How to Design Power Supplies

MANNIE HOROWITZ

All about unregulated and regulated power supplies, IC regulators, and overvoltage-protection circuits.

IN THIS, THE FINAL INSTALLMENT IN OUR series, we will turn our attention to power supplies for analog circuits. All circuits require some source of power to operate and the most convenient source of such power is an AC wall outlet. Unfortunately, many electronic circuits cannot make use of AC directly. Instead, some way to convert the AC to DC is required.

Let's look once again at the junction diode. You will recall that in our previous discussions of that device we saw that it only conducts when its anode is positive with respect to its cathode. That property is important when we are dealing with AC. If the diode were connected in a series circuit along with an AC supply and a load, its presence would mean that current could only flow through the load during the half of the AC cycle when the anode was positive with respect to the cathode. During the other half cycle the diode would not conduct and no current could flow.

Such an arrangement is referred to as a half-wave rectifier because only half the waveform (i.e. alternate half-cycles) is allowed to pass freely. The other half of the waveform is cut off.

The presence of those half-cycles of current causes pulsating DC to be generated across the load. The amount of voltage variation in that pulsating DC can be reduced by wiring a "filter" capacitor across the load. The amount of ripple in the output is then determined by the values of the capacitor and the load.

Full-wave rectifiers

When dealing with electronic circuits such as amplifiers, the power source should be as stable (i.e. free of ripple) as possible. The ideal power source then is a battery, as all DC voltages that are derived from an AC supply have some ripple. Using a battery is not always possible or practical, but fortunately most circuits can tolerate the presence of ripple if it is sufficiently attenuated.

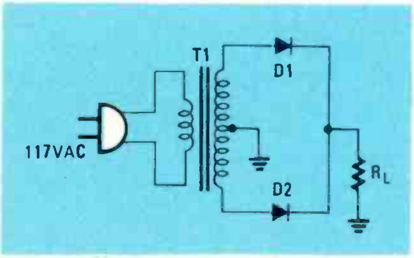

FIG. 1—A SIMPLE full-wave rectifier using a center-taped transformer.

One way to minimize ripple is to use a full-wave rectifier. Such a circuit is shown in Fig. 1-a. Note that the circuit consists of a center tapped transformer, with the tap grounded, and two diodes. Let's see how this circuit works. We'll start by looking at what happens during the positive half-cycle. During that half-cycle the polarity of the applied voltage is such that the upper terminal of the transformer's secondary is positive with respect to the center tap and the lower terminal. Also, during that half-cycle the polarity across D1 is such that the anode of the diode is positive with respect to its cathode and the device conducts. Thus, current flows from the upper transformer terminal, through D1 and R_L, and back to the center tap through the ground. Note that the voltage during this half-cycle varies in phase from 0° to 180° and that the current varies from zero, to some peak value, and then back to zero. Because of that varying current, the voltage developed across R_L varies identically with the input waveform. Finally, during the positive half-cycle the cathode of D2 is more positive than its anode, so the diode does not conduct and no current flows through it.

The polarity of the voltage across the transformer is reversed during the negative half-cycle. Now, the bottom terminal of the transformer is positive with respect to ground and with respect to the top terminal. Diode D1 ceases to conduct because its cathode is more positive than its anode. But as for D2, its anode is now positive with respect to its cathode and the device conducts. Thus, current flows from the lower terminal of the transformer, through D2 and R_L, and back to ground and the center tap, and a positive half-cycle of voltage is developed across R_L. Note that here, once again, the voltage across R_L varies identically with the input waveform, but the polarity of the voltage across the resistor is reversed—it is positive.

That sequence repeats during the succeeding positive and negative half-cycles. Note that current always flows through R_L in the same direction so that only a positive voltage with respect to ground is across the load. That is true regardless of the instantaneous polarities of the AC voltage applied to the circuit.

The advantage of the full-wave rectifier over the half-wave rectifier lies in the fact that in the half-wave circuit no voltage is developed across the load during negative half-cycles. Because of that, the ripple in the output of the half-wave rectifier is higher.

For ripple to be minimized in either type of circuit, some type of filtering must be used. To do so, a large capacitor is usually placed across R_L. That capacitor is charged to the peak voltage, V_P, during the first half-cycle. Between peaks, it discharges slowly through R_L. But it does not have enough time to discharge substantially before the next half-cycle appears and recharges it.

Without the capacitor, the ripple voltage across R_L varies from $+V_P$ to 0 volts. But with the capacitor present, it varies from $+V_P$ to whatever its voltage dropped to before the next half-cycle appeared to recharge it. From that, you should be able to see why the ripple is easier to filter in a full-wave rectifer. The reason is that the filter capacitor is recharged once during each half-cycle in a full-wave circuit, while in the half-wave arrangement it is recharged only once during each full cycle. Because of this longer recharge cycle, the voltage across the capacitor drops to a lower level. The ripple voltage, the voltage variation from $+V_P$ to that discharge voltage level, is therefore larger for the half-wave than the full-wave circuit.

In both circuits, the amount of ripple at the output is related to the values of the filter capacitor and the load resistor. For a full-wave circuit, ripple will be kept within reasonable limits if the product of the values of the load resistor and the filter capacitor is about 0.1. To keep the ripple to the same levels in a half-wave circuit, that product must be about 0.15. In other words, since we must assume the load to be fixed, the value of the capacitor must be more than 50% higher than for the full-wave circuit.

We want to mention one more thing about ripple before we move on. If the voltage across the filter capacitor varies during the cycle, the mean DC voltage output will be somewhat less than its possible maximum. Thus, for maximum DC output, the ripple must be very low.

Full-wave bridge

The circuit shown in Fig. 2 shows another type of full-wave rectifier, the full-wave bridge. Notice that it does not normally require the use of transformer, although one can be used if the input voltage needs to be stepped up or down.

Let's see how that circuit works. During positive half-cycles, current flows through D1, R_L, and D4. During the negative half-cycle current flows through D2, R_L and D3. Note that the current always flows in the same direction regardless of the polarity of the input voltage and that the end of R_L marked + is always positive with respect to the end marked −. As before, a capacitor is usually wired across the load resistor to filter out the ripple.

Voltage doubler

When a transformer is used in a rectifier circuit, the output, or DC voltage across the load, is determined by the peak voltage across the secondary of the transformer (or across one-half the secondary of a center-tapped transformer if a full-wave rectifier is being used). Should one of the previously described rectifiers be used without a transformer between it and the voltage source, the DC voltage at its output seems to be limited to the peak voltage of the AC source. But a voltage-doubler circuit can be used to increase the level of the rectified DC. Two circuits involving doublers are shown in Fig. 3.

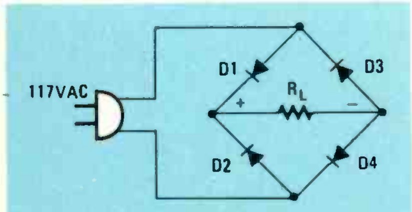

FIG. 2—A FULL-WAVE BRIDGE RECTIFIER uses four diodes but eliminates the need for a transformer.

In the circuit shown in Fig. 3-a, C1 is charged to the peak level of the supply voltage through D1 during the positive half-cycle. On the negative half-cycle, C2 is charged through D2 to the same peak level. Since the series combination of the two capacitors is across the load, the voltages across them add; and that sum is applied to the load, R_L.

In the circuit shown in Fig. 3-b, during positive half-cycles, C1 is charged to the peak supply voltage through D1. During negative half-cycles D2 conducts, allowing C2 to be charged to the peak supply voltage. In addition, the previously charged C1 discharges through D2 to C2. The supply voltage and the voltage across C1 are then summed in C2; and that sum, which is nearly twice the supply voltage, is applied to the load, R_L, when the waveform goes positive and D2 is once again cut off.

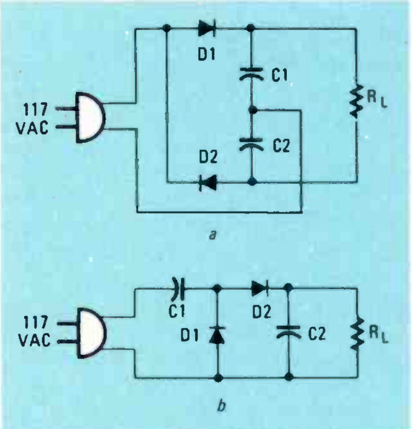

FIG. 3—TWO VOLTAGE DOUBLERS. These circuits are used between the AC source and the rectifier circuit to nearly double the level of the DC output.

Combinations of these circuits can be used to form triplers, quadruplers, and so on. A tripler is shown in Fig. 4-a. In it, the portion of the circuit involving D1, D2, C1, and C2 is identical to the circuit shown in Fig. 3-b, while the D3-C3 portion behaves just as the D2-C2 circuit of Fig. 3-a. The sum of the voltages across C2 and C3 are applied across R_L.

As for the quadrupler circuit, shown in Fig. 4-b, two circuits similar to the one shown in Fig. 3-b, are used. After the two double voltages are developed across C2 and C4 they are applied across R_L.

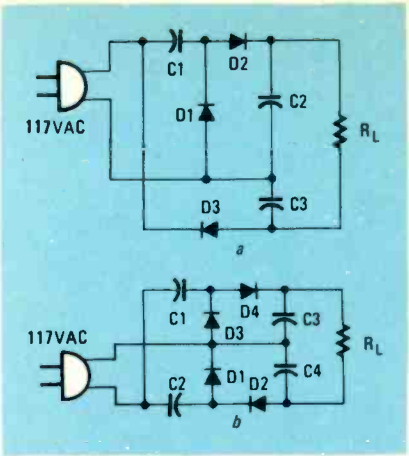

FIG. 4—TWO OR MORE voltage doublers can be combined to form voltage triplers, such as the one shown in *a*, or a voltage quadrupler, such as the one shown in *b*.

Specifying the diode and transformer

When the rectifying diode is not conducting, twice the peak supply or transformer secondary voltage may be across the device. This is true for all full-wave, half-wave and, voltage-multiplier circuits with the exception of the full-wave bridge. So when designing a power supply circuit, be certain that the diodes have a sufficient voltage rating.

The average current flowing through the diode is equal to the voltage across the load resistor divided by its resistance. The diode once again must be capable of accommodating that amount of current.

Power dissipation capabilities of the diode are limited. Information as to just what these limits are is supplied by the manufacturer and can be found on data sheets. The power the diode must be able to dissipate is equal to the average current it passes in the forward direction multiplied by 1 volt. At times, it may be necessary to mount the diode on a heat sink so that its operating temperature will not exceed its specified limit.

When a circuit involving a diode is first turned on, the filter capacitor being charged by the DC behaves as a short circuit. Because of that, a large initial current surges through the diode. That surge current is equal to the supply-voltage peaks divided by all resistance in the circuit other than the resistances wired across the shorting capacitor. If the surge current is more than the diodes being used can accommodate, the device will be damaged. The best way to avoid damage is to use diodes that can safely handle that initial current surge. Alternately, you can connect a small resistor in series with each diode to limit current surges to safe levels.

As for the transformer, it, too, can overheat if it conducts excessive quantities of current. To check if a transformer is operating within reasonable temperature limits, first measure the cold resistance of one winding while noting the ambient temperature in °C. Refer to that as R_C, the cold resistance. Then apply power to the transformer while its output is loaded as it would be normally. Be sure that all environmental factors (ambient temperature, etc.) are what they would be under normal operating conditions and run the transformer for eight hours. After that time, remove the power from the circuit. Immediately after removing the power, check the hot resistance, R_H, of the winding. Be sure that nothing is connected across this winding. The temperature rise of the transformer, in °C is:

$$\Delta T = 254\left(\frac{R_H - R_C}{R_C}\right)$$

Add the value you get for ΔT to R_C. If the total exceeds 90°C you should start to be concerned. If it exceeds 105°C, then the transformer is overheating and a different transformer should be used in the circuit.

Regulated power supplies

Throughout the discussion, it was assumed that the line voltage is fixed at 117-volts AC and that the load does not change in resistance but remains a constant R_L. If anyone assumes that to be a realistic condition, then he is living in a dream world. Line voltage fluctuates from minute to minute. Over time it can vary ± 10% or more. During periods of extremely heavy usage, power companies have been known to greatly reduce voltage levels.

As for the load, it is seldom a fixed resistor. If the supply is feeding an audio, RF, or electronic-switching circuit, the load impedance varies, sometimes from instant-to-instant, with the signal or switch current fed to it.

A fixed, stable voltage is frequently required when powering an electronic circuit. That constant voltage is not present when there are either supply-voltage or load variations. As we discussed earlier in this series, a fixed voltage developed across a Zener diode can be used to stabilize the voltage across a load if the Zener is placed across that component or circuit. That is fine where low currents are involved. But when large quantities of current must flow through the load, the Zener diode can seldom be used economically as the sole regulating device for the circuit. Series, parallel, and feedback circuits using Zener diodes along with one or more transistors have been developed as practical regulators.

Series regulators

In the series-regulator circuit, DC current flows from the unregulated portion of the DC power supply through a transistor to the load. If the circuits are like the ones shown in Fig. 5, the voltage across the load is regulated. In both of those circuits, current flows through R1 and Zener diode D1 which causes a fixed voltage to be developed across D1. In Fig. 5-a, current flowing through R1 also flows through the base-emitter junction of Q1. A fixed voltage, about 0.6 or 0.7 volt, is developed across this junction, turning on Q1. The voltage between the emitter of Q1 and ground, or across R_L, is about 0.7 volt plus the voltage across D1. That fixed voltage is across R_L regardless of supply-voltage or load variations.

In that circuit, little current flows through the Zener diode. What does flow is limited to safe values by R1. The current that is supplied to R_L flows through Q1. If the required load current is high, Q1 should be rated adequately and mounted on a heat sink. Circuit components must be chosen so that the transistor is not in saturation at any time.

The regulated output-voltage can be varied by simply placing a potentiometer across the Zener diode and connecting its wiper, rather than the cathode of D1, to the base of Q1. That is shown in Fig. 5-b. Now, the voltage across R_L is the sum of the voltages between the wiper of the potentiometer and ground, which is the voltage between the base and emitter of the transistor. Resistor R1 must be selected so that the proper current is available at the base of Q1 to keep it turned on and out of saturation at all times.

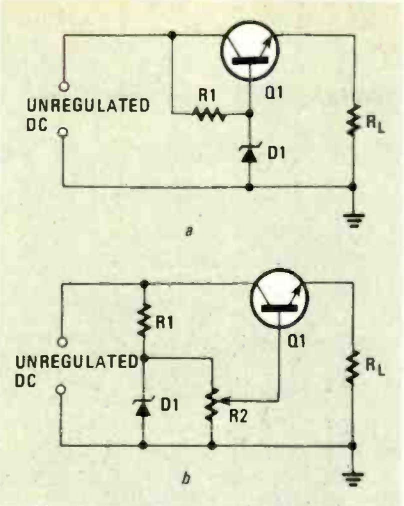

FIG. 5—SERIES REGULATOR CIRCUITS. The one in *a* provides a fixed voltage while the output from the one in *b* can be varied using R2.

Several improvements can be made in the circuit shown in Fig. 5-a. Those are shown in Fig. 6.

In order to achieve good regulation, the Zener diode should see a high impedance. In Fig. 5-a it sees an impedance equal to R_L multiplied by the beta of Q1. To increase the impedance, a Darlington circuit can be used rather than an individual pass transistor. Such a Darlington pair is shown in Fig. 6 as Q1 and Q2. The impedance seen by D1 in that circuit is essentially the product of the betas of the two transistors multiplied by R_L.

To further improve regulation, a constant current should be applied to D1 and to the base-emitter circuits of the series transistors. The circuit around Q3 establishes that constant current. Current flows through D3, D4, and R1 due to the voltage from the unregulated DC supply. The voltage across the two forward-biased diodes, D3 and D4, is relatively fixed at 1.4 volts (0.7 volt across each diode). That voltage is between the upper end of R2 and the base of Q3. Because the base-emitter junction of Q3 is turned on at 0.7 volt, the balance of the 1.4 volt, or 0.7 volt, is across R2. The fixed emitter current, in milliamps, is 0.7/R2. The collector current is just about equal to the emitter current of Q3 and the collector and emitter currents do not fluctuate to any degree. The collector current is applied to the Zener diode and base of Q2. Resistor R2 is selected to set the current at the desired level.

In the event that a short is placed accidentally across R_L, excess current will flow through Q1, which is likely to destroy the device. The circuit around Q4 performs the function of protecting Q1 in the event of a short.

Transistor Q4 is turned off when the current flow through the circuit is at its normal level. It remains off until the current flowing through R4, which is also the current through the load, is sufficient to develop about 1.4 volts across the resistor. Notice in Fig. 6 that Q4's collector is

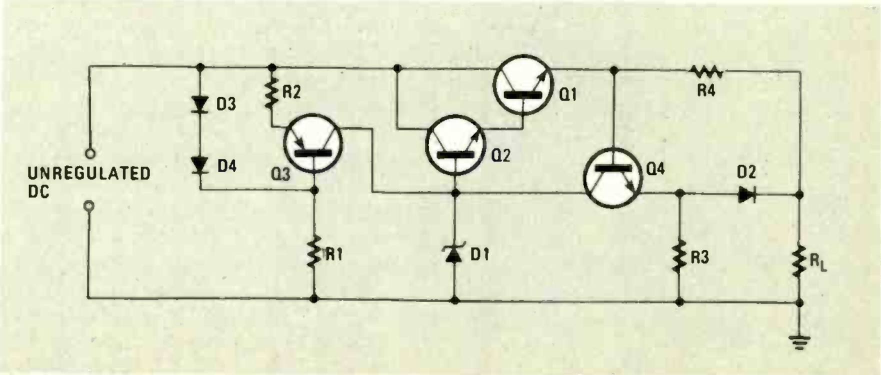

FIG. 6—THE BASIC SERIES regulator circuit can be improved by using a Darlington pair in place of Q1 and adding a constant-current source.

connected to the junction of Q2, Q3, and D1. When Q4 is on, it draws the bulk of the current from Q3 so that insufficient current remains to fully turn on the base-emitter junctions of Q1 and Q2. That also reduces Q1's collector current. Thus, less power is dissipated by Q1, preventing it from being destroyed due to the presence of an excessively heavy load.

Parallel regulators

There are two types of parallel regulator circuits—one supplying a voltage that is only slightly lower than the breakdown voltage of the Zener diode used in the circuit, and one supplying a voltage that is considerably higher than that of the diode. Both are shown in Fig. 7.

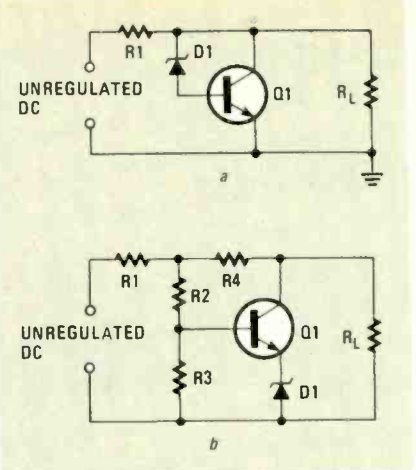

FIG. 7—PARALLEL REGULATOR CIRCUITS. The output from *a* is 0.7 volt above the Zener breakdown voltage; the output from *b* is considerably higher.

In Fig. 7-a, current flows through R1, D1, and the base-emitter junction of Q1. Fixed voltages are developed across D1 and the base-emitter junction of Q1. The sum of those two voltages is the regulated voltage applied across R_L.

In Fig. 7-b, current flows through R1, R2, the base-emitter junction of transistor Q1, and Zener diode D1. A fixed voltage is developed between the emitter and collector of Q1. The circuit's regulated output, V_R, which is across R_L, is equal to the sum of the Zener voltage, V_Z, and the voltage developed across Q1. It can be shown that that voltage is equal to:

$$V_Z\left(\frac{R_2+R_3}{R_3}\right).$$

Resistor R4 is critical in and must be selected by trial and error. That resistor should be selected for the minimum variation of voltage across R_L as the unregulated input voltage is varied from its minimum to its maximum.

Performance can be improved by using Darlington pairs rather than individual transistors and by replacing R1 with a constant-current source.

Feedback regulators

A commonly used series regulator-circuit using feedback is shown in Fig. 8.

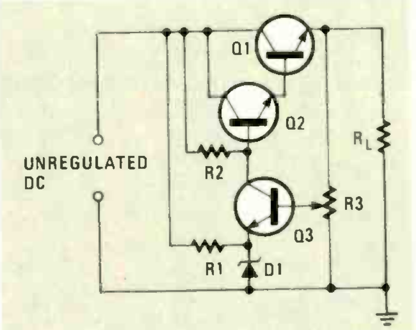

FIG. 8—THIS REGULATOR circuit uses feedback.

Current from R2 flows into both the collector of Q3 and the base of Q2. Because of D1, the emitter of Q3 is at a fixed voltage with respect to ground. Note that the regulated voltage is across R_L as well as across R3 so that R3 can be used to adjust the voltage across R_L.

Should voltage V_R across R_L increase above the desired level, the voltage at the base of Q3 rises. That transistor conducts more heavily than when V_R was at its proper level. The base of Q3 is then more positive with respect to its emitter than it was when the level of V_R was correct. That causes the transistor to draw more current than it did before from R2, reducing the amount of current previously available for the base of Q2. Because current through Q2, and consequently the current through Q1, are reduced, less current than before remains for R_L.

In the opposite condition, when the voltage across R3 and R_L is below the desired fixed level, less current flows through Q3. More current is now available to flow through Q2 and Q1, rebuilding the output voltage to its desired level.

IC regulators

Figure 9 shows a typical IC regulator and some of its surrounding circuitry; the part of the circuit enclosed by the dashed box is usually part of the IC.

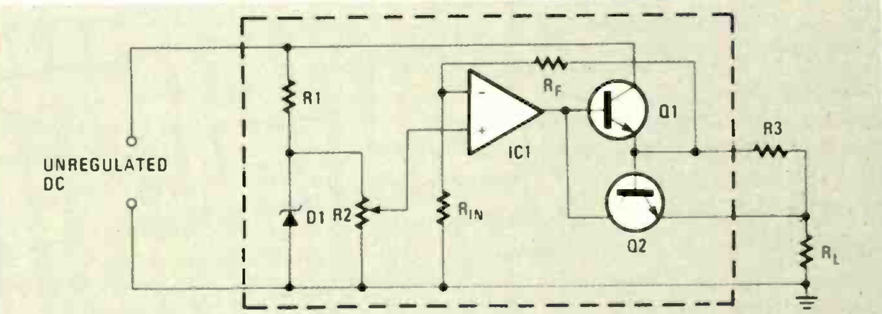

FIG. 9—REGULATOR CIRCUITS are commonly found in IC form. The circuitry within the dashed box is usually contained in the IC.

A fixed voltage is developed across D1. A portion of that voltage, as set by R2, is applied as a reference voltage to the non-inverting input of the op-amp. The output from the op-amp is passed on to Q1. The voltage at the emitter of Q1, which is close to the voltage at the output of the op-amp, is fed back through R_F to the inverting input terminal of the op amp. That inverting input is connected to ground through R_{IN}. The voltage at the inverting input, and at the emitter of Q1, is equal to the voltage at the non-inverting input multiplied by $1 + (R_F/R_{IN})$. The output voltage is therefore fixed by the voltage across D1, the setting of R2, and the ratio of resistors R_F and R_{IN} at the inverting input.

In Fig. 8 we've added a circuit to protect against damage in the event there is a demand for excessive current from the regulator. Excess current flow can not only damage a transistor, but can destroy an op-amp, and consequently an IC. Transistor Q2 is in the IC to protect it from being damaged. When excess current flows, sufficient voltage is developed across R3 to turn on Q2. When turned on, the base-collector circuit of Q2 is across the base-emitter circuit of Q1, preventing it from conducting excess current.

Crowbar circuits

A crowbar circuit is used to prevent damage to a regulated power supply in the event a high voltage is applied across the load. In the arrangement shown in Fig. 10, the inverting input of the op-amp is fixed at the breakdown voltage of D1. Resistors R2 and R3 are selected so that with normal voltage across R_L, the voltage at the non-inverting input of the op-amp is less than the voltage at the inverting input and the output from the op-amp is negative. The gate of SCR1 is then also negative with respect to its cathode so that the SCR remains off.

When a high voltage is applied across R_L, the voltage across D1 and at the inverting input of the op-amp, remain fixed. But the voltage at the non-inverting input increases. Divider resistors R2 and R3 should be selected so that the voltage at the non-inverting input exceeds that at the inverting input when a high voltage from an external source is applied across R_L. When such a high voltage is across R_L the

continued on page 134

MAKING MEASUREMENTS

continued from page 115

Another problem when reading at a distance is the cost of long runs of thermocouple wire. This is partially solved by splicing the thermocouple to "extension wire", less expensive thermocouple wire specified over a narrower temperature range. The savings are particularly important when using platinum thermocouples, since the extension wires are made from nonprecious metals.

The low sensitivity of thermocouples requires good first-stage stability in the readout circuitry. For precision measurements, low-drift amplifiers or chopper-stabilized inputs must be used. (Chopper stabilization improves the DC drift of an amplifier.)

Thermocouples are linear enough that no linearization is needed for moderate accuracy over moderate temperature ranges. Nonlinearity above 0°C is generally 1% to 5%, depending on the thermocouple and the temperature range.

Thermocouple applications are almost limitless. The wires are available in large or small gauges, in cables using a wide variety of insulations and in ceramic insulating tubes for very high temperature use. The sensing junction, formed by welding the two wires together, may be put into enclosures such as those shown n Fig. 11. The junction may be welded, epoxied or glued directly to a surface or may be exposed directly to air or liquid for fast response. The temperature of molten steel, for example, is measured by plunging the two wires directly into the steel.

Integrated Circuits

Integrated-circuit temperature sensors are fairly new and are not at all standardized. At this time at least five device families exist, each unique in design and output. They generally make use of the fact that the voltage drop across a forward-biased diode or transistor junction decreases by about 2 millivolts per degree C. IC sensors are generally offered in transistor or IC packages; they are not yet available in the same variety of assemblies as other sensors.

Despite the lack of standardization, some generalizations are possible. Operating temperatures are similar to IC's: −55 to +150°C (−67 to +302°F) or some portion thereof. Accuracies generally are several degrees, requiring user calibration for tighter measurements. Selected sensors as close as ±1°C are available, but are expensive. Stability at high temperatures is not as good as with most other temperature sensors. IC's are linear, sensitive and easy to interface with readout circuitry. But look for specifications to improve in the future. **R-E**

CRYSTAL TESTER

continued from page 130

good crystal is connected to the test clips. The output from the oscillator is then rectified by the two 1N4148 diodes and filtered by C1, a .01-µF capacitor. The positive voltage developed across the capacitor is applied to the base of Q2, another 2N3563, causing it to conduct. When that happens, current flows through LED1, causing it to glow. Since only a good crystal will oscillate, a glowing LED indicates that the crystal is indeed OK. The circuit is powered by a standard nine-volt transistor-radio battery and the SPST pushbutton power switch is included to prolong battery life.

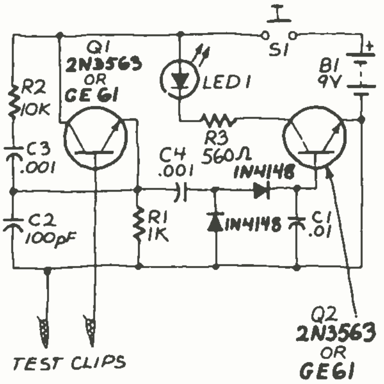

FIG. 1

The circuit is easy to build, with size—for easy portability—the only real consideration. While just about any construction technique will work well, it's easiest to use a small piece of perforated construction-board.

To use the crystal tester, simply connect a crystal to the test leads and close the SPST pushbutton power-switch. If the crystal is OK, the LED will glow brightly. If the LED does not glow, or just glows dimly, the crystal is bad and should not be used.

One note on the intended use for the tester is in order here, however. This tester will check any crystal for oscillation. However, it will not necessarily make the crystal oscillate at the frequency that it is supposed to; so you can't use this tester with a frequency counter to test for that. What the circuit *will* do is give you a way to quickly weed out crystals that are obviously bad, and, after all, that is half the battle.—*Jack Fernandes*

POWER SUPPLIES

continued from page 78

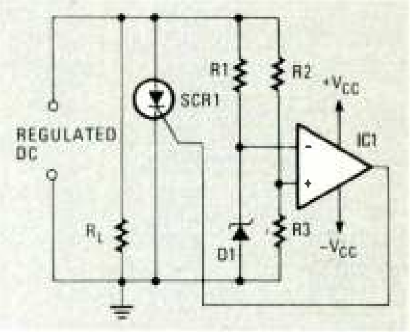

FIG. 10—AN OVERVOLTAGE crowbar circuit can be used to protect the power supply and the load in the event that an excessively high voltage is applied to the load.

output from the op-amp is positive. That positive voltage is applied to the gate of the SCR, turning it on. When on, the SCR acts like a short circuit across R_L, protecting both the load and the supply.

If the connections to the inverting and non-inverting inputs to the op-amp in Fig. 10 were interchanged, we would have an undervoltage protection circuit. The load and regulated supply would be shorted by the SCR when the voltage across R_L drops below a specific level. **R-E**

Advertisers Index

267	AMC Sales	1
216	AP Products	Cover 4
217	Beckman	Cover 3
—	CIE	35-37
210	Daetron	20
—	Electronic Technology Today	15
214,215	Electronic Warehouse	4,13
—	Fluke Manufacturing	3
212	Jameco	7
211	JDR Microdevices	5
—	NRI	17-19
—	Tektronix	Cover 2
—	Transamerican Cable	9
213	Trio Kenwood	11