HOW TO DESIGN YOUR OWN POWER SUPPLIES

Following a step-by-step procedure, you can build a line-operated, professional power supply to your personal requirements.

BY JIM HUFFMAN

ALL active electronic projects and equipment require a power supply. The battery supply, of course, is convenient for low-power and portable applications. For the majority of applications, however, the ac, or line-operated, power supply is more practical for equipment which requires moderate or high power and where portability is unimportant.

This article tells you how to design line-operated power supplies. Our building-block approach starts off with the power transformer/rectifier/filter system that is basic to all line-operated supplies. Then we introduce voltage and current regulation and finish up with the error amplifier used in the power supplies found in the most sophisticated electronic equipment. You merely design your power supply to suit your needs.

From the Beginning. The schematic diagram of a very basic power supply is shown in Fig. 1. The power transformer steps down (or up for high-voltage supplies; in this article emphasis is on the low-voltage supply) the input voltage from the ac line to roughly the voltage needed for the project. The low voltage at the transformer's secondary then goes through a rectifier system, where it is converted to pulsating dc. The filter system then smooths out the pulsations to make the dc voltage at the supply's output more like the steady-state dc characteristic of batteries.

The choice of transformer depends mainly on the supply voltage and current demands of the project for which the power supply is designed. Let us assume that the circuit requires 12 volts at a maximum of 500 mA (0.5 A). A commonly available 12.6-V, 0.5-A transformer will do nicely. If you can't find a transformer with the exact ratings for your project, a higher secondary voltage and/or current rating will do. For the higher voltage rating, you will have to devise a dropping or regulating system to reduce the supply's output voltage to the proper level. Note that lower voltage and current ratings should never be used.

To insure safety in your projects, always design a fuse into the power supply. Determining the current rating of the fuse is simple. First, divide the line voltage by the transformer's secondary voltage. Divide the secondary current by the result. Then multiply your answer by 5 if you intend to use a slow-blow fuse (by 10 if you intend to use a fast-blow fuse). For convenience, you can round out the line voltage to 115 or 120 volts and drop fractions of a volt in secondary voltages.

Applying this procedure to our sample problem we get: 120 V/12 V = 10. Then, 500 mA/10 = 50 mA, which is the primary current. Finally 50 mA × 5 = 250 mA (1/4 A) for slow-blow or 50 mA × 10 = 500 mA (0.5 A) for the fast-blow fuses.

The three basic rectifier schemes used in single-phase power supplies are shown in Fig. 2. The half-wave rectifier is difficult to filter and should be used only in projects that have no critical circuitry. The full-wave and bridge rectifiers have twice the output ripple (120 pps in a 60-Hz setup) as the half-wave scheme and are easier to filter for projects in which critical circuits are used.

The full-wave rectifier scheme requires the use of a center-tapped transformer that can deliver twice the secondary voltage of a transformer used with a bridge rectifier to obtain the same output voltage. Its current rating, however, need be only half that required by the bridge-circuit transformer. The individual rectifiers in a bridge scheme must have peak inverse voltage (PIV) ratings of at least two times the rms voltage at the transformer, while the diodes in the full-wave and half-wave schemes must be rated at four times (minimum) the rms voltages at their transformer secondaries.

To design the filter system, first cal-

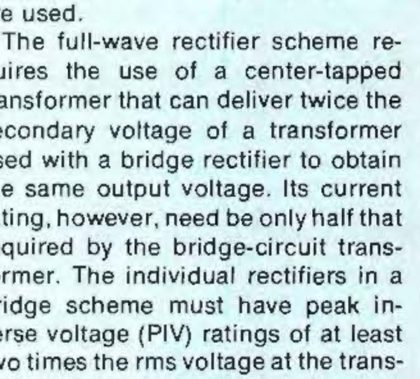


Fig. 1. Schematic of a basic power supply. The transformer steps the voltage down, the diodes rectify the voltage, and the capacitor smooths the output.

culate the power supply's load resistance by dividing the output voltage by the load current (12 V/0.5 A = 24 ohms). Then calculate the ripple period, or time constant, by finding the reciprocal of the ripple frequency (1/120 pps = 8.3 ms). Now, you can calculate the required filter capacitor value.

The value of the filter capacitor should be chosen to provide a time constant of at least three times the ripple period. In equation form, C = 3TC/R = (3 × 8.3 ms)/24 ohms = 1000 µF, which is the absolute minimum value you should consider practical. You would be better off going to a 5000-µF value.

The voltage rating of the capacitor is equally important. It must be greater than the *peak* secondary voltage. In our example, 12.6 V is an rms value. To convert it to peak, multiply by 1.414: 12.6 V rms × 1.414 = 18 V peak. A safe rating for the capacitor would, therefore, be 25 volts.

Further Considerations. The power supply we have just designed has an inherent problem: its short-term stability isn't very good. Without some form of regulation, the output voltage will vary with changes in load and even with changes in input voltage. While poor regulation might be acceptable for some applications, it can present problems in critical digital circuits, test equipment, and even audio gear.

The output voltage curves of a 12-volt power supply with 1 ohm of internal resistance are shown in Fig. 3. Notice that as the current drawn by the load increases toward 1 ampere, the output voltage decreases. The output drops 1 volt, leaving only 11 volts available. It is possible to obtain essentially the zero-resistance curve shown by electronically reversing the output curve in a voltage regulator.

In our design example, the actual no-load voltage depends mainly on the resistance of the transformer windings. The output could well be as high as 18 volts no load and drop to 16 volts under full load, a difference of 2 volts. This means that the internal resistance of the power supply must add up to that required to cause a 2-volt drop at the 500-mA full load. Using Ohm's law, R = E/I = 2V/500 mA = 4 ohms. The curves for the power supply with the 4-ohm internal resistance and with an additional 8 ohms used to yield a 12-volt output (from the no-load 18-volt maximum) are shown in Fig. 4.

If you use a transformer whose output voltage is higher than required by your project, you can either include or leave out the dropping resistor, depending on whether or not you plan to add a regulator to the circuit. Before you make this decision, however, carefully weigh the alternatives and study Fig. 4. The change in output from 18 volts no-load to a 500-mA full load is 2 volts, representing 11% regulation. The change in output voltage at 100 mA is 0.4 volt, and regulation is 2%—still not great but an improvement. So, a simple method of providing a degree of regulation is to draw only a small percentage of the available current from the power supply.

Another alternative is to "bleed" the supply by placing a load resistor permanently across the output of the supply so that the variations between no load and full load are kept to a minimum. Neither this nor the dropping resistor method provides much defense against line-voltage variations. The best alternative for this problem is to go to electronic voltage regulation.

Voltage Regulation. The reverse-biased diode is perhaps the simplest electronic voltage regulator around. Once it reaches its breakdown voltage, the diode will maintain the same voltage over a varying current range until the current reaches the point where the diode ultimately burns up. Except for burning up, this is exactly what the typical zener diode is designed to do. The point at which the zener diode breaks down is known as the "zener voltage" (same as regulator voltage).

Zener diodes are available in a wide variety of regulator voltages and powers. All current popular low voltages used in modern circuits are represented, as are most of the low- and medium-power ranges.

Designing a zener regulator into a power supply consists of calculating the resistance and power rating for the series resistor and determining the maximum amount of power the zener diode must be capable of handling in the circuit.

From the curves shown in Fig. 5, you can see that the zener regulation is good up to the point where the load current almost equals the zener current. Therefore, the current through the zener diode must be more than that required by the load. With a 0.5-ampere load current, the zener current would be best at five times this value, or 2.5 amperes. Using the power formula P = IE, at 12 volts, P = 2.5 A × 12 V = a whopping 30 watts. That's an expensive zener diode. Hence, it is practical to use zener diode regulation by itself only for low- and medium-current applications. For example, a 12-volt, 1-watt zener diode would operate with a zener current of 83.3 mA, providing reasonable regulation up to almost 83 mA as shown in Fig. 5.

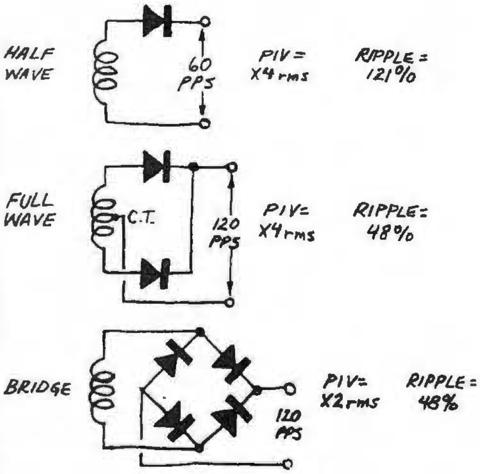


Fig. 2. Three types of single-phase rectifier circuits with some of their characteristics.

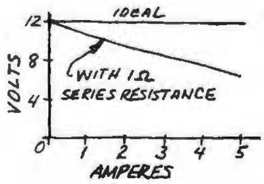


Fig. 3. Ideal output voltage occurs at all current levels. Actually, the voltage drops due to internal resistance of the power supply.

In the case of our sample power supply, the voltage coming from the

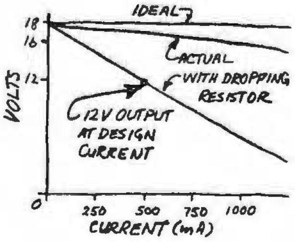


Fig. 4. Ideal and actual voltage output of ac/dc converter and filter as described in the text.

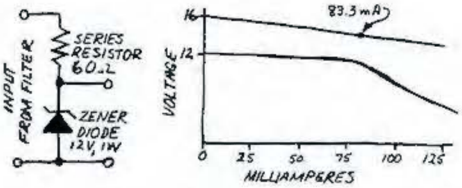


Fig. 5. Zener diode regulator is shown at left. The output is close to ideal (top) except when high current levels are reached.

rectifier bridge will be on the order of 17 volts. The zener diode will be regulating this at a 12-volt level, leaving a difference of 5 volts. So, we calculate the zener's series resistor value from R = E/I = 5 volts/83.3 mA = 60 ohms. The calculated 60 ohms, however, is a minimum value for the resistor; any higher voltage and the zener current could cause the zener diode to burn up. So, make certain you base your design calculations on the *maximum* voltage drop that can be expected across the resistor. Then figure the power rating needed for the resistor from P = IE = 5 volts × 83 mA = 0.4 watt, which is the minimum rating; play it safe by using a 1-watt resistor.

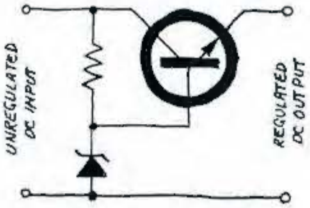


Fig. 6. Basic regulator circuit using a zener diode and emitter-follower pass transistor. This circuit provides current gain with no gain in voltage.

The zener diode regulator is simple to design, but it is uneconomical in high-current power supplies. However, it can still be used—and most often is—as a low-current input to a current amplifier.

Pass Transistor Regulator. Using a zener diode as a reference regulator, the power supply's output regulation can be improved by employing an emitter-follower pass transistor to obtain current gain with no gain in voltage. The configuration of this circuit is shown in Fig. 6.

The zener regulator described above can't cope with the 500-mA demand assumed for our sample power supply. So, the pass transistor design is a natural for our purposes. First, however, we must know the biasing and power requirements for the transistor.

The current gain of the pass transistor determines the power rating of the zener diode, and vice versa. For example, a gain of 10 would permit the power supply to safely handle 833 mA of current, based on the calculations given above. The higher the β, then, the better; in fact, two transistors can be connected in a Darlington circuit configuration to multiply the gain of the pass transistor as in Fig. 7.

If the output coming from the unregulated power supply's filter is 16 volts and you want only 12 volts, the difference is 4 volts that must be dropped across the pass transistor. Since the maximum current from the supply will be 500 mA, the transistor must be rated at a minimum of 600 mA × 4 V = 2.4 watts. It is obvious, then, that most pass transistors require proper heat sinking for safe operation.

To determine the minimum base current for the transistor, divide the required load current by the transistor's β: $I_{Bmin} = I_{max}/\beta$ = 500 mA/10 = 50 mA. Multiplying this figure by 2 provides a margin of safety in the design; so, the zener diode used as the voltage reference need be rated at only 100 mA or 1.2 watts (P = IE = 100 mA × 12 V = 1.2 W). If you can't obtain a 1.2-watt zener diode, you have the option of using a pass transistor with a higher β. For example by going to a transistor with a β of 20, the base current would be only 25 mA, and doubling this yields 50 mA, requiring that the diode have a power rating of only 600 mW (0.6 watts).

By using the pass transistor, we reap another benefit—capacitance multiplication. The base capacitance is reflected to the emitter-collector circuit. We can bypass the zener diode with an electrolytic capacitor to make the emitter-follower pass transistor appear to the ripple as a capacitance equal to β times the value of the base capacitor. (Calculate the bypass capacitor from the formulas used earlier for calculating the filter's value.)

You can make the output of the supply variable by placing a potentiometer across the zener diode and feeding the base of the pass transistor with the variable output voltage from the pot. Bear in mind that for good regulation, the current through the pot should be at least several times the current required in the base of the pass transistor. The current through the zener diode should be a couple of times greater than the current through the potentiometer.

Error Amplifier Regulator. The pass-transistor scheme isn't without its shortcomings. For example, it does not efficiently combat output variations resulting from line voltage variations. You can improve the operation of your power supply by detecting the output variations and sending the inverse of the variations back to the pass transistor. Thus, you would have a supply that would in effect turn down the output voltage level when it attempted to rise, and vice versa, which is what the sense, or error, amplifier is designed to do.

The error amplifier can be a common-emitter amplifier stage, which gives an inverted output (Fig. 8). The error amplifier must operate only on voltages other than the regulated output potential. This can be done in a couple of ways, the most common

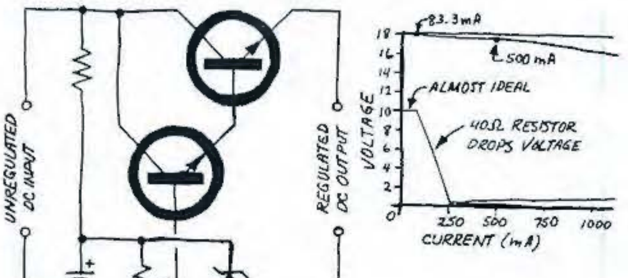


Fig. 7. Complete emitter-follower regulator. The second transistor lessens the requirements placed on the zener diode, and potentiometer is added to provide a variable output.

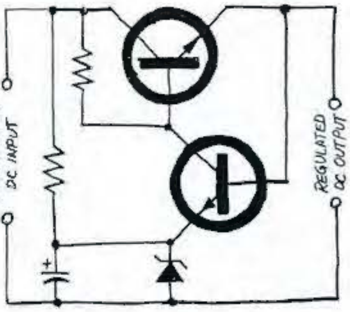


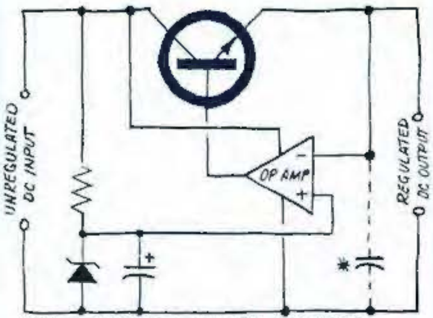
Fig. 8. Regulation using a sensing amplifier. The circuit component values are given in the text.

being the application of a voltage equal to the desired regulator output potential to the emitter of the error amplifier.

In the circuit shown in Fig. 8, the zener diode is the voltage reference. When the output voltage attempts to exceed the reference voltage, the stage conducts and reduces the output voltage. Regulation in this circuit is good for both load and line variations.

The calculations for the required drive current in the base circuit of the pass transistor and zener current remain as before. The value of the error amplifier's collector load resistor must be selected to give the desired base current for the pass transistor. In our design example, the difference between the desired 12-volt output and actual 16-volt level is 4 volts. At 4 volts, a 160-ohm resistor is needed to get 25 mA of base drive current, while an 80-ohm resistor would be needed to get 50 mA. A compromise might have to be struck if your calculations reveal that you need a non-standard resistor value. You might have to trade an exact 25-mA current if you can't find an 80-ohm resistor, but if you use a 100-ohm resistor, your compromise won't be great.

If you wish to make the power supply variable, you can vary the zener diode's output voltage as described earlier. You can also put a potentiometer in the base of the error amplifier to vary the. voltage supplied to it. The problem with the latter method is that you also divide the output voltage variations and reduce the sensitivity of the error amplifier.



*BYPASS CAPACITOR MAY BE REQUIRED

Fig. 9. Using an op amp as a sensing amplifier. High gain is an advantage of the op amp.

The sensitivity (or gain) of the error amplifier is important. In fact, the best system is one where the value of the collector resistor of the amplifier is relatively large so that gain can be high. In this manner, smaller variations in output voltage cause a larger reaction in the pass transistor circuit.

There are several possibilities for increasing stage gain. You can use a Darlington pair for the pass transistor system so that the collector resistor's value can be made larger. Another alternative is to use multiple-stage, high-gain amplifiers—inexpensive operational-amplifier (op amp) IC's.

IC Regulated Supply. The IC op amp makes an excellent regulator circuit. When used to feed a high-current pass transistor, it can regulate any load current. Using it as an error amplifier is very simple.

The non-inverting, or +, input of the op amp can be set to any desired reference level around which the power supply will regulate. The inverting, or −, input acts as an error amplifier. The signal at this input is inverted by the op amp and sent to the pass transistor. The advantage of applying inputs to both input lines of the op amp is that a much smaller current rating is required of the zener diode as a result of the IC's high gain.

Shown in Fig. 9 is an example of an op amp sensing system for an error amplifier. Designing the op amp into a power supply to serve as an error amplifier is easy. All you have to do is carefully adhere to the IC's ratings given on the specification sheet.

Current Limiting. The schematic of a "deluxe" power supply is shown in Fig. 10. This design has built into it a means for limiting the current to the load. To design current limiting into your power supply, you simply select the component values that will deliver the current to the load limited to the maximum safe current. ◆

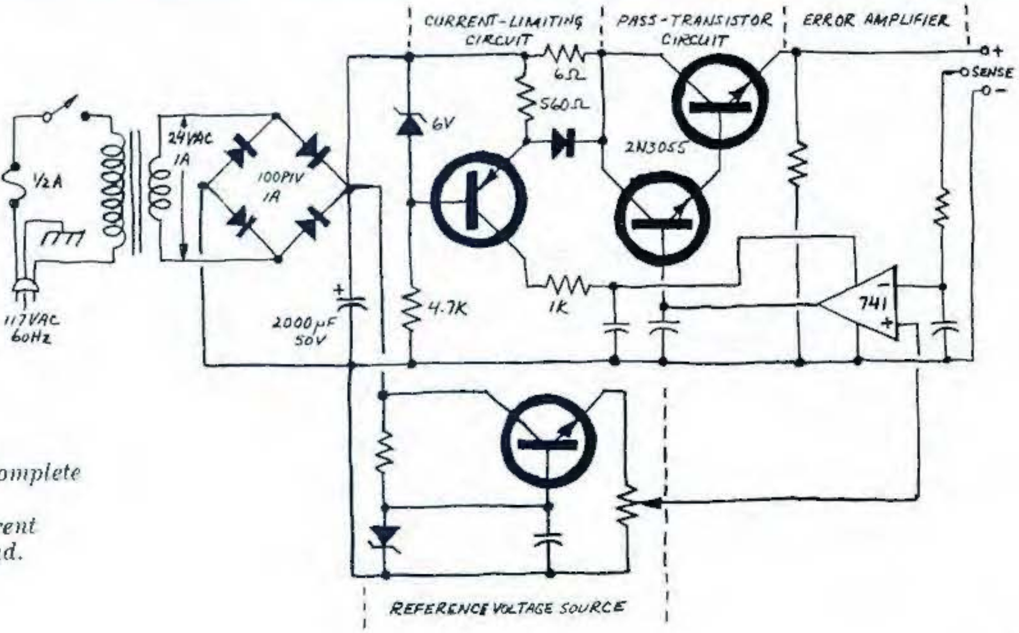


Fig. 10. Schematic of a complete "deluxe" power supply. This design includes current limiting to protect the load.