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VTVMs and FETVMs

Theory and practice.

When the loading presented by a volt-ohm-milliammeter (VOM) is too great, the vacuum tube voltmeter (VTVM) or field effect transistor voltmeter (FETVM) is there to save the day, or at least save the time needed to calculate the loading effects.

The VTVM has been largely supplanted by the FETVM; they use the same principles but different components. Vacuum tubes are hard to come by and expensive compared to field effect transistors (FETs), which in many respects are better. Since vacuum tubes are almost passé, the emphasis here will be on FETVMs. A design example is given for an FETVM.

Both the vacuum tube and N-channel FET are voltage-operated devices that require a positive supply: They respond to the voltage on their input, the voltage on the grid for a tube and the voltage on the gate for a FET. Both offer an almost infinite impedance. The FET actually comes closer to being an infinite impedance than the vacuum tube. The input resistance of an FET is several orders of magnitude greater than the grid current of a tube. Grid current is typically a microamp, while gate current is typically a picoamp. A picoamp of gate current can be ignored except when you have to pick the fly specs out of the pepper for an electrometer, an ultra-high-resistance voltmeter.

Some of you new techs may not be familiar with tubes, and some of you old guys may have forgotten some of the fine details. In any event, the grid in a tube intercepts some electrons, and while there are only a few electrons intercepted, they represent maybe a μA or so of current, but into a 1 meg grid resistor that's a volt. That can't be ignored.

In a VTVM contact current is usually balanced out by another similar tube working into an equal grid resistance. For example, a 12AU7 dual triode is often used. One half for the actual voltmeter and the other half just to balance out the contact grid current. Of course, contact current could be balanced out manually, but given the drift of tubes, that would be a cumbersome solution.

Both FETs and vacuum tubes look like an infinite resistance to the circuit under test. The voltage is indicated on

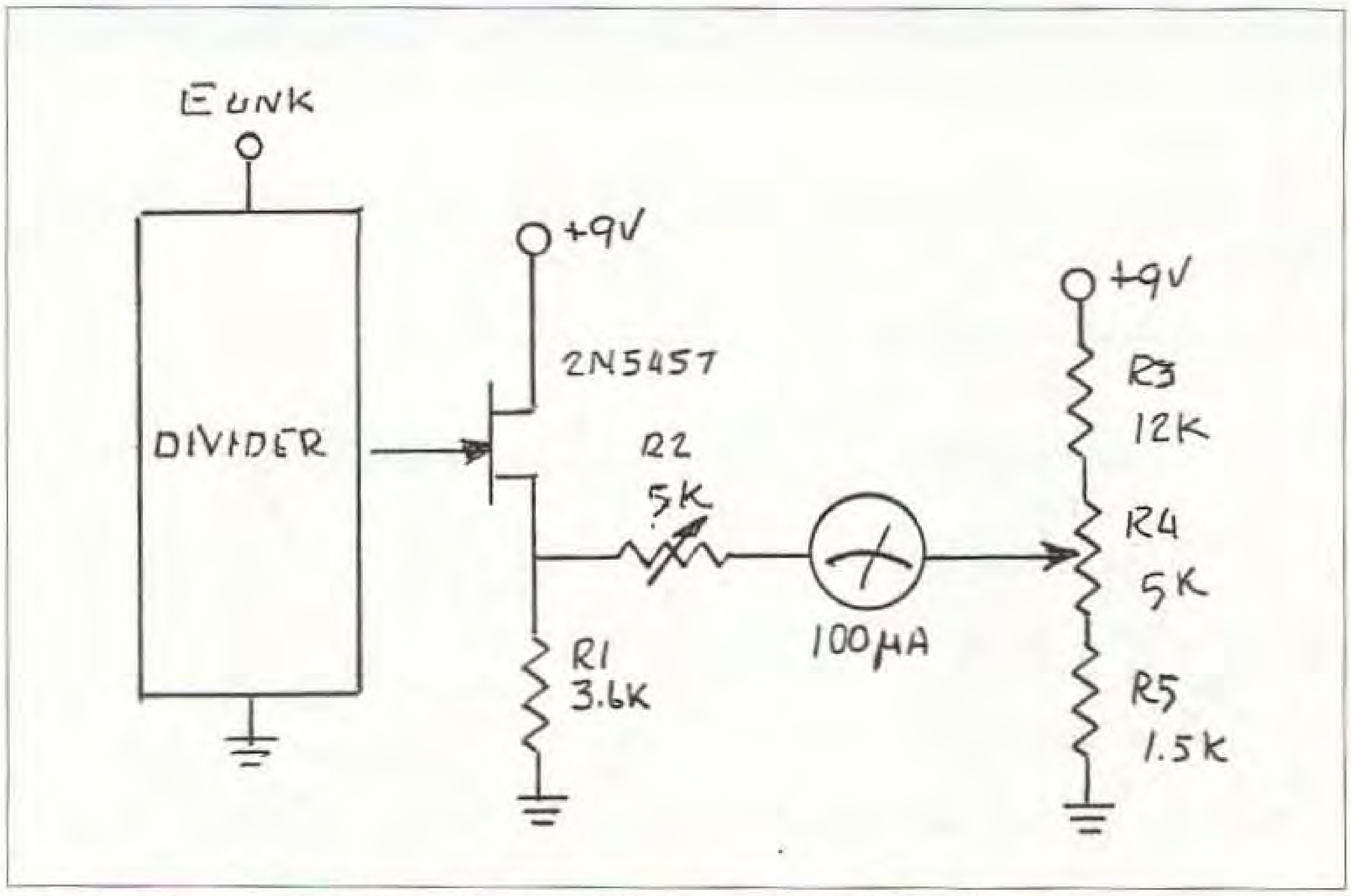

Fig. 1. A simple FETVM can have sensitivities of 1 volt full scale.

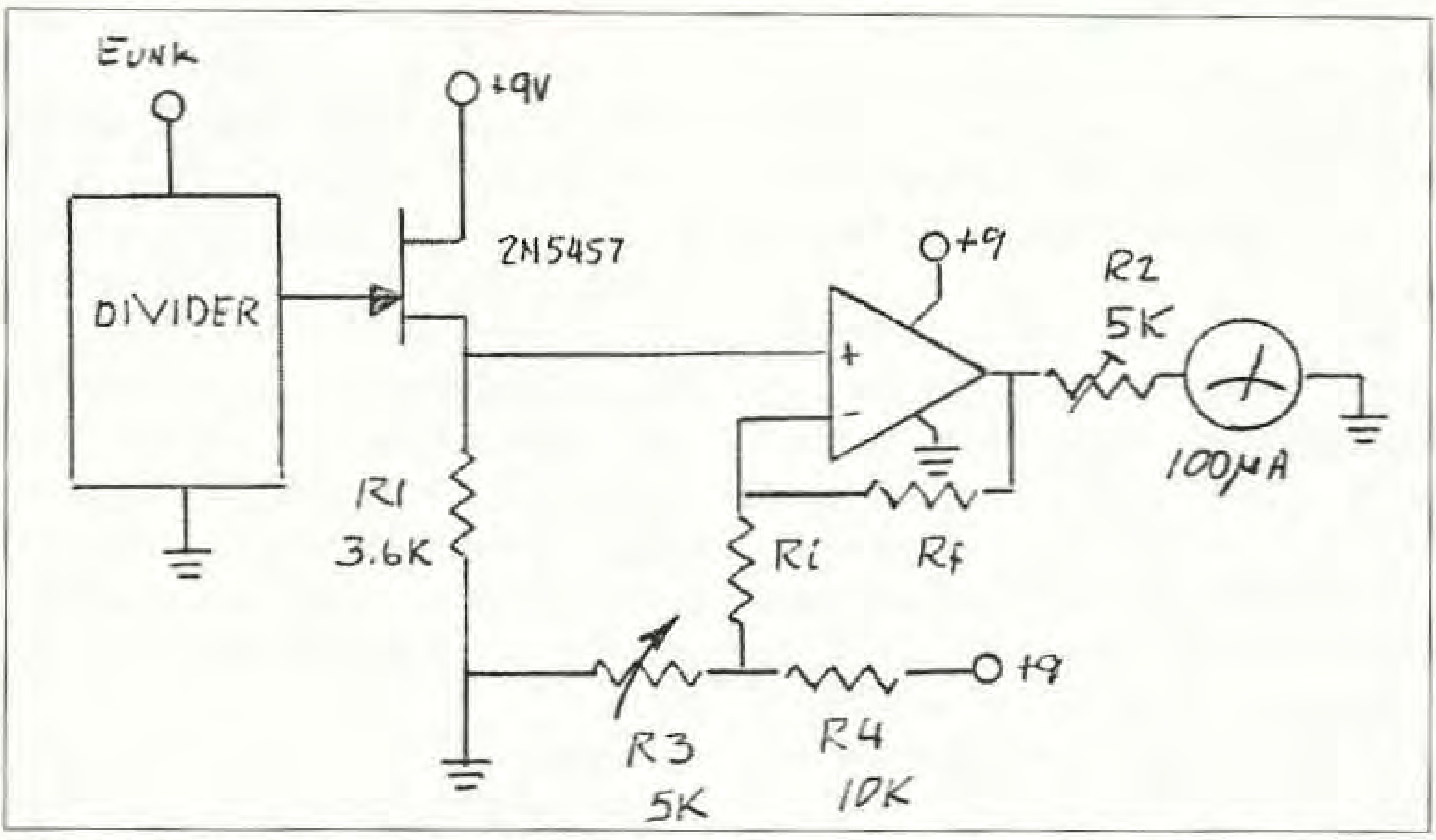

Fig. 2. Higher sensitivity can be achieved with an op-amp driving the galvanometer.

a conventional d'Arsonval galvanometer (named after the French physicist, Arsene d'Arsonval). The galvanometer requires a small current of 50 µA to 1 mA to deflect the voltage indicating needle. The tube or FET essentially isolates the galvanometer from the voltage being measured.

The FETVM is simpler than its vacuum tube counterpart because there is practically no contact current to be balanced out and it operates with a single battery supply. **Fig. 1** shows a possible FETVM. The circuit is basically a bridge with one side of the bridge composed of an FET source follower and the other side a resistance divider. A variable calibration resistor R2 in series with the galvanometer sets the current or deflection for a given gate voltage. The galvanometer connects to a zeroing pot R3 in the divider side of the bridge. The source follower circuit is used instead of an amplifier because of the improved stability as a result of the 100% negative feedback. An amplifier can provide gain and increased sensitivity, but a bias voltage is needed. A source resistor can provide the bias but it would cause a loss in gain. The complications of a separate battery weigh against it. The source follower seems the better choice.

The zero pot is adjusted for zero when the input is shorted. The calibration control is a one-time adjustment to indicate a known voltage applied to the input. The known voltage is usually a battery, but a divider on the supply can also be considered until a calibrated source like a standard cell is available.

In the circuit shown in **Fig. 1**, the 3.6k source resistance R2 controls the source current of the FET and the gain. The gain of a source follower is often assumed to be unity, but in fact it is always less than one.

The gain of a source follower is $VG_{sf} = G_mR_s/(1 + G_mR_s)$.

The G_m of the FET is $G_m = 2I_D/(V_{off} - V_{gs})$, where I_D is drain current, and V_{off} is the voltage needed to reduce the drain current to zero. V_{gs} is the gate-to-source voltage that produces I_D.

V_{off} is not always given in the data sheets but it can be easily measured: Measure the drain current as the gate is made increasingly more negative (the source is made more positive with respect to the gate) until the current is zero or at least less than 1 µA. For a typical 2N5457 V_{off} is 3.06V and V_{gs} is 1.81V for $I_D = 0.5$ mA. These conditions will exist when R1 is 3.6k. Under these conditions G_m will be 8×10^{-4}, and the voltage gain of the source follower VG_{sf}, 0.74. When 1 volt is applied to the input, the source voltage increases 0.74V to 2.55 volts. The current in the 1k galvanometer will be 100 µA when the voltage at the arm of R4 is 1.81V, and R2 plus the galvanometer is approximately 7.4k.

Measuring voltages greater than 1 volt requires a voltage divider that reduces the unknown voltage to 1 volt at the gate. The voltage divider essentially determines the input resistance of the meter and the scales of the meter. The meter's scales usually have a ratio of 1 to 3. Part of the divider is usually a built-in 1 meg resistor in the probe that isolates the circuit under test from the distributed capacitance of the divider.

For high input resistance dividers, precision high-value resistances are needed. High-value precision resistors are hard to come by, but Victoreen, Cleveland, OH, tel. (216) 248-9300, has high-voltage resistors available with values in the hundreds of megs. Obtaining and maintaining a high resistance is primarily a problem of layout and cleanliness. Leakage across a switch or PC board will lower the input resistance and upset the accuracy. Most VTVMs have input resistances of 10 megs, which is a compromise of what is practical with what is possible. Since FETs have much lower contact current, they can have much-higher-resistance input dividers.

Higher sensitivity in a source follower meter can be obtained with an op amp driving the galvanometer as shown in **Fig. 2**. The op amp's noninverting gain is $1 + R_f/R_i$, and the input resistance is essentially infinite. The inverting input becomes $(1 + R_f/R_i)E_i$ in the output. When the noninverting input voltage is +1.81V, and the inverting input is +0.181V, the output is zero. Op amp gains of 10 or so can result in full-scale sensitivities of 0.1V.

R2 is the calibration rheostat, R4 is the zero pot. Zero will change as the supply battery voltage changes. Therefore, adjust zero first and there will be no interaction between adjusting R4 and R2.

The schematic of a typical VTVM is shown in **Fig. 3**. A vacuum tube requires a power supply in the range of 150V to 250V as well as a heater supply, and is operated from the AC mains. While this can be a bother, during the heyday of vacuum tubes, the advantages of the VTVM outweighed the disadvantages of being tied to the line.

In **Fig. 3**, the two halves of a 12AUT7 are used as a differential cathode follower. The input to V1A is the unknown voltage and the input to V1B is contact voltage. The pot R3 balances out the differences in voltages at the cathodes of V1A and V1B. Assuming equal grid currents and equal R1 and R2, the cathode currents and cathode voltages will be equal when R3 is centered and no current will flow in the galvanometer. A voltage on the grid of V1A will increase the cathode voltage and upset the balance, and a current will flow in the galvanometer. The rheostat R4, the calibration control in series with the galvanometer, determines how much current flows for a given imbalance. R5 ensures a constant current to the differential amplifier and reduces the variations in the cathode follower operation due to supply voltages' variations.

The unknown input voltage is reduced to the design standard input voltage for the meter with a voltage divider. A voltage divider that divides the unknown input to 1 volt is shown in **Fig. 4**. **Fig. 4(a)** shows a 10 meg divider while **4(b)** shows a 100 meg divider. The voltage divider has no influence on the operation of the voltmeter except to set the scales and determine the input resistance of the meter.

In many VTVMs, the lowest range is in the order of 3 volts full-scale. The sensitivity of the VTVM or FETVM depends on the gain of the tubes or FET and sensitivity of the galvanometer. An FETVM can have sensitivities of less than 1 volt without benefit of an op amp.

Op amps can provide gain that increases the sensitivity of the meter to 10mV. Op amps can be married to VTVMs, but it's not a good match because an extra regulated low supply is needed. An FET marries to an op amp much more readily. Solid state op amps were not even on the horizon when vacuum tubes ruled, and the sensitivity of the usual VTVM was not particularly high. Now, with FETs and op amps, tubes have been pushed into the background. FETVMs are now the high-resistance analog instrument of choice.

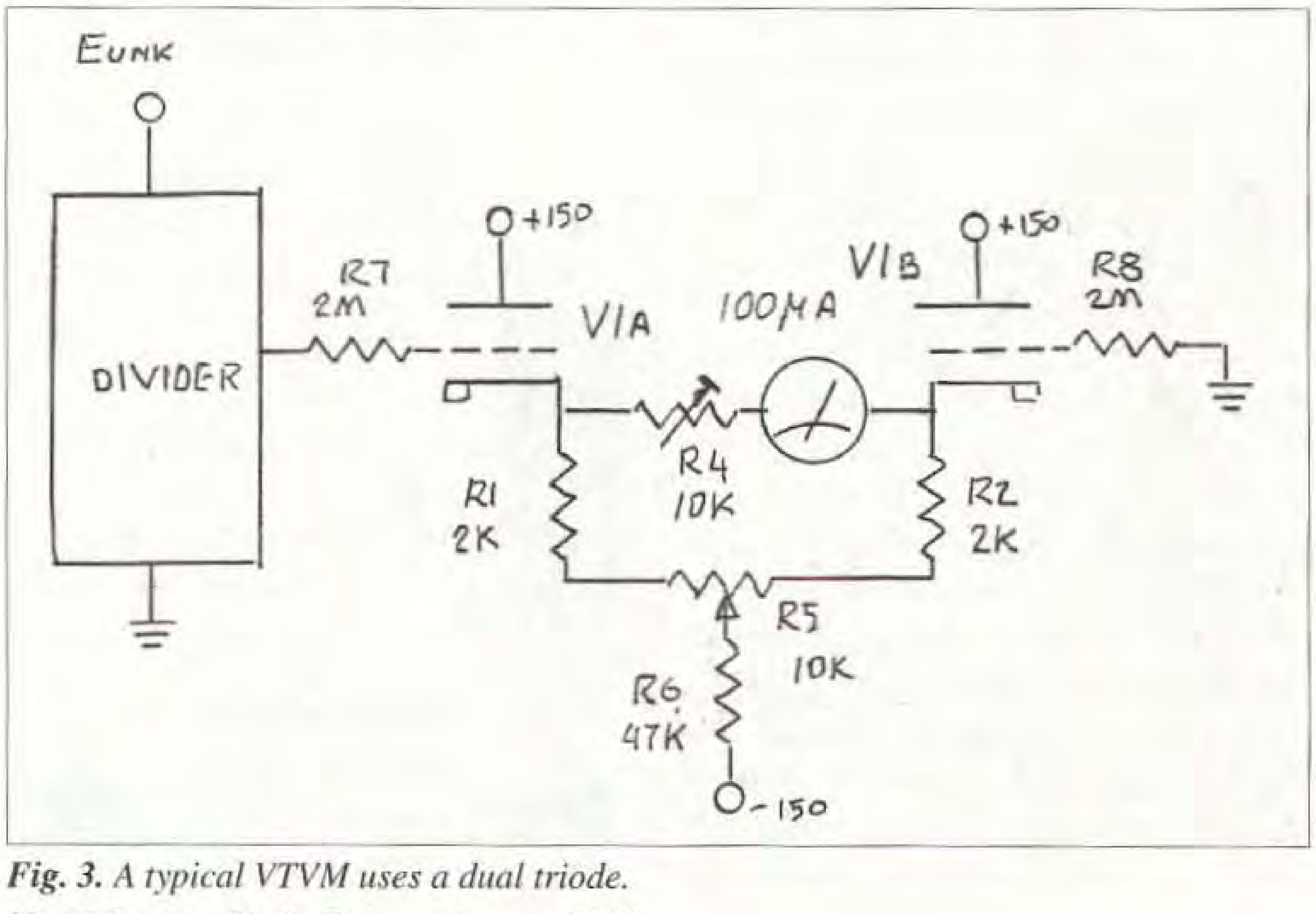

Fig. 3. A typical VTVM uses a dual triode.

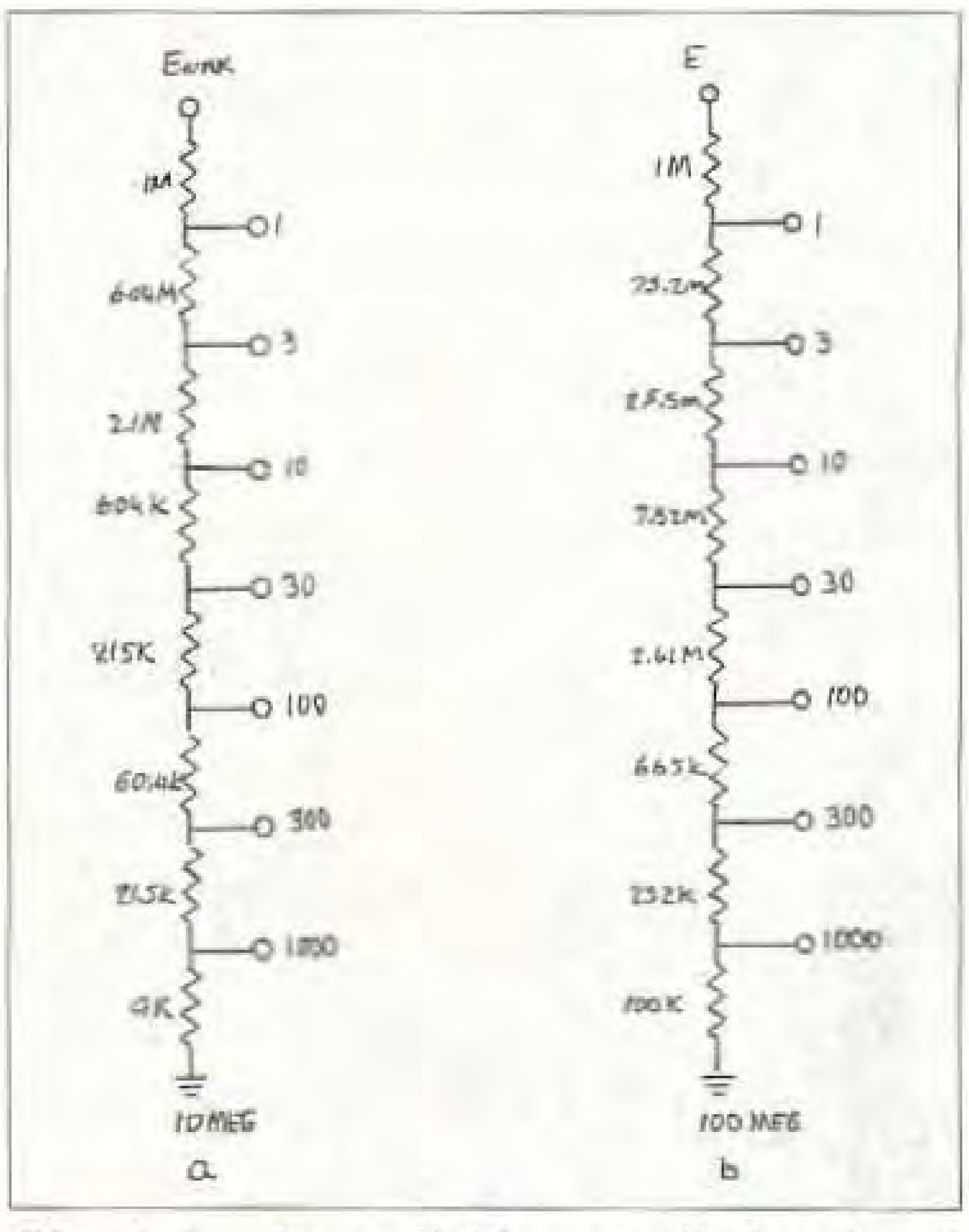

Fig. 4. A voltage divider usually has 1 and 3 scale ranges.