Designing with Power Operational Amplifiers

While most general purpose operational amplifiers provide output currents up to 10 mA and output voltages of ± 12 V, power op amps now available from several manufacturers are designed to drive inherently bigger loads, such as motors, deflection coils, transducers, heaters and dc power buses. Higher voltages, currents, and internal power dissipation tend to make the package and the internal components larger, and additional design rules must be observed to achieve reliable operation. This article deals with these design rules, goes into the construction of the power op amps, and discusses several major control applications.

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Power op amps are electronic components rated for supply voltages greater than 22 V that can source or sink output currents in excess of ± 50 mA. Devices meeting only one of these criteria are categorized as high current or high voltage op amps.

In the past, only modules were available, but now several companies offer hybrid power op amps in power transistor cases. The widest product selections are available from Apex Microtechnology Corp., Burr-Brown Research Corp., National Semiconductor, and Teledyne Philbrick. Fairchild and Intersil also offer a few models. At present, second sourcing is only available between Apex Microtechnology and Burr-Brown.

The modern power op amp is a hybrid or a monolithic integrated circuit. Both will be smaller than comparable modules and will have fewer internal connections. Presently, hybrids provide the best performance, while monolithic ICs cost less. To maximize reliability when selecting a power op amp, available monolithic devices should be considered along with hybrids to meet the requirements of your application.

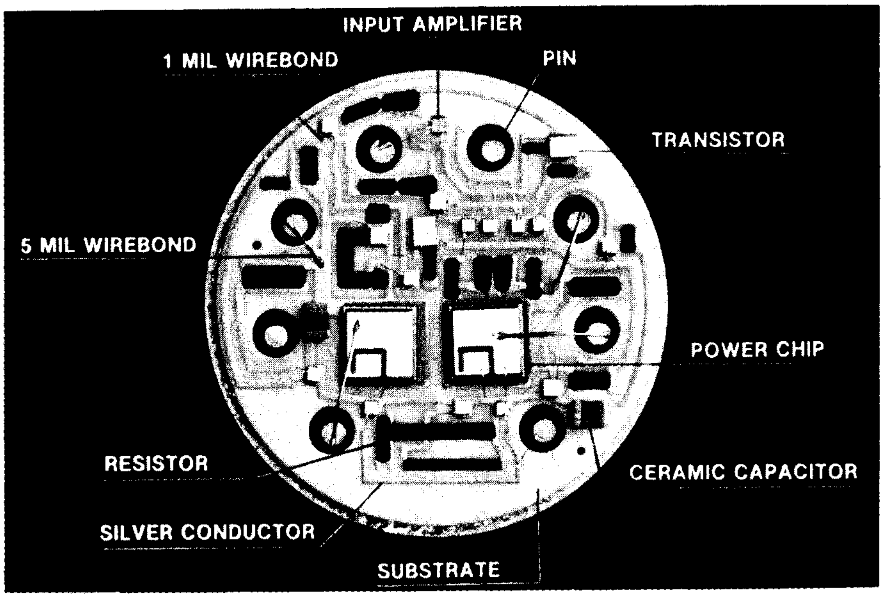
As an example of a hybrid power op amp, the first photo shows the internal layout of the Apex PA07, 8 pin, TO-3 power op amp. The most prominent components on the beryllia substrate are the two power darlington output transistor chips, next to the smaller current limiting and driver transistor chips. The monolithic dual input FET is located near the top of the substrate. It and most other chips are attached to the substrate metalization with conductive (silver) epoxy. However, the power darlingtons are soldered to the silver metalization pads using a special printed-on high temperature solder paste. The substrate itself is also soldered to the metal header. Interconnections from the top of the chips and the pins are made with either 1 mil or 5 mil aluminum wire, depending on current densities. Resistors and thermistors are printed with thick film paste to a tolerance of ± 15 percent. Two ceramic capacitors are also attached with conductive epoxy, which also provides contact with the electrodes.

Safe operating area

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, high current and high voltage op amps face additional restraints due to limits of the output transistors. A junction phenomenon called secondary breakdown can destroy most power transistors without exceeding the collector-emitter breakdown voltage, the maximum collector current, or the junction temperature limit. Secondary breakdown results from excess current densities 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. These operating restraints are reflected in the Safe Operating Area (SOA) curves published by most manufacturers of power op amps. A graph shows such a set of SOA curves (for the PA12).

These curves are easy to use. It must be known which output transistor conducts the current and how much voltage is dropped across the conducting transistor. Then the *x*-axis of the SOA graph is entered with the voltage drop across the current carrying transistor (supply to output differential voltage) and the maximum safe current is read on the *y*-axis. The schematic illustrates the current flow and voltage stress on the output transistors Q1 and Q2 of a typical power op amp. 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 the SOA limits are known, they can be observed by proper selection of the current limiting resistors.

In addition, the designer can choose the degree of protection he wants. Short circuit protection often requires a substantial reduction in the current limit due to the low maximum SOA current with the full supply voltage dissipated on the output transistors. Protection against all possible reactive or EMF loads requires even lower current limits because one output transistor has to



Hybrid power op amp is built on berrylia substrate and mounted in TO-3 can.

dissipate the sum of both (±) supply voltages during the output transitions from one supply rail to the other.

Resistive loads

When using 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:

$$R_L = \frac{V_{Omax}}{I_{Omax}}$$

Where R_L = Load resistor in ohms

V_{Omax} = Max output voltage at a given supply volts (usually −5 V)

I_{Omax} = Max output current from ratings without considering SOA

For example, if the PA12 has to drive a 4 Ω load, the supply voltage is ±42 V and the 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. At half the output current (4 A) we calculate a 26 V drop on the respective output transistor. Both conditions are shown to be safe on the SOA curve. If that same amplifier must be short circuit proof, 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

Use with dc motor loads makes the determination of the safe operating conditions more complex because of the EMF generated internally as a function of instantaneous shaft speed. The second diagram shows a PA12 power op amp driving a dc motor, and the motor's 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:

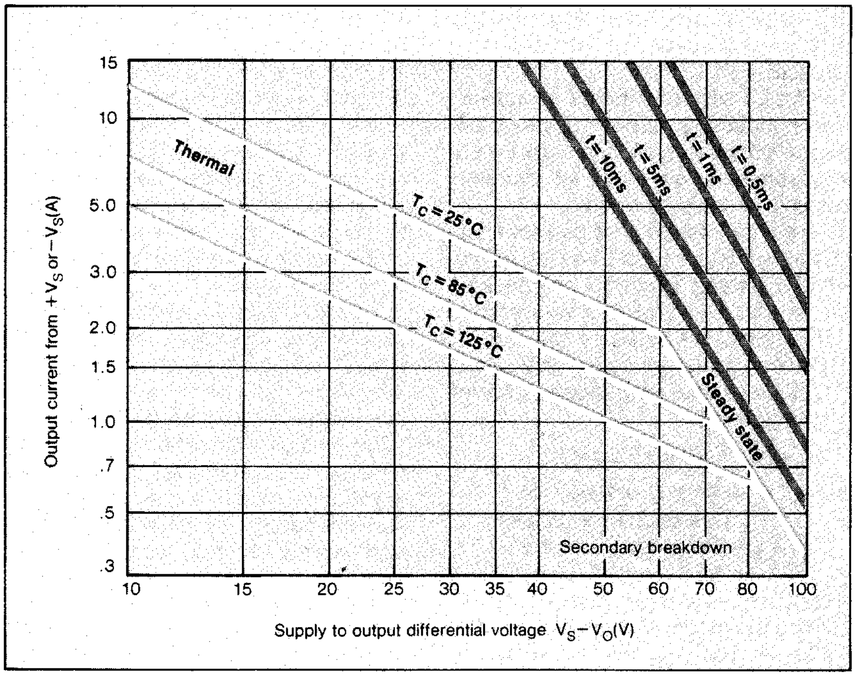
$$EMF = V_O - I_m R_w$$

Where V_O = Output voltage of the power op amp

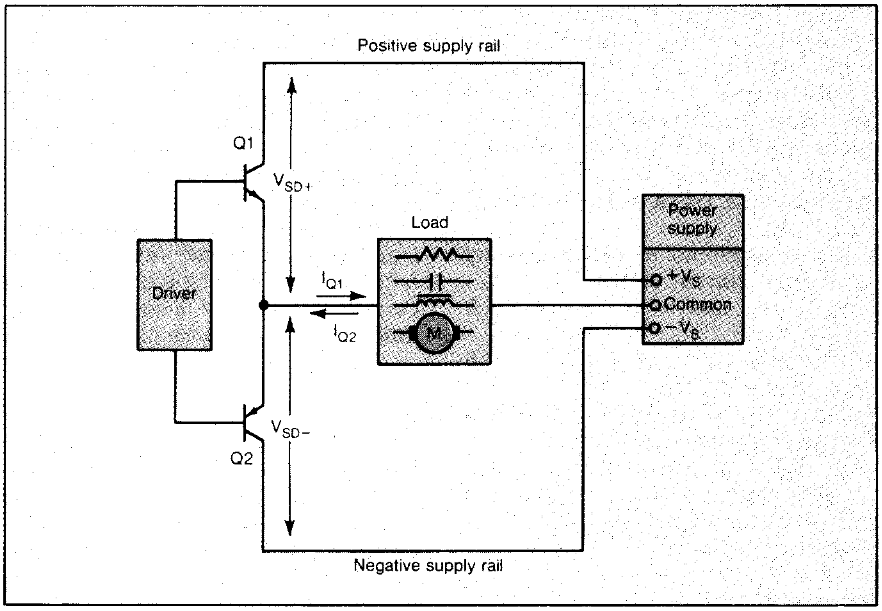
I_m = Current drawn by motor at constant speed

R_w = Winding resistance of the motor

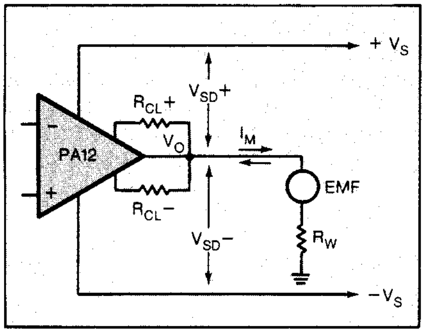
Due to the effect of the EMF, the motor will draw the least current under steady state conditions (constant speed) and the most current under transient conditions (start, stop, reverse) especially when reverse voltage is suddenly applied. The time lag from the instant that the amplifier output voltage is reversed



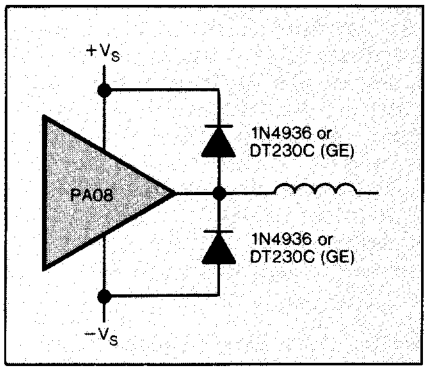
Safe operating area curves (here for PA 12) are essential for design using power op amps.



Circuit provides definitions for design with power op amps, see text.



When driving dc motors, it is necessary to calculate the effect of back EMF on the amplifier's internal voltage drop.



External diodes are sometimes necessary to protect power op amps against voltage kickback of inductive loads.

until the motor itself reverses puts the most severe stress on the amplifier because:

- The motor will draw the most current.
- 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. Proceed as follows:

1. Determine the value of the EMF at max speed as previously indicated.
2. Calculate the amplifier's internal voltage drop.

$$V_{SO} = V_S + EMF - I_{LIM}R_w$$

Where V_S = Supply voltage for conducting transistor
I_{LIM} = Programmed current limit

3. Determine the time required to reverse the motor. If it takes less than 10 msec 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} on the applicable SOA curve—interpolate if necessary.

For example, for a position control system using a 24 V motor with an internal resistance of 5 Ω and a maximum current specified of 5 A:

1. Select PA12. Use a supply voltage of ± 28 V.
2. Run loaded motor at max output and measure current of 1 A.
3. Calculate EMF = 24 V − 1 A · 5 Ω = 19 V.
4. Calculate V_{SO} = 28 V + 19 V − 5 A · 5 Ω = 22 V.
5. Enter SOA curve *x*-axis at 22 V and read maximum current of 4.5 A at T_C=85 C or 6.5 A at T_C=25 C indicating that the case temperature must be kept well below 85 C if the current limit is ± 5 A.

Inductive loads

The characteristics of inductive loads should be well understood prior to using them with power op amps. Many amplifiers have been destroyed because of one of three specific attributes of inductive loads. First is 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:

$$V_f = \Delta i\, R$$

Where Δi = Current change in the inductor
R = Equivalent parallel loss resistor

From this simple equation it can be shown that 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 will be easily destroyed by these flyback voltages.

The next diagram shows two diodes as a simple protection, clipping off the flyback voltage in excess of ± V_S. If the amplifier does not have these protection diodes incorporated internally, two external high speed diodes (D1 + D2) must be used whenever the lead has a significant inductive component. Long wires or cables are often inductive and can destroy an unprotected power op amp.

If the degree of damping of the load inductance is not known, it is recommended to 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, the diodes should be left in the circuit. Each diode should be rated for a reverse voltage equal to the sum of the supply voltages, and current equal to the limit set. Both diodes must be fast recovery types unless op-amp speed is not critical.

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

$$\frac{di}{dt} = \frac{\Delta V}{L}$$

which means the larger the inductive load, the slower the current changes after voltage is applied.

Again this imposes the greatest stress on the amplifier during reversal of its output voltage, 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 to check if a given inductive load is indeed safe:

$$L_{max} = \frac{V_O \cdot t}{I_{LIM} - I_{SAFE}}$$

Where V_O = Amplifier output voltage immediatley following reversal
I_{LIM} = Programmed current limit

Values for *t* and *I* must be found on the SOA curve by first 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} (read on *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 state 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.

The following is an example of an electron beam deflection coil with a dc resistance of 2.5 Ω and an inductance of 5 mH requiring 8 A for full deflection to be driven by a PA12 at a supply voltage of ±35 V:

1. Flyback protection is automatically provided with the PA12 because two protection diodes are built in, as shown on the schematic. Other op amps, such as the Apex PA08, PA83, and PA84, may require external diodes when driving inductive loads.
2. Calculate the maximum inductance:

$$L_{max} = \frac{V_O \cdot t}{I_{LIM} - I_{SAFE}}$$

$$= \frac{30\ \text{V} \cdot 5 \times 10^{-3}\ \text{s}}{8\ \text{A} - 4\ \text{A}} = 37\ \text{mH}$$

Note: The SOA curve below the intersection of $V_S + V_O$ = 65 V and I_{LIM} = 8 A is for 5 msec transients and intersects 65 V at 4 A.

3. Under steady state conditions the limiting current of 8 A will cause a drop of 20 V on the internal resistance of the coil, leaving 15 V to be dissipated by the amplifier output transistor. The SOA curve shows this to be safe at T_C = 25 C.

Capacitive loads

The current *i* required to change the voltage *V* on a capacitor is:

$$i = C\frac{dV}{dt}$$

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 the output. To determine the maximum safe capacitive load, use the following equation:

$$C_{max} = \frac{I_{LIM} \cdot t_S}{V_{SS} - V_{SAFE}}$$

Where I_{LIM} = Programmed limit

V_{SS} = Supply voltage rail to rail

The values of t_S and V_{SAFE} must be found on the SOA curve by entering the x-axis with I_{LIM} and the finding the next SOA curve under the intersection of these two points. Read t_S on the curve, and read V_{SAFE} on the x-axis where that SOA line crosses I_{LIM}.

Short circuits

As mentioned before, under short circuit conditions, the amplifier will current limit, and the current carrying transistor will dissipate 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.

Thermal considerations

The data sheet of most power op amps specifies 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:

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

Where P = Internal power dissipation

V_S = Supply voltage, 1 rail

and other terms are as previously defined.

The dissipation for dc and sine wave outputs is calculated easily. For complex waveforms, it is difficult, and often easier to measure. Once the internal power dissipation P is known, 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 = Max junction temperature

T_A = Max ambient temp.

Φ_{JC} = Amplifier thermal resistance

For power op amps without thermal shutoff, the power dissipation P must be calculated for the worst-case normal and abnormal operating conditions, such as maximum output and short circuit. However, thermal shutoff, now available with power op amps reduces heat sink requirements because the heat sink needs only to be calculated for worst case operating conditions. Often this means a size reduction by a factor of 5 to 10, because 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.

Applications

Power op amps can be used in all applications that general purpose op amps are used in. Many volumes have been written about the subject. The books by Jerold Craeme of Burr-Brown are highly recommended to any engineer using op amps. This article covers two control applications that are the forte of the power op amp.

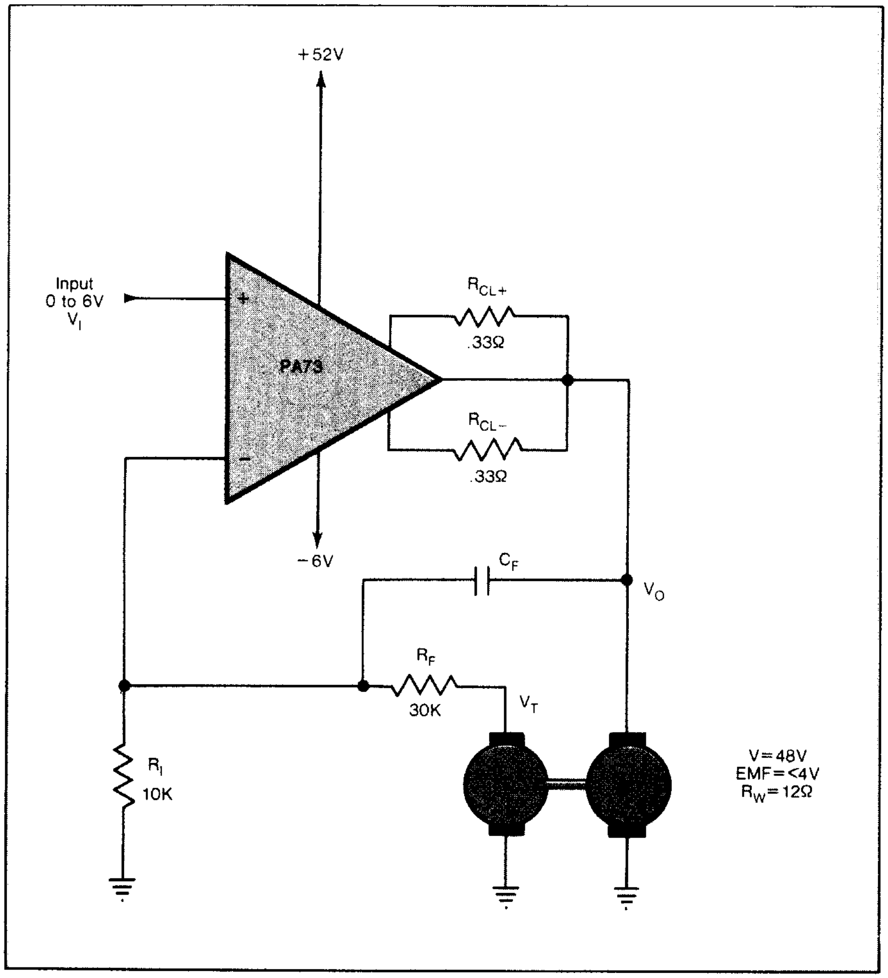
Single or dual supplies

The first choice important for any application, is whether a dual (±) or a single supply should be used. Obviously, if the load requires a bidirectional drive, such as 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 consumption and dissipation.

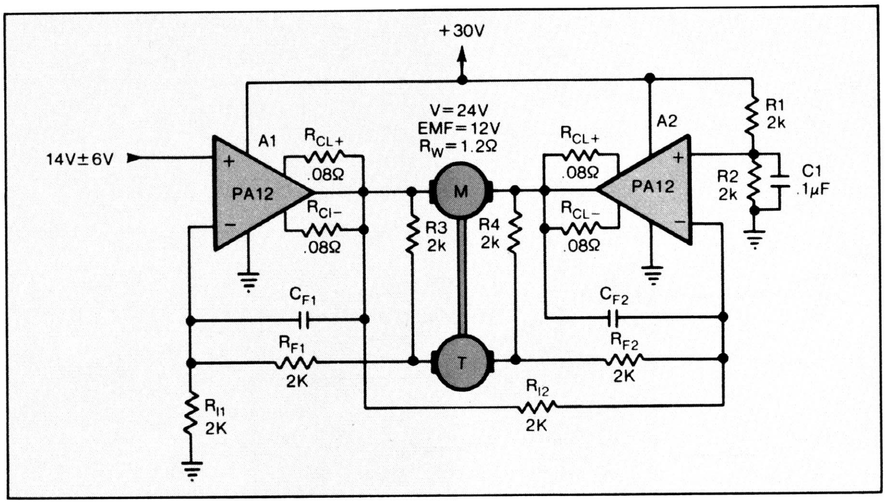
A different solution of optimizing output power and minimizing power consumption is the use of a nonsymmetrical power supply. In such a setup, each supply will provide just enough voltage to allow the output to swing the load to the required level.

Speed control

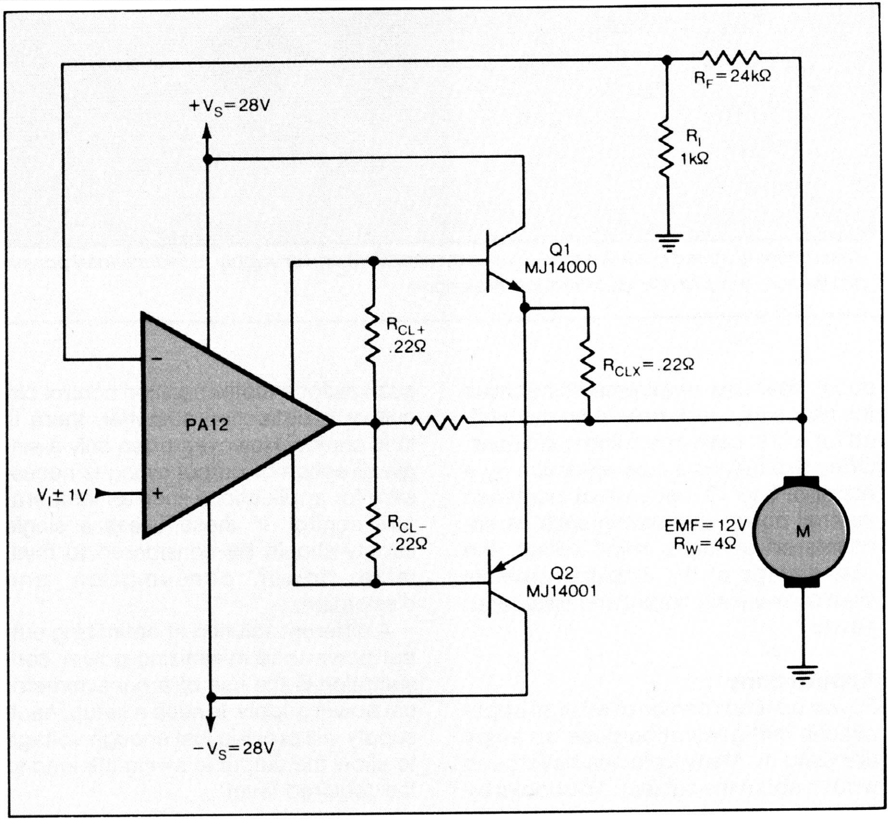
Speed control circuits for dc motors are easily implemented with power op amps. Diagrams depict two different circuits. One shows a unidirectional speed control implemented with a nonsymmetrical dual power supply where the positive supply voltage of 52 V provides for full speed control of the 48 V motor, while the negative supply biases



Unidirectional speed control circuit uses unsymmetrical power supply to reduce total power dissipation, yet provide deceleration braking.



Bidirectional speed control circuit uses two power op amps in a differential connection, so load is shared by both amplifiers.



External power transistors can always be added to power op amps to raise the output current capabilities as necessary, see text.

the amplifier input stage and allows for deceleration (braking) of the motor. With the specified motor, the SOA of the PA73 requires the current limit to be programmed for ±2 A with R_{CE+} and R_{CE-} of 0.33 Ω. The transfer function of the circuit is set by:

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

Where S = Motor speed in krpm
K = Tach EMF in V per krpm

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 capacitor must be selected for the individual application. It is best to start with a capacitor of 1μF or so and then reduce its value until the feedback loop has the proper damping in response to a step change at the input.

The second diagram 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 noninverting configuration while A2 is a unity gain inverter. At maximum input, the motor can be driven in each direction with the supply voltage less the sum of A1's and A2's saturation voltages. As in the previous circuit, capacitances C_{F1} and C_{F2} must be chosen for optimum damping in the individual application, while the current limiting resistances R_{CL} were selected to protect the amplifier. Amplifier A2 is biased to half the supply using R1, R2, and bypass capacitor C1. Resistors R3 and R4 provide dc operating point feedback. The transfer function of the circuit is:

$$S = \frac{2V_I}{K}\left(1 - \frac{R_F}{R_I}\right)$$

Increased output current

As explained previously, motors are very demanding loads because they store energy. For example, the PA12 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 safe under instant reverse conditions. However, if more current is required, two external transistors can supply extra current when needed. The circuit shows an example where Q1 and Q2 provide up to ±3 A in addition to what the PA12 can provide. Note that the MJE 14000 and 14001 are rated for 70 A, but due to SOA limitations can only supply ±3 A under the mentioned conditions of supply and load. ☐