PROTECT THOSE EXPENSIVE POWER OP AMPS

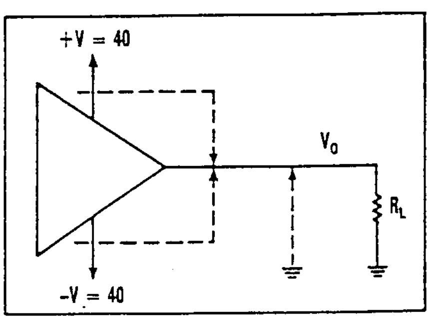
JERRY STEELE
Apex
Microtechnology Corp.,
5980 North Shannon Rd.,
Tucson, AZ 85741;
(602) 742-8600.

Hybrid, power op amps can reliably deliver large power outputs as long as proper protection is carefully considered. Unlike their discrete brethren, in which individual components can be replaced relatively easily, proper protection represents a key factor in making these devices cost effective. A failure of just one component—within an amplifier in its hermetically sealed metal can—necessitates a new amplifier.

The challenge to the designer, then, is optimizing both protection and power output. Because amplifier limits are described by safe-operating-area (SOA) graphs, to which the protection circuits must be designed to adhere, the task isn't as simple as it seems. Depending on the expected fault conditions, much of the amplifier's apparent current or voltage capacity must often be sacrificed. In addition, the protection circuitry usually shouldn't interfere with the passage of normal signals in any way.

Limiting output current is the most complex area to consider when designing amplifier protection. Either protection must be traded off against performance or a lengthy design involving more complex protection methods must be used. While current-limiting considerations are the most important aspect of power-amplifier protection, the amplifiers can also be overstressed by power supplies, the load itself, and even by input signals.

All power op amps are equipped with current limiting. In some, it is fixed internally to a single value. Others may have externally programmable current limiting. To fully protect an amplifier, it must be kept within SOA limits. The first task is to determine what constitutes the worst-case expected load fault *(Fig. 1)*. For instance, must the amplifier tolerate shorts to either supply rail, or will tolerance of shorts to ground be adequate? The designer then refers to the SOA curves to determine where to set current limits *(Fig. 2)*. The PA04 with its MOSFET output stage can handle more current at high voltage. Unlike the bi-



1. WHEN USING POWER op amps, designers must define whether worst-case load faults include shorts (dashed lines) to ground or to either rail. Extremely reactive loads or motor reversals can be equivalent to shorts to either supply rail.

polar output PA12, it has no secondary breakdown.

With resistive loads, the worst-case fault condition is likely to be a short circuit to ground. In a split-supply application, the voltage stress is then simply equal to one of the supply voltages, or half the total rail-to-rail voltage.

With a resistive load to ground in a single-supply application, ground is the negative supply rail. In this case, the voltage stress is equal to the total supply voltage rail-to-rail. The voltage stress also equals the total rail-to-rail voltage in split-supply applications with load faults to either supply rail—or when driving inductive loads.

Once the fault condition is defined, it's up to the designer to ensure that the current is limited to a value, coincident with the voltage stress, that's safe for the amplifier. What is safe depends on several other factors. In general, the dc SOA limit at 25°C should be some minimum value for amplifier protection. Realistically, however, such a limit can't be sustained indefinitely due to the amplifier's temperature rise.

By knowing the highest temperature the amplifier's case will reach, due to both ambient temperature and dissipation, a completely reliable current limit can be selected along the dc SOA lines—generally at temperatures of 70°, 85°, and 125°C when available. While these lines don't appear in figure 2, most amplifier SOA curves do supply them.

Using the bipolar output PA12 as an example, refer again to the SOA curves in figure 2 for the bipolar output PA12. Point 1 will be a safe current limit for shorts to ground. Point 2 will be safe for shorts to either rail or for reactive loads.

Limited Safety

Amplifiers with a fixed internal current limit are safe under a very limited set of conditions. In many applications, these amplifiers will not be safe even for short circuits to ground. However, external current limiting can be applied to any internally limited amplifier to meet SOA requirements under load faults *(Fig. 3)*.

In this circuit, a biasing current is supplied to Q_2's base at all times by R_1. The value of R_1 is determined by the minimum beta of Q_2, and the minimum supply voltage:

$$R_1 = (V_s - V_{beq2}) / (I_{lim}/\beta Q_2)$$

where the $V_{beq2} \approx = 1.2$ V.

The current limit is activated when the drop across R_{CL} is enough to turn on Q_1, so the current limit is equal to:

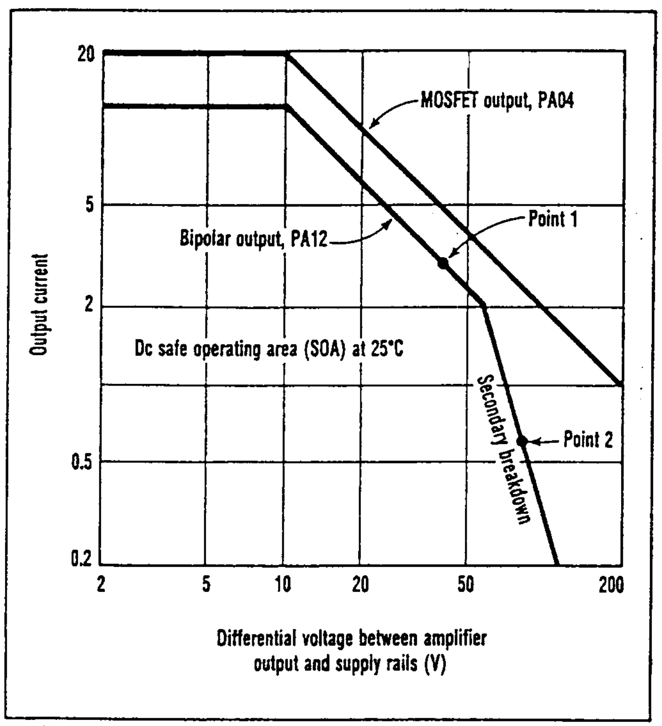
$$I_{lim} = V_{beq1}/R_{CL}$$

where $V_{beq1} \approx 0.7$ V.

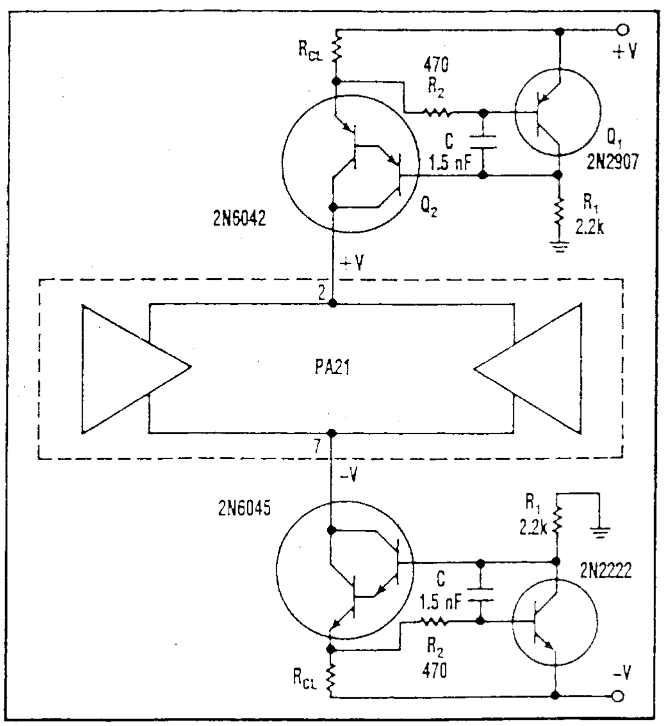
R_2 and capacitor C keep the current-limit circuit from oscillating.

Two of these current limiters are used, one between each supply rail and the op amp's power-supply pins. A single-supply bridge circuit however, where one is confident that load faults will occur only between amplifier outputs and not to ground, can be protected with one current limiter in the positive supply line of each amplifier.

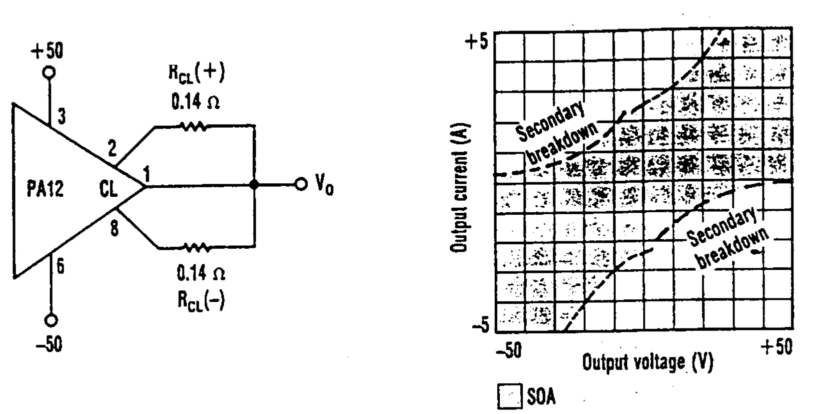
Amplifiers with externally programmable current limiting are easi-



2. POWER-OP-AMP OUTPUTS must be kept within their safe-operating-area (SOA) limits. Defining fault condiditons and their associated voltage stress determines maximum load current.



3. EXTERNAL LIMITING HELPS protect internally limited power op amps (such as the PA21) as output swings approach the supply rails. This clamp circuit works to 5 A while keeping losses below 1.5 V per limiter.



4. A PA12 WITH A 5-A CURRENT LIMIT isn't safe for output shorts to ground. Here, safe-operating-area curves are drawn on a "map" of attainable output voltages and currents.

er to keep within their SOA. Though they're simpler, all simple current-limit methods make great sacrifices in amplifier current-handling capability in the interest of reliability. It's not unusual for a seemingly robust 10-A amplifier to be reduced to a 600-mA weakling in order to remain within the SOA under load-fault conditions. Point 2 in figure 2 represents the resulting capability of a typical bipolar amplifier, the PA12, when total load fault safety is a requirement. A MOSFET amplifier, the PA04 (also shown), indicates that while MOSFETs offer some improvement, by eliminating the secondary breakdown region, even simple power limits greatly reduce safe attainable currents.

Foldback Limiting

Unfortunately, amplifier manufacturers believe that designers will be attracted by the simplicity and reduced component count offered by amplifiers with programmable current limiting which use one external resistor. What actually is needed, however, is multislope foldback (or foldover) limiting.

As will be pointed out later, this technique requires not only a two-resistor current limit—but also free access to the bases of the current-limit transistors inside the op amp. That is the only way to get the flexibility needed to optimize both protection and power output.

Perhaps this obsession with reducing component count is the same trap that reliability people fall into: The higher the component count, the lower the reliability. This fallacy results in many power-op-amp failures because about a dollar's worth of extra diodes to protect an unrepairable, $50 amplifier aren't included. The effect of foldover limiting compared to fixed current limiting can be graphically illustrated with the PA12 *(Fig. 4)*. The PA12 was selected because it features an internal, single-slope, foldover current limit.

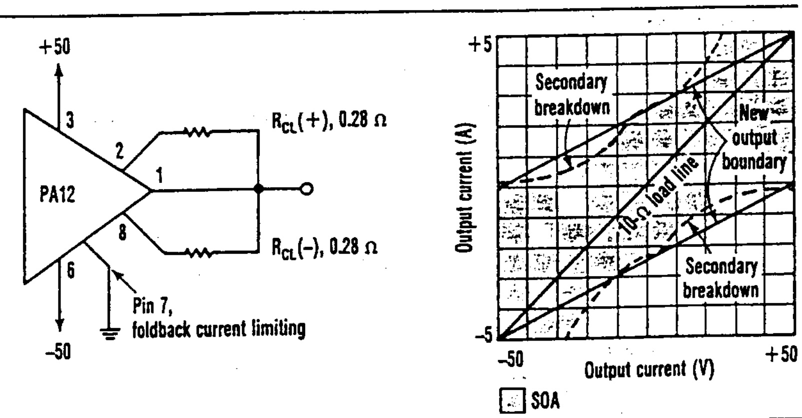
The coordinates of the graph, –5 A to +5 A and –50 V to +50 V, represent the limits of the combinations of output voltage and current attainable from a PA12 using a fixed current limit. The lines represent the SOA limits of the PA12. There are significant opportunities (operating points), however, to exceed the SOA. Making the circuit safe for a short to ground, or other load faults, requires a significant reduction in current available (from the supply).

To improve these limitations, foldover current limiting is added to increase the available current as the output swings closer to the rail that's supplying the current. This equates to reducing current available as the output voltage approaches the opposite supply rail. Foldover limiting is often referred to as "load-line limiting" because it can be designed to conform to a specific resistive load.

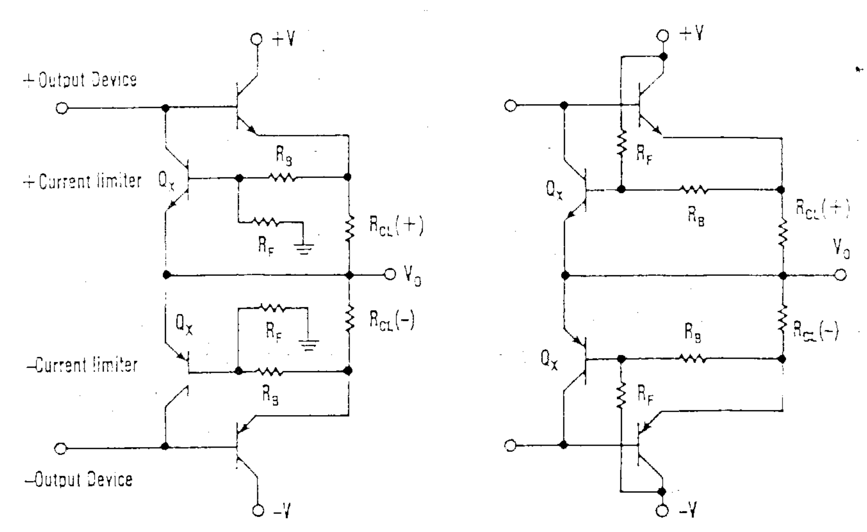
Foldover limiting essentially "tilts" the output map so that it presents a better fit to SOA limitations *(Fig. 5)*. The 10-Ω load line illustrates the power output ability of the circuit. This foldover limiting is built into the PA12 and PA10. This limiting is "activated" in split-supply applications by connecting pin 7 to ground.

In single-supply bridge applications, pin 7 should be returned to a low impedance (less than 2 kΩ) point at half the supply voltage. In single-supply applications with a load to ground (equivalent to a load to the negative supply rail), it's feasible and probably desirable to connect pin 7 to ground. To reduce the slope of the foldover action, a resistor can be inserted in series with pin 7.

Two techniques can implement foldback current limiting: the subtractive and the additive *(Fig. 6a and Fig. 6b, respectively)*. However, the



5. FOLDBACK CURRENT LIMITING, WHICH IS BUILT INTO the PA12 power op amp, makes the device safe for shorts, but still lets it deliver 5 A to a load along a 10-Ω load line.



6. FOLDBACK SUBTRACTIVE **current limiting is used inside the PA10 and PA12 power op amps (a). Additive limiting isn't adaptable to any current power op amps (b).**

additive approach doesn't adapt to currently available power op amps.

The subtractive circuit obtains its foldback characteristic from the slight voltage divider effect of R_B and R_F. As the output swings toward a supply rail, the divider effectively reduces the V_{be} drive available to the current-limit transistor Q_x from the current limit resistor R_{CL}.

As the output swings away from a rail, the divider adds drive to the base of Q_x. The technique increases the available current when the output is close to a supply rail, and reduces it when the output is away from a supply rail.

While the PA10 and PA12 are the only amplifiers currently available with foldover limiting built-in, the four-wire limiting on a PA04 lends itself to implementing foldover current limiting with two external resistors and a capacitor *(Fig. 7)*. The capacitor prevents oscillation during current limit. The base resistor R_B is set to the same value as the base resistor in the previous example using the PA10 and PA12. The same equations apply with adjustments made for the value of R_F.

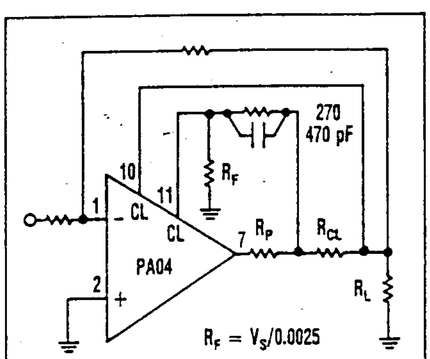
An additional op amp adapts virtually any amplifier hosting an externally settable current limit to foldover limiting *(Fig. 8)*. The high-voltage small signal IC on the right (such as a Harris HA-2645 or a National LM343), modifies the base-emitter voltage of the current-limit transistors, inside the power device, by driving their emitters through pins 2 and 8. The resistors R_B and R_F serve identical functions, and have identical values with their equivalents in the PA10 and PA12. No resistance should ever be located between the op-amp output and current-limit emitters. They would soften the current-limit transistors' clamping action on the power-device base drive. Initially, C_1 and C_2 should be at least 100 pF, and then increased to the minimum value necessary to overcome any oscillations that occur during current limit.

There's a maximum benefit which can be realized by using the single-slope foldover limiting built into the PA12, or the add-on universal foldover limiting. By referring back to the foldover-limiting output map, it can be seen that the current available at full output swing is twice that at zero-volts out *(Fig. 6, again)*. Moreover, the current available when the output voltage is at the rail opposite the one supplying current is nearly 0.

This 2-to-1 relationship between maximum available current and the current for zero-volts out—is the maximum attainable with this basic method of foldover limiting. Setting R_F to too low a value will activate the opposite-side current limit before full output voltage swing has occurred, clamping any drive that would otherwise be available to swing the output voltage in the opposite direction. This then leads to a nondestructive latch-up in output voltage, which can only be recovered from by removing power.

R_F must be kept small enough so that, for example, when the output is at full positive swing, there's less than 0.7 volts across the negative current-limit transistor base-emitter junction. This base-emitter drop is the voltage that appears across R_B (inside the power op amps). The lower limit of R_F is determined by:

$$R_F = V_s/(0.7/R_B)$$



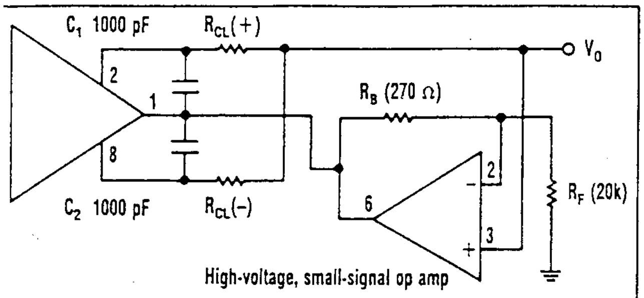
7. THE FOUR-WIRE **current limiting technique used by the PA04 power op amp easily adapts to external foldback current limiting.**

Reactive Loads

Reactive loads require special consideration with foldover limiting. A reactive load in the circuit of figure 6 would have an elliptically shaped load line that may be difficult to contain within the SOA and the output characteristic map.

If it extends outside the limiting curve, current limiting and distortion will occur. Reducing reactance or raising current limits are the only solution. In addition, foldover current limiting with a reactive load will produce a sharp flyback pulse that mandates using external, ultra-fast-recovery flyback diodes.

It's this limitation of foldover limiting that could make the designer wish that not only were two current



8. FOLDBACK CURRENT LIMITING can be adapted to virtually any power op amp by adding a high-voltage, small-signal op amp externally.

limit resistors used, but that both current-limit device bases were brought out separately—and independently—of any other connections.

The foldover limiting techniques described so far have a single slope. But referring back to the output map of figure 6 and looking at the SOA lines, it indicates that a steeper slope of foldover limiting is acceptable in the regions where output voltage and current have the same polarity. In fact, the SOA regions are nonlinear on the output map, suggesting a multislope foldover can offer an even better fit.

Multislope foldover can only be implemented if the current-limit transistor bases are separated both from each other and from the output transistors. No currently available power op amp lends itself to this arrangement. However, the technique can be used if you're building power boosters for available amplifiers—or are building your own power op amps from scratch.

The most basic multislope technique is a two-slope method offering a steeper foldover characteristic as the output passes through zero *(Fig. 9).* R_B serves the same function as in typical current limiting. Depending on output polarity, diodes D_1 and D_2 provide different values for the resistance R_F. Looking at the positive limiter for instance, when the output voltage swings positive, D_1 is forward biased, and the value of R_F is equivalent to R_1. During this interval, D_2 is reversed biased and R_F for the negative limiter is equal to $R_2 + R_3$. If the output swings negative, D_1 is off and D_2 is forward biased. Now the positive current limiter R_F is equal to $R_1 + R_2$.

R_1 and R_3 can be made very low to provide a very sharp curve for foldover limiting. The SOA's curved edges, however, again limit the usefulness of the two-slope current limit. This problem can be solved by adding yet another breakpoint in the foldover curve.

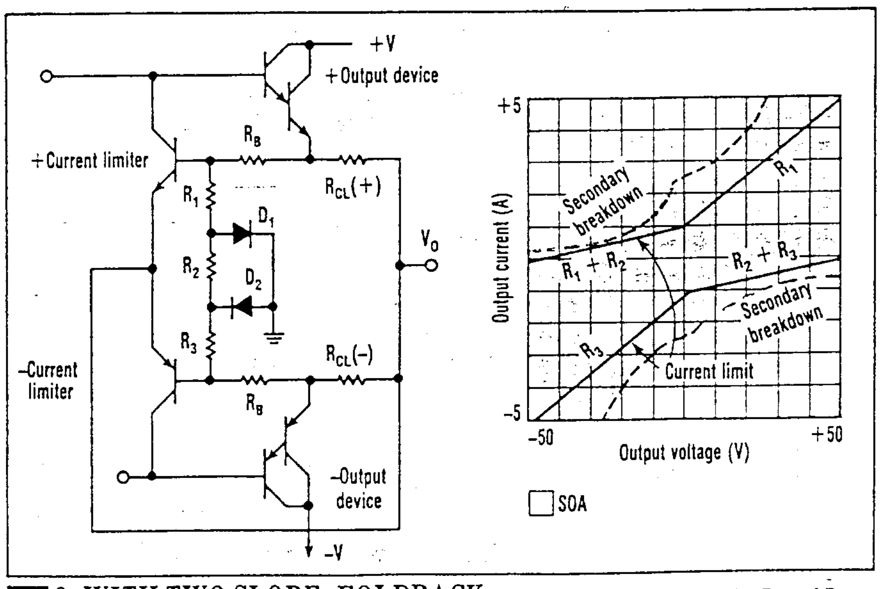
In a three-slope foldover circuit, the first break occurs around 0 V out with the activation of either D_1 or D_2, depending on output signal polarity *(Fig. 10).* At a higher output voltage, either Zener diode DZ_1 or DZ_2 turn on to further reduce the effective value of R_F. This three-slope foldover offers the best fit yet to the amplifier SOA. A totally independent circuit is used on both halves of the multislope limiting to avoid any possible interaction that could latch-up the amplifier.

HEAT'S THE ENEMY

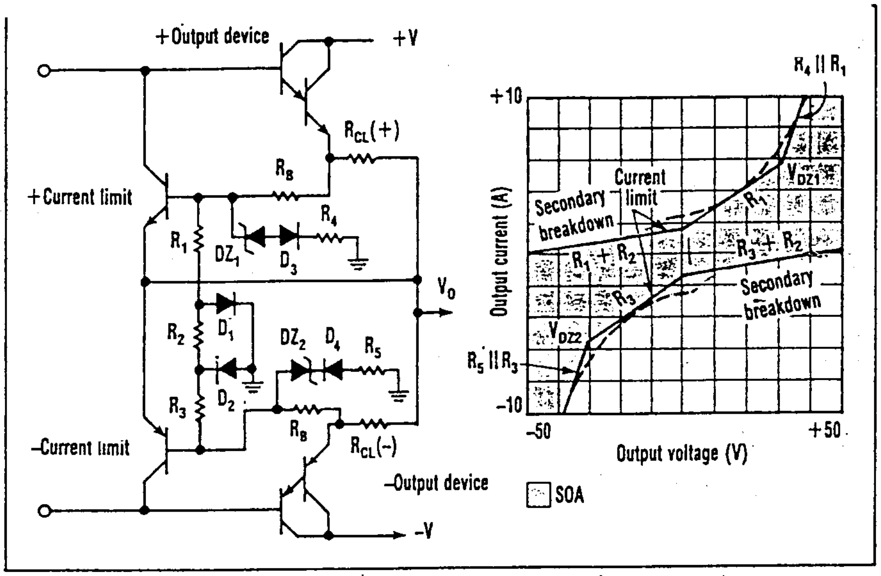
The destruction of an amplifier's power transistors is first and foremost a function of temperature. For a MOSFET operated within current and voltage limits, failure is only a function of temperature. Therefore sensing power device temperature is an essential element to any ideal protection scheme. It's currently used on several power op amps and power transistors. The Apex PA03 and the National LM12 are both equipped with power-output-device temperature sensing.

Power-die temperature sensing should not be confused with the thermal shutdown available on many power and high-voltage op amps, such as the Apex PA80 series high-voltage amplifiers and PA21 and PA07 power amplifiers. The most common form of thermal shutdown is a slow-action case temperature-sensing system that protects amplifiers from excessive temperatures. However, it doesn't provide load-fault protection.

The Apex PA03 is an example of a hybrid realization of power-die temperature sensing. It's accomplished by mounting a small-signal temperature-sense transistor directly on top of the power die. This intimate thermal sensing acts rapidly enough so that when the op amp is operated within proper voltage limitations, it's fully protected from load faults. This output-transistor temperature



9. WITH TWO-SLOPE, FOLDBACK current limiting, the diodes let R_1 and R_3 set the current limits at low currents. Their combination with the resistance of R_2 sets the current limit at high currents.



10. WITH THREE-SLOPE, FOLDBACK current limiting $R_1 + R_2$ or $R_2 + R_3$ set the low-current limit, and R_1 or R_3 sets the mid current limits. R_1 in parallel with R_4 or R_5 in parallel with R_3 sets the high current limits.

→ PA05

sensing is coupled with a package-temperature sensor that thermally shuts the whole PA03 down in the event of sustained excessive package temperatures.

Though thermal sensing is the most sophisticated form of protection, it does have its peculiarities. It *is not* a "clean" form of limiting, and can result in odd-looking waveforms when it becomes activated. Due to secondary breakdown, thermal limiting becomes less effective as higher voltages are used with the currently available bipolar power output stages. Secondary breakdown creates isolated "hot spots" on a die that can escape sensing by the thermal protection. This causes thermal runaway, destroying the power device.

Yet to be seen is a power op amp combining MOSFET outputs with thermal sensing. Without secondary breakdown limitations, thermal sensing should be very effective with MOSFETs. In theory, as a MOSFET develops a hot spot, the local on-resistance rises, shifting the load into the lower resistance remainder of the MOSFET.

In the process, the thermal load is spread. Moreover, tests of prototypes of the 90-V (rail-to-rail), 20-A PA[illegible] (the first power op amp with MOSFET outputs and thermal protection), indicates that the theory holds. The device stands up under continuous shorts to ground while trying to put out maximum voltage (it will be out early in 1991). Final proof will have to wait until the Apex ~~PA[illegible]~~ becomes available.

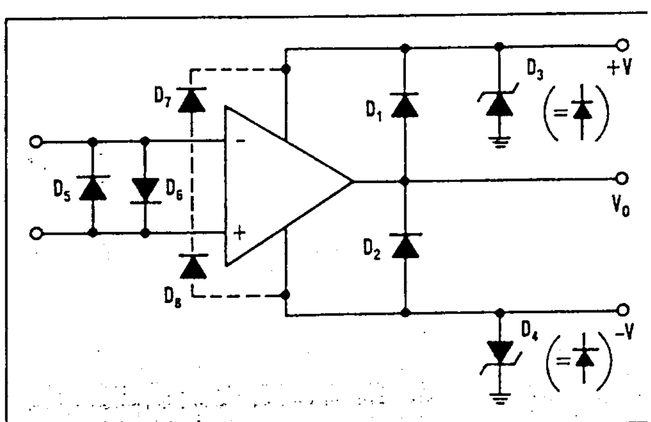
Operating a power op amp within an SOA doesn't eradicate all of the possibilities of destroying it. For example, any time current is interrupted in inductive or even partly inductive loads, a flyback kick will be generated. This kick will reach whatever voltage level is necessary to maintain current flow—and will apply it to the amplifier's output.

Most amplifiers with built-in flyback diodes (for protection from inductive kicks) use the substrate diode of their output transistor. In bipolar devices, these substrate diodes are slow, their continued use is inefficient, and it generates heat. Consider also that certain loads, such as brush-type DC motors, have a continuous interruption of current flow due to commutation. This produces a continuous train of kickback pulses that, averaged over time, can cause power-device failure.

The need for external flyback diodes was discussed in connection with inductive loads and foldover current limiting. Anytime inductive loading is expected, external flyback diodes are an inexpensive reliability enhancement. Ideally, these diodes should be ultra-fast-recovery types, but fast recovery or standard recovery is often better than none at all.

Power-supply transients are another source of amplifier overstress. In fact, adding flyback diodes merely couples flyback pulses into power supply lines—it's usually assumed that the power supply has the storage capacity to absorb them. If the only energy storage on the power supply is a large electrolytic filter capacitor, its high series inductance won't absorb extremely fast transients. A regulated power supply isn't a guarantee of safety either. Most regulated supplies are excellent current sources and lousy current sinks.

Ultimately, the only protection from power supply transients is Zener-diode transient suppressors. No other type of transient protection is fast enough. The Zeners must be rated below the amplifier maximum rating, but greater than the expected maximum supply voltage. Unregulated supplies where this transient protection is mandatory often neces-



11. DIODES AND ZENER diodes protect power op amps from inductive kick-back spikes, power-supply transients, and high input-common-mode transients.

sitates great sacrifices in operating voltages when tolerance stack-up is considered *(Fig. 11)*. Transient absorbing Zeners (called Transorbs by General Semiconductor, Tempe, Ariz.) D_3 and D_4 are shown operating with a PA03 amplifier.

Using this circuit as an example, with unregulated supplies, the maximum permissible supply voltage will be calculated. The PA03 has a maximum allowable supply rating of ±75 V. The nearest standard Transorb, a 1N6291, has maximum and minimum breakdown voltages of 74.8 and 61.2 V, respectively. The power-supply dc level must never exceed the lower breakdown value.

Assuming that a maximum ac line voltage of 130 V corresponds to a dc level of 60 V (using slightly less than 61.2 to provide a guardband), the dc level at a nominal 117 V will be ±54 V. This is the highest unregulated voltage with which the PA03 should be used. Obviously, an amplifier running off a tightly regulated supply could handle higher supply rails safely.

Some amplifier overstresses occur through its input terminals. While there's a tendency to attribute input-stage damage to input overstress, occasionally power supplies are responsible for input-section damage. Keep in mind that most power op amps tolerate input voltages up to the limits of the supply rails. If power supplies ever reverse polarity, especially in split-supply applications, they will overstress the input stage by violating input common- mode limits. Outputs are generally protected from supply reversals by their built-in flyback diodes.

The chance of supply reversal furthers the argument for using Zener diodes to protect the supply lines. If the supply reverses, the Zeners act as forward biased diodes to clamp the reverse polarity excursion—if unidirectional Zener diodes are used.

The need to keep an amplifier's inputs within the supply rails generally falls under the heading of common-mode protection of amplifier inputs. This is in contrast to differential-mode protection considerations. Differential-mode input protection is easily implemented with the diode clamps shown between amplifier inputs. With FET input amplifiers (when the low bias current of the FET is important to the application), these may need to be low leakage diodes. Alternatively, if high slew rates are important, multiple diodes may have to be used in series to allow for overdrive.

There are many opportunities to develop excessive differential-input overstress Essentially, it can occur any time an op amp becomes nonlinear, such as during clipping or slew-rate limiting. Paths for input overstress may be difficult or impossible to find. These include breakdown paths through circuit board material in high-voltage circuits.

Figure 11 shows schematically some of these final details of amplifier protection. D_1 and D_2 provide flyback protection. D_3 and D_4 provide supply transient and reversal protection. D_5 and D_6 offer differential-mode protection for the amplifier input. D_7 and D_8 represent an example of another type of common-mode protection most often used on noninverting circuits and required on the non-inverting input only.

Not all of these protection methods are always needed. But until the designer knows just what isn't necessary, there isn't such a thing as too much protection. It may seem like a lot of additional componentry just for protection. But only a few dollars worth of additional diodes and components are invested to protect amplifiers that could cost up to $300-$500. Don't fall into the mental trap of taking it for granted that reduced component counts and reliability always go together.

Jerry Steele, a senior applications engineer with Apex Microtechnology, has 15 years of experience in electronic engineering, application engineering, and seminar presentations.