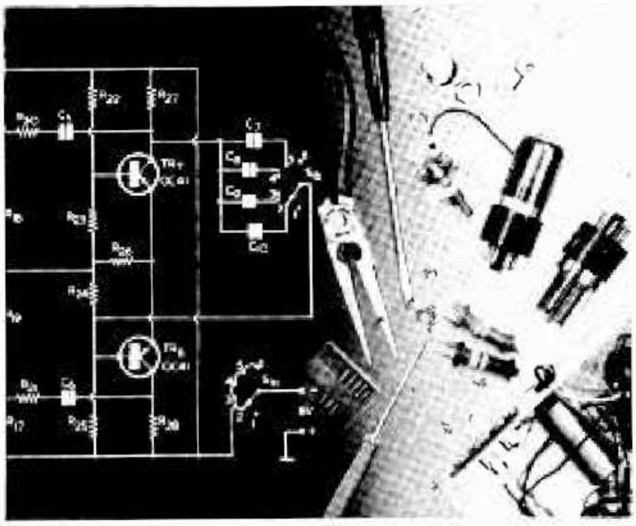
D.C. VOLTMETER



by G. A. FRENCH

THE DEVICE WHICH FORMS THE subject of this month's 'Suggested Circuit' article is a d.c. voltmeter having a sensitivity of 200kΩ per volt. This is, of course, a much higher sensitivity than is provided by a standard testmeter, and it corresponds to a current, at full-scale deflection, of 5μA. A feature of the circuit is that it can be made up, in one version, with standard 5% resistors in the input section. It incorporates a readily obtainable integrated circuit operational amplifier.

CIRCUIT PRINCIPLE

To appreciate the basic manner in which the voltmeter functions it will be helpful to commence by examining Fig. 1(a). This diagram shows an operational amplifier, depicted by the triangle, with connections applied to it under theoretical conditions. The inverting input is identified by a minus sign and the non-inverting input by a plus sign, whilst the output appears at the right-hand apex of the triangle. R2 is a resistor applying negative feedback to the inverting input of the op-amp and R1 is a resistor in series between this inverting input and the input to the complete circuit. It is assumed that the source of input voltage has zero internal resistance. Under these conditions the voltage gain offered by the complete circuit is R2 divided by R1.

In Fig. 1(b) we use the circuit of Fig. 1(a) to function as a voltmeter. Across the output from the op-amp is connected a current reading meter in series with a pre-set variable resistor, the pre-set resistor being set up such that the meter reads full-scale deflection when the voltage at the op-amp output is 1 volt. R2 and R1 are given the values shown. Since both these resistors have the same value, R2 divided by R1 becomes equal to unity, and the voltage gain of the complete circuit is similarly unity. If, therefore,

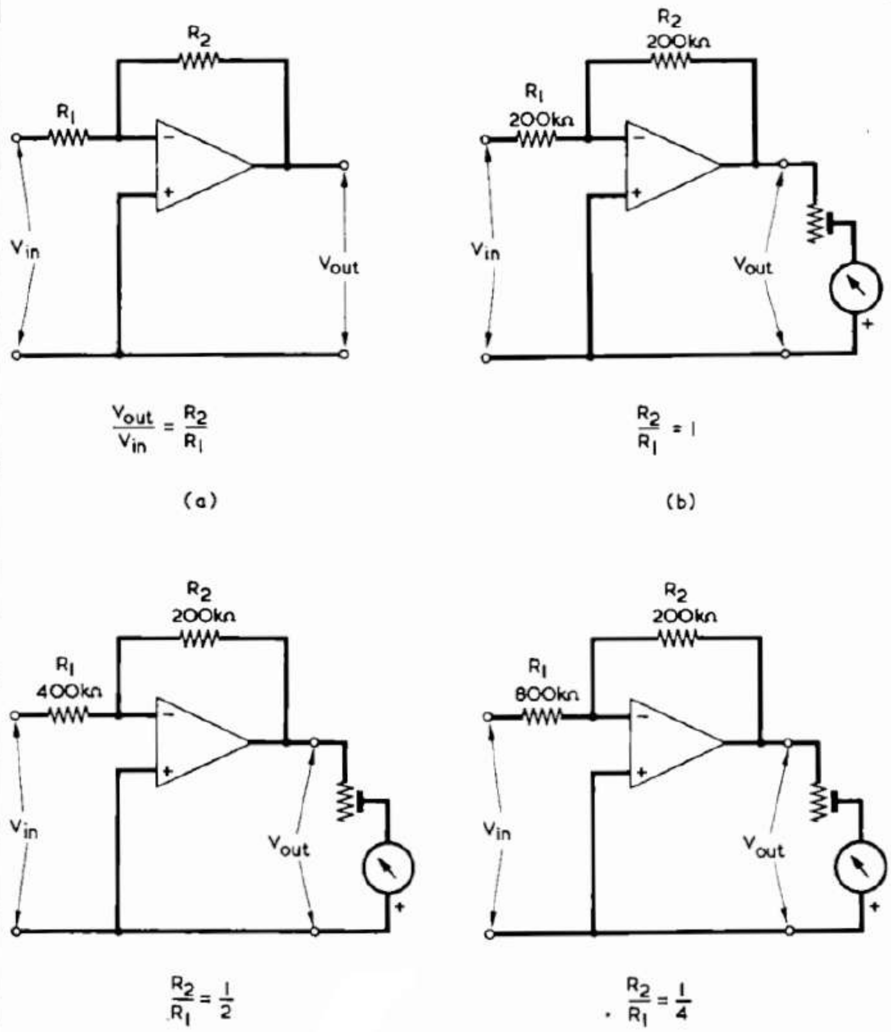


Fig. 1 (a). Basic operational amplifier circuit with feedback
(b). Amplifier circuit offering a voltage gain of unity
(c). An amplifier whose voltage gain is one-half
(d). Here, the voltage gain is one-quarter

we apply a voltage of 1 volt to the input, the output will also be 1 volt, and the meter will read full-scale deflection. The polarity of the input voltage is such that the upper input point is positive. Since this point is coupled to the inverting input of the op-amp, the op-amp output will be negative. This output polarity corresponds with the polarity ascribed to the meter in Fig. 1(b).

We turn next to Fig. 1(c), in which the conditions are the same as before, except that R1 has been increased to 400kΩ. R2 divided by R1 and, hence, the voltage gain of the circuit, is now one-half, and it follows that an input voltage of 2 volts will cause an f.s.d. reading to be given in the meter. In Fig. 1(d) R1 is increased to 800kΩ, whereupon the gain of the complete circuit becomes equal to one-quarter. The input voltage which produces f.s.d. in the meter is now 4 volts.

It will be obvious that we have, in Figs. 1(b), (c) and (d), an embryo voltmeter having a sensitivity of 200kΩ per volt. As has been demonstrated, the voltmeter is capable of giving an f.s.d. reading for any input voltage provided that the value of R1, in kilohms, is 200 times that voltage. A further point which may now be taken into consideration is that the inverting input of the op-amp is a 'virtual earth', since its potential varies by a negligible amount despite large shifts in the input voltage applied to the complete circuit. The circuit becomes, in consequence, a true voltmeter because the right hand end of R1 terminates in a point which is, to all intents and purposes, connected to the lower input terminal by zero resistance. The circuit responds, nevertheless, to the current which flows in R1, and this current is the applied voltage divided by R1.

It is assumed here that, for zero input and zero output voltage, the inverting input of the op-amp is at the same potential as the non-inverting input. In practice there is a small offset voltage but, with the integrated circuit which is employed in the practical version, this is of the order of a few millivolts only, and should not noticeably influence circuit operation.

Brief mention of a minor point of detail may be included here for the benefit of newcomers to voltmeters of this nature. It was said, when Fig. 1(d) was discussed, that an applied voltage of 4 volts results in an f.s.d. reading in the meter. An input voltage of 2 volts will result in a half f.s.d. reading, and an input voltage of 1 volt will give a reading of a quarter of f.s.d. Thus, the arrangement of Fig. 1(d) is capable of measuring all voltages up to 4 volts. Similarly, the arrangement of Fig. 1(c) can measure voltages up to 2 volts and that of Fig. 1(b) voltages up to 1 volt.

Returning to the main theme, we may next consider R2. At first sight it might appear that this needs to be a close tolerance component, but such is not the case and a standard 5% resistor will be quite suitable here. If the resistor employed happens to be, say, on the upper limit of its tolerance, at 210kΩ, all the gain figures shown in Figs. 1(b), (c) and (d) become multiplied by a factor of 210 divided by 200. This discrepancy is taken up, quite simply, by adjusting the variable resistor in series with the meter accordingly. The variable resistor now becomes a 'Calibrate' component. The circuit of Fig. 1(b) could then be used to set it up, a known voltage of 1 volt being applied to the input of the complete circuit and the variable resistor then adjusted to give an f.s.d. reading in the meter. The circuit will still, under these circumstances, give its 200kΩ per volt performance. It is possible, even, to dispense with close tolerance resistors in the R1 position, the variable resistor in series with the meter being again adjusted to take up any discrepancies introduced thereby. This point is discussed at the end of the article, when a second version of the input circuit is discussed.

A final design point is concerned with that fact that it has been assumed up to now that the device, functioning as a voltmeter, gives an f.s.d. reading in the meter when the output voltage from the op-amp is nominally 1 volt. This assists in the explanation because it enables simple figures to be employed. But it would be possible to adjust the variable resistor in series with the meter to a setting which gave an f.s.d. reading for 0.5 volt, 2 volts, 5 volts or any other voltage, within reason, at the output of the op-amp. The complete circuit would still be capable of functioning as a voltmeter although, of course, it would then be necessary to recalculate the value of R2 to obtain an input sensitivity figure of 200kΩ per volt. It so happens, however, that in addition to easing the description of circuit operation, the nominal 1 volt figure represents a satisfactory practical value to work to, and it also enables a simple meter protection circuit incorporating two silicon diodes to be employed.

WORKING CIRCUIT

The full working circuit of the voltmeter is given in Fig. 2. In this diagram R1 of Fig. 1 is replaced by whichever of R1 to R4 is switched in by the Range switch S1. R2 of Fig. 1 reappears in Fig. 2 as R7. The pre-set variable resistor and meter are now given by VR2, R8, R9 and M1. The two silicon diodes just mentioned are D1 and D2.

The integrated circuit is an ML741C and the numbers around its outline correspond to the 14 pin dual-in-line tag layout shown in the inset. Pin 4 of the i.c. is the inverting input and pin 5 the non-inverting input. Pin 11 is the connection for the positive supply and pin 6 is the connection for the negative supply. The similarity with Fig. 1 becomes very noticeable when it is remembered that the only major change introduced in Fig. 2 is the introduction of the battery supply which, of course, the i.c. must have in any case if it is to operate. The non-inverting input at pin 5 is not now returned to the 'zero line' as in Fig. 1, but to the potentiometer given by R5, VR1 and R6 connected across the supply lines. VR1 is the Set Zero control and it is adjusted for a zero reading in the meter when there is no input voltage at the test terminals, thereby causing the circuit to be balanced and taking up such things as differences in the voltages of the two batteries.

S1 provides four ranges, these being 0-1V, 0-2.5V, 0-10V and 0-25V. The corresponding series input resistors have values of 200kΩ, 500kΩ, 2MΩ and 5MΩ respectively. These values are each 200kΩ multiplied by the f.s.d. voltage figure of the corresponding range. Should it be desired to have ranges in the series 0-1V, 0-3V, 0-10V, etc., the series resistor for the 0-3V

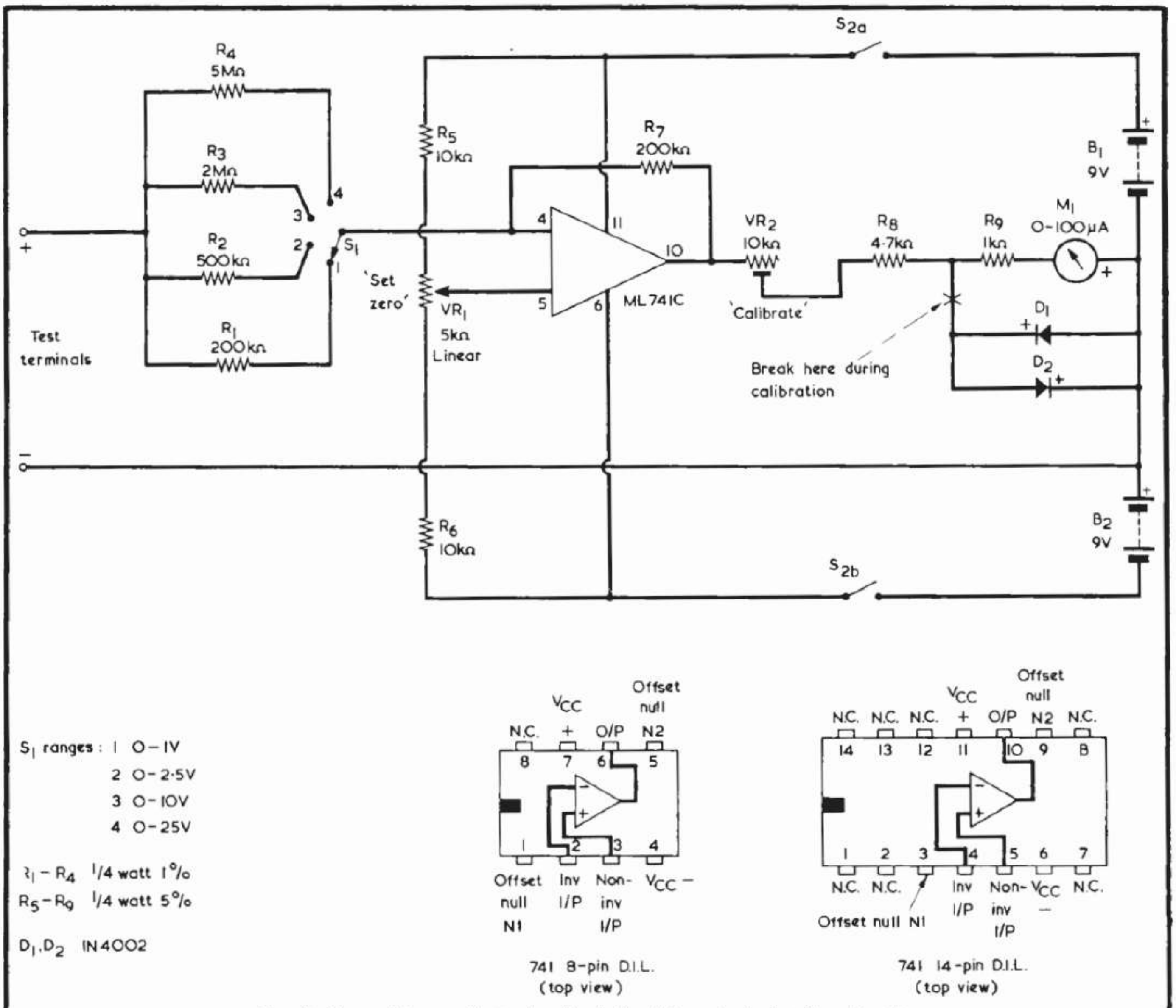


Fig. 2. Complete working circuit of the integrated circuit voltmeter

range would be 600kΩ. Any other ranges within reason can be incorporated by employing the appropriate multiplying factor for the series resistance required. In this version of the input switching circuit the series resistors should all have a tolerance of 1%.

In the meter section, diodes D1 and D2 provide protection when the voltage across the meter and R9 approaches the voltage at which forward conduction in the diodes takes place.

The ML741C integrated circuit was obtained from Henry's Radio, Ltd., by which firm it is advertised as a '741C (DIL)'. This i.c. has the 14 pin dual-in-line pin configuration shown, the rectangular identifying point between pins 1 and 14 being replaced by a paint dot. Other integrated circuits of the 741 type, such as SN72741, μA741, etc., could be employed instead, but it should be mentioned that the author has only checked the circuit with the i.c. obtained from Henry's Radio. Some versions of the 741 are available in 8 pin d.i.l. and the tag layout of this type is included in Fig. 2. Note that both tag layouts are top views, with the pins pointing away from the reader.

The 741 is a development from the earlier 709 op-amp, and it is a particularly useful i.c. for amateur experimental and constructional projects since it has its own internal compensation and does not require any external capacitors to maintain stability. ('Compensation' defines the process where capacitance is employed to prevent instability in an i.c. due to excessive amplification at high frequencies). As will be seen from Fig. 2 it is necessary to make only five connections to the i.c. Also, the only components external to the i.c. are those which are directly involved in voltmeter operation. It is, incidentally, possible to obtain fine control of offset voltage by suitably connecting a potentiometer to the two 'offset null' pins, but this is not needed in the present design and no connections are made to these pins.

COMPONENTS AND CONSTRUCTION

Of the components, the series input resistors and the integrated circuit have already been discussed. VR1 is a panel-mounted potentiometer, whilst VR2 is a pre-set skeleton component. S2(a) (b) should be a double-pole toggle switch. The current drawn from each battery is 2mA only, and any small 9 volt batteries can be employed. They should be of the same type and both should be discarded at the same time when exhausted. The voltmeter should not be operated with one battery new and the other nearly exhausted. Diodes D1 and D2 can be any small silicon diodes or rectifiers. The author employed 1N4002's, which happened to be on hand.

All the components may be housed in a small case with VR1, S1, S2, M1 and the test terminals on the front panel. Wiring layout is not critical provided that R7 is fitted close to the i.c., and the i.c. output lead does not too closely approach the wiring to the two i.c. inputs. The connection between the junction of R8 and R9 and the junction of the positive lead-out of D1 and the negative lead-out of D2 should be of a temporary nature, as it is broken during the process of calibration. The author found it helpful to employ a d.i.l. holder for the i.c., wiring this up first and then inserting the i.c.

Calibration of the completed unit consists of checking it against another voltmeter, using the method shown in Fig. 3. In this diagram, the potentiometer should have a value which causes some 5 to 10mA to flow through its track. Thus, with a 12 volt battery the potentiometer could have a value of 2kΩ. Any suitable range is selected by S1 and the i.c. voltmeter is then switched on with VR1 slider at mid-track. VR1 is next adjusted for zero reading in the meter with the two test terminals short-circuited. The test terminals of the i.c. are then applied to the potentiometer shown in Fig. 3, after which that potentiometer is adjusted to give the f.s.d. value of the range selected, as indicated by the monitoring voltmeter. VR2 is then adjusted for f.s.d. in the i.c. voltmeter. After one range has been set up in this manner, all the other ranges will be correct.

Next, the i.c. voltmeter is switched off and D1 and D2 are disconnected from R9 and M1 as indicated in Fig. 2. The i.c. voltmeter is then switched on again. If the meter gives the same reading as before, all is well, and no further action is required other than the permanent connection of D1 and D2 into the circuit. If on the other hand, the meter gives a higher reading with D1 and D2 disconnected, the value of R9 will have to be reduced experimentally until D1 and D2 have no effect on meter reading. Each change in the value of R9 necessitates a re-setting of VR2. The check with D1 and D2 is desirable because a few 0-100μA meters have relatively high internal resistance, and the voltage dropped across the meter and R1 may conceivably just fall within the level at which some diodes commence to pass forward current. It is improbable that this effect will be present in most units made up to the circuit, but it is worthwhile carrying out the check nevertheless.

ALTERNATIVE INPUT CIRCUIT

As was mentioned earlier, it is possible to dispense with close tolerance resistors in the input circuit, as discrepancies from the nominal resistance can be taken up by adjustment of the Calibrate potentiometer, VR2. An alternative input circuit employing 5% fixed resistors is illustrated in Fig. 4. The three pre-set potentiometers in this circuit may all be skeleton types.

The circuit of Fig. 4 is set up by selecting Range 4 and connecting the unit to a source of voltage, monitored by another voltmeter as in Fig. 3, which is equal to f.s.d. value (i.e. 25V) on this range. VR2 is then set up for full-scale deflection in the meter. The test voltage is then reduced to the f.s.d. value for Range 3, Range 3 is selected, and the pre-set potentiometer in the Range 3 input circuit adjusted for an f.s.d. reading. The process is repeated with Range 2 and Range 1, after which the setting of the voltmeter is complete.

With the input circuit of Fig. 4, the input resistance of the i.c. voltmeter is not exactly 200kΩ per volt but only nominally so. If it should happen that the 5MΩ resistor is on the lower limit of its tolerance, at −5%, then the input resistance is 200kΩ −5% per volt.

If ranges other than those shown in Fig. 4 are to be used, the values shown in this diagram may be changed accordingly. The single fixed series resistor in the input circuit should be that which is selected on the highest voltage range, since this means that the pre-set potentiometers will then, assuming a reasonable choice of ranges, be required to have values of 1MΩ or less.

It should be mentioned that it may be a little difficult to obtain close tolerance 1% resistors having values higher than 1MΩ, whereupon some of the resistors in the input circuit of Fig. 2 will need to be made up of a number of single close tolerance resistors in series. The alternative input circuit of Fig. 4 may, in consequence, be more attractive than that of Fig. 2, even though it does require three pre-set potentiometers.

The experienced constructor with a good stock of resistors may be able to make up the lower range series resistors in Fig. 4 by experimental selection, if necessary 'trimming up' individual resistances by inserting small value resistors in series. This process dispenses with the pre-set potentiometers.

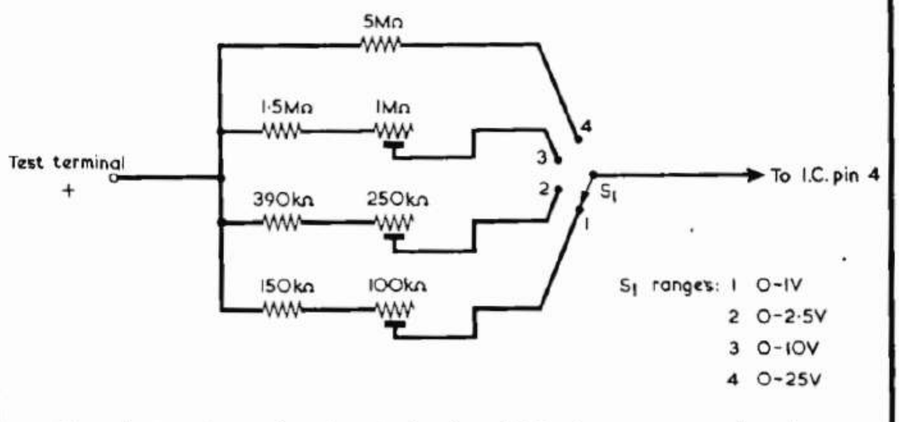


Fig. 4. An alternative input circuit which does not require close tolerance resistors

RESULTS WITH THE PROTOTYPE

The prototype circuit gave an acceptable performance with good linearity over each range. It was found that the Zero Set control did not have to be re-set frequently, this being particularly the case when the batteries had settled down to a steady voltage, as opposed to the high voltage given in the brand-new state. Although it is preferable to have the test terminals short-circuited when adjusting the Zero Set control, it was found that this was not essential and that the meter reading remained at zero after the short-circuit had been removed. This indicates a high level of basic stability in the circuit, a factor which is not always evident in what are sometimes described as 'electronic voltmeters'.

As was stated earlier, the current drawn from each battery was 2mA only. ■

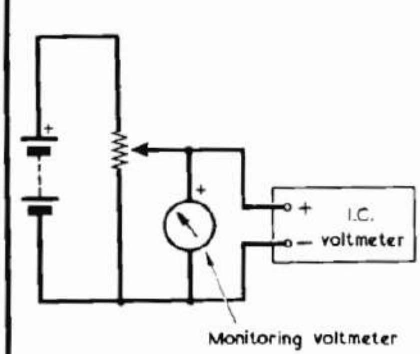


Fig. 3. The set-up required for calibration