25 INSTRUMENTATION PROJECTS

Operational amplifiers can be used in a variety of instrumentation circuit applications. They can be used as precision voltage sources, as variable voltage supplies, as stabilised power supply units, and as precision rectifiers and a.c./d.c. converters. When used in conjunction with moving coil meters they can be made to function as d.c. and a.c. voltmeters and millivoltmeters, as d.c. microammeters, as linear-scale ohmmeters, and as linear-scale capacitance meters.

Twenty-five useful op-amp instrumentation projects of various types are described in the present chapter. All of these projects are designed around the popular type 741 integrated-circuit op-amp, and the pin connections shown in the following diagrams apply to the 8-pin dual-in-line version of this device only.

Precision voltage source circuits

Electronics laboratories often need a precision voltage reference or source for calibrating instruments accurately. A Weston standard cell generates an accurate potential of 1.018 V, and is useful as a voltage standard. These cells normally have an output impedance of one or two kilohms, however, and this relatively high output impedance makes the devices unsuitable for use as precision voltage sources at output currents in excess of one microamp or so. *Figure 3.1* shows a circuit that overcomes the basic disadvantage of the Weston cell, and enables it to be used as a precision voltage source at currents up to several milliamps.

The op-amp in the *Figure 3.1* circuit is connected as a unity-gain voltage follower, with the Weston cell connected directly to its positive input terminal. The op-amp has a very high input impedance in this application, and typically draws only 0.03 μA from the Weston cell, but has an output impedance of virtually zero and can provide output currents up to 5 mA or so. Thus, the circuit gives a precision output of 1.018 V, and can supply currents up to about 5 mA.

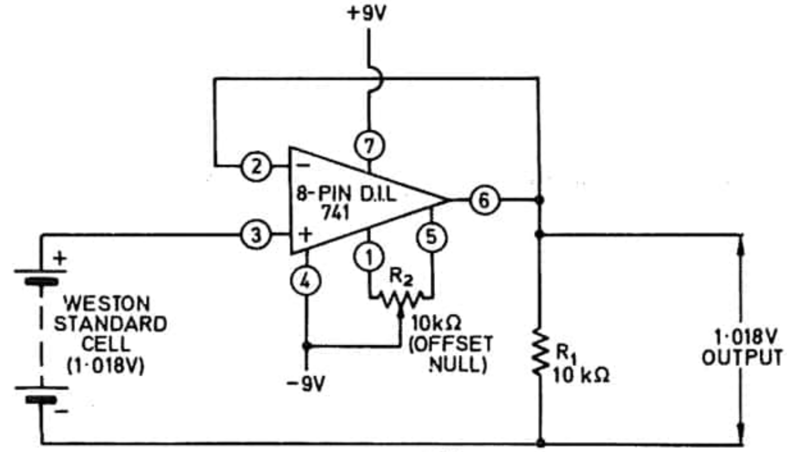


Figure 3.1. Precision voltage source.

If required, the output current capability of the circuit can be boosted by wiring an emitter follower stage in series with the op-amp output, as shown in the precision voltage source circuit of *Figure 3.2*. Note that the base-emitter junction of the emitter follower is in series with the op-amps negative feedback loop, so the junction does not inhibit the voltage following action of the circuit.

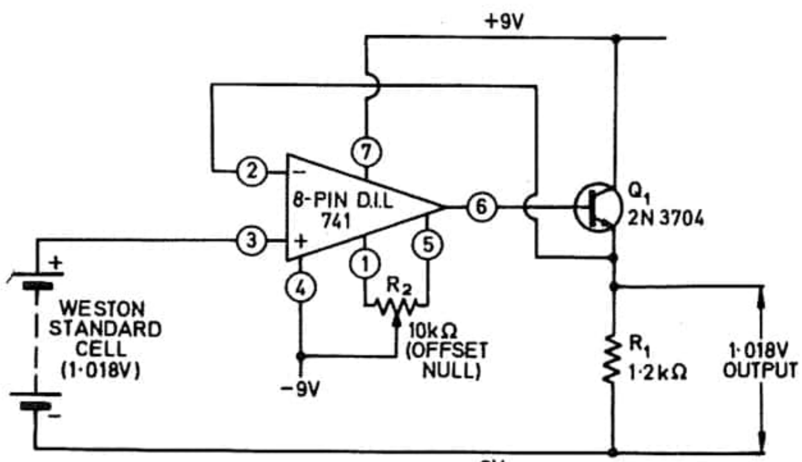


Figure 3.2. Precision voltage source with boosted output.

Also note that a 10 kΩ offset null control is used in both of these precision voltage source circuits. This control is used to ensure precise tracking of the input and output voltages, and is simply set to give zero voltage differences between the positive input and the output terminal of the op-amp with the Weston cell connected in place. If output voltage errors of a few millivolts can be tolerated, the offset null control can be eliminated from the circuit.

Normally, the *Figure 3.1* or *3.2* circuits should be built into a small box, complete with battery power supply and on-off switch, but with the Weston cell connected to the circuit externally via a pair of input terminals. In this case the cell should not be connected to the circuit until after the on-off switch controlling the op-amp has been turned on. If preferred, however, the Weston cell can be enclosed in a box with the rest of the circuit, but in this case a switch should be wired in series between the Weston cell and the positive terminal of the op-amp and ganged to the main on-off switch, so that the cell is automatically disconnected when power is removed from the op-amp.

Variable power supply circuits

Op-amps can be made to function as high-performance variable power supply circuits in a number of alternative ways. One simple way of making an op-amp function as a variable power supply is shown in *Figure 3.3*. This circuit gives an output that is fully adjustable from 0V to 12 V at currents up to a maximum of about 50 mA.

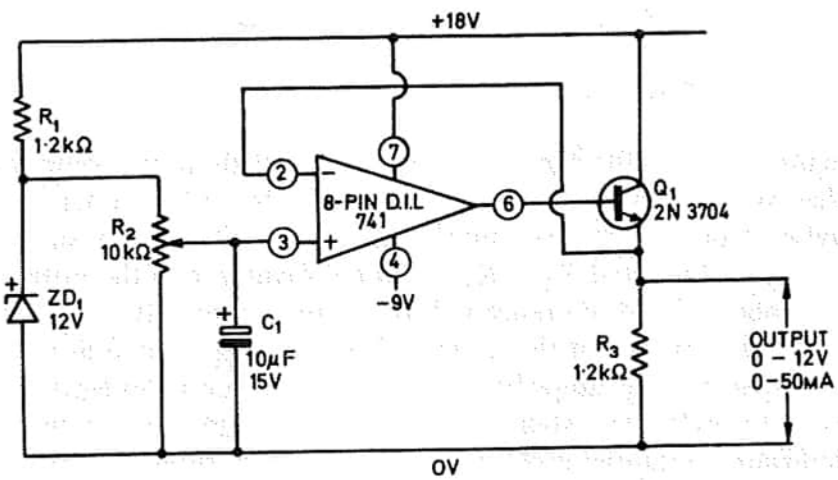


Figure 3.3. **Simple variable-voltage supply.**

The operation of the *Figure 3.3* circuit is quite simple. ZD_1 is a zener diode, and is energised from the positive supply line via R_1. A constant reference potential of 12 V is developed across the zener diode, and this voltage is fed to variable potential divider R_2. The output of the potential divider is fully variable from 0V to 12 V, and is fed to the positive input terminal of the op-amp. The op-amp is wired as a unity-gain voltage follower, with Q_1 connected as an emitter follower current-booster stage in series with the output. Thus, the output voltage of the circuit follows the voltage set at the positive terminal via R_2, and is fully variable from

0V to 12 V. Note that this particular circuit uses an 18 V positive supply and a 9 V negative supply.

An alternative type of variable power supply circuit is shown in *Figure 3.4*. The output of this circuit is fully variable from + 3 V to + 15 V, at currents up to a maximum of about 50 mA. Although the output of the circuit is not fully adjustable down to 0 V, the circuit has the great advantage of using only a single 18 V positive supply.

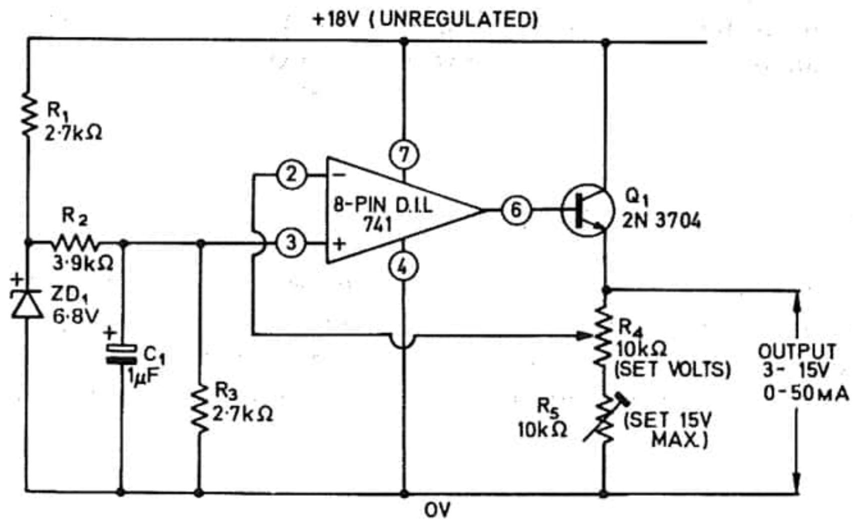


Figure 3.4. Simple 3 V - 15 V variable supply.

The operation of the *Figure 3.4* circuit is slightly more complicated than that of *Figure 3.3*, and is as follows. ZD_1 is a 6.8 V zener diode, and is energised from the positive supply line via R_1. The output of the zener diode is fed to the fixed $R_2 - R_3$ potential divider, and the potential divider applies a fixed reference voltage of approximately 3 V to the positive input terminal of the op-amp. The op-amp is wired as a variable-gain non-inverting d.c. amplifier, with Q_1 connected as an emitter follower current-booster stage in series with its output, and with variable gain-determing potential divider $R_4 - R_5$ wired between the emitter follower output and ground.

With the slider of R_4 set to the Q_1 emitter position, the amplifier operates with 100 % negative feedback, and thus gives unity-gain: under this condition the amplifier acts as a voltage follower, and gives an output of 3 V, i.e., the same potential as the reference voltage that is applied to its positive input terminal. With the slider of R_4 set to the $R_4 - R_5$ junction, the amplifier operates with reduced negative feedback, and gives a voltage gain of approximately x 5: under this condition the circuit gives an output of 15 V, i.e., 5 times the 3 V reference voltage. In practice R_5 is pre-set so that the circuit gives a maximum output of 15 V, and the output is then fully variable via R_4 from 3 V to 15 V at currents up to 50 mA. Since the gain-determing $R_4 - R_5$ potential divider is fed directly from the units output terminal, the output voltage of the circuit is fully stabilised and is virtually unaffected by variations in output load current.

A number of useful modifications and improvements can be made to the simple variable supply circuit of *Figure 3.4*. The regulation of the output voltage, for example, depends on the precision of the reference voltage that is applied to the positive input terminal of the op-amp. In the *Figure 3.4* circuit the reference voltage is simply derived from a zener diode that is energised from the unregulated 18 V supply line. One improvement, therefore, is to feed the zener diode from a pre-regulated supply, and so improve the precision of the reference voltage. Other improvements that can be made are to boost the output current capability of the circuit by replacing Q_1 with a super-alpha-connected* pair of power transistors, and to boost the output voltage range of the circuit by using a higher voltage supply.

Figure 3.5 shows the practical circuit of a variable power supply that incorporates all three of these improvements and modifications. The circuit is capable of providing output voltages that are fully variable from 3 V to 30 V at currents up to 1 A.

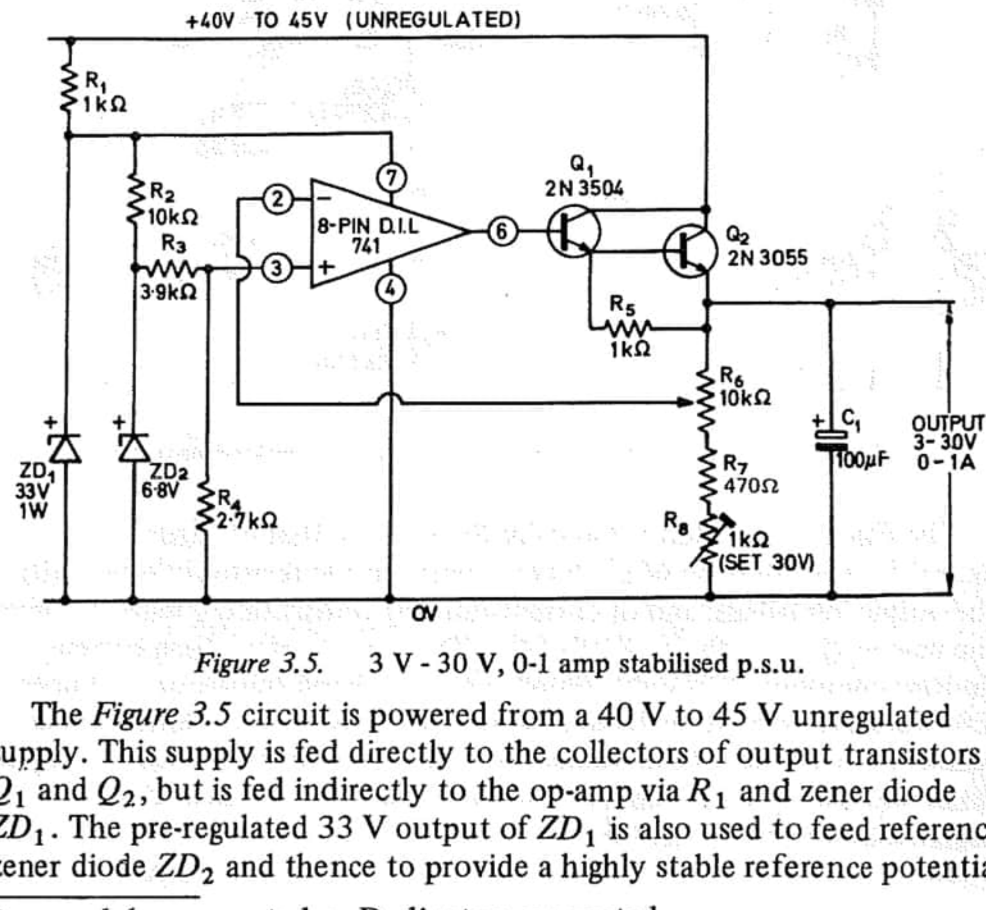


Figure 3.5. 3 V - 30 V, 0-1 amp stabilised p.s.u.

The *Figure 3.5* circuit is powered from a 40 V to 45 V unregulated supply. This supply is fed directly to the collectors of output transistors Q_1 and Q_2, but is fed indirectly to the op-amp via R_1 and zener diode ZD_1. The pre-regulated 33 V output of ZD_1 is also used to feed reference zener diode ZD_2 and thence to provide a highly stable reference potential

*super-alpha-connected or Darlington connected of 3 V to the positive input terminal of the op-amp via potential divider $R_3 - R_4$. Transistors Q_1 and Q_2 are super-alpha connected in series with the output of the op-amp, and the transitor/op-amp combination is connected as a variable-gain non-inverting d.c. amplifier, with gain control via variable potential divider $R_6 - R_7 - R_8$. The potential divider enables the gain of the amplifier to be varied between unity and x 10. The output voltage of the circuit can thus be varied between 3 V and 30 V, at currents up to 1 A, and is fully stabilised.

A major weakness of the *Figure 3.5* circuit is that it has no short-circuit protection, and the circuitry may be damaged if a short occurs across the output terminals. One way around this snag is to fit a fuse in series with the output, but a far better solution is to fit the circuit with electronic short-circuit protection, as shown in the stabilised power supply circuit of *Figure 3.6*.

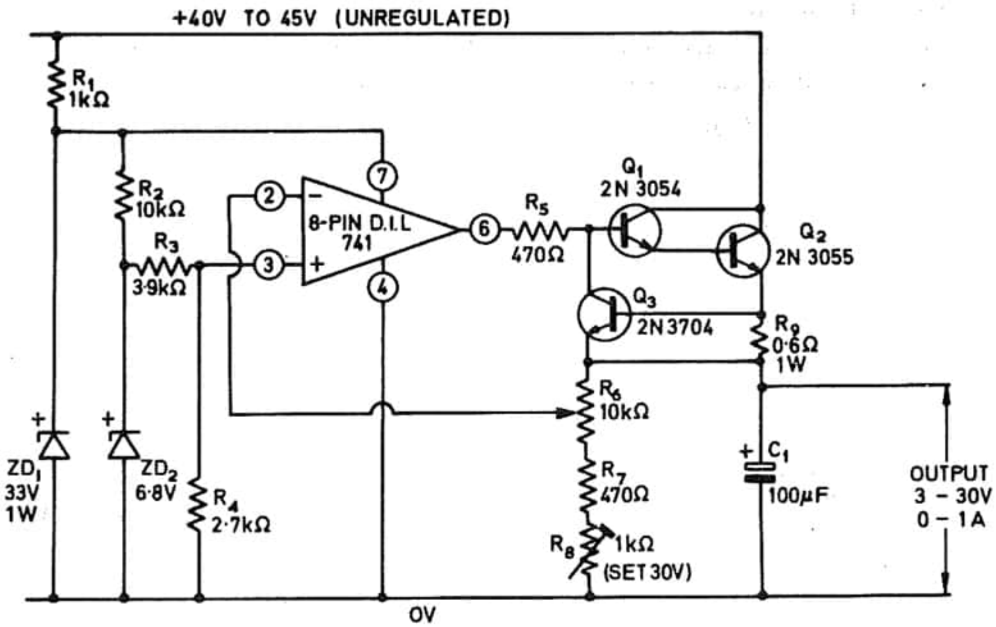


Figure 3.6. 3 V - 30 V stabilised p.s.u. with overload protection.

The *Figure 3.6* circuit is basically the same as that of *Figure 3.5*, except for the addition of a 0.6 Ω current-sensing resistor in series with the output terminals, and of current-limiting transistor Q_3 wired between the base of Q_1 and the emitter of Q_2. The operation of these current limiting components is quite simple. Q_3 is a silicon transistor, and needs a forward-base emitter voltage of greater than 600 mV to turn on. The base-emitter voltage of the transistor is derived from 0.6 Ω resistor R_9 in series with the output terminals, and the magnitude of this voltage is dictated by the output current of the circuit.

Normally, the output current of the circuit is less than 1 A, so insufficient voltage is developed across R_9 to bias Q_1 on: under this condition Q_3 acts like an open circuit, and has no effect on the operation of the system. If a short is placed across the circuits output, on the other hand, the output current will tend to rise above 1 A, and at least 600 mV will be developed across R_9: under this condition Q_3 is biased on, and acts as a shunt between the base of Q_1 and the emitter of Q_2, and tends to turn Q_1 and Q_2 off and so reduce the output current of the circuit. In practice, a large degree of degeneration tends to take place via the $Q_1 - Q_2 - Q_3 - R_9$ loop, and the output current automatically self-limits at a value of 1 A if a short occurs at the output. The *Figure 3.6* circuit thus provides an output that is fully variable from 3 V to 30 V at currents up to 1 A, but has fully automatic overload protection and will not be damaged by short-circuits at the output terminals.

Each of the four variable power supply circuits that we have looked at so far has a single pair of output terminals, and acts as a single power source. In cases where two sets of supplies are required (as in the case of op-amp circuits), two separate single-output power supply units must be interconnected to provide the necessary supplies. A possible alternative, that can be used in cases where the two supplies are required to be of equal amplitude but opposite polarity, is to use a single power supply with a centre-tapped output. The circuit of a simple power supply of this type is shown in *Figure 3.7*.

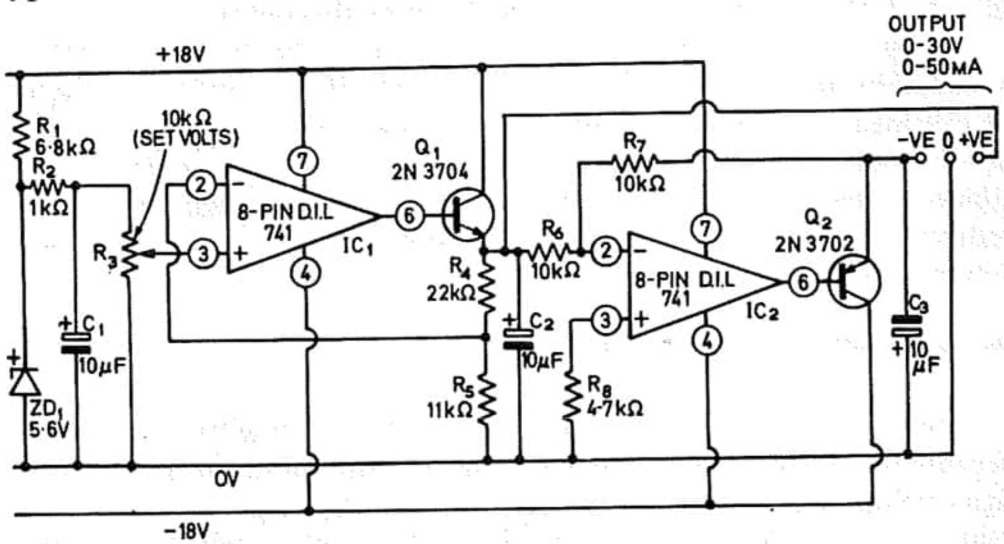


Figure 3.7. Simple centre-tapped 0-30 V p.s.u., for driving op-amp circuits.

The *Figure 3.7* circuit has three output terminals, marked '-ve', '0', and '+ve', and can provide three sets of outputs. The three outputs can be varied simultaneously from 0V to +15 V between the 0 and +ve terminals, from 0V to −15 V between the 0 and -ve terminals, and between 0V and +30 V between the -ve and +ve terminals. The circuit can provide maximum output currents of roughly 50 mA between any set of terminals. The circuit operates as follows.

Zener diode ZD_1 is used to generate a fixed reference potential of 5.6 V from the 18 V positive supply line via R_1. This reference voltage is fed to variable potential divider R_3 via R_2 and C_1, making a variable potential of 0 V to +5 V available at the R_3 slider. This variable reference potential is fed to the positive input terminal of IC_1 , which (together with npn transistor Q_1) is wired as a x 3 non-inverting d.c. amplifier, with its output taken to the +ve output terminal of the power supply circuit. Thus, the potential between the 0 and +ve output terminals can be varied between 0V and +15 V via R_3, and output currents up to 50 mA are available.

IC_2 and pnp transistor Q_2 of the design are wired together as a unity-gain inverting d.c. amplifier, with input applied from the +ve output terminal of the power unit, and the output taken to the units −ve output terminal. Consequently, the output potential between the 0 and −ve terminals is equal in magnitude but opposing in polarity to that between the 0 and +ve terminals, and can be varied between 0 V and − 15 V via R_3, at output currents up to 50 mA. Since the output at the +ve terminal can be varied between 0 V and + 15V, and that at the −ve terminal can be varied between 0 V and −15 V, it follows that the potential between the −ve and +ve terminals can be varied between 0 V and 30 V via R_3, and that the 0 terminal acts as a centre-tap between this output.

The basic centre-tapped power supply circuit of *Figure 3.7* is capable of supplying maximum output currents of only 50 mA, and incorporates no overload protection. The output current capability of the circuit can be increased to 1 A or so by replacing Q_1 and Q_2 with super-alpha connected pairs of power transistors of suitable polarity, and overload protection can be built in by fitting each output stage with the kind of automatic current limiting described in the *Figure 3.6* circuit.

Precision half-wave rectifier circuits

Conventional diodes act as imperfect rectifiers to low-level a.c. signals, because they do not begin to conduct significantly until the applied signal voltage exceeds a certain 'knee' value. In silicon diodes this knee value is of the order of 600 mV, so silicon diodes give negligible rectification tó signal voltages below this level.

Operational amplifiers can be combined with silicon diodes in such a way that the effective knee voltage of the diode is reduced by a factor equal to the open-loop gain of the op-amp, the combination then acting as a near-perfect rectifier even to signals with amplitudes of only a fraction of a millivolt. *Figure 3.8a* shows the practical version of a precision unity-gain half-wave rectifier circuit of this type.

The operation of the *Figure 3.8a* circuit is fairly simple. The op-amp is wired as an inverting amplifier, with input applied via R_3, and negative feedback applied via $R_1 - D_1$ or $R_2 - D_2$. On positive input half-cycles the op-amp output swings negative, so D_2 conducts via R_2, and D_1 is reverse biased: zero output is available at the circuit's output at the $R_1 - D_1$ junction under this condition. On negative half-cycles the op-amp output goes positive, so D_1 conducts via R_1, and D_2 is reverse biased: a positive output is available at the $R_1 - D_1$ junction under this condition. The circuit thus acts as a half-wave rectifier, and gives a positive output at the $R_1 - D_1$ junction, or a negative output at the $R_2 - D_2$ junction.

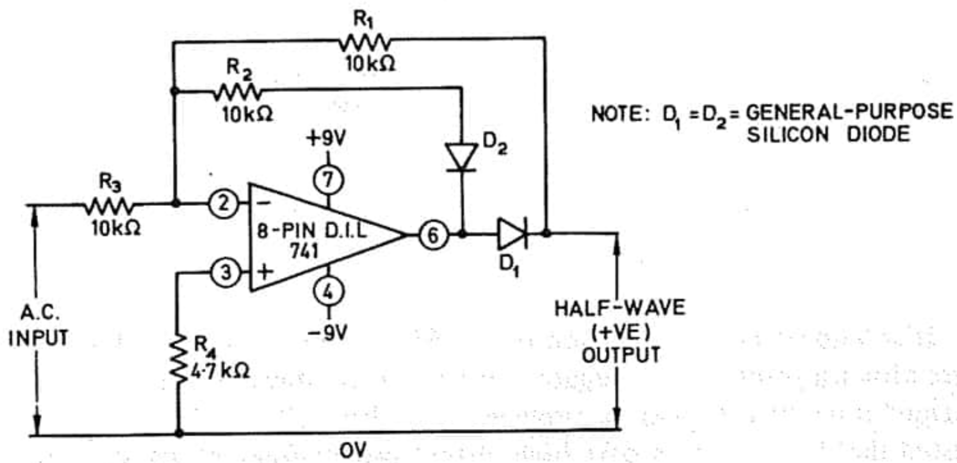


Figure 3.8a. Precision unity-gain half-wave rectifier.

When the applied forward voltage of a silicon diode is below the 600 mV knee value, the diode acts as a virtual open circuit. In the *Figure 3.8a* circuit, therefore, the diodes act as open circuits when zero input is applied to the op-amp: under this condition zero negative feedback is applied to the op-amp, which thus operates in the open-loop mode and gives a voltage gain of about 100 000. Consequently, an input signal of only 6 μV or so is needed to raise the forward diode voltage to the 600 mV knee value beyond which effective rectification takes place, so the circuit effectively reduces the knee voltage by an amount equal to the open loop gain of the op-amp. Once the forward voltage of the diode has exceeded the knee value, the diode acts as a virtual short circuit, and under this condition the gain of the circuit is dictated almost entirely by the $R_1 - R_3$ or $R_2 - R_3$ values. The *Figure 3.8a* circuit gives unity voltage gain under this condition, and acts as a near-perfect half-wave rectifier that gives a positive output from the $R_1 - D_1$ junction, or a negative output from the $R_2 - D_2$ junction.

The overall voltage gain of the *Figure 3.8a* circuit is dictated by the ratios of R_1 to R_3, or R_2 to R_3, as in the case of a conventional inverting amplifier. Normally $R_1 = R_2$, and the voltage gain $A_v = R_1/R_3$. The circuit can thus be made to give voltage gain as well as rectification by simply making the values of R_1 and R_2 larger than that of R_3, as in the case of the precision x 10 half-wave rectifier circuit shown in *Figure 3.8b*.

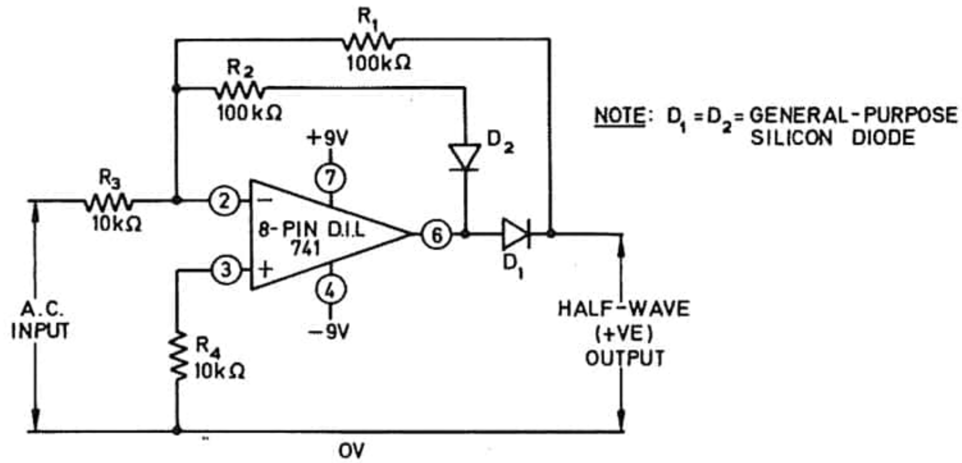


Figure 3.8b. Precision x 10 half-wave rectifier.

It should be noted that both of the *Figure 3.8* circuits are designed to give either a positive or a negative output, as required; if only a positive output is needed, R_2 can be replaced by a short circuit. It should also be noted that both circuits have high output impedances, so the outputs must not be fed into loads having impedances appreciably less than 1 MΩ.

The *Figure 3.8* circuits can be made to act as precision half-wave a.c./d.c. converters by designing them to give voltage gains of 2.22 to give form-factor correction, and by integrating their rectified outputs. *Figure 3.9* shows the practical version of such a circuit. Resistors R_1 and R_2 ensure that the required gain is attained, and capacitor C_2 carries out the function of integration. The circuit is designed to give unity conversion gain, with a maximum r.m.s. input and d.c. output of 2 V. Output linearity is better than 0.1 % of full scale, i.e., the accuracy is better than ±2 mV of reading.

The *Figure 3.9* circuit is specifically designed to feed into the high-impedance input of a digital panel meter, and has a high output impedance. If the output is to be fed to a low-impedance indicator, such as a moving coil meter, a high-impedance voltage-follower buffer stage must be interposed between the converter output and the input of the indicator. The converter has an input impedance of only 10 kΩ, and a voltage-follower can also be interposed between the input signal and the input of the converter to give a high input impedance to the entire measuring circuit, if required.

Another application of the *Figure 3.8a* circuit is as a peak-voltage

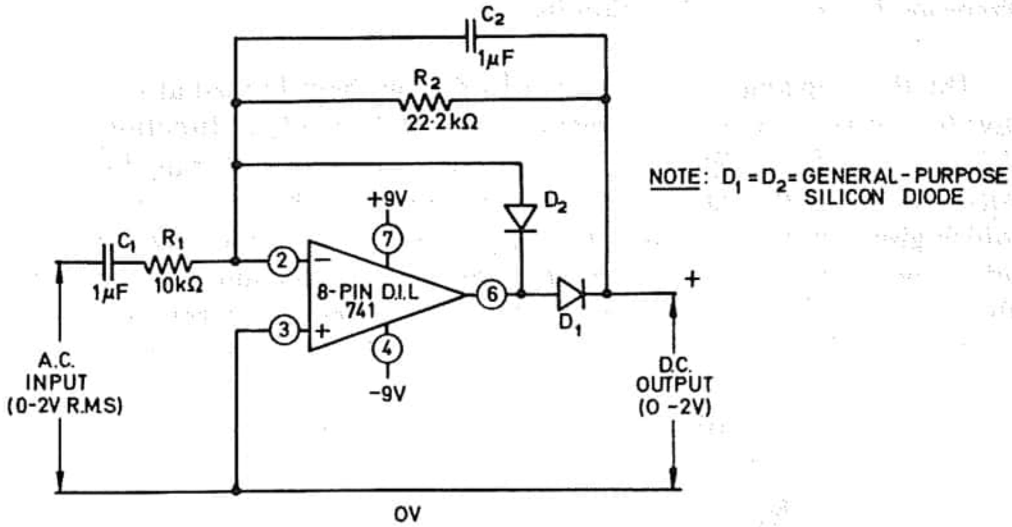


Figure 3.9. Precision half-wave a.c./d.c. converter.

detector: the circuit can be made to read peak voltage by simply connecting a reservoir capacitor across its output terminals. An even simpler peak-voltage detector circuit is shown in *Figure 3.10.*

Here, the op-amp is wired as a unity-gain voltage-follower, with feedback provided via D_1, and with reservoir capacitor C_1 wired between the output and ground, so that C_1 charges to the peak positive value of any input voltage applied to the non-inverting input of the op-amp. The capacitor charges rapidly via D_1 and the low-impedance output of the op-amp, but discharges slowly via the input impedance of the inverting input terminal (typically 1 MΩ). The discharge rate can be increased, if required, by wiring a shunt resistor across the capacitor, as shown. Note that this shunt appears directly across the circuits output, so the circuit has a high effective output impedance.

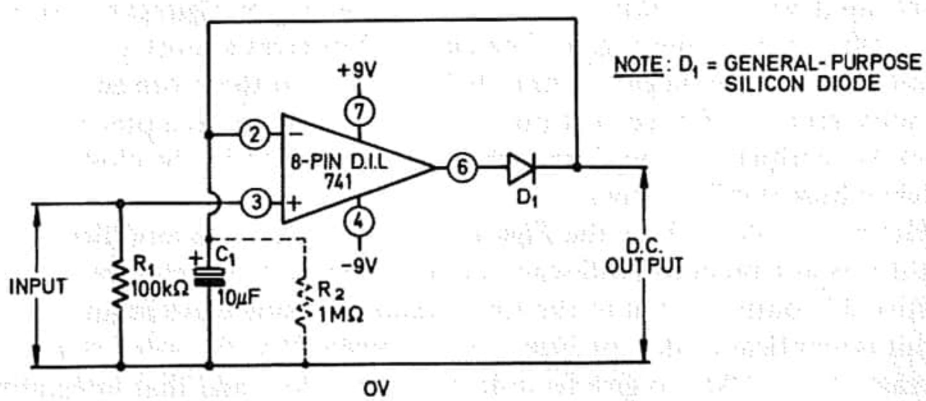


Figure 3.10. Peak voltage detector (positive).

Precision full-wave rectifier circuits

The three op-amp rectifying circuits that we have looked at so far all give half-wave rectification. Op-amps can also be made to function as full-wave rectifiers. *Figure 3.11* shows one method of obtaining full-wave rectification. In this case IC_1 is wired as a precision half-wave rectifier which gives a negative output, and IC_2 is wired as a 2-input inverting adder, with one input taken directly from the circuits input terminal, and the other taken from the output of IC_1. The adder gives a gain of unity to the direct-input signal, but a gain of x 2 to the IC_1 output signal.

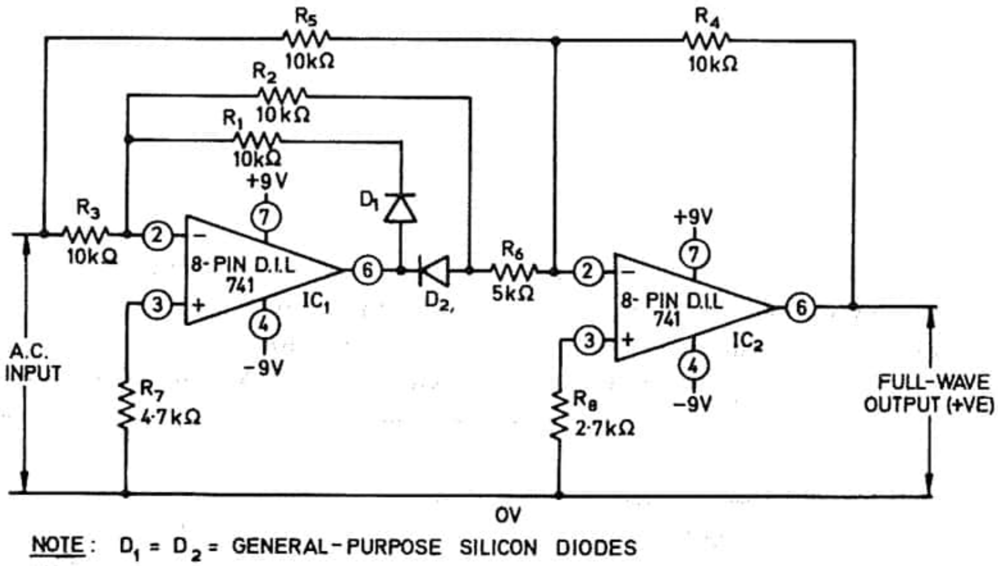


Figure 3.11. Precision full-wave rectifier.

On positive input signals IC_2 gives a negative output at unity gain from the direct input, and a positive output at a gain of x 2 from IC_1, thus giving an aggregate output that is positive with a gain of unity. On negative input signals IC_2 gives a positive output at unity gain from the direct input, and zero output from IC_1, thus giving an aggregate output that is positive with unity gain. The circuit thus gives a unity-gain output to both positive and negative input half-cycles, and therefore acts as a full-wave rectifier. For correct operation of this circuit as a precision full-wave rectifier, it is important that resistors R_2 to R_6 be closely matched high stability types.

Figure 3.12 shows how the *Figure 3.11* circuit can be modified so that it acts as a precision full-wave a.c./d.c. converter which gives a positive d.c. output equal to the r.m.s. value of a sine wave input. The circuit is identical to that of *Figure 3.11*, except that the value of R_4 is increased to 11.1 kΩ to give form-factor correction, and that integrating capacitor C_1 is added between the output and the negative input of IC_2.

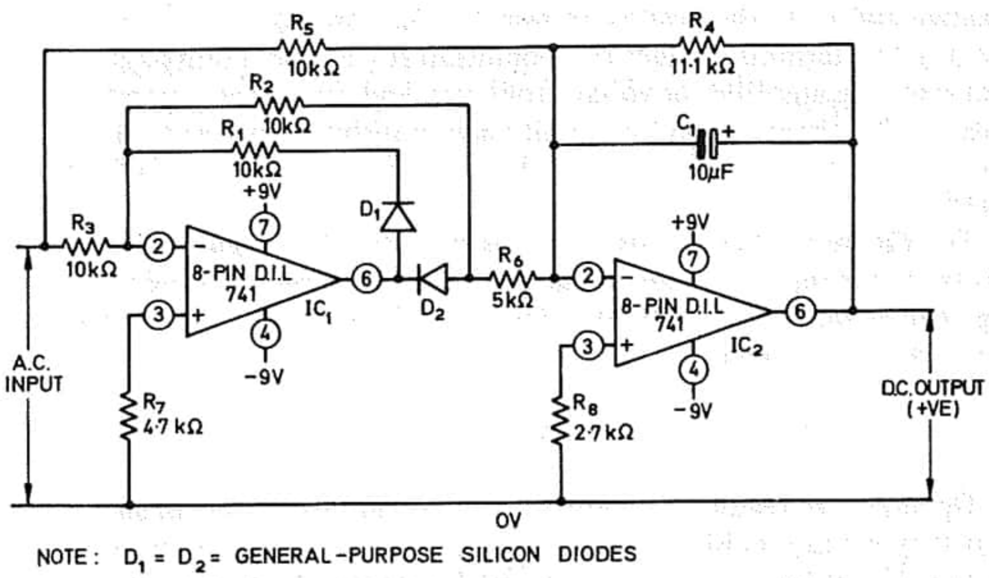


Figure 3.12. Precision full-wave a.c./d.c. converter.

The circuit can be used as a unity-gain converter for inputs up to 2 V r.m.s., over the frequency range 20 Hz to 15 kHz. The accuracy of the converter depends on the accuracies of the R_2 to R_6 resistors.

Finally, *Figure 3.13* shows an alternative way of using op-amps to make precision full-wave rectifiers. In this case IC_1 is used as a half-wave rectifier, but gives both positive and negative outputs, which are fed to IC_2. On positive input half-cycles IC_1 applies a negative output to the negative terminal of IC_2, and applies zero input to the positive terminal. Under this condition IC_2 acts as a unity-gain inverting amplifier, and gives a positive output. On negative input half-cycles IC_1 applies a

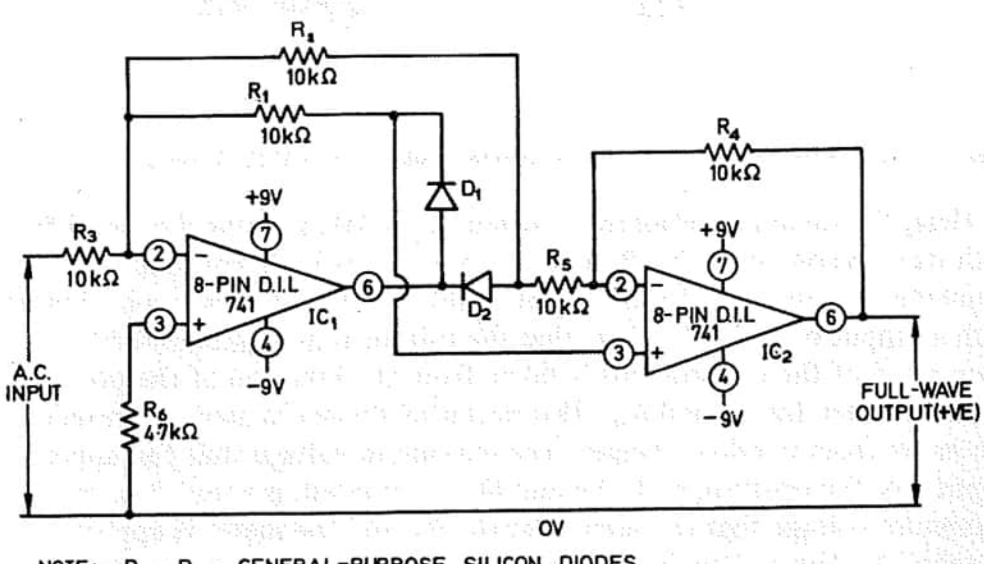


Figure 3.13. Alternative precision full-wave rectifier.

positive output to the positive terminal of IC_2, and applies zero input to the negative terminal. Under this condition IC_2 acts as a unity-gain non-inverting amplifier or voltage follower, and again gives a positive output. The circuit thus gives a unity-gain positive output to both positive and negative input half-cycles, and therefore acts as a full-wave rectifier.

The *Figure 3.13* circuit uses two resistors less than *Figure 3.11*, and has twice the input resistance. The *Figure 3.13* circuit can thus be regarded as the better of the two designs, although both circuits give identical performance.

D.C. volt and current meter circuits

Op-amps can readily be connected to moving-coil meters in such a way that they act as precision d.c. voltmeters, millivoltmeters, or current meters. If required, op-amps can be used as converters to extend the ranges of existing moving-coil d.c. voltmeters. *Figure 3.14* shows the practical circuit of a simple converter that enables a 1 V d.c. meter to read 100 mV full scale.

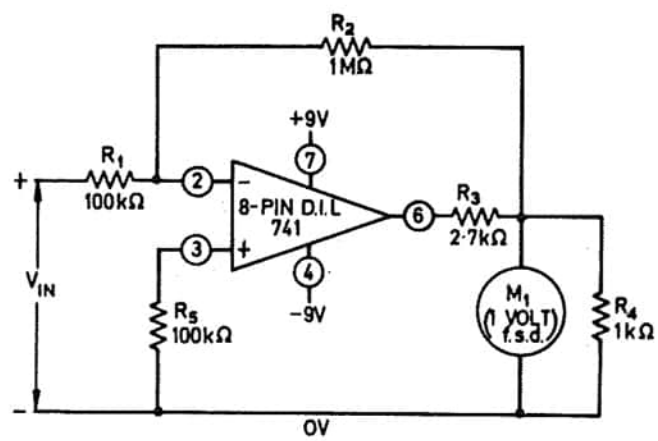
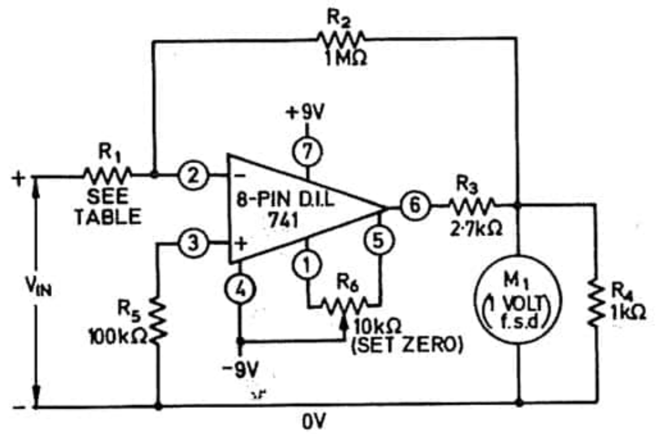


Figure 3.14. Simple d.c. voltmeter converter giving 100 mV f.s.d. on a 1 V meter.

Here, the op-amp is effectively wired as a x 10 inverting d.c. amplifier, with its gain controlled by R_1 and R_2, and the existing voltmeter is connected across the circuits output so that a full scale reading is obtained with an input of 100 mV. Note that the output is not taken directly from pin 6 of the op-amp, but is taken from the junction of the potential divider formed by R_3 and R_4. This potential divider is used to protect the meter from overload danger. The maximum voltage that can appear at pin 6 of the op-amp, with the amplifier saturated, is about 8 V, so the maximum voltage that can appear across R_4 and the meter is approximately 2 V. This voltage is too small to damage the meter, but great enough to ensure that full scale deflection can be linearly obtained under normal operating conditions. The voltmeter used in this circuit can be any 1 V type with a sensitivity greater than 1 kΩ/V.

Figure 3.15 shows an improved version of the d.c. voltmeter converter. The circuit is similar to that of *Figure 3.14*, except that the R_1 value can be selected to give full scale voltage values between 1 mV and 10 V (as shown in the table), and that offset-null control R_6 is wired into the circuit to act as a 'set zero' control. The voltmeter used in this circuit can again be any 1 V type with a sensitivity greater than 1 kΩ/V.



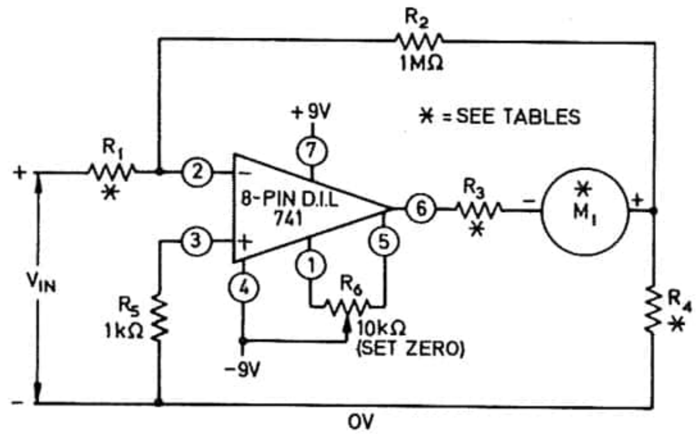
$V_{f.s.d}$	R_1
10V	10MΩ
1V	1MΩ
100MV	100kΩ
10MV	10kΩ
1MV	1kΩ

Figure 3.15. High-performance d.c. voltmeter converter.

Note in both of the above circuits that the converter has an effective sensitivity of 1 MΩ/V, irrespective of the sensitivity of the actual voltmeter used. Also note that the accuracy of the converter is dictated by the accuracies of R_1 and R_2. If required, R_2 can be replaced by a 820 kΩ fixed resistor and a 500 kΩ variable resistor in series: the variable resistor can be adjusted to calibrate the meter to a precise full scale voltage value.

Figure 3.16 shows how an op-amp and a moving-coil d.c. current meter can be wired together to form a precision d.c. volt or millivolt meter. The meter can be any type with a full-scale sensitivity in the range 100 μA to 5 mA, and the circuit can be made to give any decade value of full scale voltage reading in the range 1 mV to 1 000 V. The two tables show the component values that must be used to suit different meter types and to give alternative full scale voltage readings. The circuit has a basic sensitivity of 1 MΩ/V, irrespective of the meter type used.

Basically, the *Figure 3.16* circuit is wired as an inverting d.c. amplifier, with its output voltage appearing across R_4 and its gain determined by R_1 and R_2. The meter is wired in series between the $R_2 - R_4$ junction and the pin 6 output terminal of the op-amp, and gives a reading equal to the total output current of the op-amp. Since R_2 is large relative to R_4, the magnitude of the output current is dictated almost entirely by the magnitudes of R_4 and the output voltage, and is directly proportional to



M1	R4	R3
100μA	10kΩ	27kΩ
500μA	2kΩ	5·6kΩ
1MA	1kΩ	2·7kΩ
2·5MA	400Ω	1·5kΩ
5MA	200Ω	470Ω

Vf.s.d	R1
1000 V	1000MΩ
100V	100MΩ
10V	10MΩ
1V	1MΩ
100MV	100kΩ
10MV	10kΩ
1MV	1kΩ

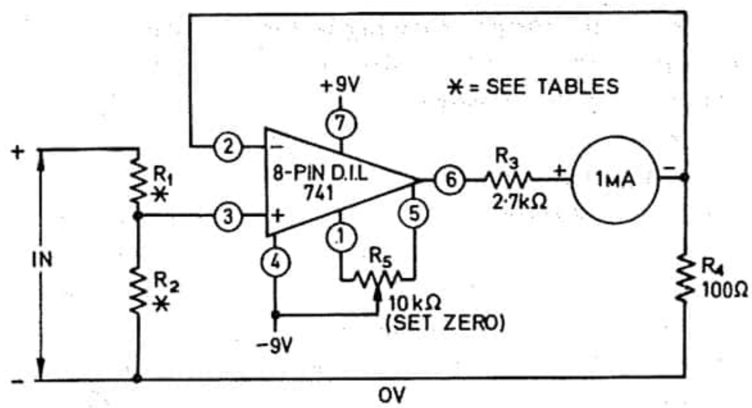
Figure 3.16. D.C. volt/millivolt meter, with alternative component values.

the input voltage. Offset-null control R_6 is used as a *set zero* control. If required, R_2 can be replaced by an 820 kΩ fixed resistor and a 500 kΩ variable resistor in series, to facilitate precise calibration of the meter.

Figure 3.17 shows an alternative way of using an op-amp and a moving-coil meter as a simple voltmeter or as a current meter. In this case the op-amp is wired as a unity-gain non-inverting d.c. amplifier or voltage follower, with its output appearing across R_4. The circuit uses a 1 mA f.s.d. meter as a readout indicator, and this meter reads the value of the current flowing into R_4 from the op-amp output. Consequently, the meter reading is directly proportional to the magnitude of the input voltage appearing across R_2, and equals full scale with an input of 100 mV.

Potential divider $R_1 - R_2$ enables the input voltage to be ranged so that the circuit acts as a voltmeter giving full scale decade readings from 100 mV to 1 000 V, or as a current meter giving full scale decade readings from 1 μA to 1 A. The two tables show suitable R_1 and R_2 values for using the circuit as a volt or current meter. If required, R_4 can be relaced by an 82 Ω fixed resistor and a 50 Ω variable resistor in series, to facilitate precise calibration of the meter.

Figure 3.18 shows how the *Figure 3.17* circuit can be modified so that it acts as a precision multi-range d.c. millivoltmeter, with a maximum sensitivity of 1 mV full scale. In this case the op-amp is wired as a non-inverting x 1 000 d.c. amplifier, with gain controlled by R_8 and R_9, and



VOLTMETER		
f.s.d	R_1	R_2
1000V	10MΩ	1kΩ
100V	10MΩ	10kΩ
10V	10MΩ	100kΩ
1V	900kΩ	100kΩ
100mV	0Ω	100kΩ

CURRENT METER		
f.s.d	R_1	R_2
1A	0Ω	0·1Ω
100mA	0Ω	1Ω
10mA	0Ω	10Ω
1mA	0Ω	100Ω
100μA	0Ω	1kΩ
10μA	0Ω	10kΩ
1μA	0Ω	100kΩ

Figure 3.17. Simple d.c. voltage or current meter.

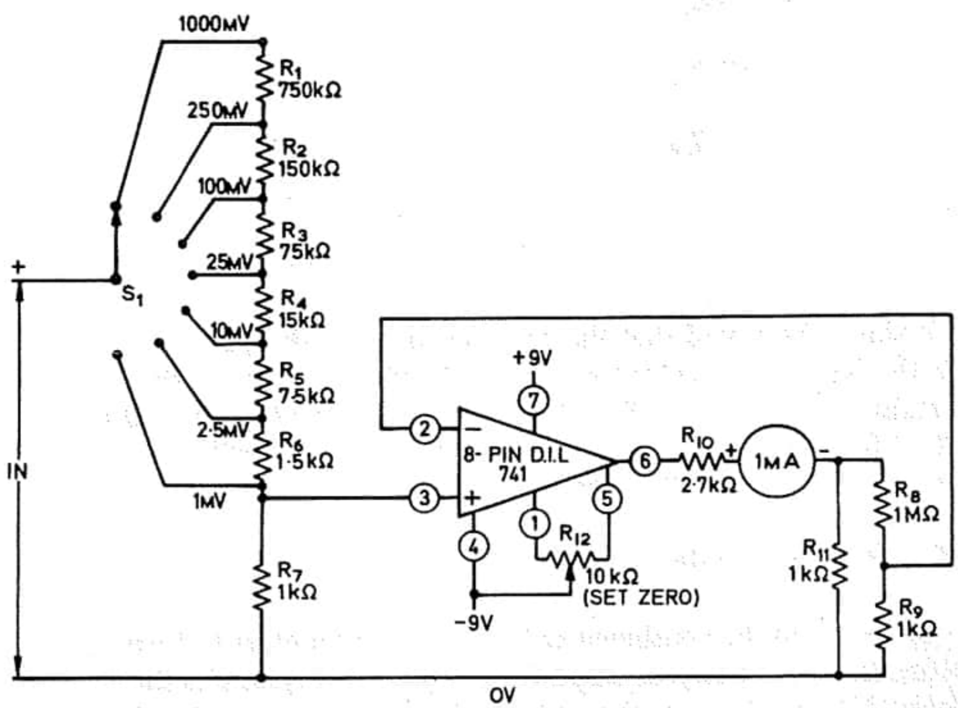


Figure 3.18. Precision d.c. millivoltmeter.

the meter measures the current flowing in load resistor R_{11}. The meter is a 1 mA f.s.d. type, and R_{11} has a value of 1 kΩ, so the full scale indication corresponds to an output of 1 V or an input (across R_7) of 1 mV. The R_1 to R_7 potential divider enables the input to be ranged to give full scale voltage values from 1 mV to 1 V.

Finally, *Figure 3.19* shows how the *Figure 3.18* circuit can be modified so that it acts as a precision multi-range d.c. microammeter, with a maximum sensitivity of 1 μA full scale. In this case the op-amp is wired as a non-inverting x 100 d.c. amplifier, and gives a full scale reading with an input of 10 mV. The R_1 to R_7 resistance chain is wired across the input of the op-amp as a tapped current shunt, and developes an input voltage proportional to the magnitude of the input current. Thus, the meter reading is directly proportional to the magnitude of the input current.

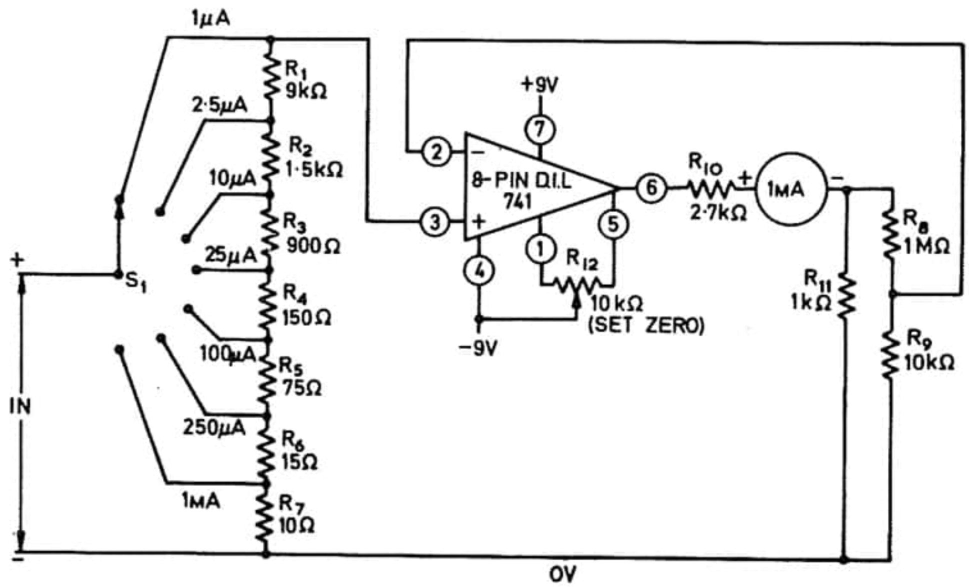


Figure 3.19. Precision d.c. microammeter.

It should be noted that the basic accuracy of the *Figure 3.18* circuit and the *Figure 3.19* circuit is dictated by the accuracy of the meter and of resistors R_8, R_9, and R_{11}. If required, R_{11} can be replaced by an 820 Ω fixed resistor and a 500 Ω variable resistor in series, to facilitate precise calibration of the meter.

A.C. voltmeter circuits

Op-amps can be combined with moving-coil meters to form a.c. voltmeters in a variety of ways. One very simple system is shown in *Figure 3.20*. In this case the op-amp is wired as an inverting d.c. amplifier, with R_1 acting as an input resistor, and the meter and the D_1 to D_4

bridge rectifier acting as the negative feedback element. In this configuration the currents in R_1 and the feedback element are always equal. A virtual earth exists between ground and the negative input terminal of the op-amp, so the signal current of R_1 (and thus of the meter) is directly proportional to the magnitude of the input signal voltage, and the meter gives a perfectly linear reading of the input voltage.

In effect, the op-amp in the *Figure 3.20* circuit is used purely to linearise the characteristics of the bridge rectifier, and gives no increase

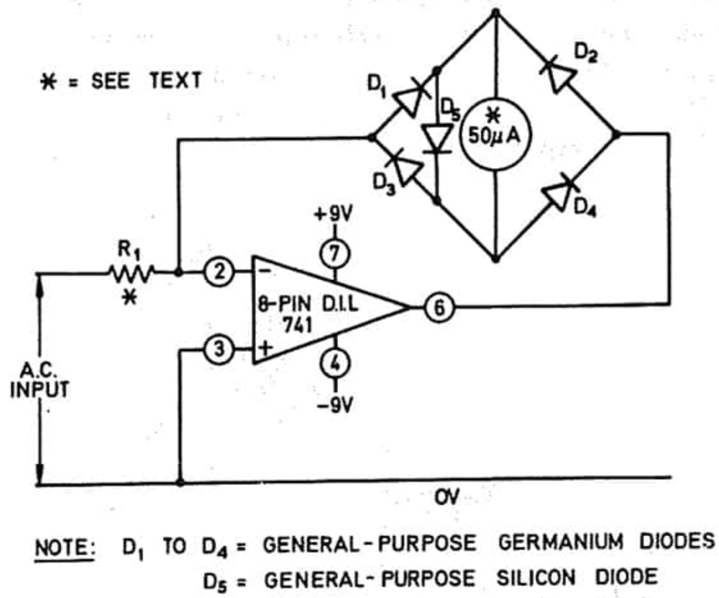


Figure 3.20. Simple a.c. voltmeter.

in the meter sensitivity, and R_1 is used as a ranging or multiplier resistor to enable the circuit to give indications in terms of a.c. voltage. The value of R_1 is determined by multiplying the basic ohms/volt d.c. sensitivity of the meter by 0.9 to establish an a.c. ohms/volt sensitivity figure, and by then multiplying this figure by the required full scale voltage value, e.g. A 50 μA meter has a d.c. sensitivity of 20 kΩ/V, so the a.c. sensitivity works out at 18 kΩ/V. R_1 must thus be given a value of 18 kΩ if the meter is required to read 1 V f.s.d., or 1.8 MΩ if the meter is required to read 100 V f.s.d.

In practice, the *Figure 3.20* circuit can be used with any moving coil meter giving a full scale value in the range 50 μA to 1 mA, and R_1 can be selected to give any required full scale voltage value in the approximate range 100 mV to 1 000 V. The voltmeter gives a useful performance at frequencies up to about 40 kHz. If the circuit is to be used to measure a.c. voltages imposed on d.c., a capacitor must be wired in series with the input terminals to block the d.c. component.

The input impedance of the *Figure 3.20* circuit is equal to the R_1

value, and may be quite low. In many applications it may be essential to use a voltmeter having a high input impedance, and in such cases a circuit of the type shown in *Figure 3.21* can be used. This circuit has a typical input impedance of tens or hundreds of Megohms, and gives a useful performance up to frequencies of about 40 kHz.

The operating theory of the *Figure 3.21* circuit is quite simple. The op-amp is wired as a unity-gain a.c. voltage follower, with its output appearing across load resistor R_1, and with input resistor R_2 boot-strapped so that it appears as a virtual open circuit to a.c. signals. The meter and bridge rectifier are effectively wired in series with the output of the op-amp, and the meter reads the a.c. signal current flowing in load resistor R_1. The magnitude of this current is directly proportional to the magnitude of the a.c. input signal voltage, so the circuit acts as a highly linear a.c. voltmeter, and has a very high input impedance.

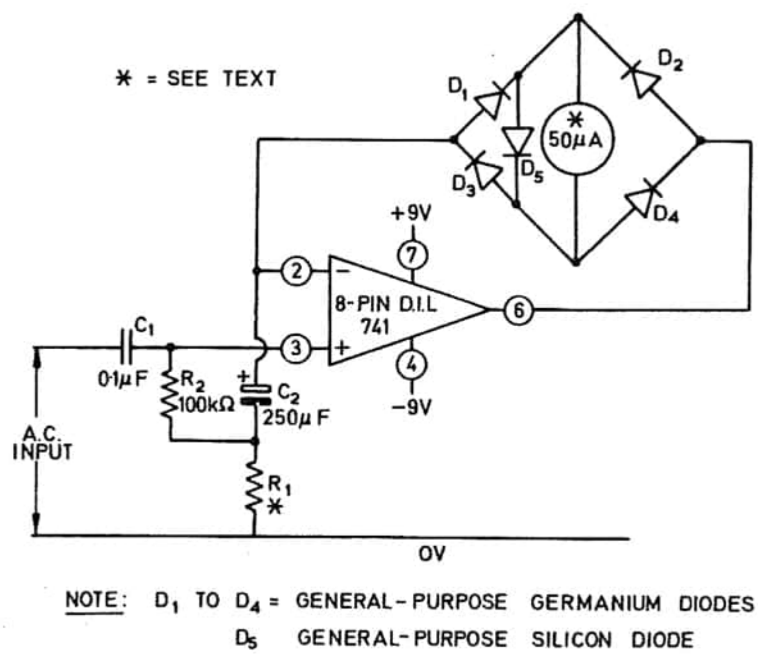
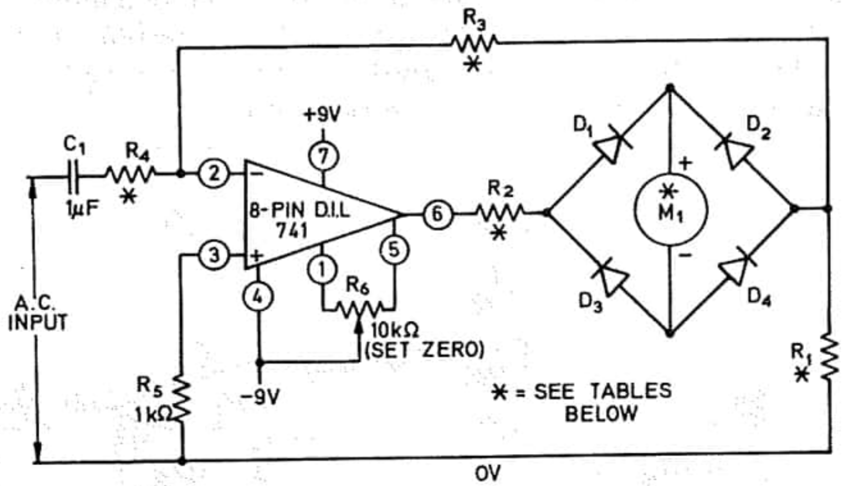


Figure 3.21 High-impdance a.c. voltmeter.

The *Figure 3.21* circuit can be used with any moving-coil meter giving a full scale value in the range 50 μA to 1 mA, and R_1 can be selected to give any full scale voltage value in the range 100 mV to 1 V. If higher voltage ranges are required, they can be obtained by connecting the test voltage to the input of the op-amp via a ranging potential divider. The procedure for selecting the R_1 value is the same as that described for the *Figure 3.20* circuit. Thus, if the circuit is required to read 1 V full scale when used with a 50 μA meter, R_1 must be given a value of 18 kΩ, and if the circuit is required to read 1 V full scale when used with a 1 mA meter, R_1 must be given a value of 900 Ω. Using a 50 μA meter, the prototype circuit gives an input impedance of 33 MΩ in parallel with 18 pF when R_1 is given a value of 1.8 kΩ for 100 mV full scale, and gives an input impedance of 330 MΩ in parallel with 5 pF when R_1 is given a value of 18 kΩ for 1 V full scale.

It should be noted in the *Figure 3.20* and *3.21* circuits that diode D_5 is wired directly across the indicating meter within the bridge rectifier. This diode is used to protect the meter against overload damage, and can be any general-purpose silicon type.

Finally, *Figure 3.22* shows the circuit of a precision a.c. volt or millivolt meter. The circuit can be used with any moving coil meter giving a full scale reading in the range 100 μA to 5 mA, and can be made to give any full scale a.c. voltage reading in the range 1 mV to 1 000 V.



NOTE: D_1 TO D_4 = GENERAL-PURPOSE GERMANIUM DIODES

M_1	R_1	R_2
100μA	9kΩ	27kΩ
500μA	1·8kΩ	5·6kΩ
1MA	900Ω	2·7kΩ
2·5MA	360Ω	1·5kΩ
5MA	180Ω	470Ω

VALUES FOR USE WITH DIFFERENT METER MOVEMENTS

$V_{f.s.d}$	R_4	R_3
1000V	10MΩ	10 kΩ
100 V	10MΩ	100 kΩ
10V	10MΩ	1MΩ
1V	1MΩ	1MΩ
100MV	100kΩ	1MΩ
10MV	10kΩ	1MΩ
1MV	1kΩ	1MΩ

DIFFERENT f.s.d VOLTAGE SENSITIVTIES

Figure 3.22 **Precision a.c. volt/millivolt meter.**

The operating theory of the circuit is quite simple; the op-amp is wired as an inverting amplifier in which the meter reads the magnitude of the a.c. current flowing in load resistor R_1. The magnitude of this current is directly proportional to the input voltage of the circuit and to the gain of the circuit, so the circuit acts as a linear a.c. volt or millivolt meter. The circuit is in fact designed so that the meter reads full scale when 1 V appears across R_1, so the full scale voltage reading is dictated by the ratios of R_3 and R_4. One of the tables in *Figure 3.22* shows suitable R_3 and R_4 values for alternative full scale decade voltages from 1 mV to 1 000 V.

The circuit has automatic overload protection provided by limiting resistor R_2, and the second table in *Figure 3.22* shows suitable R_1 and R_2 values for use with alternative meter types. Offset-null control R_6 is used in the circuit as a set-zero control.

Linear-scale ohmmeter circuits

Figure 3.23 shows how an op-amp can be connected to a moving-coil meter to form a linear-scale ohmmeter giving full scale readings in the range 1 kΩ to 10 MΩ. The circuit is divided into two parts, and consists of a voltage generator that is used to generate a standard test voltage, and a readout unit which indicates the value of the resistor under test.

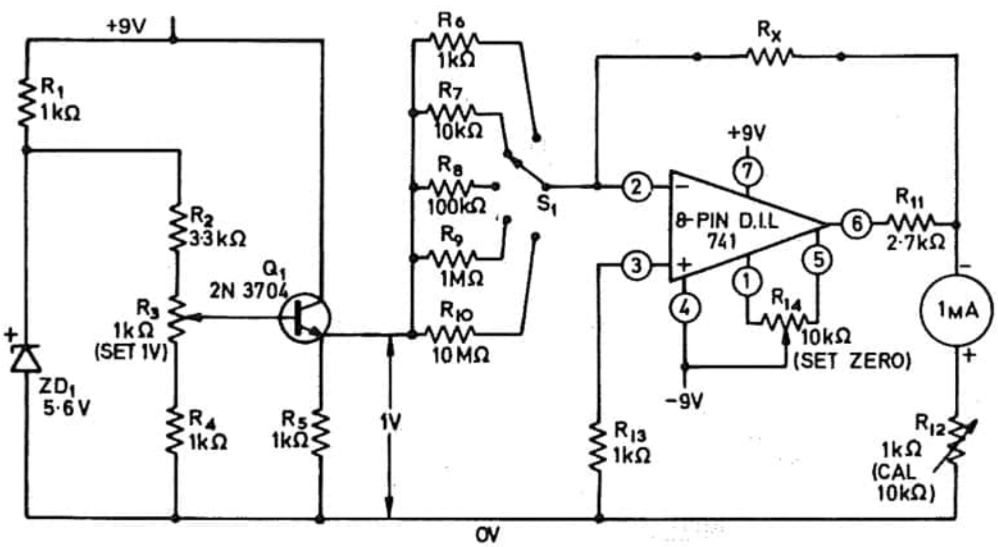


Figure 3.23. Linear-scale ohmmeter.

The voltage generator section of the circuit comprises zener diode ZD_1, transistor Q_1, and resistors R_1 to R_5. The action of these components is such that a stable reference potential of 1 V is developed across R_5, but is adjustable over a limited range via R_3. This reference voltage is fed to the input of the op-amp readout unit. The op-amp is wired as an inverting d.c. amplifier, with the 1 mA meter and R_{12} forming a 1 V f.s.d. meter across its output, and with the op-amp gain determined by the values of ranging resistors R_6 to R_{10} and by negative feedback resistor R_x. Since the input to the amplifier is fixed at 1 V, the output voltage reading of the meter is directly proportional to the value of R_x, and equals full scale when R_x and the ranging resistor values are equal. Consequently, the circuit functions as a linear-scale ohmmeter.

The circuit has five full scale decade ranges, from 1 kΩ to 10 MΩ. The linearity of the meter is excellent on all but the 10 MΩ range, where linearity errors may be as great as 10 %. The full-scale accuracy of the circuit is dependent on the accuracies of ranging resistors R_6 to R_{10}.

The procedure for initially calibrating the *Figure 3.23* circuit is as follows. First, switch the unit to the 10 kΩ range and secure an accurate 10 kΩ resistor in the R_x position. Now adjust R_3 to give an accurate 1 V across R_5, and then adjust R_{12} to give a precise full scale reading on the meter. All adjustments are then complete, and the circuit is ready for use.

Figure 3.24 shows an alternative type of linear-scale ohmmeter circuit. This particular design is specifically intended to give accurate readings of

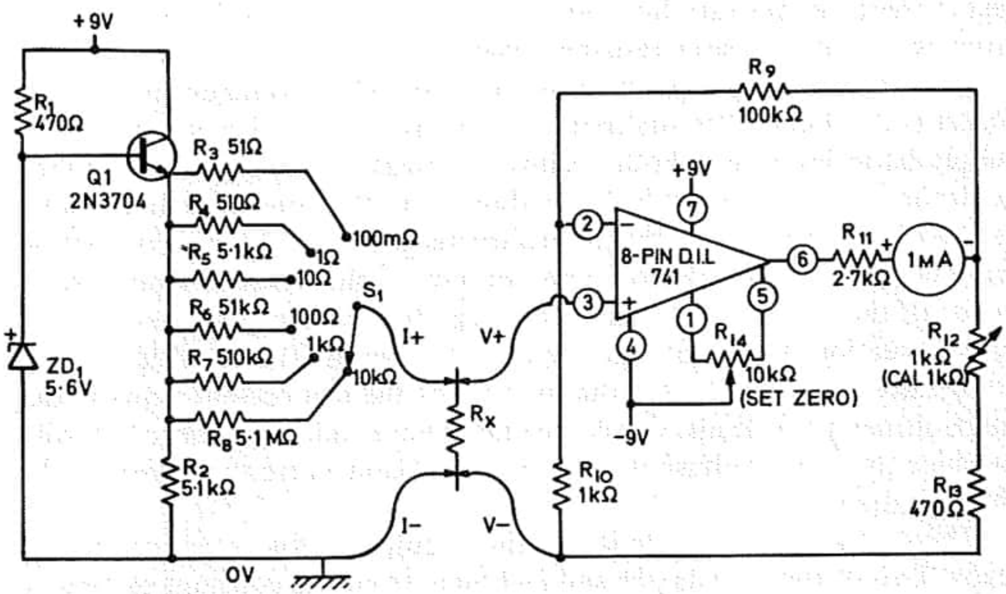


Figure 3.24. Low-value linear ohmmeter, with probe details shown in inset.

low values of resistance, and its most sensitive range reads 100 MΩ full-scale. The design is such that the accuracy of the reading is not influenced by the resistance of the actual connecting leads that are used to connect the meter to the resistor under test.

The circuit is made up of two separate sections. One of these is a constant current generator, which is used to pass a fixed current through the resistor under test, and the other is a d.c. millivoltmeter, which measures the voltage that is developed across the test resistor by the fixed current. Since the test current is fixed, the magnitude of this voltage is directly proportional to the resistance of R_x, and the circuit thus functions as a linear-scale ohmmeter.

The d.c. millivoltmeter or readout section of the circuit is designed around the op-amp, which functions as a non-inverting x 100 d.c. amplifier. The circuit requires an input of 10 mV for full-scale deflection on the meter, and the input voltage is applied to the high-impedance positive terminal of the op-amp.

The constant current section of the unit is designed around emitter-follower transistor Q_1, which has a zener-stabilised potential of 5.6 V applied to its base and thus generates a stable reference potential of approximately 5 V at its emitter. This reference potential is fed to R_x via ranging resistors R_3 to R_8, which determine the current flowing in R_x. Since only 10 mV needs be developed across R_x to give a full scale reading on the meter, the R_x voltage has negligible effect on the voltage developed across the ranging resistors or the current flowing in them, and these resistors thus effectively act as constant current test sources. These test currents in fact vary by a mere 0.2 % when the R_x value is varied from zero to its full-scale resistance value.

Two very important points must be noted when constructing the *Figure 3.24* circuit. The first point to note is that the circuit uses two supply batteries, to give both positive and negative supply rails, and the common or 0 V line *must* be taken directly to the constant current side of the circuit, and *not* to the millivoltmeter section. The 0 V connection must be made to the millivoltmeter section via the negative input test probe of the readout unit and via the negative probe of the constant current section, as indicated in the circuit diagram. This method of connection is used to ensure that no part of the test current flows in the millivoltmeter test leads, which inevitably have finite resistance and will produce their own voltage readings if appreciable currents are passed through them.

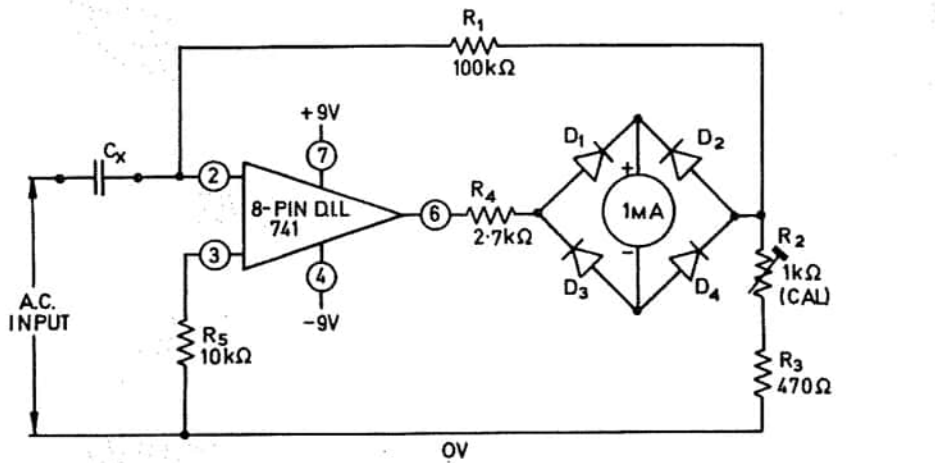
The second point to note is that the circuit uses *four* separate test leads. Two of these leads (*I*+ and *I*–) came from the constant current section, and are used to apply the test current to R_x, and the other two (*V*+ and *V*–) go to the readout unit, and are used to measure the voltage directly across R_X. By using separate supply (*I*+ and *I*-) and sense (*V*+ and *V*-) leads, the voltage drop across the contact resistance between the supply-current leads and the resistor's leads is *not* measured by the voltage-sensing leads. Therefore, the contact-resistance voltage drop does *not* contribute any appreciable error to the resistance measurement.

Once construction of the circuit is complete, the unit can be tested and calibrated. To test the unit, first check that the meter can be zeroed via R_{14}. Then set the range switch to the 100 ohm range, connect the *V*-lead to the *I*-lead, and the *V*+ lead to the *I*+ lead. This should drive the meter reading beyond full scale deflection. Now connect the four leads to a short thick piece of bright copper wire. (This simulates a zero-ohm resistor.) If all is well the meter reading should drop to zero. As a further check, turn the range switch to the 100 MΩ range, and check that a meter reading of no more than 2 MΩ is obtained.

When all is well, the unit can be calibrated by switching it to the 1 kΩ range, connecting a 1 kΩ resistor in the R_x position, and then adjusting R_{12} to obtain full scale deflection on the meter. All adjustments are then complete, and the unit is ready for use, since the accuracy of the meter on all remaining ranges is determined primarily by the accuracies of ranging resistors R_3 to R_8.

A linear-scale capacitance meter

To conclude this chapter, *Figure 3.25* shows the basic circuit of a linear-scale capacitance meter which can give full-scale readings in the range 100 pF to 1 μF when powered from a suitable sine wave source. The operating principle of the circuit is quite simple. The op-amp is wired as an inverting a.c. amplifier, with the meter and bridge rectifier connected to its input in such a way that the meter reads full scale when approximately 1 V r.m.s. appears at the $R_1 - R_2$ output junction. The gain of the op-amp is determined by the relative impedances of R_1 and C_x, and equals unity when these two impedances are equal.



f_{IN}	$V_{IN(RMS)}$	$C_{f.s.d}$
≏18kHz	≏ 1V	100pF
≏1·8kHz	≏ 1V	1000pF
≏180Hz	≏ 1V	·01μF
≏ 18Hz	≏ 1V	0·1μF
≏ 18Hz	≏100MV	1μF

Note: D_1 to D_4 = GENERAL PURPOSE GERMANIUM DIODES

Figure 3.25. Basic circuit of linear-scale capacitance meter, with details of approximate input signal requirements for full-scale decade capacitance ranges from 100 pF to 1 μF.

Suppose then that a 1 V r.m.s. sine wave signal is applied to the input of the circuit, and that this signal is adjusted to a frequency (approximately 1.8 kHz) at which the impedance of a 1 000 pF capacitor equals

100 kΩ. If a 1 000 pF capacitor is now placed in the C_x position the meter will read full scale, since the op-amp gives unity-gain under this condition. If, on the other hand, the C_x value is reduced by a factor of ten, to 100 pF, its impedance will rise by a factor of ten, to 1 MΩ, and the circuit gain will fall to 0.1, and the meter will read only 1/10th of full scale. The meter reading is thus directly proportional to the C_x capacitor value, and the circuit functions as a linear-scale capacitance meter.

To make the meter read alternative full-scale capacitance values, it is simply necessary to adjust the input frequency and/or amplitude to the approximate values shown in the table of *Figure 3.25*, and to then place an accurate capacitor with the required f.s.d. value in the C_x position. Adjust R_2 to give a full scale indication on the meter, remove the calibration capacitor, and the circuit is ready for use as a linear-scale capacitance meter. The meter can be used in conjunction with any reasonable sine wave generator having an output impedance less than 1·kΩ or so.