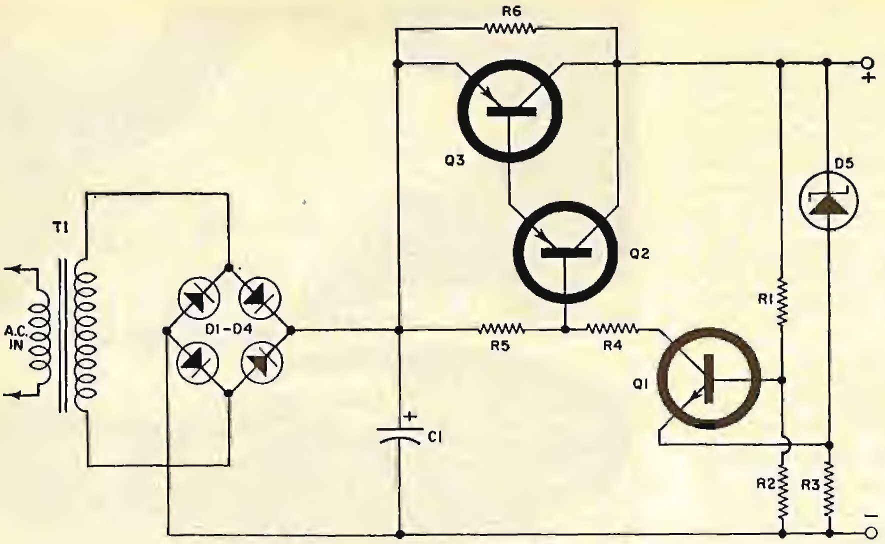


Fig. 1. Basic regulated power-supply circuit showing bridge-rectifier circuit, reservoir capacitor, regulator circuit.

Design and Construction of Regulated Power Supplies

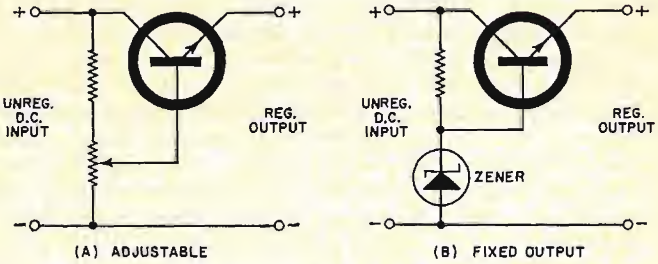
By RICHARD H. DUTTON

Construction hints and design criteria for building some inexpensive, but very stable, series-pass regulated power supplies. The fabrication of a 20-volt, 1.5-ampere regulated power supply with a dynamic impedance under 0.4 ohm and with regulation better than 1 percent is described thoroughly.

NEARLY all experimental projects need a power supply of one kind or another. Batteries are convenient for experimental and portable use but are not adequate when large amounts of power are required for extended periods of time.

Most a.c. power supplies function with a simple rectifier and choke-capacitance or resistance-capacitance filter. The choke filter (Fig. 2A) is bulky and relatively costly while the resistance filter (Fig. 2B), to be really effective, wastes considerable power. Neither power supply is regulated and, when high currents are drawn from the supply, output voltage falls while ripple increases. Some improvement in power-supply output can be obtained by the addition of the simple emitter-follower stabilizer shown in Fig. 3. However, the output impedance of this device is still on the order of several ohms so that unwanted feedback and cross coupling can still occur when several amplifier stages are placed in parallel on the same power-supply bus.

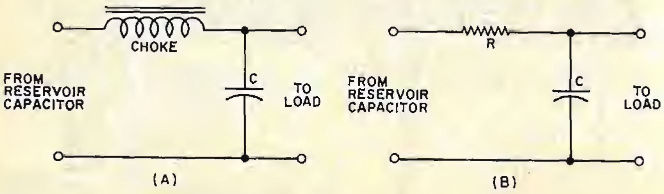
The power supply described in this article tends to overcome the disadvantages mentioned by being efficient, using only inexpensive non-critical parts which are readily available, and by being of very low impedance and fully regulated. Using only spare parts, the 20-volt, 1.5-amp version described is presently powering both channels of a home stereo center with both the power amplifier and preamp power-supply lines connected in parallel. The measured power-supply dynamic impedance is less than 0.4 ohm, regulation is better than 1 percent, and there is no trace of audible hum, line noise, nor channel crosstalk.



(A) ADJUSTABLE (B) FIXED OUTPUT

Fig. 3. (A) Adjustable and (B) fixed type of emitter-follower stabilizers used to regulate output of power-supply units.

Fig. 2. Two filter networks, (A) choke-capacitance and (B) resistance-capacitance, commonly used with power supplies.



(A) (B)

Basic Circuit

Two unusual features of this power supply are shown in Fig. 1. First, no choke or smoothing component of any kind, other than the usual reservoir capacitor and the regulator itself, is included. Second, series-pass transistor Q3 is used in the collector-follower mode instead of the more commonly used emitter-follower configuration, thus contributing quite significantly to the voltage gain of the regulator loop and maintaining a low output impedance without the need for additional amplification stages. There are, in fact, only two voltage-amplifying stages, *Q*1 and *Q*3, with phase inversion occurring in *Q*3 only, so that undesirable interstage feedback is eliminated and excellent output voltage stability is maintained.

How it Works

Transformer *T*1, diodes *D*1 through *D*4, and capacitor *C*1 form a standard bridge-rectifier circuit with reservoir capacitor. If the available transformer secondary is center-tapped, a standard full-wave configuration can be used instead of the bridge. The remainder of the circuit forms the regulator proper with *Q*1 functioning as a differential voltage amplifier. Any voltage change appearing at the top of the voltage dividers, formed by *R*1 and *R*2 and by *D*5 and *R*3, is sensed at the base and emitter of *Q*1, respectively. Since the emitter of *Q*1 is connected to the voltage source through zener diode *D*5, the full amount of the change appears at the emitter because the zener maintains a constant voltage drop within its operating range. However, the voltage change at the base of *Q*1 is less than the change at the emitter because of the voltage-divider effect of *R*1 and *R*2. The voltage across the emitter-base junction of *Q*1 is, therefore, the differential between these two changes, resulting in *Q*1 tending to carry more current if the output voltage falls and less if it rises.

The collector current of *Q*1 flows through *R*4 and through *R*5 which is in parallel with the base-emitter junction of *Q*2.

The change at the base of *Q*2 is current amplified, in phase, by emitter-follower action of *Q*2, and appears as a larger current change at the base of *Q*3. The increased current in the base-emitter junction of *Q*3, originally caused by the amplification of the drop in voltage at the output terminal by *Q*1 and *Q*2, causes *Q*3 to conduct more, reducing the voltage drop between collector and emitter and thus effectively raising the output voltage by the amount necessary to cancel out the original change. Since the loop is completely d.c.-coupled and there are no *RC* time constants, this correction is, in effect, instantaneous with only a minute residual change in output voltage. Basically, the operation can be compared with that of a high-gain power amplifier with virtually 100 percent negative feedback, as shown in the block diagram of Fig. 4.

Function of *R*6

At this point, to explain the function of *R*6, we must first consider the basic circuit with *R*6 removed. Then, at switch on, the rectified d.c. voltage would appear across *C*1, in parallel with the load and *Q*3, which are in series. However, with this setup there is initially no voltage across the load itself and *Q*1 remains cut off because of the absence of a differential between its emitter-base junction. As a result, no current will flow in the base-emitter junctions of *Q*2 and *Q*3 so that these transistors remain at cut-off. Consequently, no current will flow and all of the voltage will appear across the pass transistor, *Q*3.

This situation can be rapidly corrected by introducing sufficient voltage at the base of *Q*1 to overcome the emitter-base junction bias and turn it on. As soon as *Q*1 turns on, voltage appears across the load and the normal loop gain takes over, stabilizing the output voltage at the selected level. The voltage required to turn *Q*1 on can be introduced by a flashlight battery connected through a diode to the base of *Q*1, with the other battery terminal grounded. At switch-on current would be drawn and then, during normal operation, the connecting diode would back-bias and disconnect the battery. However, it is more convenient to tap the unregulated supply for the necessary starting potential by adding *R*6. With *R*6 in the circuit, the starting potential is the voltage across *C*1, dropped by *R*6, *R*1, and *R*2 and by *R*6, *D*5, and *R*3, to the base and emitter of *Q*1, respectively. Since the zener is initially non-conducting and *R*3 is small compared to *R*2, the differential across the emitter-base junction at *Q*1 is initially quite large, causing the supply to turn on very quickly.

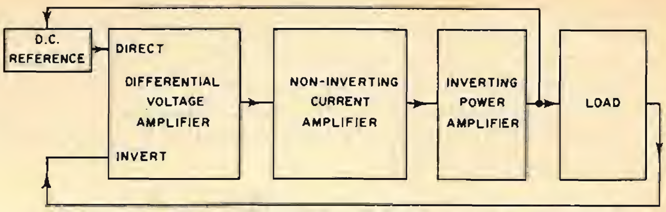


Fig. 4. Block diagram of high-gain, 100 percent negative feedback power amplifier used as analog of regulated power supply.

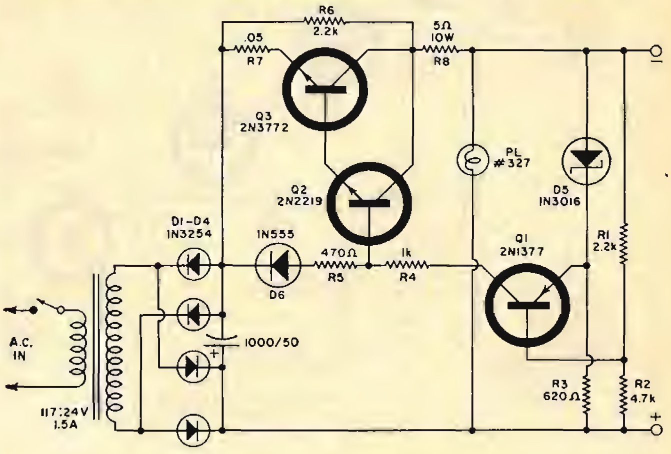
Once the supply has turned on, the voltage across the starter resistor (*R*6) and therefore the current through it, drops to a very low value and has no effect on the regulation or the output voltage. This action emphasizes a couple of other things that can be done with the supply if we want to. First, we can place a normally open push-button, relay contacts, photocell, or other control device in series with *R*6. Even though a.c. power is applied, d.c. power will not come on until the control device is activated either locally or remotely, and once on will stay on regardless of the operating condition of the control.

A similar device across *R*2 can operate as a remote cut-off, and variation of *R*2, within the limits discussed later in the article under "Construction Hints," can be used to adjust the output voltage. Second, the output terminals can be short-circuited without causing any damage since there is no capacitive storage at the output and the current surge through the short circuit will last only long enough for *Q*1 to react and turn *Q*2 and *Q*3 off. However, if *R*6 is in the circuit the output voltage will be restored immediately when the short or overload condition is removed. This is very important when using the supply to power a construction project where accidental short circuits may occur.

Final Circuit Design

The final circuits, Figs. 5 and 6, show three components not in the basic circuit (Fig. 1). Although the circuit will work perfectly well without these components they provide protection against inadvertent thermal runaway. *D*6 provides a d.c. bias on *Q*2 which reduces the necessary amount of swing at the collector of *Q*1 and thereby increases the loop gain. At the same time, the potential drop across *D*6 varies inversely as its temperature, thus reducing the bias on *Q*2 and the current through *Q*3, as the resistance of *Q*3 also falls with temperature. *R*7 is a positive temperature-coefficient resistor whose value increases with temperature, thus having

Fig. 5. Schematic diagram of the 20-volt, 1.5-ampere regulated power-supply unit showing the components (D6, R7, and R8) that provide protection against inadvertent thermal runaway.



the same effect of reducing the forward bias. *R*8 is a "power waster" and need only be used when the rectified d.c. voltage at the emitter of *Q*3 is significantly higher, with respect to ground, than the desired output voltage. By inserting *R*8 the power dissipation in *Q*3 can be considerably reduced while not affecting the regulation of the supply, because *R*8 is within the feedback loop.

Construction Hints

Parts placement for the construction of the power supplies shown in Figs. 5 and 6 is non-critical except that *Q*3 must be mounted on an adequate heatsink and be capable of dissipating the maximum necessary power; that is, the product of the maximum voltage across *Q*3 times the maximum current through it should be no greater than the transistor power rating, even though these two conditions are unlikely to occur together. The voltage rating should be at least one and a half times the expected output voltage, or about 10 percent greater than the no-load voltage across *C*1, whichever is larger. If in doubt, select a "bigger" transistor and check it for leakage by connecting base-to-emitter, putting it in series with a milliammeter and, making sure that the polarity is correct, connect it across a 12-volt battery.

If the leakage current is less than 1 mA, mount *Q*3 to the heatsink, using an appropriate mounting kit and plenty of silicone grease. *Q*3 can be either silicon or germanium, according to which is handy, and either of the TO-3 or door-knob-size package. Silicon is preferred because of its higher temperature capability but germanium is perfectly satisfactory if it is adequately cooled. Mount R7 and D6 to the heatsink about 1 to 1½ inches from *Q*3, and on opposite sides of it if possible to compensate for uneven heat distribution in the heatsink. Closer mounting is permissible if space is particularly tight. Don't use a silicon diode with a germanium transistor but, if you don't have a silicon diode handy when using a silicon transistor, use two germanium diodes in series.

Fasten diode *D*6 to the heatsink with a spot of epoxy or use a small stud-mounted type, insulated from the heatsink with a mica washer. *R*7 can be a bolt-on type resistor of any value that will provide a voltage across it that is less than 0.5 volt at maximum current when *Q*3 is silicon, or less than 0.25 volt when *Q*3 is germanium. *R*7 can be replaced by either a 1-ampere slow-blow fuse seated in a clip bolted to the heatsink or by about 15 inches of #26 magnet wire wound around the body of a 1-watt resistor and epoxied to the heatsink. The other components should be mounted on a piece of phenolic, perfboard, etc. and spaced at least ½ inch from the heatsink. Using a separate heatsink, if necessary, mount the transformer and rectifier bridge so that they don't contribute to or are affected by the heat generated by *Q*3. Select a transformer that is rated to carry the maximum current required at a voltage rating about 5 volts higher than the maximum output rating, and connect it to the rectifier assembly and to *C*1.

If the voltage across *C*1 is much greater than 5 volts higher than the output voltage desired, calculate the value of *R*8 that would be necessary to drop the additional voltage at maximum rated current, leaving about 5 volts across *Q*3. Use a high-wattage resistor for *R*8 and mount it where it will be adequately ventilated. The proper selection of *R*8 will reduce the power dissipation in *Q*3 and lengthen its life. However, if *R*8 isn't necessary then leave it out and connect the output terminal and divider chains directly to the collector of *Q*3. *Q*2 can be any convenient transistor of the same polarity and material as *Q*3 and capable of providing the necessary base current to *Q*3. A collector current rating of 150 mA for *Q*2 is usually adequate.

The differential amplifier, consisting of *Q*1, *R*1, *R*2, *R*3, and *D*5 is the most sensitive part of the regulator and any drift in this area will cause a corresponding output voltage change. It is more desirable to use a germanium transistor for *Q*1 because the junction potential is less than silicon, thereby requiring a smaller differential. However, when making an adjustable power supply use a silicon transistor and a trimmer to offset the increased differential.

For a fixed-voltage output the calculation of resistor values must take into account the junction differentials. Since *R*4 limits the collector current of *Q*1 to less than 10 mA, the transistor current can be neglected when calculating *R*3. To calculate *R*3 first select a zener or reference diode with a zener voltage between one-quarter and three-quarters of the design output voltage. High values within this range will improve the regulation slightly by increasing the relative base-emitter change across *Q*1, while low values will reduce zener dissipation and long-term drift. Make sure the reference zener is of good quality since the stability of this device determines the stability of the power supply. Subtract the zener voltage from the required output voltage and, using Ohm's Law, calculate the resistance value of *R*3 that will draw the current which will cause the zener to run about one-third of its maximum rating. Do not starve the zener or its voltage will not be constant with time.

When building a variable supply, calculate *R*3 so as not to cause more than 90 percent of the rated dissipation in the zener at the highest voltage and not less than 15 percent at the lowest voltage. Use a 1-watt zener for power supplies in the 12-volt-and-up range and a 400-milliwatt zener for lower voltages. Very low voltage supplies, such as a 4.5-volt IC supply, can use three or four forward-biased silicon diodes in series as a reference instead of a zener. Always be sure to use diodes of large enough current capacity so that the current through *R*3 will be at least five times the emitter current of *Q*1. Next, calculate those values of *R*1 and *R*2 which, together, will permit a current flow of 3 to 5 mA at the desired

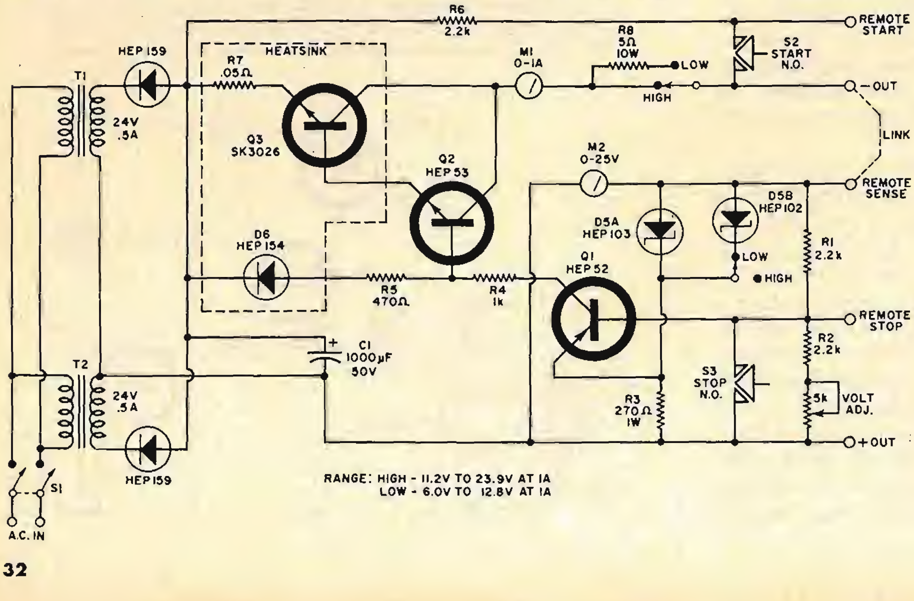


Fig. 6. Schematic diagram of laboratory version of closely regulated power supply. When remote start/stop is not required, leave connections open; when required, connect N.O. push-button switches at terminals in parallel to internal push-button. If local start/stop is not required, remove push-buttons and bridge remote start lead internally to negative output terminal and use power switch S1 to control. Length of remote leads is not critical if resistance is small. Twisted pair of leads, connected together at the load, should be used for remote sense and negative bus. The supply is floating, therefore either bus may be grounded. All transistors must be of the low-leakage type for the various "remotes" to function correctly.

Table 1. Alternate component values for outputs other than that shown in Fig. 7.

OUTPUT VOLTAGE FOR SINGLE-ENDED SUPPLY (nominal)	RANGE OF TRANS. SEC. VOLTAGE (r.m.s.)	ZENER DIODE 400 mW RATING (volts)	RESISTORS ±10% R1	R2	R3
5	6.3	3.6	270	180	47
6	6-10	3.6	510	510	56
9	12	6.2	680	1100	68
12	12.6-18	9.1	1200	510	68
18	18-24	12.0	1100	1000	390
30	28-36	12.0	2000	3300	1200

output voltage while dropping a voltage across $R2$ that is equal to the voltage across $R3$ plus the junction potential of $Q1$. The junction potential will be between 0.2 and 0.4 volt for a germanium transistor and close to 0.6 volt for a small-signal silicon transistor. Ignore the base current of $Q1$, since it is too small to influence the calculation.

It is unlikely that calculated values for $R1$ and $R2$ will exactly match the normally available quarter-watt 10-percent tolerance resistor scale, so the trick is to increase or decrease both calculated values in the same ratio to the nearest standards. If the tolerances add up incorrectly or the junction potential of $Q1$ is not quite what it was indicated to be, the power-supply output voltage will be slightly different from the design value, but otherwise operation will be normal. If the discrepancy is troublesome, reduce the value of $R2$ by, say, 500 ohms, connect a 1000-ohm miniature potentiometer in series with it, and "trim" the supply to the desired voltage.

Adjustable Supplies

An adjustable supply can be obtained in the same way. Calculate the value of $R2$ alone, for the lowest voltage obtainable within the zener-current limits described before and then the value of $R2$ plus potentiometer that will give the highest voltage. The potentiometer can be connected either locally or remotely. If a remote pot is used it is better to put it in series with $R1$ rather than $R2$ because then, if the remote line is opened, the supply will switch off rather than swinging to highest voltage. If more than one "range" is required, the zener diode can be switched. Use a make-before-break switch or switch the lower voltage zener in parallel with the higher one so that the emitter of $Q1$ never loses voltage. If you wish to package the power supply for bench use, with meters, and without losing regulation because of meter impedance, simply connect the voltmeter across the output terminals and the current meter within the feedback loop between the collector of $Q3$ and the junction of $R1$ and $D5$. If $R8$ is used, the meter can be placed on the side of $R8$ that is most convenient. The slight amount of current drawn by the voltmeter and voltage-amplifier chains may shift the zero on the ammeter a little if it is sensitive enough, but this can be overcome by resetting the pointer to zero with the power supply on and no load connected. A #327 pilot lamp, connected as shown in Fig. 5, draws very little current and provides a good visual indication of power-supply operating conditions, especially when meters are not included in the design.

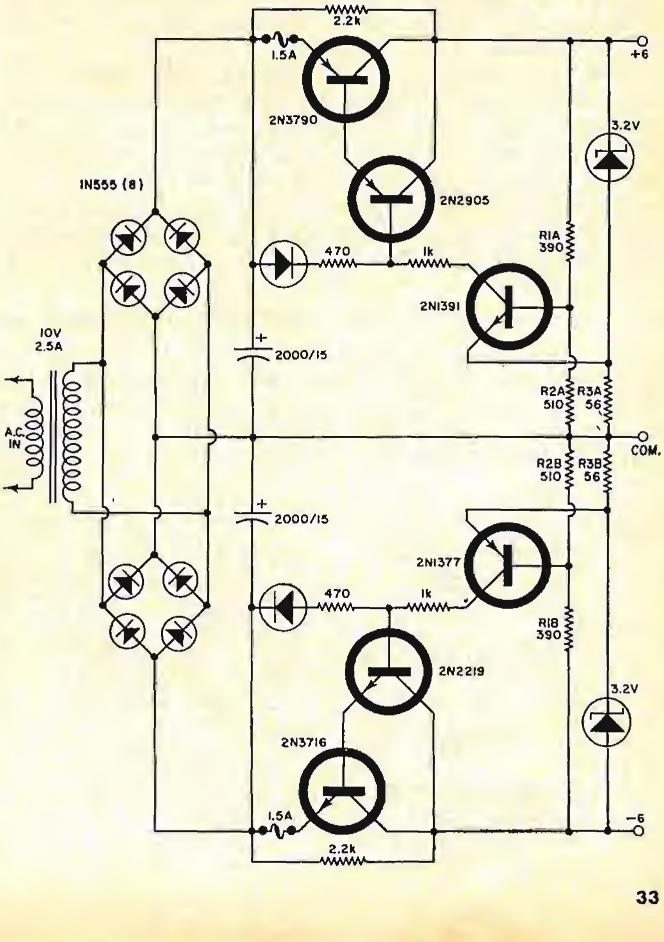
Dual Supplies

Fig. 7 shows a dual power supply with positive and negative outputs symmetrical about the common point. This type of supply is useful for servo-motor drive and similar applications where symmetrical outputs are desired. It can also be used to power complementary-transistor type OTL audio amplifiers, permitting the normal amplifier output blocking capacitor to be eliminated by connecting the amplifier to the positive and negative power-supply terminals and the speaker between amplifier output and power-supply common. Typical component values are given in Fig. 7 for 6-volt operation and alternate component values for other popular outputs are listed in Table 1. It is not essential that the positive and negative voltages be equal but the transformer must be capable of supplying the total current of both halves at the voltage necessary for the higher output bus. Be sure that semiconductor ratings are adequate for the maximum voltage that can appear across them under "worst-case" conditions. Transistors should be rated for at least 1.5 times the r.m.s. voltage of the transformer secondary, as should the capacitors, with adequate rectifier p.i.v. ratings as well.

Multiple voltage supplies can be readily obtained by designing the regulator for the requirements of the main bus and then using this bus as the input for one or more emitter-follower regulators of the type shown in Fig. 3. This method provides closely stabilized collector and base potentials for the emitter-follower, thus improving its stability over the unregulated input version by several orders of magnitude. The current drawn from such a device should be small and nearly constant, otherwise it might be better to provide a separate fully regulated supply, in order to maintain a low dynamic impedance.

(Continued on page 89)

Fig. 7. Dual polarity power supply used for servo-motor drive and similar applications where symmetrical outputs are required. The component values shown are typical for ±6-volt operation.



It will be evident to the more experienced experimenter that several additional features could be incorporated into the design of this type of power supply. The addition of meters as shown in Fig. 6 is a case in point. Other features include both fine- and coarse-voltage control, presettable current limiting, and a means of overcoming the nominal 1.5-volt minimum voltage output inherent in the basic design. However, it was felt that the basic premise of this article would be violated by the additional complexity and expense involved in incorporating such features. Hence no attempt has been made to do more than acknowledge the feasibility of such features and to suggest their incorporation only when the additional cost is justified. The basic design described here is more than adequate for its purpose, having been used to power audio systems, experimental musical instruments, and electric trains and slot cars (for which its constant voltage-variable current characteristic at each setting of the speed control is ideal). In no case has the minimum voltage offset been a problem. Additional uses, besides general-purpose bench service, include power for IC circuits, regulation of inverter output, brightness adjustment of a low-voltage-type reading lamp, and constant-speed motor control using tachometer feedback. The HO train version includes a switch to disconnect C1. This provides "pulse power" with the amplitude of the flat-top pulses controlled by the throttle potentiometer.

Additional uses will no doubt occur to the reader, for which this simple, stable regulator will more than justify its very nominal cost. ▲