 100 dB. The IC subtractors tune the front-end transistors to enable optimal matched performance. Then they use film resistors deposited on the IC substrate to match the resistors. Although thin-film matched resistors are accurate, they still need some help to achieve 100-dB+ performance, so the thin-film resistors are laser trimmed to the final accuracy.

Subtractors have resistors; thus they don't present the highest possible impedance to the load. Many measurements like strain-gage bridge measurements need high common-mode rejection to eliminate common-mode noise, but bridge circuits have appreciable output resistance that interacts with the subtractor input resistance. These applications need a high-input-impedance circuit that eliminates common-mode noise.

## Instrumentation amplifiers (IAs)

An instrumentation amplifier has high input impedance coupled with high common-mode rejection, so it is the circuit of choice for many instrumentation and industrial applications (see Figure 3).

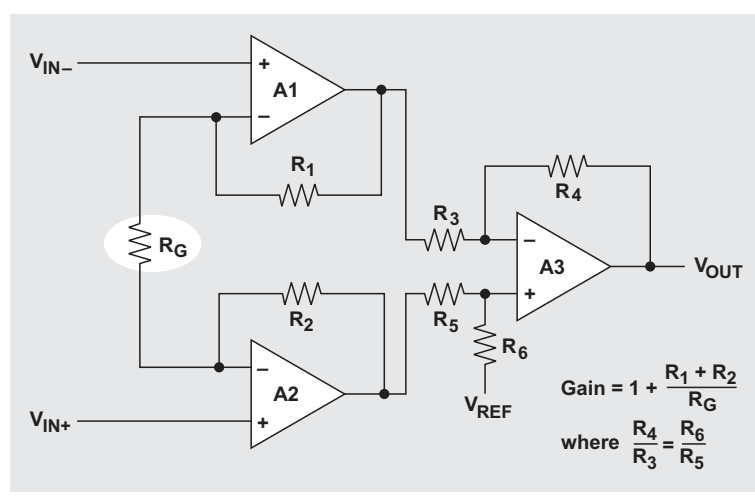
Notice that each circuit input of the three-op-amp instrumentation amp is the noninverting input to an op amp; this configuration yields the highest input impedance without resorting to fancy feedback tricks. The subtractor is comprised of  $R_3$  through  $R_6$  and A3. The subtractor still provides the excellent common-mode rejection capability, but A1 and A2 buffer the subtractor, keeping the input impedance high. This circuit can amplify the bridge signal voltage and strip off the common-mode voltage with very little error. Another advantage of the instrumentation amplifier is that a single, nonmatched resistor determines the gain, so the resistor matching problem goes away. The down side of the instrumentation amplifier is increased cost, extra signal delay, and a reduced common-mode voltage range.

The two-op-amp instrumentation amplifier also contains a subtractor to obtain high common-mode rejection capability (see Figure 4). It also has two noninverting op amp inputs acting as the circuit inputs, thus it has the high input impedance of the three-op-amp instrumentation amplifier. This instrumentation amplifier has the added advantage of having a wider common-mode voltage range because it only has two op amps stacked instead of three. The disadvantage of the two-op-amp instrumentation amplifier is unequal stage delays for the input signals. The inverting input has two stage delays while the noninverting input has one stage delay. Unequal stage delays introduce distortion at any frequency above dc, and the distortion increases as the input signal frequency increases. The distortion is present but minimal at frequencies within the IA's operating range.

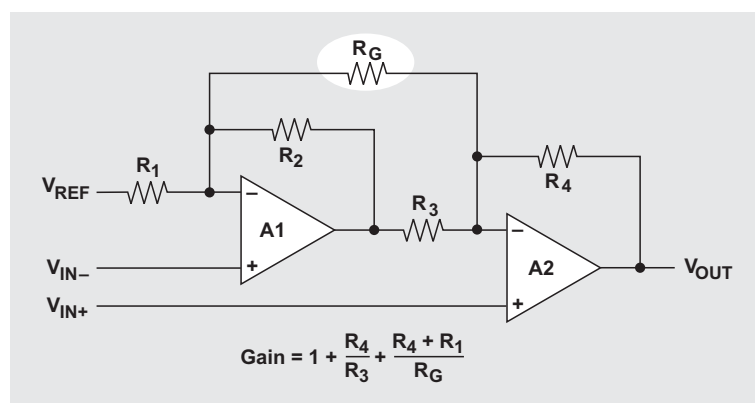
## Current feedback amplifiers (CFAs)

Current feedback amplifiers exist because they have high bandwidth. All of the previous amplifiers discussed were voltage feedback amplifiers (VFAs). VFAs have an open-loop gain that starts decreasing at very low frequencies (often at 10 Hz) with a rate of decrease of  $-20$  dB/decade of frequency. This gain decrease causes poor accuracy at high frequencies. Referring to Figure 5, it is obvious that the voltage feedback amplifier loses gain at high frequencies while the current feedback amplifier retains its high gain on into very high frequencies. VFAs must

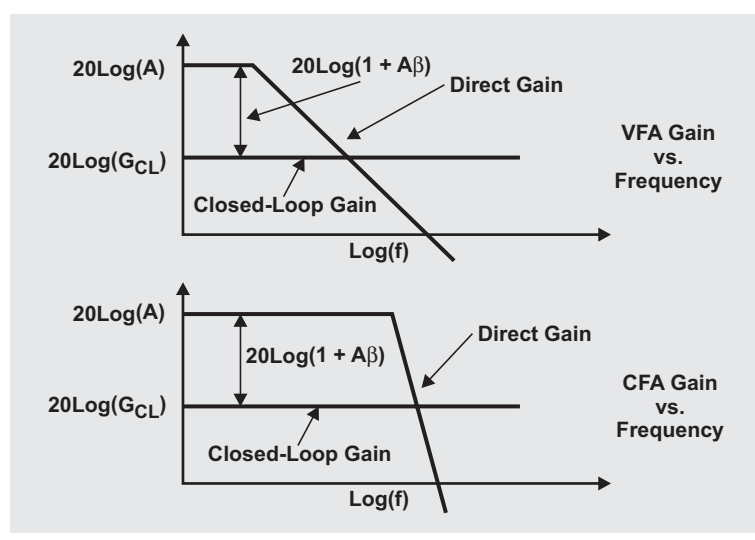
**Figure 3. This instrumentation amplifier uses three op amps**



**Figure 4. This instrumentation amplifier does the job with fewer parts**



**Figure 5. Frequency responses of VFAs and CFAs**

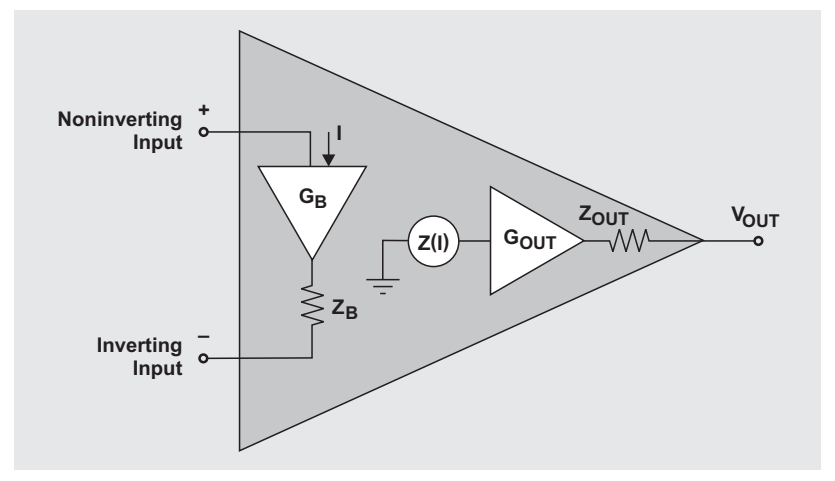


operate in the frequency spectrum where the gain is decreasing because their open-loop gain begins to fall off so quickly. CFAs don't work under this constraint, so they offer better distortion performance. The rate of gain decrease is equal for both amplifiers; it looks worse for a CFA because the frequency scale is compacted.

The model in Figure 6 shows that the CFA uses transimpedance rather than gain. The input current is mirrored to the output stage and buffered by the output buffer. This configuration offers the highest bandwidth circuit possible with a given process. CFAs are usually limited to bipolar transistors because the applications they serve, communications and video, don't require high input impedance or rail-to-rail output voltage swing. Notice that the inverting input lead looks into the output of a buffer; so it has low input impedance, usually the output impedance of an emitter-follower stage.

The noninverting lead looks into a buffer input, so it is a high-impedance input. The inputs of a voltage feedback amplifier look into the base-emitter junctions of a long-tailed pair (differential amplifier fed by a current source). Accurately matching the long-tailed pair minimizes the input offset voltages and currents, and this is where the voltage feedback amplifier derives its accuracy. It is impossible to match the input and output stages of a buffer, so the CFA is not a high-precision circuit. We design the CFA for speed, and while the VFA usually tops out at about 400-MHz GBW, the CFA often reaches a GBW of several gigahertz. Later we discuss an exception to this rule, a

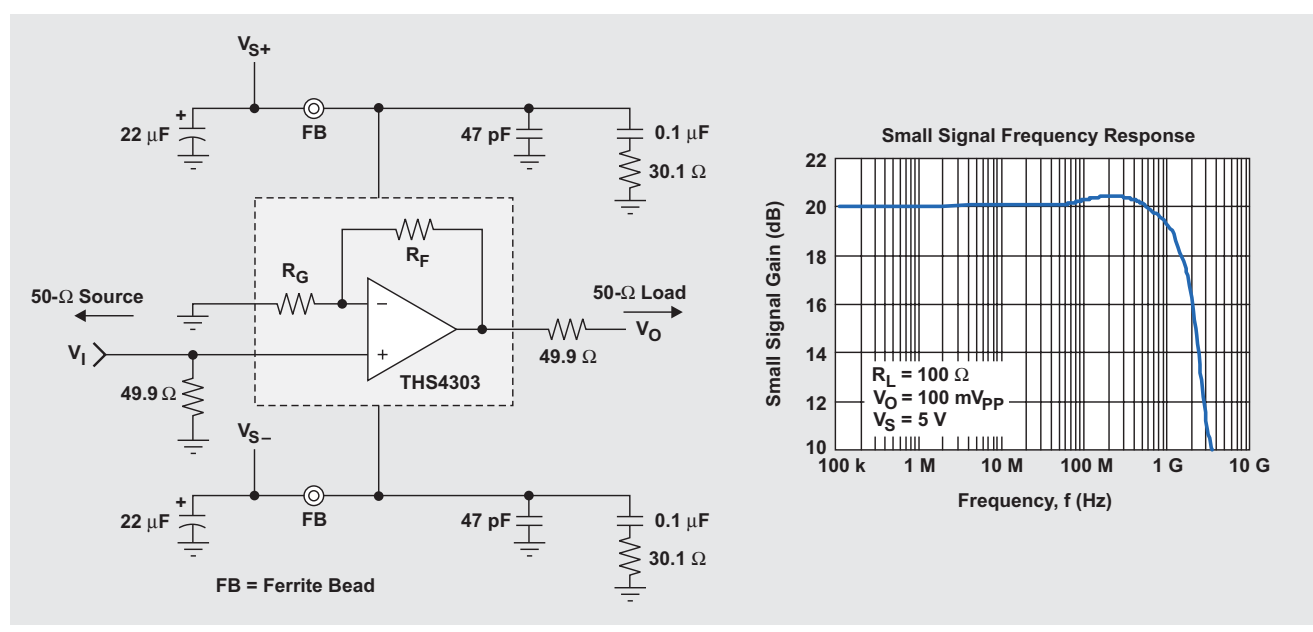
**Figure 6. Simplified model of a CFA**



special class of VFAs called wideband fixed-gain amplifiers (WFGAs). The CFA covers the frequency range from approximately 25 MHz to the low gigahertz area quite well.

A caution about using CFAs is mandatory. Many designers unconsciously depend on the decreasing gain versus frequency attribute of the VFA for stability because a circuit with a gain less than one is unconditionally stable. This CFA keeps its gain as frequency increases, thus it doesn't have a hidden stability advantage. Circuits that were stable with VFAs can become unstable when implemented with CFAs. Furthermore, the input lead and feedback resistor of a CFA is sensitive to stray capacitance, so the designer must be much more aware of the layout. Vendor evaluation boards are usually free, and they should be used for testing and as a layout example.

**Figure 7. Notice the special decoupling used in a WFGA application**



## High-frequency amplifiers

High-frequency amplifiers are usually fixed-gain amplifiers. Most amplifiers in the low to tens of gigahertz range are hybrid amplifiers; i.e., the circuit is constructed from discrete transistors and passive components mounted on a substrate. This type of construction is costly; the cost reflects in the final selling price. Most hardware developers are willing to spend the extra money for a hybrid amp because the technology required to develop such an amplifier is expensive and hard to obtain.

WFGAs are a new IC product, and their secrets are not yet general knowledge. They use a special high-frequency process to obtain the high GBW required to make a circuit that functions in the gigahertz region. They also use non-standard internal compensation techniques to obtain stability. These op amps are available in fixed circuit configurations with fixed gains, but their GBW goes up to 10 GHz, a dramatic increase in performance.

Any type of high-frequency amp needs a lot of tender loving care before it performs as advertised in the datasheet. The cautions given for CFAs apply here, along with the added advice to adhere strictly to the datasheet applications information.

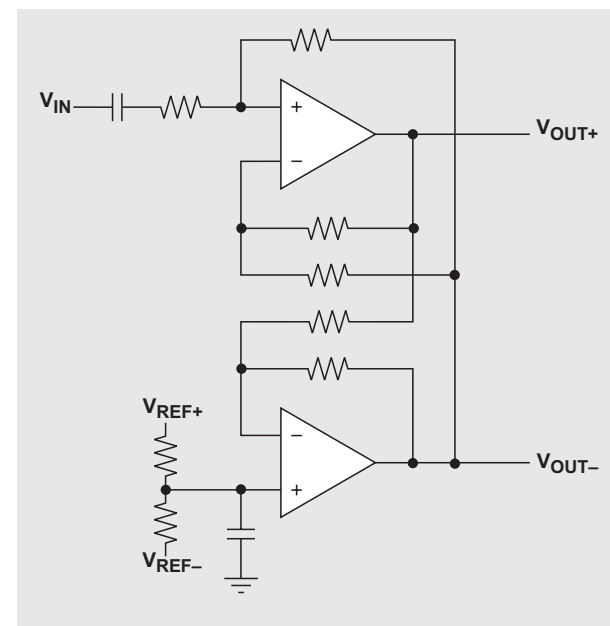
## Fully differential amplifiers (FDAs)

FDAs create and use fully differential signals. Many ADCs require a differential input signal to achieve maximum performance, and the FDA can easily convert a single-ended signal to a differential signal. Before the advent of the FDA, single-ended signals were converted to differential signals with the aid of the circuit shown in Figure 8.

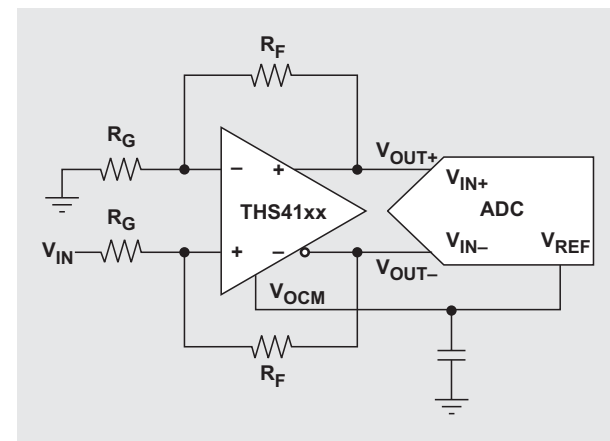
A discrete single-ended to differential signal converter requires two op amps and a handful of matched resistors. This ends up being a difficult design job that is not cost-effective. An FDA simplifies the signal conversion job, and it offers other advantages like fewer components (see Figure 9).

Besides simplicity and low cost, the FDA provides for a common ground point determined by the ADC. Signals transmitted differentially force the noise coupled into the signals to be common to both inputs, thus the coupled noise is common-mode noise. The ADC or receiver rejects common-mode noise through its built-in common-mode rejection capability.

**Figure 8. Traditional single-ended to differential converter circuit**



**Figure 9. The FDA converts a single-ended signal to differential**





## Power amplifiers (PAs)

When an op amp has to deliver more than a few hundred milliamps at several volts, it is time to think of using a PA because PAs can handle large currents and voltages. PAs are not switching-type amplifiers; rather, they are linear amplifiers that are capable of handling large amounts of power. Making a power amp is not attaching the biggest heat sink possible to an op amp with the lowest thermal resistance. Heat sinks and thermal resistance are critical in PAs, but other functions like current sense, overload shutdown, and hooks for paralleling devices are very important (see Figure 10).

The new PA can handle considerable current for a precision op amp, but it has peripheral functions like current limit set, current monitor, parallel connections, enable, a current limit flag, and a thermal limit flag. Of course, there are PAs that can handle much more current at higher voltages, but the similar characteristics of the new devices are the bells and whistles.

## Audio amplifiers

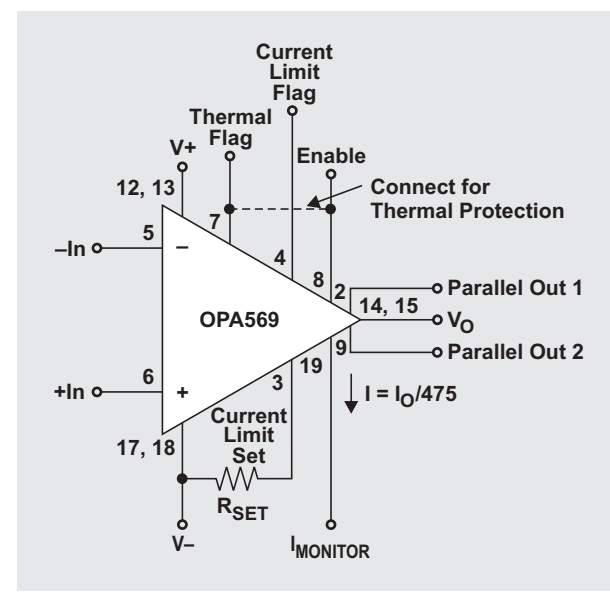
The volume of audio amplifiers is so high that there has been a special category for them since the 1950s. Most semiconductor manufacturers offer a line of audio amplifiers that ranges from simple op amps to involved switching power amps. Seek, and you shall find.

## The next step

This discussion should get you into the specialty area that deals in the type of amplifiers you need to solve a problem. Naturally, you ask, "Where do I go from here?" The answer is to the Web. Any IC manufacturer worth doing business with has a Web site, and you can visit all the pertinent sites in a few hours. When you are on a site, look at the interesting ICs for problem solutions, but don't neglect the applications information.

Some IC manufacturers flood the engineer with applications information while others offer little or no applications information. This information often determines how quickly and completely you can do your job. If you don't know about decoupling capacitors or thermal runaway, the hardware mistakes you make will teach you; but if you read

**Figure 10. The new breed of power amplifier does more than handle power**



about these phenomena in the applications section, you can avoid designing them into the hardware. The choice of manufacturer is yours and shouldn't be influenced by applications information unless the choice is even or you don't want to stray too far from the source of knowledge.

## References

1. Ron Mancini, *Op Amps for Everyone* (Newnes Publishers, 2003). An earlier 2002 edition is available at [www-s.ti.com/sc/techlit/slod006](http://www-s.ti.com/sc/techlit/slod006)
2. Ron Mancini, "Worst-case circuit design includes component tolerances," *EDN* (April 15, 2004), pp. 61–64. Also available online at [www.edn.com/article/CA408380.html](http://www.edn.com/article/CA408380.html)

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