1

Fundamentals

1. Magnet [Fig. 1.1 (a)].

A body which attracts a piece of iron placed near it is known as a magnet. Any material which can either be made into a magnet or is attracted by another magnet is called magnetic material. Iron and steel are the principal materials of this nature.
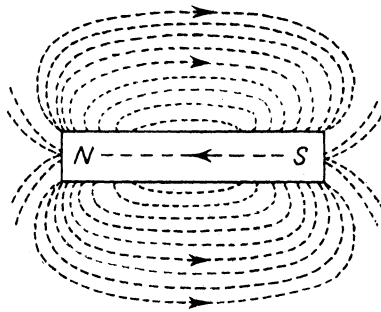

Fig. 1.1 (a)

There are two types of magnets, natural or permanent and electromagnets. Permanent magnets are manufactured from different steels and alloys of steel, aluminium, nickel and cobalt. Because of simplicity and ruggedness, there is increasing use of permanent magnets in manufacture of small alternators and other industrial applications.

In electromagnets, the magnetic effect is created by electric current flowing through a winding placed around a core of soft-iron or soft-steel.

2. Magnetic Field

The area around a magnet within which it can exert pull on a magnetic substance is known as the magnetic field.

3. Lines of Force - Magnetic Flux (ϕ)

If iron filings are placed near a magnet or around a conductor carrying electric current, the iron filings arrange themselves in a definite pattern as shown in Fig. 1.1 (*b*). This is due to the presence of lines of force also known as magnetic flux in the magnetic field. Magnetic flux is designated by the symbol ϕ and is expressed in Maxwells.
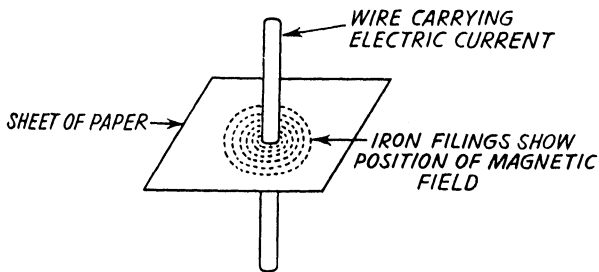

Fig. 1.1 (*b*)

The lines of force travel from north pole to south pole outside the magnet and from south pole to north pole within the magnet.

4. Flux Density (B)

It is the flux per unit area and is expressed in gauss or max-wells/sq. cm.

$$B = \frac{\phi}{a}$$

where ϕ = magnetic flux in maxwells.

            a = area in sq. cm.

5. Magnetomotive Force (MMF)

It is the force which produces magnetic flux in a magnetic circuit and corresponds to the electromotive force. It is expressed in 'gilberts' in c.g.s. units or in ampere-turns in m.k.s. units.

For a closed magnetic circuit,

$$F = 0.4 \, \pi \, NI \text{ gilberts}$$

where F = magnetomotive force

            NI = ampere–turns.

6. Magnetising Force

Magnetising force or magnetic field strength (H) is defined as mmf per unit length of path of the magnetic flux. It measures the ability of magnetized body to produce magnetic induction. The c.g.s. unit of measurement is 'Oersted' and the m.k.s. unit is ampere-turns per metre.

7. Permeability (μ)

It is the ratio of magnetic induction or field strength (B) in a material to the corresponding magnetising force producing that induction.

$$\mu = \frac{B}{H}$$

Permeability is equal to unity for air and non-magnetic substances.

8. Reluctance

The flux in a magnetic circuit is the ratio of magnetomotive force and the reluctance of the magnetic path, *i.e.*

$$\phi = \frac{F}{S}$$

where ϕ = flux
                         F = magnetomotive force in gilberts
                         S = reluctance.

The above law corresponds to ohm's law for current.

The reciprocal of reluctance is known as permeance.

Reluctance $S = \dfrac{l}{\mu A}$

Permeance $= \mu \dfrac{A}{l}$

where A and l are the cross-sectional area and length of the magnetic path in centimetre units and μ the permeability.

Reluctances in series are added like resistances, *i.e.*

$$S = S_1 + S_2 + S_3 + \text{....for reluctances in series}$$

$$\frac{1}{S} = \frac{1}{S_1} + \frac{1}{S_2} + \frac{1}{S_3} + \text{...for reluctances in parallel}$$

where S is the combined reluctance and S_1, S_2...... the individual reluctances.

9. Saturation Curve or Magnetization Characteristic

The magnetic properties of a magnetic substance are represented by the magnetization curve, which indicates the relationship between the magnetizing force and the flux density (Fig. 1.2). The
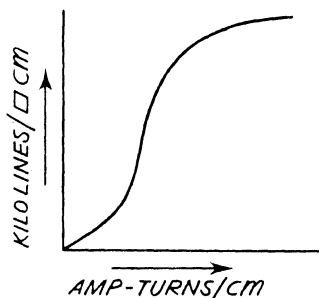
Fig. 1.2.

magnetic intensity in amp-turns/cm. is plotted as abscissa and the corresponding flux densities in kilolines/sq. cm. as ordinate. The amp-turns required for any flux density can be read from this curve. It would be seen from Fig. 1.2 that the flux density increases rapidly at first, and gradually slows down till a stage is reached when any further increase in amp-turns is accompanied by little increase in flux density. The material is now said to be in a state of saturation.

10. Ampere-turns for an Air Gap

Ampere-turns required for a flux density B through an air gap l cm. in a magnetic path can be worked out from the formula :

Flux density in lines/sq. cm. $= 0.4\pi l NI$

or Amp-turns/cm. $= 0.8 \times$ flux density / sq. cm.

11. Ampere-turns

Ampere-turns required for a simple closed magnetic circuit in c.g.s. units can be calculated from the formula,

$$F = \phi S = 0.4\pi \, NI = 1.257 \, NI$$

or Amp-turns (NI) $= 0.8 \, \phi S$

where ϕ is the flux and S the reluctance.

12. Formulae for Magnetic Field Strength

(a) **Straight Conductor.** The magnetizing force or magnetic field strength H at a distance d cm from a long straight conductor carrying a current 1 ampere is

$$H = \frac{0.2 \, I}{d} \text{ oersteds.}$$

(b) **Short Coil.** The field strength H at the centre of a coil which has large radius compared to its length is given by

$$H = \frac{0.2 \, \pi \, NI}{r} \text{ oersteds.}$$

where
N = number of turns in the coil
r = radius in cm.
I = current in amp.

(c) **Long Coil.** In the case of a long coil, where length is large compared to the diameter of the coil, the field strength at the centre of coil is given by

$$H = \frac{0.4 \, \pi \, NI}{L} \text{ oersteds}$$

where L is the axial length in cm.

13. (a) The force

On a straight conductor L cm. long carrying current I amp. and inclined at an angle θ to the lines of force in a magnetic field is given by $F = 0.1 \, BIL \sin \theta$ dynes

where B is the flux density in gauss.

For $\theta = 90^\circ$,

                $F = 0.1 \, BIL$ dynes.

(b) The force between two parallel conductors of length L cm., spaced d cm. apart and carrying currents of I_1 and I_2 amperes is given by

$$F = \frac{0.02 \, I_1 \, I_2 \, L}{d} \text{ dynes.}$$

If the currents flow in the same direction, the force is one of attraction.

(c) The mutual force F in dynes between two magnetic poles of strength m_1 and m_2 at distance r is given by

$$F = \frac{m_1 \, m_2}{r^2} \text{ dynes.}$$

(d) Force between two magnetised surfaces is given by,

$$F = \frac{B^2 \, a}{8} \text{ dynes.}$$

where a is the area of each surface in sq. cm. and B the flux density in gauss.

14. Right-hand Rule for Electromagnets [Fig. 1.3 (a)]

If an electromagnet is held in right hand with fingers pointing in the direction of current flow, the thumb will point in the direction of north pole.
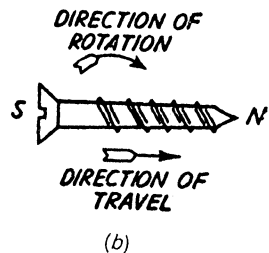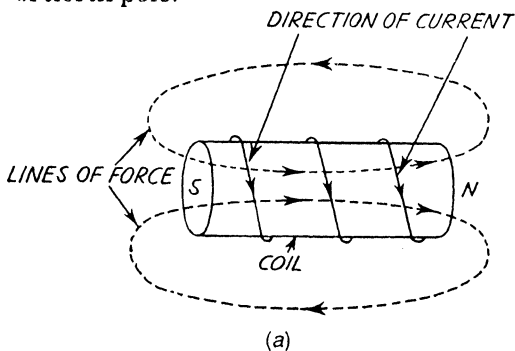

Fig. 1.3

15. Screw Rule for Electromagnets [Fig. 1.3 (*b*)]

If a screw is turned in the direction of current flow, the screw travels in the direction of north pole.

16. Electromotive force (EMF)

If a conductor moves in a magnetic field cutting the lines of force [Fig. 1.4 (*a*)], an e.m.f. is generated in it. Electric current will flow through the conductor if it has closed circuit.
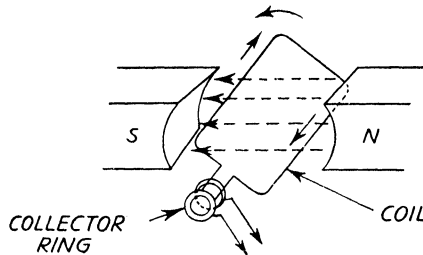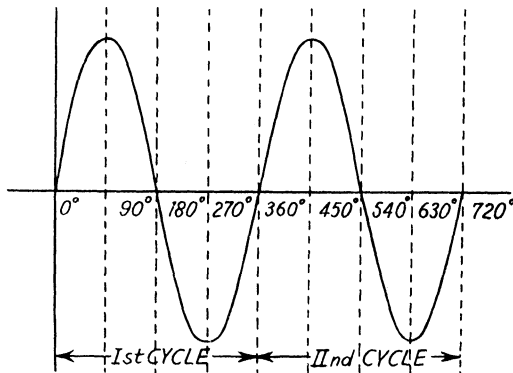
Fig. 1.4 (*a*)

Fig. 1.4 (*b*)

The magnitude of the e.m.f. is given by,

$$E = BLV \sin \theta \times 10^{-8} \text{ volts}$$

where
E = electromotive force
B = flux density in gauss.
V = velocity of conductor in cm./ sec.
L = length of conductor in cm.

θ = angle at which the conductor cuts the lines of force.

The voltage induced is maximum when the coil is in horizontal position and is minimum when the coil occupies the vertical position, *i.e.* when θ is zero.

The instantaneous value 'e' of the induced e.m.f. at any point in the cycle is given by

$$e = E_m \sin \theta \quad \text{or} \quad E_m \sin \omega t$$

where E_m is peak value of e.m.f., θ the electrical angle, and t the time in the cycle corresponding to the angle θ.

The shape of the voltage waveform is a sine curve as shown in Fig. 1.4 (*b*). This is known as alternating current. A cycle is completed when the conductor moves through 360 electrical degrees. The frequency is equal to the number of such cycles per second. For obtaining continuous or direct current, a.c. is converted into d.c. by the use of a commutator or power rectifiers.

17. Fleming's Right-hand Rule (Fig. 1.5)

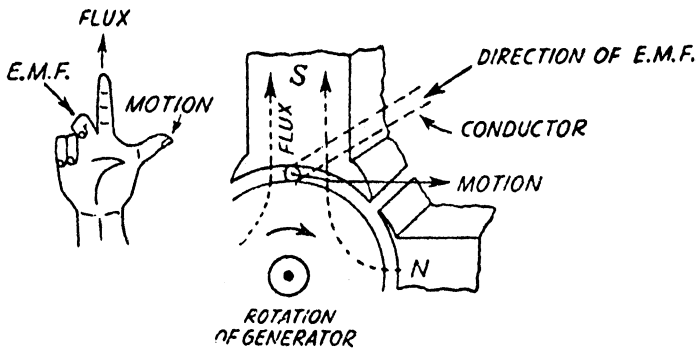The direction of the induced e.m.f. in a conductor is given by this rule.

Fig. 1.5.

If thumb of the right hand points in the direction of the conductor motion and the forefinger in the direction of the flux, then the middle finger will point in the direction of the induced e.m.f.

18. Volt

It is the practical unit for measuring electromotive force. The potential difference that will cause a current of one ampere through a resistance of one ohm is equal to one volt.

19. Ampere

It is equal to the current that flows through a circuit of one ohm when one volt is applied across it.

Actually, it is that "Unvarying current which when passed through a solution of nitrate of silver in water in accordance with standard specification, deposits silver at the rate of 0.001118 grams per sec."

20. Ohm

It is the unit of resistance. It is equal to the resistance offered to unvarying electric current by a column of mercury 106.3 cm. long and having a cross-sectional area of 1 sq. mm., at the temperature of melting ice.

In practical terms, an e.m.f. of one volt will cause a current of one ampere through a resistance of one ohm.

21. Coulomb

It is the unit for measurement of quantity of electricity and is equal to the quantity of electricity transferred in one second by a current of one ampere.

22. R.M.S. voltage

In alternating voltage, the magnitude of voltage is varying all the time. For practical purposes, the root mean square (r.m.s.) value is adopted which produces the same heating effect as the actual voltage. In sinusoidal wave-form,

$$E = \frac{E_{max}}{\sqrt{2}}$$

or $E_{max} = 1.41\,E$

where E is the r.m.s. voltage.

23. Average Voltage

The average value of voltage over one half cycle is equal to $\frac{2}{\pi}\,E_{max}$ for sinusoidal wave-form.

It has little practical usefulness.

24. Peak Factor

It is the ratio of the peak value and the r.m.s. value.

It is equal to $\sqrt{2}$ or 1.41 for sinusoidal wave-form.

25. Form Factor

It is the ratio of r.m.s. value to the average value. It is equal to 1.11 for sinusoidal waveform.

26. Resistance

All materials offer resistance to flow of current which is directly proportional to length and inversely proportional to the cross-sectional area of the conductor, *i.e.*

$$R = \frac{\rho L}{A}$$

where R = resistance in ohms.

L = length of conductor in cm.

A = cross–sectional area of conductor in sq. cm.

ρ = resistivity in cm. cube.

27. Conductance

Reciprocal of resistance is known as conductance and is expressed in mhos.

Current through a circuit is given by voltage multiplied by the conductance of the circuit, *i.e.*

$$I = EY$$

where Y is the conductance.

28. Resistances

These are added when in series and conductances when in parallel, *i.e.*

$$R = R_1 + R_2 + R_3 + \ldots\ldots\text{For resistances in series}$$

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \ldots \text{ For resistances in parallel}$$

or $Y = Y_1 + Y_2 + Y_3 \ldots\ldots$ For conductances in parallel

For two resistances R_1 and R_2 in parallel,

Eq. resistance $R = \dfrac{R_1 R_2}{R_1 + R_2}$

or $= \dfrac{\text{Product of resistances}}{\text{Sum of resistances}}$

29. Resistivity

Resistance offered by any substance to flow of current per unit area per unit length is known as its 'resistivity'. It is expressed in ohms/cm. cube or ohms/inch cube and is designated by symbol '*rho*'.

Resistivity of different materials is given in Table 1. For all practical purposes, the resistivity of aluminium conductor per sq. mm. per metre length may be assumed as 0.028 ohms and that of copper as 0.018 ohm.

TABLE 1.
Physical Constants of Materials

Material	Weight in grams/cu. cm.	Specific Heat	Melting point $^{\circ}C$	Resistance in microhms per cm. cube at $18^{\circ}C$	Unit Resistance increase per $^{\circ}C \times 10^{-4}$
Air (0°C)	0.0013	0.2417	...	...	...
Aluminium	2.70	0.2096	660	3.21	38
Antimony	6.68	0.0508	630.5	40.5	...
Bismuth	9.80	0.0304	269	119.0	42
Brass	8.4-8.7	0.088	800-1000	6-9	10
Bronze (Phosphor)	8.7/8.8	...	1000	5/10	...
Cadmium	8.64	0.0547	320.9	7.54	40
Chromium	7.1	0.104	1830	13.1	...
Constantan	8.88	0.098	...	48	−.4/+.1
Copper	8.93	0.0909	1083	1.59	42.8
Gold	19.32	0.0303	1062.8	2.48	40
Graphite	2.3	0.160	3500	3000	...
Iron (Grey, Cast)	7.1-7.7	0.1045	1100	12.0	62
Lead	11.37	0.0302	327.4	20.8	43
Magnesium	1.74	0.246	649	4.35	...
Manganin	8.5	...	...	44.5	0.02/0.5
Mercury	13.56	0.0335	−38.86	95.76	9.0
Nickel	8.9	0.106	1455	11.8	27
Nichrome	...	...	1500	110	1.7
Platinum	21.50	0.0324	1773.8	11	38
Silver	10.5	0.0556	960.5	1.66	40
Steel	7.7/7.9	...	...	19.9	16/42
Tin	7.29	0.0536	231.86	11.3	45
Tungsten	19.3	0.034	3387	5.5	51
Water (0°C)	0.99987	1.0094	0	...	...
Zinc	7.1	0.0918	419.5	6.1	37

30. Example

Find the resistance of a 10 m. long aluminium conductor having 4 sq. mm. area.

$$R = \rho \frac{l}{A}$$

$P = 0.028 \ \Omega/\text{sq. mm/m.}$

$L = 10$ m.

$A = 4$ sq. mm.

$$R = \frac{0.028 \times 10}{4} = 0.07 \text{ ohm.}$$

31. Ohm's Law (Fig. 1.6)

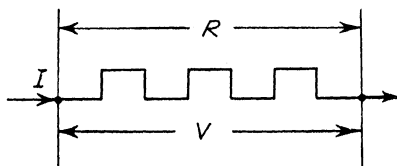It lays down the relationship of voltage, current and resistance.

$$I = \frac{V}{R}$$

Fig. 1.6

where V, I and R are the voltage, current and resistance respectively.

In a.c. circuits, $I = \dfrac{V}{Z}$ where Z is the impedance.

32. Self-induction or Inductance

In an a.c. circuit, the magnetic field set up by the alternating current is constantly changing in magnitude, which by interaction with the conductor induces an e.m.f. in it. The direction of this e.m.f. is such that it opposes the flow of current. This phenomenon is known as self-induction or inductance. It is measured by the unit 'Henry' and is designated by symbol L.

For inductances in series

$$L = L_1 + L_2 + L_3 + \ .....$$

where L_1, L_2 etc. are individual inductances.

For inductances in parallel

$$\frac{1}{L} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \ .....$$

33. Inductive Reactance

The resistance offered by inductance to flow of current is known as inductive reactance and is given by

$$X_L = \omega L$$

or $\qquad\qquad X_L = 2\pi f L \text{ ohms}$

where L is the inductance in henry, f the frequency and X_L the inductive reactance in ohms.

Current through an inductance is equal to voltage divided by inductive reactance $i.e.$

$$I = \frac{E}{X_L}$$

The current lags voltage by 90^0 in a purely inductive circuit.

34. Henry

It is a unit of inductance. A circuit possesses an inductance of one henry, when one volt is induced in it if current through it changes at the rate of one ampere per second.

35. Formulae For Inductance

(i) *Straight Round Non-magnetic Wire.*

$$L = 0.002l \left(2.3 \log \frac{4l}{d} - 0.75 \right) \text{micro-henries } (\mu H)$$

where l is the length of wire in cm. and d the diameter of wire in cm.

(ii) *Two Parallel Wires.*

$$L = 0.92 \log \frac{S}{r} \, \mu H \text{ per metre run}$$

where r is the radius of each wire and S the spacing between their centres measured in similar units.

(iii) *Concentric Line.*

$$L = 0.46 \log \frac{D}{d} \, \mu H \text{ per metre}$$

where D = inner dia. of the outer conductor, and
$\qquad d$ = outer dia. of the inner conductor in similar units.

(iv) *Single-layer Air-cored Coil.*

$$L = \frac{0.2 \, d^2 \, N^2}{3 \, d + 9l} \, \mu H \text{ app.}$$

where d and l are the mean diameter and length of the coil in inches and N the number of turns.

(v) *Multi-layer Air-cored Coil.*

$$L = \frac{0.2 \, d^2 \, N^2}{3 \, d + 9l + 10t} \, \mu H$$

where t is the radial depth of the winding in inches.

(*vi*) *Toroid or Long Solenoid.*

If $\dfrac{d}{l}$ is small and the coil is air-cored,

$$L = \frac{0.01\, d^2\, N^2}{l}\, \mu H$$

where d is the dia. in cm., l the length in cm. and N the number of turns.

(*vii*) *Any Inductive Circuit.*

$$L = \frac{N\phi}{I} \times 10^{-8} \text{ henrys,}$$

where N is the number of turns linking with flux ϕ produced by current I amps.

(*viii*) The combined inductance of two inductors in parallel having mutual inductance M is,

$$L = \frac{L_1 + L_2 - M^2}{L_1 + L_2 \pm 2M}$$

(*ix*) The combined inductance of two inductors in series, having mutual inductance M is,

$$L = L_1 + L_2 \pm 2M$$

36. Capacity or Capacitance

If two conducting materials are separated by an insulating substance or dielectric, the arrangement has the property of storing electrical energy and is known as a condenser or a capacitor. The displacement Q of electricity through a dielectric is proportional to the applied voltage, *i.e.*

$$Q = CE$$

or

$$\frac{dQ}{dt} = C\, \frac{dE}{dt}$$

where C is the capacitance.

If Q is in coulombs and E in volts, C is in farads. Microfarad is the unit used in actual practice.

37. Farad

If stored electric energy increases by one coulomb when the voltage across it changes by one volt or a current of one ampere flows when voltage changes at the rate of one volt per second, the condenser is said to have a capacity of one farad.

38. Capacitors in Series

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots\ldots$$

where C is the equivalent capacity and C_1, C_2 etc. are the individual capacities in series.

For capacitors in parallel

$$C = C_1 + C_2 + C_3 + \ldots\ldots$$

39. Example

Let two capacitances $C_1 = 0.4\ \mu F$ and $C_2 = 0.1\ \mu F$ be connected in parallel with each other and in series with a third condenser $C_3 = 0.5\ \mu F$.

Combined capacitance of

C_1 and $C_2 = 0.4 + 0.1 = 0.5\ \mu F$

Combined capacitance of C_3 and $C_1 + C_2$

$$= \frac{1}{0.5} + \frac{I}{0.5}$$
$$= 2 + 2$$
$$= 4\ \mu F.$$

40. Capacitive Reactance

The resistance offered to flow of current by capacitors is known as capacitive reactance and is given by

$$X_C = \frac{1}{wc}$$

or
$$= \frac{1}{2\pi fc}\ \text{ohms}$$

where X_C is the capacitive reactance in ohms and C the capacity in farads.

Current through a capacitor is given by voltage divided by its reactance. In a condenser current leads voltage by $90°$.

41. Energy Stored in a Capacitor

$$W = \frac{1}{2}CV^2$$

$$= \frac{1}{2}QV = \frac{Q^2}{2C}\ \ \text{Joules}$$

where W is the energy stored in joules, Q the charge in coulombs, C the capacitance in farads, and V the potential difference between the plates in volts.

Also $Q = CV,$

$$C = \frac{Q}{V} = \frac{It}{V}$$

where I is the current in amps, and t the time in seconds

42. Formulae for Capacitance

(i) Two parallel plates

$$C = \frac{0.088 \, KA}{t} \times 10^{-12} \text{ farads}$$

where K is the permittivity, A the area of each plate in sq. cm. and t the thickness of the dielectric in cm.

(ii) N-parallel plates.

$$C = \frac{0.088 \, K A(N-1)}{t} \times 10^{-12} \text{ farads}$$

(iii) Two parallel wires.

$$C = \frac{12.06}{\log \dfrac{S}{r}} \times 10^{-12} \text{ farads per metre run}$$

where r is the conductor radius in mm. and S the spacing between their centres in mm.

(iv) Concentric line.

$$C = \frac{24.13 \, K}{\log \dfrac{D}{d}} \times 10^{-12} \text{ farads per metre}$$

where D is inner dia. of the outer conductor, d the outer dia. of the inner conductor and K the permittivity of the insulating medium between the conductors.

43. Permittivity

The property of a dielectric that determines its ability to store energy is known as permittivity. It is expressed as energy stored per unit volume for unit potential gradiant. In c.g.s. units, the permittivity of vacuum is unity. It is also equal to unity for air. For any substance, its permittivity is numerically equal to its dielectric constant.

44. Dielectric Constant

It is the ratio of the permittivity of a dielectric (insulating material) to the permittivity of vacuum and is designated by symbol K.

$$K = \frac{\text{Capacity of a condenser having that material as dielectric}}{\text{Capacity of the same condenser with air as dielectric}}$$

45. Phase Angle (Fig. 1.7)

In an a.c. circuit having inductance and/or capacitance in addition to resistance, the voltage and current do not attain their maximum, zero and other corresponding intermediate values at the same time, and are said to be out of phase. The number of electrical degrees by which the two quantities are out of phase is known as the phase angle (Fig. 1.7). For a purely resistive circuit, phase angle

is zero. In an inductive circuit, current lags voltage and in a capacitive circuit, current leads voltage, the angle of lag or lead depending upon the relative values of reactance and resistance.

$$\tan \phi = \frac{\text{Reactance}}{\text{Resistance}}$$

where ϕ is the phase angle.
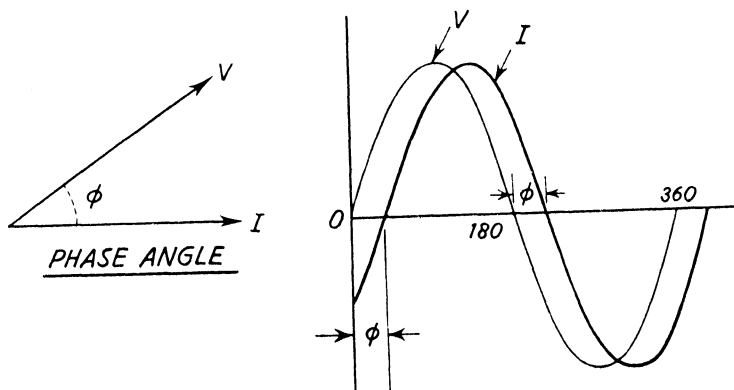
Fig. 1.7

46. Impedance

Combined resistance offered to flow of a.c. current by a circuit having resistance, inductance and capacitance is known as impedance. It is expressed in ohms and is designated by the symbol Z. The resistance, inductance and capacitance are added vectorially.
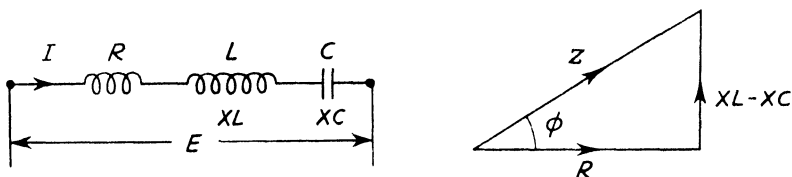

Fig. 1.8

In the circuit in Fig. 1.8

$$Z = \sqrt{R^2 + (\omega L - \frac{1}{\omega C})^2}$$

or
$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

Current through the circuit

$$I = \frac{E}{Z}$$

where E is the applied voltage and Z the impedance.

Phase angle $\quad = \tan^{-1} \dfrac{\omega L - \dfrac{1}{\omega C}}{R}$

Current will lag or lead according as the magnitude of X_L is more or less than X_C.

In complex numbers,
$$Z = R + jX$$

Admittance is the reciprocal of impedance and is designated by the symbol Y.

$$Y = g + jb$$

where g is the conductance and b the susceptance.

Current $\quad\quad I = EY$
$$= E\sqrt{g^2 + b^2}$$

If two or more impedances are in series or parallel, the equivalent impedance is worked out by vectorial addition of impedances when in series, and by vectorial addition of admittances when they are in parallel.

For impedances in series,
$$R + jX = R_1 + jX_1 + R_2 + jX_2$$

For impedances in parallel,
$$g + jb = g_1 + jb_1 + g_2 + jb_2$$

47. Power

It is the rate of doing work. In electrical units, it is expressed in 'watts' or 'kilowatts'. The work is done at the rate of one watt when an e.m.f. of one volt maintains a current of one ohm through a circuit of one ohm resistance.

For d.c. circuits

$$P = EI = I^2 R = \frac{E^2}{R}$$

where P is the power in watts, E the voltage and I the current in amperes.

For a.c. single-phase circuits,
$$P = EI \cos \phi \text{ watts}$$
where $\cos \phi$ is the power factor. It is equal to unity for a purely resistive circuit.

For three-phase circuits,
$$P = 3 E_{ph} I_{ph} \cos \phi \text{ watts}$$
$$= \sqrt{3} E_L I_L \cos \phi \text{ watts}.$$
where E_{ph} and I_{ph} are phase voltage and phase current respectively, and E_L and I_L are the line voltage and line current respectively. Power is expressed by the unit 'horse power' in mechanical units.

$$1 \text{ HP} = 746 \text{ watts};$$
$$1 \text{ KW} = 1.34 \text{ H.P.}$$
$$\text{H.P.} = \frac{2\pi n T}{76}$$

where T = torque in kgm
          n = revolutions/sec.

48. Apparent Power

The KVA flowing through a circuit is known as the apparent power.

Apparent power in a single-phase circuit
$$= \frac{\text{Volts} \times \text{amperes}}{1000} \text{ KVA}$$

Apparent power in a three-phase circuit
$$= \frac{\sqrt{3} \times \text{line voltage} \times \text{line current}}{1000} \text{ KVA}$$

Apparent power consists of two components, the useful power in KW and the reactive power in KVAR (Fig. 1.9).
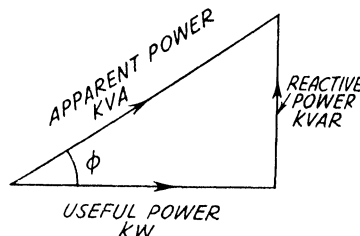

Fig. 1.9

Useful power   = Apparent power $\times \cos \phi$
or   KW = KVA $\times$ p.f.

Reactive power   = Apparent power × sin φ
i.e.   KVAR = KVA × sin φ.

49. Energy

It is the total power consumed over a certain period and is measured in kilowatt-hours (KWH). One kilowatt-hour is equal to the energy consumed when power is utilized at the rate of one kilowatt for one hour. The term 'unit' used for expressing consumption of electric energy is equal to one kilowatt-hour, and all tariffs for electric energy consumption are based on this unit.

50. Three-phase Circuits

The three windings in a three-phase machine or apparatus are connected in the following manner.

(*i*) Star or Y-connection, when the starting points of the three windings are connected together [Fig. 1.10 (*a*)].

(*ii*) Delta-connection, when the starting end of one winding is connected to the terminal end of the next winding [Fig. 1.10 (*b*)].
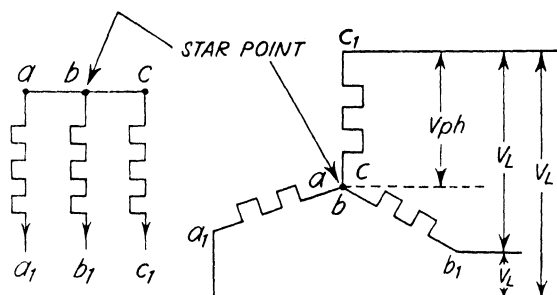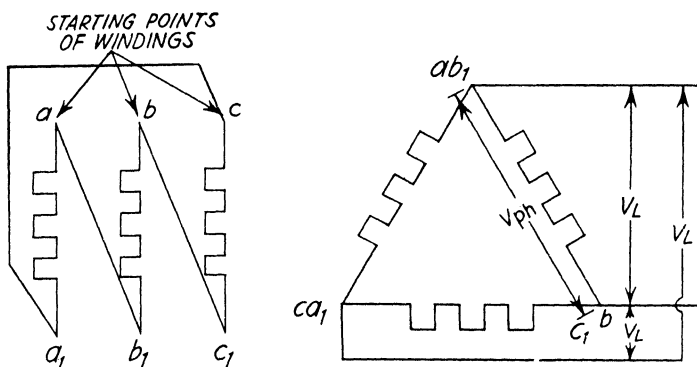

Fig. 1.10 (a)

Fig. 1.10 (*b*)

In star connection,
$$I_{ph} = I_L$$
and
$$V_L = \sqrt{3}\ V_{ph}$$

In delta connection,
$$I_L = \sqrt{3}\ I_{ph}$$
and
$$V_L = V_{ph}$$

Power in both types of connections is given by
$$\sqrt{3}\ V_L\ I_L\ \cos\phi$$
or
$$3\ V_{ph}\ I_{ph}\ \cos\phi$$
where ϕ is the phase angle.

51. A.c. and d.c. Resistance—Skin Effect

The resistance offered by a conductor to flow of a.c. current is more than to d.c. due to the 'skin effect'. The former is known as a.c. resistance to distinguish it from the d.c. resistance.

This is because the induced e.m.f. due to self-induction is not uniform within the cross-section of a conductor. It is maximum at the centre and minimum at the periphery. This results in uneven distribution of current with maximum current density near the periphery and minimum current density at the centre. This is known as 'skin effect'. Its practical effect amounts to offering increased resistance to flow of a.c. The increase in resistance can be worked out from Table 2 by multiplying d.c. resistance by factor K which is given as a function of X. The value of X is given by :

$$X = 0.063598\sqrt{\frac{\mu}{1.6\,R}}$$

where R is the d.c. resistance/km at operating temperature, f the frequency and μ the permeability which is equal to unity for non-magnetic substances.

TABLE 2
Skin Effect

X	K	X	K
1.0	1.00519	2.4	1.15207
1.2	1.01071	2.6	1.20056
1.4	1.01969	2.8	1.25620
1.6	1.03323	3.0	1.31809
1.8	1.05240	3.2	1.38504
2.0	1.07816	3.4	1.45570
2.2	1.11126	3.6	1.52879
		3.8	1.60314

52. Temperature Co-efficient

Resistance offered by most materials to flow of current increases with increase of temperature and the proportion by which the resistance increases per degree rise in temperature is called its temperature co-efficient.

Resistance R_2 at temperature T_2 is given by

$$R_2 = R_1 \left\{ 1 + \alpha(T_2 - T_1) \right\}$$

where R_1 is resistance at temperature T_1 and α the temperature co-efficient.

Temperature co-efficient for different materials is given in Table 1.

Resistance at temperature T_2 is also given by

$$\frac{R_2}{R_1} = \frac{M + T_2}{M + T_1}$$

where M = 234.5 for 100% conductivity copper

= 241.5 for 97.5% hard-drawn copper

= 228.1 for aluminium.

53. Electrical Degrees

There are supposed to be 180 electrical degrees between two adjacent poles of opposite polarity and 360 electrical degrees between two nearest poles of the same polarity (Fig. 1.11). One complete cycle of voltage is generated when the conductor moves through 360 electrical degrees.
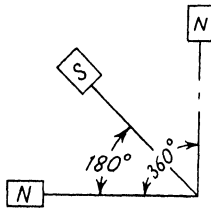

Fig. 1.11

54. Kirchhoff's Laws (Fig. 1.12)

In an interconnected network, the distribution of currents is such that

(i) The algebraic sum of the currents toward any junction point is zero.

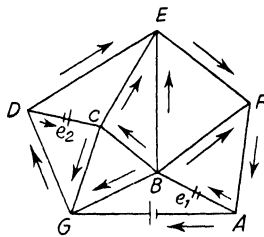(ii) The algebraic sum of the voltages around any closed circuit in the network is zero.

Fig. 1.12

55. Eddy Currents

It is the term used for the secondary currents which are established in those parts of a circuit which interlink with the alternating flux. The loss on account of eddy currents is equal to I^2R, where R is the resistance of the circuit. It is because of the eddy current losses that laminated construction is employed for the cores of a.c. appliances such as transformers, motors, magnetic conductors etc.

The total iron losses in laminated construction are equal to $\dfrac{1}{n^2}$ times the loss in the solid core, where n is the number of laminations.

The loss in sheets is given by :

$$P_e = \frac{(\pi t f B_{max})^2}{6_\rho \, 10^{16}} \text{ watts/cu. cm.}$$

where t is the thickness in cm., f the frequency in cycles per second, B_{max} the maximum flux density in lines per square centimetre, and ρ the specific resistance.

For iron sheets, the loss is given by

$$P_e = 13.4 \, f^2 \, B^2 \, t^2 \, V \times 10^{-12} \text{ watts per cu. cm.}$$

For stalloy sheets, the loss is about half of the above value.

Measuring and Testing

56. Checking Presence of Voltage

Whether a conductor is live or dead can be ascertained by the following methods :

(i) **By Touch.** If the circuit voltage is less than 60 volts, the presence of voltage can be checked by cautiously touching it with a finger or the finger knuckle joint. Sensation of shock will indicate presence of voltage.

(ii) **By Test Lamp** (Fig. 1.13). Voltage within the range of a lamp can be conveniently checked with the help of a test lamp. A

shock-proof rubber socket with two test prongs is used for the purpose. One lead is held against the conductor under test and the other against ground. The presence of voltage is indicated, by a glowing lamp. The lamp should be checked for its sound condition.
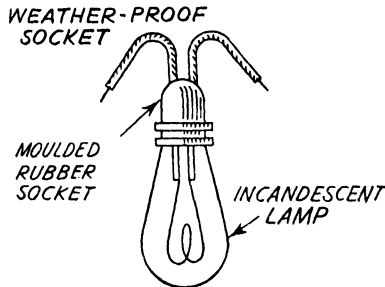

WEATHER-PROOF SOCKET

MOULDED RUBBER SOCKET

INCANDESCENT LAMP

Fig. 1.13.

(*iii*) **By Neon Glow-lamp Testers.** A glow lamp tester provides compact, safe and rugged means of checking presence of voltage. The type of voltage, whether a.c. or d.c. and its approximate magnitude can also be ascertained with it. Various proprietory brands are available in the market.

(*iv*) **High Voltage Testers.** The presence of high voltage in a conductor without actually touching it can be detected by holding such a tester in close proximity to the conductor. A glowing tip indicates presence of voltage. Such testers are particularly suitable for overhead bare lines.

57. Measurement of Current

Current can be measured by the following means :

(*i*) Ammeter. (*ii*) Voltmeter. (*iii*) Clip-on ammeter.

(*i*) An Ammeter records current directly. It is always connected in series in the circuit under measurement. Moving-coil type are used for d.c. and moving-iron type for both a.c. and d.c.

Since the resistance of an ammeter is very low, usually a few milli-ohms only, it will be ruined if it is connected by mistake across any potential.

A preferable method of connecting an ammeter in a circuit is indicated in Fig. 1.14. Current is measured by opening the switch.

For measuring large current which cannot be passed directly through the instrument, measurement is made by using:
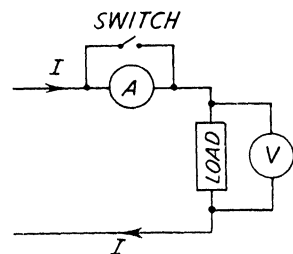

SWITCH

I

A

LOAD

V

I

Fig. 1.14

(*a*) **Shunt** (Fig. 1.15).

(*b*) **Current Transformer.** (Fig. 1.16). In the case of a shunt ammeter, the instrument is actually a millivoltmeter which is calibrated in amperes. The shunt is made of high resistance alloy like manganin.

Current transformers (C.T.'s.) can be used with a.c. only. The C.T.'s should always have a closed circuit; otherwise, dangerously high voltage which can destroy the C.T. will be induced. A switch as indicated in Fig. 1.16 for shorting the C.T. may be provided.
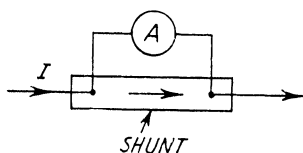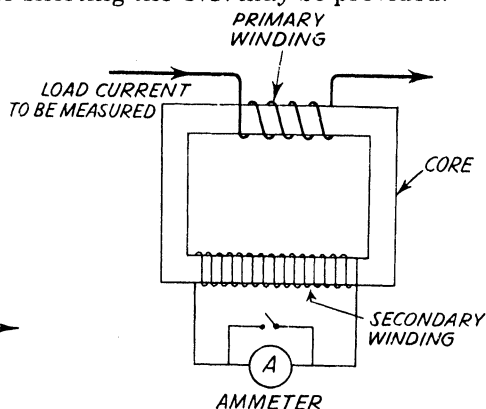
Fig. 1.15

Fig. 1.16

(*ii*) **By Voltmeter.** Current in a circuit can be measured by a voltmeter by inserting a known resistance in the circuit and measuring the voltage drop across it. Current is equal to voltage drop divided by resistance.

(*iii*) **By Clip-on Ammeter or Tong-Tester** (Fig. 1.17). This is a very handy instrument for measuring current where ·results with an accuracy of ± 5% are acceptable, as no connections have to be made. The ammeter has a split iron core which is placed around the conductor by pressing a trigger mechanism and the current is read directly on the scale. A clip-on ammeter actually measures magnetic flux which is proportional to current. Instruments for use both with a.c. and d.c. to suit different ranges are available. The size of the instrument should be

Fig. 1.17.

selected keeping in view the size of the largest conductor through which current is to be measured.

58. Measurement of Voltage

A voltmeter is used to measure voltage which is always connected in parallel with the circuit whose voltage is to be measured (Fig. 1.14).

For measuring power consumed by appliances working with low voltage and high current like self-starters etc., the voltage should be measured immediately across the appliance for maximum accuracy.

Potential transformers are used for measuring high voltage, where a voltmeter cannot be connected directly to the circuit.

59. Measurement of Resistance

Resistance can be measured by the following methods :-

(*i*) **By Ohmmeter.** It is an instrument used for measuring resistance directly. The instrument, which is a galvanometer in effect, has a number of ranges with a suitable selector switch. Dry cells fitted in the instrument, supply the source of e.m.f. and the scale on the galvanometer is calibrated to register ohms. The instrument should be checked for zero resistance before use, by touching the two test prongs together. Measurement should be started with a high range till the right range is reached; otherwise, the ohmmeter will be damaged.

(*ii*) **By Comparison Method** (Fig. 1.18). A known resistance R is connected in series with the unknown resistance R_X. Current is passed through both the resistances, and voltage drop is measured across each. The value of the unknown resistance R_X is given by
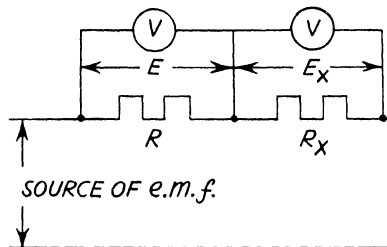

Fig. 1.18

$$\frac{E_X}{R_X} = \frac{E}{R}$$

or $$R_X = E_X \times \frac{R}{E}$$

where E is the voltage drop across R and E_X the voltage drop across R_X.

(*iii*) **By Volt-meter and Ammeter** (Fig. 1.19). This method is particularly suitable for measuring small contact and joint resistances. Current is passed through the resistance and the voltage drop across it is measured as indicated in Fig. 1.19. The current is regulated by the variable resistance in series. Resistance R_X is given by $R_X = \dfrac{E}{I}$, where E and I are the voltage drop and current through the resistance R_X.
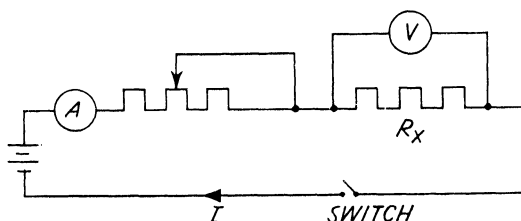

Fig. 1.19

(*iv*) **By Wheatstone Bridge.** The arrangement is shown in Fig. 1.20. The network consists of four resistances of which R_1 and R_2 are known resistances of fixed values, R a variable resistance and R_X the resistance under measurement. The resistances and galvanometer are connected to a battery as indicated. Resistance R is adjusted so that there is no deflection on the galvanometer.
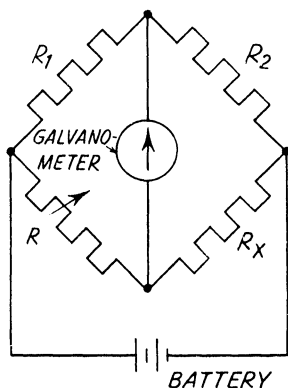

Fig. 1.20. Wheatstone Bridge.

In this condition, the value of R_X is given by

$$R_X = R \times \frac{R_2}{R_1}$$

Ratio $\dfrac{R_2}{R_1}$ is usually a multiple of 10 and is selected by selector switch provided for the purpose.

For accurate results, all the resistances should be nearly equal.

The method is not suitable for measuring resistances below one ohm and above 1,00,000 ohms.

(v) **By Post-Office Bridge.** It is an adaptation of the Wheatstone Bridge already discussed. The resistances are varied by means of brass plugs which shunt out a portion of the resistance coils in the instrument.

The unknown resistance is given by the same formula as for the Wheatstone Bridge.

(vi) **By Slide-Wire Wheatstone Bridge** (Fig. 1.21). This is also an adaptation of the Wheatstone Bridge. A known resistance R and the unknown resistance R_X are connected across a resistance wire one metre long placed over a divided scale. One terminal of the galvanometer is connected to the point joining the resistances R_X and R and the other terminal is moved along the slide wire until the galvanometer gives null indication. The value of the resistance R_X is given by :

$$R_X = R \times \frac{d}{1000} - d$$

where d is the distance in millimetres of the contact from the end of the slide-wire connected to R_X.
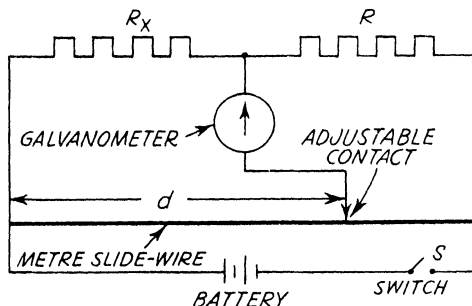

Fig. 1.21

(vii) **By Voltmeter** (Fig. 1.22). This method is suitable for measuring high resistances. A voltmeter of known resistance is

connected in series with the unknown resistance across a source of known d.c. e.m.f. V. If the voltmeter reading is V_1, the value of R_X is given by :

$$R_X = R \times \frac{V - V_1}{V}$$

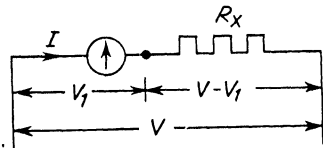where R is the resistance of the voltmeter.

Fig. 1.22

60. Measurement of Insulation Resistance

(*i*) **By Voltmeter.** Measurement of insulation resistance involves measuring high resistance and can be measured with the help of a voltmeter of known resistance and a source of d.c. as discussed in section 59. The voltmeter is connected in series with the insulation resistance under test (Fig. 1.23) and is given by the formula :

$$R_X = R\,\frac{V - V_1}{V_1}$$

where R_X = insulation resistance.

V = total voltage across the circuit.

V_1 = reading of the voltmeter.

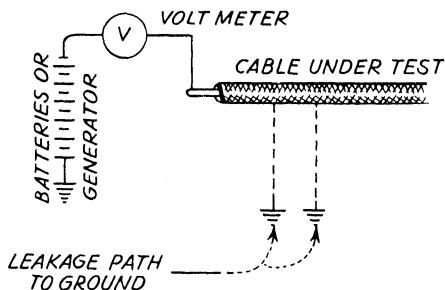Insulation resistance between two conductors can also be measured in the same way.

Fig. 1.23

(*ii*) **By Megger** (Fig. 1.24). Insulation resistance can be measured directly with the help of a megger. The instrument generates its own e.m.f. when the cranking handle is turned. It has two terminals marked 'Line' and 'Earth'. The crank is turned at a moderate speed till a constant deflection of the needle is obtained.

Before making connections, the two leads should be touched together and the crank handle turned gently at a slow speed. The

pointer should indicate zero resistance. Paint, enamel, dirt etc. should be removed from the surface where 'earth' terminal of the megger is connected.
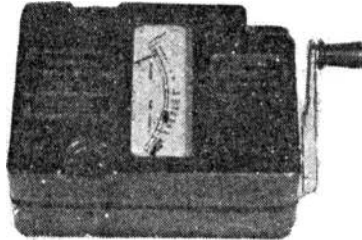

Fig. 1.24.

Meggers of 250 and 500 V are used for medium voltage appliances and those of higher voltage like 1 KV, 2.5 KV etc. for high voltage appliances. The test leads or prongs should have proper insulation and should be handled with care to avoid shock. In addition to measuring insulation resistance a megger is also used for testing grounds, short circuits and continuity of conductors.

The insulation resistance of a grounded conductor between the conductor and earth is zero. Similarly two conductors in a short circuited condition have zero insulation resistance.

Continuity of a conductor is tested by earthing it at one end and measuring its resistance to ground at the other end. Zero reading will indicate continuity while high resistance indicates a 'break'.

'Megger' is also used for identification of wires in a conduit. Each wire is earthed in turn at one end and the wire that gives zero earth resistance at the other end forms the other end of the wire under test.

61. Bridge-Megger

It is an instrument with a megger and Wheatstone Bridge built in one case. The instrument can be used either as a 'Bridge' for measuring resistance or as a 'megger' for measuring insulation resistance. It is a very useful instrument in repair workshops for measuring resistances in the range of .01 ohm to 1000 ohms as well as the insulation resistance.

62. Measurement of Inductance

Inductance can be measured by the following methods :

(*i*) Ammeter and voltmeter method.

(*ii*) A.c. Bridge method.

(*iii*) **Ammeter and Voltmeter Method**. This method is suitable for measuring inductances in the range of 50 to 500 millihenrys.

Impedance 'Z' of the coil is measured by passing alternating current through it and measuring voltage drop across it. Impedance is equal to voltage divided by current.

The d.c. resistance 'R' of the coil is measured by one of the several methods already described. This resistance is approximately equal to the a.c. resistance at power frequency.

Inductance L of the coil is given by the relationship,

$$L = \frac{\sqrt{Z^2 - R^2}}{2\pi f} \text{ henrys}$$

where Z = impedance of coil in ohms
R = d.c. resistance of coil in ohms
f = the frequency of a.c. supply.

(*ii*) **A.c. Bridge Methods.** Bridge networks provide simple and accurate methods of measuring inductance. Current in the bridge arms is balanced both in respect of magnitude and phase.

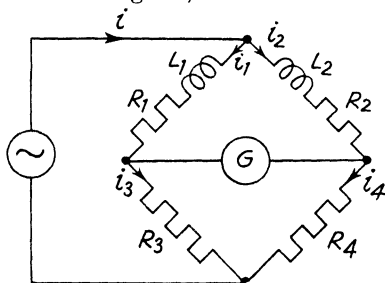Fig. 1.25 shows one such arrangement which is also known as Maxwell's method. In this figure,

Fig. 1.25

L_1 = unknown self-inductance of resistance R_1.
L_2 = known self-inductance of resistance R_2.
R_3 and R_4 = non-inductive resistances.
G = Galvanometer.

The bridge is balanced by varying L_2 and one of the resistances R_3 or R_4.

In condition of balance

$$\frac{R_1}{R_2} = \frac{R_3}{R_4} = \frac{L_1}{L_2}$$

63. Measurement of Capacity

Capacitance can be measured directly by bridge-methods or by an ammeter and voltmeter.

(*i*) **Ammeter and Voltmeter Method.** Current through a condenser of capacity C farads is given by $2\pi f CV$. If I and V are measured, C can be worked out from this relation.

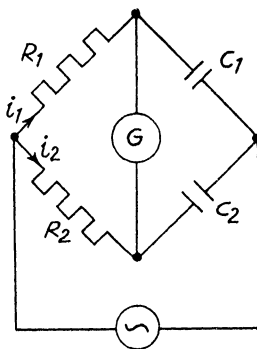(*ii*) **A.c. Bridge Methods.** A simple arrangement is shown in Fig. 1.26.

Fig. 1.26

In this figure,

$$C_1 = \text{condenser under measurement}$$
$$C_2 = \text{a standard condenser}$$
$$R_1 \text{ and } R_2 = \text{non-inductive resistances.}$$

At balance

$$\frac{R_1}{R_2} = \frac{C_2}{C_1}$$

or

$$C_1 = C_2 \frac{R_2}{R_1}$$

In this simple form, the method is not so accurate. However, the same principle is used in more sophisticated instruments like Schering Bridge etc.

64. Measurement of Power

Power can be measured with the help of

(*i*) Voltmeter and Ammeter

(*ii*) Wattmeter

(*iii*) Energy Meter.

(*i*) Power in d.c. circuits and a.c. resistive circuits can be measured by measuring circuit voltage and current and the application of the appropriate formula (See section 47).

(*ii*) *By Wattmeter.* A wattmeter indicates the power in a circuit directly. Most commercial wattmeters are of the dynamometer type with two coils, the current coil and the voltage coil (Fig. 1.27). The

current coil is made of heavy strip and is in two parts connected in series. The voltage or the moving coil consists of a large number of turns of thin wire in series with a high resistance. The moving coil is placed within the two sections of the current coil and is supported in jewel bearings. The instrument records power directly on the scale.
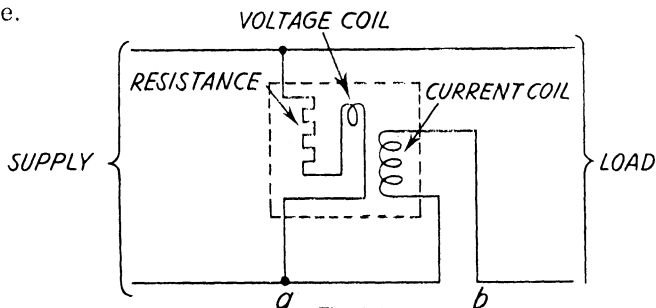

Fig. 1.27

A wattmeter should be connected in the main circuit so that the moving coil end of the voltage coil and the series coil are on the same side of the load being measured. With P.T's, the moving coil end of the voltage coil should be connected to the grounded P.T. terminal. It ensures more accurate results and there are less chances of damage to the instrument.

Power in three-phase circuits can be measured with the help of poly-phase wattmeters which consist of one, two or three single-phase meters mounted on a common shaft.

One wattmeter is used for balanced three-phase, three and four-wire systems. In a three-phase four-wire circuit, the voltage coil is connected between a phase and ground wire and in a three-phase three-wire system, an artificial start point is used for connection of the voltage coil (Fig 1.28). This artificial point is obtained by connecting three resistances/reactances in star. The power in the circuit is equal to three times the wattmeter reading.
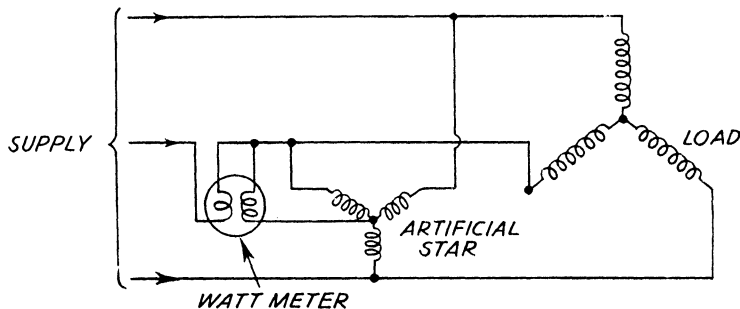

Fig. 1.28

Two wattmeters, connected as per arrangement in Fig. 1.29 are suitable for three-phase three wire circuits for all conditions of balance, load and p.f. The current coils are connected in lines 1 and 3 and their respective potential coils are connected between lines 1 and 2 and 3 and 2 respectively. The total power is the algebraic sum of the readings of the two wattmeters which is recorded directly, if the two meters are mounted on the same shaft. For balanced load, each instrument records half the total power at unity p.f. At 50% p.f. one instrument records the total power and the other zero. At less than 50% p.f., one of the wattmeters will record negative.
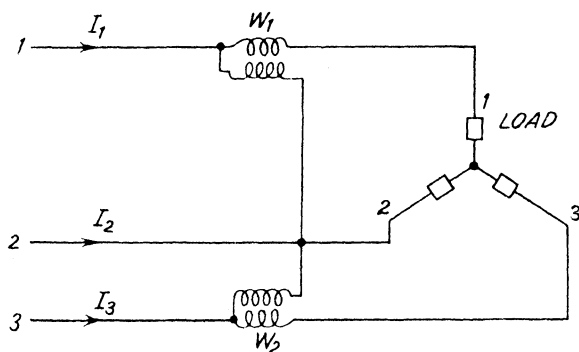

Fig. 1.29

Three wattmeters are used for measurement of power in three-phase 4-wire circuits (Fig. 1.30). The potential coils are connected between a phase and the neutral wire. Such meters are suitable for all conditions of balance, load and p.f.
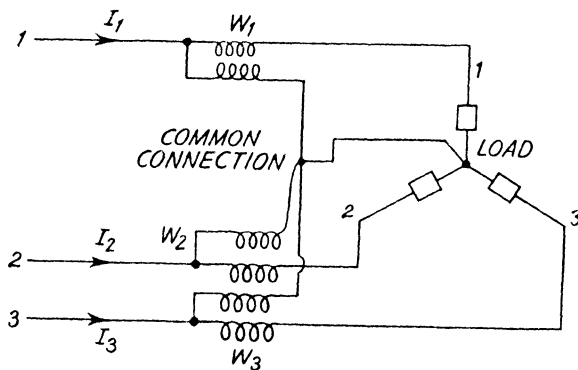

Fig. 1.30

(*iii*) *By Energy Meter.* Power can be measured with the help of an energy meter by measuring the speed of the meter disc with a watch, with the help of the following formula :

$$P = \frac{N \times 60}{K} \text{ KW}$$

where N = actual r.p.m. of meter disc

                           K = meter constant which is equal to disc
                           revolutions per KW hr.

65. Energy

It is measured with the help of a watt-hour, meter which is actually a small motor in which the speed of rotation of the revolving element is proportional to the power. A registering mechanism indicates the total energy consumption. Induction type watt-hour-meter, which operates on the principle of an induction motor, is used for A.C.

Energy meters have two elements for three-phase three-wire circuits and three elements for three-phase four-wire unbalanced circuits.

Current transformers are used for meters larger than 100 amp. capacity and voltage transformers (P.T's.) are used irrespective of current where the voltage exceeds 400 volts.

Power and energy meters will record correctly, if connections are made with due care to the polarity and the terminal markings. The accuracy of connections can be checked in the following simple manner.

If the p.f. is above 0.5, rotation of the meter will always be forward when the potential or the current coil of either element is disconnected. The meter speed will be more in one case. If the p.f. is less than 0.5, the rotation in one case will be backward. The forward speed is less in this case than with p.f. more than 0.5. This test can be performed with an induction motor by running it with and without load, as its p.f. is less than 0.5 on no-load and more than 0.5 near full load.

It may be pointed out that all the instruments described in preceeding sections are now abailable in electronic versions with LCD display.

66. Universal Meter or Avometer (Fig. 1.31)

It is an instrument that can be used for measurement of resistance, current and voltage both in a.c. and d.c. circuits. Provision is also there for measurement of inductance and capacitance in some makes.

Though the accuracy in such instruments is not of very high order, such instruments are indispensable tools for routine testing and measurements in workshops.

Fig. 1.31

67. Polarity Test for D.C.

The positive and negative wires of a circuit can be distinguished by dipping the ends of the two wires in a dilute solution of water and common salt. The wire where bubbles appear is the negative one.

68. Electromagnetic Force on Bus-Bars

In a three-phase system, the peak force between conductors parallel to each other, during a symmetrical three-phase short-circuit is given by

$$F_p = \frac{11 \times L \times 1^2}{S} \times 10^{-8} \text{ kg.}$$

where

F_p = Peak value of electromagnetic force in kg. on span length L.

I = Symmetrical three-phase short-circuit current in amperes (r.m.s.)

L = Length of span of bus—bars between centres of supports in cm

S = Centre to centre spacing of phases in cm.

69. Newton

It is the unit of force in m.k.s. system and is equal to force that will give a mass of one kg. an acceleration of one metre per second per second. It is equal to 10^5 dynes.

70. Dyne

The dyne is the c.g.s. unit of force. It is that force which will give a mass of one gram an acceleration of one centimetre per second per second.

71. Erg

It is the c.g.s. unit of work or energy and is equal to the work done when a force of one dyne acts for a distance of one centimetre.

72. Joule

It is the m.k.s. unit of work or energy. It is the work done when a force of one newton acts for a distance of one metre. The joule is equal to 10^7 ergs.