Designing Practical DC Power Supplies

Engineering concepts used in the design of DC power supplies for hobby and amateur projects are easy to understand and apply to practical situations once you understand the theory related to rectifiers, filters and regulators!

By Joseph J. Carr

☐THE COMMON DC POWER SUPPLY IS MOST OFTEN RELEgated to a position of no importance by project builders who design electronics devices. Even in industry, where the designer should know better, the job of power-supply design is often given to newcomers who do not yet appreciate the problems associated with power-supply design.

But the power supply is far more important; consider some examples: A microcomputer power supply with too little current capacity drops out of regulation and allows the +5 volts DC to sink to +4.1 volts DC. The result is erratic operation causing programming errors. In another case, insufficient heat sinking causes a series-pass voltage regulator transistor to short out placing +8-volts DC on the +5 volt DC bus causing a $127 digital panel meter to turn to carbon.

In addition to output voltage, we must consider current capacity, internal resistance, voltage regulation, heat transfer, component reliability, and sensitivity to abuse. We might also have to consider whether we want certain features such as transient-noise suppression, over-voltage protection, and output-current limiting. Also, we might want to remotely sense the output voltage of a high-current power supply located only a few inches from the equipment it serves.

Power Supply Components

The principal components of a low-voltage DC power supply are as follows: transformer, rectifier, filter, and (sometimes) voltage regulator. If our requirements dictate additional features, then we might add transient suppressors, current limiting, overvoltage protection, and/or status indicators.

Transformers are used as voltage and current converters. The main job of the transformer is to convert the AC powerline potential (nominally 117-volts AC at 60 Hertz in the US) to the voltage required for the electronic device being powered. A secondary use for the transformer is to provide isolation between some electronic device and the AC line.

The transformer consists of two or more coils of wire wound over a common core of (usually) an iron alloy. Figure 1-A shows the basic transformer configuration. There are two windings shown in Fig. 1A—the primary and secondary

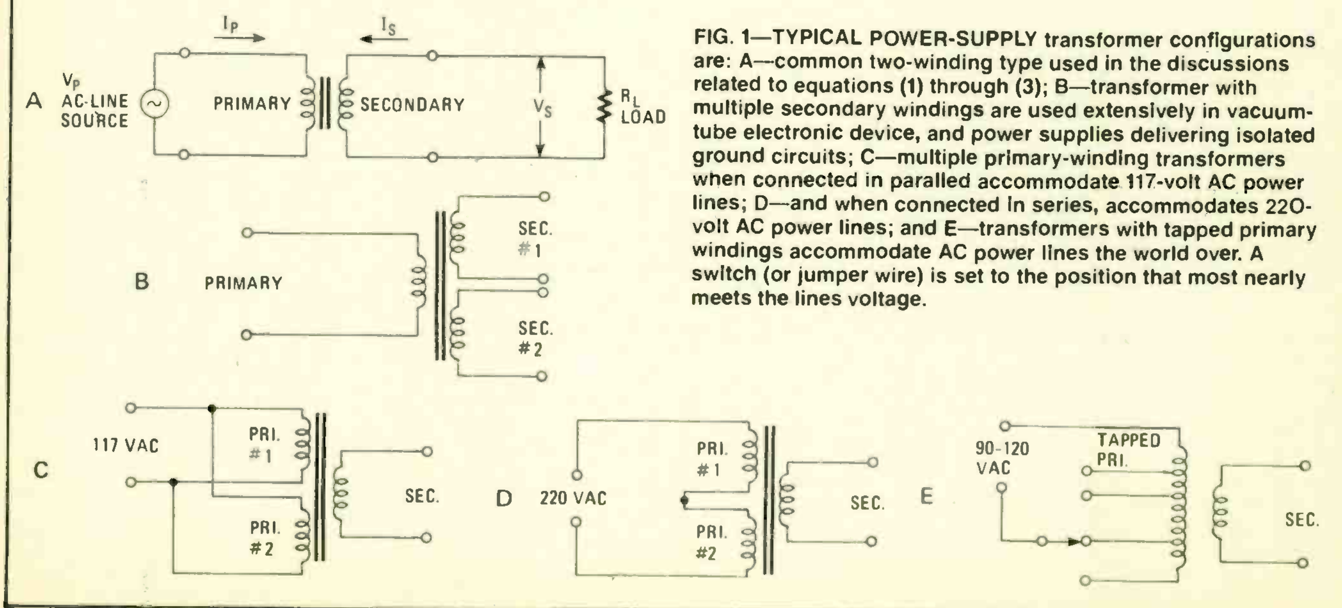

FIG. 1—TYPICAL POWER-SUPPLY transformer configurations are: A—common two-winding type used in the discussions related to equations (1) through (3); B—transformer with multiple secondary windings are used extensively in vacuum-tube electronic device, and power supplies delivering isolated ground circuits; C—multiple primary-winding transformers when connected in paralled accommodate 117-volt AC power lines; D—and when connected in series, accommodates 220-volt AC power lines; and E—transformers with tapped primary windings accommodate AC power lines the world over. A switch (or jumper wire) is set to the position that most nearly meets the lines voltage.

windings, each electrically isolated from each other.

There is a mathematical relationship between primary and secondary voltage/current values:

(1) $$V_P I_P = V_S I_S$$

where V_P is the voltage applied to the primary winding, V_S is the voltage appearing across the secondary winding, I_P is the current flowing in the primary winding, and I_S is the current drawn from the secondary winging.

We can rewrite equation (1) in a more useful form, as follows:

(2) $$V_P/V_S = I_S/V_S$$

In order to maintain the important equality of equation (1), we find in equation (2) that the voltage and current ratios are reciprocals of each other.

The voltage ratio is totally dependent upon the turns ratio of the transformer, and obeys the following equation:

(3) $$V_P/V_S = V_P/V_S$$

where N_P and N_S are the numbers of turns in primary and secondary windings, respectively, and V_P and V_S are as previously defined.

Unless otherwise specified, the voltage rating of a transformer is the root-mean-square (*rms*) value. Thus, a 6.3-volt AC transformer produces a peak voltage will be 1.414 times the *rms* voltage; or 6.3-volt AC produces a peak voltage of 8.9.

Volt-Ampere Rating

A principal rating of a power transformer is the volt-ampere (VA) rating. The VA rating basically tells us how much power the transformer will provide. Transformers tend to be highly-efficient devices (96 to 99 percent), so that the primary VA rating is usually considered equal to the secondary VA rating (see equation 1). For most cases, however, it is the primary VA rating that is of importance. That is done because the primary winding is innermost, and is closest to the core. Hence, the primary winding receives less cooling from the environment. It is not safe to exceed the primary VA rating.

Transformers come in configurations other than the basic type shown in Fig 1-A. Other transformer variations are shown in Figs. 1-B through 1-F.

Rectifiers

Electronic circuits don't usually operate on alterating current—direct current (DC) is a strict requirement. The main feature of DC is that it is unidirectional—that is, DC flows in only one direction. A rectifier is a device that permits current to flow in only one direction; therefore, a rectifier is a one-way valve (gate or switch) for electric current. Both vacuum-tubes and solid-state diodes are used as rectifiers.

A word of explanation: Early in the study of electricity, it was decided to mark one terminal of the battery positive (+) and the other negative (−). Not knowing about atomic physics and the electron, either selection would have had a 50-50 chance to be correct. We lost, because the incorrect choice was made. Thus, current flows from positive to negative, and electrons flow from negative to positive. The diode symbol has its arrow pointing in the direction of current flow. Remember that, and you'll have no problem following the text below.

Figure 2-A shows a simple circuit using a solid-state diode rectifier. When the polarity of the AC is such that the anode of the rectifier is positive (Fig. 2-A), then the diode is forward biased so current (i) flows. On the negative half-cycle of the AC, the rectifier anode is negative (Fig. 2-B), making the diode reverse biased. Under that condition, no current flows because the diode is cut-off—it is essentially an open circuit.

The result of rectfication action by the diode is shown in Fig. 2-C. Since only one-half of the AC waveform causes current to flow, the circuits of Figs. 2-A and 2-B are called a halfwave rectifier. Since the rectifier output waveform consists of undirectional pulses of current, it is refered to a pulsating DC. That pulsating DC is not useful in most circuits. It must be filtered to produce pure (or nearly pure) DC voltage that appears to be steady when measured by a voltmeter.

Filtering is not the only problem with halfwave rectifiers—they are also inefficient. The transformer used in halfwave rectified circuits typically must have a primary VA rating at least 40 percent higher than that of a transformer feeding a fullwave recitfier circuit providing the same voltage and current capaciy. The average output potential for halfwave circuits is 45 percent of the applied RMS potential. The ripple, degree of pulsation or departure from pure DC, is 120 percent.

Fullwave Rectification

A fullwave rectifier is shown in Fig. 3-A. The transformer is a special type that has a center-tapped secondary winding. On any give cycle, one end of the secondary winding will be positive and the other end is negative. The potential at the center tap is half the overall potential. With the center-tap as the common, the potentials at the points A and B will be equal in amplitude but have opposite polarity.

On one-half the AC input cycle point A will be positive with respect to the center-tap, while point B is negative. Under that condition, diode D1 is forward-biased and D2 is reverse-biased. Current flows out of the transformer at point

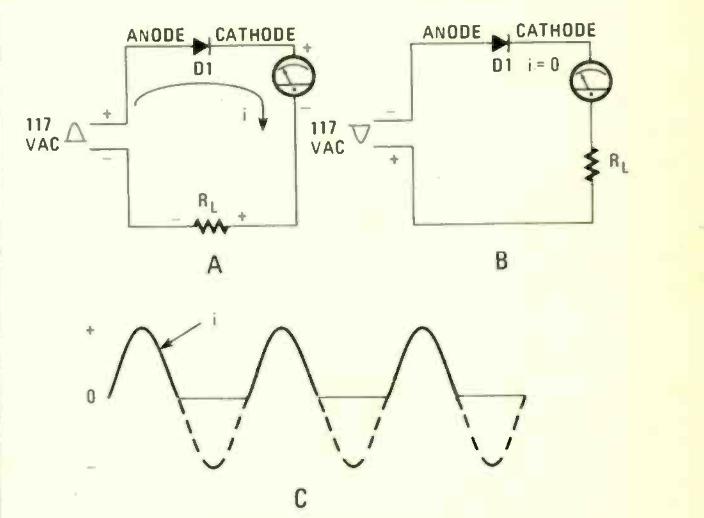

FIG. 2—THE ACTION of a solid-state diode on one cycle of AC voltage applied to the terminals of a halfwave rectifier: A—current *i* flows, B—current cutoff, and C—graph of current *i* for three cycles.

A, through through diode D1, load resistor R_L, and then back to the transformer at the center tap. Note the direction of current flow in R_L when diode D1 conducts on the positve half cycle.

On the second half-cycle, the transformer secondary winding polarities reverse. Under that condition, diode D1 is reverse-biased and D2 is forward-biased. Current flows out of point B, through diode D1, resistor R_L, and returns to the secondary winding at the center tap.

The important thing to note is that current flows in the load resistor R_L in the same direction on both halves of the AC cycle. That action produces the waveform of Fig 3-B. The double-humped current waveform is easier to filter and is more efficient than that of the halfwave rectifier. The ripple is 48 percent, while the ripple frequency is twice the AC line frequency (120 Hz in the US). The average potential of the unfiltered output is approximately 90 percent of the applied *rms* potential.

The Bridge Rectifier

Another form of fullwave rectifier is shown in Fig 4. That circuit is called a bridge rectifier, and consists of four diodes. No transformer secondary-winding centertap is needed in the bridge circuit.

As on any other transformer, the polarities of the transformer secondary ends are opposite each other. Thus, on each half-cycle, two diodes are forward-biased and two are reverse-biased. It could be said that, in effect, the diodes were center-tapped!

On the first half-cycle, the voltage at point A is positive with respect to point B, so diodes D1 and D2 are forward-biased while diodes D3 and D4 are reverse-biased. Current flows out of the transformer at point A, through D1, load resistor R_L, diode D2, and then back to the transformer secondary winding at point B.

On the second half-cycle, the AC polarities reverse, making point A negative and point B positive. Under that condition, diodes D3 and D4 are forward-biased and diodes D1 and D2 are reverse-biased. Current leaves the transformer at point B, travels through D3, R_L, D4 and then returns to the transformer via point B. Again, as in any fullwave rectifier, the direction of the current in the load resistor is the same on both halves of the AC cycle (see Fig. 3).

The pulsating DC produced by a bridge rectifier is not usuable in most electronic circuits. To produce nearly pure DC from the rectifier output a filter must be used. The simplest form of filter is a single capacitor in parallel across the load resistor. See Fig. 5. The operation of filters will be discussed shortly, but included here, because the filter capacitor affects rectifier ratings which is our real topic. For now, let's be content with the fact that the filter capacitor (C1) is charged to the peak of the AC waveform. That means that the bridge rectifier's output voltage under no load is 1.414 × volts_{rms}. It comes to 165.4-volts DC from a line isolation transformer T1 delivering 117-volts AC.

Rectifier Ratings

There are four main specifications used with rectifiers: surge current, leakage current, forward current and peak-inverse voltage (PIV). Of those, the latter two are of greatest importance most of the time.

Surge current is the maximum short-term current usually defined as on AC cycle (1/60 second, or about 17 milliseconds). That current can be extremely high and is not the operating current!

Leakage current is the current that flows when the rectifier diode is reverse-biased. This value is typically very low, and the lower, the better.

The forward current is the maximum sustained current that the diode will handle without damage to itself.. When a *spec* sheet says that a diode is a *1-ampere* type, it is the forward current that is being quoted.

There seems to be a little creative specification writing with respect to forward current. Some blister-pack venders rate a diode at 1.5 to 2 times the actual current rating. They get away with that practice as long as the diode is specified as operating under Intermittant Commercial and Amateur Service Code (ICAS), instead of Continuous Commerical Service (CCS) code.

In general, it is best to select a rectifier with a forward

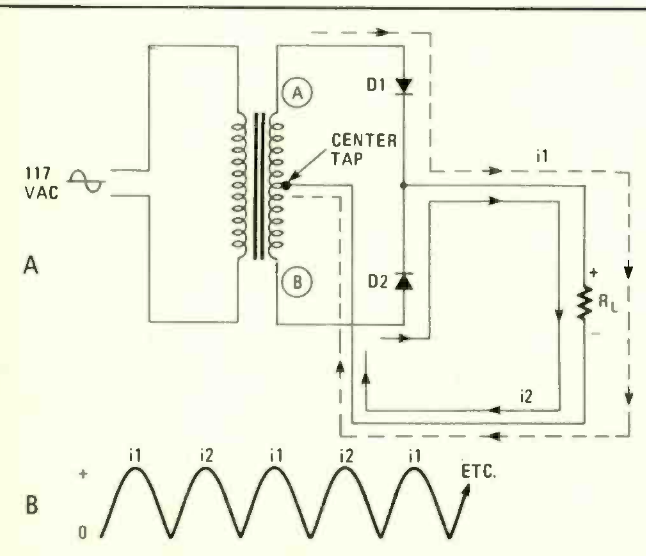

FIG. 3—A FULLWAVE RECTIFIER (A) takes current from both halves of the AC voltage cycle so that two positive current pulses per cycle (B) flow through the load resistor.

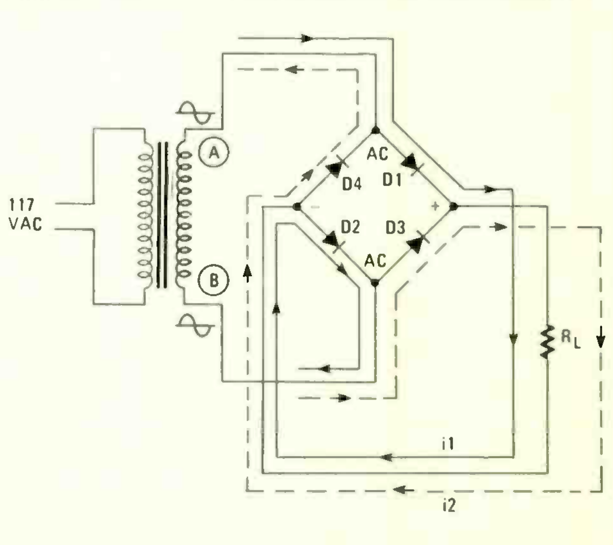

FIG. 4—THE BRIDGE FULLWAVE RECTIFIER provides the same rectification action as in Fig. 3 but it does not require a center-tapped power transformer.

current rating that is twice the expected average current. For rectifiers of *uncertain parentage*, one-fourth to one-third (rather than one half) would be an appropriate *de-rating* factor.

Peak-inverse voltage (PIV), also called peak-reverse voltage (PRV), is the maximum reverse bias potential that the diode will sustain without damage to itself. The PVI rating is the one that causes the most trouble with power-supply designers! Whenever a power supply routinely blows diodes, it is almost a sure bet that the PIV rating is insufficient.

Some designers fail to recognize the true reverse-bias voltage in a filtered power supply. On one half-cycle, the diode will be forward-biased and current flows. On that half-cycle, the filter capacitor (C1 in Fig. 5) charges to peak positive voltage (i.e. 1.414 × *rms*). That voltage charge remains on C1. On the next half-cycle, the AC voltage reverse-biases the rectifier to the peak negative voltage (again, 1.414 × *rms*). That potential is added to the capacitor voltage to make the actual PIV twice normal peak voltage (i.e. 2 × 1.414 *rms* = 2.83 *rms*: or approximately 320.8 PIV). It would be wise to use diodes in the bridge circuit rated at a standard value of 400 PIV.

I personally prefer to use 1000-volt PIV diodes for all low-voltage (under 165-volts) applications in the low- to medium-current 1 to 3 amperes range. The popular 1N4007 is rated at 1000-volts PIV at 1-ampere. They are cheap and easily available.

When laying out a DC power supply, be sure to give the rectifier plenty of *breathing* room. Rectifiers generate heat, so they need room for ventilation. Stud-mounted rectifiers often require ample heat-sinking. Axial-lead rectifiers should be mounted with ⅛-inch-space between the printed-circuit board and the rectifiers, and with .4-inch of lead showing on either end. Also, do not mount rectifiers close to heat sensitive devices and such as op-amps, oscillators and transistors.

Geting into Filters

The purpose of the filter in a power supply is to smooth out the pulsating DC produced by the rectifier, and make it as near to pure DC as possible. Very few electronics circuits will operate properly on unfiltered DC.

The simplest form of filter is a single capacitor connected in parallel with the rectifier output and the load. Such a filter is called a *brute-force* filter. An example is shown in Fig. 5.

During the time when the rectifier output voltage is increasing, capacitor C1 will be charging. See Fig. 6. After the peak voltage (V_P) passes, however, the rectified voltage decreases and will soon reach a point where its potential is lower than the potential across the filter capacitor, C1. At that time, the charge stored in the capacitor begins to dump into the circuit load, R_L. That action has the effect of filling in the space between peaks (shaded area in Fig. 1B), therefore raising the average output voltage to a value closer to the peak voltage (Vp). The discharge slope noted in Fig. 6 indicates that current is being taken from the filter capacitor during the interval when the rectifier's output voltage is below the capacitor's voltage.

The degree to which the filter smoothes the output voltage (reduces the discharge slope to a horizontal line in Fig. 6) depends on both R_L and C1, and is expressed by a nondimensional ripple factor (R.F.):

(4) $$R.F. = V_R \div V_a$$

where R.F. is the dimensionless ripple factor; V_R is the ripple amplitude with C1 disconnected, and V_a is the average ouput voltage with C1 in the circuit.

Equation (4) can be replaced with the more useful general form shown below:

(5) $$R.F. = 1 \div 3.461fR_LC1$$

where f is the ripple frequency in Hertz, R_L is the load resistance in ohms, and C1 is the capacitance in Farads. (Note: R_L is the output voltage divided by the output current—$V_O \div V_O$.)

In the U.S., the AC line frequency is almost universally 60 Hz, so the power-supply ripple frequency will be 60 Hz when halfwave rectification is used, and 120 Hz when fullwave rectification is used. Therefore, we rewrite the general form equation to simpler specific forms:

Halfwave rectifiers:

(6) $$R.F. = 1 \div 208R_LC1$$

Fullwave rectifiers:

(7) $$R.F. = 1 \div 416R_LC1.$$

Example

Find the ripple factor (% RF) of a 12-volt DC (V_O), 2-ampere (I_O) power supply that uses a fullwave rectifier and a 1000-uF filter capacitor (assume line frequency of 60 Hz). Equation (7) is used in this instance. However, it should be noted the load resistance, R_L is determined by:

$$R_L = V_O \div I_O = 12 = \text{div } 2 = 6 \text{ ohms.}$$

Then,

$$R.F. = 1 \div (416)(6)(10)$$
$$R.F. = 0.4.$$

Normally, we will have a ripple-factor percentage in mind as a design goal, and the load resistance is set by other requirements. We will want to rearrange Eqs. (6) and (7) to find the minimum value of capacitance (C1 in Fig. 5) required to do the job. Also, we will want our result in microfarads (μF), not Farads. To accomplish those goals we can rewrite Eqs. (6) and (7) into a final form:

Halfwave Circuits:

(8) $$C1\ (\mu F) = 10 \div 208R_L(\%\ R.F.)$$

Fullwave Circuits:

(9) $$C1\ (\mu F) = 10^6 \div 416R_L(\%\ R.F.)$$

Equations (8) and (9) are valid for power supplies using brute force filtering as diagrammed in Fig. 5 and operating from 60 Hz AC power lines. On 50-Hz power systems, increase the value of C1 by approximately 20 percent.

There's a rule of thumb calling for a minimum value for C1 of 1000 microFarads per ampere of load current. That advice is based upon a ripple-factor of 0.5, and is especially valid if a voltage regulator follows the filter section. Incidentally, many designers prefer to double the rule-of-thumb value to 2000 μF/ampere.

The filtering action has the effect of raising the average output voltage. The voltage produced by Fig. 5 will be as follows:

Halfwave Circuits:

(10) $$V_O = V_P - (1 \div 120C1)$$

Full-wave Circuits:

(11) $$V_O = V_P - (1 \div 240C1)$$

Where V_O is the DC output potential, V_P is the peak rectifier voltage (1.414 × V_RMS), I_O is the output load current in amperes, and C1 is the capacitance in Farads.

RC Pi-Section Filter

A pi-section filter of Fig. 7 offers improved filtering, because of improved ripple reduction at the expense of poorer voltage regulation and current limiting caused by R1. Both of those defects result from the fact that R1 has the effect of increasing the series output impedance of the power supply.

The defects of the pi-section filter can be overlooked if

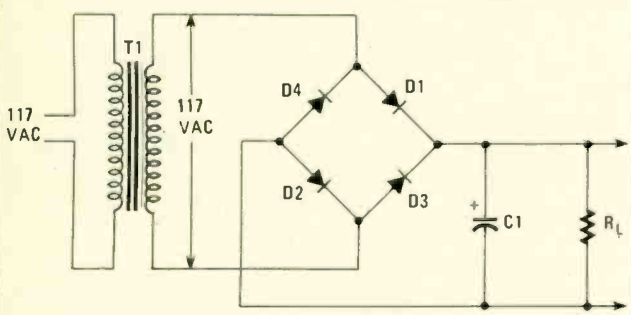

FIG. 5—CAPACITOR C1 provides ripple voltage filtering so that R_L always has a DC voltage across it. Refer to text for discussion on PIV rating of C1.

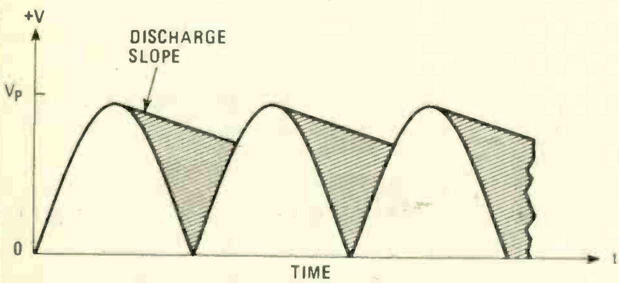

FIG. 6—THE DISCHARGE SLOPE of the voltage curve will droop even more than it does should the current drain from the power supply be increased.

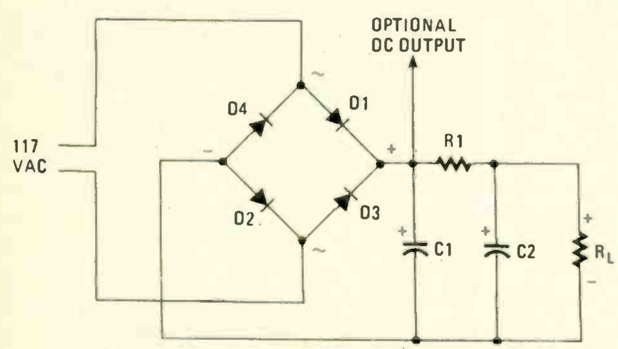

FIG. 7—THE PI-SECTION RC FILTER offers improved filtering at the expense of voltage regulation. This circuit best suits near constant-current loads.

ripple reduction is of prime concern, and the load current is relatively constant. A good example of such an application is a class-A, audio-preamplifier stage. Such a circuit offers low power, but nearly constant-current requirements. At the same time, the audio preamplifier needs to be free of ripple-produced, power-supply hum.

The ripple factor at the output of Fig. 7 (across R_L) is given by the equation:

(12) $$R.F. = K \div C_1C_2R1R_L$$

where C_1 and C_2 are in Farads, R1 and R_L are in ohms, K is a constant (10^{-5} for halfwave circuits and 2×10^{-6} for fullwave circuits). Here is a simple example: Find the ripple factor of a 12-volt DC, 500 mA power supply in which C1 is 1000 µF, C2 is 500 µF and R1 is 68 ohms. Assume fullwave rectification. The solution is as follows:

$$R.F. = 2 \times 10^{-6} \div (10^{-3})(5 \times 10^{-4})(68)(12 \div 0.5)$$
$$R.F. = 2 \times 10^{-6} \div 8.2 \times 10^{-4}$$
$$R.F. = 0.002$$

In many cases, practical DC power supplies similar to Fig. 7 will have two output connections. The low-ripple output is across C2, and an optional high-current output across C1. Each DC output will have its own ripple factor.

Selection of Filter Capacitors

Power supply filter capacitance values are generally considered *high*, or *large* compared to the values of other capacitors found in the circuits fed by the power supply. A high-voltage DC supply will have filter capacitors in the 5-µF to 100-µF range (especially where RC or LC pi-sections are used), while low-voltage supplies have filter capacitors in the over-500-µF range. You can expect to find filter capacitor values of 150,000-µF in some computer power supplies.

Complicating the issue is the fact that power supplies in many multi-stage equipments provide decoupling between stages in order to prevent oscillations due to unwanted feedback paths.

The equations presented thus far provide the ripple-factor percentage reduction required, but may not be sufficient for by-passing low frequency AC signals. For audio, the calculated value % R.F. is generally sufficient, but as the low-frequency response of the amplifier approaches DC (as it might in instrumentation or control system applications) we might need a larger value capacitance to accommodate decoupling. The usual rule is to select a capacitor value that: (a) gives the desired low-frequency response, or (b) gives the desired ripple reduction. When those values are not equal, use the higher value capacitance.

The general rule of thumb is to select a capacitive value for decoupling that offers a reactance equal to one-tenth the apparent circuit resistance at the lowest frequency of operation. The equation is:

(13) $$C = 1 \div 2F(0.1R_S)$$

where C is the capacitance in Farads, F is the −3 dB low-frequency response point, and R_S is the circuit source resistance.

The proper design procedure is to calculate the minimum capacitance from both ripple factor and frequency response and then use the higher of the two values.

High values of capacitance are available only in the form of electrolytic capacitors, of which there are two kinds: aluminum and tantalum. For most filter applications it is the aluminum that is most commonly used.

The two ratings for electrolytic capacitors which must be observed are the capacitance and the DC working voltage (WVDC). Typically, the capacitance value of aluminum electrolytics has a tolerance of −20%/+100%. If either ripple factor or frequency response is critical, then increase the value of the calculated filter capacitance by 20 to 30 percent. Normally, there is no penalty for using *too much* capacitance!

The WVDC rating is normally subject to a tolerance +20 percent. As a result, it is not good design practice to operate a filter capacitor at potentials greater than 80% of the WVDC rating. Also, keep in mind that circuit potentials may vary by ±20 percent, so it may pay to select a WVDC-rating at least 40-percent higher than the anticipated nominal voltage.

Earlier we referred to a design error in a piece of equipment that caused massive failures of filter capacitors. The power supply was +200-volt DC regulated supply in which the pre-regulator potential across the filter section was nominally +280 volts. The designer used 350-WVDC electrolytic capacitors for the filter section. Good practice, right. Wrong!. let's consider the worst case in which the capacitor voltage (V_C) is −20% lower than its rated working voltage and the power-supply voltage (V_{PS}) is +20% higher than the nominal 280 volts.

$$V_{PS} = 280 + (0.2 \times 280) = 336\text{-volts DC}$$
$$V_C = 350 - (0.2 \times 350) = 280\text{-volts DC}$$

In the worst case situation, we have a 280-volt DC capacitor in a 336-volt DC circuit!. True, the worst case may never occur, but those capacitors were over stressed to cause massive failures in critical equipment. The cure was to replace all of those 350-WVDC electrolytic capacitors with 450-WVDC replacements of the same capacitive value.

It is sometimes necessary to combine capacitors in order to obtain higher capacitive values. When two or more filter capacitors are connected in parallel (Fig. 8), the total capacitive value C_T is determined by the equation:

$$C_T = C_1 + C_2 + \ldots + C_n$$

The WVDC rating of a parallel combination of capacitors, however, is the lowest of the individual WVDC rating in the parallel group. For example, if a 50-WVDC capacitor is connected in parallel with 25-WVDC unit, then the usable rating of the pair is only 25-WVDC.

Figure 9 shows capacitors connected in series in order to increase the WVDC rating. Unfortunately, that method reduces the effective capacitance by the usual rule for series capacitors. In most cases, all series capacitors in the stack have the same capacitive value, so the total capacitance is merely $C \div n$, where C is the capacitance of each unit, and n is the number of units.

If all capacitors have equal capacitance and WVDC ratings, then the total WVDC rating is the sum of individual WVDC ratings. Thus, four 200-μF, 450-WVDC capacitors in series are equal to a single 50 μF, 1800-WVDC capacitor. It is quite common to find such capacitor stacks in high-power, vacuum-tube, linear-RF amplifiers used by Amateur Radio operators.

There are some caveats in the scheme, however. One is that voltage-balance resistors, R1, R2, etc. (Fig. 9) must be connected in parallel with each capacitor. Those resistors should have a resistance (R_O of approximately 100-ohms per volt, and a power rating greater than $V_C^2 \div R$. In a case where 450-WVDC capacitors are used, then $R = (450 \times 100) = 45{,}000$ ohms (47,000-ohms standard fixed value) with a power rating greater than $(450^2 \div 45{,}000)$ or, 4.5 watts. In that case, a 5-watt resistor will *do*, but a 7-watt or 10-watt unit is preferred. Some designers use lower wattage resistors in hope that power supply voltages will never approach the WVDC rating. For example, if we are certain that not more than 250 volts will appear across a capacitor, then we might get away with using 2-watt resistors

Another possible caveat involves the voltage drops across unequal capacitances. Normally, we can sum the WVDC ratings. If the capacitances are not equal, then the actual voltage drops will be unequal. We will have to calculate the reactances of each capacitor at the ripple frequency, and then calculate the voltage drops across each reactance (they will divide according to the voltage-divider equation). It may be that one or more capacitors will receive more than a fair share of the voltage drop.

Finally, in Fig. 10 we see a scheme used sometimes in power supplies that power RF amplifiers. The electrolytic capacitors are not readily capable of bypassing RF, or even high, ultrasonic frequencies. For those applications we need a high-value electrolytic for ripple reduction, and a disc ceramic, or mica, capacitor for high-frequency decoupling, or by-passing. In Fig. 10 we have a 2200-μF capacitor for power supply ripple reduction, and 0.1 μF for high-frequency decoupling.

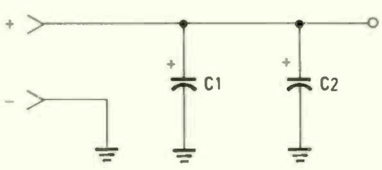

FIG. 8—FILTER CAPACITORS are ganged in parallel —their total capacitance is the sum of each capacitor.

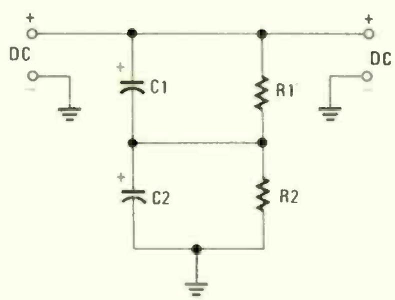

FIG. 9—FILTER CAPACITORS connected in series effectively increase the overall DC working voltage.

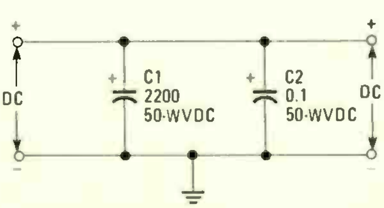

FIG. 10—ELECTROLYTIC capacitors cannot readily pass high frequencies—a small ceramic does the job.

Voltage Regulators.

The purpose of a voltage regulator is to maintain a constant output voltage despite changes in either output load current, input voltage, or both. There are two primary sources of voltage-regulation problems that cause considerable difficulty with consumer appliances. One is variation of the supply voltage from the AC power line that can fluctuate 20 percent (the usual range is 105 to 125 volts RMS). Many areas of the U.S. suffer *brown-outs* when the area power lines drop to 100-volts AC, or even as low as 90-volts. Some motor-vehicle battery voltages vary 40 percent, with 20-25 percent being typical. Those extreme battery-supply variations play havoc with consumer audio equipment, Amateur Radio gear, and CB rigs installed in cars.

The second cause of output-voltage variation is changes in output current. The root of the problem is that no practical power supply is ideal. All power supplies have internal resistance (sometimes called source resistance, R_S). That internal-resistance problem is modeled in Fig. 11 by R_S in series with a perfect voltage source, V_I.

When no output current is drawn, the output voltage V_O is equal to V_I. But, when an output current is being drawn there will be a voltage drop ($I_O \times R_S$) across the power supply internal, series resistance. Under that condition the actual output potential is $V_O = V_I - (I_O \times R_S)$. We can minimize output-voltage change by: (1) making I_O constant (not always possible), (2) minimizing R_S (often expensive and always impossible), or (3) providing a voltage regulator. The last option is the most reasonable.

The percentage of regulation (%REG) is the measure of voltage regulation, and is given by the equation:

$$\%REG = (100)(V_O - V_{Lmax}) \div V_O$$

where V_O is the open-terminal, no-load, output voltage, and V_{Lmax} is the output voltage when the power supply's maximum, rated-output current is drawn.

Series-vs.-Parallel Regulators

Voltage regulators fall into two basic categories—series and parallel. A parallel (*shunt*) regulator is one in which the actual regulating element is in parallel with the load. An example is a circuit that uses a Zener diode as the regulating element. The series regulator uses an active element in series with the load; examples include all circuits using a series-pass transistor to control output-voltage level.

Zener Diode Voltage Regulator

The Zener diode is the simplest form of regulator available. Figure 12 shows the schematic symbol for a Zener diode and the I-vs.-V characteristic curve.

The Zener diode is an ordinary PN junction diode with a predetermined and well controlled avalanche voltage (V_Z) called the *Zener potential*.

The Zener diode behaves exactly like any other PN junction diode when operated in the forward-bias region illustrated in Fig. 12. Between 0 volts and about 0.7 volts (V_g) the current increases from elementary leakage current (I_L) to some specific forward current, but in nonlinear manner. Above V_g, the current rises linearly with increasing voltage; that is called Ohm's law region of operation.

The Zener diode acts like any PN junction diode in that portion of the reverse-bias region between 0 volts and V_Z. Only a minute reverse-bias leakage current (I_L) flows.

The difference between the Zener diode, and other PN diodes, is seen where the reverse-bias potential reaches the Zener point, V_Z. At that potential, the diode junction *breaks over* (avalanches), and the current increases rapidly. Furthermore, the voltage drop across the Zener diode remains constant despite changes in applied voltage. It is that phenomenon that permits voltage regulation by the Zener diode.

Figure 13 shows a Zener-regulated DC power supply. Resistor R_L represents the load applied to the power supply (i.e. $V_Z \div I_3$). Capacitor C1 is the regular filter capacitor used in any DC power supply. A good rule of thumb is to make C1 not less than 1000-µF per ampere of load current, or 500 µF (whichever is larger).

Capacitor C2 in Fig. 13 is used to suppress avalanche *hash* noise produced by the Zener diode. In many circuits that noise is negligible, so C2 may be deleted.

Designing a Zener-diode regulator circuit as seen in Fig. 13 is a four-step process: (1) Determine the operating condition (explained below); (2) select the Zener potential; (3) select

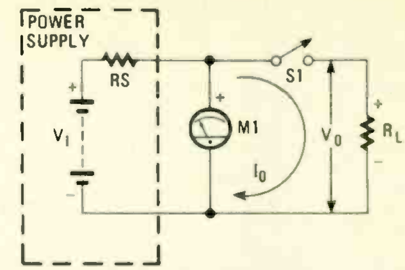

FIG. 11—LOW INTERNAL RESISTANCE, R_S, assures the designer of good voltage regulation under conditions where the value of R_L varies considerably.

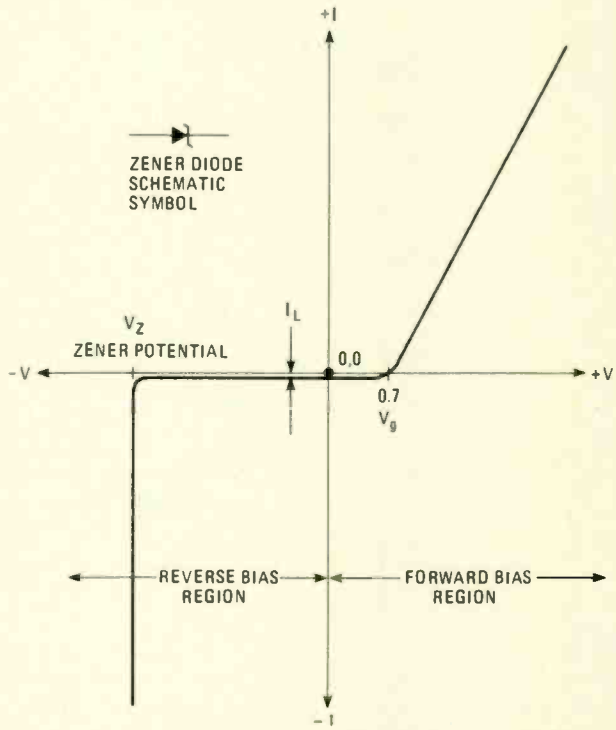

FIG. 12—ZENER DIODE voltage regulation is experienced in the reverse-bias region. Under forward-bias conditions its just another high-current diode.

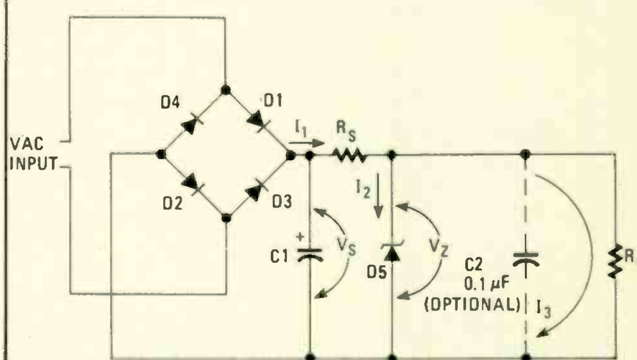

FIG. 13—ZENER-REGULATED DC power supply provides constant voltage to R_L. Capacitor C1 provides basic filtering keeping V_s always higher than V_Z.

the resistance and power rating of R_S; and, (4) calculate the power dissipation of Zener diode.

There are three circuit conditions under which the Zener diode might have to operate. Step (1) of the design process

TABLE 1
FORMULAS FOR ZENER DIODE REGULATOR

Calculation of Value of R_S in Ohms

Condition 1:

$$R_S = \frac{V_{MIN} - V_Z}{1.1 I_3}$$

Condition 2:

$$R_S = \frac{R_{IN} - V_z}{1.1 I_3(\text{maximum})}$$

Condition 3:

$$R_S = \frac{V_{MIN} - V_Z}{1.1 I_3(\text{maximum})}$$

Power Dissipation of D5 in Watts

$$P_{D5} = \frac{(V_{MIN} - V_Z)^2}{R_S} - (I_3 V_Z)$$

Power Dissipation of R_S in Watts

$$P_{Rs} = \frac{(V_{MAX} - V_Z)^2}{R_S}$$

or $P_{Rs} = P_{D5} + (I_3)(V_Z)$

requires that we determine which of those conditions most nearly represents the conditions in our circuit. The three conditions are:

1—Variable supply voltage V_S, constant load current I_S
2—Constant V_S, variable I_3
3—Variable V_S, variable I_3

The equations used to design for those three cases are shown in Table 1 that is found immediately above. Below are the design steps, and an example for Condition 1. The three conditions are so similar that providing examples for all three would be repetitive.

Design for Condition 1

Follow the listing of steps below to determine circuit parameters:

1—Select V_Z from the application
2—Select load current I_3
3—Calculate R_S (see Table 1)
4—Calculate Zener diode power dissipation
5—Select Zener diode power rating
6—Calculate resistor (R_S) power dissipation
7—Select resistor (R_S) power rating

Example:

Design a Zener diode voltage regulator such as Fig. 13 to provide a 6.8 VDC to a circuit that draws 75 milliamperes. The power source is an automobile battery, which normally varies 12 to 15 VDC as the engine speed changes from an idle to high RPM.

Step 1. Select V_Z = 6.8 VDC (given)
Step 2. Load current = 0.075 Amperes (given)
Step 3. $R_S = (V_{min} - V_Z) \div (1.1 I_3)$
(Note: 1.1I is used to allow added 10% current flow in R_S)

$R_S = (12 - 6.8) \div (1.1 \times 0.075)$
$R_S = (5.2V) \div (0.083A) = 63$ ohms

Step 4. Calculate P_{D5}

$P_{D5} = [(V\max - V_Z)^2 \div R1] - (I_3 V_Z)$
$P_{D5} = [(15 - 6.8)^2 \div 63] - (0.075)(6.8)$
$P_{D5} = [(8.2)^2 \div 63] - (0.5)$
$P_{D5} = [(67.2) \div (63)] - (0.5)$
$P_{D5} = 1.07 - 0.5 = 0.57$ watts

Step 5. Select D5 power rating. Since P_{D5} is 0.57 watts, we can reasonably use a 1-watt Zener diode. In general, it is good practice to use a diode with a rating that is 20% (or more) higher than the computed value for P_{D5}.

Step 6. Calculate P_{Rs}

$P_{Rs} = P_{D5} + (I_3 \times V_Z)$
$P_{Rs} = 0.57 + (0.075)(6.8)$
$P_{Rs} = 0.57 + 0.5$
$P_{Rs} = 1.08$ Watts

Step 7. Determine R_S power rating. Since P_{Rs} is 1.07 watts, we must use a 2-watt resistor for R_S—the next higher standard rating. We follow the same "120% or more" rule here as for the diode power rating.

Design for Conditions 2 and 3

The technique for designing to conditions 2 and 3 are exactly the same as for condition 1, except as follows:

Condition 2—use I_{3max}, instead of I_3 (condition 2 represents variable current)

Condition 3—use V_{min}, as in condition 1 and I_{3max} as in condition 2.

Limitations

Some people erroneously believe that the Zener diode is a universal voltage regulator—it is not! For most situations, it is limited to power supplies of low- to medium-current capacity. Higher current levels can be accommodated by using a circuit in which a Zener diode is used to provide a reference voltage, but requires some other active device to handle the current.

Zener diodes suffer from voltage error due to temperature change, and also from the fact that Zener voltage tends to be nominal rather than rigidly fixed. There are strategies available to overcome those limitations. For the present, however, be aware that precision, relatively-stable, reference voltages are available both from special-reference diodes, and integrated-circuit devices, that contain an internal Zener diode.

Series-pass Transistor Regulator

We can boost the current capacity of a Zener diode by using a power transistor to carry the current load, and the Zener diode to control the transistor *b-e* junction.

Figure 14 shows the circuit of a voltage regulator that uses a series-pass transistor (Q1). Figure 4 is an example of a series regulator, because the c-e path of Q1s in series with the load (R_L).

Capacitor C1 in Fig. 4 is the regular filter capacitor at the output of the rectifier. That capacitor should have a value of at least 1000 µF per ampere of rated maximum output current, I_{Omax}.

The output voltage is determined the Zener potential V_Z, and is approximately:

$$V_O = V_Z + V_{be}$$

where V_{be} will be approximately 0.7 volts on silicon transistors.

The load current for the Zener diode in Fig. 14 is the base current of Q1 (I_b). Since that current tends to vary, as does V_{IN}, we use the design equations for Condition 3 stated above for the Zener diode regulator.

We must select a transistor for Q1 that will: (1) Carry the maximum value of output current I_O, (2) sustain collector voltages at least as high as the maximum value of V_{IN}, (3) dissipate the power represented by $(V_{IN} - V_O) \times (I_O)$, and (4) have sufficient current gain (h_{fe}) to be driven by a reasonable I_b.

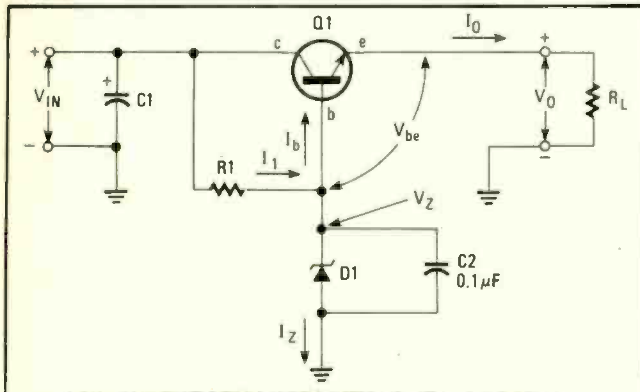

FIG. 14—CURRENT CAPACITY of a Zener diode can be boosted by the addition of a series-pass transistor. V_{be} is added to V_Z to obtain regulator's output, V_O.

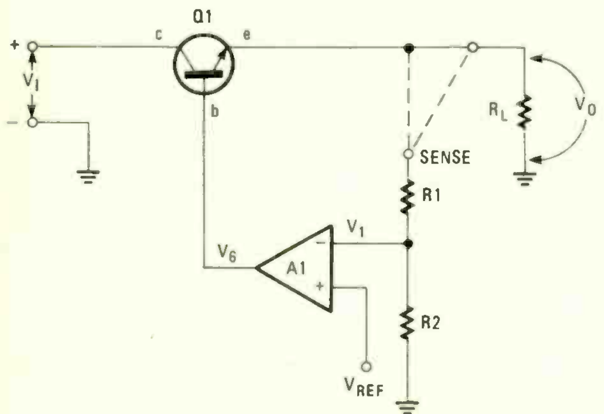

FIG. 15—VOLTAGE FEEDBACK from the output is compared to the reference voltage in an amplifier that controls the series-pass transistor current flow.

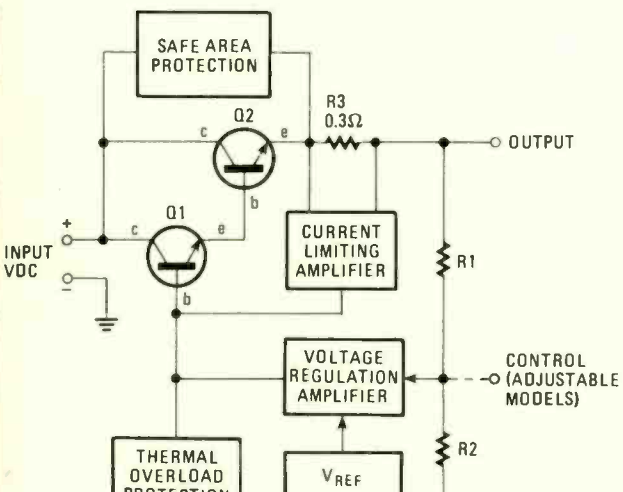

FIG. 16—BLOCK DIAGRAM of a typical three- and four-terminal voltage-regulator integrated circuit used in countless circuits, and available everywhere.

Current gain (beta, or h_{fe}) is the ratio of collector current (I_g) to base current (I_e):

$$h_{fe} = I_C \div I_B.$$

The transistor selected for Q1 must meet that criteria.

A variation on the series-pass regulator scheme is shown in Fig. 15. The series-pass transistor (Q1) is the same as in Fig. 14, but there is a new circuit to control the transistor base. In Fig. 15, the base-control voltage is the output potential (V_B) produced by amplifier A1. That amplifier has differential inputs. A reference voltage (V_{REF}) is applied to the non-inverting input, while a sample of the actual output potential is applied to the inverting input of A1. The latter voltage may be either the actual V_O, or a percentage (V_1) of V_O derived through a voltage divider (R1 and R2).

The output of amplifier A1 is proportional to: (a) the differential voltage gain of A1, and (b) the differential voltage (V_{REF} - V_1).

The regulator of Fig. 15 is sometimes called a feedback voltage regulator, because it operates by comparing the actual output voltage with what it should be, as represented by V_{REF}.

The sense line is used to acquire the output-voltage sample. In many cases, the sense line is connected directly to the output terminal of the regulator. In other cases, however, the sense line is separate, so that it can be connected to the V+ line at the load. That feature becomes important where a high-current supply is connected to its load through more than a few inches of conductor. The voltage drop in such a conductor can be substantial, and a separate sense line allows the regulator to see the voltage at the load rather than at the power-supply output.

IC Voltage Regulators

Very few people still design discrete voltage-regulator circuits, because of the large number of highly reliable integrated circuits (IC's) and other hybrid regulators available. Some of those devices are simple-minded, while others are highly sophisticated. Devices are available in current ranges from 100 mA to 35 A, and voltages from 2 VDC to 24 VDC. Some devices have only three terminals (input, output, and common), and they operate at fixed *standard* voltages, while others have more terminals and are adjustable. Device packaging runs from simple three-terminal transistor cases (including TO-5, TO-3, and TO-220), to DIP, and metal-can, IC cases, to special packages used on no other device.

Figure 16 shows the internal block diagram for a typical high-quality, three- or four-terminal voltage-regulator IC of the sort normally mounted in standard transistor packages. The over-current protection feature will be discussed later.

In general, three-terminal IC voltage regulators will operate with input voltages from (V_O + 3 volts) to 35 or 40 volts (depending upon model); some models require only (V_O + 2 volts) input-output differential. For a +5 volt regulator, then, an input voltage of 7 to 8 volts is required; that is the reason why the S-100 microcomputer bus uses +8 volts (unregulated) on the main power bus. Note that a 6.3 volt AC *rms* filament transformer will supply the correct voltage if a fullwave bridge rectifier, and 1000-µF/amp filter are used.

(Continued on page 101)

DESIGNING DC POWER SUPPLIES

(Continued from page 65)

On most three-terminal IC voltage regulators, the type number tells us something about the specifications. We can tell, for example, the voltage rating, approximate current rating, and whether the device is for positive or negative voltages.

The main part number gives us the voltage polarity. Two main families exist for both positive and negative types, making four type numbers:

Positive: 78XX and LM340NXX

Negative: 79XX and LM320NXX

In all four cases, the XX denotes the output-voltage rating. For example, 7805 and LM340N05 are 5 volt regulators, while 7812 and LM340N12 are 12-volt regulators.

The *N* term in the above designations gives us the package style, and, indirectly, the approximate current rating. The package destinations are:

H	TO-5	100mA
K	TO-3	1 A*
T	TO-220	750 mA

*Suspended in free-air; may be increased with appropriate heat-sinking and/or an air blower. TO-3 devices are seen with ratings of 3.5 and 10 A, but most are 1 Amp rated.

Thus, a LM340L05 device is a 5 volt, positive regulator in a TO-3 package, and will safely handle 1 Amp of output current.

Concluded Next Issue

We have covered considerable ground this issue on designing power supplies.Justice to you, our reader, demands that we cut this special feature into two parts, so that we would have additional articles in this issue of **Hands-on Electronics**. In the next issue, we will conclude this theory article when we cover three-terminal voltage regulators, problems common to power supplies, high-voltage power supplies, and inverters. To be assured of obtaining a copy of **Hands-on Electronics**, the Editor suggests you seriously consider becoming a first-year charter subscriber to the magazine. One small payment sent by you to us will insure that the mailman delivers your future copies of *Hands-on Electronics*. See the subscription advertisement in this issue. ■