EXPANDED SCALE

Build an analog voltmeter with a scale equivalent to one 36 inches long! The meter also features reverse-polarity, over- load indicators and protection, and a special circuit for AC.

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IS IT POSSIBLE FOR AN ANALOG METER to rival digital accuracy, yet not cost an arm and a leg? Sure—with a nearly forgotten technique known as expanded-scale operation.

As a matter of fact, here's a scale expander you can build for less than the price of the cheapest DVM. Easily constructed and easier to operate, it'll put an ordinary VTVM to shame. Besides being accurate, it's smart. It will tell you if you are "over-ranging" and protect the movement from damage if you are. It will even recognize AC voltage and DC polarity-reversal.

Expanded-scale theory

A major drawback of conventional instruments is the necessity of selecting the most appropriate scale to measure a particular voltage. If you wish to measure 55 volts, let's say, it gets a bit tricky.

The 50-volt scale is too small—the needle pegs—so, you have to switch to the next range—150-volts. Unfortunately that places your reading in the bottom third of the meter—the most inaccurate portion.

Why put up with this, when all you're really interested in is a portion of the scale—not the whole 150-volts worth? Why not start at 50 volts and set the upper limit at 60, for a total range of only 10 volts? In other words, the pointer won't budge until the input exceeds a minimum value, and then will be read against a much more accurate scale?

The always-useful op-amp will permit you to do just that. Using the amplifier in a standard inverting configuration, as shown in Fig. 1, you'll have a voltmeter...nothing fancy, but the basic building block of our unit.

Apply a voltage and the meter will respond. When it gives a full-scale reading, then that's the limit...right? Wrong! We can "zero" the meter and measure higher voltages by a method called junction summing. A summing amplifier is shown in Fig. 2.

The output of a summing amplifier is the algebraic sum of *all* the inputs. So, when the output reaches maximum, we can inject a voltage of the opposite polarity into one of the summing resistors...just enough to make the sum of the inputs equal to zero. Now we can increase the input voltage and still obtain an on-scale meter reading.

After reaching the next plateau, we can connect another summing resistor, re-zero the meter, and be able to read still-higher voltages.

We now have an input voltage three times that of the meter's full-scale capacity; yet we are still using the original, more precise, scale. That can continue indefinitely since the inputs don't interact. (Of course there's a practical limit!)

How it works

Basically that's how our meter works—but we've added a few improvements. Resistors R6 and R7 (see Fig. 3) determine the gain of the stage, with R6 also providing the input impedance. Resistors R1 through R5 are the summing resistors.

The upper limit of our instrument has been set at 120 volts, with 10-volt increments. (150 volts is the absolute maximum; beyond that, you run the risk of damage to the op-amp.) This means that 11 summing resistors are necessary for proper operation. Although that would be true *ordinarily*, we can reduce the component count by taking a hint from binary math.

Resistor R1 is selected to match one unit exactly, and R2 to match two units, of reverse voltage—which means that the combination will be three units (sound familiar?).

Accordingly, R3 is four units, and R4 (which is actually two resistors in parallel—R4 and R5) is eight. (The schematic refers to R4-R5 as R4). Now, by paralleling different combinations of those resistors, we can develop any summing current from one to sixteen units. That's exactly what the range switch, S1, does.

This leaves us with one *small* problem. Let's assume we've input 70 volts and properly compensated for it with the biasing inputs—and then remove the input. Zap! There goes the meter movement...*backwards*!

To prevent that, we'll include a transistor, Q1. It is normally reverse-biased and doesn't enter in the performance. But let the voltage go just a little negative and the transistor saturates—shunting the op-amp's output to ground and saving the meter's life.

We've also protected our monitor from forward overloads with diodes D1, D2 and LED1. As long as the output from the op-amp is under about 2.5 volts, the diodes won't conduct. Once it exceeds the diodes' combined forward voltage, the LED lights—indicating overload—and clamps the output, again rescuing the movement from harm.

Resistors R28 and R11 are for calibration. Potentiometer R27 is mounted on

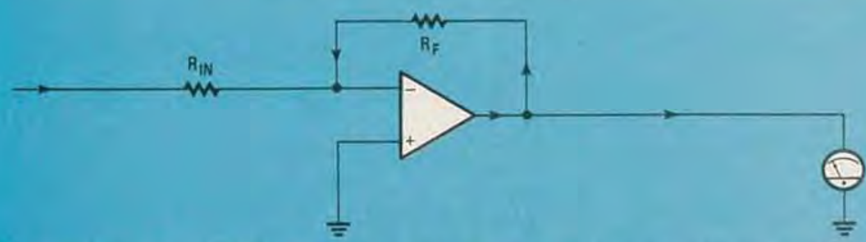

FIG. 1—AN ORDINARY OP-AMP is the heart of the expanded-scale voltmeter. Resistors R_{IN} and R_F set the gain.

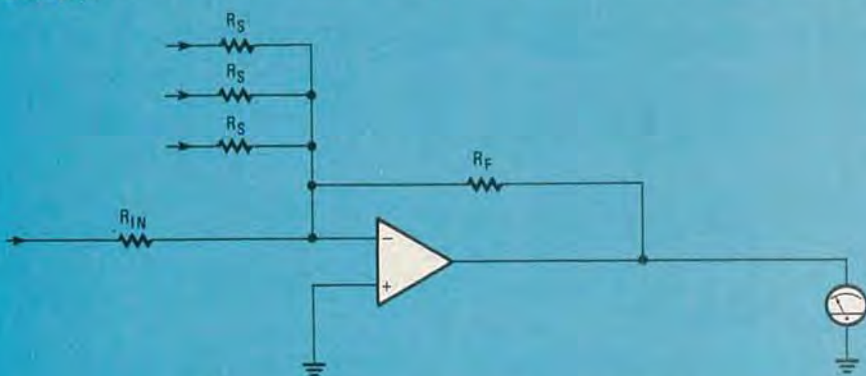

FIG. 2—A SUMMING AMPLIFIER works on the basis that the total input is the algebraic sum of the individual inputs.

VOLTMETER

the front panel and nulls the input amp.

The voltage for the summing resistors is obtained from IC2-b, a Norton amplifier operating from only one supply voltage—positive. Resistor R19 limits the Zener current, which is used to reference the inverting input. Potentiometer R29 controls the output.

In order to educate our machine, an amplifier, IC1-b, is used as a comparator. Resistor R13 provides an input impedance. If the input is negative (negative, in our case, is proper operation), it swings the comparator's output positive—to the limit.

Light-emitting diode LED2 is a special tri-color device with two lamps in one case. Internally, the diodes are connected in parallel with opposite polarities. The device works in the following manner: with current flowing in one direction the unit glows green; reverse the flow and it's red. Light both diodes and it's yellow!

So, we connect the LED so it glows green with a negative input. If we apply a positive input, the comparator swings negative...lighting our red lamp. That signals that the leads are reversed. An AC voltage will cause the LED to glow yellow.

AC too?

You bet! The expanded voltmeter will also measure AC. Our clever clamping device, the transistor, also serves as a rectifier by clipping the negative peaks.

Because the expanded function offsets the input voltage the way it does, it distorts the AC waveform. As the input voltage increases, the half sinewave narrows—you're sampling closer and closer to the top.

A simple solution: Use a peak detector. The peak value is independent of the pulse width, eliminating the problem of the meter's averaging the pulses and giving erroneous readings.

The Norton amp (IC2-a) receives the pulsating DC from the main amplifier through R24, which, in conjunction with R25, sets the gain at unity. As the level of the input waveform rises, so does the voltage across C1, until a peak is reached.

Diode D3 performs two functions. First, it references the output to ground; in other words, it removes the offset voltage...with a little help from R22 and R23 (R31 is zero adjust).

Secondly, it isolates capacitor C1 from the output, allowing it to charge to the peak voltage—but as the input voltage decreases, D3 becomes reverse biased, thus making it impossible for the capacitor to follow the decline. The capacitor remains charged at the peak input voltage and *slowly* discharges through R30 and R26, the calibration resistors which, we should add, are adjusted for RMS—not peak—reading.

That fact requires the addition of another bias supply for the summing resistors, since our range per step has changed—it's 1.4 times that of the indicated value on the AC ranges. The AC-bias supply is IC2-c and works in the same way as the DC supply. (Zener diode D5, R21, and R32 are the associated parts.)

Because the forward voltage on the base of the transistor must be exceeded before clipping begins, AC voltages in this area are non-linear. (That only happens on the first portion of the lowest range.) A transistor was selected instead of a diode because once the transistor saturates, it effectively shorts the signal to ground while a diode would still carry the forward offset voltage, permitting the output to dip below ground.

Construction

Layout isn't critical, so you can duplicate the unit in almost any manner that pleases you. A printed-circuit board layout and parts placement diagram are shown in Figs. 4 and 5 for those wishing to go that route; however, the prototype was fabricated on perforated construction board.

If you elect not to use the PC board, try to keep the calibration pots along the edges for easy access. The case is large enough so that crowding isn't a problem. We suggest using sockets for the IC's.

Even though IC1's input impedance is *fairly* high (about 1 megohm), it might not be high enough to satisfy your requirements. Unplug the 1458 IC and replace it with an LF353N—it has FET inputs. Change R15 to 2 megohms and R16 to 10 megohms. You may have to change (reduce) the value of R7 to restore the original amplification. Voila! This is liable to out-perform any voltmeter you'll run across for some time!

Resistors R4 and R5 are two 750K units in parallel to obtain the non-standard value of 375K. Any combination will work: 300K and 75K in series, 360K and 15K in series, etc.

The meter mounts on the front panel, and is then bolted to the foil side of the circuit board, so make sure when positioning it that everything lines up. Speaking of meters, the accuracy of the system is limited only by the meter.

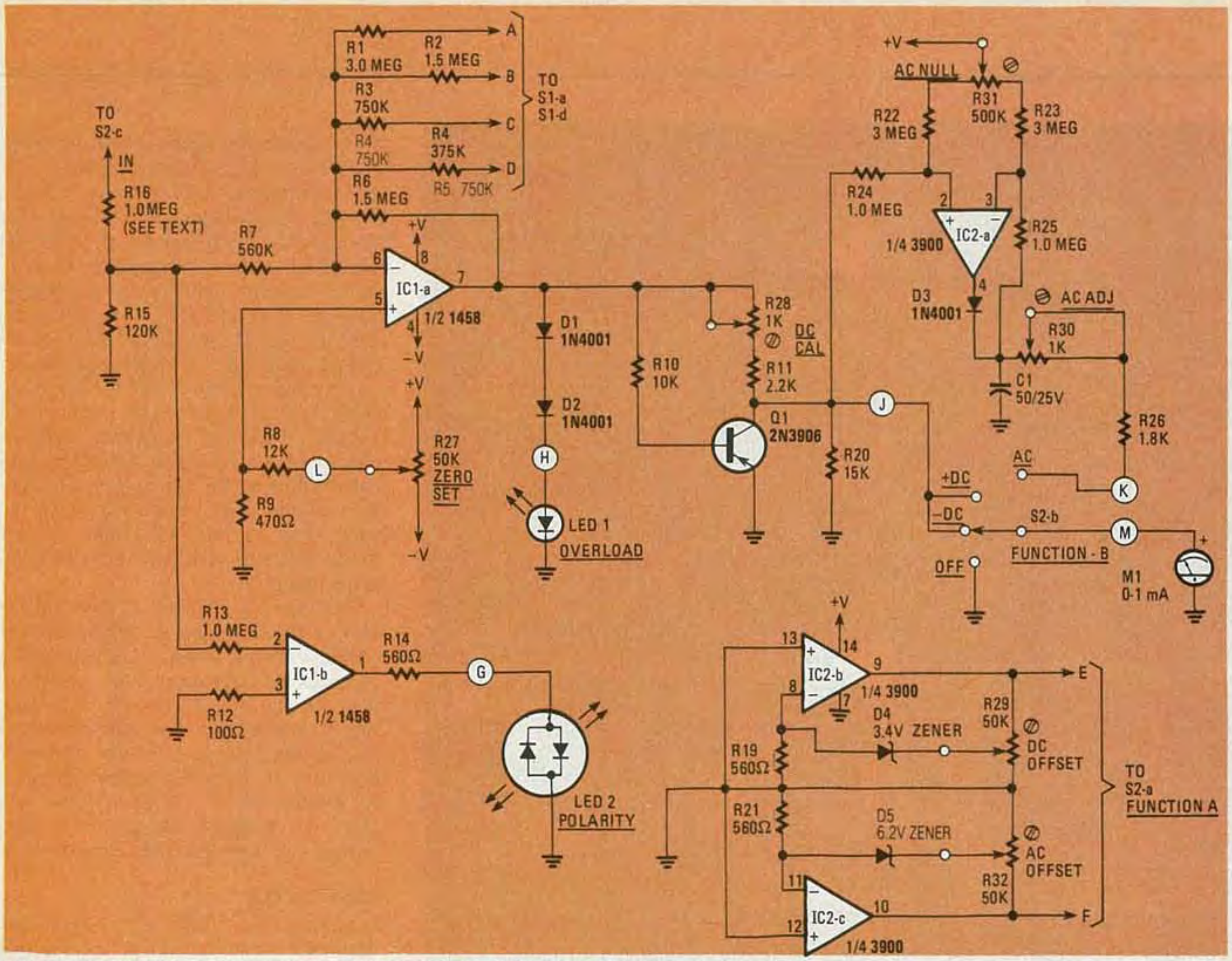

FIG. 3—SCHEMATIC OF EXTENDED-RANGE VOLTMETER. Circled letters refer to connection points on board.

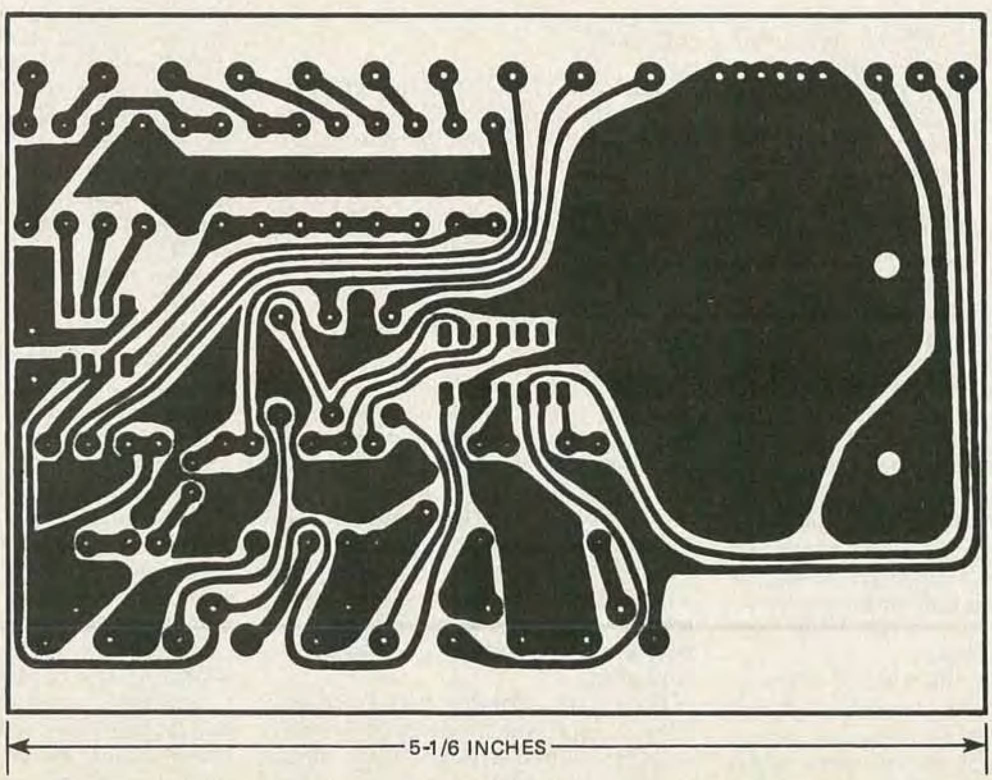

FIG. 4—PC BOARD will fit comfortably in a 6¼ × 3¾-inch box.

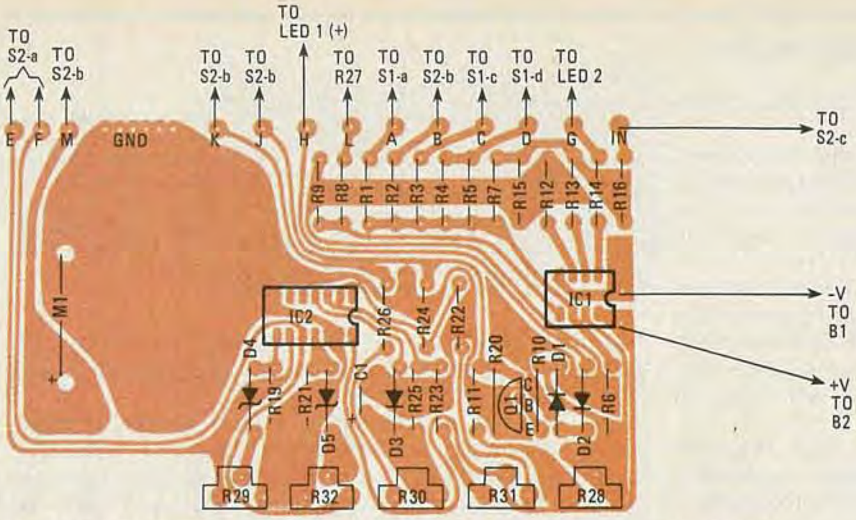

FIG. 5—MOUNT TRIMMER POTS R28-R32 so they can be adjusted from outside of board.

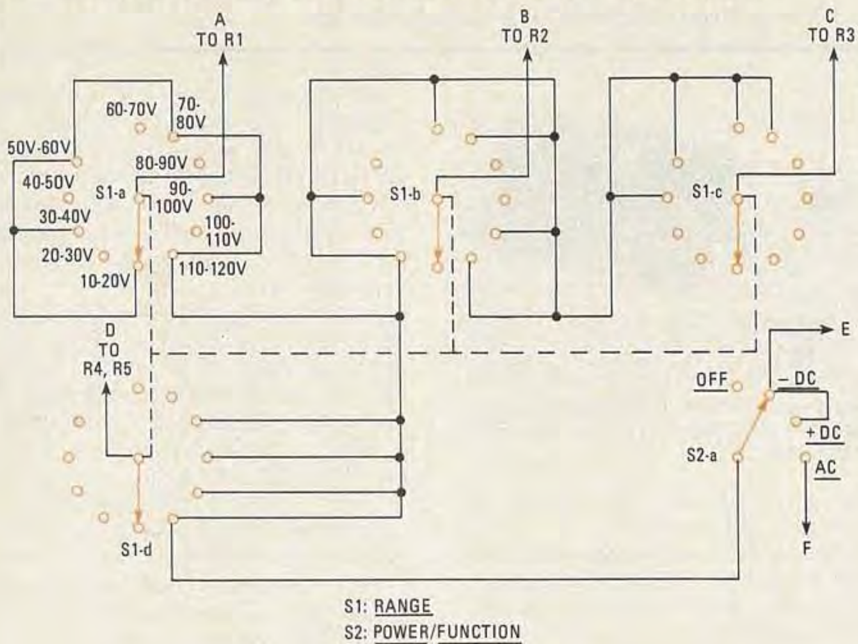

FIG. 6—WIRING FOR SWITCH S1 and one section of S2. Switches are mounted on enclosure and connected to points A through F on PC board.

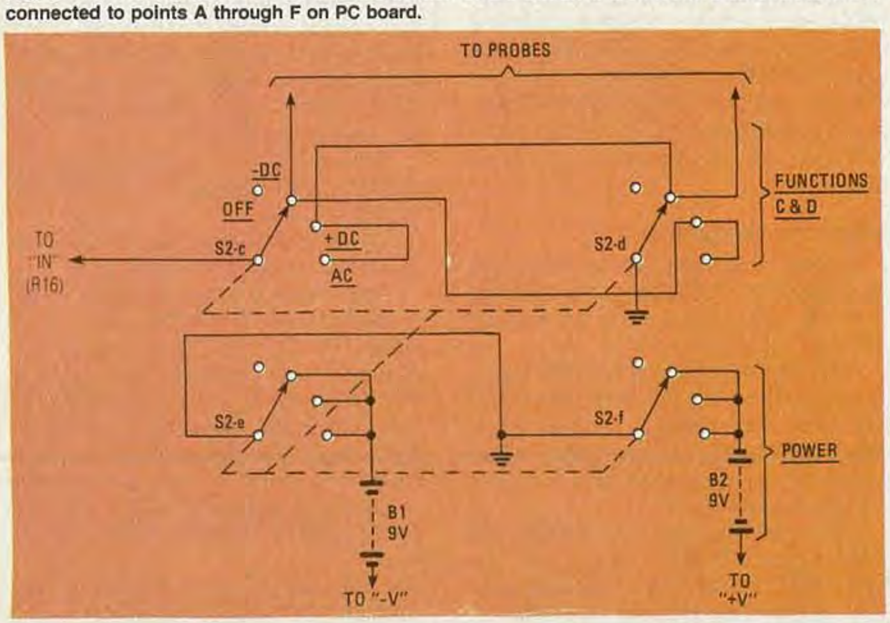

FIG. 7—WIRING FOR FOUR of the six sections of switch S2. This switch is used to select mode of operation and to turn unit on and off.

The movement specified is a standard panel unit, but any equivalent can be substituted. Resolution is limited only by the meter you select and your pocketbook! (Taut-band, mirrored-scale devices don't come cheap.)

Switch wiring is shown in Figs. 6 and 7. When routing the wires to the panel controls, use ribbon cable. It definitely makes for a neater package and there's less chance of committing an error. The LED's are placed in holders and the leads spliced. Slip a piece of spaghetti or shrink tubing over the exposed splices.

Observe diode and capacitor polarity, and follow good work habits in general when soldering. Figure 8 shows the completed board. Keep the input wire to a minimum to avoid noise. Either run a ground wire alongside it, if you're using ribbon cable, or use coaxial cable to reduce stray coupling.

The instrument is powered by two 9-volt batteries; mercury cells should be used since their voltage remains stable throughout their useful life. The ON/OFF switch is incorporated into the function selector, S2.

Calibration

Familiarize yourself with the calibration controls. Potentiometer R27 is the overall zero-set and is mounted on the front panel. DC calibration is done using R28, and R30 is the AC-adjust. Potentiometer R31 is for AC null, or zero. The bias offset, the function which gives our instrument its expanded scale mode, is controlled by R29 and R32—DC and AC respectively.

First you must zero the instrument. Switch the function selector to +DC VOLTS and the range to the lowest scale, 0-10 VOLTS. Adjust R27 for zero. (Of course, you've already *mechanically* zeroed the meter before applying power.)

Apply 10-volts DC to the input. Since that is the most critical adjustment, the accuracy of the instrument will directly depend on how precise your reference is. Adjust potentiometer R28 for full-scale deflection.

Move the RANGE switch to the next range (10-20 VOLTS). Now, turn pot R29 until the meter again indicates zero, and that's it! Well, the DC part anyway. You may have to strain your eyes a little to insure that your initial calibration is right on the button—as the ranges progress, any small error will be significantly magnified.

Assure yourself the meter is nulled and switch to the AC function. Set the RANGE switch to the lowest range. Using R31, zero the meter; it's imperative you set the overall zero in the DC position prior to trimming the AC pot—they are *two* different amplifiers with *two* offsets!

Place a 10-volt RMS sinewave across

A SIMPLE EXPANDED-SCALE VOLTMETER

A SIMPLE EXPANDED-SCALE METER CAN BE MADE USING A ZENER diode. (As shown in Fig. 9.)

The diode is normally reverse-biased and little current flows in that mode. However, as the voltage across the Zener is increased, a point is reached where the diode begins conducting—heavily. This voltage is called the breakdown voltage.

When breakdown occurs in normal diodes, they are destroyed. But, Zeners are heavily doped to permit the reverse conduction. A resistor is placed in series with the regulator to limit the current flow. Once the diode conducts, the series resistor drops voltage according to Ohm's law—*minus* the Zener voltage!

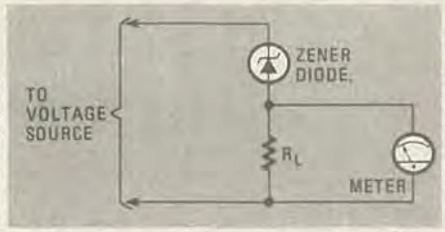

FIG. 9—A SIMPLE expanded-scale voltmeter can be made using just a Zener diode and a resistor. Add a conventional diode and you have an AC line-voltage monitor.

Suppose the Zener is rated at 10 volts. Up to the point of 10-volts input, no current flows through the resistor and no voltage is developed. After the 10-volt threshold is reached, and the Zener conducts, the current through the resistor generates a voltage.

A meter across the resistor will measure that voltage. The meter can have any scale desired—if it is a 0 to 10-volt meter, it becomes a 10- to 20-volt meter when used with a 10-volt Zener diode.

The Zener is, unfortunately, a low-impedance device and it takes a tidy sum of current to begin to induce an avalanche condition. This more or less restricts its use to power-supply monitors. By inserting a conventional diode in series with the Zener, you rectify the input-voltage—making the meter particularly attractive as an expanded-scale AC line-voltage monitor.

PARTS LIST

All resistors ½-watt, 5%

R1, R22, R23—3 megohms
R2, R6—1.5 megohms
R3-R5—750,000 ohms
R7—560,000 ohms
R8—12,000 ohms
R9—470 ohms
R10—10,000 ohms
R11—2200 ohms
R12—100 ohms
R13, R16, R24, R25—1 megohm
R14, R19, R21—560 ohms
R15—120,000 ohms
R20—15,000 ohms
R26—1800 ohms
R27—50,000 ohms, potentiometer, panel-mount
R28, R30—1000 ohms, trimmer potentiometer, vertical-mount
R29, R32—50,000 ohms, trimmer potentiometer, vertical-mount
R31—500,000 ohms, trimmer potentiometer, vertical-mount

Capacitor

C1—50 µF, 25 volts, electrolytic

Semiconductors

IC1—LM1458 or LF353N dual op-amp (see text)
IC2—LM3900 quad Norton amp
Q1—2N3906
LED1—jumbo red LED
LED2—tri-color LED (also known as bi-polar LED)
D1-D3—1N4001
D4—3.4-volt Zener diode
D5—6.2-volt Zener diode
M1—0.1 mA panel meter (Radio Shack 270-1752 or equivalent)
S1—4-pole, 12-position rotary switch (Centralab PA-2012 or equivalent)
S2—6-pole, 4-position rotary switch (Centralab PA-2021 or equivalent)

Miscellaneous: IC sockets, binding post, enclosure, two 9-volt mercury batteries, battery clips, ribbon cable, LED holders, solder, etc.

An etched and drilled PC board is available from: Danocinths, Inc., P.O. Box 261, Westland, MI 48185 for $9.40 plus $1.25 for postage & handling (order No. HSIF-36). MI residents please add 4% sales tax; allow four weeks for delivery.

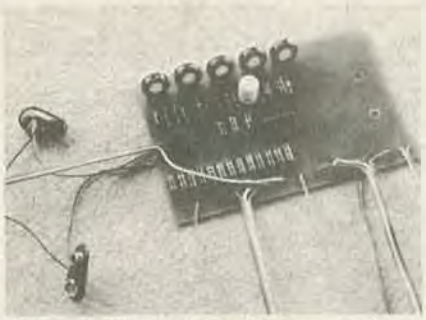

FIG. 8—COMPLETED BOARD ready to be installed in box. Note how ribbon cable keeps things neat.

the input leads and adjust R30 for full-scale deflection. Move the RANGE switch to the next position and adjust R32 for a zero reading. The same requirements apply here as they do in the DC calibration.

The AC amplifier *won't* go below ground—the zero on the meter. Keep that in mind when setting R32. Turn the control to obtain an indication above zero, then back off the pot until it *just* reaches the line. If you retard it any further, you won't know it because you will not get a reverse indication on the meter!

Using the instrument

Button everything up, inserting the batteries first, and apply power. There's nothing tricky about using the expanded-scale voltmeter.

With the RANGE switch in the lowest position, the LED will glow green with no input. Now apply a voltage across the leads. Right away the meter, which is now pretty smart, will tell you quite a bit about your input.

If the polarity is correct, the light will remain green; if not, it changes to red, indicating that the leads are reversed. The situation can be easily remedied by twisting the function knob to the −DC VOLTS setting.

If the voltage is higher than the scale capability—for example, 45 volts on the 0-10-volt range—the OVERLOAD LED, LED1, will glow. Since the meter is fully protected from overloads, it won't be harmed. Simply switch through successively higher ranges until the lamp goes out.

In that example it will go out at the 40-50-volt range, so you know the voltage is between those figures. Merely take the meter reading, in this case 5, and mentally add it to the lower number of the range (40-50) you are using; hence, 40 + 5 for 45 volts.

If the POLARITY LED glows yellow, this indicates that you have an AC voltage present. Turn the function switch to AC VOLTS and proceed just as you would with a DC voltage reading—expanded scale and all!

Below 2 volts, the AC scale is non-linear—but then, most AC meters are, and special scales are required. If that bothers you, or you wish to measure those low-level signals with this instrument, there's an unused amplifier in IC2 that could be used.

However, for voltages that low, a good AC millivoltmeter would probably be the best bet.

The AC scale has another unique characteristic: it's peak reading.

That means you can measure *any* AC voltage, *any* waveform (yes, even pulses, if the repetition rate is high enough), and obtain a peak reading. The value will have to be multiplied by 1.414 since we calibrated for sinewave RMS. But, you can calibrate for peak voltage by using 10-volts peak instead of RMS as a reference. Zener diode D5 will have to be changed to a 3.4-volt device.

If you calibrate your expanded-scale voltmeter for peak volts, an RMS value can be found easily by multiplying the reading by 0.707. **R-E**