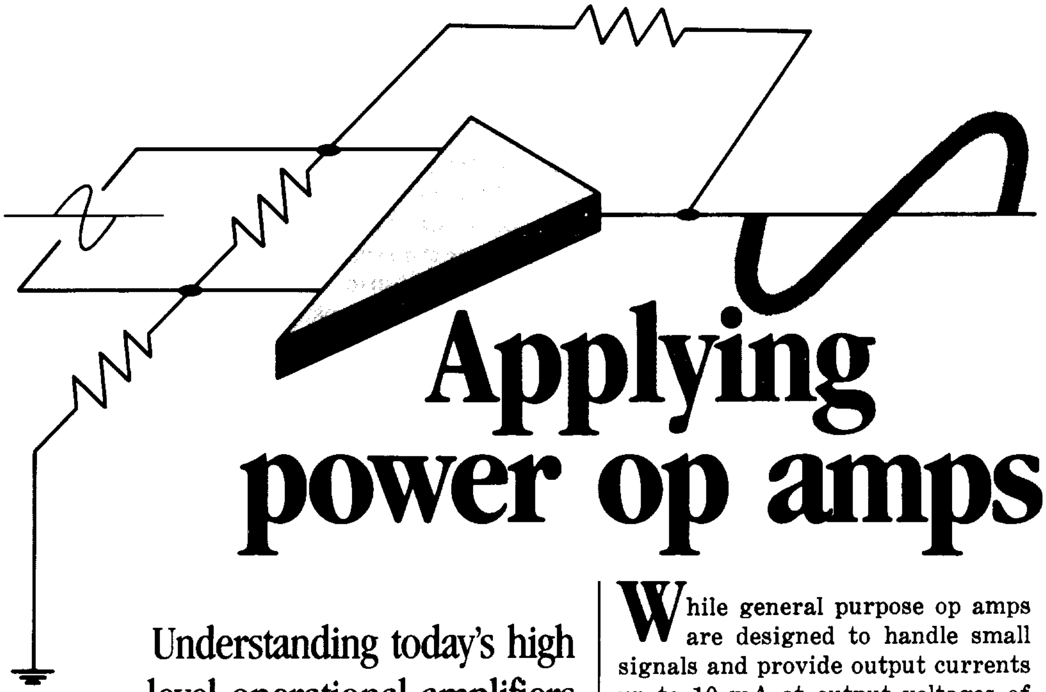

Applying power op amps

Understanding today's high level operational amplifiers allows you to streamline power stages in motor drives, low noise audio amplifiers, high voltage deflection circuits, and the like. Here's a look at some general considerations and practical circuits

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While general purpose op amps are designed to handle small signals and provide output currents up to 10 mA at output voltages of up to ±12 V, power op amps are designed to drive bigger loads, such as motors, deflection coils, transducers, heaters, and DC power buses, with currents of several amperes and amplitudes of up to several hundred volts. In most respects, power op amps function very much like general purpose op amps, requiring the same design rules. However, due to higher voltage, current and internal power dissipation, the internal components as well as the packages of power op amps tend to be larger.

Most often a power op amp can handle the combined function of a general purpose op amp and a power booster, thereby simplifying the circuit, reducing component count, and increasing reliability. Several companies offer power op amps. The widest selections come from Apex Microtechnology, Burr-Brown Research, National Semiconductor, and Teledyne-Philbrick, with Fairchild, RCA, Comlinear, and Intersil offering one or two models. At present, second sourcing is available between Apex Microtechnology and Burr-Brown (three models) as well as Apex Microtechnology and National Semiconductor (one model).

Before selecting a power op amp, you should determine your supply voltage and load characteristics, and check the safe operating area (SOA) against supply and load characteristics. Most output stages are biased for Class A/B operation to keep crossover distortion at a negligible level. However, some power op amps have Class C output stages and are suitable only for applications like motor and actuator control circuits — where linearity is not critical. A typical product is the 80-W Apex Type PA51, which is also second sourced by Burr-Brown as the OPA501. For linear applications, the PA51 can always be replaced by the Apex PA12, which has the same pinout. A wide range of input stages are available from low performance bipolar to high performance FET.

The first decision that has to be made for any application is whether a dual (±) or single supply should be used. Obviously, if the load requires a bidirectional drive, such as that used for a motor position control circuit or a deflection amplifier, there is little choice. However, often only a single direction of output swing is necessary (for applications such as temperature control). In these cases, a single supply should be considered, to minimize power dissipation.

Asymmetrical swings

A different way to optimize output power and minimize dissipation is to use a nonsymmetrical power supply. In such a setup, each supply will provide just enough voltage to allow the output to swing the load to the required level. Often the proper selection of the power supply can cut the cost of the power op amp required, reduce the size of the heat sink, save on power supply expenses, and increase efficiency and reliability. All of the applications discussed later in this article have been optimized for minimum power dissipation.

The safe operating criteria for general purpose op amps are usually satisfied if the maximum supply voltage and other absolute maximum ratings are observed. Power op amp users face additional restraints due to limits of the output transistors. Secondary breakdown can destroy most bipolar power transistors without exceeding the collector-emitter breakdown voltage, the maximum collector current, or the junction temperature limit.

Secondary breakdown results from excess current density in the base region and is induced by simultaneous stress with high collector-emitter voltage and high collector current — separately well below their respective absolute maximums. Of course, the maximum junction temperature is also limited to between 150 and 200°C. Newer MOS transistor output amplifiers do not have secondary breakdown limitations. These operating restraints are reflected in the SOA curves published by most manufacturers of power op amps. Figure 1 shows such a set of SOA curves.

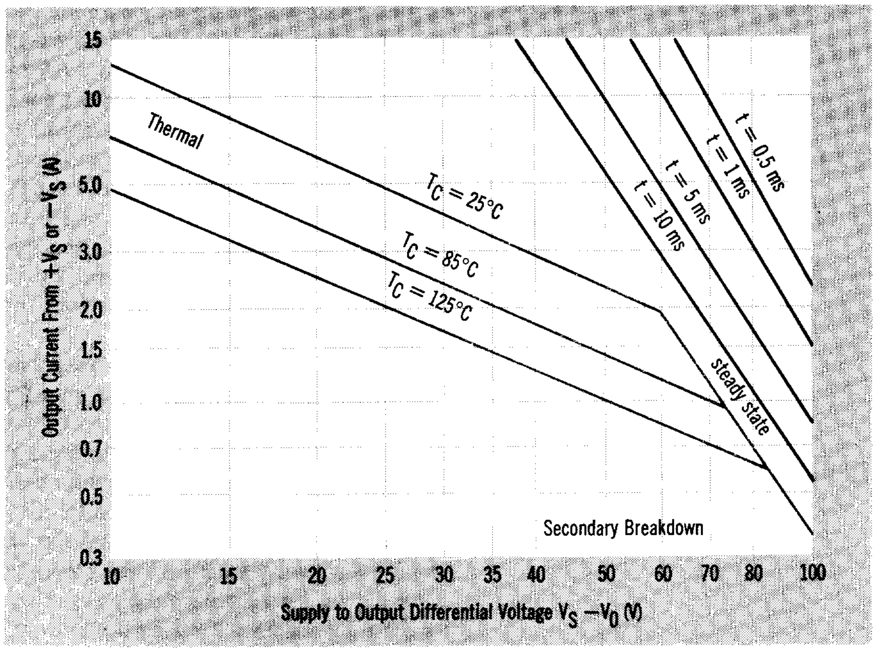


Fig. 1. Safe operating area curves for a typical power amp

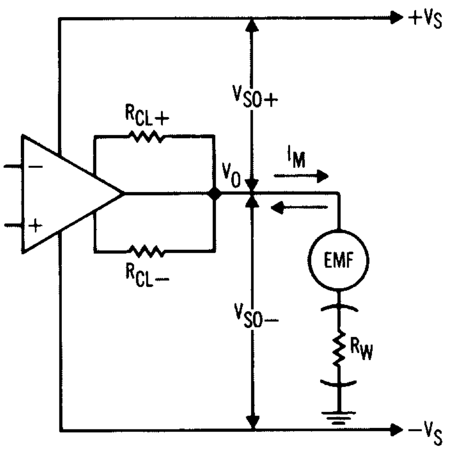


Fig. 3. Motor circuits place additional demands on power op amps due to counter-EMF generation.

These curves are easy to use. First you must determine which output transistor conducts the current and how much voltage is dropped across the conducting transistor. Then enter the X-axis of the SOA curve with the voltage drop across the current-carrying transistor (supply-to-output differential voltage), and read the maximum safe current on the Y-axis. Figure 2 illustrates the current flow and voltage stress on the output transistors of a typical power op amp. Remember, the direction of current is independent of the polarity of the output voltage for all but resistive loads and must be determined by proper load analysis or by measurement.

Once you know the SOA limits, you can maintain them by making the proper selection of the current-limiting resistors. In addition, you can choose the degree of protection you want. Short-circuit protection often requires a substantial reduction in the current limit due to the low maximum SOA current with the full supply voltage on the output transistors. Protection against all possible reactive or CEMF loads requires even lower current limits because one output transistor has to dissipate the sum of both (±) supply voltages during the output transitions from one supply rail to the other.

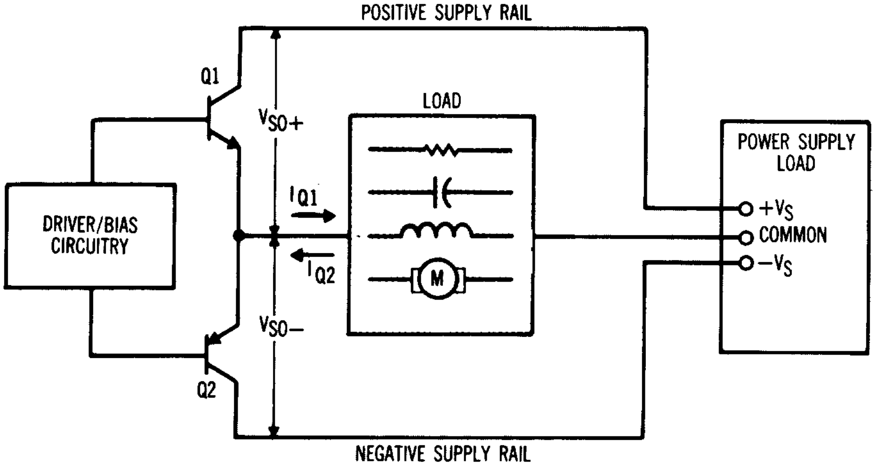


Fig. 2. Current flow and voltage stress on an op amp's output stage

With resistive loads, the supply-to-output voltage differential is the lowest when the output current is at its maximum. This condition makes it easy to meet SOA considerations with resistive loads if

$R_L = V_O \max / I_O \max$, where:

R_L = load resistor in Ohms,

$V_O \max$ = maximum output voltage at a given supply voltage (generally supply minus 5 V), and

$I_O \max$ = maximum output current from ratings without consideration of SOA.

For example, if the op amp has to drive a 4-Ω load, the supply voltage is ±42 V, and a maximum output swing is ±36 V, then the calculated output current is 8 A and the drop on the respective output transistor is 6 V. When the output current is at one half (4 A) you can calculate a 26-V drop on the respective output transistor. Both conditions are shown to be safe on the SOA curve (see Fig. 1). If that same amplifier must be short-circuit-proofed, then the maximum voltage drop across the current-carrying output transistor will be 42 V. This reduces the safe current to 3 A. In other words, a current limit set at 3 A would render the amplifier safe under short circuit conditions, provided it is properly heat sinked.

DC motors make the determination of the safe operating conditions more complex because of the electromotive force (EMF) generated internally as a function of instantaneous shaft speed. Figure 3 shows a power op amp driving a DC motor and an EMF in series with the internal winding resistance R_W. The value of the EMF at a given shaft speed or RPM can be determined as follows:

$\text{EMF} = V_O - I_m R_W$, where:

V_O = output voltage of the power op amp,

I_m = current drawn by the motor at constant speed, and

R_W = resistance of the motor winding.

Due to the effect of the EMF, the motor will draw the least current under steady state conditions (constant speed) and the most current under transient conditions (start, stop, reverse) especially when reverse voltage is suddenly applied. It is the time lag — from the instant the amplifier output voltage is reversed until the motor itself reverses — that puts the most severe stress on the amplifier. This is because (1) the motor will draw the most current and (2) the conducting output transistor will current-limit, and due to the back EMF, a large voltage drop (V_{SO}) will develop across it (supply-to-output). It is this combination of current-limiting and the large supply-to-output differential voltage that must be checked against the SOA.

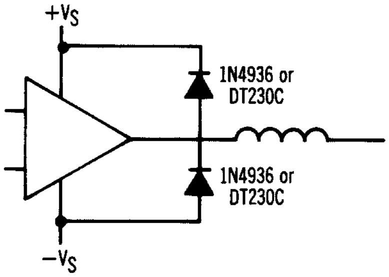


Fig. 4. Protective diodes clamp dangerous flyback voltages when driving inductive loads.

Proceed as follows:

1. Determine the value of the EMF at max speed, as previously indicated.

2. Calculate the amplifier's internal voltage drop:

$V_{SO} = V_S + \text{EMF} - I_{LIM}(R_W)$

where: V_S = supply voltage for the conducting transistor and

I_{LIM} = programmed current limit point.

3. Determine the time required to reverse the motor. If it takes less than 10 ms, you may take advantage of higher transient SOA ratings. If not, use the steady state plot.

4. Enter the X-axis of the SOA curves with V_{SO} and read the maximum allowable current I_{LIM} at the

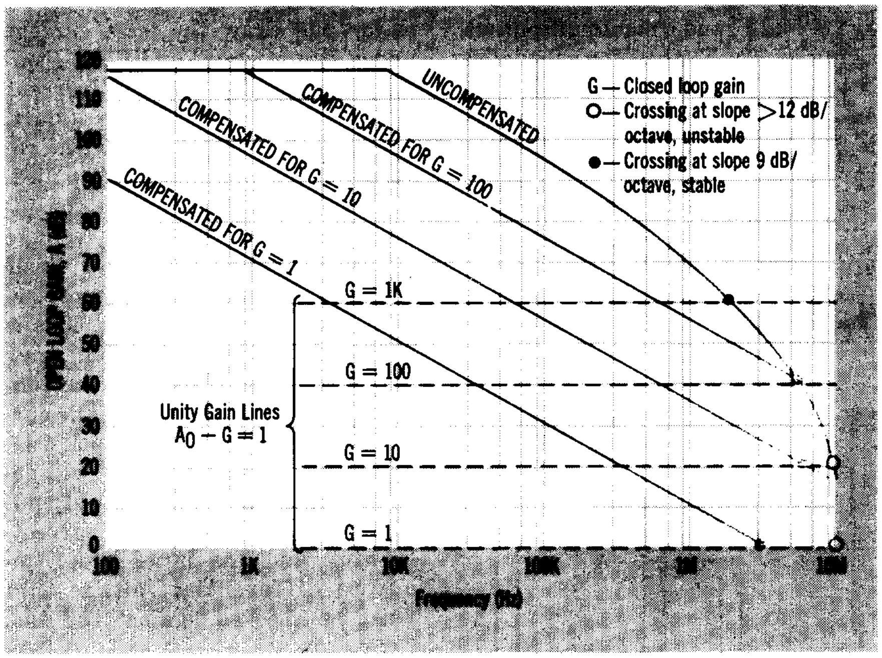


Fig. 5. Bode plots show the need for phase compensation.

intersection of V_{SO} with the applicable SOA plot. Interpolate if necessary.

It is also important to understand the characteristics of inductive loads before using them with power op amps. Many amplifiers have been destroyed by the flyback (kickback) effect encountered whenever instantaneous current changes are forced upon an inductor. Due to the current change, the impressed voltage reverses rapidly. The reverse voltage (V_f) is equal to $\Delta i(R)$, where: Δi = current change in the inductor and

R = equivalent parallel loss resistor.

As this equation shows, the higher the equivalent parallel resistor, the higher the flyback voltage. In a low-loss inductor such as an ignition coil, the flyback voltage can reach a level 10 to 100 times higher than the voltage applied prior to the current interruption. Like all active electronic devices having an internal breakdown mechanism, power op amps are easily destroyed by these flyback voltages. Figure 4 shows two diodes clipping off the flyback voltage in excess of $\pm V_S$. If the amplifier does not have these protection diodes internally, two external high speed diodes must be used whenever the load has a significant inductive component.

Long wires or cables are often inductive and can destroy an unprotected power op amp. If you don't know the degree of damping of the load inductance, you should connect the diodes initially and drive a low-frequency square wave into the circuit. If the output shows transients one diode drop above the supply voltage, leave the diodes in the circuit. Each diode should be rated for a reverse voltage equal to the sum of the supply voltages and for a current equal to the limit set. Both diodes must be fast-recovery types unless op amp speed is not critical.

Critical coil currents

Another problem with inductive loads (essentially the reverse of the first problem) is that the change of the current (i) through the inductor is governed by the relationship:

$$di/dt = \Delta V/L,$$

which means the larger the inductive load, the slower the current changes after voltage is applied. Again, an inductor imposes the greatest stress on the amplifier during reversal of its output voltage. This is because the current carrying transistor will remain on but must now sink the current generated by the inductor while developing a very large voltage from its supply to the output. As the current decays and the voltage on the current-sinking transistor drops, the stress on the amplifier will subside.

Here is the equation for checking whether a given inductive load is safe:

$$L_{max} = \frac{V_O(t)}{I_{LIM} - I_{SAFE}}, \text{ where:}$$

V_O = output voltage of the amplifier immediately following reversal and

I_{LIM} = programmed current limit. (t and I must be found in the SOA curve by finding the voltage drop on the transistor sinking the inductive current on the X-axis and the current limit on the Y-axis. The first SOA curve below the intersection of these two points will give the values of t [read on curve] and I_{SAFE} [Y-axis]. If the only SOA curve below the intersection is the steady state curve, then all values of inductance are safe with the programmed current limit.)

The third and last problem with inductive loads relates to steady output conditions after the current in the inductor has stabilized at $I_L = V_{OUT}/R_S$ or I_{LIM}, whichever is smaller. This condition can be checked against the SOA in the same fashion as a resistive load equal to the series resistance of the inductor.

Capacitive loads also require careful consideration. The current (i) required to change the voltage (V) on a capacitor is expressed as:

$$i = V\frac{C}{t}$$

This means that a fast reversal of the output voltage will cause a large current to flow into the capacitor. If the conducting transistor current-limits, it will develop a large voltage drop between its supply and output. To determine the maximum safe capacitive load, use the following equation:

$$C_{max} = \frac{I_{LIM}\,(t_S)}{V_{SS} - V_{SAFE}}, \text{ where:}$$

I_{LIM} = programmed limit, and

V_{SS} = supply voltage rail to rail. (t_S and V_{SAFE} must be found on the SOA curve by entering the X-axis where the SOA line crossed I_{LIM}.)

As mentioned before, under short-circuit conditions, the amplifier will current-limit, and the current carrying transistor will handle the full supply voltage. This condition can easily be checked against the SOA by entering the X-axis with the supply voltage and entering the Y-axis with the programmed current limit. The thermal (not the secondary breakdown) limit of the SOA may be exceeded if the power op amp has a thermal shutoff circuit built in.

The data sheets of most power op amps specify the maximum case temperature, the maximum junction temperature, and the thermal resistance from junction to case. These considerations are generally part of the SOA curves but should also be considered separately. Generally, the internal power dissipation is the difference between what comes out (output power) and what goes in (supply voltage times supply current). For DC or instantaneous values,

$$P = (V_S - V_O)\, I_O + V_{SS}\, (I_Q),$$

where: P = internal power dissipation,

V_S = supply voltage, one rail,

V_O = output voltage,

I_O = output current,

V_{SS} = supply voltage, rail to rail, and

I_Q = quiescent current.

The dissipation for DC and sine-wave outputs is calculated easily. For complex waveforms, it is difficult to measure. Once you know the internal power dissipation (P), it is simple to select a heat sink with the required thermal resistance (ϕ) since it is generally specified. The required ϕ can be calculated as follows:

$$\phi = \frac{T_J - T_A}{P} - \phi_{JC},$$

where: T_J = the maximum junction temperature,

T_A = the maximum ambient temperature, and

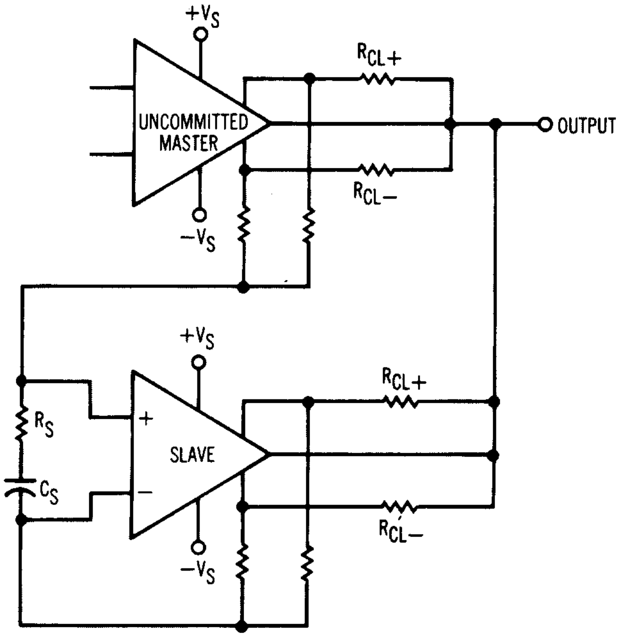
ϕ_{JC} = the thermal resistance of the amplifier.

For power op amps without thermal shutoff, the power dissipation (P) must be calculated for worst case operating conditions only. Often this means a size reduction by a factor of 5 to 10. At increased internal power dissipation, such as encountered during a short circuit, the output stage of the amplifier protects itself by reducing output and dissipated power.

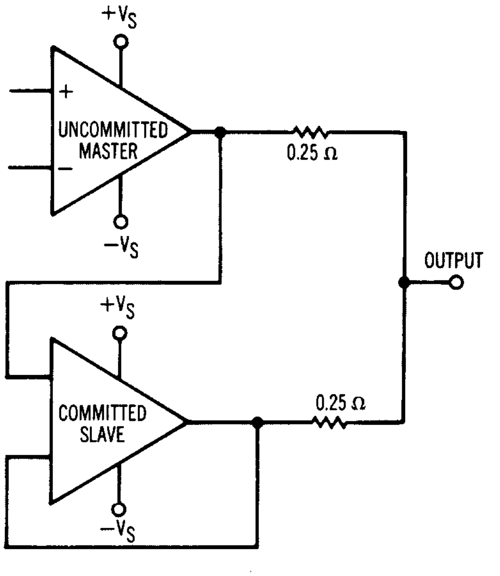
Continued on page 108.

PARALLELING POWER OP AMPS

Due to their low output impedance, power op amps cannot be connected in parallel without modifying the circuits of all but one of the amplifiers. The circuit in Fig. a shows such an arrangement. The prime amplifier is called the master. It is uncommitted and can be connected in any circuit suitable for a specific application. The additional amplifier is simply a current amplifier for the master. It functions by sensing the current on the current-limiting resistors of the master and amplifying it with unity current gain. Two input and two feedback resistors are required to sense the positive and negative output currents if the current sense resistors are split. If the current-limiting resistors are not externally accessible, two separate sense resistors must be used (see Fig. b). This simplifies the circuits but causes extra voltage drops and power losses.



(a)



(b)

Motor speed control

Speed control circuits for DC motors are easily implemented with power op amps (see Figs. a and b). The circuit in Fig. a shows a unidirectional speed controller implemented with a nonsymmetrical dual power supply — where the positive supply voltage of 52 V provides for full speed control of the 48-V motor and the negative supply biases the amplifier input stage and allows for deceleration (braking) of the motor. With the specified motor, the SOA of the op amp requires the current limit to be programmed for ±2 A with R_C+ and R_C- of 0.33 Ω. The transfer function of the circuit is set by

$$S(KRPM) = \frac{V_I}{K}\left[1 - \frac{R_F}{R_I}\right]$$

where S = motor speed in 1000s of RPM and

K = tachometer EMF in V/(KRPM).

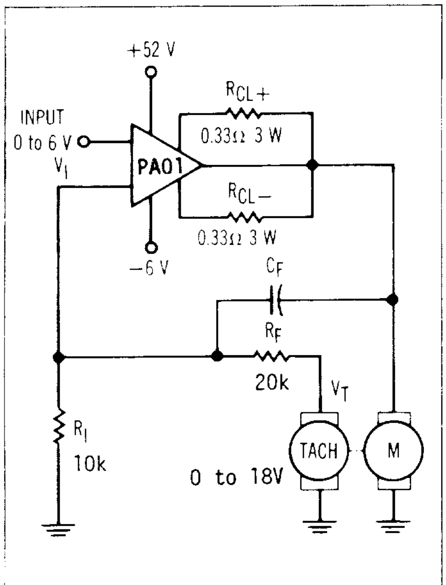


Fig. a. Unidirectional speed control with tachometer feedback

The feedback capacitor C_F helps to filter the tachometer output and prevents oscillation due to play in the shaft, as well as the dynamic lag of the motor speed behind applied voltage. The value of the capacitor must be selected for the individual application so the feedback loop has the proper damping in response to a step change at the input.

Fig. b shows a bidirectional speed control operating from a single 30-V supply. The circuit configuration is generally referred to as a differential or bridge output. It allows for the load to be shared by two amplifiers thereby increasing the available output voltage and power. Amplifier A1 operates in a non-inverting configuration, while A2 serves as a unity gain inverter. At maximum input, the motor can be driven in each direction with the supply voltage less the sum of A1 and A2 saturation voltages. As in Fig. a, capacitors C_{F1} and C_{F2} must be chosen for optimum damping in the individual application, while the current-limiting resistors (R_{CL}) are selected to protect the amplifier. Amplifier A2 is biased-on to one half the supply using R1, R2, and bypass capacitor C1. Resistors R3 and R4 provide DC operating feedback. The transfer function of the circuit is

$$S(KRPM) = \frac{2\,V_I}{K}\left[1 + \frac{R_F}{R_I}\right]$$

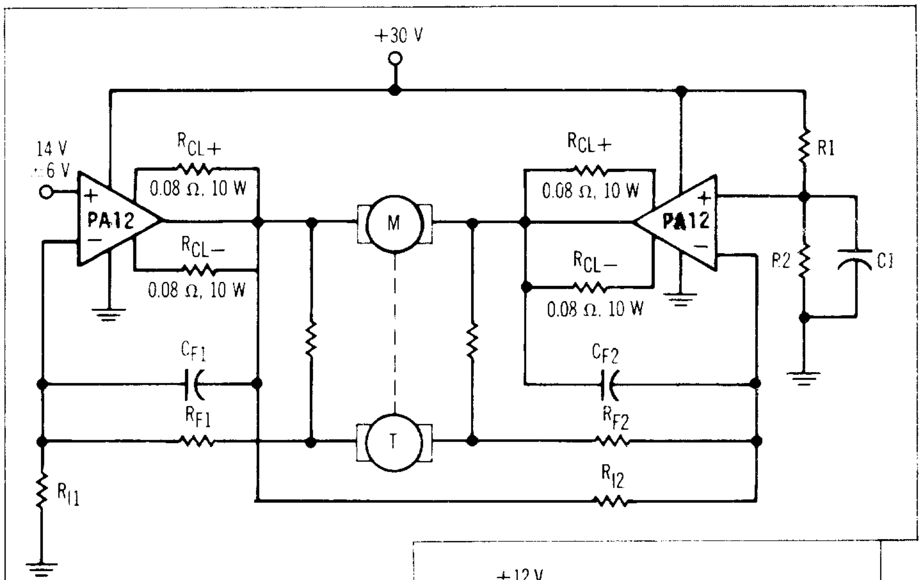


Fig. b. Unidirectional speed control using two op amps

Position control system

Power op amps are ideally suited for position control because of their fast response. The optoelectronic position controller

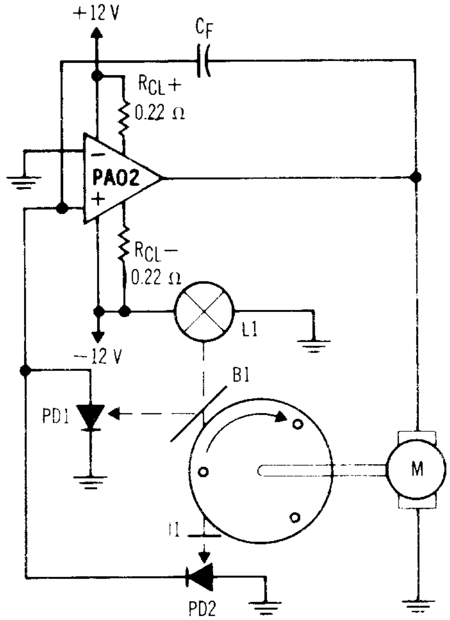


Fig. c. Beam splitter position control shown in Fig. c requires only one amplifier because the op amp's FET input stage works well with photodiodes.

At 2 A, the op amp will swing within 1 V of the supply rail, providing the high efficiency required for battery-operated systems. In the circuit, the output of light source L1 is split by beam splitter B1 into a first beam for sense photodiode PD1 and a second beam for sense photodiode PD2. Whenever the light beam to PD2 is interrupted, the output of PD1 will drive the amplifier output negative, causing the motor to rotate the wheel to the next hole; this exposes PD2 until its current cancels the photo-current out of PD1. The differential photodiode configuration results in very accurate position control with high repeatability because the light source output affects only the gain, not the position. The feedback capacitor C_F determines the speed (response) of the circuit and should be adjusted for the desired degree of damping, as outlined earlier. The current limit has been set at 3 A to keep the op amp within the SOA with the motor load specified.

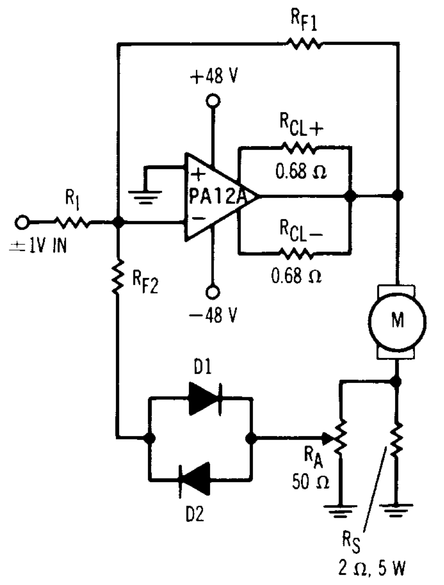


Fig. e. Feedback limiting motor current

As explained previously, motors are very demanding loads because they store energy (CEMF). For example, the PA12 op amp shown, at a supply voltage of ±28 V, with a motor that has an EMF of 12 V and an internal resistance of 4 Ω, requires the current limit to be set at ±3 A to make the load safer under instant reverse conditions. However, if more current is required, two external transistors can supply it. The circuit in Figure d shows an example of such a circuit, where Q1 and Q2 provide up to ±3 A in addition to what the PA12 can provide. Note that the MJE14000 and 14001 are rated for 70 A but due to SOA limitations, can supply only ±3 A under these conditions of supply and load.

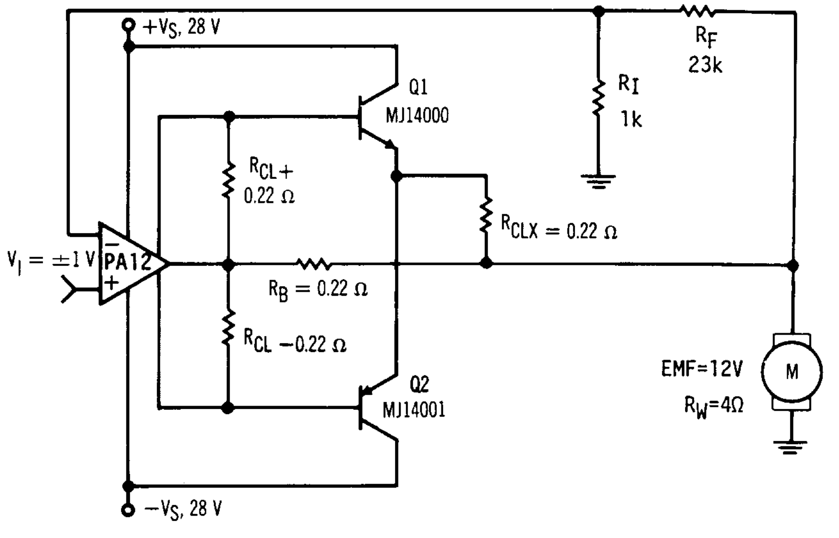


Fig. d. External driver transistors handling high current motors

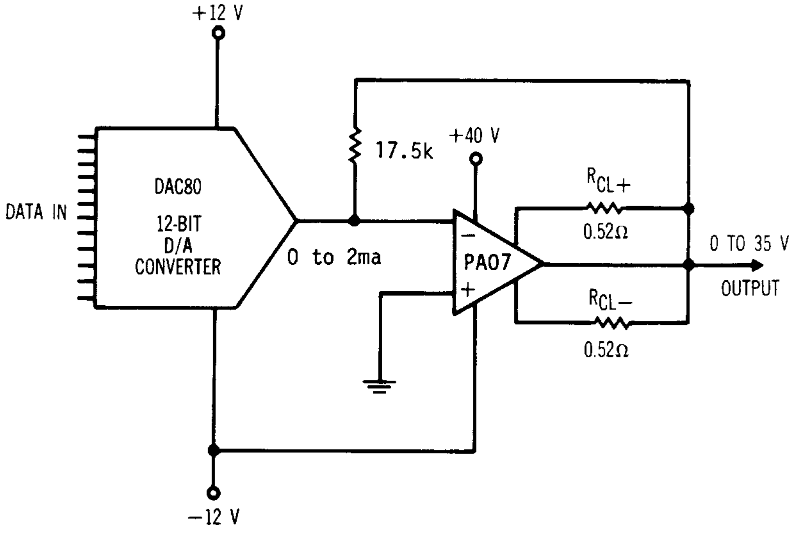


Fig. f. Digitally programmable power supply

Adjustable current limiter

If an application calls for a variable current limiter, it would seem necessary to make the current-limiting resistors adjustable. However, this is not very practical because of the low value resistance needed and the high current carried. Feedback techniques such as these shown in Fig. e can be used to vary the current limit. Feedback current limiting leaves the SOA protection (current limit) intact but allows for current limiting to be adjusted downward. In Fig. e, diodes D1 and D2 provide a threshold of about 600 mV. Whenever this threshold is exceeded by the current feedback voltage on the wiper of R_A, the amplifier will switch to current feedback. The sharpness of the limiting knee can be set with R_{FZ}. Zero Ohms will provide a very sharp knee, while higher values of resistance (100 Ω to 1 kΩ) will soften the limiting effect.

Programmable power supplies

Digitally programmable power supplies are most often used in automatic test equipment. A circuit for such a supply, programmable for zero to 35 V at 1 A, is shown in Fig. f. A current output Type DAC80 D/A converter converts the 12 bits of control data into a current of zero to 2 mA. The amplifier then converts this current into a voltage swing of zero to 35 V. To maintain safe operation under short circuits, the current limits have been set to 1.25 A. The internal thermal shutoff the PA07 protects it under prolonged short circuits even with a heatsink designed only for normal operation.

Deflection amplifiers

Magnetic cathode ray tube deflection is used for most large, bright displays such as television monitors, computer terminals, and headsup displays. Power op amps can be used to implement very linear raster or X-Y scan deflection circuits.

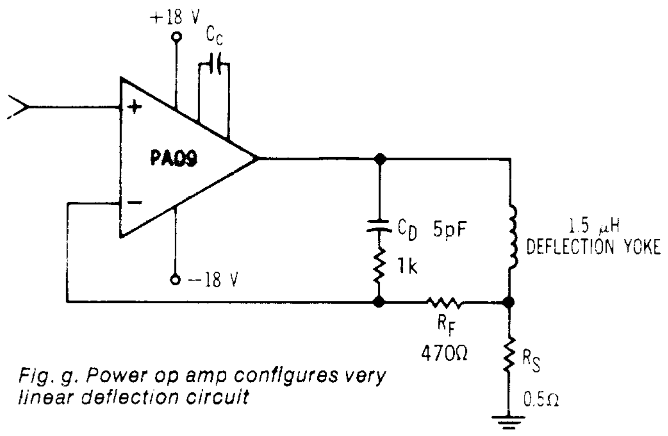


Fig. g. Power op amp configures very linear deflection circuit

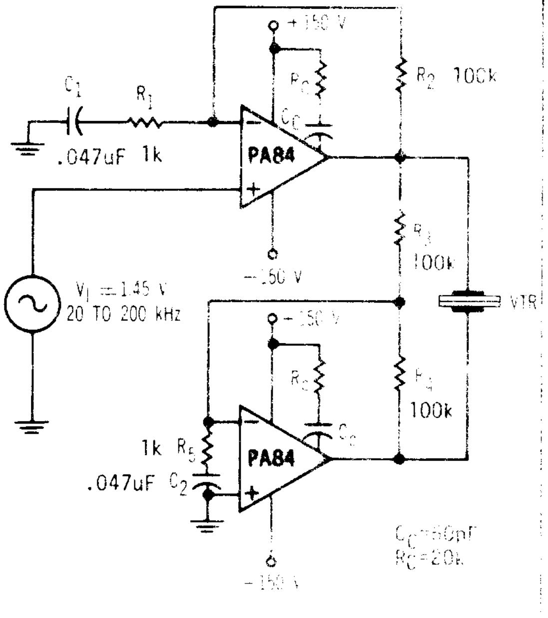


Fig. h. High voltage piezoelectric transducer driver

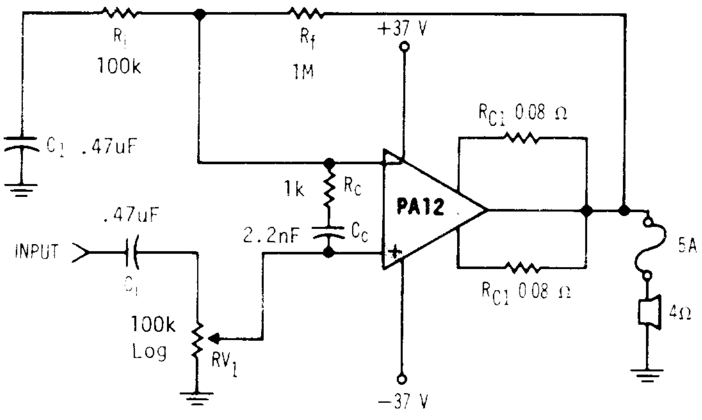


Fig. i. Distortion is less than 0.1% at 10 kHz and below with this 120-W audio amplifier. The fuse protects against short circuits in the external output.

Fig. g shows an example of an X or Y deflection amplifier using a video power op amp. Since the beam deflection amplitude is directly proportional to yoke current, the op amp is best operated as a voltage-to-current converter. This transfer function is very accurately implemented with R_S converting the current in the yoke into a feedback signal, which in turn is fed back to the inverting input via R_F. Capacitor C_D provides damping near the

unity gain frequency of the amplifier. Without it, the 90° phase shift of the inductor added to the phase shift of the amplifier would exceed 180° and make the circuit unstable. The current limit is set internally to 5 A to ensure safe operation with the inductive load at supply voltages up to ±18 V. For optimum speed, however, it may be desirable to use a higher supply voltage, since the current slew rate is directly proportional to the voltage applied to the yoke.

High voltage transducer drive circuits

Many ceramic or piezoelectric transducers require very large drive voltages to reach their full acoustic output power. Fig. h shows a circuit that can drive such a transducer with up to 580 Vpp or 205 V_{RMS}. The power op amp chosen exhibits large power bandwidth (200 kHz) at a gain of 100. Provided that $R_3 = R_4$, the gain for the circuit is

$$G = \frac{V_{TR}}{V_I} = 2 \left[1 + \frac{R_2}{R_1} \right].$$

Capacitors C1 and C2 provide DC stability by making the DC gain of the circuit equal to 2. Rc and Cc are external compensation capacitors required for the op amp if operated at an AC gain of 100.

Audio amplifiers

A closed loop amplifier circuit can provide low distortion and phase shift as well as flat frequency response, making it especially well suited for a high performance audio amplifier. Fig. i shows such a 120 W_{RMS} audio amplifier operating from a ±37 V supply. Input DC is decoupled by Ci. RV1 provides a volume control. The audio gain is set up by the ratio of RF/Ri. C2 reduces the DC output offset by making the DC gain equal to unity. Rc and Cc improve the high frequency stability. Since a typical speaker coil has less than 100 μH of inductance, no special precautions have to be taken to ensure conformance to the SOA with inductive loads.

The failure analysis file at Apex Microtechnology shows the three most common causes for user-induced premature failures and the generally recommended remedies, as follows:

1. Transient on supply exceeded maximum rating — use Zener diodes to clip transients.

2. Output voltage exceeded supply rails due to inductive load; in one case only 2 feet of cable — use external diodes.

3. Secondary breakdown of output transistor due to exceeding the SOA limit with inductive or CEMF generating loads — analyze load and check against SOA. Empirical measurements can often be made at reduced supply voltages, and current limits can then be scaled up to full power.

If you have designed and breadboarded your circuit, but you're not absolutely sure it is wired correctly and within the SOA, turn the power supply down to ±15 V before you turn it on for the first time. Once the circuit is operating as it should, put it into the worst case operating mode (i.e., motor reversal) and raise the supply gradually to the maximum. This approach can save a lot of failures and pinpoint problems to specific supply voltages.

Most power op amps have internal phase compensation, but some require an external compensation capacitor. While internal compensation requires fewer parts, an external capacitor provides more flexibility because it allows you to optimize the phase compensation for the gain of your circuit. The higher the gain, the less compensation required. Less compensation results in higher slew rates and greater bandwidth.

Illustrating the need for phase compensation, Fig. 5 (page 102) shows several Bode plots for Type PA84 power op amp. The plot for the uncompensated PA84 shows rapid gain rolloff at high frequencies, making it unstable where the plot crosses the unity loop gain line at more than 12 db/octave (180° phase shift) and marginally stable where it crosses the unity loop gain line at more than 9 db/octave. In addition, it shows the Bode plot when compensated for unity gain of 10 and a gain of 100.

Once the amplifier has been properly compensated, the external connections must be considered. External circuitry adds capacitance and inductance to the circuit, thereby modifying its closed loop response and phase shift. Excess phase shift may cause uncontrolled oscillations, which in turn may cause overheating, premature thermal shutdown, and in extreme cases, the destruction of the amplifier. Therefore, it is important that a power op amp output be thoroughly checked for parasitic oscillations under all possible load and signal conditions. This is best done by sweeping the amplifier with a small signal from 1 kHz to two times its unity gain frequency. The amplitude should decrease with increased frequency. Any peaking greater than 6 db is an indication of marginal stability.

Oscillations or peaking may be caused by any of the following conditions:

1. Poorly bypassed power supplies, causing feedback via the supply;

2. Unwanted current feedback through the common by improper connection of the load (ground loop);

3. Excessive inductance or delay-line effect in the feedback path, caused by long wires;

4. Excess stray capacitance between the output and the + input, causing positive feedback; or

5. Excessive sumpoint impedance and high capacitance between the − input and the common, adding phase shift.

These conditions can generally be remedied. You can sometimes increase the amplifier phase compensation rolloff to compensate for the problem, by increasing the value of the external compensation capacitor. However, adding a Series RC network between the input pins generally does it more efficiently without degrading slew rate. The effect of the RC network will be to attenuate feedback at high frequencies. ☐