SECTION 6

MEASURING INSTRUMENTS

SECTION 6

CHAPTER 1

AMMETERS AND VOLTMETERS

AMMETERS AND VOLTMETERS

Introduction

1. Reference has been made in previous chapters to the *values* of various electrical quantities without any explanation of how such quantities are measured in practice. The quantities which commonly require measurement are the currents established in, and the p.d.s developed across, various parts of a circuit. The measuring instruments used for these purposes are termed *ammeters* and *voltmeters* respectively. In this Chapter the operation of certain types of these "meters" is discussed.

Essentials of a Measuring Instrument

2. Measuring instruments have a moving system (usually mounted in jewelled bearings and free to rotate about a fixed axis) which carries a pointer over a graduated scale. When discussing the principle of operation of such instruments three forces have to be considered:—

(*a*) *Deflecting force*. This is the force which moves the pointer over the scale and it exists only when the meter is connected to a "live" circuit. The rotating system is deflected from its zero position by a torque that is some function of the quantity to be measured.

(*b*) *Controlling force*. This force acts in opposition to the deflecting force and brings the pointer to rest at a position on the scale where the deflecting and controlling forces are equal. In addition, the controlling force returns the pointer to zero when the deflecting force is removed, and for this reason it is sometimes termed the *restoring force*. The majority of meters have a "zero adjustment" on the controlling system so that the instrument can be set to zero when there is no deflecting force. Most instruments use a hairspring system to supply the controlling force, but control by a system of weights is sometimes used.

(*c*) *Damping force*. It is important that the movement should take up its final position quickly and without oscillation. Mechanical damping by a small plunger moving in a cylinder, or electromagnetic damping by induced eddy currents, are the means employed to secure this.

Differences Between Ammeters and Voltmeters

3. Most meters are current-operated; that is, the deflecting force results from a *current* passing through the instrument, although the meter may be scaled to read either amperes or volts. Thus in general, ammeters and voltmeters both work on the same principles. (An important exception is the electrostatic voltmeter described in Para. 26). The differences that occur in design are due only to their different functions:—

(*a*) *Ammeter*. This instrument is inserted *in series* with the circuit so that the current to be measured passes through it. The ammeter must be of *low resistance*, otherwise the circuit current will be considerably reduced when the meter is inserted and test conditions upset.

(*b*) *Voltmeter*. This instrument measures p.d. and so must be connected *across* the two points in a circuit between which the voltage is to be found. It must therefore have a *high resistance*, otherwise it will by-pass considerable current from the circuit being examined and test conditions will be upset.

4. The same instrument can be used either as an ammeter or as a voltmeter by suitably adjusting its resistance value (see Para. 9). The various types of ammeters and voltmeters in general use are classified as follows:—

(*a*) Moving coil.
(*b*) Rectifier.
(*c*) Moving Iron.
(*d*) Hot-wire.
(*e*) Thermo-junction.
(*f*) Electrostatic (voltmeter only).

Moving Coil Instruments

5. The operation of the moving coil meter is based on "the motor principle"; that is a current-carrying coil in a magnetic field experiences a torque (see Sect. 3, Chap. 2). The construction of a moving coil meter is illustrated in Fig. 1. The magnetic field is provided by a horse-shoe permanent magnet. Between the poles is fixed a cylindrical soft-iron core (concentrator) which serves to concentrate the flux in the air gap and give

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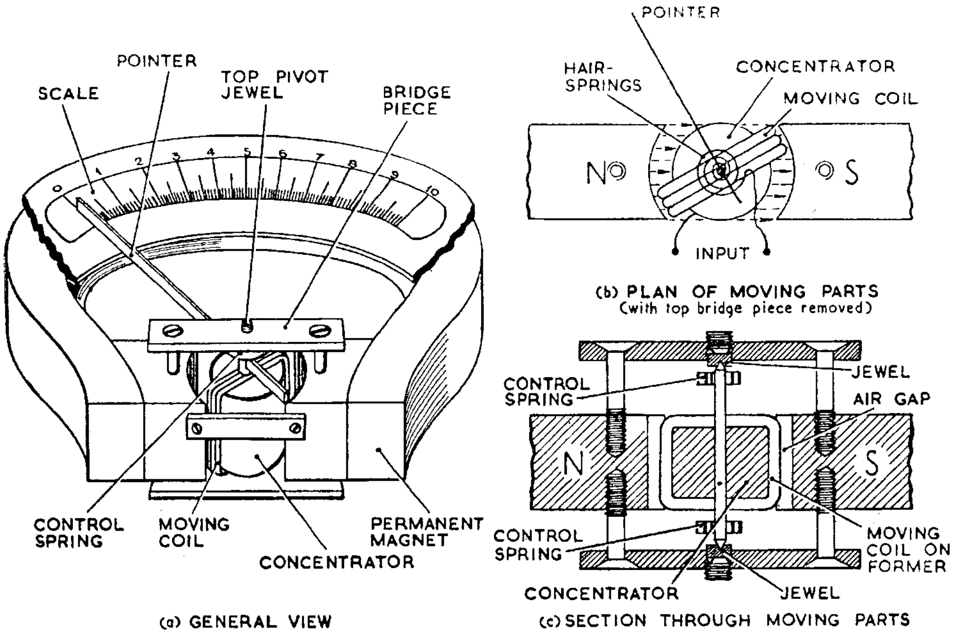

Fig. 1. MOVING COIL METER, CONSTRUCTION

a uniform *radial* field. A moving coil of fine copper wire is mounted on a light, rectangular, aluminium former placed over the iron core. The coil is pivoted to move freely in the air gap between the pole faces and the cylindrical core. The electrical connections to the coil are made by two hairsprings, one at either end of the coil former. The hairsprings are of phosphor-bronze or beryllium-copper, both of which have very stable elastic properties. The springs also provide the controlling force and are coiled in opposite directions to reduce the effect of temperature variation. The tension of the springs can be varied slightly to give zero adjustment. The pointer is attached to the same spindle as the coil former.

6. When the instrument is inserted in a circuit, current flows through the hairsprings to the coil. The resultant force tends to turn the coil on its pivots in a direction dependent upon that of the current (Fleming's left hand rule). Since the magnetic field is of the same intensity at all coil positions, the coil is subjected to a *constant* torque directly proportional to the current in it. As the coil rotates, the hairsprings become twisted and set up an opposing torque proportional to the angle through which the coil has turned. The coil therefore takes up a position in which the controlling force due to the springs just balances the deflecting force due to the current. Since these forces are proportional to the angle of rotation of the coil and to the current in the coil respectively, it follows that the deflection of the pointer attached to the coil is directly proportional to the current in the coil; the scale is therefore evenly divided. When the aluminium former is in motion, circulating eddy currents are established in it. From Lenz's law, the eddy currents produce a force tending to oppose the motion producing them, thereby acting as a damping device to bring the pointer to rest without oscillation.

7. The main *attributes* of moving coil meters are:—

(*a*) High sensitivity.

(*b*) Low power consumption.

(*c*) Suitability for adaptation as voltmeters or ammeters.

(*d*) Freedom from the effects of external magnetic fields.

(*e*) Linear scale.

(*f*) Excellent damping.

8. A *disadvantage* of moving coil meters is that, unless suitably modified, they are useful only for d.c. measurements. Since the direction in which the coil rotates is depend-

ent on the direction of the current, the meter must be connected in the correct polarity. For this reason the two test terminals are marked with + and — signs. Some moving coil meters have a centre-zero scale and can be read in either direction, in which case polarity is not important. If an alternating current of *very low frequency* is applied to such a moving coil meter, the meter will be able to follow the alternations and the pointer will move from side to side about the zero mark. At frequencies in excess of a few cycles per second however the pointer will be unable to follow and will read the *average* value of the current — i.e., zero. Hence, alternating current will not register on a moving coil meter. On the other hand, if the current consists of d.c. *plus* an a.c. component, a moving coil meter in the circuit will read the d.c. and be unaffected by the a.c.

Extension of Meter Range

9. It was stated in Para. 4 that a meter can be adapted as either an ammeter or voltmeter by suitably adjusting its resistance value. Consider a moving coil meter, having a coil resistance of 100 Ω and a full scale deflection (f.s.d.) current of 1 mA, as shown in Fig. 2.

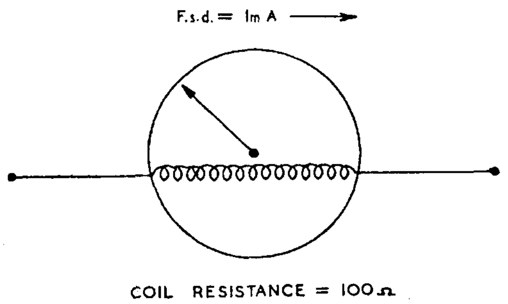

Fig. 2. BASIC MOVING COIL METER CIRCUIT

The voltage necessary for f.s.d. is:—

$$V = IR \text{ (volts)}$$

$$V = \frac{1}{1{,}000} \times 100$$

$$\therefore V = 0 \cdot 1V \text{ or } 100 \text{ mV}.$$

Thus, the meter scale could be calibrated to read either *current* or *voltage*, but only to a maximum of 1mA or 100mV respectively. To extend these to more practical ranges, suitable meter "shunts" or "multipliers" must be incorporated to change the meter resistance.

10. **Adapting as a Voltmeter.** The basic instrument is adapted by inserting a suitable resistor (known as a *multiplier*) *in series* with the coil. These resistors are usually made of a material which has a low temperature coefficient (e.g., manganin) to minimize inaccuracies due to temperature changes. The value of the necessary multiplier can be calculated by Ohm's law. Fig. 3 shows a moving coil meter which has a coil resistance of 100 ohms and a f.s.d. current of 1 milli-

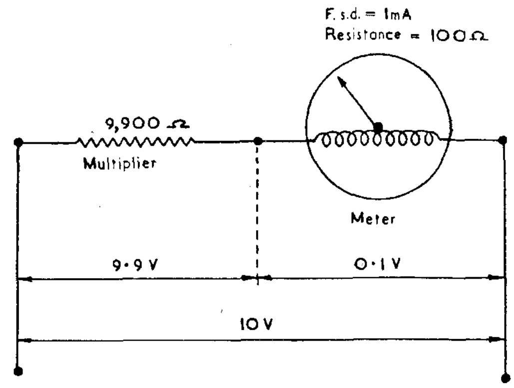

Fig. 3. ADAPTATION AS A VOLTMETER

ampere. To adapt the instrument for use as a voltmeter reading 0—10 volts, a resistor must be inserted in series with the coil. To find the value of this series multiplier:—

Maximum voltage to be measured = 10V

Maximum (f.s.d.) current = 1mA = 10^{-3}A

Total resistance of coil and multiplier = R_T

$$\therefore R_T = \frac{V}{I}$$

$$R_T = \frac{10}{10^{-3}}$$

$$\therefore R_T = 10{,}000 \ \Omega$$

Resistance of coil = 100 Ω

$\therefore$ Resistance of multiplier = 10,000—100 = 9,900 Ω

11. **Ohms Per Volt Rating.** A basic requirement of a meter is that it has minimum effect on the circuit under test. Thus, the less the current taken by a voltmeter, the more independent the circuit conditions will be of the meter loading. In practice the "resistance per volt" is made high to permit a low power consumption, 1,000 ohms per volt being a useful standard.

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12. **Adapting as an Ammeter.** Currents larger than the normal f.s.d. current can be measured by connecting a resistor (known as a *shunt*) *in parallel* with the coil of a moving coil meter. The resistance of the shunt is adjusted so that a definite fraction of the total current passes through the coil of the instrument, the remainder passing through the shunt. The scale of the meter is graduated to read the *total* current. Fig. 4 shows

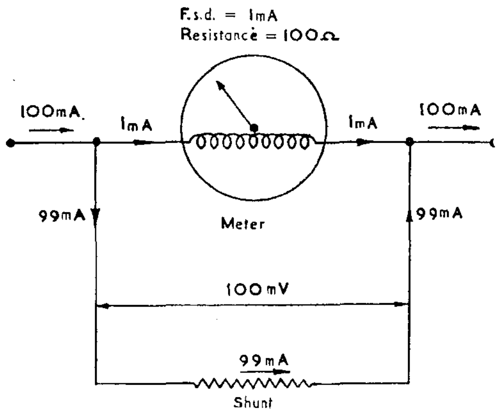

Fig. 4. ADAPTATION AS AN AMMETER

a moving coil meter, which has a coil resistance of 100 ohms and a f.s.d. current of 1 milliampere. To adapt the meter for use as a milliammeter reading 0—100 milliamperes, a shunt resistor must be connected in parallel with the coil. With 100 milliamperes total current, the division of current must be:—

Coil current = 1mA

Shunt current = 100 — 1 = 99 mA

P.d. across coil = Coil current × coil resistance

$$\therefore V = \frac{1}{1{,}000} \times 100$$

$$\therefore V = 100\text{mV}$$

Since the coil and shunt are in parallel, the p.d. across the shunt is also 100mV.

$$\therefore \text{Resistance of shunt} = \frac{\text{Shunt p.d.}}{\text{Shunt current}}$$

$$R = \frac{100 \times 10^{-3}}{99 \times 10^{-3}}$$

$$\therefore R \simeq 1\,\Omega$$

13. **Swamping resistors.** The shunt of an ammeter is made of manganin or similar alloy, having a low temperature coefficient, while the coil of the instrument is of fine copper wire which has a relatively high temperature coefficient. The passage of current through the instrument increases the temperature of the coil and results in an increase in coil resistance; but the resistance of the shunt will remain virtually constant. The ratio of coil resistance to shunt resistance is thus varied, and the meter tends to become inaccurate. The inaccuracy can be reduced by inserting a "swamping" resistor of manganin in series with the coil (Fig. 5).

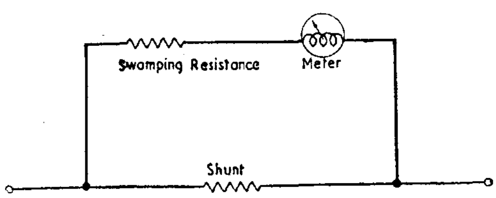

Fig. 5. SWAMPING RESISTOR

If the added resistance is high in relation to the coil resistance, any small changes in coil resistance due to heating are "swamped" by the constancy of the remainder of the resistance in the coil circuit.

Rectifier Instruments

14. A rectifier is a component which, while permitting the free passage of current in one direction, virtually stops the flow in the opposite direction, (see Sect. 9). Thus, on applying a.c. to a rectifier, current flows in one direction only. A rectifier fitted in series with the coil of a moving coil meter will ensure that only current in the correct direction is established in the meter, thereby

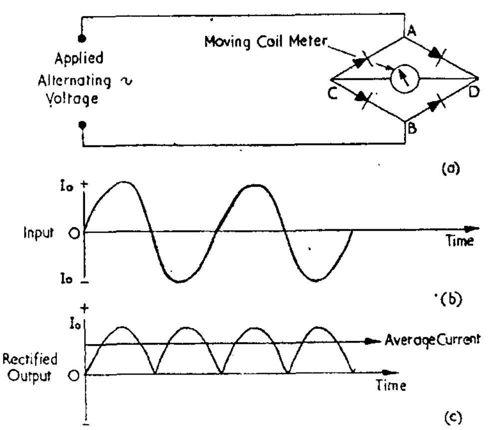

Fig. 6. PRINCIPLE OF THE RECTIFIER INSTRUMENT

preventing reversal of the deflecting force on the coil. By this means, a moving coil meter *with a rectifier* can be used to measure alternating currents and voltages. A typical arrangement is shown in Fig. 6(*a*). When the alternating voltage of Fig. 6(*b*) is applied between terminals A and B, the current through the moving coil meter connected between C and D is a "rectified" current as shown in Fig. 6(*c*). The meter reads the *average* value of the rectified current, but the scale is normally calibrated to indicate *r.m.s. values*. When a moving coil meter has been modified in the manner described it can be used for a.c. measurements up to frequencies of the order of 100 kc/s.

Moving Iron Instruments

15. There are two types of moving iron instrument which differ according to whether deflection is produced by magnetic attraction or repulsion. The former makes use of the attraction of iron in the electromagnetic field of a current-carrying solenoid; the latter depends upon the mutual repulsion of two similar, magnetised pieces of iron within an energised solenoid, one being fixed and the other movable.

16. **Attraction type.** This instrument is illustrated in Fig. 7. The current to be measured passes through a coil wound on a non-magnetic former, thereby establishing a magnetic field whose strength is proportional to the current. An eccentrically pivoted soft iron vane, which carries a light pointer, is magnetised by induction from the field and assumes *opposite* polarity, irrespective of the direction of the current. It is consequently attracted into the open end of the coil, thus moving the pointer over the graduated scale. The controlling force is provided by a hairspring (as shown) or by the pull of gravity on the soft iron vane. Damping is provided by a piston moving in a dashpot.

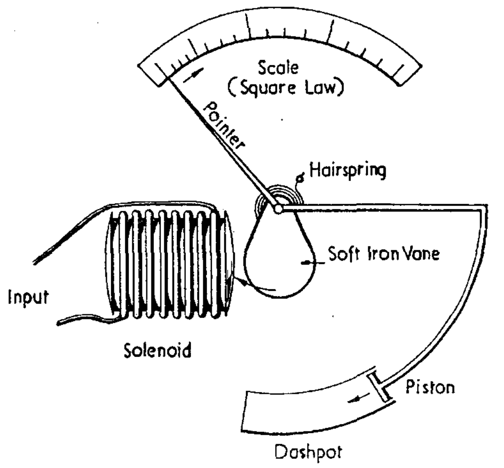

Fig. 7. ATTRACTION TYPE MOVING IRON INSTRUMENT

17. The force of attraction between the soft iron vane and the coil (i.e. the deflecting force) is proportional to the strength of the field due to the current in the coil, and to the strength of the induced magnetism in the soft iron vane. *Both* are proportional to the coil current. The deflecting force is, therefore, proportional to the *square* of the current. As a result, the graduations of the scale are not uniform, but are crowded at the lower end. A scale of this type is generally known as a "*square-law*" scale. The meter scale is fundamentally a square-law one, but by suitable shaping of the vane, the scale may be made to approach a linear law.

18. **Repulsion type.** This is illustrated in Fig. 8. Two pieces of soft iron are arranged

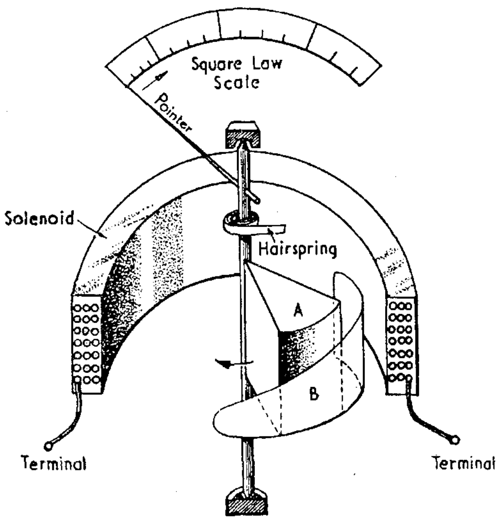

Fig. 8. REPULSION TYPE MOVING IRON INSTRUMENT

inside and parallel to the axis of a circular magnetising coil, which is carrying the current to be measured. One of the pieces (A) is of uniform breadth and is attached to a pivoted spindle which also carries the

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pointer. The other piece (B), which is *fixed* to the case, is curved to a circular arc and is tapered in breadth. Under the magnetising force of the current in the coil both pieces of iron are magnetised in the *same sense* and, since like poles repel each other, the moving iron (A) will be repelled from the wide to the narrow end of the fixed iron (B). The controlling force is provided by hairsprings, and damping is by the air dashpot method (not shown).

19. The force of repulsion is proportional to the *product* of the magnetic field strengths of the two iron pieces. Since each of the field strengths is proportional to the coil current, the movement of the pointer is proportional to the *square* of the current, and the scale is square-law.

Note. Since the meter reads $(\text{current})^2$, the scale must be calibrated to give the square root of this. A meter whose scale has been graduated in this way will read the true value for d.c. or the r.m.s. value for a.c.

20. **Advantages of the moving iron instrument.**

(*a*) Cheap, simple and robust.

(*b*) Can be used to measure d.c. or *low frequency* a.c. since the deflecting force is in the same direction irrespective of the direction of the current.

(*c*) Can be used as either ammeters or voltmeters; ammeters have a coil of few turns of thick wire to provide a low resistance; and voltmeters use a coil of many turns of fine wire to give a high resistance.

21. **Disadvantages of the moving iron instrument.**

(*a*) Affected by external magnetic fields.

(*b*) Subject to errors from hysteresis.

(*c*) Uneven scale; can be made more linear by suitably shaping the soft iron pieces.

(*d*) Sensitivity and accuracy are poorer than that of the moving coil meter.

Hot-wire Instruments

22. The hot-wire instrument shown in Fig. 9 measures current by using the heating effect. The construction consists of a wire W, which has a high melting point and a large coefficient of expansion (e.g., platinum-silver), stretched between a fixed point A and a zero-adjusting screw B. One end of a phosphor-bronze wire P is attached to W at C the other end being fixed to an insulated post. A silk fibre is attached to P at D, and the fibre passes round a pulley E which carries a pointer. The silk is kept in tension by a spring F. When a current is passed through W, the wire expands and sags. The sag in W is taken up by the spring F acting through the silk fibre and P, and the pulley rotates, moving the pointer over the scale. A small expansion of the wire W is greatly magnified and conveyed to the pointer. Eddy current damping is introduced by an aluminium disc H (carried on the spindle of the pulley) moving between the poles of a permanent magnet G. The heating effect of the current is proportional to the *square* of the current so that the expansion of W, and consequently the pointer deflection, also varies as I^2. The scale is, therefore, square-law.

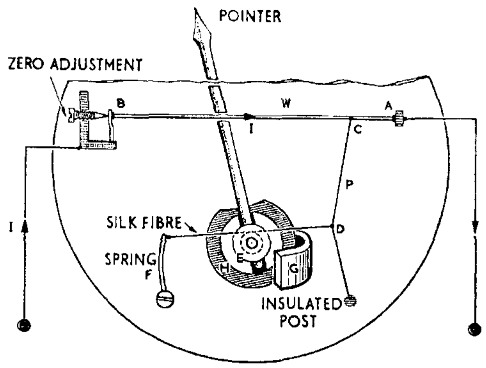

Fig. 9. HOT-WIRE INSTRUMENT

23. The advantages and disadvantages of the hot-wire ammeter are listed below:—

(*a*) *Advantages.*

(i) Can be used for d.c. or moderately high-frequency a.c. measurements since the heating effect is independent of the current direction.

(ii) Efficient damping.

(*b*) *Disadvantages.*

(i) Fragile and easily overloaded.

(ii) Suffers from zero drift due to thermal and elastic fatigue in the wire.

(iii) The power absorbed is high.

(iv) Sluggish in action.

(v) Square-law scale.

Thermo-junction Instruments

24. If two dissimilar metals are joined at one end and the junction heated, a *thermo-*

electric e.m.f. is set up and current will flow in any circuit connected to the other ends of the two metals. The usual "*thermo-junction*" used in meters consists of bismuth and antimony, but other combinations may be used.

25. This principle is used in the thermo-junction meter illustrated in Fig. 10. The current to be measured passes between A and B, raising the temperature of the heater

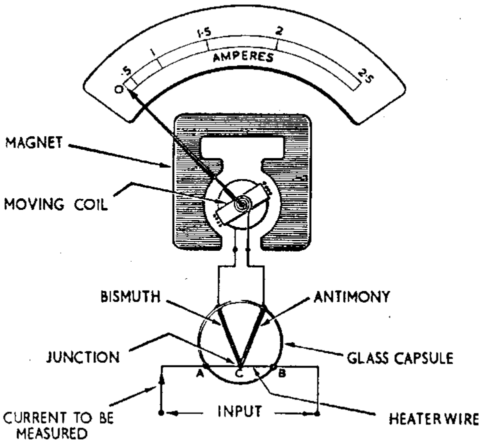

Fig. 10. THERMO-JUNCTION INSTRUMENT

wire. The thermo-junction can be spot-welded to the heater wire at C, or simply placed close to the heater without actually touching it. In either case the junction is normally surrounded by a glass capsule which is evacuated to reduce heat losses. As the temperature of the heater wire (and hence that of the thermo-junction) rises with increased current, so the e.m.f. across the two dissimilar metals rises. The current resulting from the thermo-junction e.m.f. is indicated by a moving coil meter, and the meter is calibrated to read directly the current in the external circuit of which the heater wire AB forms a part. Since the heating effect is independent of the direction of the current, the thermo-junction meter is suitable for both a.c. and d.c. The meter is so built that the junction is neatly encased in the instrument and it often resembles an ordinary moving coil meter though, as it depends for its action on the heating effect of a current, its scale is *square-law*. The thermo-junction meter has all the advantages of the moving coil meter, with the added advantage that it can be used for the measurement of *radio frequency current*.

Electrostatic Voltmeters

26. The action of this instrument depends on the force of attraction which exists between two bodies having opposite electric charges. This principle cannot be applied to the measurement of current, but it is frequently used in the measurement of high voltage. One type of electrostatic voltmeter is illustrated in Fig. 11. It consists of a spring-loaded pivoted spindle on which is mounted a pointer and a light aluminium vane C, the latter being so positioned that it can rotate between two fixed plates A and B. The fixed plates are electrically common and are insulated from the metal body of the instrument. Also mounted on the spindle

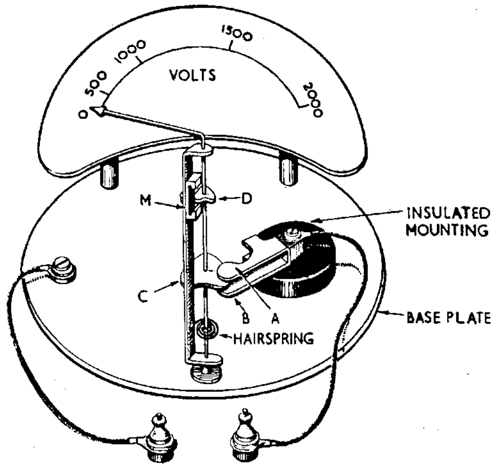

Fig. 11. ELECTROSTATIC VOLTMETER

is an additional small vane D which moves between the poles of a permanent magnet M to give eddy current damping. The hairspring tends to hold vane C away from the fixed plates and acts as the controlling force. One terminal of the meter is connected to the fixed plates, the other terminal being connected to the moving vane C via the metal base plate and the spindle.

27. When a voltage is being measured, a difference of potential is established between vane C and the fixed plates, and they acquire equal and opposite charges in a manner similar to that of a capacitor. The electrostatic attraction between the oppositely-charged plates causes vane C to move into

the space between the fixed plates, and the pointer moves over the scale. This movement continues until the deflecting force is balanced by the controlling force of the hairspring, when the pointer comes to rest. The equal charges on the fixed and moving plates are proportional to the voltage being measured, but the force of attraction between the plates is proportional to the *product* of the charges (Coulomb's law). The movement of vane C and the pointer is thus proportional to the *square* of the applied voltage, giving a square-law scale. Since the deflection depends on V^2 the instrument can be used both for direct and alternating voltage measurement. When calibrated for d.c. measurement it reads r.m.s. values on a.c.

28. The great advantage of the electrostatic voltmeter is that the power consumption is negligible. It is not affected by external magnetic fields. It must, however, be screened against the effect of external *electrostatic* fields. The number of vanes on the instrument varies with the range; on a typical 150V instrument there are 13 moving vanes arranged in a manner similar to that of an ordinary variable capacitor; on a 3,500V instrument there is a single moving vane (Fig. 11). Electrostatic voltmeters are used mainly for high voltage measurement.

Summary

29. The main points concerning the meters discussed in this Chapter are summarised in Table 1.

Type	Scale	Remarks	Main Use
Moving coil	Linear	Sensitive and accurate. D.C. only	Most d.c. circuits
Moving coil (Rectifier)	Linear. If calibrated on d.c., reading must be multiplied by 1·11 to give r.m.s. value on a.c.	D.C. and a.c. up to frequencies of the order of 100 kc/s.	In testmeters
Moving iron (both types)	Square-law. If calibrated on d.c., gives r.m.s. value on a.c.	D.C. and low frequency a.c.	A.C. power supply circuits.
Hot-wire	— ditto —	D.C. and a.c. up to moderately high frequencies. Sluggish in action	Not often used
Thermo-junction	— ditto —	D.C. and a.c. up to very high frequencies	Radio frequency currents
Electrostatic voltmeter	— ditto —	D.C. and a.c. Negligible power consumption	High voltage measurement

TABLE 1. AMMETERS AND VOLTMETERS

SECTION 6

CHAPTER 2

TEST INSTRUMENTS

TEST INSTRUMENTS

Introduction

1. The primary concern of the radio fitter is to maintain the equipment for which he is responsible in an efficient state. This involves the location and rectification of faults in the equipment and this can be achieved by careful observation and routine testing using appropriate test equipment. The quantities which normally require to be measured during "fault-finding" are current, voltage and resistance at various points in a circuit. Current and voltage measurements are carried out with ammeters and voltmeters, such as those described in Chap. 1. The instruments used for resistance measurement—together with the multi-purpose test instruments which combine the measurement of current, voltage and resistance—are described in this Chapter.

2. Instruments used for measuring resistance are of three main classes:—

(*a*) General purpose instruments which are used to measure *medium* values of resistance fairly accurately. The "*simple ohmmeter*" satisfactorily fulfils this function.

(*b*) Continuity testers, to indicate *very low* values of resistance such as those which occur when testing the continuity of a cable. The "*bonding tester*" does this accurately.

(*c*) Insulation testers, to measure *very high* values of resistance such as those which occur when testing the insulation between cables. The "*megger*" is the instrument generally used for this.

Simple Ohmmeter

3. Approximate measurements of resistance may be carried out by means of the simple and convenient arrangement illustrated in Fig. 1. A sensitive milliammeter is connected in series with a single 1·5V cell and a variable resistor R. Terminals X and Y are short-circuited and R adjusted to give full scale reading on the meter. This adjustment allows for variation in the p.d. of the battery with use. If now the short-circuit is removed, and a resistor of *known* value is connected between X and Y, the resultant *decrease* of current is a measure of the value of the resistance, and the current scale can be calibrated in ohms. The *greater* is the resistance, the *less* the deflection. Such an arrangement is called an ohmmeter and is invariably included as an integral part of the multi-range test sets described later.

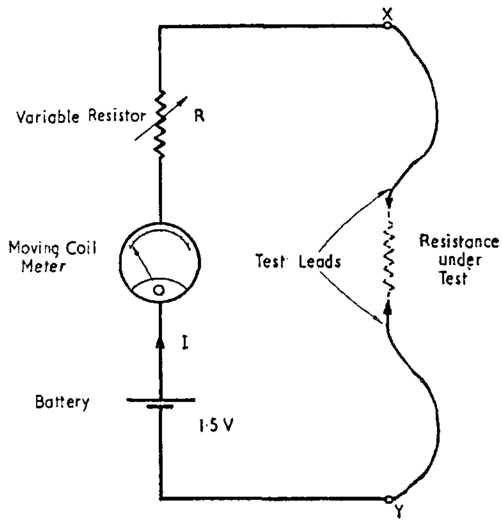

Fig. 1. SIMPLE OHMMETER CIRCUIT

Multimeters

4. These are multi-purpose, multi-range testmeters for the measurement of voltage, current and resistance values, the basic measuring unit being a sensitive moving coil meter. For the first two of these functions it is simply a question of arranging suitable switches to bring in the appropriate series multiplier or shunt resistors. A second set of voltage and current circuits *with a rectifier* may be provided for a.c. measurements. For resistance measurement an ohmmeter assembly, with battery and variable resistor, is switched in.

5. A typical multimeter uses a moving coil meter which itself has a resistance of 50 ohms and gives f.s.d. with 2 milliamperes. Fig. 2 shows the d.c. voltmeter arrangement. Terminal X goes to a suitable switch which makes contacts A, B, C, D or E, and terminal Y goes directly to the meter. The series multiplier resistors are arranged in cumulative steps, with the results of Table 1.

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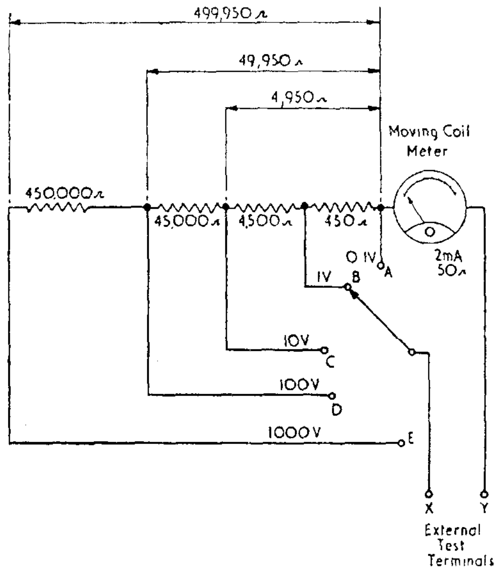

Fig. 2. D.C. VOLTMETER ARRANGEMENT

Position of Switch	Series Multiplier (Ohms)	Total Resistance (Ohms)	P.d. between X and Y for f.s.d.
A	0	50	$50 \times 0 \cdot 002 = 0 \cdot 1V$
B	450	500	$500 \times 0 \cdot 002 = 1V$
C	4,950	5,000	$5{,}000 \times 0 \cdot 002 = 10V$
D	49,950	50,000	$50{,}000 \times 0 \cdot 002 = 100V$
E	499,950	500,000	$500{,}000 \times 0 \cdot 002 = 1{,}000V$

TABLE 1. VOLTAGE MEASUREMENT.

6. For the d.c. ammeter ranges, the universal shunt principle is used. The full resistance of the tapped shunt (Fig. 3) is 12·5 ohms, which is one quarter of the meter resistance. Thus, when the switch is in position A, *one fifth* of the total current passes through the meter, and f.s.d. corresponds to $5 \times 0 \cdot 002 = 0 \cdot 01$ A. The tappings are at $\frac{1}{10}$, $\frac{1}{100}$ and $\frac{1}{1{,}000}$ of the total shunt resistance, giving the ranges shown in Table 2.

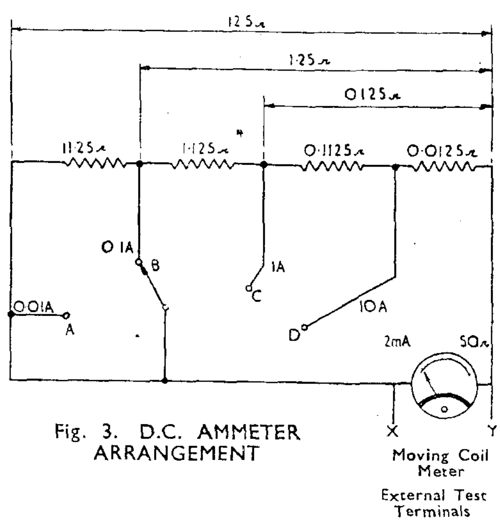

Fig. 3. D.C. AMMETER ARRANGEMENT

Position of Switch	Fraction of Shunt in Parallel with Meter	Current between X and Y for f.s.d.
A	All	0·01A
B	$\frac{1}{10}$	10 × 0·01 = 0·1A
C	$\frac{1}{100}$	100 × 0·01 = 1A
D	$\frac{1}{1,000}$	1,000 × 0·01 = 10A

TABLE 2. CURRENT MEASUREMENT.

7. Where a.c. measurements are included, the moving coil meter is connected to the output of a bridge rectifier, the input to which is from a *transformer* (see Sect. 7). The current and voltage a.c. ranges are then obtained by adjusting the transformer on each switch position.

8. When the meter is switched to read resistance, a battery is connected in series with an adjustable resistance network and the meter, as in the simple ohmmeter.

Testmeter Type D

9. The Testmeter Type D, commonly known by its trade name of "Avometer" is a multimeter of the type described in the preceding paragraphs, and is illustrated in Fig. 4. It is a 34-range instrument giving the ranges shown in Table 3.

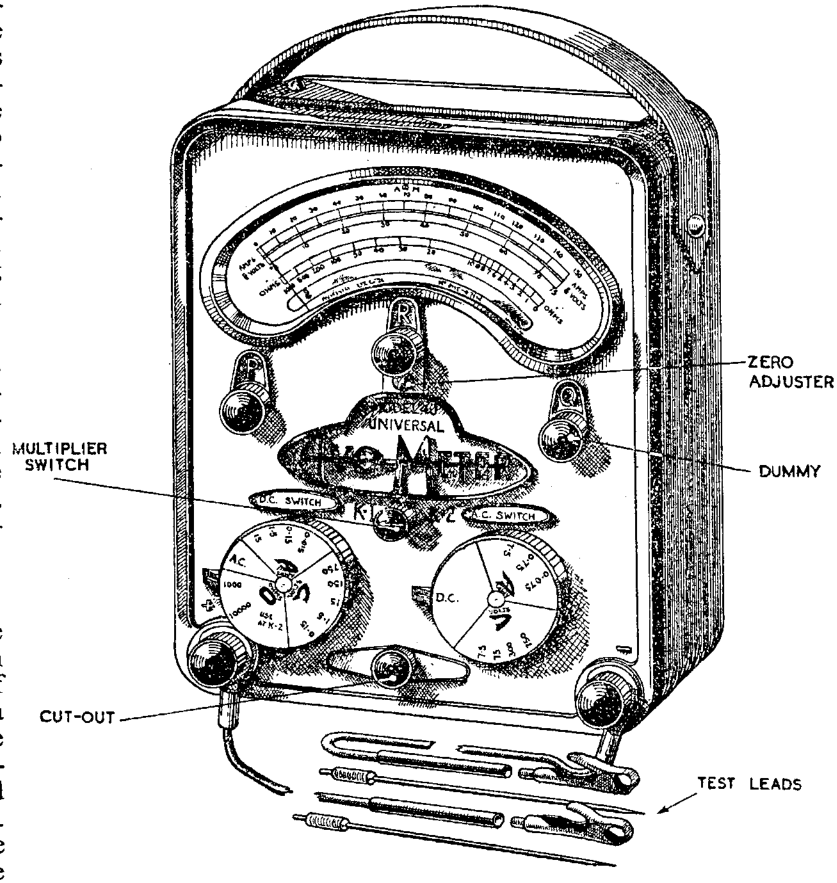

Fig. 4. TESTMETER TYPE D

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Voltage		Current	
D.C.	A.C.	D.C.	A.C.
Ten ranges, 0 — 150mV to 0 — 1,500V	Eight ranges, 0 — 7·5V to 0 — 1,500V	Eight ranges, 0 — 15mA to 0 — 30A	Six ranges, 0 — 75mA to 0 — 15A
	Resistance		
—	0 — 1,000 Ω 0 — 10,000 Ω		—

TABLE 3. RANGE MEASUREMENTS.

10. The scale has three sets of calibrations marked in Amps, Volts and Ohms (hence the name "Avo"). A 1·5V dry cell supplies the voltage when the testmeter is used as an Ohmmeter, and the two controls P and R are used to adjust variable resistors which compensate for variation of voltage with use. An automatic cut-out, operated by the pointer when the latter travels beyond the f.s.d. point, safeguards the movement from overload by opening the circuit; it is re-set by pressing the knob shown in Fig. 4. Two test leads, coloured red and black, are connected to terminals marked + and − respectively. Two range switches are adjusted for the type and range of measurement required. In the K = 2 position of the multiplier switch, f.s.d. is produced by *twice* the value shown on the range switch. This applies to current and voltage ranges only.

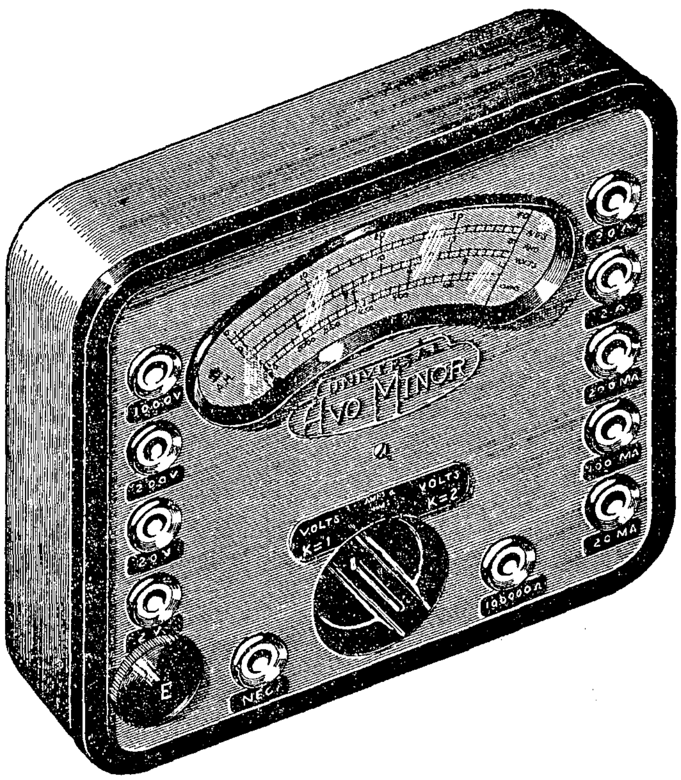

Fig. 5. TESTMETER TYPE E

Testmeter Type E

11. This instrument, illustrated in Fig. 5, is commonly referred to as the "Avo Minor", and is a multimeter used for d.c. measurement only. Thus, no rectifier or transformer is fitted. It is a 14-range instrument giving the ranges shown in Table 4.

12. The front of the testmeter carries eleven protected sockets and a three-position switch. The movement is protected by a fuse held in a detachable carrier marked E, which screws into the front panel. A slotted screw in the centre of the front panel provides zero adjustment on the volts and amps scales. A second zero adjuster, used to compensate for battery voltage variations when measuring resistance, is located on the bottom edge of the testmeter (not seen in Fig. 5). The socket marked NEG is

Voltage	Current
Eight ranges, 0 — 2V to 0 — 2,000V	Five ranges, 0 — 20mA to 0 — 20A
	Resistance
	0 — 10,000Ω
Multiplier switch on the panel doubles *voltage* indications in position K = 2	

TABLE 4. RANGE MEASUREMENTS.

common to all ranges and carries one of the test leads, the other test lead being plugged into the socket covering the desired range. The three-position switch must be correctly set.

13. The simple ohmmeter, as used in Testmeters Types D and E, requires continual adjustment if the error due to variation in supply voltage is to be eliminated. This error occurs since the deflecting force varies with the applied voltage, but the controlling force exerted by the springs of the instrument remains unaffected. This unsatisfactory feature is overcome in the *ratiometer* type of ohmmeter.

The Ratiometer Principle

14. In the ratiometer the controlling force is an electrical force which is derived from the same supply voltage as the deflecting force. Any variation in supply voltage affects both forces equally, and error due to variation in the supply voltage is eliminated. The ratiometer is illustrated in Fig. 6. It is essentially a moving coil instrument in which the usual solid cylindrical iron core is replaced by a *hollow* concentrator which is mounted eccentrically to give a varying air gap. The flux density between the pole faces and the concentrator therefore varies from a maximum at the lower pole faces to a minimum at the upper portion. In addition to the normal deflecting coil A, a second coil B is wound on the same former-unit, but at an angle to coil A. Only one side of coil B is exposed to the magnetic flux, the other side being screened from the flux by the concentrator. The coils are wound in such a way that when they are connected to a single source they will produce *opposing* torques. The instrument has no hairspring control so that with both coils disconnected from the supply the pointer will "wander", having no fixed position.

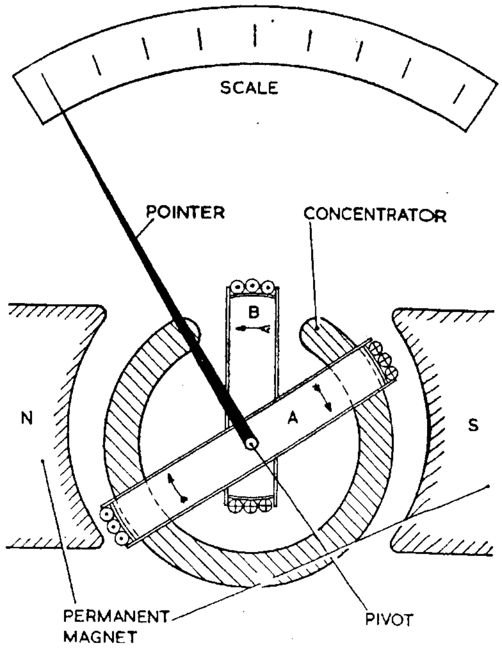

Fig. 6. RATIOMETER TYPE OF OHMMETER

15. The coils are wound with very fine wire and can carry only a small current. Each coil is therefore connected in series with a resistor in order to limit the current. Coil B, with its associated resistor X, is connected across the supply voltage. Coil A, with its

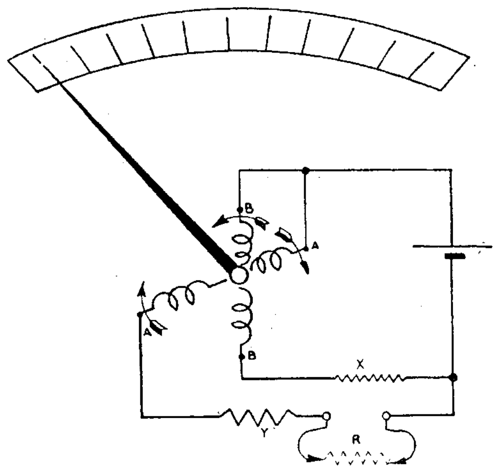

Fig. 7. CIRCUIT OF RATIOMETER

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resistor Y, is also connected across the supply when an external resistance R is connected across the test leads (Fig. 7). With a given current in coil A, the torque exerted will be relatively constant, irrespective of its position in the air gap, since a weaken ing of flux at one side of the coil is compensated by a corresponding strengthening of flux at the opposite side. The torque due to coil B, with a given current, will vary according to the position of the unscreened side of the coil, being zero at the position shown in Fig. 6 and increasing steadily as the unscreened side of the coil moves into the decreasing air gap.

16. (*a*) With the test leads open-circuited there is no circuit through coil A. Coil B exerts an anti-clockwise torque, and when it reaches the magnetic neutral position (Fig. 6), the torque ceases and the pointer takes up a position at the left hand side of the scale, reading infinity.

(*b*) With the test leads connected to a circuit, current is established in coil A. This current is inversely proportional to the resistance of the circuit under test, and the resulting torque moves the former unit *clockwise* and the pointer traverses the scale. As the unscreened side of coil B moves into the air gap an *anti-clockwise* torque is developed, and this increases steadily as coil B moves into the decreasing air gap. The torque due to coil A remains constant. When the torques due to each coil are equal, the coil former stops and the pointer indicates the external circuit resistance on the scale.

Bonding Tester

17. This is a ratiometer type of instrument designed to measure very low values of resistance. It is intended primarily for testing the continuity of "bonded" connections in aircraft to ensure that the resistance between such connections does not exceed a certain authorised maximum value. It can also be used for continuity testing of other circuits. The simple ohmmeter is not sufficiently accurate to perform this function satisfactorily. The bonding tester consists of a wooden case in which is housed a ratiometer type of ohmmeter and a 1·2V battery, a 6 ft. length of twin flexible cable (A) carrying a double-spike probe, and a 60 ft. length of similar cable (B) attached to a single-spike probe (Fig. 8).

18. Reference to Fig. 9 will show that with both probes connected to the bond under test, the low resistance coil A is energised by current flowing from the cell to the single spike, through the bond under test to the right hand spike of the double probe, to the coil, and so to the negative pole of the cell. That is, coil A is *in series* with the bond under test. The high resistance coil B is *in parallel* with the bond under test; it will therefore carry a current proportional to the *p.d.* across the bond. The position taken up by the pointer is determined by the ratio between opposing torques, i.e., by the ratio

$$\frac{\text{Voltage across bond}}{\text{Current in bond}} = \text{Bond resistance.}$$

Megger

19. A distinct difference exists between resistance measurement as applied to conductor resistance, and resistance measurement of insulation. The ability of an

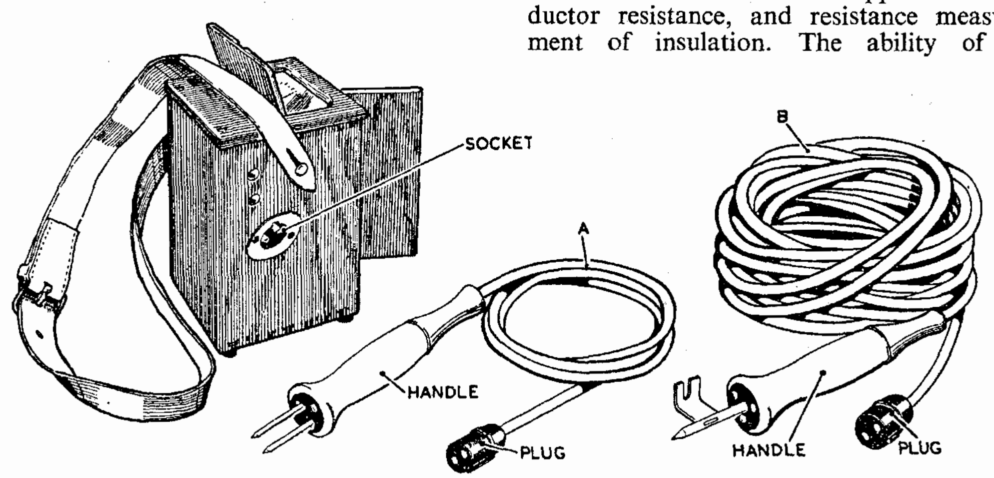

Fig. 8. BONDING TESTER

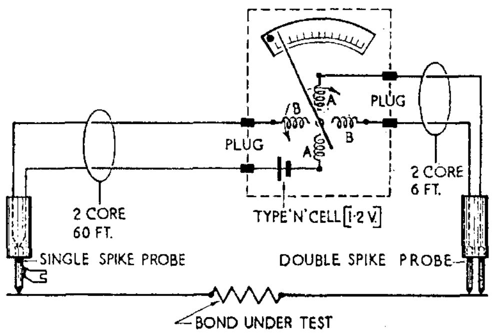

Fig. 9. CIRCUIT OF BONDING TESTER

insulator to resist the passage of current is affected by the voltage applied to it, and in extreme cases the insulation may break down completely under increasing voltage. Insulation resistance measurement is usually carried out with a testing voltage considerably in excess of the normal voltage of the circuit. If the resistance value remains high under high voltage conditions, it is safe to assume that there is little risk of failure in operation at the normal supply voltage.

20. Several types of insulation testers are available, but the majority consist of a ratiometer type of ohmmeter with a hand-driven generator as the source of supply. Typical of those approved for insulation testing of radio installations and equipments is the Insulation Tester Type C, more generally known as the "Wee Megger" (Fig. 10). The generator is of the two-pole permanent magnet type, driven through gears by a handle which folds back into a recess in the casing when not in use. A clutch is provided to restrict the output voltage of the generator to 250V d.c. at a handle speed of 160 r.p.m. The scale reads from zero to infinity with intermediate readings between 10,000 ohms and 20 megohms.

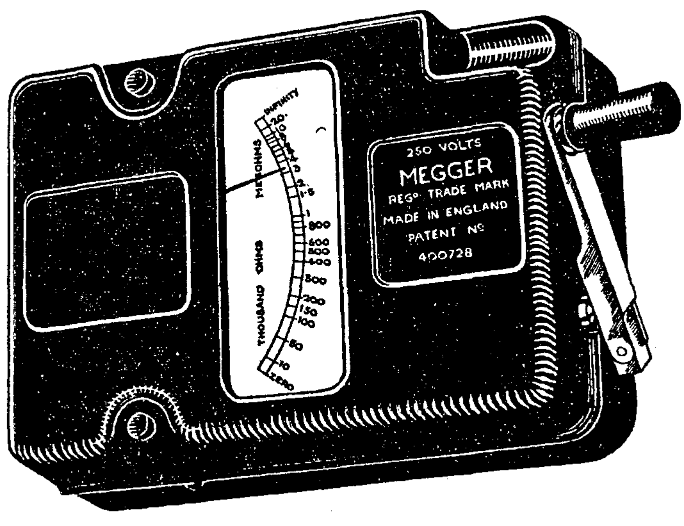

Fig. 10. INSULATION TESTER TYPE C

21. Insulation tests may be divided into two categories, examples of each being given below:—

(*a*) *Insulation to earth.* This test is to establish that a circuit is electrically isolated from metal which surrounds or supports it. One lead of the Megger is connected to the circuit and the other to a clean surface on the frame on which the circuit is installed (Fig. 11). The tester handle is turned at 160 r.p.m. and the insulation resistance between the circuit and the frame is read off the scale. It should not normally be less than several megohms.

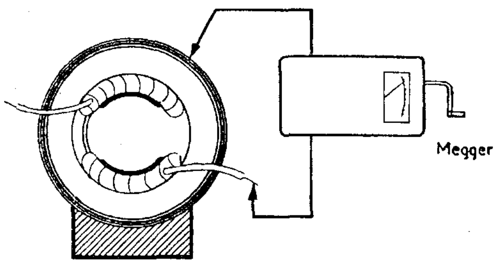

Fig. 11. TESTING INSULATION TO EARTH

(*b*) *Pole to pole tests.* These tests verify that the insulation is satisfactory between one part of a circuit and another, e.g., the insulation between the cores of a cable (Fig. 12). The tester leads are connected to the conductors between which it is desired to test the insulation. On turning the Megger handle at approximately 160 r.p.m. the insulation resistance will be indicated. The

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minimum permissible insulation resistance for any given circuit or component is given in the appropriate servicing schedule.

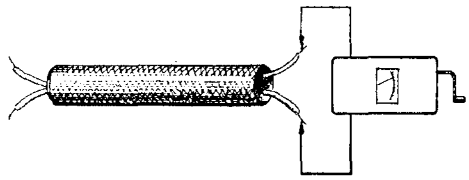

Fig. 12. TESTING INSULATION BETWEEN THE CORES OF A CABLE

Summary

22. The main points concerning the test instruments discussed in this Chapter are listed in Table 5.

Instrument	Details	Use
Testmeter Type D (Avometer)	Multimeter using shunts and multipliers to give current and voltage d.c. ranges: rectifier and transformer for a.c. ranges: simple ohmmeter for resistance measurement.	General purpose testing and fault-finding: moderate values of resistance where a high accuracy is not essential.
Testmeter Type E (Avominor)	Similar to the Testmeter Type D but with the a.c. ranges excluded.	D.c. measurements only during general purpose testing.
Bonding tester	Ratiometer type of ohmmeter.	Accurate measurement of very low resistance values.
Insulation Tester Type C (Wee Megger)	Ratiometer type of ohmmeter with a hand-driven generator supply.	Insultation testing and measurement of very high resistance values.

TABLE 5. SUMMARY OF TEST METERS.

SECTION 6

CHAPTER 3

MEASUREMENT OF POWER

MEASUREMENT OF POWER

Introduction

1. In a d.c. circuit, the product VI, where V is the steady p.d. across a load and I the steady current through it, measures the power consumption of the load. In an a.c. circuit, the product of the instantaneous values of voltage and current gives the *instantaneous* rate of working. The product of the r.m.s. values of V and I gives the *apparent power* in the circuit. Except in the case of a purely resistive load, there will be a phase difference θ between voltage and current. The *true power* in the circuit is then VI cos θ, where cos θ is the power factor of the load. An instrument designed to measure true power in an a.c. circuit is termed a *wattmeter*. It combines in itself the functions of voltmeter and ammeter, and responds to phase difference in such a way as to record the true power VI cos θ.

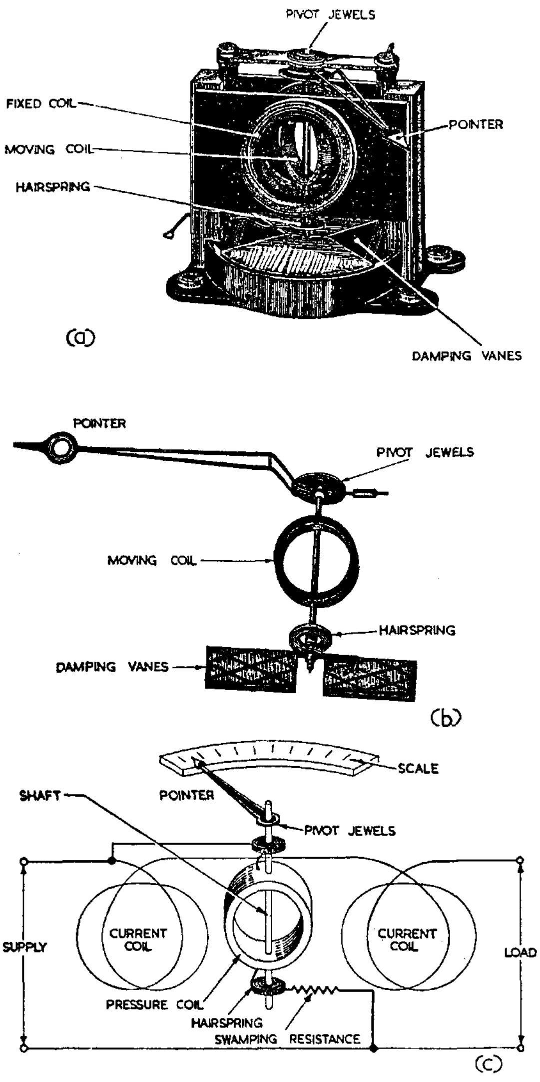

Fig. 1. THE DYNAMOMETER WATTMETER

Dynamometer Wattmeter

2. This type of instrument is in general use for the measurement of power at *low frequencies* and is the only one considered in this Chapter. The complete assembly of a typical dynamometer wattmeter is shown in Fig. 1(*a*), the assembled moving system (i.e., the moving coil, damping vane, control springs and pointer) being shown in Fig. 1(*b*). Fig. 1(*c*) shows the connections in diagrammatic form. The fixed coil assembly (the "*current*" coil) consists of two air-cored coils connected in series with the load. The moving coil (the "*pressure*" coil) is of fine wire, wound on a light frame which is mounted on a spindle and pivoted to turn in the magnetic field produced by the current coil. The movement is controlled by two hairsprings of phosphor-bronze, which also serve as the connections to the pressure coil. Air damping is provided.

3. A simplified circuit diagram of the dynamometer wattmeter is given in Fig. 2. The low resistance current coil L_1, is connected *in series* with the load and carries

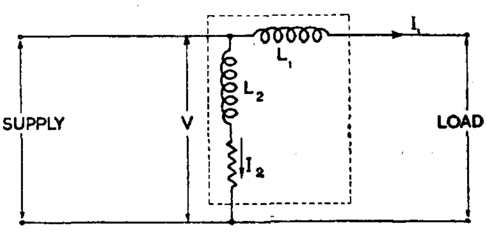

Fig. 2. SIMPLIFIED CIRCUIT OF THE DYNAMOMETER WATTMETER

the whole of the load current. The magnetic field of this coil is thus proportional to the instantaneous current. The high resistance pressure coil L_2 is connected in series with a high resistance, *across* the load voltage.

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The reactance of this circuit can therefore be neglected at low frequencies, and the current in the pressure coil is *in phase with*, and proportional to, the load voltage. The connections of the fixed coil L_1 resemble those of an ammeter and the connections of the moving coil L_2 those of a voltmeter.

4. The torque exerted upon the moving coil is proportional to the product of the currents in each of the coil assemblies; that is, to the product of the instantaneous current and the instantaneous voltage in the load, namely the instantaneous power. The *average* value of this torque over any number of complete cycles gives an indication of the true power (VI cos θ) and the scale is graduated accordingly.

5. At high frequencies, the increased reactance of the instrument introduces additional phase shift and the meter becomes increasingly inaccurate. The usual practice at high frequencies is to measure the current in a known resistance in the circuit. Alternatively, the voltage across a standard resistance inserted in the circuit can be measured. The power is then calculated from the relationship:—

$$P = I^2 R$$

$$P = \frac{V^2}{R} \text{ (watts).}$$

The ammeter or voltmeter used will normally be a rectifier type of instrument, and the scale may be calibrated directly in watts (when used with a standard resistance).

Power Ratios

6. No device can deliver more power than is supplied to it. *Amplifiers* are designed to increase the power of an a.c. by drawing additional power from an independent supply. If the power supplied to operate the amplifier (the input) is 2 watts, and the power delivered from the amplifier to a load (the output) is 40 watts, the power ratio or "*gain*" is $\frac{40}{2} = 20$. The power drawn from the supply is $40 - 2 = 38$ watts.

7. Power losses occur under certain conditions, and circuits called *attenuators* are designed to reduce the power of an a.c. If the input power to the attenuator is 5 watts and the output power is 3 watts, then the power ratio, or "*loss*" is $\frac{3}{5} = 0{\cdot}6$.

8. If power is delivered at the rate of P_1 watts to an amplifier or attenuator, and taken from it at the rate of P_2 watts, the ratio $\frac{P_2}{P_1}$ is the "power gain" (greater than unity) or the "power loss" (less than unity) of the system. Consider three amplifiers connected "in cascade" or "in tandem" as shown in Fig. 3; that is, the output of one is connected to the input of the next. The overall power gain $\frac{P_4}{P_1}$ is obtained by *multiplying together* the individual power gains :—

$$\frac{P_4}{P_1} = 4 \times 100 \times 10$$

$$\therefore \text{Gain} = 4{,}000$$

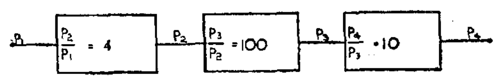

Fig. 3. AMPLIFIERS IN TANDEM

The Decibel

9. The usual way of expressing power gains or losses is by a logarithmic unit known as the "*decibel*" (abbreviated to db). The gain or loss of a system expressed in this unit is defined as:—

$$\text{Power gain or loss} = 10 \log_{10} \frac{P_2}{P_1} \text{ (db)}$$

where P_2 = Output power.

P_1 = Input power.

If $\frac{P_2}{P_1}$ is less than unity, then $10 \log_{10} \frac{P_2}{P_1}$ will be *negative*. A negative sign thus indicates a power *loss*, and a positive sign a *gain*. The overall power gain in decibels of the system shown in Fig. 3 is:—

$$\text{Gain} = 10 \log_{10} 4 + 10 \log_{10} 100 + 10 \log_{10} 10$$

$$\text{Gain} = 6 + 20 + 10$$

$$\therefore \text{Gain} = +36 \text{ db.}$$

10. As an example, consider an amplifier with an input of 1mW giving an output of 10W. The power gain in decibels is:—

$$\text{Gain} = 10 \log_{10} \frac{P_2}{P_1}$$

$$\text{Gain} = 10 \log_{10} \frac{10}{10^{-3}}$$

$$\text{Gain} = 10 \log_{10} 10^4$$
$$\text{Now } \log_{10} 10^4 = 4$$
$$\therefore \text{Gain} = +40 \text{ db.}$$

Thus, + 40 db. indicates a power gain of $\frac{10}{10^{-3}} = 10{,}000$.

11. Given the gain of an amplifier in decibels the ratio of output to input powers can be obtained.

$$\text{Power gain in db} = 10 \log_{10} \frac{P_2}{P_1}$$

$$\therefore \log_{10} \frac{P_2}{P_1} = \frac{\text{Power gain in db.}}{10}$$

$$\therefore \frac{P_2}{P_1} = \text{Antilog}_{10} \frac{\text{Power gain in db}}{10}$$

Thus, in an amplifier which has a power gain of +20 db, the power output for an input of 100mW is:—

$$\frac{P_2}{P_1} = \text{Antilog}_{10} \frac{20}{10}$$
$$\frac{P_2}{P_1} = \text{Antilog}_{10} 2$$
$$\frac{P_2}{P_1} = 100$$
$$P_2 = 100 \times P_1$$
$$P_2 = 100 \times 10^{-1}$$
$$\therefore P_2 = 10 \text{ W.}$$

12. There are obvious advantages in using the decibel in power transfer. Multiplication and division are replaced by addition and subtraction, and + and − signs distinguish gains and losses. However, the the original reason for using logarithmic units was that the human ear responds to power *ratios* in such a way as to interpret them as *differences* in signal strength; *squaring* a power *doubles* the sound intensity, and so on. Thus, the decibel is a natural unit for expressing sound intensities since it is logarithmic, and it is now universally employed for measuring gain and loss in all cases of power transfer.

Absolute Powers Expressed in Dbm

13. Instead of recording the gain or loss of an amplifier or attenuator, it may be required to measure the *actual power level* at some stage in the circuit. This means comparing the observed power level P_2 with some *standard* power level P_1. The standard usually adopted is 1 mW. Power levels expressed in decibels with reference to a standard power of 1 mW are written as so many "*dbm*". Using this standard, any power P can be expressed as $10 \log_{10} P$(dbm). Thus:—

$$1 \text{ W} = 10 \log_{10} 1{,}000 = +30 \text{ dbm.}$$
$$5\text{mW} = 10 \log_{10} 5 = +7 \text{ dbm.}$$
$$5\mu\text{W} = 10 \log_{10} \frac{5}{1{,}000} = -23 \text{ dbm.}$$

Current and Voltage Ratios

14. Consider two equal resistances each of R ohms carrying currents of r.m.s. values I_1 and I_2, and having voltages across them of r.m.s. values V_2 and V_2 respectively. The powers developed in these two resistors are:—

$$P_1 = I_1^2 R = \frac{V_1^2}{R}$$
$$P_2 = I_2^2 R = \frac{V_2^2}{R}$$
$$\therefore \frac{P_2}{P_1} = \left(\frac{I_2}{I_1}\right)^2 = \left(\frac{V_2}{V_1}\right)^2$$

The power ratio $\frac{P_2}{P_1}$ expressed in decibels is:—

$$10 \log_{10} \frac{P_2}{P_1} = 10 \log_{10} \left(\frac{I_2}{I_1}\right)^2$$
$$\therefore 10 \log_{10} \frac{P_2}{P_1} = 20 \log_{10} \left(\frac{I_2}{I_1}\right)$$
$$10 \log_{10} \frac{P_2}{P_1} = 10 \log_{10} \left(\frac{V_2}{V_1}\right)^2$$
$$\therefore 10 \log_{10} \frac{P_2}{P_1} = 20 \log_{10} \left(\frac{V_2}{V_1}\right)$$

Thus, *provided that the two resistances are equal* through which the two currents I_1 and I_2 (or across which the two voltages V_1 and V_2) are measured the gain or loss of a circuit in decibels is:—

$$\text{Gain or loss} = 10 \log_{10} \frac{P_2}{P_1}$$
$$\text{Gain or loss} = 20 \log_{10} \frac{I_2}{I_1}$$
$$\text{Gain or loss} = 20 \log_{10} \frac{V_2}{V_1}$$

15. In Sect. 5, Chap. 2 it was stated that the bandwidth of a series tuned circuit was the separation between two frequencies either side of resonance at which the current has

fallen to 70% of its peak value. In terms of decibels, the current ratio is:—

$$20 \log_{10} \frac{0 \cdot 707}{1} = -3 \text{ db.}$$

The bandwidth is then expressed as so many kc/s at "3 *db down*". Another figure at which the bandwidth is commonly measured is 6 *db down.* At this latter figure the current has fallen to *half* its peak value.

Decibel Meters

16. By comparing the voltages they cause when connected in turn across a standard impedance, the powers of two sources can be compared. A high impedance voltmeter (Fig. 4) is connected across the impedance

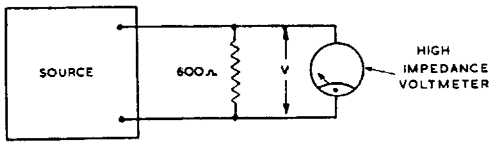

Fig. 4. POWER COMPARISON

and the meter can be calibrated to read power levels above and below 1 mW directly in dbm. The standard impedance usually chosen is a pure resistance of 600 ohms. The r.m.s. voltage V which must be applied across a resistance of 600 ohms in order to dissipate the reference power of 1 mW is 0·775 volts. Thus, when the voltmeter registers 0·775 volts, the reference power of 1 mW is developed and the pointer indicates O dbm on the scale. When the voltmeter registers r.m.s. voltage V_1, the power level is $20 \log_{10}\frac{V_1}{0 \cdot 775}$ (dbm). For instance the power dissipated in the 600 ohms resistance when the voltmeter reads 2 volts r.m.s. is:—

$$20 \log_{10} \frac{2}{0.775} = 20 \times 0 \cdot 417$$
$$= + 8 \cdot 23 \text{ dbm.}$$

The scale is calibrated directly in dbm in accordance with Fig. 5. The instrument

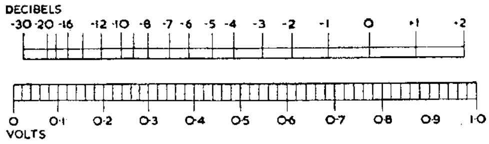

Fig. 5. CALIBRATION OF VOLTMETER TO READ DBM.

used up to frequencies of the order of 50 kc/s will be a rectifier type, moving-coil meter; at higher frequencies, special *valve-voltmeter* circuits are used (see Sect. 18).

The Neper

17. This is a unit based on the *natural* logarithm of the ratio of two *current* values, regardless of the resistance value of the circuits. It can be used to express power and voltage ratios when the resistances of the components are equal. It is mainly used in calculations concerned with filters and attenuators in line transmission. The gain or loss of a circuit in nepers is:—

$$\text{Gain or loss} = \log_e \frac{I_2}{I_1}$$

$$\text{Gain or loss} = \log_e \frac{V_2}{V_1}$$

$$\text{Gain or loss} = \tfrac{1}{2} \log_e \frac{P_2}{P_1}$$

Note. There are 8·686 decibels to the neper.