Build this electronic multimeter

These days many people want a digital multimeter but they are not the best tool for all measurements. Here is an analog alternative to the digital multimeter which offers better bandwidth and simple circuitry.

by FRANCO UBAUDI & LEO SIMPSON

Commercial multimeters tend to fall into two classes. Either they are digital models with all the bells and whistles or they are simple analog instruments which suffer from a relatively low input impedance, depending on the range in use.

Now we're offering an easy-to-build alternative: an electronic multimeter. It uses an analog meter movement driven by one FET-input op amp. Building it will only take a couple of hours and there is a minimum of wiring. In the process you will gain a good insight into the workings of multimeters.

The functions offered by our multimeter are the usual AC/DC voltage, current and resistance measurements. The voltage ranges for AC and DC are 1V, 10V, 30V and 100V. For current measurement (AC or DC), the ranges are 100mA, 10mA, 1mA and 100μA. Finally, the Ohms ranges are 1kΩ, 10kΩ, 100kΩ and 1MΩ.

The performance specifications for the electronic multimeter are shown in an accompanying panel. As shown, the performance is adequate for most hobbyist measurements but in one respect it is vastly superior to the average digital multimeter.

It has a much wider frequency response than all but a few of the best digital meters.

The circuit

Even when produced by the best draughtsman (ours), multimeter circuits look confusing. All those switches and resistive dividers make the circuit look a lot more complicated than it really is.

To make the circuit easier to understand it is best to split the circuit up into its various functions. Fig. 1 shows the first function: DC voltage measurement.

DC voltage measurement

Fig.1 consists of an operational amplifer IC driving a meter movement and a few low value resistors.

The resistors connected to the non-inverting input of the op amp are the input voltage divider. In the full circuit diagram there are actually seven resistors in the input voltage divider but we have shown only two, for simplicity.

Since the op amp is a FET-input type, the current which can flow into or out of the op amp inputs is exceedingly small, much less than one nanoamp. This means that the op amp itself will cause negligible loading on the input voltage divider even though it has a total resistance of about ten megohms.

So what does the op amp do? It is like any other op amp which has feedback applied around it. It operates so that its two inputs have very little voltage difference between them. This means that the voltage at the inverting input is almost identical to that at the non-inverting input.

But note that the resistors connected to the inverting input have a very low value (relative to those at the non inverting input). This means that IC1 acts as a voltage-to-current converter with the current through the meter movement being precisely defined by the voltage applied to the input voltage divider.

At full scale deflection, the voltage at the non-inverting input of IC1 is 200mV (by virtue of the input voltage divider). This means that a current of 200/166.4 milliamps (1.2mA) will flow through the resistor string connected to the inverting input. This current is shared by the 1mA meter movement and the calibration shunt trimpot which takes 0.2mA. (See main circuit.)

AC voltage measurement

Now have a look at Fig.2. This shows how Fig.1 has been modified to take care of AC voltage measurements. First, there is a capacitor in series with the input voltage divider. This prevents DC voltages from being fed to the op amp non-inverting input.

Second, the meter is connected within a bridge rectifier so that it can respond equally to positive and negative currents generated by the op amp response to positive and negative input voltages (ie, AC voltages).

Having the meter and bridge rectifier within the op amp feedback loop means that the voltage losses and non-linearity of the bridge rectifier are neatly cancelled out by the feedback mechanism. However, this does not overcome all the problems of reading the value of an AC waveform. AC voltmeters are normally required to indicate the RMS value of a sine wave signal. However, moving coil meter movements respond to the average value of their driving current. The average value of a sine wave voltage (or current) is very close to 90% of its RMS value. Accordingly, for our op-amp circuit to read sine wave signals correctly, the value of the current sink resistor must be reduced by 10%, to 150Ω.

If we now refer to the complete circuit diagram, we can further discuss the input voltage divider. This provides four ranges using seven resistors. This may seem a little odd at first but has been done this way to avoid using parallel combinations of resistors while still using values that are readily available.

Note that each resistor in the voltage divider chain is bypassed with a capacitor which is inversely proportional to the value of the resistor. Why is this necessary? After all, the LF351 op amp by itself will have a very good frequency response, because of the low "closed loop" gain.

The trouble is that stray capacitance in the switch wiring and between the input pins of the op amp itself (typically several picofarads) inevitably causes high frequency losses. This stray capacitance

We estimate that the cost of parts for this project is approximately

$50-60

This includes sales tax.

is swamped out by the capacitors shunting the voltage divider.

To this end, the highest value resistor in the divider chain is shunted with a 47pF capacitor. The capacitors shunting consecutive divider resistors increase by the same proportion as the ratio between consecutive ranges. The total effective capacitance of the capacitors shunting the divider string (not including the 3.3MΩ resistor) is 36pF which gives a time-constant for the divider of 248μS.

To nullify the severe high-frequency roll-off effect that this time constant would otherwise have, the 3.3MΩ input resistor is bypassed with a parallel combination of a 68pF capacitor and 10pF trimmer. This enables the AC performance of the circuit to be optimised for flat response to beyond 250kHz.

Current measurement

Now take a look at Fig.3: This is a combination of Figs.1 and 2, and provides us with a basic circuit with which to discuss the current ranges. The resistor connected between the input switch wiper and ground is a "current shunt". This resistor is switched, on the main circuit diagram, by S2c.

Four values of shunt resistance are provided: 2kΩ, 200Ω, 20Ω and 2Ω. Given the basic 200mV sensitivity of IC1 for full-scale deflection of the meter, the current ranges are 100μA, 1mA, 10mA and 100mA.

Note that since the values of the current shunts are low in value, there is no need for AC compensation capacitors as are required for the AC voltage measurement mode. For sine wave currents the bandwidth of the meter circuit is flat to 75kHz.

Resistance measurement

Fig.4 shows the basic circuit for resistance measurement. While this looks quite different from the previous circuits, the mode of operation is really just another variation. The main difference is that it incorporates a constant current source, which is depicted by the overlapping circles symbol.

A constant current source is the complement of a constant voltage source. Whereas, in theory, a constant voltage source maintains the same output voltage regardless of how low the load may be, a constant current source maintains the same output current, regardless of the value of series resistor it may be feeding.

The constant current source feeds the resistor which is connected across the input terminals of the instrument. The constant current develops a voltage across the unknown resistor and this is measured by the meter circuit to give the value in "ohms". Simple.

In practice, the constant current source is a three-terminal semiconductor device, the National Seminconductor LM334. This is connected to a number of adjustable switchpots by S2b, on the main circuit diagram. These are adjusted to give four fixed currents of 4μA, 40μA, 400μA and 4mA.

Now we note another difference in the resistance measuring circuit. The resistor string connected to the inverting input of IC1 has been increased by the addition of 3.3kΩ (which is switched by S1d on the main circuit diagram). This additional resistor increases the input voltage for full-scale deflection to 4 volts (instead of 200mV, as before).

Combined with the four fixed currents noted above, this gives resistance measurement ranges of 1kΩ, 10kΩ, 100kΩ and 1MΩ.

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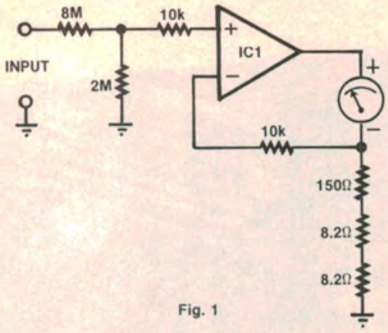


Fig.1: basic DC voltmeter. Input impedance is close to 10MΩ.

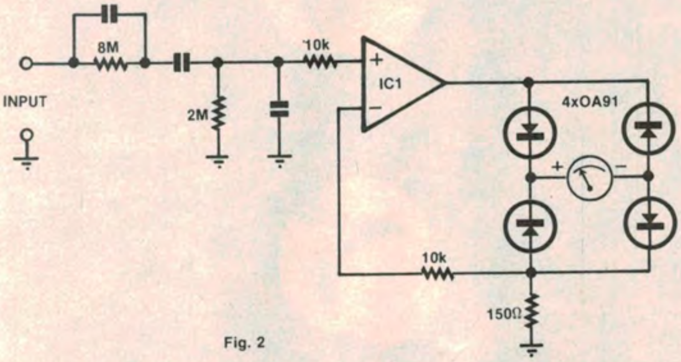


Fig.2: this is how the circuit is modified for AC voltage measurements.

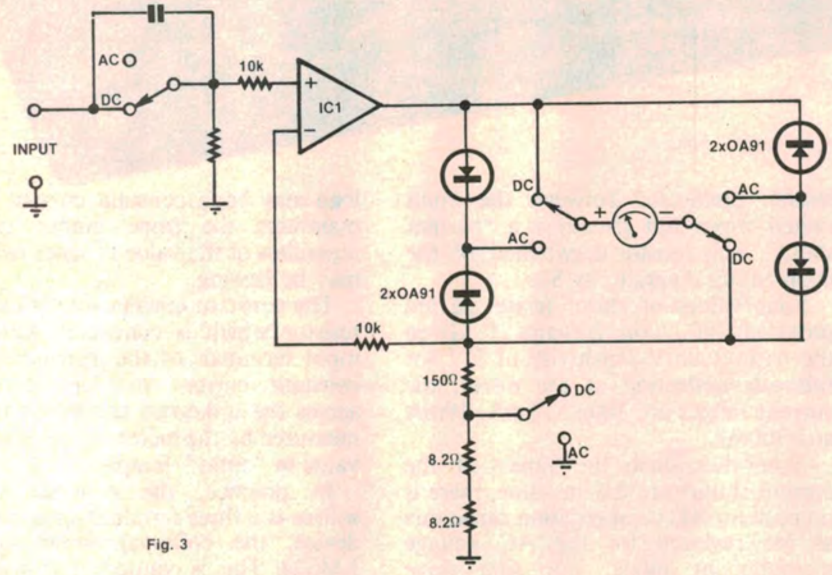


Fig.3: basic current measurement circuit. Note the shunt resistor on the input.

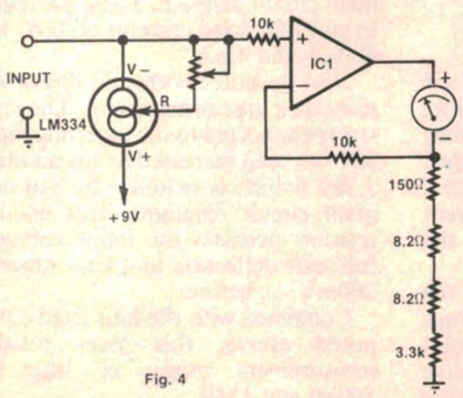


Fig.4: resistance measurements require a constant current source (LM334).

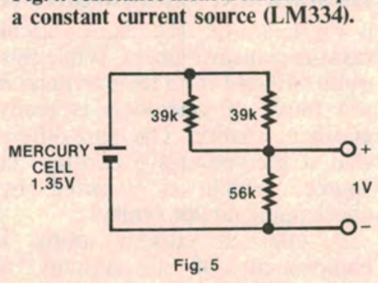


Fig.5: this accurate 1V reference uses a mercury cell and 1% resistors.

Note that the AC/DC switch (S3) must be in the DC position for a resistance measurement to be made. If S3 is in the AC position the meter pointer will be fully deflected.

Having explained each of the circuit functions in turn, there is not much left to discuss of the complete circuit

PARTS LIST

- 1 PCB, code 84vm10, 104 x 106mm
- 1 Scotchcal label, 191 x 107mm
- 1 plastic zippy case, 60 x 113 x 196mm
- 1 panel meter, 0-1 mA, 80 x 66mm
- 1 4-pole 3-position rotary switch
- 1 3-pole 4-position rotary switch
- 1 2-pole 2-position toggle switch
- 1 4-pole 2-position toggle switch
- 2 probe sockets, one red & one black, 4mm
- 1 set of probe test leads
- 2 9 volt transistor batteries + clips
- 2 knobs

Semiconductors

- 1 LF351, TL071, FET-input op amp
- 1 LM334 3-terminal adjustable current source
- 4 OA91 germainium diodes or similar
- 1 1N4148, 1N914 diode

Capacitors

- 2 100μF/16V PC electrolytic
- 1 0.1μF/600VW polycarbonate
- 3 0.1μF metallised polyester (greencap)
- 1 .01μF metalised polyester
- 1 .0047μF metallised polyester
- 1 .0015μF metallised polyester
- 1 470pF ceramic
- 1 150pF ceramic
- 1 47pF ceramic
- 1 68pF ceramic
- 1 10-40pF miniature ceramic trimmer

***Resistors** (1%, ¼W unless noted)*

1 × 4.7MΩ ½W, 1 × 3.3MΩ ½W, 1 × 1.5MΩ, 1 × 330kΩ, 1 × 130kΩ, 1 × 47kΩ, 1 × 20kΩ, 1 × 3.3kΩ, 1 × 1.8kΩ, 1 × 180kΩ, 1 × 150kΩ, 1 × 18kΩ, 2 × 8.2kΩ, 1 × 2kΩ.

***Resistors** (5%, ¼W)*

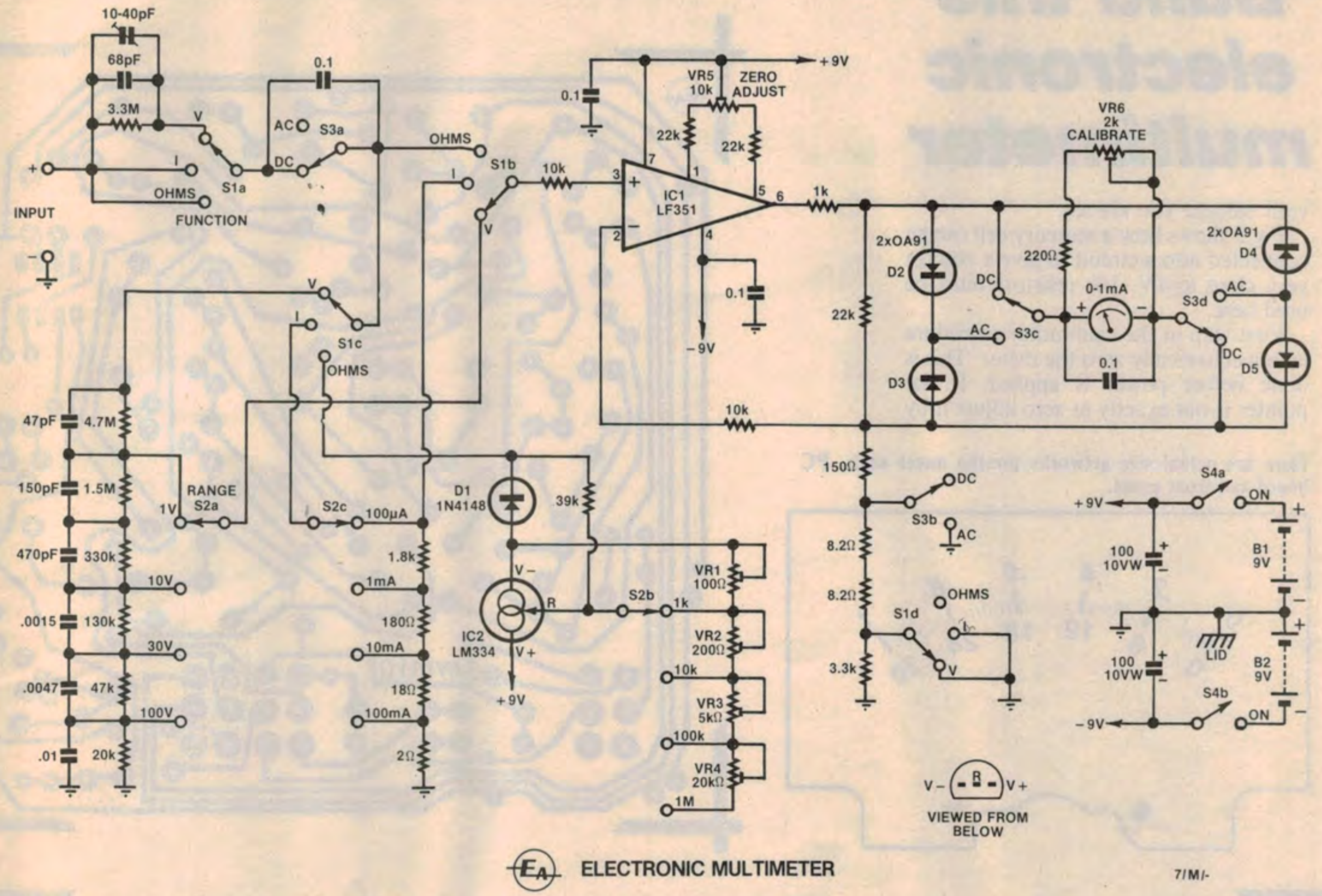
1 × 39kΩ, 3 × 22kΩ, 2 × 10kΩ, 1 × 1kΩ, 1 × 220kΩ,

Trimpots

1 × 20kΩ, 1 × 10kΩ, 1 × 5kΩ, 1 × 2kΩ, 1 × 200Ω, 1 × 100Ω

Miscellaneous

4 rubber feet, 1 battery bracket (aluminium strip 120 x 20mm), nuts & bolts, hook up wire, tinned copper wire, solder.



The circuit is essentially a combination of Figs.1-4, with some additional refinements.

diagram. There are some components which should be mentioned though. The first of these are the 10kΩ resistors in series with the input leads to the op amp, IC1. These are to prevent gross overload to the IC, in the event of the wrong range being selected.

Similarly, the 1kΩ resistor in series with the output, pin 6, of the op amp, is there in case the op amp is being overdriven and may be overdriving the meter as a result. The 1kΩ resistor limits the current to a safe value.

A trimpot network is connected between pins 1 and 5 of IC1 to provide a zero adjustment for the meter.

Finally, the 22kΩ resistor across the bridge rectifier is provided so that a feeback current always flows around IC1, even when the output voltage of the circuit is insufficient to make the diodes conduct.

Construction

Assembling this project is easy. All the parts, including the switches, are mounted on the printed circuit board which measures 104 x 106mm and is coded 84vm10.

First step in assembly is to install all the links and small components such as resistors and diodes. Note that most of the resistors are 1% types with only a few non-critical values being 5% tolerance.

With the small components installed, the capacitors, trimpots and switches can be mounted. Finally, the op amp and LM334 current source can be installed.

Calibration

This task must be performed before the PC board and meter is assembled into the case. You will need an accurate DC voltage source, an audio oscillator which can range up to 300kHz or more and a number of accurate resistors.

Perhaps the cheapest and most readily available accurate DC source is a mercury button cell, as used in many cameras and digital clocks. These cells have an output voltage of 1.35V over most of their operating life and cost only a few dollars. If you already have one in

Specifications

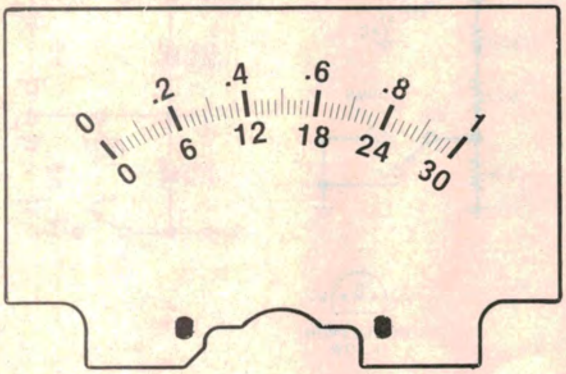
Voltage	
DC & AC ranges	1, 10, 30, 100V FSD
Input impedance	10MΩ//27pF
Accuracy	± 5% FSD for AC and DC
Bandwidth:	−3dB at 13Hz & 250kHz
Current	
DC & AC ranges	100μA, 1mA, 10mA, 100mA FSD
Input impedance	2kΩ, 200Ω, 20Ω, 2Ω
Accuracy:	± 5% FSD for AC and DC
Bandwidth:	−3dB at 25Hz & 75kHz
Burden voltage:	200mV
Resistance	
Ranges	1kΩ, 10kΩ, 100kΩ, 1MΩ
Accuracy	± 5% FSD

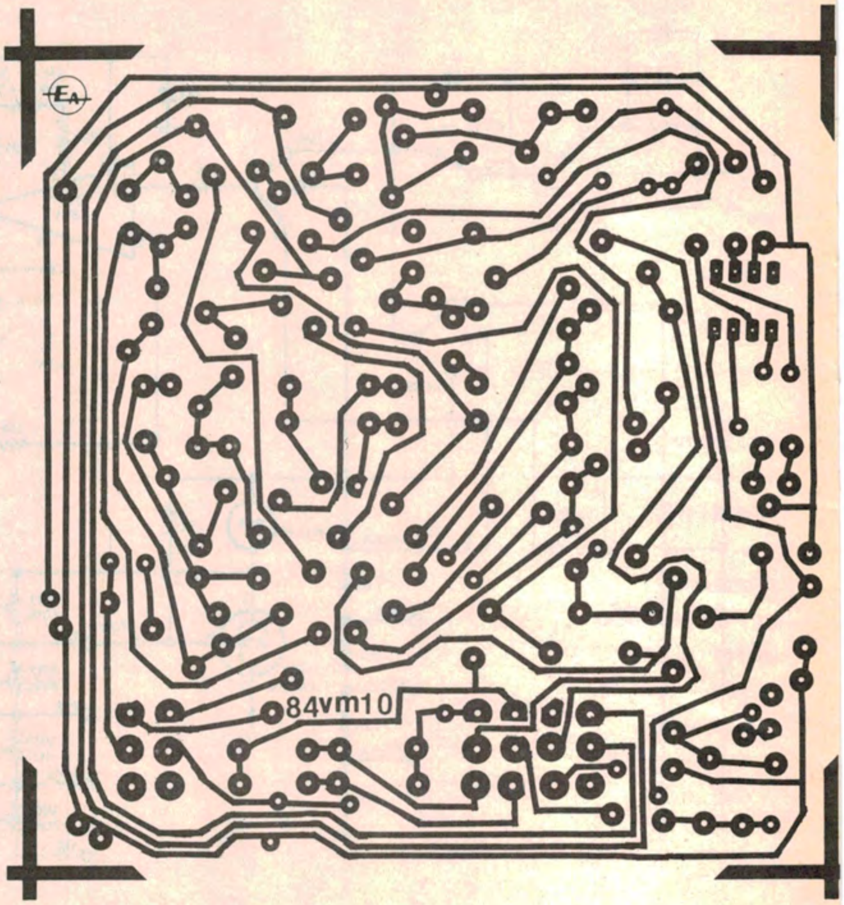
your camera you are set.

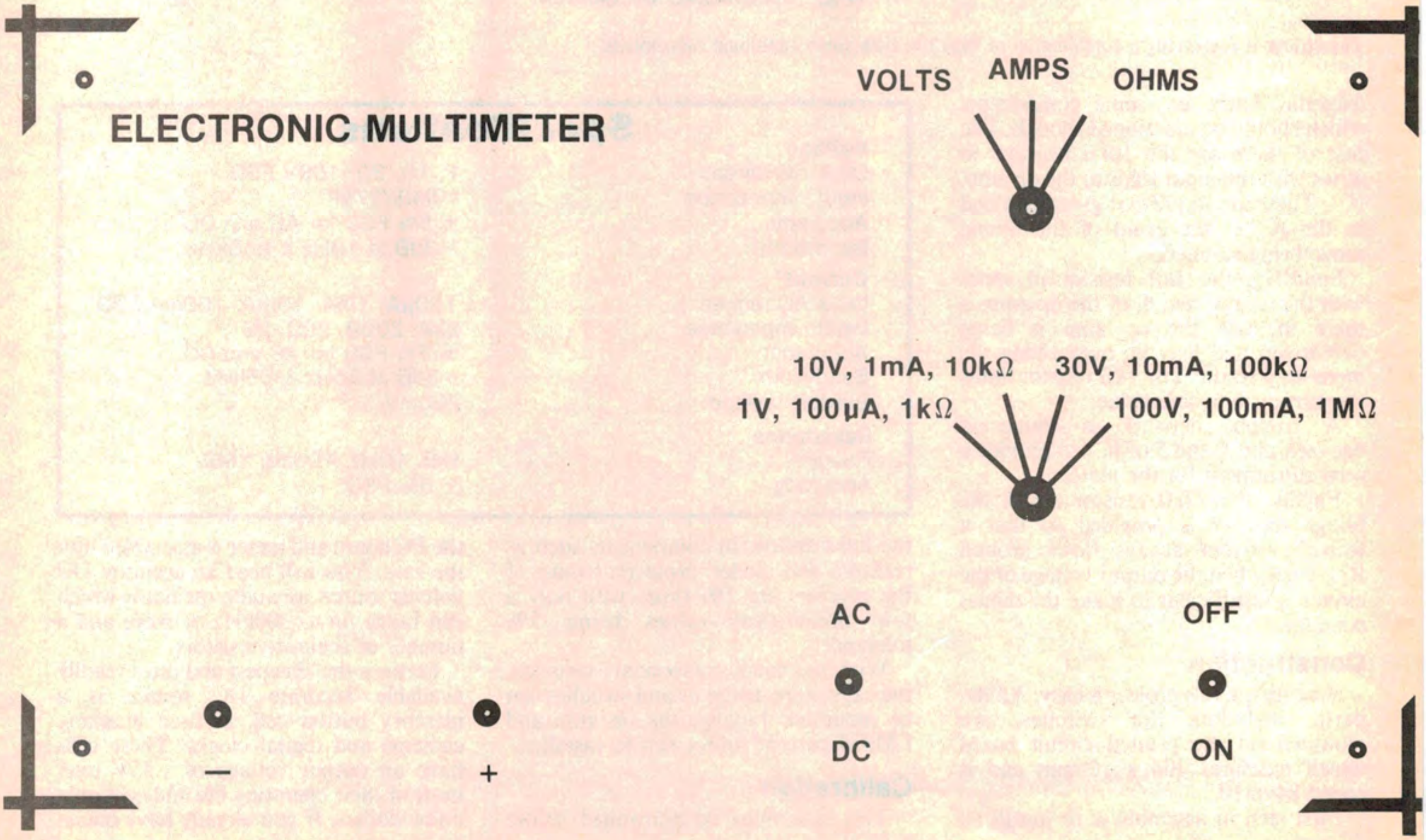
Fig.5 shows how a mercury cell can be connected into a circuit to give a voltage very close to 1V. 1% resistors must be used here.

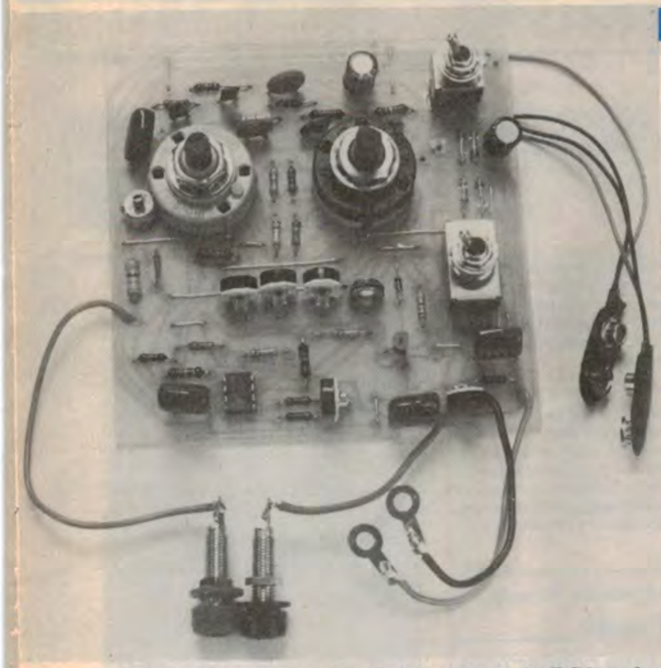
First step in the calibration procedure is to mechanically zero the meter. This is done before power is applied. If the pointer is not exactly at zero adjust it by

Here are actual size artworks for the meter scale, PC board and front panel.

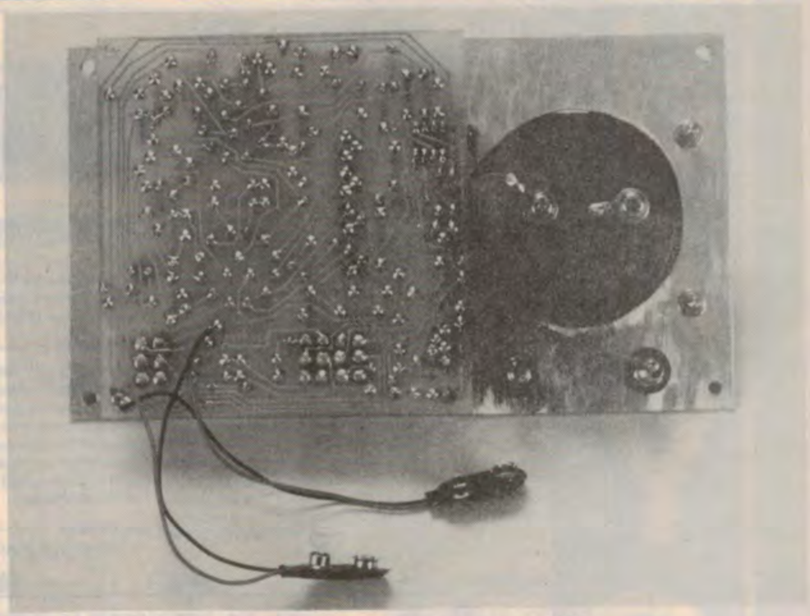




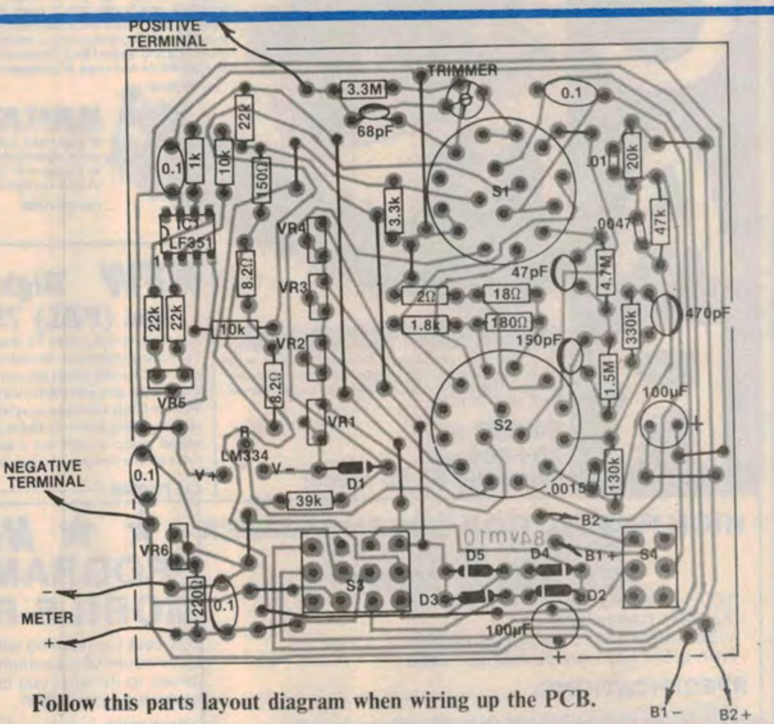




Most of the parts are mounted directly on the PC board.



The PC board is supported on the front panel by the switches.



Follow this parts layout diagram when wiring up the PCB.

turning the plastic screw on the front of the meter case.

Now turn the power on with the function switch selected to "volts". If the needle is no longer pointing to zero, use the zero adjust trimpot near the op amp to zero the needle. Once the needle is zeroed, apply a known DC voltage (see Fig.5) and check the performance of the multimeter. If the multimeter continues to read zero, you may have the AC/DC switch set to AC.

Note that only one calibration adjustment is provided for AC and DC volts. If you have an audio oscillator you can use it to set the compensation trimmer. Set the oscillator to around 1kHz or so and set the meter range to suit the output of the oscillator which should be ideally around 10 volts.

Now you engage in a repetitive procedure to obtain the flattest and most extended AC frequency response. Set the oscillator to a frequency of around 200kHz and adjust the trimmer to give the same reading as at 1kHz. (We assume that the oscillator has a constant output over its whole operating range). Now increase the oscillator to 300kHz and check that the meter reading is the same and not higher.

Try adjusting the trimmer to give the same result as at 1kHz and 200kHz but note that if you over-compensate the reading at 200kHz it will be higher than that at 1kHz and 300kHz. A number of spot checks will be necessary to obtain the flattest and most extended response.

We are now ready to carry out the final setting of the multimeter. What we are going to do now is trim the four current setting trimpots. For this you will need four resistors: 1kΩ, 10kΩ, 100kΩ and a 1MΩ. Note that the ultimate accuracy of the multimeter is determined by the tolerance of the resistors you use for this exercise.

Set the multimeter to ohms measurement and the range to 1kΩ. Make sure the AC/DC switch is selected to DC. Now attempt to measure the resistance of the 1kΩ resistor. Using a screwdriver, adjust VR1 to give fsd (full-scale deflection). Next switch the range to 10kΩ and insert the 10kΩ resistor between the probes of the multimeter. Adjust VR2 to give fsd. Repeat the process for the 100kΩ and 1MΩ ranges (ie, VR3 and VR4).

Final assembly

When the calibration has been performed, the meter may be assembled into the case along with the PC board. Before that can be done the Scotchcal label (if you have made or purchased one) should be affixed to the lid of the zippy box. With that done, you will have to drill the front panel holes and make the meter cut-out.

Use the wiring diagram as a guide to help in the final assembly and wiring. The order of assembly is to mount the meter first, then the PCB and lastly the probe sockets.