OP-AMPS IN INSTRUMENTATION

Op-amps show their versatility in instrumentation circuits.

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PRECISION VOLTMETERS, AMMETERS, AND ohmmeters use op-amps in a wide variety of applications. You'll find op-amp rectifiers, range-scaling networks, converters, and voltage references. Let's take a look at how those circuits work.

Electronic rectifiers

Conventional diodes can't rectify millivolt AC signals because they don't conduct until their *knee* voltage is exceeded. Silicon diodes have knee values of about 600 mV, and thus don't rectify AC voltages below that value. Luckily, op-amps can effectively reduce the diode's knee voltage by a factor equal to the open-loop gain; a diode can then rectify AC-signal amplitudes that are smaller than a millivolt.

Figure 1 is a half-wave rectifier connected as a noninverting amplifier; feedback is through D1. (Notice that the rectified output is taken from the inverting input.) When the noninverting AC-V_{IN} swings positive by only a few microvolts, the output is quickly driven to D1's 600-mV knee voltage. The feedback through D1 forces the inverting input to accurately follow the positive-input signals. However, when the AC-V_{IN} swings negative, the negative output causes D1 to become reverse-biased, whose reverse-leakage resistance (typically hundreds of megohms) acts as a voltage divider with R1; that determines the op-amp's voltage gain during the negative-input swing. The circuit thus follows the positive-input signals, but rejects the negative ones and, hence, has the characteristics of a nearly perfect rectifier.

Figure 2 shows a peak-voltage detector. Capacitor C1 charges rapidly through D1 to the peak positive value of AC V_{IN}, but discharges slowly

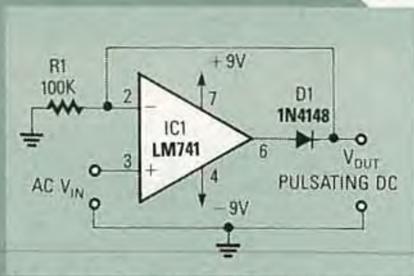


FIG. 1—HALF-WAVE RECTIFIER circuit.

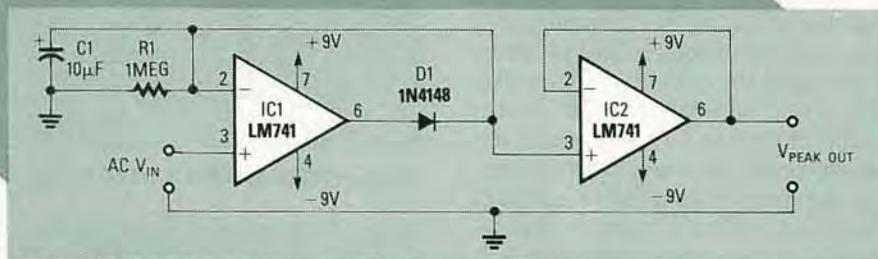


FIG. 2—PEAK DETECTOR with buffered output.

through R1 when the signal falls below the peak value. Meanwhile, IC2 is used as a (voltage follower) buffer stage, so that R1 is not shunted by any external loading.

Precision rectifiers

Figure 3 shows a precision half-wave rectifier. When the AC V_{IN} goes negative, the output swings positive, which forward biases D1. The op-amp's gain equals unity because D1's forward resistance is negligible. When the AC V_{IN} goes positive, the output swings negative, but is limited to -600 mV by D2. Resistor R3 corrects for op-amp DC-current errors, and holds the noninverting input at ground potential. The negative-feedback loop will always try to hold pin 2 at virtual ground (because the idea is to drive the inverting input to the same potential as the noninverting input.) Consequently, the output at D1's cathode does not swing much below zero. The V_{OUT} is a positive-going half-wave rectified signal that resembles pulsating DC. To produce a negative-going half-wave rectified output, the polarities of the two diodes must be reversed.

Figure 4 shows how to combine an op-amp half-wave rectifier and an inverting amplifier to build a precision full-wave rectifier. When the AC V_{IN} swings negative, the inverted output of IC1 goes to near zero because of D2. At the inverting input of IC2, the

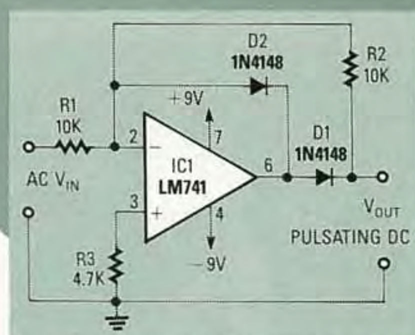


FIG. 3—PRECISION HALF-WAVE rectifier.

AC V_{IN} (via R4–R5) is simply inverted to produce a $+V_{OUT}$. The circuit analysis for the positive swing of AC V_{IN} is a bit more complicated. Op-amp IC1 inverts the signal to produce a negative output that is passed through D1 to the summing junction of IC2, where it's combined with the positive AC V_{IN} (via R4-R5). At the summing junction, the negative output of IC1 is doubled and inverted via IC2, R3-R5, to produce a $+2V_{OUT}$, while the positive AC V_{IN} is only inverted via IC2, R4–R5, to produce

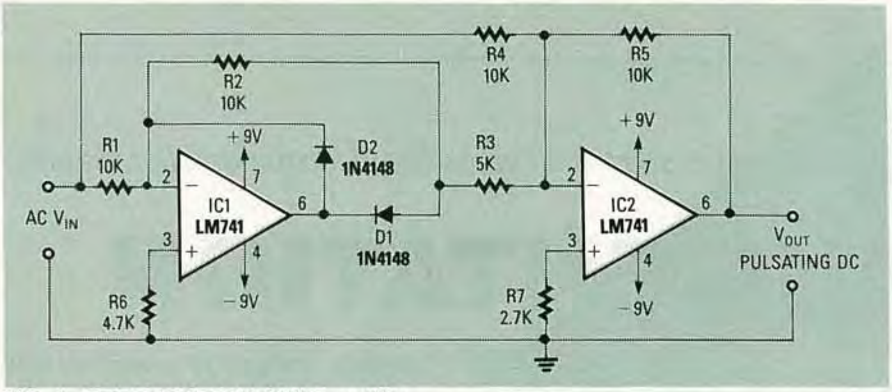


FIG. 4—PRECISION FULL-WAVE rectifier.

a $-V_{OUT}$. The summing resultant is $+V_{OUT}$ at the IC2 output that is equal to the original AC V_{IN} positive swing. Therefore, the IC2 output signal is always a positive-going full-wave rectified signal.

AC-to-DC converters

In a standard DC power supply, a rectifier takes the AC current from a step-down transformer and produces a pulsating DC current, which is then filtered into steady-state DC by a large filter capacitor. That system has worked great for years, and still does, but designers' would like to get rid of those bulky filter capacitors; and indeed, a more compact arrangement is possible by using an op-amp rectifier combined with an integrating feedback-capacitor.

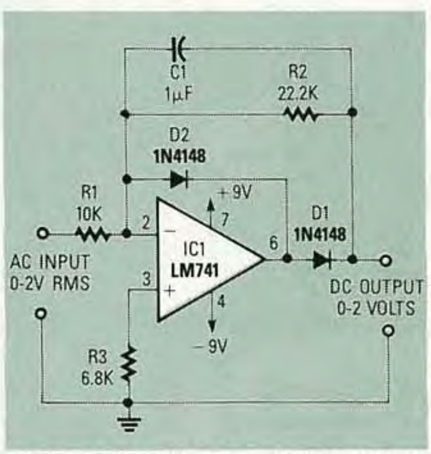


FIG. 5—PRECISION HALF-WAVE AC/DC converter.

Figure 5 shows a half-wave converter that uses a voltage gain of 2.22 via R2/R1, while integration is accomplished via C1-R2. Figure 6 shows a full-wave converter with a voltage gain of 1.11, while integration is accomplished via C1-R5. Notice that op-amp converters compute the average value of rectified AC-voltage; that is distinguished from power supplies using an output filter-capacitor, which delivers a steady-state DC equal to the rectifier's peak output-voltage.

Digital meters

Precision *D*igital *V*olt *M*eter (DVM) modules using op-amps can form the basis of a DC multimeter. To function as a multirange DC voltmeter, the input voltage is conditioned through an attenuation network; for a multirange DC ammeter, the input current is applied through a multirange current shunt.

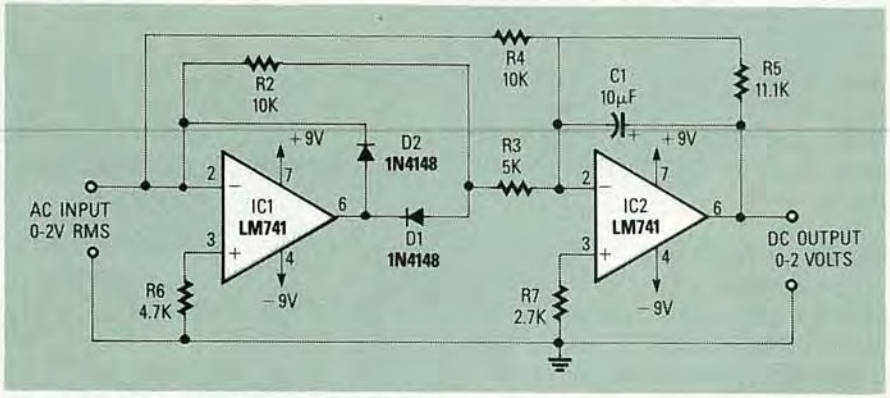


FIG. 6—PRECISION FULL-WAVE AC/DC converter.

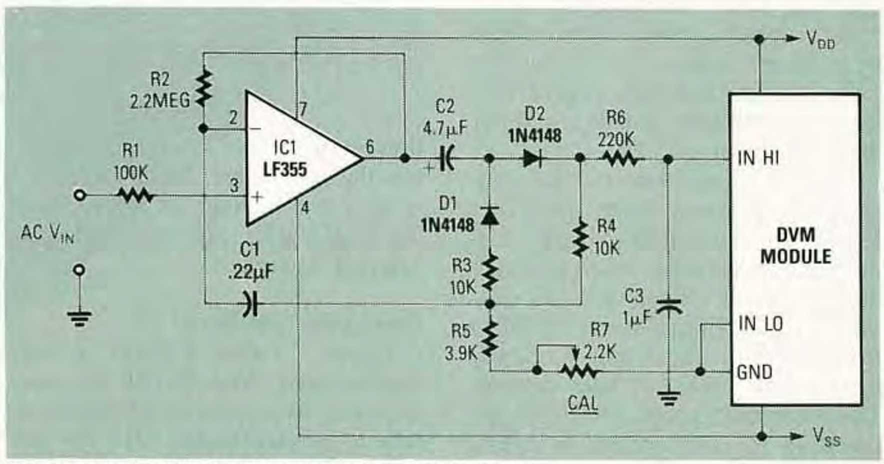


FIG. 7—AC/DC CONVERTER used with a DVM module.

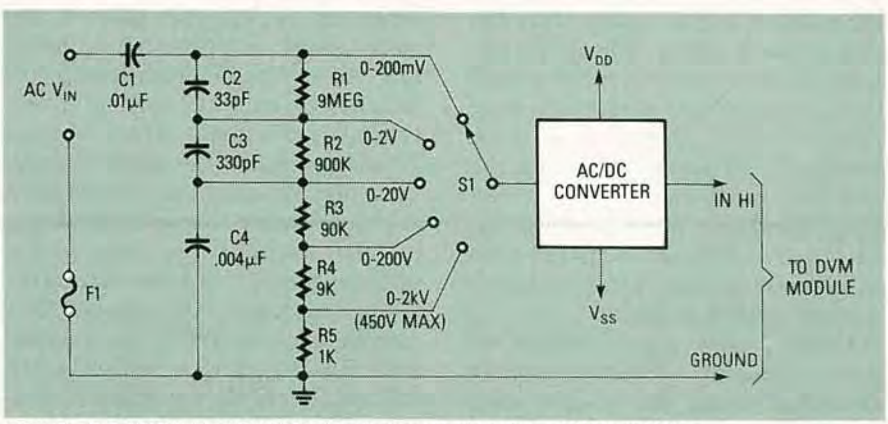


FIG. 8—5-RANGE AC VOLTMETER (converter) using a DVM module.

As shown in Fig. 7, a DVM module can be used to measure AC (rather than DC) voltage by connecting a suitable AC-to-DC converter to its input. Op-amp IC1 is used in the noninverting mode, with DC feedback applied through R2, and AC feedback applied through C1–C2 and the diode-resistor network. Resistor R7 adjusts the amplifier gain over a limited range. The rectified output of the circuit is filtered by components R6-C3 for DC conversion.

Figure 8 shows a frequency-compensated attenuator network used to convert a standard DVM module into a 5-range AC voltmeter. Figure 9 shows how a switched-shunt network can be used to convert a DVM module into a 5-range AC ammeter.

Figure 10 shows how to convert a DVM module into a 5-range ohmmeter. The circuit actually functions as a multi-range constant-current generator, where a constant current feeds (from Q1 collector) into R_X. The resulting voltage drop across R_X—which is directly proportional to the unknown R_X value—is read by the DVM module.

Transistor Q1 and the op-amp are wired as a voltage-follower—the emitter-voltage follows the voltage set by potentiometer R8. In practice, that voltage is set at precisely 1 volt below V_{DD}. Consequently, the Q1 current source equals 1 volt divided by the selected (R3 to R7) range-resistor value. For example, the current through the R3 range resistor when the noninverting input is set to 1 volt equals 1 volt/1000 ohms, or 1.0 mA. The DVM module typically reads full scale when its input voltage equals 200 mV. That reading is obtained when 1.0 mA × R_X has a value equal to 200 mV; therefore, R_X should equal 200 ohms for a full-scale DVM reading.

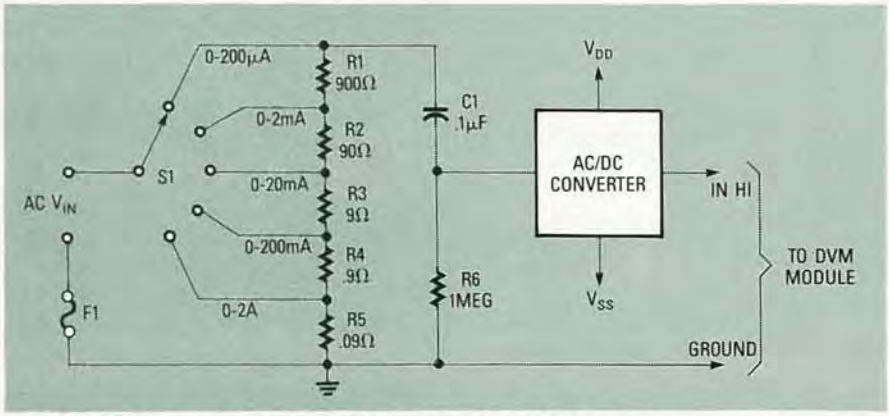
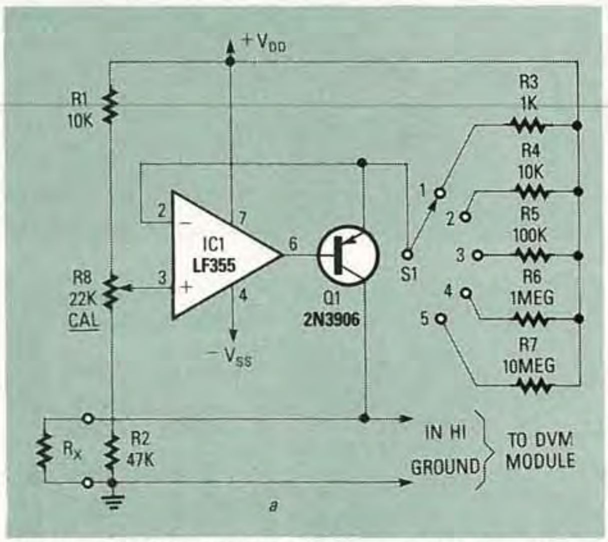


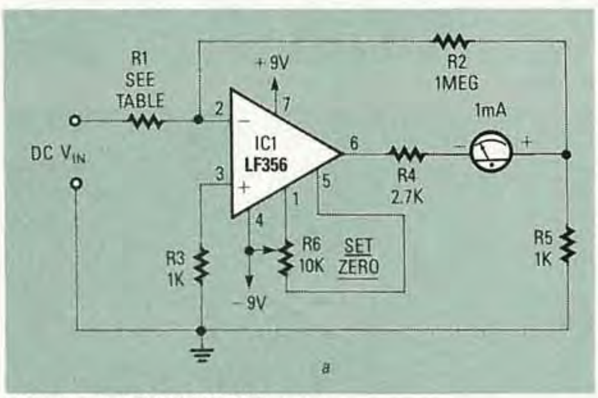
FIG. 9—5-RANGE AC AMMETER (converter) using a DVM module.



S1 POSITION	RANGE
1	0-200Ω
2	0-2K
3	0-20K
4	0-200K
5	0-2MEG

b

FIG. 10—5-RANGE OHMMETER (converter) using a DVM module.



VOLTAGE FULL SCALE	R1
1V	1MEG
100mV	100K
10mV	10K
1mV	1K

b

FIG. 11—A DC MILLIVOLT meter.

Analog meters

As shown in Figs. 11 to 15, an op-amp can also convert a standard (D'Arsonval) moving-coil meter into a sensitive voltage, current, or ohmmeter. All of the circuits are designed around the LF356 JFET op-amp, which has a high input impedance, and operates from a ±9-volt supply. Offset nulling is provided to set the output to precisely zero. The moving-coil meter should have a full-scale sensitivity of 1 mA.

Instead of using a 1-mA moving-coil meter, the 1-mA DC range of an existing multimeter can be substituted, and the circuits shown in Figs. 11 to 15 will function as "range converters." Notice that each circuit has a 2.7K resistor in series with the op-amp's output. That resistor limits the available output current to a few milliamps, thereby providing the meter movement with automatic overload protection.

Figure 11 shows a simple method to convert a 1-mA meter into a fixed-range DC-mV meter having a full-scale sensitivity of 1 mV, 10 mV, 100 mV, or 1 volt. The table shows appropriate values of R1 for the full-scale sensitivities. To null the op-amp's input-offset voltage, short-circuit the input terminals and adjust R6 for zero deflection of the meter.

Figure 12 shows how you can put together a 4-range DC-mV meter having full-scale ranges of 1 mV, 10 mV,

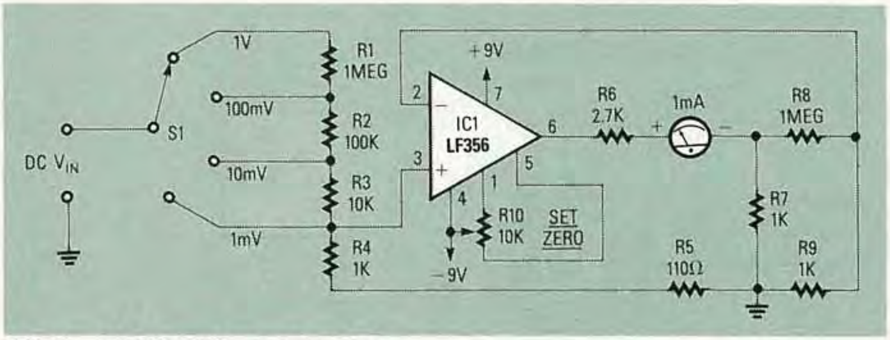


FIG. 12—4-RANGE DC millivolt meter.

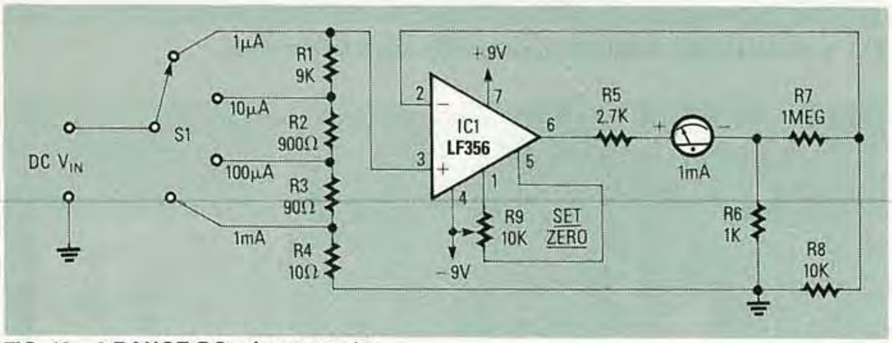
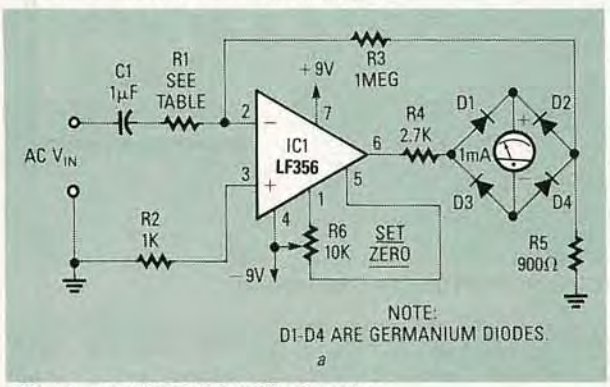


FIG. 13—4-RANGE DC microammeter.



VOLTAGE FULL SCALE	R1 VALUE
1V	1MEG
100mV	100K
10mV	10K
1mV	1K

b

FIG. 14—4-RANGE AC millivolt meter.

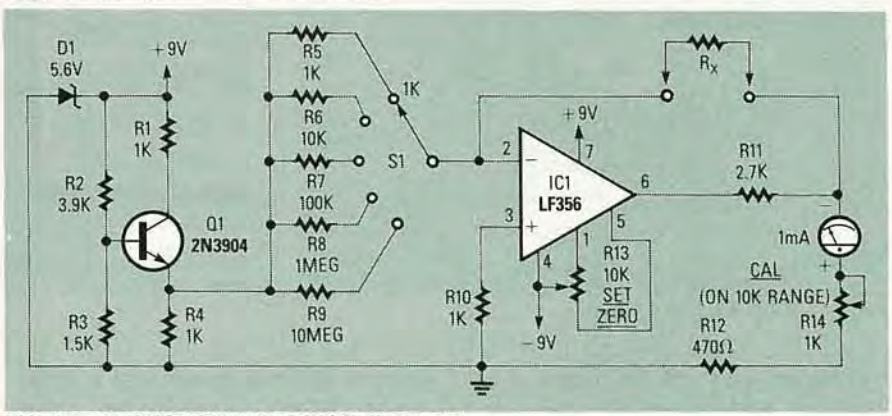


FIG. 15—5-RANGE LINEAR-SCALE ohmmeter.

100 mV, and 1 volt. Figure 13 shows how you can make a DC-μA meter having full-scale ranges of 1 μA, 10 μA, 100 μA, and 1 μA. The range resistors should have a tolerance of 2% or better.

Figure 14 shows a useful fixed-range AC-mV meter. The circuit's input impedance is equal to R1, which varies from 1000 ohms at 1-mV full-scale sensitivity, to 1 megohm at 1-volt full-scale sensitivity. The useful frequency range is about 100 kHz when used in the 1- to 100-mV range, and 50 kHz for the 1-volt range.

Figure 15 shows a 5-range linear-scale ohmmeter, having full-scale ranges from 1000 ohms to 10 megohms. Range resistors R5–R9 determine the full-scale values. Transistor Q1 applies 1 volt to one side of the range-resistor network. The gain of the op-amp is determined by the ratios of the selected range resistor and R_X. When the range resistor and R_X are equal, the meter will read full scale.

To zero-set the meter in Fig. 15, follow this procedure: Set S1 to the 10,000-ohm position and short circuit the R_X terminals. Now adjust R13 to set the meter needle to zero. Next, remove the short circuit and connect an accurate 10,000-ohm resistor in the R_X position. Now adjust R14 for full-scale deflection. The circuit is now fully calibrated and ready to be used.

Voltage reference

An op-amp can function as a voltage reference by connecting a known voltage to its noninverting input. Figure 16 shows a positive-voltage reference whose output is fully variable via R3 from +0.2 to +12 volts. Zener diode D1 provides a regulated 12-volt source voltage. The CA3140 op-amp can track input reference voltages to within 200 mV above ground. Figure 17 shows a negative-voltage reference whose output is fully variable via R3 from −0.5 to −12 volts.

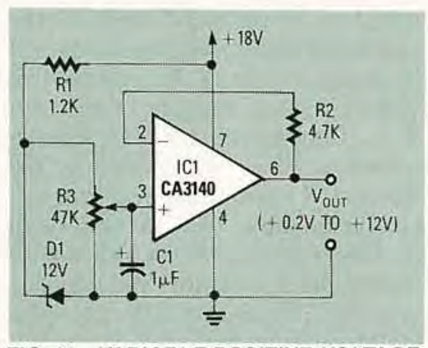


FIG. 16—VARIABLE POSITIVE-VOLTAGE reference.

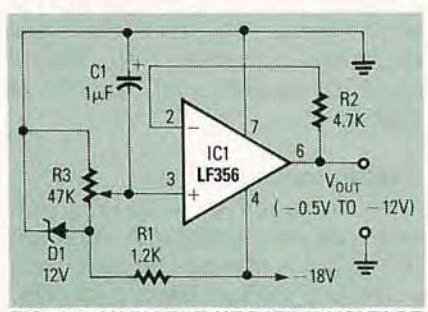


FIG. 17—VARIABLE NEGATIVE-VOLTAGE reference.

The LF356 op-amp can track input reference voltages to within −0.5 volts below ground. The op-amps in Figs. 16 and 17 are wide-band devices; resistor R2 is used to enhance their circuit stability.

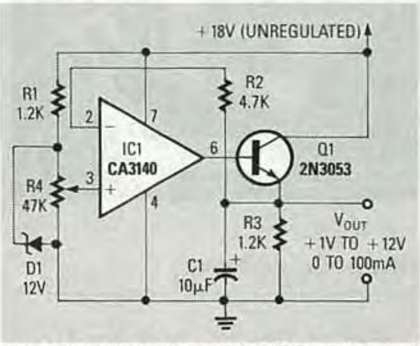


FIG. 18—VARIABLE-VOLTAGE regulated power supply.

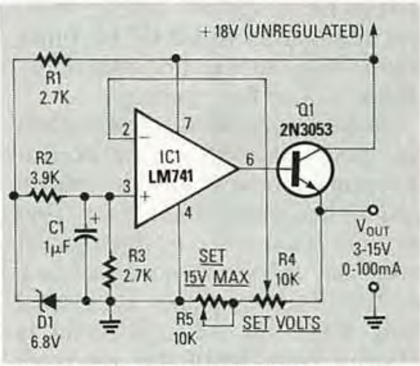


FIG. 19—STABILIZED POWER SUPPLY, 3–15 volt, 0–100 mA.

Voltage regulators

Figure 18 shows how to modify Fig. 16 to function as a 1–12-volt variable power supply having an output current capability of about 100 mA. Notice that the base-emitter junction of the output transistor is included in the negative feedback loop to minimize the affects of temperature changes on the junction voltage. The output-current limit is determined by the power rating of the transistor. To extend the output range down to zero volts, connect pin 4 to a −2-volt power supply.

Figure 19 shows an alternative type of power supply circuit, whose output voltage is variable from +3 to +15 volts at currents up to 100 mA. A fixed 3-volt reference is applied to the non-inverting input via Zener diode D1 and the R2-R3 divider network. Variable voltage gain is set by potentiometer R4. When R4's wiper is at one extreme position, the circuit has unity gain for an output of +3 volts; when the wiper is in the other extreme position, the circuit has a gain of ×5 for an output of +15 volts. The gain is fully variable between the two values.

It is quite easy to modify the power-supply circuit shown in Fig. 19 so that it can supply up to ten times the output current. That can be done by using a Darlington transistor pair at the output instead of the single transistor shown, to supply the current. You'll also have to power the circuit with 40 to 45 volts, instead of 18.

Of course, any of the circuits we've shown can be altered to suit your specific needs. Just don't exceed any component's ratings.

Figure 20 shows how you can incorporate automatic overload-protection circuitry. Here, resistor R6 senses the magnitude of the output current. When 1 amp is exceeded, the resulting voltage drop across R6 starts to bias Q3 on; that shunts away transistor Q1's base-drive current, thereby limiting the output current. **R-E**

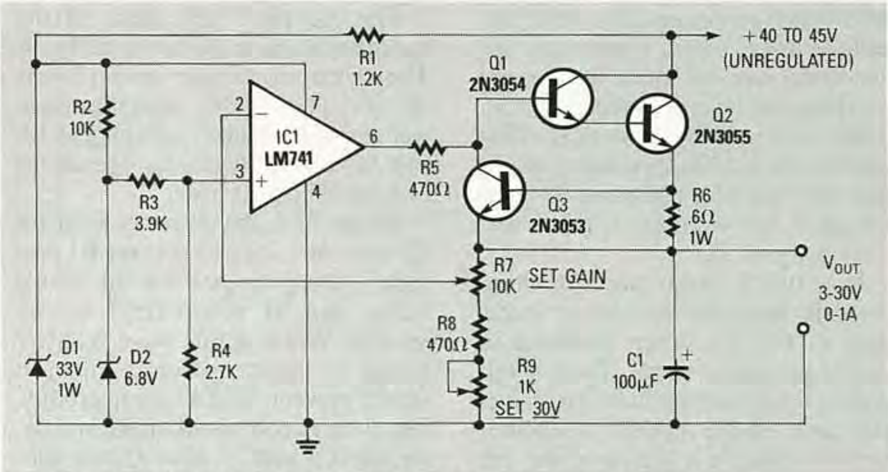


FIG. 20—OVERLOAD PROTECTED, 3–30-volt stabilized power supply.