SOLID-STATE V.O.M.

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Design of an instrument with minimum drift and good linearity. Field-effect input transistors and a true difference amplifier make the instrument unique.

TWO problems face the designer of a really good instrument. One is the matter of active devices whose properties are almost always nonlinear and vary from one device to the next; the other is unavoidable changes in device characteristics with temperature, supply voltage, and aging.

Here is a relatively simple high-resistance, solid-state meter circuit whose linearity is limited only by the meter movement characteristics. It measures d.c. voltages from 150 millivolts full-scale to 1500 volts full-scale and resistances from 10 ohms to 1 megohm. It requires few specialized parts and it's simple to build. Once assembled and calibrated, its stability and drift resistance are excellent.

The Drift Problem

An elementary, but often used, method of reducing unwanted drift is to provide a drift in the opposite direction, usually from a non-signal-carrying active device in a circuit similar to that of the signal device. This works, after a fashion, but it is not really suited to accurate, reliable instrument design.

A better technique is to develop a circuit that is blind to its own drifts; typically, a difference amplifier biased from a constant-current generator. This circuit configuration has additional advantages. Nonlinearities tend to balance out and the output is an almost perfectly linear function of input.

Two other methods for reducing drift and improving linearity are to use large, regulated power supplies and to choose devices having a very high input resistance. All three of these techniques are used in this ohmmeter: true difference amplifier, large supply voltages, and field-effect input transistors.

The simplified schematic of Fig. 1 shows how the meter circuit works. A constant-current generator regulates the current to $Q1$ and $Q2$ at 3 mA, by maintaining a fixed voltage across $Q3$'s emitter resistor and transferring the resulting current to its collector terminal and the difference amplifier. If either $Q1$ or $Q2$ needs more current, the other has to get by with less. Now suppose a small d.c. signal is applied to $Q1$, as in making a voltage measurement. As the transistor's current changes, the other transistor's current must change in the opposite direction. Thus, input-output nonlinearities will balance out.

During normal operation both transistors are warmed a few degrees by current flow in the circuit. The base-emitter voltage of both devices rises slightly, increasing base and collector currents. Collector voltages are slightly reduced; but since this change occurs equally at both collector terminals, the meter does not indicate a change in its zero points.

The actual circuit (Fig. 3) operates in a similar manner. But, each transistor in Fig. 1 is replaced by a combined FET and bipolar transistor, the constant-current generator has moved to the collector side of the transistors and a current source has been added in its place. Calibrating pots $R23$ ("Volts") and $R24$ ("Ohms") and a reversing switch have also been added.

Voltage ranges are determined by the 150-mV full-scale sensitivity of the calibrated circuit and by the voltage divider resistors $R1$ through $R9$. This arrangement is appropriate for d.c. measurements only.

The ohmmeter circuit is a simple variation of the voltage-divider idea. An ordinary "D"-size cell supplies 1.5 volts d.c. through a series resistance consisting of some or all resistors $R10$ through $R16$. Fig. 2 shows how the ohmmeter works. In effect, the unknown resistance is compared with the ohmmeter resistances. If R_x is shorted, the meter reads zero volts or zero ohms. If R_x is infinitely large, the entire battery voltage appears across the ohmmeter terminals, giving full-scale reading. And when R_x equals the value of the series resistance (10 ohms on the lowest resistance range), the meter reads one-half full-scale.

An ohmmeter calibration curve can be calculated very easily. The equation for R_X in Fig. 2 is the familiar voltage-divider equation turned inside out to show resistance rather than output voltage.

Power Supply

Bipolar supply voltages (Fig. 3) are provided from a sin-

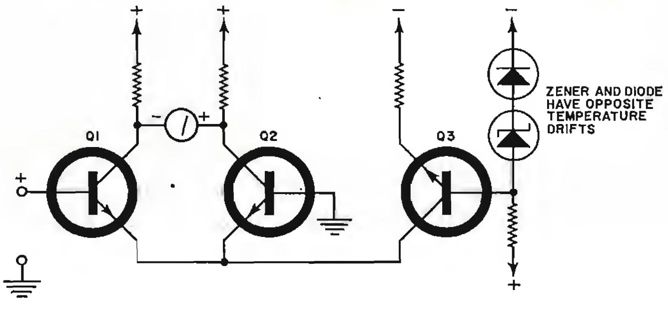
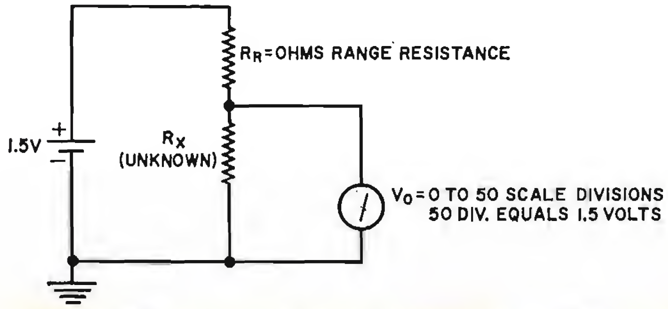


Fig. 1. Simplified circuit of difference amplifier and constant current source. The amplifier is impervious to its own drifts.

Fig. 2. This schematic shows the ohmmeter's divider feature. The equations included are used to calculate calibration points.



$$V_O = 50\frac{R_X}{R_R + R_X} \qquad V_O R_R = 50 R_X - V_O R_X \qquad R_X = \frac{V_O R_X}{50 - V_O}$$

gle transformer through two emitter-follower regulators. Most of the instrument's power is dissipated in the form of zener current. The transformer and rectifier can be replaced by a pair of batteries, but the emitter-follower regulator should be retained to avoid calibration errors from battery aging.

Supply voltages (±15 volts) are not critical, but deserve respect because they indirectly determine the circuit's operating points. Two half-wave rectifiers, *D*3 and *D*4, rectify the 24-volt transformer output, feeding two large filter capacitors. Current drain is only a few mA and ripple is small. The d.c. output voltage is regulated down to 15 volts by two emitter-follower regulators referenced to a pair of inexpensive *G-E* zener diodes. Capacitors across the diodes control any zener noise. *C*6 and *C*7 are output filters.

Construction and Calibration

It is relatively easy to build the linear meter. A 3″ × 5″ × 10″ aluminum box can be used. The right-hand half of the box could be used for power-supply components and the relatively large meter. There is more than enough room in the left half for the controls, circuit boards, and the 1.5-volt ohmmeter battery.

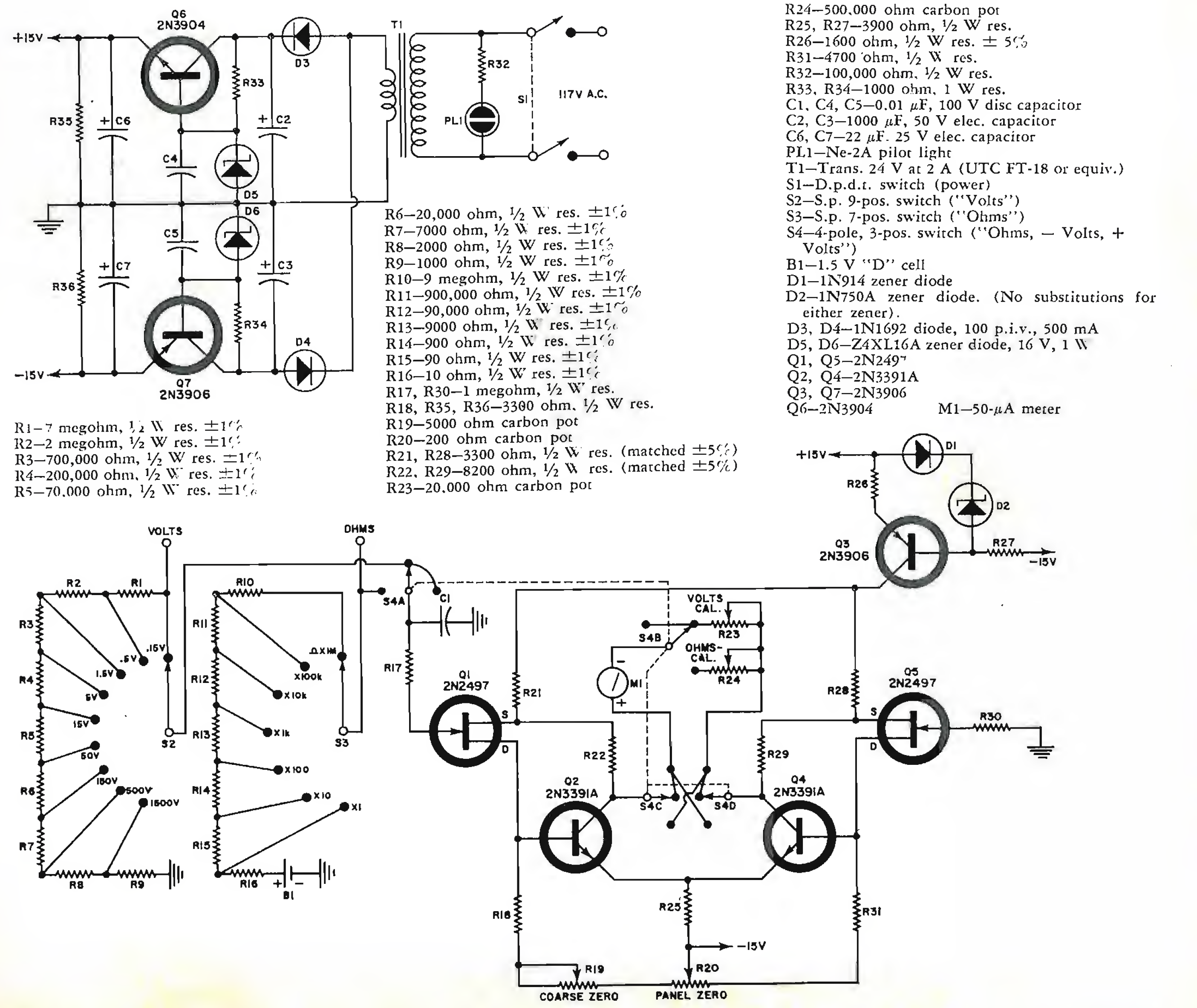
Just about all of the solid-state meter's components can be mounted on pre-punched terminal boards. This serves to make a neat assembly and reduce wiring requirements.

While construction is not critical, there are a few areas where the builder should take special care. Transistors *Q*2 and *Q*4 should be heat-sinked for stability. Diodes *D*1 and *D*2 should not be replaced with so-called equivalent types. These devices are especially chosen for the direction of their temperature drifts. The 1N914 has a slightly negative temperature drift, the 1N750A a positive drift, thus the two cancel. However, the relatively expensive 2N2497 FET's (priced at $6.45 in single quantities) can be replaced by Type 2N2386 (about $3.75). They differ only in transconductance. Resistors *R*21 and *R*28 (3300 ohms) and *R*22 and *R*29 (8200 ohms) should be matched pairs. Incidentally, the 50-microampere meter should have large scale-divisions if the circuit's linearity and stability are to be put to best use.

Meter calibration is easy. Use an accurate low-voltage source (about 1.35 volts) as a check. Adjust the voltage reading to the correct value by varying the resistance of the *R*23 voltage calibrator. If the meter movement is linear and the circuit's resistors stable, this calibration should be good at all voltage ranges.

The resistance function is similarly checked. Short the test leads to verify meter zero. Then adjust the "Ohms Calibrate" pot to read full-scale with the ohmmeter's terminals open. This reading should be in agreement with the calibration curve. ▲

Fig. 3. The complete schematic diagram and parts list for the solid-state volt-ohmmeter and its regulated power supply.



R1—7 megohm, ½ W res. ±1%
R2—2 megohm, ½ W res. ±1%
R3—700,000 ohm, ½ W res. ±1%
R4—200,000 ohm, ½ W res. ±1%
R5—70,000 ohm, ½ W res. ±1%
R6—20,000 ohm, ½ W res. ±1%
R7—7000 ohm, ½ W res. ±1%
R8—2000 ohm, ½ W res. ±1%
R9—1000 ohm, ½ W res. ±1%
R10—9 megohm, ½ W res. ±1%
R11—900,000 ohm, ½ W res. ±1%
R12—90,000 ohm, ½ W res. ±1%
R13—9000 ohm, ½ W res. ±1%
R14—900 ohm, ½ W res. ±1%
R15—90 ohm, ½ W res. ±1%
R16—10 ohm, ½ W res. ±1%
R17, R30—1 megohm, ½ W res.
R18, R35, R36—3300 ohm, ½ W res.
R19—5000 ohm carbon pot
R20—200 ohm carbon pot
R21, R28—3300 ohm, ½ W res. (matched ±5%)
R22, R29—8200 ohm, ½ W res. (matched ±5%)
R23—20,000 ohm carbon pot
R24—500,000 ohm carbon pot
R25, R27—3900 ohm, ½ W res.
R26—1600 ohm, ½ W res. ± 5%
R31—4700 ohm, ½ W res.
R32—100,000 ohm, ½ W res.
R33, R34—1000 ohm, 1 W res.
C1, C4, C5—0.01 μF, 100 V disc capacitor
C2, C3—1000 μF, 50 V elec. capacitor
C6, C7—22 μF. 25 V elec. capacitor
PL1—Ne-2A pilot light
T1—Trans. 24 V at 2 A (UTC FT-18 or equiv.)
S1—D.p.d.t. switch (power)
S2—S.p. 9-pos. switch ("Volts")
S3—S.p. 7-pos. switch ("Ohms")
S4—4-pole, 3-pos. switch ("Ohms, — Volts, + Volts")
B1—1.5 V "D" cell
D1—1N914 zener diode
D2—1N750A zener diode. (No substitutions for either zener).
D3, D4—1N1692 diode, 100 p.i.v., 500 mA
D5, D6—Z4XL16A zener diode, 16 V, 1 W
Q1, Q5—2N2497
Q2, Q4—2N3391A
Q3, Q7—2N3906
Q6—2N3904
M1—50-μA meter