Designing Practical DC Power Supplies

Once you know all about rectifiers, filters, and basic regulators you are ready for three-terminal regulators, current regulators, output-current limiting, over-voltage protection, heat sinks, switching regulators, and inverter circuits

By Joseph J. Carr

☐IF YOU ARE CONFIDENT THAT YOU KNOW ALL THERE IS TO know about designing the basic rectifying and filtering circuits for a power supply, you can dig into this article that begins with voltage-regulator circuits. Covered here are not only the standard three-terminal devices, but also certain special applications of three-terminal, integrated-circuit voltage regulators and adjustable integrated-circuit voltage regulators. You can also obtain information on switching voltage regulators— and we have even gone into the discussion of protection devices that every project builder should know about. Should you desire to beef-up your knowledge on power supply circuit design before getting into this article, we suggest that you look through the Summer, 1984 issue of **Hands-On Electronics** and read the first part of this feature article.

Three-Terminal Regulators

Three-terminal, integrated-circuit voltage regulators are a family of devices that provide fixed-output voltages, and are packaged in (usually) standard power-transistor cases (TO-3, TO-39, TO-92, TO-5 and TO-220). Rated output currents range from 100 mA in the TO-5 (and TO-39, TO-92) package up to 10 amperes in certain TO-3 types; most TO-3 and TO-220 devices are rated 750 mA to 1 ampere.

Figure 1 shows package outlines for the most common forms of three-terminal, integrated-circuit voltage regulator. Note that all use standard transistor packages. Other packages are used, but most are special house-brand types and are, therefore, unique to a company.

An all but *universal* circuit for using three-terminal integrated-circuit voltage regulators is shown in Fig. 2. Some elements of that circuit are optional, while others are found all of the time. Not shown in Fig. 2 is the transformer and AC-line input circuitry, which are unchanged regardless of whether or not a regulator is used.

Bridge rectifier BR1 and capacitor C1 (Fig. 2) are the same for any power supply. Selection of those components was covered in the previous installment. A rule-of-thumb for ripple filter capacitor C1 is not less than 1000-µF per ampere maximum load current. Thus, for a 3-ampere power supply, use 3000 µF (or more) of filter capacitance.

Capacitors C2 and C3 (Fig. 2) are used to improve the noise immunity of the circuit, and will have values between 0.1 µF and 0.47 µF. The actual value selected is optional, except that (generally) higher load current designs prefer higher capacitances. We can use 0.1 µF for all 1-ampere supplies and either 0.33 µF or 0.47 µF for 3- and 5-ampere designs. Those values are guidelines, and are suitable for

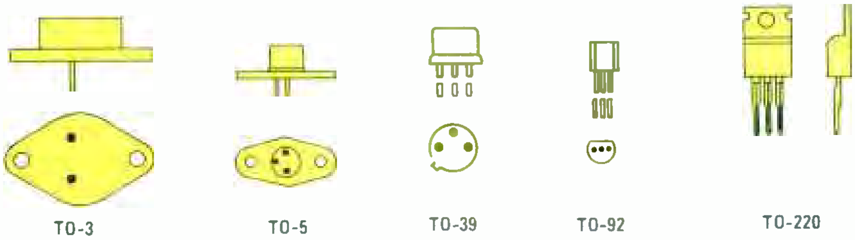


FIG. 1—MANY 3-TERMINAL voltage regulators are compacted into packages common to transistors and integrated circuits. The most common are illustrated in outline form and identified by their universal package number. The TO-3 type relies on its case as one electrical circuit termination. The TO-220 type has the mounting bracket and center terminal electrically connected.

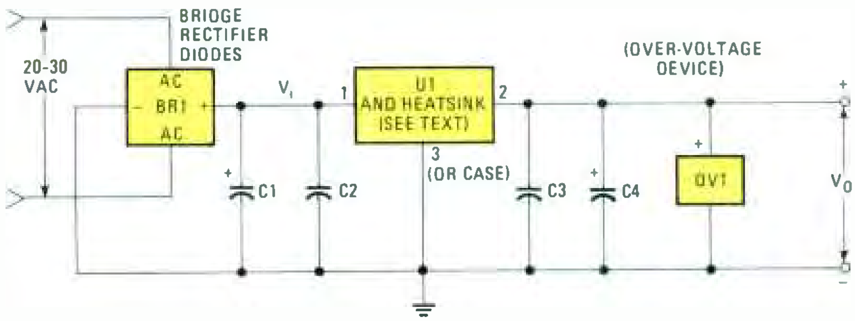


FIG. 2—CIRCUIT DRAWING of a typical voltage regulator circuit using a 3-terminal device. Capacitors C2 and C3 are used to suppress transient impulse noise common to voltage-regulator devices. Over-voltage protection circuit (OV1) prevents voltages in excess of the predetermined amount from reaching the output terminal.

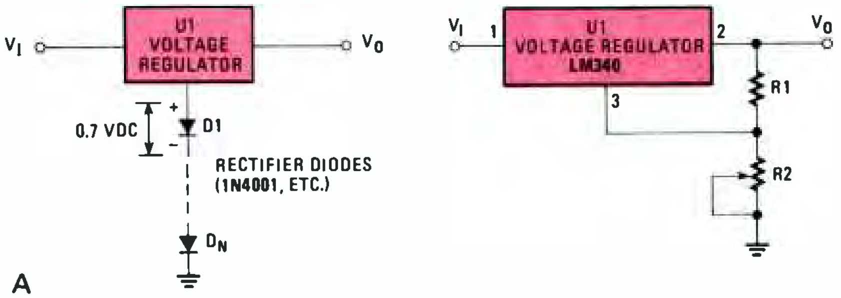


FIG. 3—NON-STANDARD VOLTAGES can be obtained from voltage regulators that were designed to produce one fixed regulated voltage. In A, one, or more diodes raise the device's V_O output by .7-volt DC for each diode connected in series. A resistance divided in B is used to provide an offseting voltage that is variable.

most applications.

The location of C2 and C3 is critical. Those capacitors are used to suppress transient impulse noise, which implies high-frequency content pulses. Therefore, C2 and C3 must be mounted as close as possible to the body of the voltage regulator integrated-circuit (i.e. U1). Many projects call for mounting C2 and C3 on the body of U1! If those capacitors are mounted too far from U1, or if their leads are too long, then the function of the capacitors is compromised.

Capacitor C4 (Fig. 2) is optional but highly recommended, except in circuits that experience wide shifts in load current over short durations; digital circuits are examples. In those cases, C4 is mandatory.

The function of C4 is to improve the transient response of the voltage regulator. The capacitor serves as a local reservoir to supply current to the load for a brief instant while the regulator readjusts itself to the new, higher, level of current demand.

The device marked *OV1* is an over-voltage protection circuit, sometimes called an *SCR-crowbar*. The function of OV1 is to protect the external circuitry served by the voltage regulator in the event of a catastrophic failure of U1. Keep in mind that input voltage V1 is at least 2-3 volts higher than regulated output voltage V_O, and may be much higher than V_O. If U1 fails to the point that V1 appears on the V_O line (a frequent failure mode), then failure of the devices receiving V_O is likely. In a TTL circuit, for example, a U1 failure would place +8 volts on the +5 volt line—and that will burn out TTL chips!

The heatsink for U1 is sometimes pronounced *optional* by manufacturers and authors. I personally prefer heatsinking of all voltage regulators, contrary advice notwithstanding. Voltage regulators are power-dissipating semiconductor devices and, as such, their reliability is directly affected by temperature. For 1-ampere and under models, the metal chassis (if any) may be sufficient. Otherwise use a finned heatsink on U1.

Changing Output Voltage

Three-terminal integrated-circuit voltage regulators come in fixed voltages such as 2.0, 5.0, 10.0, 12.0, 15.0. 18.0, and 24.0 volts. If we need voltage values between the *standard* voltages, then some other tactic is necessary. Figure 3 shows two methods for changing V_O on fixed-voltage three-terminal integrated-circuit voltage regulators.

Figure 3A shows the use of rectifier diodes (e.g. 1N4001-1N4007, or equivalent) in the common lead of the voltage regulator to increase V_O. The value of V_O changes about 0.7 volt for each diode connected in series. Although that method works, it is not recommended because of the temperature dependence of the 0.7-volt drop across the rectifier's PN junction! In most cases, the method of Fig. 3B is preferable.

The circuit of Fig. 3B places the common terminal of the regulator at a potential that is a fraction of the desired V_O, rather than ground.

Perhaps the best solution to the variable voltage problem is the use of a regulator designed for such operation. Common voltage-regulator types available are the LM317 (1.5 ampere), LM338 (5-ampere) and Lambda Electronics' LAS*XX*U devices.

The LM338 is a 5-ampere horse of a regulator in a TO-3 case. It must be heatsinked at that current level, especially in situations where the input voltage (V_I) is much larger than V_O. That situation occurs in variable supplies when V_O is at its minimum value. In the LM338 circuit of Fig. 4, for example, a 28-volt V_I will permit an adjustible V_O of 1.2 volts to 25 volts. At the low voltage, therefore, power dissipation P_D at 5 amperes load current will be:

$$P_D = (28\text{-}1.2 \text{ V}) \times (5 \text{ A}) = 134 \text{ watts!}$$

The problem is less acute at the maximum value of V_O where:

$$P_D = (V_I - V_O) \times (I_{Load}) = (28\text{-}25 \text{ volts}) \times (5 \text{ A})$$
$$P_D = (3 \text{ V}) \times (5 \text{ A}) = 15 \text{ watts.}$$

The LM338 output voltage V_O is set by a voltage-divider network (R1 and R2) that may be either a single potentiomenter, or a combination of a fixed resistor and a potentiometer. If a fixed output voltage is desired, then both R1 and R2 can be fixed. The output voltage is determined by:

$$V_O = (1.25 \text{ V}) \times (R2/R1 + 1).$$

In most cases, the value of R1 will be 120 ohms to 250

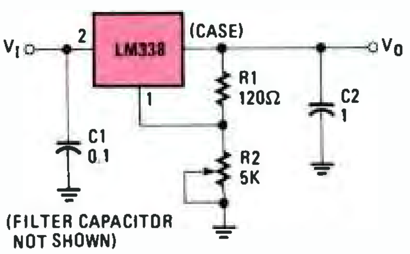
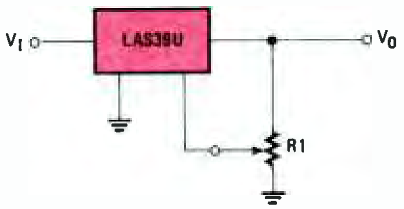


FIG. 4—THE LM338 voltage regulator must be mounted on a heat sink when a large internal voltage drop is expected. As the text details, a V_I of 28 volts and a V_O output of 1.2 volts will burn up about 134 watts at a load current of 5 amperes. Under the same conditions, except V_O is 25 volts, the power dissipated is only 15 watts.



ohms, and R2 is set to produce the desired voltage. The above equation can be rewritten in more practical form as follows:

$$R2 = (V_O/1.25 - 1) \times R1$$

Example

Design an LM338 regulator to produce an 13.8 VDC output so that CB radios can be bench-tested. Assume that R1 = 120 ohms.

$$R2 = (V_O/1.25 - 1) \times R1$$
$$R2 = (13.8/1.25 - 1) \times 120$$
$$R2 = (11.04 - 1) \times 120$$
$$R2 = 10.04 \times 120$$
$$R2 = 1205 \text{ ohms}$$

Of course, one would not try to find a 1205-ohm resistor, but would make R2 a series combination of a fixed resistor and a potentiometer. For example, a 1000-ohm fixed resistor and a 500-ohm linear-taper potentiometer to precisely set V_O.

Keep in mind that the LM338 is a 5-ampere voltage regulator. As such, it should be heatsinked with a finned heatsink, and silicone heat-transfer grease should be applied to touching surfaces. In the the TO-3 package, the case is the output terminal so it must be isolated from the chassis ground. That requirement means either insulating the heatsink assembly, or using a mica insulator under the LM338 TO-3 package.

Figure 5 shows another variable regulator, Lambda Electronics' LAS-39U. That device is similar to LM338, but will pass 8 amperes. The value of the adjustment potentiometer in ohms is:

$$R1 = V_O/10A$$

Higher-Current Regulators

Voltage regulators capable of *higher currents* are sometimes needed for digital projects, amateur transmitters, and audio power amplifiers. We will define *higher current* to be over 5-8 amperes. One of the easiest ways to accomplish that job is to use one or more high-current transistors as a series-pass element. Figures 6 and 7 show how that is done. The advantages of those circuits are that design is simplified immensely, and we can use power transistors with lower beta ratings, because of the higher current availability of the integrated-circuit regulator.

In both circuits, the output voltage V_O is approximately 0.6 to 0.7 volt lower than the rated output voltage of the three-terminal integrated-circuit regulator. Thus, using an LM340T-12 regulator will produce an output voltage of about 11.4 volts.

The version of Fig. 6 uses a plastic PNP power transistor such as the popular TIP-34 for the series-pass element. That circuit will handle 5-6 amperes.

Somewhat higher currents can be accommodated by the circuit of Fig. 7. That circuit also provides a means for adjusting the actual output voltage to a precise value.

The heart of the circuit is an LM317 integrated-circuit adjustable voltage regulator (U1). That device will set the reference voltage at the base of the series-pass transistors (hence, also V_O), and can supply up to 1.5 amperes of base current to those transistors. If more base current is needed, then use an LM338 device (which produces up to 5 amperes) instead of LM317.

The output voltage V_O will be 0.7 volt less than the voltage produced by U1. The U1 voltage will be set in a manner that is similar to the LM338 discussed earlier. In that case, however, R2 is represented by two resistors, R2a and R2b. The overall equation is:

$$V_O = 1.25V\ (R2a - R2b)/R1 + 1 - 0.7.$$

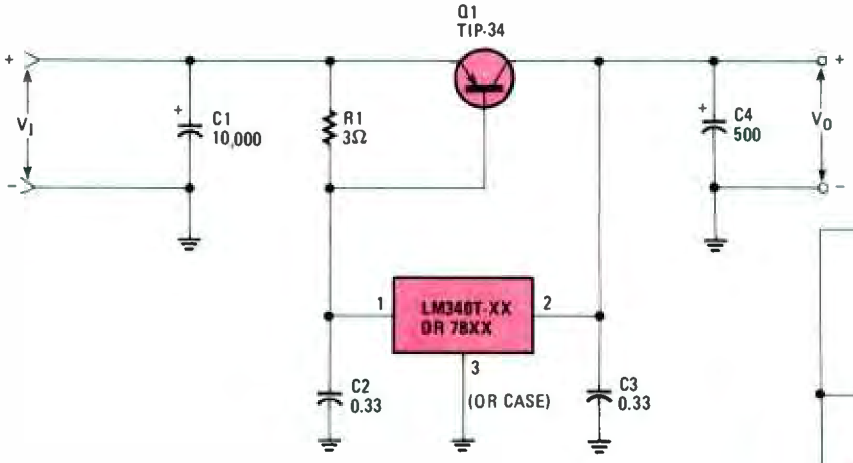


FIG. 6—THIS CIRCUIT will deliver up to 6-7 amperes using a voltage regulator to drive a plastic-case, PNP "series-pass" transistor.

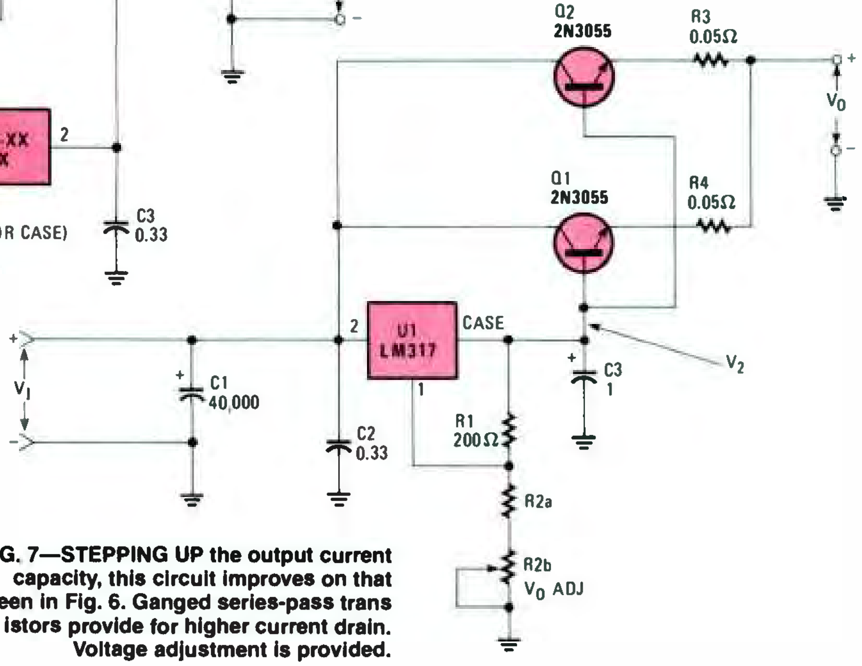
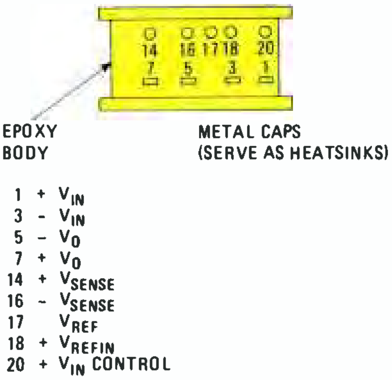


FIG. 7—STEPPING UP the output current capacity, this circuit improves on that seen in Fig. 6. Ganged series-pass transistors provide for higher current drain. Voltage adjustment is provided.

◀ FIG. 5—The LAS39U adjustable voltage regulator is an improved variation of the LM338 in Fig. 4. The LAS39U requires only one circuit element, an output voltage-setting potentiometer.



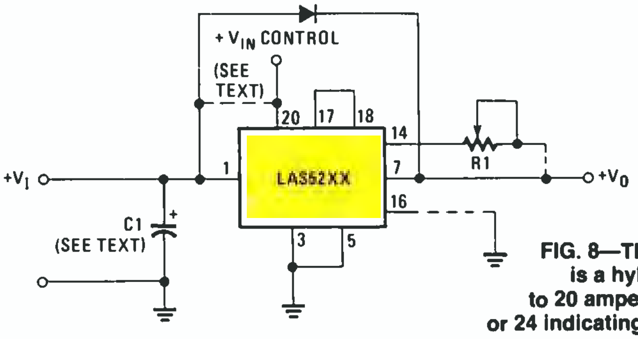


FIG. 8—THE LAS52XX voltage regulator is a hybrid device that can deliver up to 20 amperes. The XX could be either 05 or 24 indicating the regulated-voltage output.

You should recognize that equation as being a modified version of the LM338 equation. Normally, potentiometer R2b will be from 10 to 50 percent of the total (R2a + R2b). The precise ratio of R2a to R2b depends upon the degree of control (i.e. resolution) and range (maximum to minimum values of V_O) desired.

The high current is handled by one or more series-pass transistors. Two ratings are of primary consideration when selecting transistors: collector power dissipation and collector current. In addition, we must also be certain that each transistor has a V_{CC} rating high enough to accommodate all reasonable excursions of input voltage V_I.

The power dissipated in the collector of the series-pass transistor is the product of the collector current (maximum) and the C-E voltage drop which, in that case, is the difference (V_I-V_O). For adjustable regulators, then, the actual maximum power dissipation that the transistors must sustain is:

$$P_{d(mam)} = I_{C(max)}(V_{I(max)} - V_{O(min)}).$$

When two or more transistors are connected in parallel to increase the current capacity of the regulator, we must use emitter ballast resistors R3 and R4 (Fig 7) in series with each emitter. Also, if there are wide differences in the beta gain of the transistors, then the load division may not be even. Under that circumstance, it may happen that the current handled by one transistor exceeds its rated I_C. For that reason, rough matching of the power transistors may be desirable.

With the circuit shown in Fig. 7, using 2N3055 transistors for Q1 and Q2 will yield a power supply of 15 to 20 amperes ICAS rating.

Another alternative for high-current regulators are the hybrid units made by Lambda Electronics Inc. (121 International Dr., Corpus Christi, TX 78410). Lambda has long been recognized as a leading manufacturer of O.E.M. and workbench power supplies, but also sells power-supply components. Figure 8 shows one of the Lambda hybrid regulators, the 20 ampere LAS-52XX devices. The XX denotes the voltage output, and may be 5, or 24. The package for those regulators is shown in Fig. 8A, while the application circuit is shown in Fig. 8B.

The package for the LAS-52XX (Fig. 8A) is a special design of epoxy, with heatsink surfaces top and bottom. The main heatsink surface is the bottom plate, and that should be attached to a metal heatsink surface.

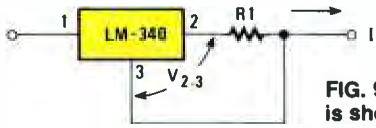


FIG. 9—A VOLTAGE REGULATOR is shown connected into a constant-current configuration.

The usual circuit for the LAS-52XX is shown in Fig. 8B. Capacitor C1 is the regular ripple-filter at the output of the rectifier. The value of that capacitor is 2000-µF/ampere, so for a 20-ampere power supply a 40,000 µF capacitor is required.

There are two V+ terminals on that device. Pin no. 1 is the main V+ terminal (high current) and is designated $+V_I$. That terminal is connected to the internal series-pass transistors. Pin No. 20 is designated $+V_{IN}$ (control), and is used to supply power to the internal control amplifiers. The voltage applied to pin No. 20 must be at least +7.5 volts DC. That requirement can be met on the LAS 5212 and LAS-5224 by connecting pins 1 and 20 together. On the LAS-5205, however, it may happen that $+V_{IN}$ is between 7 and 8 VDC, so may occasionally fall below the +7.5 VDC minimum. That situation occurred in one of my own products where the unregulated $+V_{IN}$ for a +5 VDC supply was derived from a 6.3 VAC transformer. The solution in that case was to connect Pin No. 20 to the +12-VDC supply used in the same microcomputer.

Pin Nos. 14 and 16 (Fig. 8) are sense lines, and are used to tell the internal reference amplifiers what voltage is being produced for V_O. If the wires connecting the regulator output to the load are short and heavy, then pin 14 can be connected via R1 directly to pin No. 7 (main = V_O), and pin 16 can be either grounded, or connected to pins 3 and 5. In many cases, however, we will connect the sense lines to $+V_O$ and $-V_O$ at the load. That connection permits them to be used to measure V_O where it is needed; and therefore, cancels the sometimes substantial effect of IR drop in the main current-carrying conductors.

Potentiometer R1 is used to set V_O to an exact value close to the nominal value specified by XX in the device type number. The resistance of R1 is given by:

$$R1 = .25V_O(1000\text{-ohms/volt}).$$

For a 5-volt LAS-5205, therefore, we need a resistance greater than

$$R1 = (.25 \times 5 \text{ volts})(1000\text{-ohms/volt})$$
$$R1 = (1.25)(1000) = 1250 \text{ ohms}.$$

Current Regulators

Figure 9 shows a three-terminal integrated-circuit regulator used as a current source. The output current is given approximately by:

$$I = V_{2\text{-}3}/R1 + I_Q$$

where I_O is the output current, $V_{2\text{-}3}$ is the output voltage, V_O, R1 is the resistance in ohms, and I_Q is the quiescent current of U1 (typically 1-5 mA).

Diode Protection

Rectifiers in modern DC power supplies are solid-state PN-junction diodes. The advantage of those diodes is that they pack a lot of *rectification* into a small (in fact, tiny) package. On the disadvantage side, however, those diodes tend to be sensitive to high-voltage transients and to damage caused by excessive current surges.

Figure 10 shows a diode with added components that are used to protect the diode. Note: Not all of those measures will be used in all cases, but they are seen occasionally.

Series resistor R1 is used to limit surge currents. Normally, a diode will have a large surge-current rating that is defined as the one-cycle overload. On U.S. systems (i.e. 60 Hz), that means the overload for 1/60 second or less. Longer-duration overloads must be derated. Perhaps the biggest overload seen by most rectifiers is the initial charging of the filter capacitor. At turn-on, the filter capacitor is discharged, so the current rate of charge is very high. In most low-current supplies there is no problem, because the value of the filter capacitor is low enough so that it charges rapidly. If a large filter capacitor is used, however, the high-current portion of the changing cycle is prolonged enough to damage the rectifiers. The purpose of resistor R1 is to limit the current to a safe value during that portion of the changing cycle. Depending upon voltage and current levels, the value of R1 will be (usually) 5 to 100 ohms. The appropriate value is found by applying Ohm's law (E/I), using the applied voltage and maximum safe current.

Another tactic for preventing rectifier damage is to raise the power-supply AC voltage to the diodes slowly—but more on that topic later.

The parallel resistor across the diode (R2 in Fig. 10) is used when two or more diodes are connected in series. That tactic is used to increase the PIV rating of the rectifier. Because of differences between diodes, however, the voltage drop across each may be different. Shunting equal-valued resistors across the diodes tends to equalize the voltage drop across each diode. The usual value is 1000 ohms per volts.

Capacitor C1 is parallel with D1 (Fig. 10) and is used to suppress high-voltage transients from the power line. Those transients can reach 2000 volts, and may occur several times per day. Such transients can blow a PN junction diode.

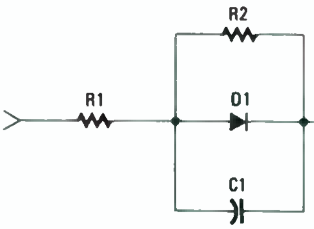


FIG. 10—AT TURN ON, rectifiers draw heavy currents because their uncharged filter capacitor appears as a short circuit for the first half cycle, or more.

Connecting .001-µF capacitor in parallel with the rectifier will eliminate many such transients (because of their high-frequency content) without passing any appreciable amount of 60-Hz current.

Figure 11 shows on form of *soft turn-on* circuit. The intent of that circuit application is to limit current flow for a few seconds, until the filter capacitor charges to a certain voltage. Various methods are used for that job. In Fig. 11, slow turn-on is accomplished by placing a resistor in series with the transformer primary winding. After a few seconds of *slow operating*, switch S2 is closed, and the power supply now operates at full capacity.

Other schemes involve substituting either lamps or *ballast* tubes for R1. Note that there is a fuse, F1, in the primary winding of transformer T1 (Fig. 11). Always fuse your power-supply circuits! The fuse should be the device that is closest to the power line's hot lead-point of entry, so that no fault can occur that will cause damage *without* blowing the fuse.

High-frequency interference signals on power lines, including those transients discussed above, can disrupt the operation of electronic equipment. A surprising amount of hash comes down the AC power lines. One way to eliminate many such signals is to place an LC filter in the power-line circuit between the point of entry into the equipment and the transformer primary winding. Figure 12 shows such a filter. Each line from the AC power mains has its own L-section lowpass filter that will pass 60-Hz power but not other frequencies and transients.

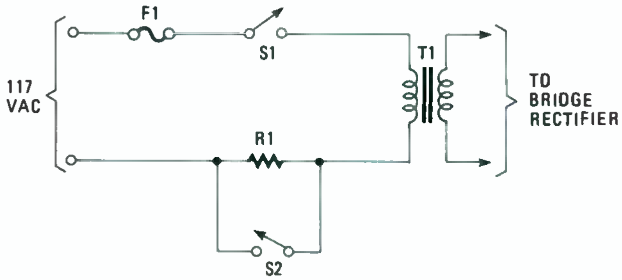


FIG. 11—ONE WAY to eliminate the heavy current through a diode during the first few moments when AC power comes on is to reduce the AC, to be rectified to a lower level.

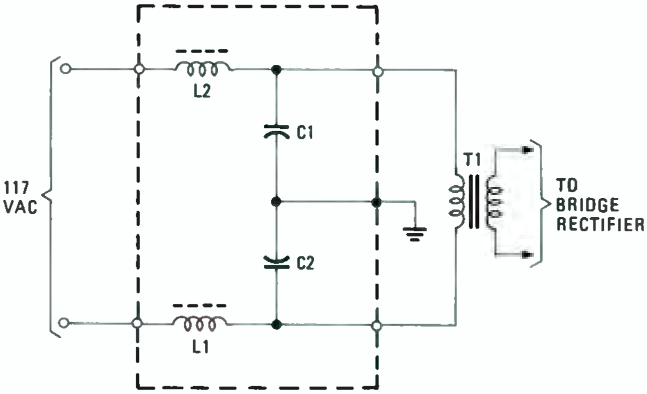


FIG. 12—WHAT APPEARS to be a safe power-line filter can kill you at the next visit to the doctor's office. Unequal capacitors and interactive inductors may produce a hot ground.

Filters such as diagrammed in Figure 12 are available ready-made, and are even available to chassis-mounted AC power receptacles. If you build your own, be sure that the capacitors are rated for use across AC power lines. Generally speaking, filters should be located as close as possible to the power-line point of entry into the equipment. That tactic prevents coupling to other conductors within the cabinet from the unfiltered section of line. If possible, the fuse should be located with the filter shield, and should be in the circuit ahead of the filter. That arrangement will prevent a catastrophe in the event of a short to chassis by a filter component.

Using an AC line filter such as Figure 12 automatically increases the current flowing in the power line ground (i.e. the *third wire*). In certain applications, that current is intolerable—medical equipment is an example. The amount of added ground current is proportional to the values of C1 and C2, and to some extent, mutual coupling between inductors L1/L2 and chassis. For those cases, that type of an AC line filter may not be applicable.

As mentioned above, high-voltage power-line transients cause problems in electronic equipment. Besides damaging diodes, they are also known to interfere with the operation of equipment. Digital computers seem especially prone to transient problems. Any computer that seems to "bomb" spontaneously, is probably experiencing alteration of the data due to transients. What is needed is some means for eradicating transients before they can do harm.

Figure 13 shows two methods for clipping AC line transients before they get into the power supply. In Fig. 13A we see two Zener diodes connected back to back. The breakover voltage (V_Z) of those diodes should be greater than the maximum peak AC voltage expected. Most equipment is specified to operate on 125 VAC (rms), so the maximum peak voltage will be (1.414) (125), or 177 volts. For a margin of safety, select V_Z to be 200 volts for both D1 and D2.

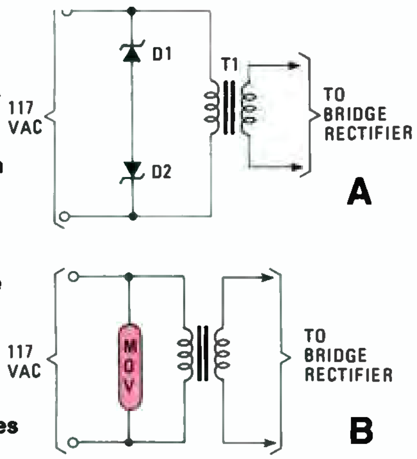


FIG. 13—TWO WAYS to reduce the possibility of damage to circuits due to transient high-voltage spikes on the AC line to the power supply. In A, back-to-back Zener diodes, rated large enough for the AC line used, lop off the excess-voltage spikes. In B, a metal-oxide varistor, a voltage-sensitive resistor element, also eliminates the high spikes.

A second popular alternative is the metal-oxide varister (MOV) device shown in Fig. 13B. General Electric makes MOV devices for that application. The MOV can be modelled as a pair of Zener diodes (per 4A), but it is actually a type of voltage-senstitive resistor. It will have a high resistance at all potentials below a certain threshold, but breaks down to a low resistance above that potential. Thus, high-voltage transcients are chipped away by the MOV, while the AC line voltage is not affected.

Output Current Limiting

If the output of an unprotected DC power supply is accidentally shorted, then immediate destruction of the power supply will result. Power supplies do not like to see direct short circuits across their outputs.

Figure 14 shows a simple overcurrent, or short-circuit, protection circuit. Transistor Q1 is the regular series-pass element found on many regulated supplies. The output voltage is set by V_Z of diode D1, and will be approximately 0.6 to 0.7 volt less than V_Z.

The overcurrent protection circuit consists of Q2 and R2. Resistor R2 is in series with the output current line, so it will develop a voltage drop of $I_O \times$ R2. That voltage becomes the base-emitter bias for Q2. When I_O µlt R2 reaches 0.6 volt, the junction potential for silicon transistors, Q2 will turn on hard and effectively shorts out series-pass transistor Q1 from base-to-emitter. Under that conditions, Q1 is cut off.

Some power supplies are designed to permit variation of the current limiting point. The quick and dirty way to do that job is to make R2 a variable resistor.

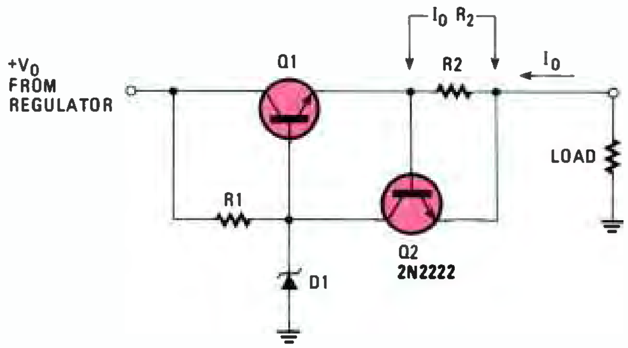


FIG. 14—A SERIES SENSING RESISTOR develops a voltage drop that triggers Q2 into action at a selected current drain. Transistor Q2 restricts the passage of current through Q1.

Regardless of whether variable- or fixed-resistor configuration is used, the value of R2 is found from Ohm's law in which the voltage value used is 0.6 volt:

$$R2 = 0.6/I_{O(max)},$$

Where: R2 is in ohms and I_O is in amperes.

For most DC power supplies, the value of R2 is very low, often a fraction of an ohm. A 10-ampere power supply, for example, requires a .06-ohm resistor. Such resistors can be made either by paralleling higher fractional value resistors (e.g. five 0.33 ohm), or, from custom-winding resistive wire over a form such as a high-valued 1 or 2 watt resistor.

Over Voltage Protection

There is always a differential between input and output voltage on a regulated power supply. Typically, there will be at least 2-volts differential, and possibly as much as 35 volts. If something happens to cause the input voltage to appear on the output, then it is likely that circuitry served by the power supply will be damaged. Standard TTL digital circuits, for example, operate from +5 VDC regulated supplies that, in turn, operate from +8 VDC unregulated supplies. If either the series-pass transistor shorts, or, the Zener diode opens, then +8 VDC will appear at the regulator output; that potential will burn out TTL chips. Obviously, single-point failure in the power supply can wipe out massive amounts of digital logical!

The solution to that problem is the so-called *SCR crowbar* overvoltage protection circuit, an example of which is shown in Fig. 15. An SCR crowbar is a hard-fisted, brute-force method of dealing with the problem. When the circuit senses an overvoltage condition it shorts the output of power supply, blowing the fuse in the process.

An SCR (silicon controlled rectifier) exhibits a high impedance between the cathode and anode terminals until a

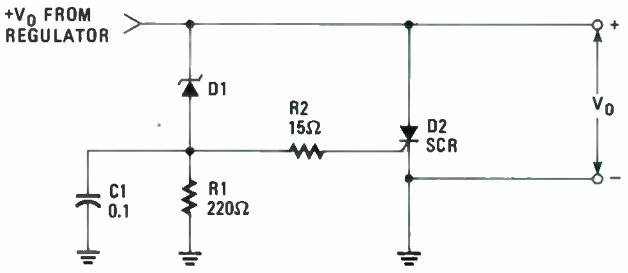


FIG. 15—FORCED SHUTDOWN! That's what happens when the overvoltage occurs. The SCR fires, and the circuit's fuse blows!

current is injected into the gate terminal. When that happens, the SCR becomes like any other PN junction diode. Only a brief pulse is required on the gate terminal to make the SCR turn on and stay on. The SCR will remain on until the cathode-anode current drops below a *hold* value.

In Fig. 15, the SCR is D2, and it is connected directly across the power supply V_O output. The SCR will remain dormant until Zener diode D1 breaks over and causes a gate current to develop in R2. The Zener voltage of D1 is selected to be higher than V_O, but less than the V_I applied to the regulator input. For a +5 VDC power supply, either 6.2 volts or 6.8 volts is typically chosen for V_Z of D1.

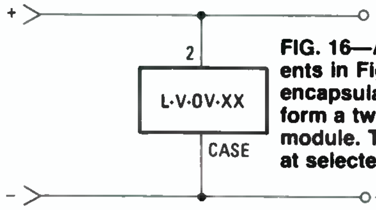


FIG. 16—ALL of the components in Fig. 15 are effectively encapsulated in one module to form a two-terminal over-voltage module. These modules are available at selected voltage levels.

Lambda Electronics, Inc. makes a line of overvoltage-protection modules that are essentially SCR crowbar circuits in two-terminal packages (Fig. 16). Those OV modules are packaged in TO-66 and TO-3 transistor packages (low- to medium-current modles) and special packages (high-current models)—various models are available in popular voltages, at currents from 2 amperes to 35 amperes.

A method for making a low-current (2 ampere) Lambda OV module operate a high current is possible. The low-current OV module is used to sense the overvoltage condition and then supply gate current to the SCR. That method is very much like Fig. 15, but with an OV module replacing the Zener diode, and that circuit could be used with SCR's in the 50 to 100 ampere range.

Heat

The single, largest cause of failure in electronic equipment is *heat*. Studies of failure records on electronic equipment indicate a seemingly inordinate number of failures among power transistors, voltage regulators, rectifiers and power amplifiers, and integrated circuits.

When the microcomputer rage hit several years ago, I built a Digital Group Z80-based machine that required a central regulated +5 VDC, 10-ampere power supply. I used a Motorla MC-1569R and HEP-57000 transistor in the power supply. Even on a finned heatsink, that series-pass transistor grew too hot to touch after a few seconds of operation. That condition is a recipe for a premature failure that could have disastrous effect!

The solution to the heat problem was a 40 cubic-feet-per-minute (cfm) muffin fan mounted so that it blew air over the heatsink. After the fan was added, the series-pass regulator cooled off to the point where you could hold a finger on it.

When my homebrew microcomputer was finally mounted inside a Vector Electronics Cabinet (modified by me from S-100 to DG configuration), I used two fans. The small 40 cfm fan blew across the power-supply components, while a 110 cfm fan ventilated the circuit cards. Added one-inch holes were drilled along the top edge of the cabinet sides to allow air to escape—and carry off heat.

No power-supply voltage regulator should be operated without a heatsink. If you use an H-package (TO-5) device, then use a *hat* type transistor heatsink. Where TO-66, TO-220 or TO-3 packages are used, mount them on a finned heatsink if at all possible. For regulators pulling more than 5 amperes, blow air across the heatsink (even where the regulator is rated for use without forced air!). Taking a few precautions about heat buildup will more than repay you in added reliability.

High-Voltage Power Supplies

In this current age of solid-state integrated-circuit chips and modules, it is difficult to find theory discussions on power supplies and regulated supplies rated above 30 volts DC. Those supplies we tag as *high-voltage* with the understanding that the range is anywhere from 30-volts to many kilovolts. While the techniques used at the extreme ends of that voltage span are a bit different, it is reasonable to lump them together in the same category.

At its lower end, the high-voltage range can be further subdivided into "under 100-volts" and "over 100-volts." In the under 100-volts range we can use techniques identical to the low-voltage supplies discussed in earlier parts of this series. All we need to do is substitute transformers, rectifiers, and filter capacitors of suitable ratings. For regulated supplies, we need to obtain series-pass power transistors with adequate collector power dissipation at the collector-emitter potentials (V_{CE}) expected. Zener diodes of correct rating need to be obtained either singly (ratings to over 200-volts DC are available), or, by series-connecting lower-voltage Zener diodes.

FIG. 17—ZENER DIODES can be stacked to effect higher Zener voltages; but power ratings must be considered.

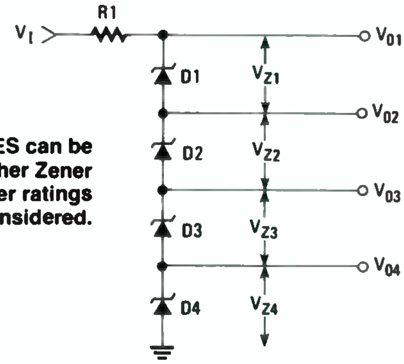


Figure 1 shows a stack of four Zener diodes connected in series to provide a high voltage V_{OI}. The total voltage from that stack will be:

$$V_{OI} = Z_{Z1} + V_{Z2} + V_{Z3} + V_{Z4}.$$

An added benefit of that circuit is that we can tap off at any of the diodes to also produce certain lower voltages. That latter tactic, however, should be limited to cases where the lower voltages only lightly load the supply.

The diodes used in Fig. 17 will have to be selected with a power rating that takes into account each V_Z rating. If Zener diodes with vastly different V_Z ratings are used for D1 through D4, then it is possible that the power rating for one or more diodes will be exceeded, even though some will operate within rating. Some people prefer using diodes with equal (or nearly equal) V_Z ratings and the same wattage rating.

Transformerless Power Supplies

Many consumer products use transformerless power supplies in order to reduce cost (transformers are relatively

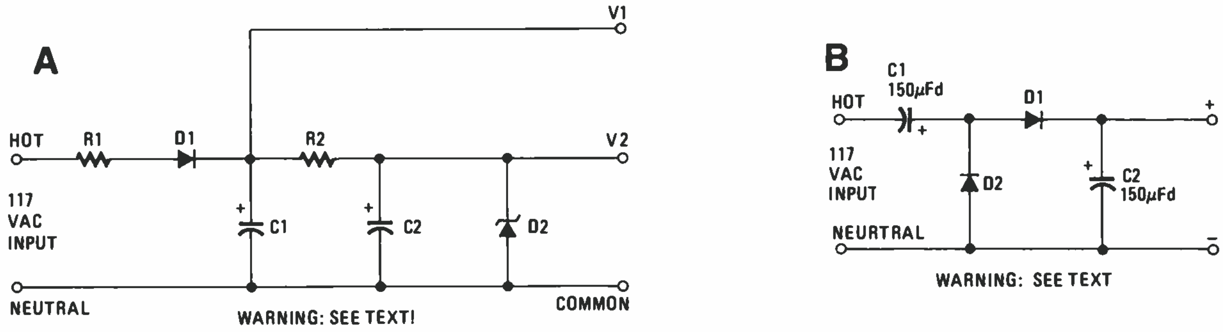


FIG. 18—TRANSFORMERLESS POWER SUPPLIES are quite common. In A, this halfwave rectifier circuit is common to the vacuum-tube radios for several decades.
In B, the voltage doubler uses two identical capacitors to provide twice the voltage normally pssible in A.

expensive). Figure 18 shows two different versions of transformerless supplies.

The version of the transformerless power supply shown in Fig. 18A is a simple halfwave rectifier supply that is operated directly from the 117-volts AC power line. The rectifier is in series with the hot side of the AC line, while the common is the neutral side. The high-output voltage, V_1, will be approximately equal to the peak AC voltage. Since the AC *rms* voltage may vary between 105 and 125 volts, V_1 may vary from 148 to 178 volts DC. A lower voltage, V_2, may be provided by a series-dropping resistor (R2) and, in that case, a Zener diode (D2). Resistor R1 is not always used, and serves both as a current-limiter, and fuse to protect the rectifier (D1).

Figure 18B shows a voltage-doubler power supply; also half-wave rectified. The output of that supply will be slightly less than twice the output voltage of Fig. 18A. It is advisable to have C1 and C2 of equal value and rating.

Warning

Transformerless power supplies contain an inherent danger that is potentially lethal! If used incorrectly, or carelessly, those supplies can kill you. If, for any reason, the hot and neutral become reversed (and it does happen), then the power supply will continue to work but the common will be the lethal hot side of the AC power line. Touching the normally cold common line (negative side in Figs. 18A and 18B) is extremely dangerous in that case. If such a supply is used so that common is chassis, then the entire chassis must be insulated from the outside of the cabinet. That is the way TV and radio sets are designed. In that situation, beware of *sneak circuits* that lend to the lethal chassis via mounting screws, knobs with metallic paint, signal commons, or antenna return paths. Transformerless power supplies should always be operated using a polarized AC line cord; that is, one that fits into the AC outlet only one way. Whenever possible, transformerless power supplies, commonly called AC/DC supplies, **are not recommended** for project construction.

High-Voltage, High-Power

The classic high-voltage power supply for 500-watt (and over) audio and RF vacuum-tube applications provides from +800-volts DC to +5000-volts DC at currents up to 1 ampere. A typical high-voltage power supply for a linear RF 1-kW amplifier might be 2700-volts DC at 500 mA.

The transformer used in the high-power, high-voltage supply will often have two primary windings (see Fig. 19A). That arrangement allows you to use either 117-volts AC or 220-volts AC. Most users prefer 220-volts AC for high-power applications because of the lower current requirements. A 2-kW PEP SSB linear amplifier might draw 10 amperes on 220-volts AC, and 20 amperes on 117-volts AC. The connections for 220-volts AC and 117-volts AC are shown in Figs. 19B and 19C, respectively.

Most designers do not even try finding multi-kilovolt diodes for use as rectifiers in high-voltage high-power supplies. A usual trick is to connect several diodes in series to form each rectifier (see Fig. 20). Recall that the rectifier I_V rating must be 2.82 times the applied *rms* AC voltage. If our transformer delivers 2000-volts AC *rms* (a common value), then the IV rating of the rectifiers must be (2000-volts AC) x (2.82), or 5640 volts. A reasonable margin for error would be realized by making the actual PIV rating 6 kV or 7 kV. A 7-kV rectifier is realized by connecting seven 1000-volt PIV

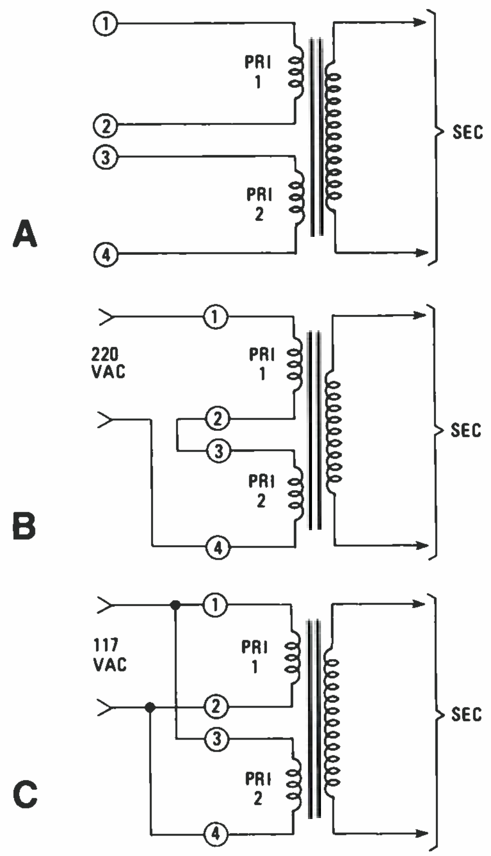


FIG. 19—TWO PRIMARY WINDINGS in a power transformer offer the opportunity to double the voltage of the secondary.

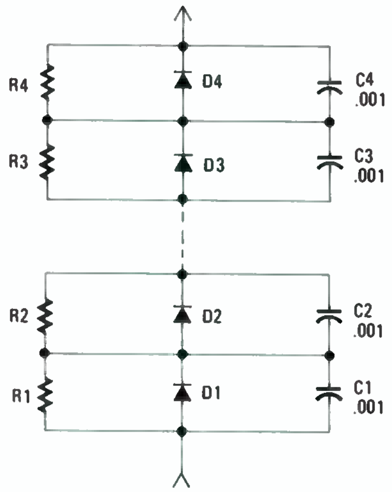


FIG. 20—HINTS on how to overcome the problems of connecting many diodes in series are revealed in the drawing.

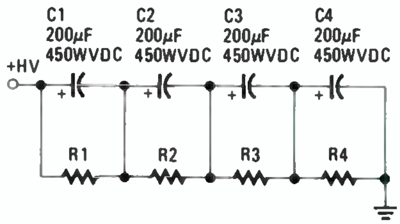


FIG. 21—A USEFUL TECHNIQUE to fabricate an inexpensive high-voltage filter capacitor of common workbench service parts. In practice, all parts should be of equal values and ratings.

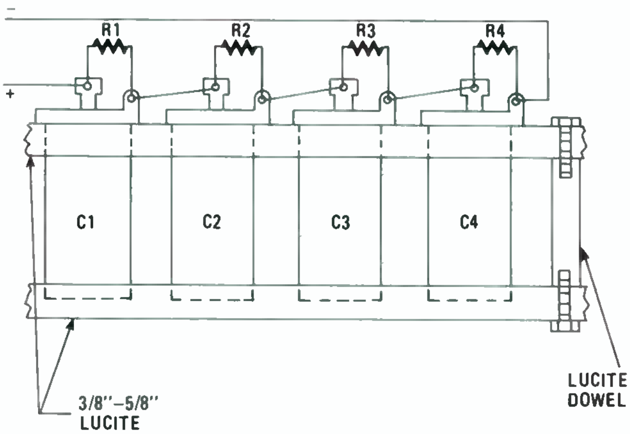


FIG. 22—THIS IS HOW the diagram in Fig. 21 is fabricated for project use—remember, you are dealing with high-voltages!

diodes in series per Fig. 20. The total PIV rating is the sum of the individual PIV ratings.

A problem with connecting diodes in series is that, unless the diodes are truly identical (not just the same type number), there will be a difference in voltage drops among the diodes. That difference could prove disastrous. The solution is to connect equalization resistors in parallel with the diodes (R1-R4 in Fig. 20). Those resistors are usually rated at 1-watt, and have a value of 50 to 100 ohms per volt PIV. Thus, for 1000 volt PIV diodes, the value of the resistors will be 500,000 to 1 Megohm, at 1 watt. It is important that the values of those resistors be equal to each other, otherwise the purpose of an equalization resistor will be lost. Should one resistor discolor quickly during the first few minutes of operation of the power supply, the chances are that the resistor, or the diode it shunts, is out of specification.

The capacitors are used to protect the diode rectifiers against high-voltage transients arriving on the AC power lines. For most applications, each capacitor will have a value of 0.001 μF, and they will be a disc ceramic type. The voltage rating of the capacitor is at least the PIV rating of the diodes, and preferably higher. It would not be inappropriate to use 3-kV disc capacitors with 1-kV PIV, rectifier diodes.

The diodes and other components of the rectifier of Fig. 20 must be mounted so that the high voltage is well insulated from chassis or common. The usual procedure is to construct the rectifier on a wiring board of bakelite, phenolic, or fiberglass. That board is then mounted on ceramic or lucite stand-off insulators that are 2-3 inches thick.

Connections made in high-voltage power supplies must be rounded and smooth. No sharp points can be allowed to stick out of the solder joints, nor can sharp points be allowed elsewhere. High voltage into sharp points produces high-voltage corona discharge—a phenomenon familiar to TV service technicians.

The filter section of a high-voltage power supply can be any of several types, but we will consider only the *brute-force* filter. Such a filter, which we have used before, consists of a single capacitor across the output of the rectifer.

There are at least two options for filter capacitors in high-voltage power supplies. We can, for example, use a high-voltage capacitor with a capacitance demanded by the desired ripple factor. Such capacitors are oil-filled, and very expensive—also sometimes difficult to obtain. The other alternative is to use several lower-voltage capacitors (the type used by servicemen since they are easy to find) in series (Fig. 21).

Each capacitor in the series stack of Fig. 21 is a 450-WVDC (working-Volts DC) electrolytic capacitor. Although not required, it is highly advisable to make all of the capacitors in the stack equal in both capacitance and WVDC rating.

The resistors in parallel with the capacitors are used to equalize the voltage drop across the capacitors. In most cases, the resistors will have a value of 50,000 to 150,000 ohms. The wattage rating should be:

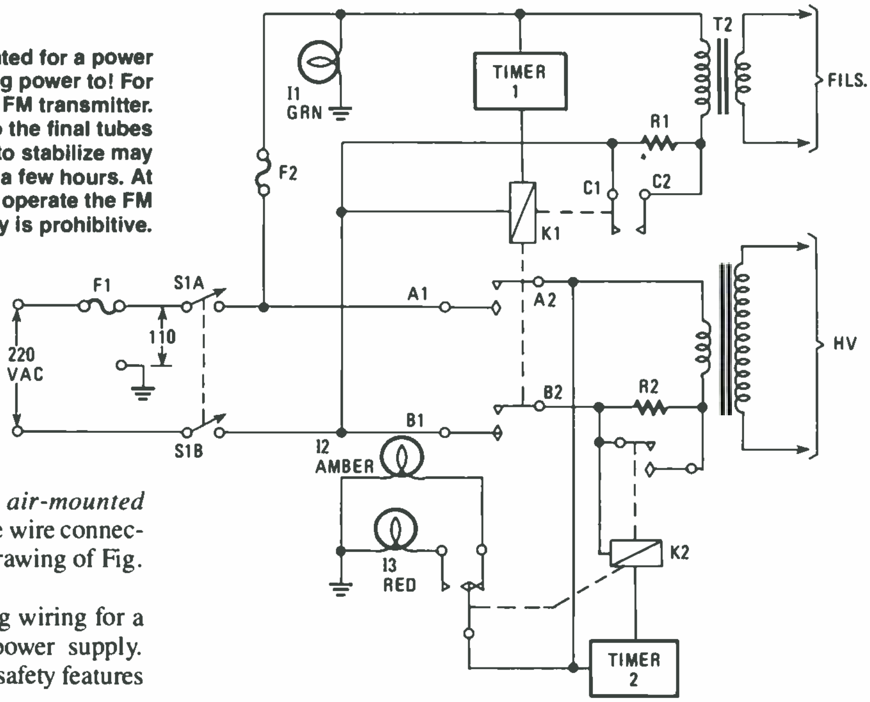
(WVDC)2/R.

For 150,000-ohm resistors and a WVDC of 450 volts, 2-watt rated resistors are sufficient; for 50,000-ohm resistor, a 7.5-watt rating should be used.

The electrolytic capacitors used in Fig. 21 are constructed in metal cans. The outer metal case of each can is the negative electrode of the capacitor. The insulated connector on the capacitor is the positive terminal. Normally, the metal can is grounded and poses no danger. But in that arrangement, the cases of all but one of the capacitors are above ground and could be lethal if touched. Because the cases are electrically hot, special care must be taken in the assembly of the filter stack. Figure 22 shows a typical set-up.

Two sheets of ⅜- to ⅝-inch Lucite are used to hold the filter capacitors. Holes are drilled in the top sheet large enough to admit the body of the capacitors, but not the mounting collar. The bottom sheet is inset with shallow holes just deep enough to allow the bottom of the filter cans to seat firmly. Of course, the holes in both top and bottom must line up with each other. The sheets are held apart by Lucite dowels at the four corners of the sheets. Note: the thickness of the lower Lucite sheet must be great enough to withstand the high voltage. That thickness is measured from the bottom of the sheet to the bottom of the hole inlet for the capacitors.

FIG.23—THIS MAY LOOK overly complicated for a power supply, but consider the circuit it is supplying power to! For example, the supply may be feeding a 5000-watt FM transmitter. The sudden application of high-voltage to the final tubes before the oscillator has an opportunity to stabilize may reduce the life of the final amplifiers to a few hours. At $130 per tube, 4-tubes total, the cost to operate the FM transmitter without this power supply is prohibitive.



The voltage-equalization resistors can be *air-mounted* from the tabs on the electrolytic capacitors. The wire connections between capacitors are as shown in the drawing of Fig. 22.

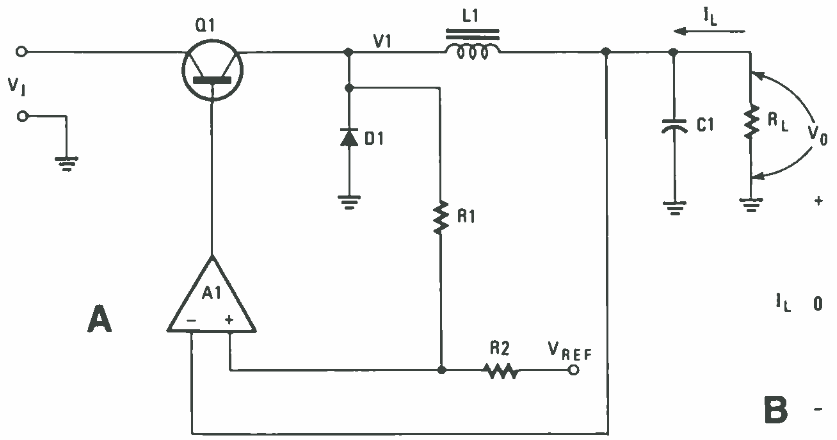
Figure 23 shows the typical primary winding wiring for a high-voltage, high-power AC-operated DC power supply. Besides the two transformers, there are several safety features to that circuit.

Two transformers are used if the power supply is used for RF linear-amplifier service. Such amplifiers most often are vacuum tubes which require a low-voltage, high-current filament supply (T2).

Vacuum tubes must be brought to operating temperature before high voltage is applied. That requirement means that the filament must be turned on before you turn on the high-voltage DC supply. That job is accomplished by the switching arrangement of Fig. 23. Switch S1 is the main power-on switch, and will turn on the filament transformer. That switch must be a heavy type that can pass the primary currents of the two transformers. The main current will be that of the high-voltage transformer. That current can be 20-amperes on a kilowatt linear operated from 117-volts AC.

The primary winding of high-voltage transformer T1 is controlled by the A1/A2 and B1/B2 contacts of relay K1. Those contacts close (A1-A2 and B1-B2) when the coil of K1 is energized. The coil is energized when Timer-1 *times out*. The duration of the timer is set to a value that will permit the tubes to heat up. In some cases, the timer will be electronic, but most are electro-mechanical.

The cold filaments of a high-power vacuum tube draw a tremendous amount of current. As the filament heats up, however, the current drops to the operating level. That *in-rush* current can reduce the life of a vacuum tube. In order to reduce that in-rush current, a resistor is placed in series with the filament transformer primary winding. That resistor generally has a value that will reduce the current to about one-half its normal value. When Timer-1 *times out,* contacts C1-C2 of K1 close and short out the resistor. With R1 shorted, the primary of T2 receives its full voltage.



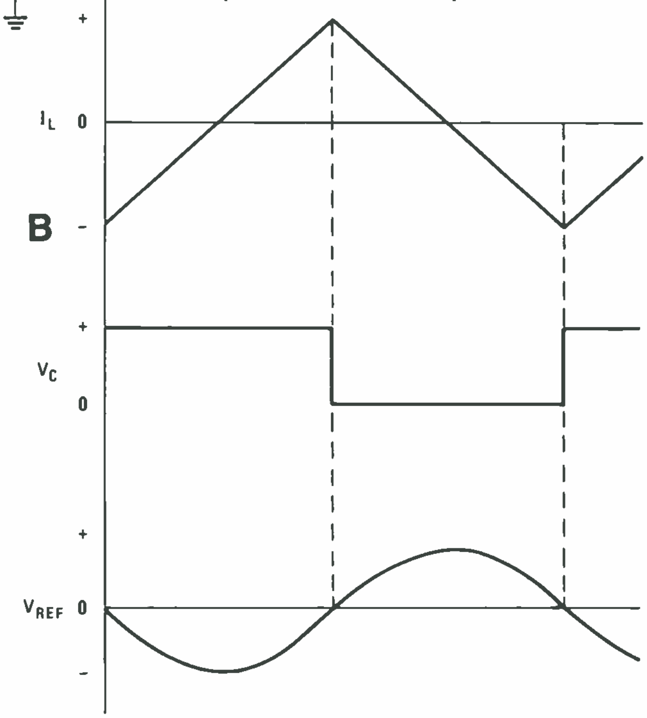


FIG. 24—TRANSISTOR Q1 is not operating as a series-pass transistor. It is functioning as an electronic switch, alternately opening and closing—depending upon the control and reference voltages fed to amplifier A1. Text describes circuit and relationship of curves to circuit operation.

A similar problem exists on the high-voltage side of the power supply. The charging current of the filter capacitors at turn-on is very high. That current can damage the rectifier diodes. Resistor R2 performs the same current-limiting function as R1. Another timer, Timer 2, is used to energize relay K2 at a time that will permit the filter capacitors time to charge enough to reduce the current flow. Generally, the duration of Timer-2 is much shorter than that of Timer-1.

The lamps are an optional –nice touch. Lamp T1 is green, and comes on as soon as S1 is closed; I2 is amber and comes on when Timer-1 is energized; lamp I3 is red and comes on when the high-voltage finally comes on.

The power supply in Fig. 23 must use two fuses. That scheme is necessary, because of the vastly different power levels of the two transformers. If we have just one fuse, it would have to pass a high enough current to power the high-voltage side. Should a catastrophe occur on the filament side of the supply, it might be severe enough to burn out T2. By placing two fuses in the circuit, however, we overcome that problem and fully protect the circuit.

Cutting Down the Heat

All of the voltage regulators presented thus far suffer from a major defect. The active element, the series-pass transistor, dissipates substantial amounts of power. All of those previous circuits required an input-output differential ($V_I - V_O$) across a resistive element that is a source of wasted power. The power dissipated by the series-pass transistor is given by the expression:

$$P = I_O(V_I - V_O),$$

where P is the power dissipated in watts, I_O is the output current in amperes V_I is the input voltage in volts, and V_O is the output voltage in volts.

If the input-output voltage differential ($V_I - V_O$) is large, then the power dissipation is large. At a current of 1 ampere, the standard +5-volt regulator will dissipate only 3 watts at the minimum value of ($V_I - V_O$). But those voltage regulators can work at potentials (V_I) up to +40 volts, at which the power dissipation would be (40 volts −5 volts) time 1 ampere, or 35 watts.

Along with the wasted power comes heat, and heat is the great *killer* of electronics equipment. All of that power which is dissipated becomes heat, so we may conclude that the voltage regulator contributes substantially to the heat build-up in equipment. A solution to that problem is the switching voltage regulator.

Figure 24A shows a simple block diagram of a switching regulator, while Fig. 24B shows the waveforms. Transistor Q1 is not a series-pass transistor, as in ordinary voltage regulators, but rather is an electronic switch. When the base of Q1 is made positive, the collector-emitter resistance drops to a very low value. The voltage drop across Q1 under that circumstance is also low, $V_{CE(SAT)}$. When the base of Q1 is zero, or negative, it is cut off so the collector-emitter resistance is very high.

Amplifier A1 in Fig. 24A is used as a voltage comparator. There are two inputs to the comparator. If the voltages applied to those inputs are equal, then the output voltage is zero. If the voltage to the negative (−) input is larger than the voltage at the positive (+) input, then the output will be negative. But if the negative (−) input is at a lower voltage then the positive (+) input, then the output is high positive. The

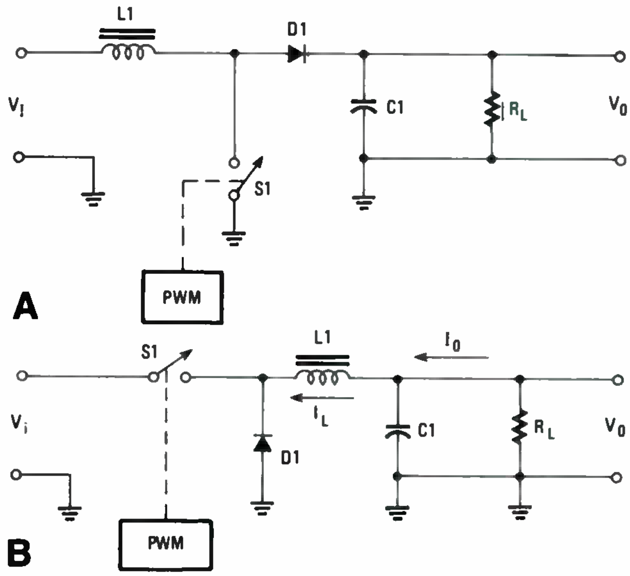


FIG. 25—THE TWO SWITCHING power supplies shown here provide for a step-up voltage (A) and step-down voltage (B). Switch S1 is actually transistor Q1 shown in Fig. 24A.

output of the voltage comparator, A1, drives the base of switching transistor Q1.

When the base of Q1 is *high*, current I_L will flow in inductor L1 and also in load resistor R_L. The voltage appearing across the differential inputs of the comparator A1 is the voltage across inductor L1, which is given by the equation

$$V = L1 \times \Delta I_L/\Delta t$$

That circuit will oscillate at a frequency between 2 and 20 kHz, which is given by

$$F = [V_O(V_I - V_O)] \div [(L1)(V1)(I_{MAX} - I_{MIN})$$

There are two basic configurations for the switching power supply (See Fig. 25:), step-up (Fig. 25A) and step-down (Fig. 25B). The step-up version provides an output voltage that is greater than the input voltage, while the step-down version produces an output voltage that is lower than the input voltage. The main differences between those two configurations is the relative positions of the inductor (L1) and switch S1 (which corresponds to transistor Q1 in Fig. 24A). In the step-up version, the inductor is between V_I and the switch. The switch is connected in shunt across the line so that, when S1 closes, the inductor is across the V_I power supply. The counter-electromotive force (CEMF) generated by collapse of the magnetic field around L1 produces the increased voltage that sums with V_I.

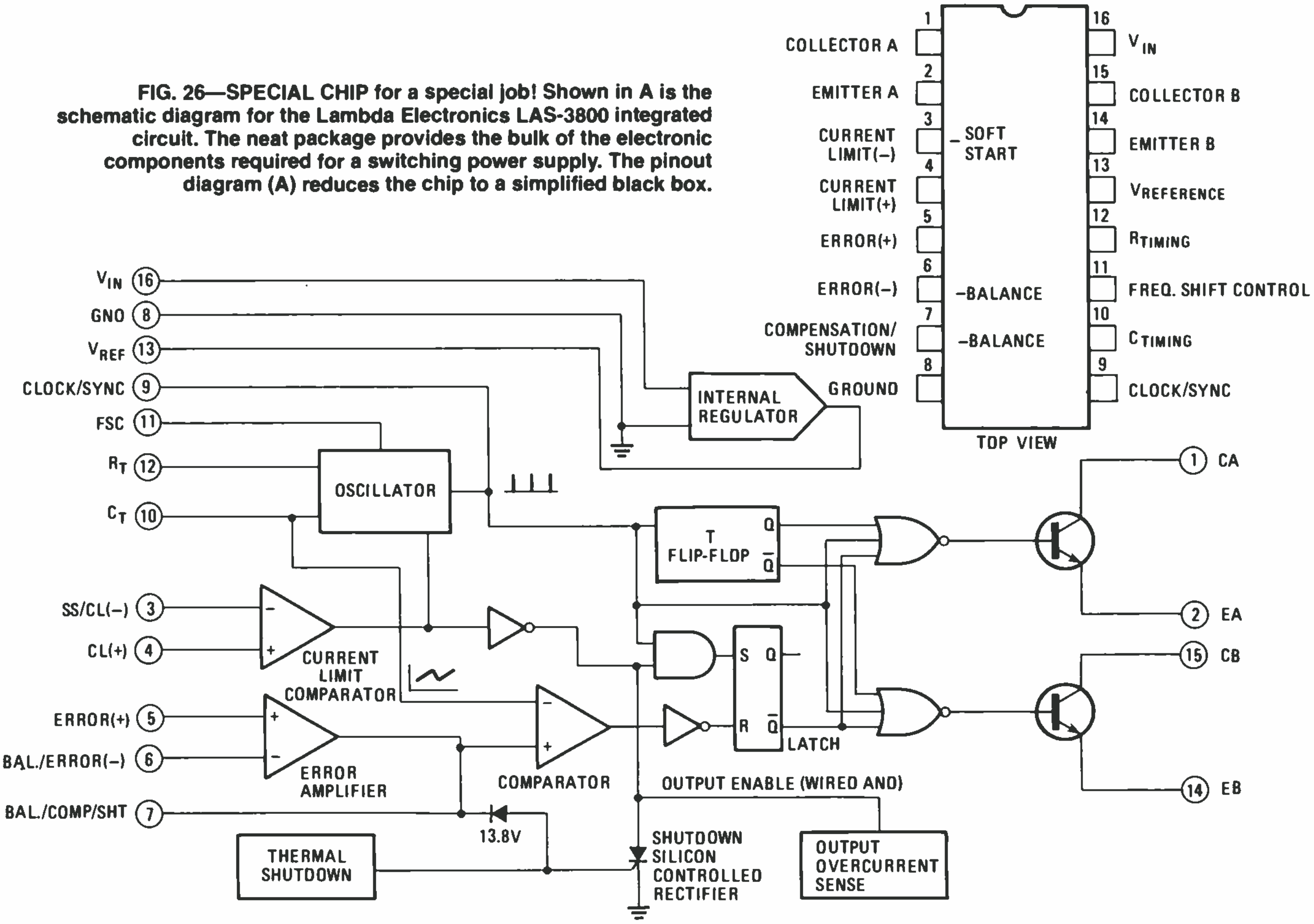
The step-down version is shown in Fig. 25B. In that circuit, the switch is between V_I and the inductor, and is in series with the line rather than shunted across it.

Both versions of the circuit shown in Fig. 25 use a pulse-width modulator (PWM) to drive the switch. The PWM produces a variable-width drive pulse whose duration is determined by the discrepancy between the desired output voltage and the actual output voltage.

IC Switching Regulators

Several semiconductor manufacturers now make integrated circuits perform most (or all) of the functions of a

FIG. 26—SPECIAL CHIP for a special job! Shown in A is the schematic diagram for the Lambda Electronics LAS-3800 integrated circuit. The neat package provides the bulk of the electronic components required for a switching power supply. The pinout diagram (A) reduces the chip to a simplified black box.



switching regulator. Figure 26A shows the block diagram of the Lambda Electronics LAS-3800 device; Fig. 26B shows the package pin-outs.

The 16-pin DIP integrated-circuit package contains a temperature-compensated reference voltage source, a sawtooth oscillator (with overcurrent frequency shift), pulse-width modulator, error amplifier, current limit comparator and a pair of 500-mA, NPN output transistors (with overcurrent protection). The LAS-3800 is designed as a fixed-frequency regulator for both power supply and DC motor-control applications. The LAS-3800 will operate over an input voltage (VI) range of 12 to 40 volts, with a fixed frequency up to 500 kHz. The timing resistor connected between pin 12 and ground must have a minimum value of 5000 ohms. Figures 27A and 27B show step-up and step-down voltage-regulator circuits using the Lambda LAS-3800 IC switching regulator.

The step-up version (Fig. 27A) oscillates at a frequency of approximately 58 kHz, and provides an output of 48-volts DC at a current of 0.25 ampere. The unregulated input voltage is 12-volts DC. Line regulation is 10-millivolts for input shifts over the range 10-14 volts; load regulation is 13 millivolts. Note that the E_A and E_B outputs are tied together on the LAS-3800. Those outputs combine to drive the switching transistor, Q1.

The step-down version is shown in Fig. 27B. That power supply will produce a regulated output voltage that is lower than the line voltage. That is the generic type of power supply used in many microcomputers. Notice that the configuration is similar to that shown earlier for that class of switching voltage regulator. In that case, the LAS-3800 internal transistors are used as the electronic switches. The E_A and E_B outputs are tied together to increase the current capability of the chip. Diodes D1 and D2 are used to isolate the chip's outputs from each other.

The circuit of Fig. 27B oscillates at 90 kHz, and will produce +5-volts DC output from a 12- to 24-volts DC input. The full output load current is 500 mA, so the power available is 2.5 watts. Regulation levels are similar to Fig. 27A.

The step-down version contains a component not used in the step-up version. The device marked L2-OV6 is an IC over-voltage protection module. The L2-OV6 is a 2-ampere, 6-volt SCR crowbar. If the switching regulator fails, and permits V_I to get onto the V_O line, the L2-OV6 breaks down and shorts the output line. In both cases, the actual output voltage can be adjusted by a sample of the output voltage selected by a potentiometer across the output line.

Inverter Circuits

An inverter is a special kind of switching power supply that produces an AC output. The actual output is more like a squarewave than a sinewave, but it can be used to power lights and other devices which represent non-reactive loads (i.e. small inductance or capacitance). The inverter also forms the basis for DC-to-DC converter circuits. Such circuits are sometimes used to provide DC voltages of a different level than the power-supply voltage, while in other cases their function is to provide isolation between the two DC power supplies. That latter application is used in medical instruments for patient safety reasons.

The Lambda LAS-3800 can be used in an inverter circuit such as Fig. 28. That circuit is similar to the old *vibrator power supply* used in pre-transistor auto radios. The inset in

Fig. 28 shows how both circuits work. The switch, whether vibrator or solid-state, is essentially an SPDT switch (S1). Power is applied to the center-tap of the primary winding on transformer T1. The switching action causes the current to flow in first one half the primary winding then the other. The switch will ground first side A and then side B of the transformer. The result is a constantly charging near-squarewave applied to the transformer.

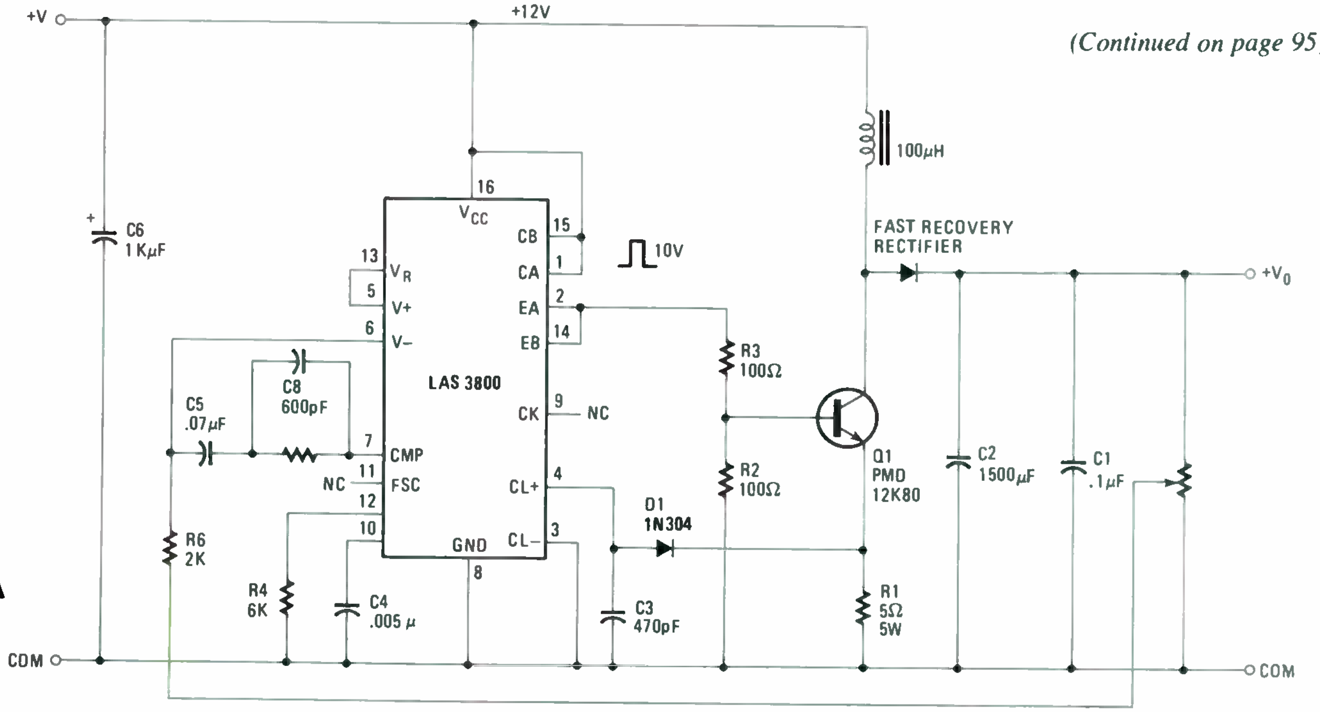
In the solid-state version of Fig. 28, transistors Q1 and Q2 form the switch. In analogy with the mechanical switch, we find the common emitters form the single-pole switch sections, while the two collectors are the *throw* terminals. Like the vibrator version, the action of the transistor *switch* is to ground first side A then side B of transformer T1. As in the previous case, the DC input power is applied to the primary-winding center-tap. LAS-3800 outputs E_A and E_B are used to drive transistors Q1 and Q2 out of phase with each other. The current-sense resistor, R_S, is connected to the current-limit and frequency-shift inputs of the LAS-3800.

The transistors are power types. They should have a high enough collector power dissipation, and voltage and current ratings high enough to carry the load. The current and power dissipation ratings are easy enough to see, but the voltage rating may be a problem. The switches essentially place a squarewave across the primary of the transformer, which is an inductive load. Since the transformer current has a high rate of change, and the load is inductive, the voltage spike will be high. The CEMF produced will be:

$$V = L(\Delta I/\Delta t).$$

(Continued on page 95)

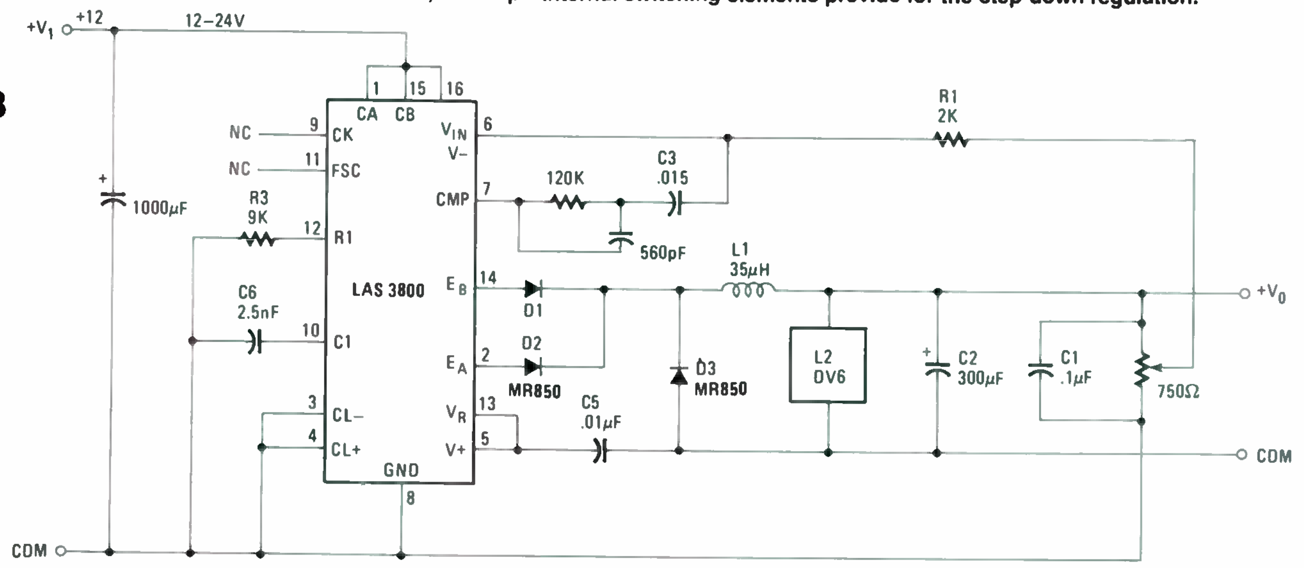
A



NC NOT CONNECTED

FIG. 27—EITHER STEP-UP OR STEP-DOWN voltages are possible from the Lambda LAS3800 integrated circuit. In A above, a step-up circuit alternately switches coil L1 from a short-circuit to ground via R1 to the rectifier/filter network. In B below, the chip's internal switching elements provide for the step-down regulation.

B



NC NOT CONNECTED

DESIGNING POWER SUPPLIES

(Continued from page 93)

The inductor, in that case the inductance of the transformer's primary winding, need not have a large value to generate a high voltage, because the current pulse rate of change ($\Delta I/\Delta t$).

Sometimes, designers place an RC *snubber* network across the primary winding from collector-to-collector (Q1 to Q2). Typically, such a *snubber* consists of a series combination of 0.001-μF capacitor (at 1000-volts or more) and 100-

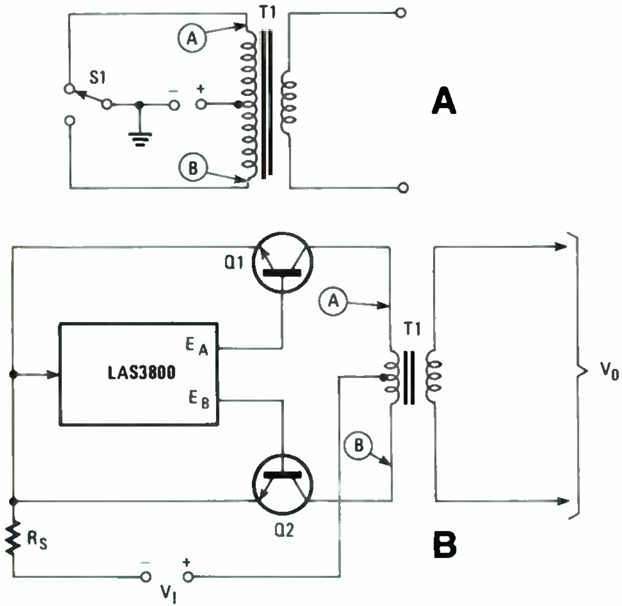


FIG. 28—OLD TIMERS will recall the circuit in A that is similar to the vibrator power supplies common to automobile radios that used vacuum tubes for many years. The LAS3800 chip B provides the same function by driving two switching transistors in an almost identical switching circuit.

ELECTRONIC COIN TOSS

(Continued from page 53)

If all components in the circuit could be exactly matched, the chances of either transistor being on at the instant S2 is released would be exactly even—a 50:50 chance. However, the adjustable trimmer potentiometer, R7, is included so that you can compensate for variances in the components' values. If you have access to a oscilloscope, check the waveform at either collector while S2 is held closed. Adjust the trimmer for equal on and off periods.

Putting It Together

The circuit layout is shown in the photo and in Fig. 2. Most of the components are on a small piece of printed-circuit board (half of a 300 PC Experimenters board from Global Specialties Corp. or Radio Shack Experimenters PC board No. 276-174). The switches and LED's are mounted on a 2 × 4½-inch piece of blank PC board. The LED anodes, and all + 9-volt DC connections, are soldered to the copper foil.

Run off 100 tosses and record the fall of the coin. The count should be no further than 52:48 from a 50:50 expectation. If the gap is larger, reset S1 slightly, and do it again. After all, give the suckers a break! ■