SECTION 3

D.C. MOTORS AND GENERATORS

SECTION 3

CHAPTER 1

THE D.C. GENERATOR

Paragraph

PART 1, SECTION 3, CHAPTER 1

THE D.C. GENERATOR

Introduction

1. While a circuit is moving in a magnetic field in such a way that the magnetic flux linkage is changing, there is in the circuit, an induced e.m.f. which at each instant is proportional to the *rate of change* of flux linkage (see Sect. 2, Chap. 2). If this e.m.f. is applied to a closed circuit an electric current will be established; mechanical energy has thus been converted to electrical energy. Any machine which does this is known as a generator. The *d.c. generator* is a machine which when driven by mechanical power causes a system of conductors rotating in a magnetic field to generate an e.m.f. and maintain a d.c. output voltage.

The Simple Generator

2. The simplest form of generator consists of a single loop of wire able to rotate freely in the space between the poles of a permanent magnet. Connection is made to the external circuit (or "load") by *brushes* pressing on two *slip rings* which are connected to the ends of the loop (Fig. 1).

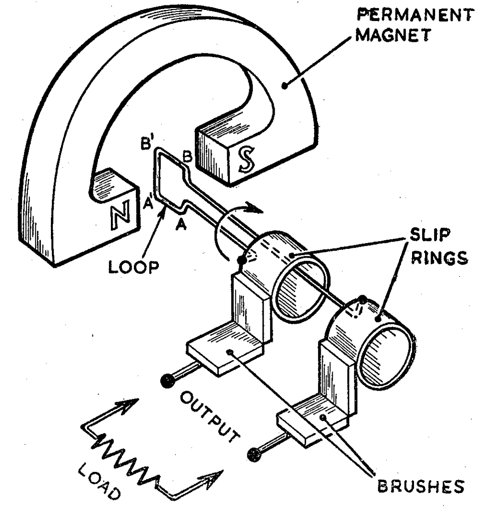

Fig. 1. THE SIMPLE GENERATOR

3. When the loop is caused to rotate, the magnetic flux linkage is changing and e.m.f.s will be induced in each of the straight sides A—A^1 and B—B^1. The *direction* of the induced e.m.f.s given by Fleming's Right Hand Rule, is such that the two e.m.f.s in series are additive and combine to establish a current when the load is connected.

4. The *magnitude* of the induced e.m.f. is proportional to the *rate of change of flux linkage;* thus, assuming the speed of rotation to be constant, the induced e.m.f. will at any instant depend on the position of the loop in the magnetic field. This is illustrated in Fig. 2, which represents the view from the commutator end of the loop.

5.(*a*) In position (*a*) Fig. 2, the conductors A and B are moving parallel to the lines of magnetic flux and are linking maximum flux. However, in a very small period of time dt about the instant shown in (*a*) the change of flux linkage is zero. Thus, the *rate of change* of flux linkage $\frac{d\Phi}{dt}$ is *zero* and since $E = -\frac{d\Phi}{dt}$ volts, the e.m.f. induced in the loop at this instant is zero.

(*b*) Position (*b*) shows the conductors cutting the flux at right angles. The *rate* at which the flux linkage is *changing* is now a *maximum* and the e.m.f. induced in the loop is a maximum, the direction being given by Fleming's Right Hand Rule. At this position, the e.m.f. is arbitrarily assumed to be maximum in a *positive* direction.

(*c*) Position (*c*) represents a position where the rate of change of flux linkage is again zero and no e.m.f. is induced in the loop.

(*d*) Position (*d*) is similar to position (*b*) except that the side of the loop which was previously moving *downwards* (side A) is now moving *upwards* and *vice versa.* The rate of change of flux linkage is again a maximum and Fleming's Right Hand Rule will confirm that in relation to (*b*), the e.m.f. is now a maximum in a *negative* direction.

(*e*) Position (*e*) is identical with position (*a*).

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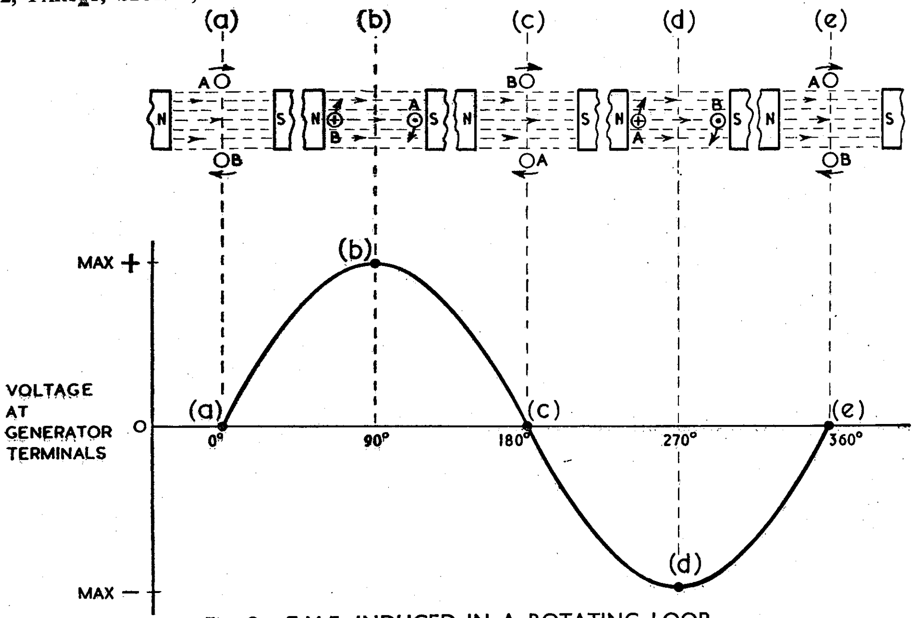


Fig. 2. E.M.F. INDUCED IN A ROTATING LOOP

6. At other positions of the loop the rate of change of flux linkage is intermediate between zero and maximum and so, therefore, is the e.m.f. Thus, during one complete revolution of the loop the voltage at the terminals of the generator will vary in the manner shown in the graph of Fig. 2. This shows *one cycle* of *alternating voltage*.

7. The **frequency** of the alternating voltage at the generator terminals depends on the speed of rotation and on the number of *pairs* of poles in the field magnet system (see Para. 14). Thus :—

$$\text{Frequency f} = \frac{\text{pN}}{60} \text{ (c/s)} \quad \ldots \quad \ldots \quad \ldots (1)$$

where p = Number of pairs of poles.
N = Revolutions per minute.

Hence, the frequency of an alternating voltage produced by a 4-pole a.c. generator running at 1500 r.p.m. is:—

$$\text{f} = \frac{\text{pN}}{60} = \frac{2 \times 1500}{60} = 50 \text{ c/s.}$$

Production of Direct Current

8. Where direct current in the external circuit is required a form of automatic reversing switch (known as a *commutator*) is substituted for the slip rings. The commutator automatically reverses the connections between the loop and the external circuit at the instant that the e.m.f. induced in the loop is zero and reversing, thus maintaining the direction of the current in the external circuit. A simple form of commutator for a single-loop generator consists of the two halves of a split ring, separated from each other by a layer of insulation. Each end of the loop is connected to a *segment* of the commutator, and the external circuit is connected to the loop by brushes bearing on opposite sides of the commutator, as shown in Fig. 3.

9. As the loop rotates, the e.m.f. induced is alternating as described in Para. 6. However, since the commutator rotates with the loop, the brushes bear on opposite segments of the commutator during each half cycle (compare Figs. 3 (*b*) and 3(*d*)). The left-hand brush is always in contact with that segment which is positive, and the right-hand brush with that segment which is negative—the changeover occurring at the instants when the e.m.f. induced in the loop is zero (Figs. 3 (*a*), (*c*), and (*e*)). A uni-directional current is, therefore, established in the external circuit. The variation in brush voltage and the external circuit current during one complete revolution of the loop is illustrated in Fig. 3 (*f*).

10. A more constant brush voltage and a smoother flow of current can be obtained by placing additional loops symmetrically round the axis of rotation. This necessitates additional segments on the commutator, the loops being so arranged that each loop is connected between adjacent segments, the end of one loop being connected to the same segment as the beginning of the next loop as shown schematically in Fig. 4(*a*). For instance, loop A is connected between

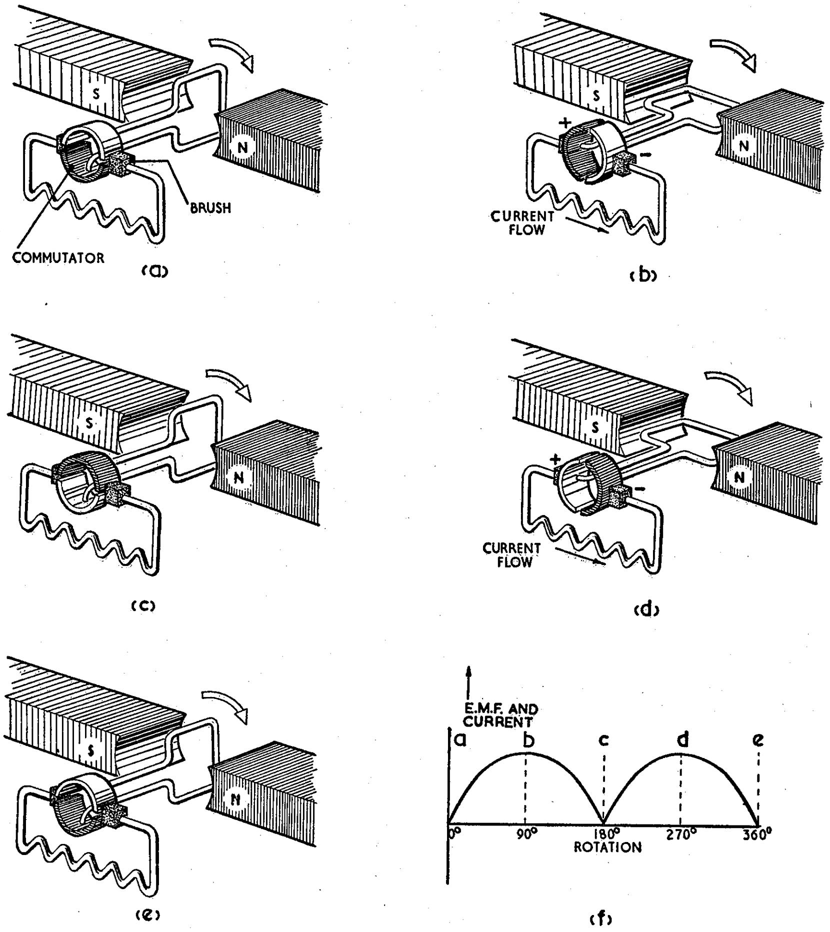


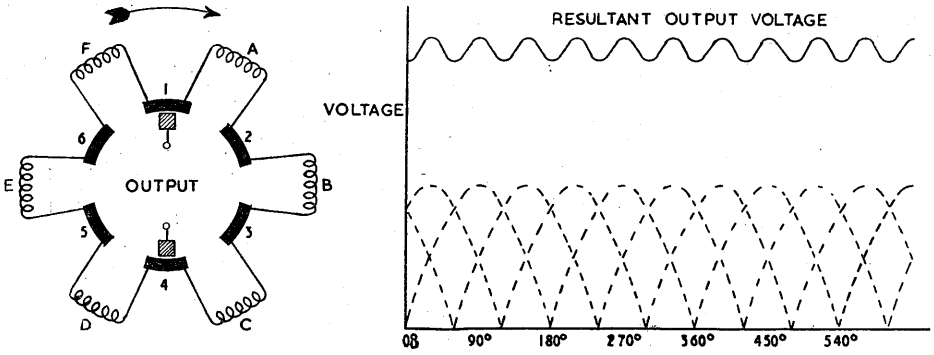
Fig. 3. PRODUCTION OF DIRECT CURRENT

segments 1 and 2, loop B between segments 2 and 3, and so on. With this arrangement, the e.m.f. induced in each loop will reach its maximum value when the e.m.f. in the preceding loop is already decreasing, and that in the succeeding loop still increasing. Thus at the instant in Fig. 4(*a*), if the e.m.f. induced in loop E is a maximum, the e.m.f. in loop F is decreasing and that in loop D increasing. The voltage at the brushes comprises the sum of the e.m.f.s induced in the loops connected in series between the brushes. Thus, in Fig. 4(*a*) loops A, B, and C are in series between the brushes on the right, and loops D, E, and F on the left, the two branches being *in parallel* with each other. The graph showing the resultant voltage between the brushes is shown in Fig. 4(*b*). Only three loops have had to be considered as the arrangement is symmetrical and loops A, B, C, in parallel with loops D, E, F, give the same voltage at the instant shown. As the number of loops is increased the ripple in the brush voltage becomes smaller and the magnitude of the output voltage increases.

Magnitude of Induced E.m.f.

11. From Faraday's and Lenz's laws, the e.m.f. induced in a circuit moving through a magnetic field is $E = -N\frac{d\Phi}{dt}$ volts. The e.m.f. of a generator, therefore, depends on:—

(*a*) The number of conductors connected in series between the brushes.



(a) (b)

Fig. 4. RESULTANT E.M.F. PRODUCED BY ADDING MORE LOOPS

(*b*) The speed of rotation.

(*c*) The magnetic flux density.

12. In practice, the number of conductors is fixed and the speed is nominally constant, so that control of the e.m.f. must be obtained through variation of the magnetic flux density. This cannot be done with permanent magnets but by substituting electromagnets the e.m.f. can be controlled by varying the current in the windings (see Sect. 2, Chap. 1, Para. 31).

Basic Construction of a D.C. Generator

13. The arrangement of the main components of a d.c. machine is shown in Fig. 5. Such a machine consists of two main assemblies—the *stator* (or fixed portion) and the *rotor* (or armature assembly). The stator carries the field magnet system and the brush gear. The rotor carries the coils in which the e.m.f. is induced, the commutator, and in many cases a series of fan blades to assist in cooling.

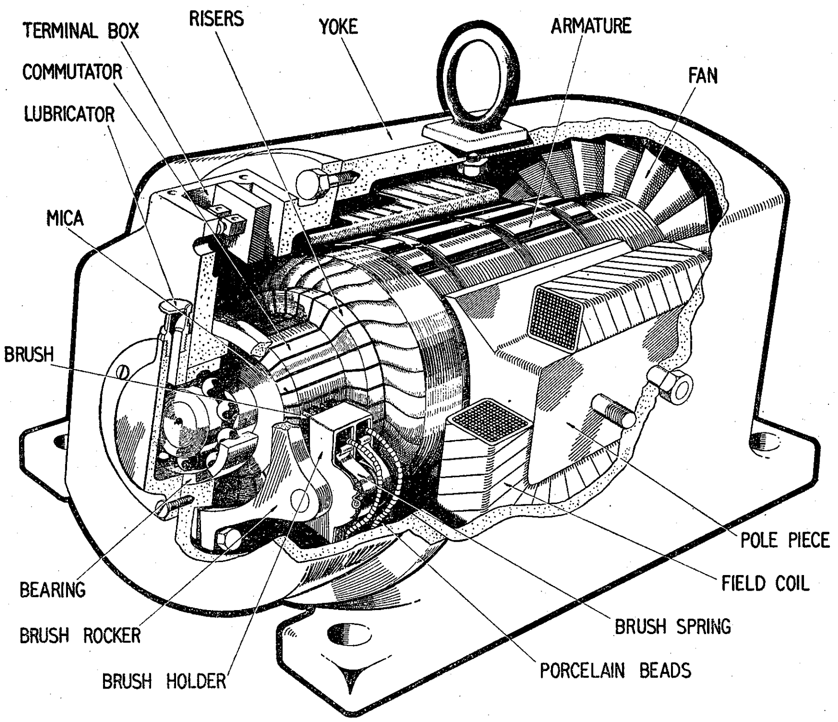


Fig. 5. CONSTRUCTION OF A TYPICAL D.C. MACHINE

14. **The Field Magnet System.** Except for very small machines the magnetic field is provided by electromagnets in such a way that the armature conductors pass under North and South Poles alternately. Several pairs of poles can be used, depending on the flux required. The number of poles is always even, with 2 poles for very small machines and as many as 20 for large machines. The field magnet system for a 6-pole d.c. machine is shown in Fig. 6. To obtain a strong magnetic field for the minimum expenditure of electrical energy, ferro-magnetic materials of high permeability are used, and the magnetic circuit is so arranged that it has the least possible reluctance.

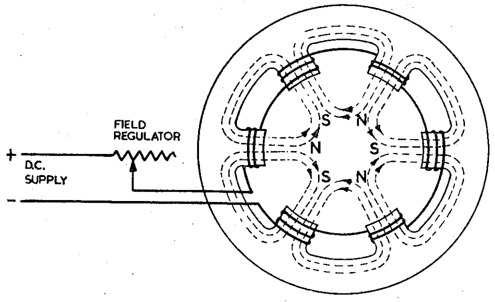


Fig. 6. THE MAGNETIC CIRCUIT OF A 6-POLE D.C. MACHINE

15. **The Armature Assembly.** This consists of the main shaft, the armature core and windings, the commutator, the fan blading, and the bearings. The armature is the practical application of the rotating loop and it is driven by a prime mover—i.e., a heat engine (steam, petrol, or diesel), an electric motor, or a water turbine.

16. (*a*) *Armature.* The armature consists of a soft iron drum, on the surface of which are fixed the conductors to be rotated between the pole pieces of the field magnets. The core is laminated to reduce eddy current losses and the material used has a narrow hysteresis loop. The individual coils which make up the armature winding are identical, and after being taped and impregnated, they are fitted into slots cut in the armature core parallel to the axis of rotation (Fig. 7). The flux from the poles threads through the drum intersecting the sides of each coil as it moves under a pole piece. The coils are not actually wound into adjacent slots but, as shown in Fig. 7, are spread so as to embrace the angular distance between adjacent poles; that is, if there are four poles spaced round at 90° intervals, the two sides of a given coil accupy slots that are 90° apart on the drum, and so on. The two ends of each coil are connected to separate commutator segments, the finish of one coil being connected to the same segment as the beginning of another coil. Thus, the complete winding forms a closed circuit.

(*b*) *Commutator.* This is mounted towards one end of the shaft and is built up of copper segments insulated from each other by thin sheets of mica. The ends of the coils are soldered into lugs or "risers" on the end of the commutator segments.

17. **The Brushgear.** The brushes are made almost invariably of some form of carbon; they are self-lubricating and cause little commutator wear. In addition, their comparatively high resistance minimizes reactive sparking (see Para. 20). They are carried

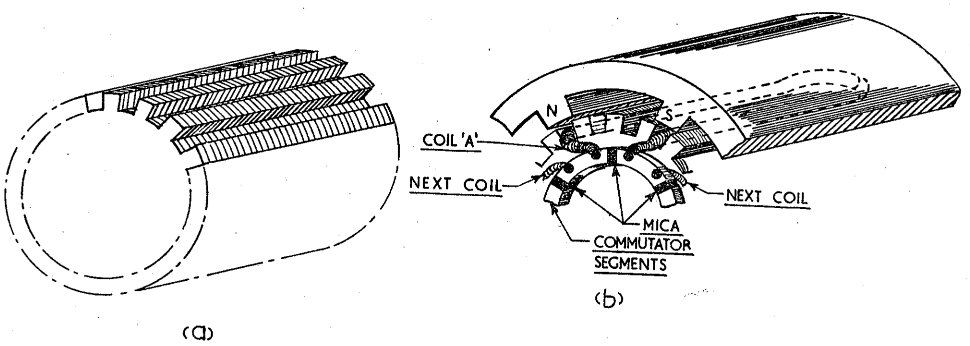


Fig. 7. ARMATURE AND ARMATURE WINDINGS

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in small open-ended boxes termed *brush-holders*, pressure being applied to the top of the brush by an adjustable spring in order to maintain the rubbing contact between the brush and the commutator. Connection to the external circuit from the brushes is normally by "pig-tails" of flexible copper braid. The brush-holders are bolted to *brush-rockers* which can be adjusted to move through a few degrees round the periphery of the commutator to alter the position of the brushes in order to give the best possible commutation (see Para. 21).

Commutation

18. Faulty collection or incorrect commutation at the commutator and brushgear of a d.c. machine produce similar results—the formation of a destructive spark or arc between the trailing edges of the brushes and the commutator surface. Sparking due to faulty collection is usually caused by bad servicing or lack of maintenance. Sparking due to incorrect commutation (usually termed *reactive sparking*) arises from unsuitable positioning of the brushes, or faults in the magnetic circuit.

19. **Reactive Sparking.** The commutator segments connected to the ends of a coil are normally short-circuited by the brush when the sides of the coil are in a magnetically neutral zone and no e.m.f. is being induced in the coil. Consider the ideal case for a 2-pole machine. Immediately before short-circuiting, the coil B would be carrying *half* the total armature current; during the short-circuit period the current in the coil would be zero; and immediately after the short-circuit period the coil would be carrying half the total armature current in the *reverse* direction (Fig. 8).

20. In practice the current cannot change instantly because of the self-induced back e.m.f. (or reactance e.m.f.) in the coil. Thus the current in coil B will *not* have reached its final value in the reverse direction immediately after the short-circuit period. The result is that the *difference* in current between coils B and C will "jump" between the commutator and the brush in the form of a spark.

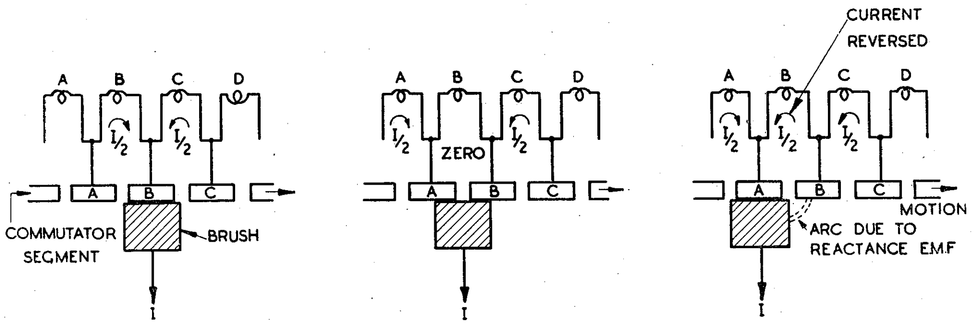
21. **Reduction of Reactive Sparking.**

(*a*) *Resistance Commutation.* By using high resistance carbon brushes the inductive time constant $\frac{L}{R}$ seconds is *reduced;* this ensures a much more rapid build-up of current in the reverse direction in coil B. In addition, the high resistance contact causes more current to go through coil B and assists in attaining the full reversed value of current at the end of the short-circuit period. Resistance commutation suffers from two main dis-advantages:—

(i) Power losses (I^2R watts) are high.

(ii) Slight sparking may still occur at the brushes since the current is still changing although at a greatly *increased* rate.

(*b*) *Brush Position Commutation.* If the brushes of a generator are slightly *advanced* (by means of the brush-rocker) in the direction of rotation, the short-circuiting of the coil will be delayed until it has come under the influence of the next main pole. In these circumstances, an e.m.f. will be induced in the coil considered and this e.m.f. will be in such a direction as to assist the collapse and the build-up of the reversed current in the shorted coil. In this way, reactive sparking can be prevented since the brush position can be so adjusted that the reversed current is a



a) BEFORE SHORT CIRCUIT b) DURING SHORT CIRCUIT c) AFTER SHORT CIRCUIT

Fig. 8. CAUSE OF REACTANCE SPARKING

full value before the end of the short-circuit period. The disadvantage of brush position commutation is that the position of the brushes requires to be adjusted for every variation in "load".

(*c*) *Compoles.* A more satisfactory method of forcibly reversing the current in the shorted coil (so that the current has reached its correct value by the end of the short-circuit period) is by the use of compoles (also known as commutating poles, or interpoles). These are auxiliary poles located midway between the main poles. Their windings are connected in series with the *armature* winding and in generators are so arranged that the compole has the same polarity as the next main pole *ahead* in the direction of rotation (Fig. 9). When the armature coil is in a magnetically neutral zone as far as the main poles are concerned, commutation takes place; the compoles will then induce an e.m.f. in the coil considered, this e.m.f. being in such a direction as to assist in the collapse and the build-up of the reversed current in the shorted coil. Since the compole windings carry the *armature* (load) current, any variation in load is automatically accounted for.

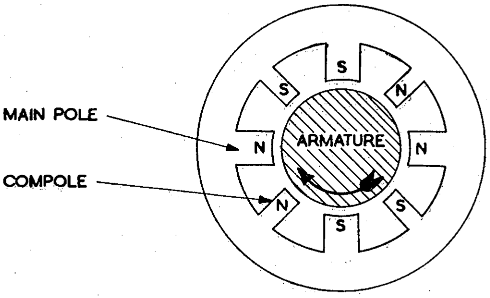


Fig. 9. COMPOLES IN A GENERATOR

Armature Reaction

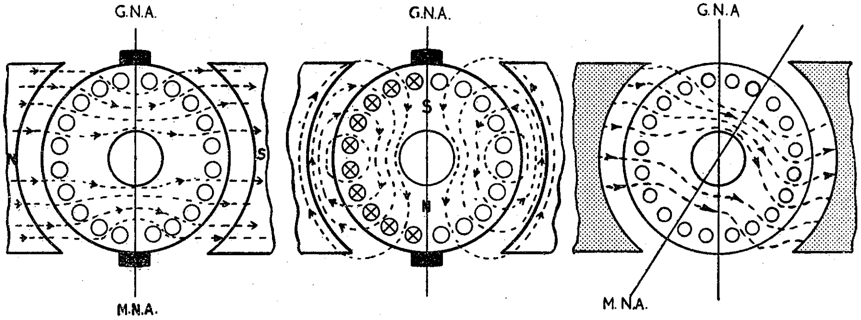
22. **Cause of Armature Reaction.** When a generator is running on load, a magnetic field is created by the current flowing in the *armature* winding. This magnetic field is superimposed on the main field (produced by the current in the *field* winding) to give a resultant field which is distorted and weakened to an extent dependent on the load. This effect is termed *armature reaction* (Fig. 10).

23. A line drawn vertically at a point midway between the poles is termed the *Geometrical Neutral Axis* (G.N.A.). A line joining the two points at which no e.m.f. is induced in a coil is known as the *Magnetic Neutral Axis* (M.N.A.). With the generator on load, the M.N.A. is seen to have *advanced* in the direction of rotation so that it has an angle of lead on the G.N.A.

24. **Effects of Armature Reaction.** Armature reaction, if uncorrected, produces two bad effects:—

(*a*) It causes the M.N.A. to move when the load is varied, thus upsetting commutation.

(*b*) It weakens the main field, causing a reduction in the generated e.m.f.



MAIN FIELD FLUX
Fig. a

ARMATURE FLUX
Fig. b

RESULTANT FLUX
Fig. c

Fig. 10. ARMATURE REACTION IN A GENERATOR

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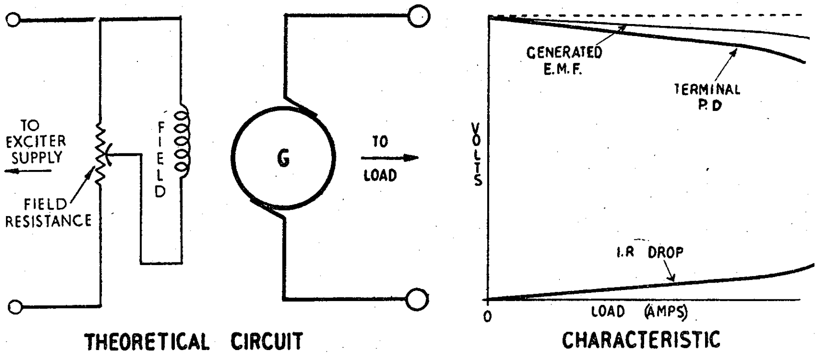


THEORETICAL CIRCUIT

CHARACTERISTIC

Fig. 11. SEPARATELY-EXCITED GENERATOR

25. **Correction of Armature Reaction Effects.**

(*a*) By moving the brushes through the appropriate angle of *lead* so that their axis coincides with the M.N.A. it is possible to restore good commutation. However, as was shown in Para. 21(*b*), the angle of lead then requires to be adjusted for every variation in load.

(*b*) The effects of armature reaction can be greatly minimized by the use of compoles (although these are primarily intended to provide the necessary commutating e.m.f. as shown in Para. 21 (*c*)). The flux due to the compoles is opposite in direction to the armature flux. By placing the requisite number of turns on each compole, these two fields can be made equal *at all loads*, since both are produced by the armature (load) current. By this means the M.N.A. is made to coincide with the G.N.A. at all times and it is no longer necessary to give the brushes an angle of lead.

Classification of Generators

26. D.C. generators are usually classified according to the method by which the magnetic circuit of the machine is energised. The recognised classes are:—

(*a*) Permanent magnet generators.

(*b*) Separately-excited generators.

(*c*) Self-excited generators.

Permanent Magnet Generators

27. Permanent magnets give the simplest method of producing the magnetic flux in a generator, but their use is confined to relatively small machines because of the difficulty experienced in producing sufficient flux for larger machines.

28. The relationship between the current in the external circuit connected to the terminals of a generator (termed the load current or load), and the p.d. at the generator terminals, is known as the external characteristic of the machine. For a permanent magnet generator, the terminal p.d. falls slightly with increasing load and the machine is said to have a falling characteristic. This fall in terminal p.d. is due to two causes:—

(*a*) Weakening of the main flux by armature reaction.

(*b*) A voltage (IR) drop in the armature windings and in the brushes.

Separately-excited Generators

29. The magnetic field for this class of generator is obtained from electromagnets which are excited by current obtained from an *external* d.c. source. The field and armature windings are not connected in any way. The field winding is usually of fairly high resistance and provision is made for regulating the exciting current, *e.g.*, by a variable resistor (Fig. 11). Complete control of the terminal p.d. over a wide range can then be obtained (see Para. 12).

30. The generated e.m.f. falls slightly with load because of armature reaction, if the latter is not completely neutralized by the use of compoles. The terminal p.d. falls with load to an even greater extent because of the increasing IR drop in the armature windings (Fig. 11).

Self-excited Generators

31. This class of generator uses electromagnets to provide the magnetic flux. The

e.m.f. required to send current through the field coils of the electromagnets is generated *by the machine itself.* Self-excited generators are further classified as follows:—

(*a*) *Shunt winding*, where the field winding is connected directly across the armature (Fig. 12). To avoid unnecessary expenditure of electrical energy, the field current is kept small, the necessary ampere-turns for the required flux being obtained by using many turns of fine wire. The resistance of a shunt field winding is consequently high. Provision is made for regulating the exciting current by a variable resistor in series with the field winding. Complete control of the terminal p.d. over a wide range is then obtained.

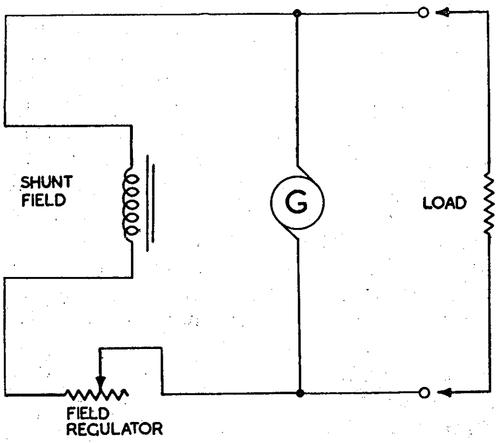


Fig. 12. SHUNT-WOUND GENERATOR

(*b*) *Series winding*, where the field winding is connected in series with the armature and the load (Fig. 13). The field coils are usually made of a relatively small number of turns of thick wire. The terminal p.d. of a series generator may be controlled by a *diverter*, i.e., a variable resistor connected *in parallel* with the field winding so as to adjust the current in the field coils. A *decrease* in resistance *reduces* the current in the field winding thereby reducing the magnetic flux to cause a fall in the generated e.m.f.

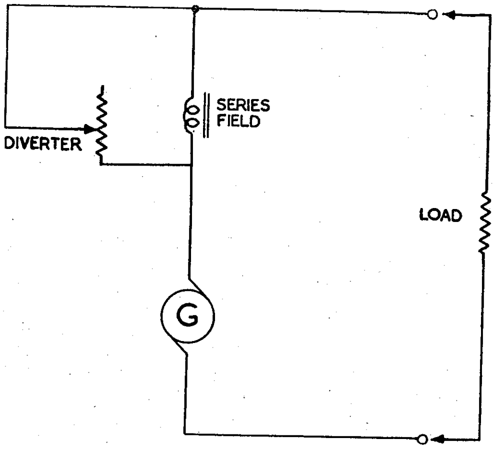
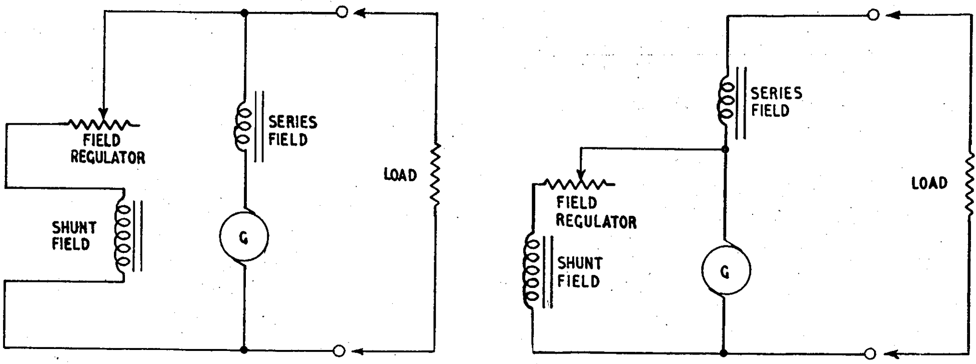


Fig. 13. SERIES-WOUND GENERATOR

(*c*) *Compound winding*, where a combination of shunt and series field windings is used. Each pole piece carries one shunt and one series coil. If the shunt



(a) LONG SHUNT CONNECTION

(b) SHORT SHUNT CONNECTION

Fig. 14. COMPOUND-WOUND GENERATORS

winding is connected across the armature and series windings a *long shunt connection* results (Fig. 14(*a*)). In a *short shunt connection*, the shunt winding is across the armature only (Fig. 14 (*b*)). Control of the terminal p.d. is usually obtained by a variable resistance in series with the shunt winding.

32. **Characteristic of shunt-wound generators.** The initial build-up of field current depends on the retentivity (or residual magnetism) of the magnetic circuit. When the armature is caused to rotate, the conductors cut the weak magnetic flux provided by the residual magnetism. A small e.m.f. is induced in the armature and this is applied across the shunt winding to establish a current in the latter; the magnetic flux increases. In this way, a progressive increase in the induced e.m.f. and in the field current occurs, until the terminal p.d. reaches a steady no-load maximum equal to the generated e.m.f.

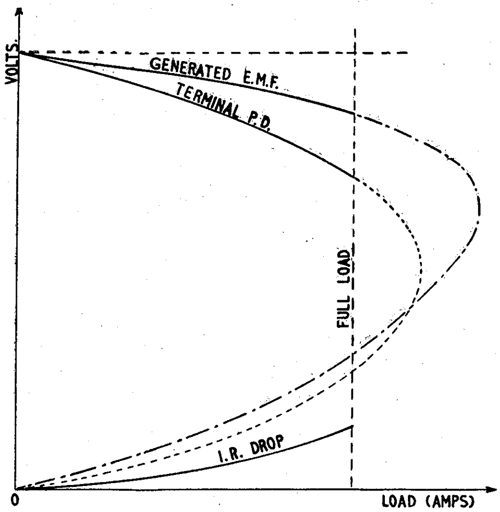


Fig. 15. CHARACTERISTICS OF SHUNT GENERATOR

33. The external characteristic of a shunt generator is similar to that of the separately-excited machine (Para. 30). However, the fall in terminal p.d. with increasing load will reduce the field current, thus weakening the main flux and producing a further fall in the terminal p.d. The total decrease in the terminal p.d. is, therefore, greater than if the machine were separately-excited. If the load is increased beyond the "full load" condition, the terminal p.d. will fall at an increasing rate until the generator shuts down and both the terminal p.d. and the load current fall to zero (Fig. 15). In effect, the field winding is shunted by the low resistance of the external circuit and the main flux collapses. For this reason, a shunt-wound generator should be allowed to build up to its full voltage before connecting the load.

34. **Characteristic of series-wound generators.** In these machines the field current is proportional to the load current. No current flows through the field winding until an external load is connected, and on no-load the only e.m.f. generated is the small amount due to the residual magnetism of the magnetic circuit. When a load is connected, current flows through the armature and field windings in series. As the resistance of the external circuit is decreased the increased load current in the field windings gives an increase of flux so that the generated e.m.f. and the terminal p.d. rise. This is progressive as shown in Fig. 16. Maximum terminal p.d. is attained when the magnetic circuit reaches saturation. Any further increase in load current will not then result in a rise of generated e.m.f. but it will, on the other hand, cause an increased voltage drop in the armature and field windings. It is this IR drop which gives the difference between the generated e.m.f. and the terminal p.d. in Fig. 16.

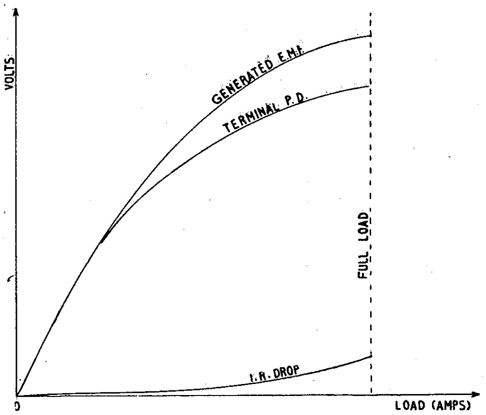


Fig. 16. CHARACTERISTICS OF SERIES GENERATOR

35. **Characteristics of compound-wound generators.** The external characteristics of these generators depend on the relative direction of the shunt and the series windings, and on the number of turns on the series winding.

(*a*) *Cumulative compound winding.* When the series winding is wound to produce the same polarity at the pole pieces as that provided by the shunt winding, the windings are cumulative in their effect. An increase of load current in such a machine will cause an increase in flux due to the action of the series field. This increase of flux may compensate for the weakening of flux which occurs when a load is imposed on a shunt-wound generator (see Para. 33) thus maintaining the terminal p.d. When the effect of the series winding increases the flux to such an extent that the terminal p.d. at full load is the same as that at no load, the machine is said to be *level compounded.* By increasing the number of series turns, the flux due to the load current will increase; the terminal p.d. at full load will then be above the no-load value and the machine is *over-compounded* (Fig. 17).

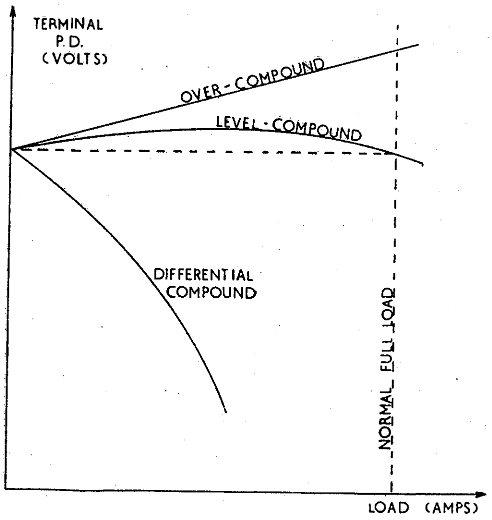


Fig. 17. CHARACTERISTICS OF COMPOUND GENERATOR

(*b*) *Differential compound winding.* These are machines in which the series and shunt fields oppose each other. With increased load, the increase in series field strength, opposing the shunt field, causes a fall in the total flux, resulting in a fall in the terminal p.d.

Generator Losses and Efficiencies

36. **Losses.** The various power losses which occur may be divided into:—

(*a*) *Copper Losses.* These are sometimes referred to as electrical losses and are caused by current passing through the resistance of the various conductors so that a power loss (I^2R watts) results. In general, they increase with the load and to prevent excessive copper losses the generator should not be overloaded.

(*b*) *Iron Losses.* These are sometimes referred to as core losses and are substantially constant at all loads. They include:—

(i) Hysteresis loss in the armature.

(ii) Eddy current loss in the armature.

(*c*) *Friction Losses.* These are purely mechanical losses and include:—

(i) Friction at the bearings and at the commutator.

(ii) Wind resistance of the rotating armature.

37. **Efficiencies.** The energy changes and losses which occur in the transformation of mechanical energy into electrical energy in a generator are shown diagrammatically in Fig. 18. From this it is seen that the electrical power developed in the armature is equal to the applied mechanical power less the iron and friction losses; and the electrical power output is equal to the power developed in the armature less the copper losses.

38. From Fig. 18 it is possible to give three separate efficiencies:—

(*a*) Mechanical efficiency =

$$\frac{\text{Power developed in armature}}{\text{Mechanical power supplied}} \times 100 \text{ (per cent.)}$$

(*b*) Electrical efficiency =

$$\frac{\text{Electrical power output}}{\text{Power developed in armature}} \times 100 \text{ (per cent.)}$$

(*c*) Commercial efficiency =

$$\frac{\text{Electrical power output}}{\text{Mechanical power input}} \times 100 \text{ (per cent.)}$$

Thus, Commercial Efficiency = Mechanical × Electrical Efficiencies.

Note. The Commercial Efficiency is the one more commonly used since it gives the *overall* efficiency of the generator.

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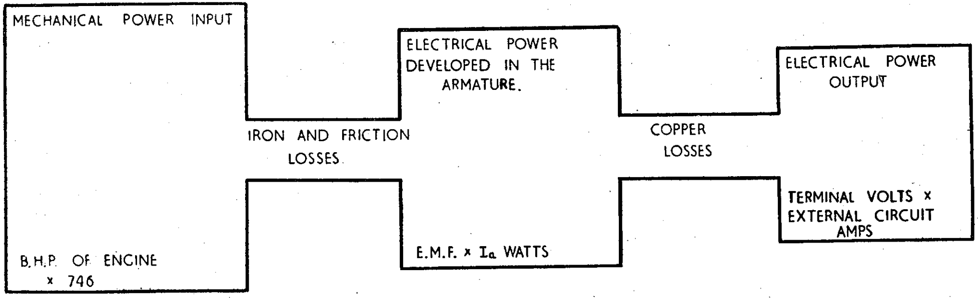

Fig. 18. STAGES IN THE TRANSFORMATION OF ENERGY IN A GENERATOR

39. The graph of Fig. 19 shows how the commercial efficiency and the losses vary with the load current in a compound generator. From this graph it is seen that, whereas the iron and friction losses are practically constant with load, the copper losses increase with the load current. Because of this the efficiency falls off when overloaded as shown.

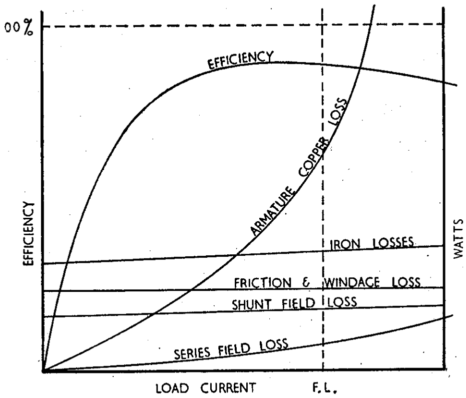

Fig. 19. VARIATION OF LOSSES AND EFFICIENCY WITH LOAD (COMPOUND GENERATOR)

SECTION 3

CHAPTER 2

THE D.C. MOTOR

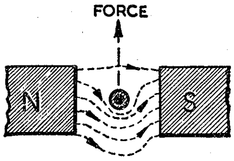

Fig. 4. FORCE ON A CURRENT-CARRYING CONDUCTOR, CURRENT REVERSED

5. The direction in which a conductor which is carrying current tends to move when it is placed in a magnetic field is given by **Fleming's Left Hand Rule**:—

If the first finger, the second finger, and the thumb of the LEFT hand are held at right angles to each other, then with the First Finger pointing in the direction of the Field (N. to S.), and the seCond finger in the direction of the Current in the conductor, the thuMb will indicate the direction in which the conductor tends to Move.

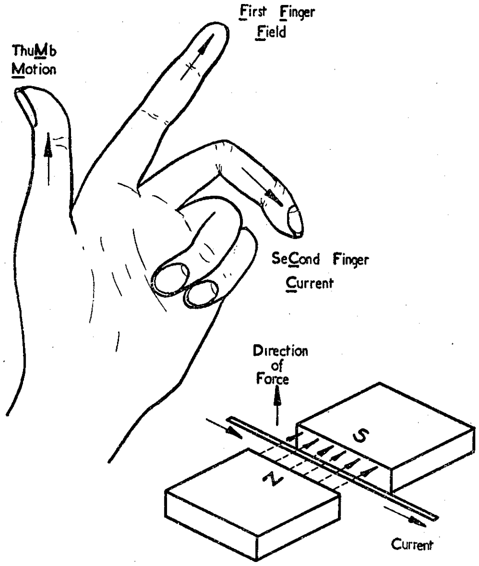

Fig. 5. FLEMING'S LEFT HAND RULE

6. The force acting on a current-carrying conductor when it is placed in a magnetic field is given by:—

$F = BIl$ (newtons) ... ... (1)

where F = Force acting on the conductor in newtons.

B = Flux density of external field in Wb/m^2.

I = Current in conductor in amps.

l = Length of conductor in metres.

7. The fact that a mechanical force acts on such a conductor is used for a number of applications in radio, including certain types of measuring instruments, loud-speakers, telephones, and the electric motor. The latter is considered in this Chapter.

The Electric Motor

8. An electric motor is a machine for converting electrical energy into mechanical energy, its function being the reverse of that of a generator. There is little difference between the construction of generators and motors; both consist of the same essential parts, and the same variations of field-winding connection are found in both types of machines. Provided it is of suitable design as regards brushgear, a d.c. machine can be used either as a motor or as a generator.

The Principles of a Simple D.C. Motor

9. A motor depends for its operation on the force exerted upon current-bearing conductors situated in a magnetic field. Consider a simple permanent magnet motor connected to a battery as shown in Fig. 6.

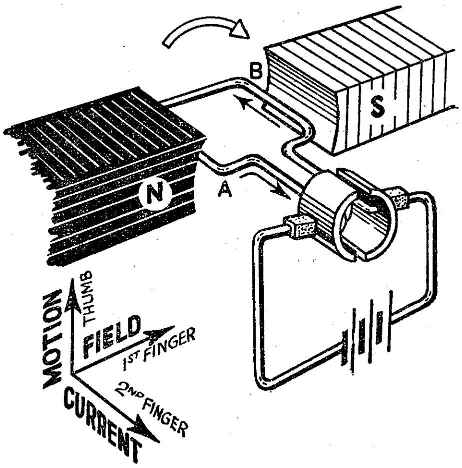

Fig. 6. D.C. MOTOR PRINCIPLE

By applying Fleming's Left Hand Rule it will be seen that side A of the loop (under the N pole) tends to move *upwards*, while side B of the loop tends to move *downwards*. The forces acting on the two sides of the loop are thus cumulative in their effect, and tend to turn the loop in a *clockwise* direction.

10. As the sides of the loop pass through the magnetic neutral position, the commutator reverses the connections of the supply to the loop, and the current in the loop is consequently reversed. Side A of the loop is now coming under the influence of the S pole, with side B coming under that of the N pole. As the current in each side of the loop has been reversed at the instant of transfer from the influence of one pole to that of the other, it follows that the force acting on side A will now be *downwards*, and on side B *upwards*. The mechanical force on the loop is thus continued in the original direction, and rotation continues so long as the supply is connected.

Back E.m.f.

11. When the armature of a motor is rotating, its conductors are cutting the lines of flux of the magnetic field of the machine. An e.m.f. is, therefore, induced in the conductors as in a generator. The direction of the *Back E.m.f.* is given by Fleming's *Right* Hand Rule and is such that it opposes the motion producing it (Lenz's Law). The motion is caused by the external current supply to the armature, and the back e.m.f. will so act as to cut down the current, i.e., it will act in opposition to the applied e.m.f. As was shown in Chap. 1, the value of the back e.m.f. is proportional to the product of the flux and the speed of rotation.

12. There are three voltages to be considered in an electric motor when it is running: the e.m.f. applied to the machine, Ea; the back e.m.f., Eb; and the voltage drop in the armature, Ia Ra. From Kirchhoff's second law, these three voltages are related as follows:—

Applied e.m.f. = Back e.m.f. + Armature voltage drop

$$E_a = E_b + I_a R_a \text{ (volts)} \qquad \ldots \quad (2)$$

Armature Reaction

13. When the armature of a motor is carrying current, the main field of the machine is distorted by the magnetic flux resulting from the *armature* current in much the same way as in a generator. In a motor, however, the effect of armature reaction is to *weaken* the main field to an extent dependent upon the value of the armature current. The magnetic neutral axis is moved *backwards* against the direction of rotation (in a generator it is moved forwards); in consequence the brushes are moved slightly *backwards* to reduce reactive sparking (Fig. 7).

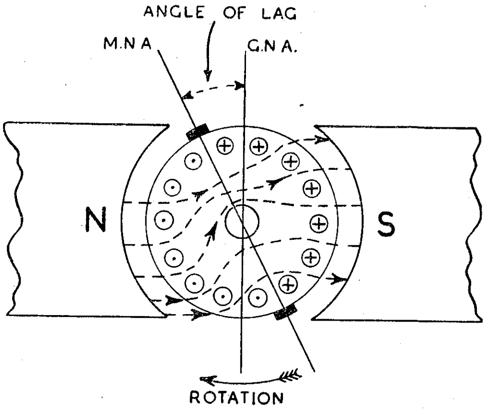

Fig. 7. ARMATURE REACTION IN A MOTOR

14. The objection to moving the brush gear is the same as that for generators, i.e., no one position is completely satisfactory over the whole load range. By the use of *compoles*, motors can be operated with fixed brush positions for all conditions of load. The compoles are connected in series with the armature as in generators, but in this case they are wound so that the magnetic polarity of each compole is *opposite* to that of the next main pole ahead in the direction of rotation.

Torque

15. Torque is the term used to express the turning or twisting effect of a force about an axis. In a d.c. motor each conductor lying in the influence of a pole face exerts a torque tending to turn the armature, the torque of each conductor being determined by the force exerted on the conductor multiplied by the distance of the conductor from the axis of the armature. The sum of these torques is termed the *Armature Torque* and is given by :—

$$\text{Torque, } T = \frac{1}{2\pi} K\Phi IZ \text{ (newton-metres)} \qquad \ldots \quad \ldots \quad \ldots (3)$$

where K = A constant depending on the machine.
Φ = Flux per pole in webers.
I = Armature current in amps.
Z = Number of conductors.

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Note. Since the factors K and Z are constant for any given machine it is seen that a variation of torque is obtained by varying either the *flux* Φ or the *armature current* I.

16. The whole of the armature torque is not available for doing useful work. Friction in the bearings, the opposition to magnetic change in the armature core, and wind resistance to the rotating armature all act as a load on the machine, and must be overcome before any useful work can be done. The torque required to overcome these losses is termed the *Lost Torque*, while the difference between the armature torque and the lost torque, i.e. the torque available for useful work, is generally known as the *Shaft Torque.*

17. The power developed by a d.c. motor is proportional to the product of the shaft torque and the speed in revolutions per minute. It follows that *for a given power* any increase in speed can be obtained only at the expense of torque, and *vice versa:* thus, at low speeds the torque will be high, and at high speeds the torque will be low.

18. A mechanical load exerts a torque opposing the motion and this *Load Torque* is constant for a given load, irrespective of the speed at which the load is driven. At low speeds, the shaft torque of the motor will be high and in excess of the load torque. The motor will therefore accelerate and, as its speed rises, the shaft torque will fall until the shaft and the load torques are equal. The motor then continues to drive the load at a steady speed.

19. If the load is increased, the load torque rises to upset the torque balance. The motor will therefore slow down, thereby increasing the shaft torque until the balance is once more restored and the speed is again stablilized. A constant speed with an increased load can be obtained only by increasing the power output of the motor.

Motor Losses and Efficiency

20. **Losses.** As with the generator, the losses in a motor can be classified as:—

(*a*) *Copper losses* due to the generation of heat (I^2R watts) in the armature and field windings; these losses vary with the load.

(*b*) *Iron losses* due to hysteresis losses in every part of the iron through which the flux changes and also to eddy currents induced in the rotating armature.

(*c*) *Mechanical losses* due to friction at the bearings and brushes, and to windage.

21. **Efficiency.** The energy changes and losses which occur in the transformation of electrical energy into mechanical energy in a motor are shown diagrammatically in Fig. 8. From this it is seen that the mechanical power developed in the armature is equal to the applied electrical power less the copper losses; and the mechanical output at the shaft is equal to the mechanical power developed in the armature less the iron and mechanical losses. The overall efficiency of the d.c. motor is:—

$$\text{Efficiency} = \frac{\text{Mechanical Power Output at the Shaft}}{\text{Electrical Power Supplied}} \times 100 \text{ (per cent)}$$

Also,

$$\text{Efficiency} = \frac{\text{Electrical Power Supplied} - \text{Total Losses}}{\text{Electrical Power Supplied}} \times 100 \text{ (per cent).}$$

Speed of a D.C. Motor

22. The back e.m.f. developed in the armature of a d.c. motor when it is running, determines the current in the armature and makes the motor a self-regulating machine in which speed and armature current are automatically adjusted to the mechanical

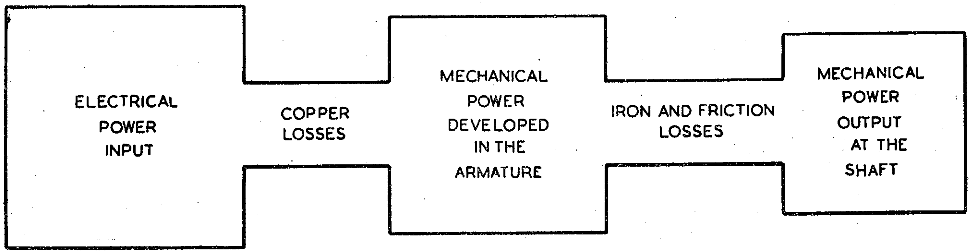


Fig. 8. STAGES IN THE TRANSFORMATION OF ENERGY IN A MOTOR

load. At small values of load the shaft torque exceeds the load torque; the armature therefore accelerates and gives rise to a larger back e.m.f. The increased back e.m.f. cuts down the armature current thus reducing the shaft torque until eventually a state of balance between the two torques is obtained and the speed is stabilized. With increasing load the load torque is increased, exceeding the shaft torque and causing a fall in armature speed. Reduced armature speed results in reduced back e.m.f. and increased armature current; the increase in armature current produces an increase in shaft torque restoring torque balance and stabilizing the speed again. The variation of speed with armature current (i.e. with mechanical load) is known as the *speed characteristic* of the motor.

Control of Speed

23. Assuming constant load, there are two methods commonly used to vary the speed of a d.c. motor:—

(*a*) *Field Control.* By weakening the main flux of a motor the back e.m.f. is reduced, increasing the effective voltage and the armature current. The increased armature current gives rise to an increased shaft torque, causing the motor to accelerate until the back e.m.f., rising with increased speed, restricts the armature current and shaft torque to restore the balance of shaft and load torques. At this point the speed of the motor will stabilize. Conversely, an *increase* in field strength will cause a *reduction* in speed.

(*b*) *Armature Control.* By reducing the voltage across the armature of a motor the effective voltage is reduced, with a corresponding reduction in armature current and shaft torque. The excess of load torque over shaft torque causes the motor to slow down to a point where the reduced back e.m.f. permits sufficient armature current to produce a state of balance between the two torques. At this point the speed of the motor will stabilize.

Types of D.C. Motor

24. D.c. motors are classified according to the method by which the field is excited.

(*a*) The majority of motors are comparable to self-excited generators, i.e., the armature winding and the field winding are supplied from a common source. Their speed and load characteristics vary according to the method of connecting the field winding to the armature, and as a class, they are capable of fulfilling most requirements.

(*b*) Separately-excited motors are used only for special purposes where the more normal types are unsuitable.

(*c*) Permanent magnet motors are employed for certain special purposes, e.g. in small control systems.

Shunt-wound Motors

25. The field winding of the shunt-wound motor is connected in parallel with the armature (Fig. 9). It is thus directly across the supply and must be of fairly high resistance to restrict the current through it. The winding consists of a large number of turns of fine wire. The armature winding is of low resistance to minimize I^2R losses, but unduly heavy current through this winding is prevented by the action of the back e.m.f. when the motor is running.

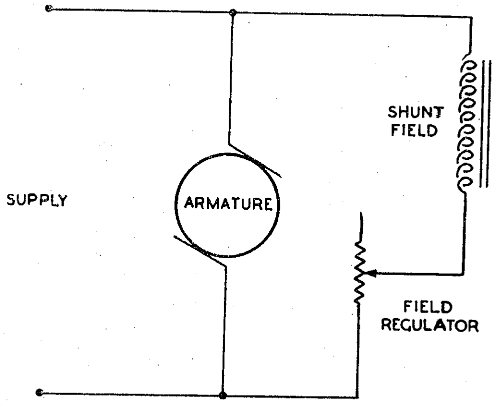


Fig. 9. SHUNT-WOUND MOTOR

26. **Speed Control.** This is normally accomplished by a variable resistor connected in series with the field winding. An increase in resistance will decrease the field strength and increase the speed of the motor (see Para. 23).

27. **Characteristics.**

(*a*) *Speed characteristic.* Whatever the load may be the back e.m.f. adjusts itself to such a value that sufficient armature current can pass to produce a torque equal to the total opposing torque. Further, owing to the low armature resistance, a small decrease in the back e.m.f. (consequent upon a slight reduction in speed) is sufficient to permit full armature current to flow. Reduction in speed from "no load" to "full load" is therefore small (see Fig. 10.) and a shunt-wound motor can be considered as a *constant-speed* machine.

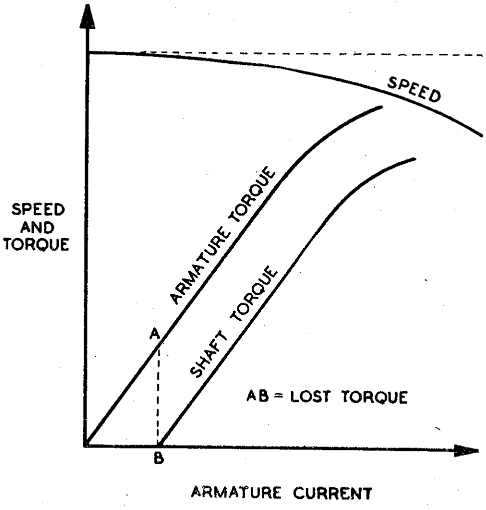


Fig. 10. SHUNT MOTOR CHARACTERISTICS

(*b*) *Torque characteristic.* Since the field current is constant the field strength is also practically constant except for the weakening effect of armature reaction with full load current in the armature. The torque is therefore, proportional to the armature current (see equation (3)) until approaching the full load condition (Fig. 10). The starting torque is small because of the restricted armature current, and shunt-wound motors should, therefore, be started on light load or no load.

28. **Uses.** Shunt-wound motors are suitable for purposes where the speed is required to remain approximately constant from no load to full load, e.g., lathes, drills, and light machine tools generally.

Series-wound Motors

29. The armature winding and the field winding of series-wound motors are in series with each other across the supply (Fig. 11). The armature and field currents

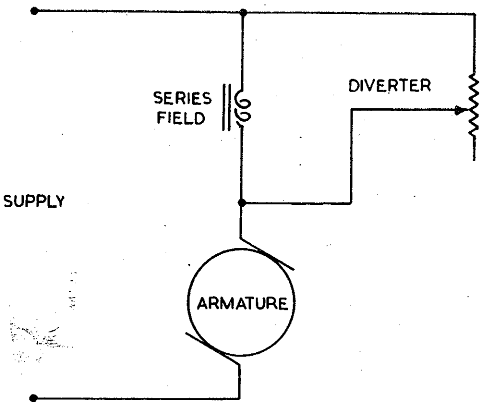


Fig. 11. SERIES-WOUND MOTOR

are, thus, proportional to each other. Both windings are of low resistance to minimize I^2R losses, the field winding consisting of a few turns of heavy wire. The current in both windings, under running conditions, is restricted by the back e.m.f. induced in the armature.

30. **Characteristics.**

(*a*) *Speed Characteristic.* In a series-wound motor the field flux is proportional to the armature current until the iron of the magnetic circuit approaches saturation. From Para. 23(*a*) it is seen that the speed is inversely proportional to the flux (and hence armature current) up to the point of magnetic saturation, so that the speed decreases with increased load. The speed characteristic is shown in Fig. 12. From

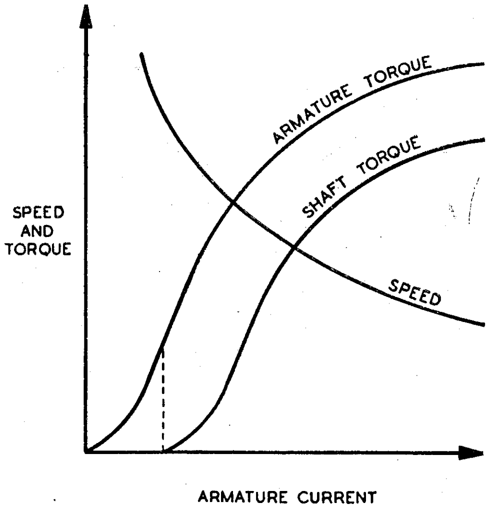


Fig. 12. SERIES MOTOR CHARACTERISTICS

its shape it is seen that the series-wound motor is essentially a *variable speed* motor, the speed being low on heavy load and dangerously high on light load. For this reason the series-wound motor is not run without some mechanical load on it.

(*b*) *Torque Characteristic.* From equation (3) it is seen that the torque is proportional to the product of the flux and the armature current. Further, in a series motor, the field flux is proportional to the armature current so that the torque is proportional to the *square* of the armature current. Hence, the torque increases rapidly as the load is increased until the iron approaches saturation (Fig. 12). The starting torque is high and series motors can be started on full load.

31. **Uses.** Series-wound motors are used where large starting torques are required and where the load is subject to heavy fluctuations. Typical uses include engine starting and traction work.

Compound-wound Motors

32. It is often necessary to modify the characteristics of normal shunt or series motors to meet certain specific requirements. For example, a motor may be required to develop a high starting torque without the tendency to race when the load is removed. Other circumstances may require a motor capable of reducing speed with increased load to an extent sufficient to prevent excessive power demand on the supply, while still retaining the smooth speed control and reliable off-load running of the shunt motor. These and other requirements can be met by suitable compounding. By arranging that part of the field winding is in series with the armature, and part in parallel with it the large starting torque of the series motor can be combined with the steady running under varying load of the shunt motor. This is the compound-wound motor. The windings can be either cumulatively-wound or differentially-wound depending on the requirement (see Chap. 1, Para. 35).

33. **Characteristics.** The torque and speed characteristics for a typical compound-wound motor are shown in Fig. 13. It will be seen that for a small load and armature current the speed is not excessive, and that over a *working range* of load the speed is fairly steady; both of these are "shunt" features. At the same time, there is an appreciable drop in speed between no-load and full-load, and this is a "series" feature.

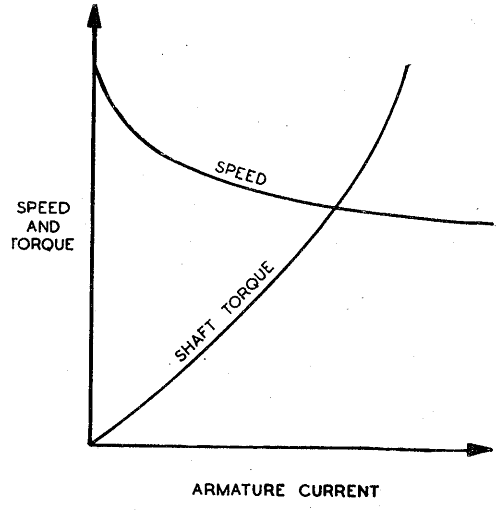


Fig. 13. COMPOUND MOTOR CHARACTERISTICS

Motor Starters

34. Small and medium d.c. motors can be started by connecting the motor terminals direct to the supply, provided the armature windings are of sufficiently high resistance to limit the initial surge of current to a safe level. Direct starting cannot, however, be adopted with larger high power motors having low resistance armature windings. When the armature is stationary there is no back e.m.f. induced in the armature winding so that on connecting the supply to the low resistance armature the current would be excessive. The build-up of flux would be delayed still more by the weakening effect of armature reaction (produced by the excessive armature current). This, in turn, would result in reduced torque and slow acceleration with consequently reduced back e.m.f. The period of excessive current would thereby be prolonged and would undoubtedly lead to damage of the armature winding. Thus, in motors having a low resistance armature winding a *motor starter* must be used.

35. The principles of starting and of the speed regulation of the various types of d.c. motors can be summarized as follows:—

(*a*) *Series Motor.*

(i) The normal starting equipment for low resistance types consists of a variable resistor connected in series with the supply (Fig. 14). The motor is started with all the resistance in circuit to limit the initial surge of armature current; the resistance is then progressively reduced until, at normal speed, all the resistance is out of circuit and the back e.m.f. is such as to keep the armature current at its normal low value. As noted in para. 30 the series-wound motor is started *on load.*

(ii) Speed regulation is obtained by either a variable resistor connected in series with the supply or by a diverter in parallel with the series field winding (see Fig. 14).

(*b*) *Shunt Motor.*

(i) This type is normally started with resistance in series with the *armature* winding only, full voltage being applied at once to the shunt field winding (Fig. 14); the starting resistance is progressively reduced as the speed rises, the increased back e.m.f. then limiting the armature current. The shunt motor is normally started *off load* (see Para. 27).

(ii) Speed regulation is normally by a variable resistor in series with the shunt field winding (see Fig. 14). Increased resistance gives increased speed.

(*c*) *Compound Motor.* Normally as for shunt motors.

Rotary Transformers

36. In many instances of both ground and airborne radio equipments the d.c. power supplies are obtained from a rotary transformer. This is a single machine combining the functions of a d.c. motor and d.c. generator. It consists of a single field system and a single armature, on which are separately

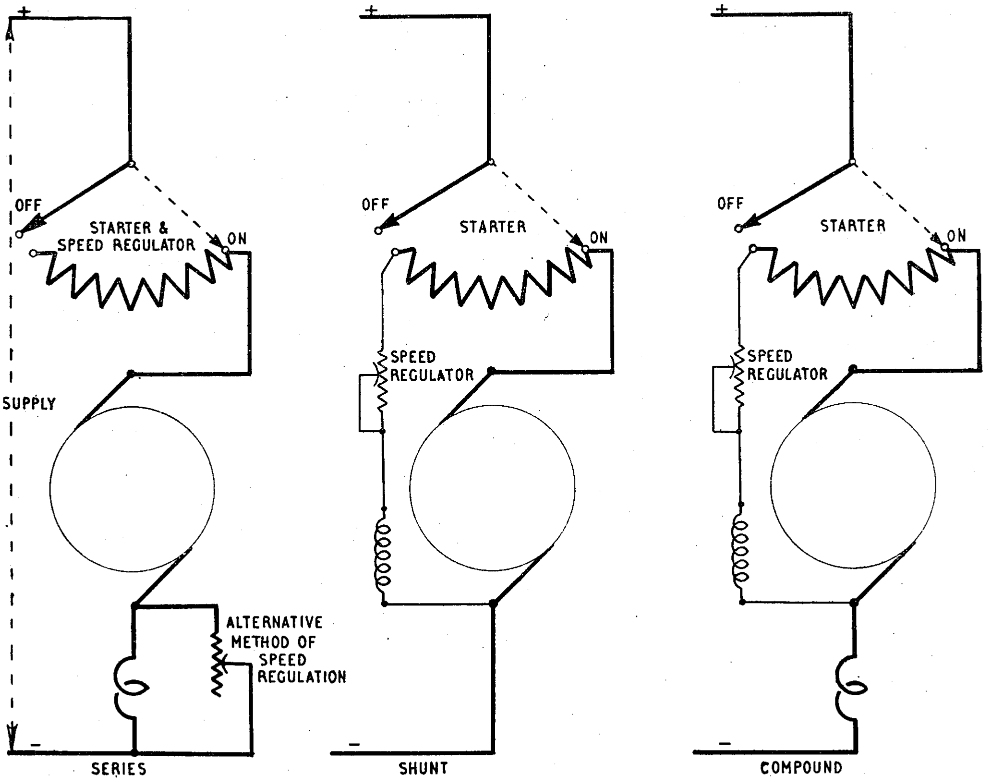


Fig. 14. STARTING AND SPEED REGULATIONS OF D.C. MOTORS

wound the motor and generator windings. On supplying the d.c. input to the field winding and to the motor winding (via the motor commutator and brushes) the armature rotates; since the generator winding on the armature is moving in a magnetic field an e.m.f. is induced in this winding, the d.c. output being taken via the generator commutator and brushgear to the external circuit. In this way it is possible to "step up" or "transform" the input voltage to any required level. For example a typical rotary transformer operates from a d.c. input of 24 volts at 7 amps and gives a d.c. output of 1,200 volts at 100 milli-amps. It should be noted however that in the conversion of energy some losses have occurred (Para. 20) and the *power* output of the machine is always less than the power input.

Rotary Inverters

37. This is the name given to machines which combine the functions of d.c. motor and a.c. generator. A rotary inverter is similar in construction to a rotary transformer with the exception that the generator windings are connected to slip rings instead of to a commutator. In this way the d.c. input to the motor commutator is "inverted" to give an a.c. output at the slip rings of the generator.

Rotary Converters

38. This is the name given to machines which combine the functions of a.c. motor and d.c. generator. It is similar in general construction to the rotary inverter, but the slip rings are now on the input (motor) side and the commutator on the output (generator) side of the machine. The a.c. input to the slip rings of the motor is "converted" to give a d.c. output at the generator commutator.

SECTION 2

MAGNETISM AND ELECTROMAGNETIC INDUCTION

SECTION 2

CHAPTER 1

THE MAGNETIC CIRCUIT

Paragraph

MAGNETISM

THE MAGNETIC CIRCUIT

MAGNETIC MATERIALS

PART 1, SECTION 2, CHAPTER 1

THE MAGNETIC CIRCUIT

MAGNETISM

Introduction

1. Certain specimens of iron ore called natural magnets or lodestones, possess the following properties :—

(*a*) When freely suspended they come to rest pointing in a North-South direction.

(*b*) They attract small fragments of iron and steel.

2. These "magnetic" properties can be imparted artificially to iron and steel to produce permanent magnets and electro-magnets.

(*a*) **Permanent magnets** are made of steel or alloys of steel, and once magnetised they retain their magnetic properties for a long period of time under normal conditions.

(*b*) **Electromagnets** are made with a core of soft iron or alloys of iron and have the property that, although easily magnetised, they lose their magnetic properties almost immediately once the magnetising influence is removed.

The Magnetic Field

3. That end of a permanent magnet which, when freely suspended in a horizontal plane, points to the earth's north magnetic pole is termed the north-seeking end, or the north (N) pole, of the magnet. The other end is the south (S) pole.

4. If the N-pole of another magnet is brought near the N-pole of the suspended magnet, the two poles repel each other. Attraction occurs between a N-pole and a S-pole. Thus :—

"*Like poles repel; unlike poles attract each other*".

5. The **magnetic field** of the bar magnet shown in Fig. 1 is the space around a magnet where magnetic forces are experienced. This field can be detected by the use of iron filings or by a compass needle, and is represented by **lines of magnetic flux.** Although some lines are shown incomplete they are always continuous.

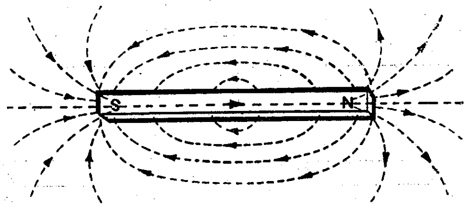


Fig. 1.—THE FIELD OF A PERMANENT MAGNET.

6. The direction of a magnetic field at any point is that in which the North pole of a compass needle would point if placed in the field. The direction is indicated by arrowheads in Fig. 1, and is seen to be from N. to S. in the space around the magnet (and from S. to N. "inside" the magnet).

Flux and Flux Density

7. The total number of lines of magnetic flux leaving a magnetic pole is termed **the magnetic flux** (symbol Φ). The practical unit is the **Weber** (Wb), which corresponds to 10^8 lines.

8. The **flux density** (symbol B) is defined as the flux per unit area and is measured in **Webers per square metre** (Wb/m²). Thus :—

$$\text{Flux density} = \frac{\text{Total magnetic flux}}{\text{Area}}$$

$$\text{i.e.,}\quad B = \frac{\Phi}{a}\,(\text{Wb/m}^2)\ldots\quad\ldots\qquad(1)$$

9. Fig. 2 (*a*) shows the magnetic field that exists between two unlike poles. Fig. 2(*b*) shows the effect of inserting an iron bar in the space between the two poles. The flux lines appear to be concentrated in the vicinity of the iron. The iron has in fact, become magnetised from the external field and produces flux lines of its own, which combine with the original flux to give an increase in the total flux in that area. Thus, iron has the property of increasing the flux density of a magnetic field.

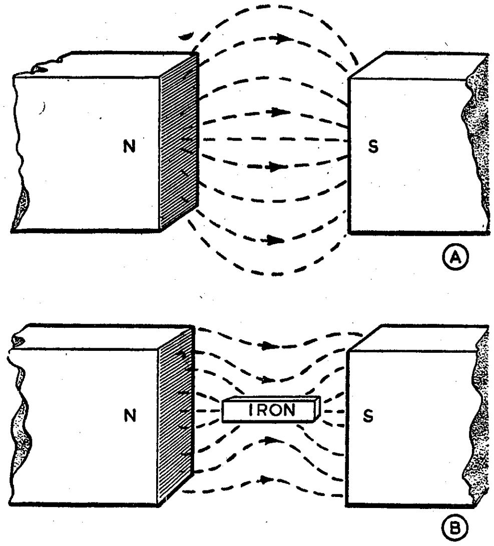


Fig. 2.—EFFECT OF INSERTING IRON IN A MAGNETIC FIELD.

The Magnetic Effect of a Current

10. Fig. 3 shows the cross-section of a conductor assumed to be carrying a current. The convential flow of current is denoted by " + ", which indicates that the current is in a direction " into the paper ". The resultant magnetic field (both inside and outside the conductor) takes the form of concentric circles. The direction of the field is seen to be clockwise in this case.

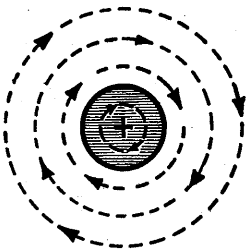


Fig. 3.—THE MAGNETIC FIELD ROUND A CURRENT-CARRYING CONDUCTOR.

The direction can be found from **the corkscrew rule,** which states :—

> " *If a corkscrew is rotated so that its direction of travel is the same as the conventional flow of current in the conductor, the direction of rotation indicates the direction of the magnetic field around the conductor* ".

This is shown in Fig. 4.

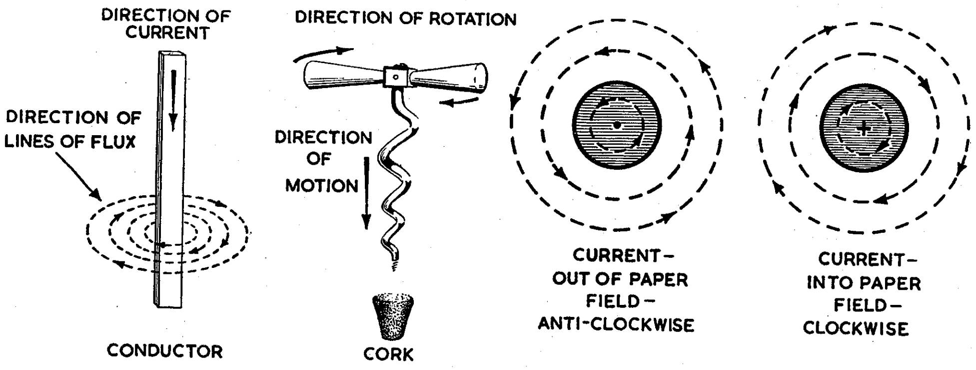


Fig. 4.—THE CORKSCREW RULE

The Magnetic Field of a Solenoid

11. A solenoid consists of a number of turns of wire wound in the same direction as in a spiral spring, to form a coil. Fig. 5 shows a solenoid connected to a battery such that the conventional current is in the direction indicated.

12. The direction of the magnetic field around any elementary part of the solenoid can be obtained from the corkscrew rule. If this is done for a large number of elementary parts, and the fields combined, the

resultant field will be as indicated in Fig. 5. It is seen that the flux lines form a complete closed path in every case, the field being very similar to that for a permanent magnet.

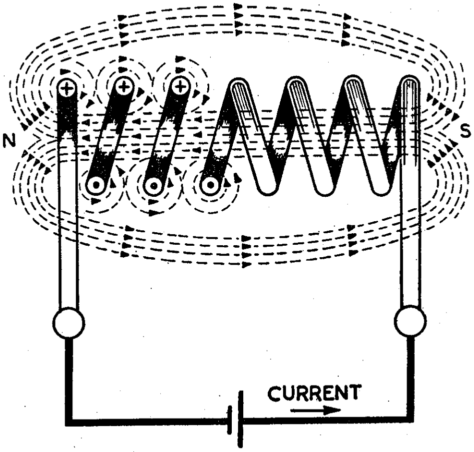


Fig. 5.—THE MAGNETIC FIELD OF A SOLENOID.

13. The polarity of the magnetic field of a solenoid can be obtained from either of two rules :—

(*a*) **The N—S rule.** Looking at one end of the coil, if the current flows in a *clockwise* direction, the end nearer the observer is a *South* pole. If the current is in an *anti-clockwise* direction, the nearer end is a *North* pole. This is illustrated in Fig. 6.

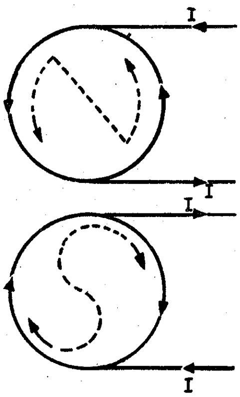


Fig. 6.—THE N-S END RULE

(*b*) **The gripping rule.** If the coil is gripped with the right hand and the fingers are wrapped round the coil in the direction of the current, the *thumb* will point to the *North* pole of the solenoid (Fig. 7).

14. Placing an iron core inside the solenoid will increase the flux density as noted in Para. 9. The iron also becomes magnetised in the polarity shown in Fig. 7. When the current is switched off, the magnetic field associated with that current collapses. If the core is made of soft iron or other similar material, the core also loses its magnetism almost immediately. This is the basis of electromagnets.

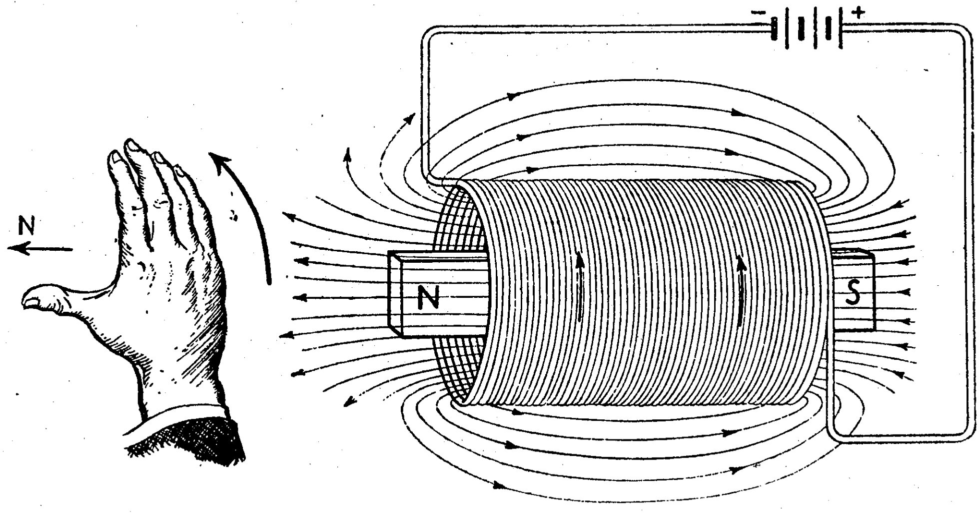


Fig. 7.—THE GRIPPING RULE

THE MAGNETIC CIRCUIT

The Magnetic Circuit

15. The closed path formed by a line (or lines) of flux is referred to as the **magnetic circuit.** One of the simplest forms of magnetic circuit is shown in Fig. 8, where part of the magnetic circuit is in the iron and part in the air gap.

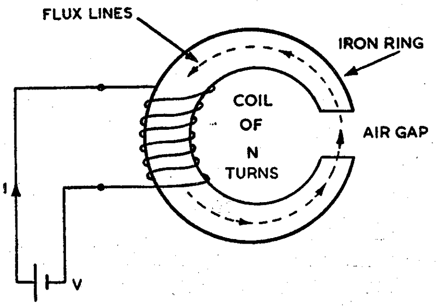


Fig. 8.—A SIMPLE MAGNETIC CIRCUIT.

Magnetomotive Force (M.m.f.)

16. In an electric circuit, a current is established due to the existence of an electromotive force (e.m.f.). In the same way, in a magnetic circuit, a magnetic flux is established due to the existence of a **magnetomotive force (m.m.f.)**; the m.m.f. is produced by the current flowing in the coil and its value is proportional to the current and to the number of turns in the coil. Appropriately, the unit of m.m.f. is the **ampere-turn (AT).** Thus, in Fig. 8 the m.m.f. is IN ampere-turns.

Magnetising Force or Field Strength

17. The **magnetising force** (symbol H) of a magnetic circuit is a measure of the intensity of the magnetic effects at any given point in the magnetic field. It is defined as the m.m.f. per unit length and is measured in **ampere—turns per metre (AT/m).**

$$\text{Magnetising force} = \frac{\text{m.m.f.}}{\text{length}}$$

$$\text{i.e.,} \qquad H = \frac{\text{m.m.f.}}{l} \text{ (AT/m)} \quad .. \ (2)$$

Permeability

18. If a coil of N turns has a current of I amps flowing through it the m.m.f. will be IN (AT). If this coil is in free space, a certain value of flux density B in Wb/m^2 may be observed. On inserting an iron core the value of B will increase. The ratio of "*flux density produced with the iron core*" to "*flux density produced in free space*" for the same applied m.m.f. is termed the **relative permeability** (symbol μ_r) of the iron.

$$\mu_r = \frac{\text{B in a medium}}{\text{B in free space}}$$

$$\text{(for the same m.m.f.)} \quad .. \quad .. \ (3)$$

For air, μ_r may be taken as unity; for certain other materials it may be as high as 100,000.

19. The ratio of "*flux density, B*" to "*magnetising force, H*" at any point in free space is termed the **magnetic space constant** (or the permeability of free space); it is represented by the symbol μ_o. The value of this constant is $4\pi \times 10^{-7}$ m.k.s. units. Thus :—

$$\mu_o = \frac{B}{H} \text{(in free space)} = 4\pi \times 10^{-7} \quad (4)$$

20. From equation (4) :—

$$\text{B in free space} = \mu_o \text{ H}$$

By substitution in equation (3) :—

$$\mu_r = \frac{\text{B in a medium}}{\mu_o \text{ H}}$$

Thus, in any medium :—

$$\frac{B}{H} = \mu_r\mu_o = 4\pi \times 10^{-7} \times \mu_r = \mu \quad (5)$$

The symbol $\mu = \mu_r \mu_o$ denotes the **absolute permeability** of a medium.

Reluctance

21. The reluctance of a magnetic circuit is a criterion of the opposition of the circuit to the establishment of magnetic flux and may be likened, by analogy, to the resistance of an electric circuit.

22. It was shown in Section 1 that :—

$$R = \rho \frac{l}{a} \text{ (Ohms).}$$

Replacing resistivity (ρ) by specific conductance (σ) :—

$$R = \frac{l}{\sigma a} \text{ (Ohms)}$$

Similarly, reluctance S is given by :—

$$S = \frac{1}{\mu a} = \frac{1}{\mu_r \mu_o a} (\text{AT/Wb}) \quad .. \quad .. \quad (6)$$

Comparison of Electric and Magnetic Circuits

23. By analogy, flux Φ in a magnetic circuit is equivalent to current I in an electric circuit, m.m.f. is equivalent to e.m.f., and reluctance S to resistance R. Fig. 9 (*a*) shows a simple electric circuit ; Fig. 9 (*b*) a magnetic circuit.

From Ohm's law :—

$$I = \frac{E}{R} \text{ (amps)}$$

By analogy :—

$$\text{Flux} = \frac{\text{m.m.f.}}{\text{Reluctance}} \text{ (Wb)}$$

$$\text{i.e. } \Phi = \frac{\text{m.m.f.}}{S} \text{ (Wb)} \quad .. \quad .. \quad (7)$$

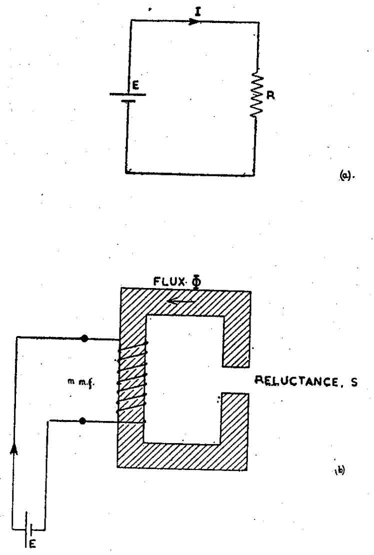


Fig. 9.—SIMPLE ELECTRIC AND MAGNETIC CIRCUITS

Relays

24. As shown in Fig 10, if an equipment is switched on from a remote control point, the heavy current taken by the equipment will develop a considerable volts drop in the connecting cable. The terminal p.d. V_1 will then be very much less than the supply voltage E.

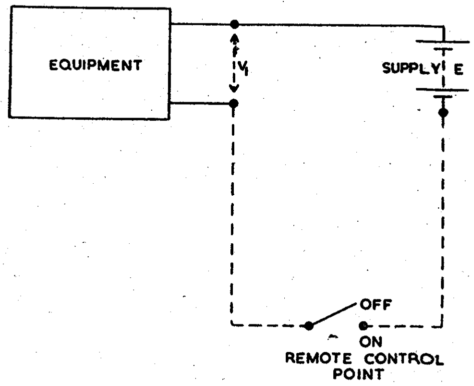


Fig. 10.—REMOTE SWITCHING WITHOUT A RELAY.

25. To prevent this excessive volts drop, a relay can be used (Fig. 11). When the equipment is switched on at the remote control point, the relay becomes "*energised*" and contact RL1 closes to connect the supply to the equipment. There will be very little volts drop in the connecting cable because :—

(*a*) There is only a short length of cable between the supply and the equipment.

(*b*) The current taken by the relay is small.

Note. In radio equipments, relays are annotated as, say $\frac{\text{RL2.}}{3}$ The numerator gives the number of the relay in the equipment and the denominator gives the number of contacts on the relay. The relay contacts are then given as RL2/1, RL2/2, and RL2/3.

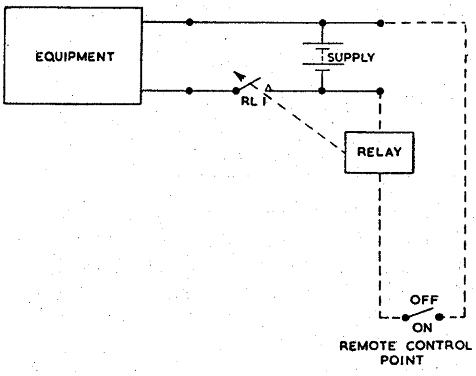


Fig. 11.—REMOTE SWITCHING BY RELAY.

26. Fig. 12 shows the magnetic circuit of a typical relay. It is seen that the flux path

is mainly in iron so that the reluctance of the circuit will be low. Thus, since m.m.f. = flux × reluctance, the ampere—turns required to produce the necessary value of flux will be small. When the circuit is switched on, the field around the solenoid rises and the resultant flux round the magnetic circuit *energises* the relay. The armature is attracted towards the core and closes the relay contact. The circuit to the equipment is then completed. The reverse applies when the on-off switch is opened.

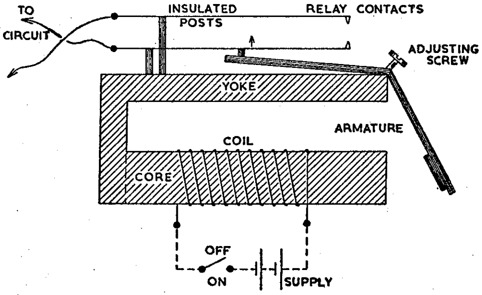


Fig. 12.—TYPICAL MAGNETIC RELAY

The Magneto-striction Effect

27. The theory of magnetism shows that each atom in a magnetic material acts as a tiny electromagnet, the magnetism being produced by the rotation of the electrons around the nucleus of the atom at high speed. The orbiting electrons may be regarded as forming current rings in the material. When the material is not magnetised, the current rings are arranged in small, self-contained, symmetrical groups, and any such group has no influence on any other. When the material is magnetised, the current rings become distorted such that their axes point, more or less, in the direction of the magnetising force. In some materials such as permanent magnets, the current rings continue to have their axes distorted even when the magnetising force is removed.

28. Some materials when magnetised, expand in a lengthwise direction due to the distorted lengthwise axes of the current rings. Conversely, if a bar of such material is caused to expand and contract lengthwise, a varying magnetic field is produced because of the forced distortion of the current rings. This is termed the **magneto-striction effect** of a material (most marked in nickel)—an effect which is used in radio in such devices as the underwater hydrophone.

MAGNETIC MATERIALS

Classification

29. Magnetic materials are used extensively in radio for such applications as the cores of transformers and coils, relay magnetic circuits, magnetic amplifiers, telephones, and loudspeakers. An elementary knowledge of the properties of such materials is required.

30. All materials are classified for magnetic purposes under one of three headings :—

(*a*) **Ferro-magnetic.** These materials (e.g. iron, nickel, and cobalt) have high values of relative permeability μ_r. Since $B = \mu_0 \mu_r H$, ferromagnetic materials have the property of greatly increasing the flux density B in a circuit for a given magnetising force H.

(*b*) **Para-magnetic.** These materials (e.g. platinum and aluminium) are virtually non-magnetic, having values of μ_r only slightly *greater* than unity. Platinum, for instance, has a relative permeability of 1·000017.

(*c*) **Dia-magnetic.** These materials (e.g. lead, copper, and bismuth) are virtually non-magnetic, having values of μ_r only slightly *less* than unity. Bismuth, for instance, has a relative permeability of 0·99996.

B—H Curves

31. In the simple circuit shown in Fig. 13, the current I amps through the coil of N turns can be varied by means of a rheostat. Thus, the m.m.f., given by IN (AT), can be varied, and so can the magnetising force H since :—

$$H = \frac{\text{m.m.f.}}{l} \quad \text{(AT/m)}.$$

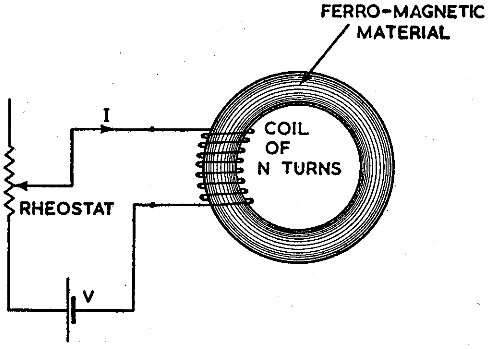


Fig. 13.—A SIMPLE MAGNETIC CIRCUIT

Further, the flux density B can be varied since :—

$$B = \mu H \text{ (Wb/m}^2\text{)}.$$

It is possible, therefore, with such a circuit to plot a graph of the flux density B against the magnetising force H ; such a graph is termed a **B—H curve** for the material used. For air, such a graph would be a straight line.

32. A B—H curve for a typical ferromagnetic material is shown in Fig. 14 :—

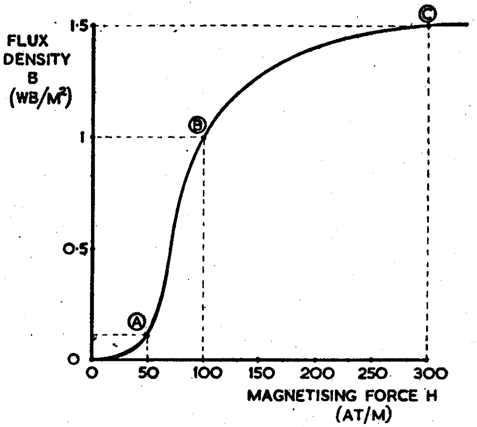


Fig. 14.—A TYPICAL B-H CURVE

(*a*) When the magnetising force H is small there is very little flux density B. According to the electron theory of magnetism quite a large force is necessary to cause the electron current rings to distort their axes in the direction of the applied force.

(*b*) When H reaches a certain value, the axes of the current rings start to change and very quickly align themselves according to the polarity of the applied force. Thus, B rises very quickly for small changes in H.

(*c*) When the current rings have their axes completely aligned with the applied force the material has reached **saturation ;** the only increase now in B is that due to H alone.

33. The ratio $\frac{B}{H}$ gives the absolute permeability of a material. From this, the relative permeability can be found from the relationship $\mu_r = \frac{\mu}{\mu_0}$ (see Para. 20).

By making the necessary calculations at three points A, B, and C in Fig. 14 it is seen that the relative permeability of a material is *not* a constant. It varies with the magnetising force H in the manner shown in Fig. 15.

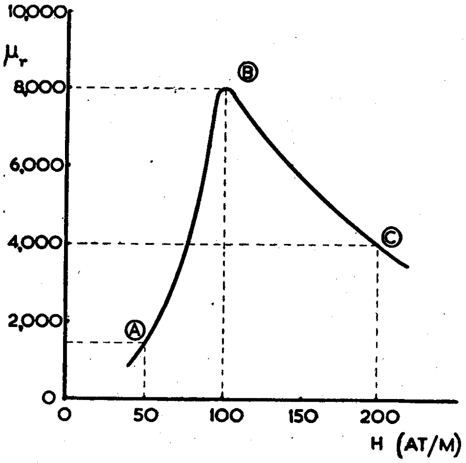


Fig. 15.—VARIATION OF RELATIVE PERMEABILITY

Hysteresis

34. Fig. 16 shows that if H is increased from zero in a positive direction, B rises as in a normal B—H curve along the points OPQ. On reducing H to zero again, however, B does not follow its original path to zero, but follows the path QR. Completing a full cycle for H gives the loop for B as shown by QRSTQ. Such a loop is known as a **hysteresis loop.** The flux density B always "*lags behind*" the magnetising force H because of the inertia of the electron current rings in the material.

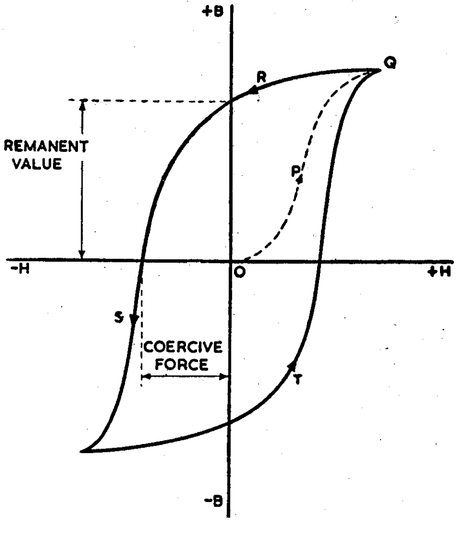


Fig. 16.—A TYPICAL HYSTERESIS LOOP.

35. A negative value of H is necessary to reduce B to zero. The actual value of H in AT/m necessary for this is termed the **coercive force.** If the material has first reached saturation this value is termed the **coercivity** of the material.

36. The value of B in Wb/m^2 remaining in the material when H has reached zero is termed the **remanent value.** If the material has first reached saturation this value is termed the **remanence** of the material.

37. **Retentivity** is a measure of the magnetism retained by a material over a long period of time. It is not to be confused with remanence since in some materials remanence is quickly reduced to zero under normal conditions. Retentivity is given by :—

$$\text{Retentivity} = \frac{\text{Coercivity}}{\text{Remanence}} \text{ of the material.}$$

This relationship shows, for instance, that for a permanent magnet a material with a high value of coercivity is required—i.e., the force required to " remove " the magnetism must be large.

A.C. Permeability

38. It was shown in Para. 33 that the relative permeability μ_r of a material was a function of the magnetising force H. Where H is alternating as in a.c. circuits, the hysteresis loop for the material must be used. The value of μ_r under these conditions is indicated by the *slope* of the hysteresis loop. If the line joining the tips of the loop has a steep slope, the a.c. relative permeability of the material will be high. Further, the slope will decrease as the magnitude of the a.c. input increases.

AL 11

Hysteresis Loss

39. Energy is expended in a magnetic material as the flux density B follows the a.c. magnetisation in a hysteresis loop. The axes of the current rings in the material have been caused to alternate and in so doing, produce heat by friction in the atomic structure of the material. Thus, some of the original electrical energy supplied to the circuit has been converted into heat energy ; this loss of energy from the circuit is termed **hysteresis loss.**

40. The area enclosed by a hysteresis loop is a measure of the hysteresis loss of the material ; the greater this area, the larger is the loss. Thus, where hysteresis loss must be kept to a minimum, a material with a narrow hysteresis loop should be selected. In addition, the loss increases with frequency —i.e., the number of times the hysteresis loop is traced out per second.

Factors Affecting the Choice of Material

41. The choice of ferro-magnetic material for any application in radio is determined by several factors :—

(*a*) The relative permeability μ_r of the material.

(*b*) The values of B and H at which the material saturates.

(*c*) The hysteresis loss as determined by the hysteresis loop.

(*d*) The coercivity and remanence which determine the retentivity of the material.

Comparison of Typical Materials

42. The main characteristics of ferro-magnetic materials can be determined from their hysteresis loops. The details of a few materials are given below:—

(*a*) **35% Cobalt-iron**
- (i) Very low value of μ_r (100).
- (ii) Very high hysteresis loss.
- (iii) Very high retentivity : makes very good permanent magnet material.

(*b*) **Tungsten** -STEEL
- (i) Very low value of μ_r (200).
- (ii) Very high hysteresis loss.

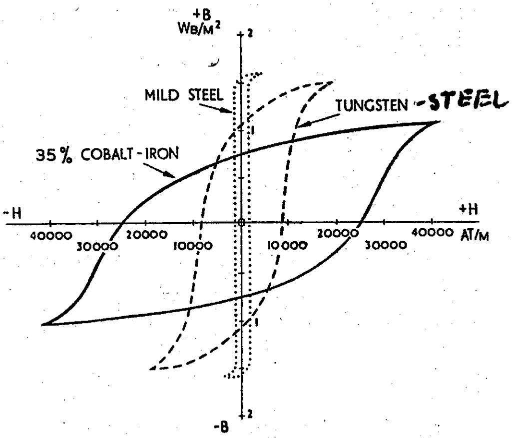


Fig. 17.—HYSTERESIS LOOPS FOR MATERIALS (*a*), (*b*), AND (*c*).

(iii) High retentivity : makes good permanent magnet material.

(*c*) **Mild steel**
- (i) Low value of μ_r (1,000).
- (ii) High hysteresis loss.
- (ii) Low retentivity : seldom used.

(*d*) **Soft iron**
- (i) High value of μ_r (10,000).
- (ii) High hysteresis loss.
- (iii) Low retentivity : used in d.c. circuits in relays.

(*e*) **Stalloy**
- (i) High value of μ_r (15,000).
- (ii) Low hysteresis loss.
- (iii) High saturation values of B and H : used considerably in a.c. circuits.

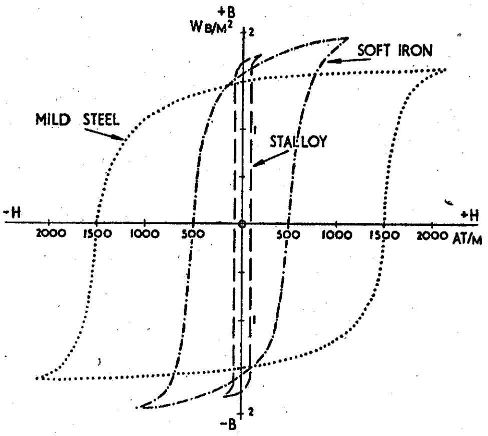


Fig. 18.—HYSTERESIS LOOPS FOR MATERIALS (*c*), (*d*), AND (*e*).

(f) **Permendur**
- (i) High value of μ_r (40,000).
- (ii) Low hysteresis loss.
- (iii) Low saturation values of B and and H : d.c. magnetisation must be kept small.

(*g*) **Permalloy**
- (i) High value of μ_r (100,000).
- (ii) Low hysteresis loss.
- (iii) Very low saturation values of B and H : cannot be used in d.c. circuits.

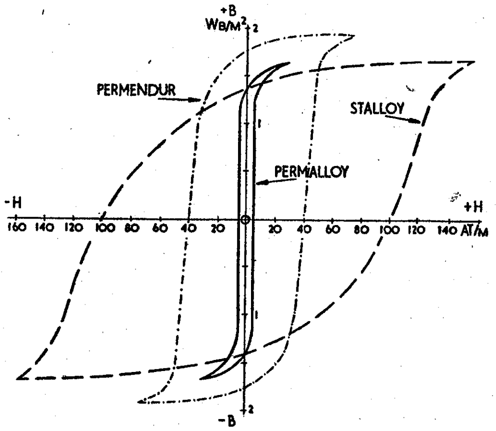


Fig. 19.—HYSTERESIS LOOPS FOR MATERIALS (e), (*f*), AND (*g*).

Note. The above graphs have been sketched to different scales. To assist in the comparison of the materials some loops have been repeated in successive graphs.

SECTION 2

CHAPTER 2

ELECTROMAGNETIC INDUCTION

Paragraph

PART 1, SECTION 2, CHAPTER 2

ELECTROMAGNETIC INDUCTION

Introduction

1. Before such devices as the transformer and the electric generator can be explained, it is necessary to understand the principles of electromagnetic induction. Two laws state the theory of electromagnetic induction very concisely :—

(*a*) **Faraday's law.** When the magnetic flux through a circuit is changing an induced e.m.f. is set up in that circuit, and its magnitude is proportional to the rate of change of flux.

(*b*) **Lenz's law.** The direction of an induced e.m.f. is such that its effect tends to oppose the change producing it.

Verification of Faraday's and Lenz's Laws

2. Fig. 1 shows a coil connected to a galvanometer : when a bar magnet is moved up and down inside the coil, the following observations can be made :—

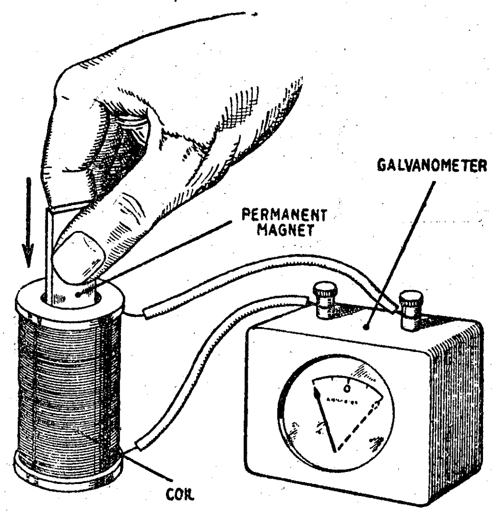


Fig. 1.—VERIFICATION OF FARADAY'S LAW

(*a*) **Relative motion** between the field (magnet) and the conductor (coil) is essential before an e.m.f. (indicated by a deflection in the galvanometer) is induced in the conductor.

(*b*) The greater this relative motion, the greater is the deflection in the galvanometer. Thus, the **rate** at which the flux is changing relative to the conductor determines the magnitude of the induced e.m.f.

(*c*) A bar magnet with a stronger field will give a larger induced e.m.f. for a similar movement.

(*d*) If the magnet is placed in a position at right angles to the axis of the coil (Fig. 2), no e.m.f. will be induced when the magnet is moved towards the coil, or *vice versa.* The lines of flux are now parallel with the turns in the coil so that the conductor is not being " cut " by the flux lines. The conductor must **cut,** or **be cut by,** lines of flux before an e.m.f. is induced in the conductor.

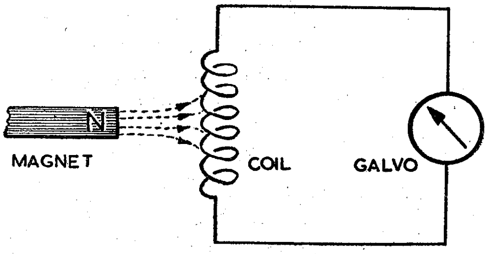


Fig. 2.—ZERO FLUX LINKAGE.

3. The **direction** of the induced e.m.f. in a conductor may be obtained by applying Lenz's law. Fig. 3 shows a conductor in a magnetic field. If this conductor is moved downward through the field it is cutting lines of flux. From Faraday's law, an e.m.f. will be induced in the conductor, the magnitude of the e.m.f. depending on the rate at which the conductor has been moved and on the flux density of the field. From Lenz's law, the direction of the induced e.m.f. will be such that its effect will tend to oppose that downward motion of the

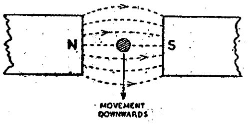


Fig. 3.—CONDUCTOR MOVING IN A MAGNETIC FIELD.

conductor producing it—i.e., it is a "**back e.m.f.**" Thus, the direction of the induced e.m.f. will be such that it tends to move the conductor *upward*. For this to happen, the direction of the current in the conductor must be "out of paper" (see Sect. 3).

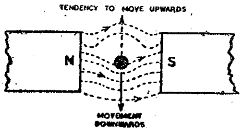


Fig. 4.—ILLUSTRATING LENZ'S LAW.

4. The direction of the induced e.m.f. in a conductor can be found directly by applying **Fleming's RIGHT-hand rule** :—

> "*The thumb, the first finger, and the middle finger of the right hand are held at right angles relative to each other. With the thuMb pointing in the direction in which the conductor has been Moved, and the First Finger in the direction of the Field (N. to S) the mIddle finger will indicate the direction in which current I would flow in the conductor ; this, in turn, gives the direction of the induced e.m.f.*"

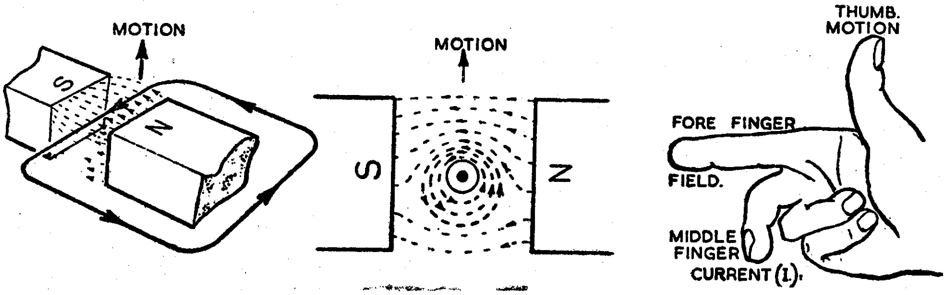


Fig. 5.—FLEMING'S RIGHT HAND RULE.

5. Both Faraday's law and Lenz's law can be summarized by the expression :—

$$E = -\frac{d\Phi}{dt} \text{ (volts)} \quad \ldots \ldots \quad (1)$$

The minus sign indicates that E is a *back* e.m.f.; Φ is the flux in Webers; t is the time in seconds ; and $\frac{d\Phi}{dt}$ is the change of flux with respect to time.

6. If the conductor is wound in the form of a coil with N turns, each turn will be cut by the flux to give a contribution to the e.m.f. induced in the coil. The total e.m.f. is then given by :—

$$E = -N\frac{d\Phi}{dt} \text{ (volts)} \quad \ldots \ldots \ldots \quad (2)$$

Self-inductance

7. If the current in a conductor changes in any way, the magnetic field associated with that current will also change and, from Faraday's law, an e.m.f. will be induced in the conductor. From Lenz's law, the induced e.m.f. will act in such a direction as to oppose the cause of the induced e.m.f. Thus, it will oppose any **change** in the value of current in the circuit, whether the current tends to increase or decrease.

8. Any circuit which has an e.m.f. induced in it by a change of current through that circuit possesses **self-inductance** (symbol L), and has the property of opposing any change of current in the circuit by virtue of the back e.m.f. Any conductor possesses self-inductance. In order to increase it, the conductor is wound in the form of a coil to increase the total induced back e.m.f. A conductor wound in this manner in order to increase its inductance, is termed an **inductor** and its uses in radio are numerous.

9. The unit of inductance L is the **henry** (symbol H). A circuit has an inductance of one henry if a current in it, changing at the **rate** of one ampere per second, induces an e.m.f. of one volt across it.

10. In any given circuit, the ratio of the induced e.m.f. to the rate of change of

current in the circuit is the constant of self-inductance, L henrys. Thus :—

$$\frac{-E}{\frac{dI}{dt}} = L \text{ (henrys)}$$

$$\therefore E = -L\frac{dI}{dt} \text{ (volts)} \quad .. \quad .. \quad (3)$$

This expression shows that the magnitude of the back e.m.f. is proportional to the value of inductance and to the change of current with respect to time.

Factors Affecting Self-inductance

11. Equations (2) and (3) each give the e.m.f. induced in a coil in terms of different factors. By equating these two expressions and substituting for flux Φ (see Chap. 1), the inductance of a coil is shown to be:—

$$L = N^2 \frac{\mu a}{l} \text{ (henrys)} \quad .. \quad .. \quad (4)$$

where N is the number of turns in the coil ; μ is the absolute permeability of the circuit ; a is the cross sectional area of the coil ; and l is the length of the coil.

12. Inductors having values of inductance ranging from a few micro-henrys to many henrys are used in radio, the value being determined by the factors given in equation (4). In this connection it should be noted that :—

(*a*) Doubling the turns will increase the inductance *four* times.

(*b*) A core, of high permeability, inserted inside the coil will greatly increase the inductance.

Mutual Inductance

13. If a change of current in one circuit induces an e.m.f. in another circuit, the two circuits possess **mutual inductance** (symbol M). Consider two inductors L_1 and L_2 connected as shown in Fig. 6. On closing the switch, the current and associated magnetic field around L_1 rise from zero. During the time that the current is rising the changing flux will produce a *self-induced* e.m.f. in L_1. In addition, some of this changing flux will cut L_2 to produce a *mutually-induced* e.m.f. in L_2, as indicated by a deflection in the galvanometer. As soon as the current in L_1 has reached its final steady value, the magnetic field will no longer be changing, and both the self-induced e.m.f. in L_1 and the mutually-induced e.m.f. in L_2 will fall to zero. E.m.f.s are induced only at the instants of opening and closing the switch, i.e., when the current is *changing*.

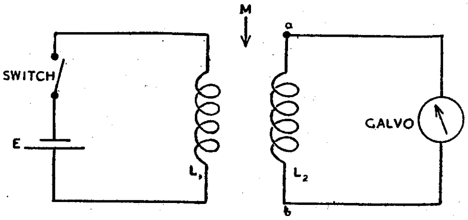


Fig. 6.—MUTUAL INDUCTANCE.

14. If the connections to the coil L_2 are reversed a *reverse* deflection will occur in the galvanometer on closing the switch. The direction of a mutually-induced e.m.f. depends on the direction in which the two coils are wound relative to each other.

15. If the coil L_2 is moved further away from the coil L_1 the deflection in the galvanometer on opening or closing the switch will be reduced. This indicates that fewer flux lines are cutting L_2, i.e., the *flux linkage* is less. The magnitude of the mutually-induced e.m.f. is, therefore, dependant on the *degree of coupling* between the two coils.

16. If the coils L_1 and L_2 are placed with their axes at right angles to each other, as shown in Fig. 7, no e.m.f. will be induced in L_2 ; the flux lines from L_1 will no longer be cutting L_2. This arrangement of coils is sometimes used in practice where it is necessary to prevent an e.m.f. being induced in one circuit from another.

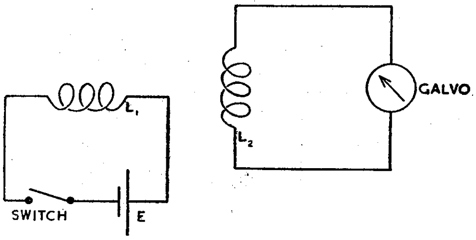


Fig. 7.—ZERO FLUX LINKAGE.

17. The unit of mutual inductance is the **henry** (H). Two circuits have a mutual inductance of one henry if a current in one circuit, changing at the *rate* of one ampere per second, induces an e.m.f. of one volt in the other circuit.

18. With two given circuits, the ratio of the mutually-induced e.m.f. in one circuit to the rate of change of current in the other circuit is the constant of mutual inductance. Thus:—

$$\frac{\pm E_2}{\frac{dI_1}{dt}} = M \text{ (henrys)''.}$$

$$\text{``}E_2 = \pm M \frac{dI_1}{dt}\text{''} \quad .. \quad .. \quad .. \quad (5)$$

The " ± " sign indicates that the induced e.m.f. can be in either direction in accordance with para. 14.

Factors Affecting Mutual Inductance

19. By taking into consideration the factors mentioned in Paras. 14 and 15, equations (2) and (5) can be resolved to give an expression for the mutual inductance of two circuits. Thus :—

$$M = \pm k \, N_1 N_2 \frac{\mu a}{l} \text{ (henrys)} \quad .. \quad (6)$$

where k is a constant, N_1 and N_2 are the number of turns in each coil, μ is the absolute permeability of the circuit, a the mean cross-sectional area, and l the length.

20. Circuits having values of mutual inductance ranging from a few micro-henrys to many henrys are used in practice in radio.

Inductors in Series

21. Fig. 8 shows three coils of self-inductance L_1, L_2, and L_3 connected in series such that the same current I flows through each coil. The e.m.f. induced in each coil is $e = -L \frac{di}{dt}$ and will be the same only if the inductance values are equal. For inductors connected in series, the total inductance is the sum of the individual self-inductances—

$$L_T = L_1 + L_2 + L_3 + \text{ (henrys)} \quad .. \quad .. \quad (7)$$

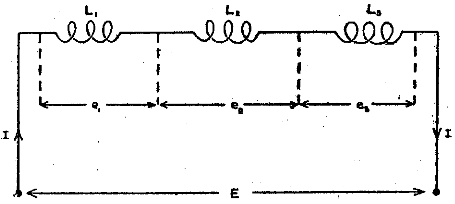


Fig. 8.—INDUCTORS IN SERIES.

Inductors in Parallel

22. Fig. 9 shows three coils of self-inductance L_1, L_2, and L_3 connected in parallel across an e.m.f. E volts such that currents I_1, I_2, and I_3 flow through each. For inductors connected in parallel, the reciprocal of the total inductance equals the sum of the reciprocals of the individual inductances:—

$$\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \quad .. \qquad (8)$$

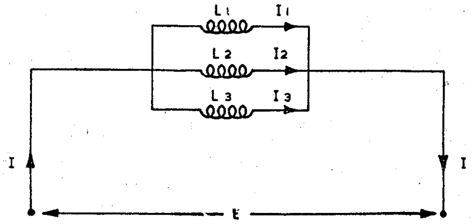


Fig. 9.—INDUCTORS IN PARALLEL.

Inductors in Series with Mutual Inductance between them

23. Consider two coils of self-inductance L_1 and L_2 connected in series across a supply as shown in Fig. 10. A certain mutual inductance M exists between the two coils. Thus, when the current changes, the total e.m.f. induced in L_1 will be the sum of its self-induced e.m.f. and the mutually-induced e.m.f. from L_2. The total e.m.f. induced in L_2 can be calculated in a similar manner. The expressions so obtained can then be resolved to give the total inductance of the circuit :—

$$L_T = L_1 + L_2 \pm 2M \text{ (henrys)} \quad .. \quad .. \quad (9)$$

The mutual inductance can be either "series aiding" or "series opposing" depending on which way the coils are wound relative to each other.

For series aiding :—

$$L_T = L_1 + L_2 + 2M \text{ (henrys)}$$

For series opposing :—

$$L_T = L_1 + L_2 - 2M \text{ (henrys)}$$

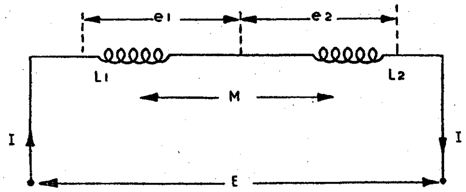


Fig. 10.—SERIES INDUCTORS WITH MUTUAL INDUCTANCE.

Energy Stored in a Magnetic Field

24. In an electric circuit, energy is being expended all the time current is flowing. In a magnetic circuit, energy is expended only in creating the magnetic field. Once the field has been established no further energy is required to maintain it. The original energy expended is stored in the magnetic field in the form of flux and is returned to the source when the field collapses. For purposes of calculation, the energy stored in the magnetic field of a coil is :—

$$W = \frac{1}{2} LI^2 \text{ (joules)} \quad \ldots \quad \ldots \quad \ldots \qquad (10)$$

SECTION 2

CHAPTER 3

INDUCTIVE CIRCUITS

Paragraph

INDUCTIVE CIRCUITS

Introduction

1. A coil, as well as having a certain value of inductance L henrys must also have a certain value of resistance R ohms. Fig. 1 shows such a coil (where L and R are shown separately) connected to a supply of e.m.f. E volts, via a switch.

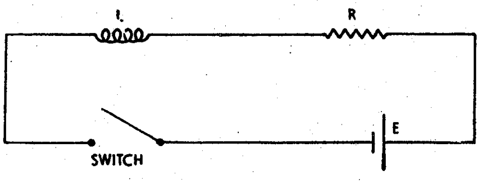


Fig. 1.—SIMPLE INDUCTIVE CIRCUIT.

2. When the switch is closed, the battery will try to pass a current $I = \frac{E}{R}$ amps round the circuit. However, as soon as the current commences to rise, a back e.m.f. is developed across the coil ; from Lenz's law this e.m.f. will oppose the original rise in the current, so that the initial rate of change of current is " slowed up ". The current will continue to rise but at a lower rate of change, and the back e.m.f. will also decrease. This process continues—the current gradually rising to its maximum value of $I = \frac{E}{R}$ amps at a progressively lower rate of change, i.e., it is an *exponential* rise. The back e.m.f. falls exponentially towards zero, reaching this value when the current has reached its maximum steady value.

Experimental Study of the Growth of Current in an Inductor

3. The facts stated in Para. 2 can be verified by means of a simple experiment. In the circuit of Fig. 2, R = 10 Ω, L = 100H, and E = 100V ; M_1 is an instrument for measuring the current in amps ; and a stop-watch is required to give accurate measurement of time in seconds.

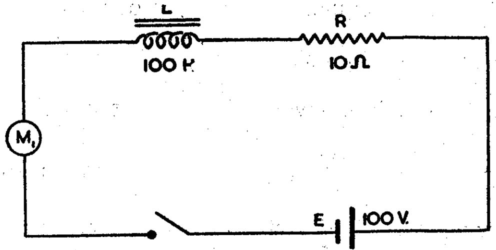


Fig. 2.—EXPERIMENTAL STUDY, GROWTH OF CURRENT.

4. Readings of the current *i* passing through M_1 are taken at intervals of 10 seconds after the closing of the switch. A typical set of readings is given in Table 1, and from these readings the graph of Fig. 3 is plotted.

Time from start (sec)	0	10	20	30	40	50	60
Current (amps)	0	6·32	8·65	9·51	9·82	9·93	9·97

TABLE 1

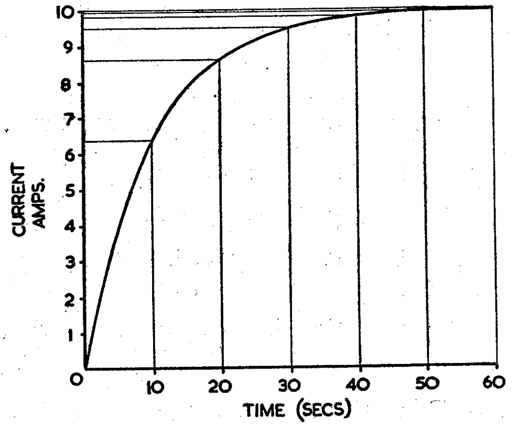


Fig. 3.—VARIATION OF *i* DURING GROWTH.

5. The experiment could be repeated with different values of L and R. It would be found that with a smaller value of L, the current would rise more rapidly. This is to be expected since the back e.m.f. would be smaller. A similar result would be seen with a *larger* value of R. The ratio of $\frac{L}{R}$ is what really determines the rate of growth of the current in the circuit.

6. It is found that whatever the actual values of L and R in such an experiment, the ratio $\frac{L}{R}$ equals the time in seconds for the current in the circuit to rise to 63·2% of its maximum value $\frac{E.}{R}$ In the circuit of Fig. 2, $\frac{L}{R} = \frac{100}{10} = 10$ seconds. Thus, in 10 seconds from the start the current rose to 6·32 amps ; this is 63·2% of its maximum value $\frac{E}{R} = \frac{100}{10} = 10$ amps. This quantity $\frac{L}{R}$ is termed the *time constant* of the circuit and is defined in full in Para. 16.

General Case of the Growth of Current in an Inductor

7. Paras. 3 to 6 have dealt with a particular circuit. In the general case, for purposes of accurate calculation, the current in the circuit at any instant t after closing the switch is given by :—

$$i = I\,(1 - \epsilon^{\frac{-R}{L}t})\ \text{(amps)} \quad \ldots\ \ldots\ (1)$$

where, i = the current at any instant.

I = the final current = $\frac{E.}{R.}$

ϵ = Napierian log base = 2·718

R = the resistance in ohms.

L = the inductance in henrys.

t = time in seconds after closing the switch.

8. (*a*) From Ohm's law, the p.d. developed across R at any instant after closing the switch is :—

$$V_R = i\,R \text{ (volts)} \quad \ldots\ \ldots\ \ldots\ \ldots\ (2)$$

(*b*) From Kirchhoff's second law, the sum of the p.d.s across R and across L must at every instant after closing the switch equal the applied e.m.f. E volts.

$$\therefore V_R + V_L = E$$

$$\therefore V_L = E - V_R \text{ (volts)} \quad \ldots\ \ldots\ (3)$$

9. A graph can be plotted showing the variation in i, V_R, or V_L with respect to the time t after closing the switch. This can be obtained in two ways :—

(*a*) Repeat the experiment of Paras. 3 to 6. Having obtained the values for i, the corresponding values for V_R and V_L follow from equations (2) and (3) respectively.

(*b*) The value of $I = \frac{E}{R}$ amps is calculated and inserted in equation (1), together with the values for R and L. Various instants of time t seconds are inserted in equation (1) and the current i at these instants is evaluated. Having obtained the values for i, the corresponding values for V_R and V_L follow from equations (2) and (3) respectively.

10. In either case, three instants of time are sufficient for most purposes :—

(*a*) *At the instant of closing the switch* ($t = o$).

$i = o \ : \ V_R = o \ : \ V_L = E$

(*b*) *At* $t = \frac{L}{R}$ *seconds after closing the switch*

$i = 0{\cdot}632I : V_R = 0{\cdot}632E : V_L = 0{\cdot}368E$

(*c*) *At* $t = 5\frac{L}{R}$ *seconds after closing the switch*

$i \bumpeq I \ : \ V_R \bumpeq E \ : \ V_L \bumpeq O$

11. These three instants of time are used to plot the graph showing the exponential rise in the current i in the circuit against the time t in seconds after closing the switch (Fig. 4). The graph for V_R will rise in a manner similar to that for i ; that for V_L will fall to zero as i rises to its maximum value.

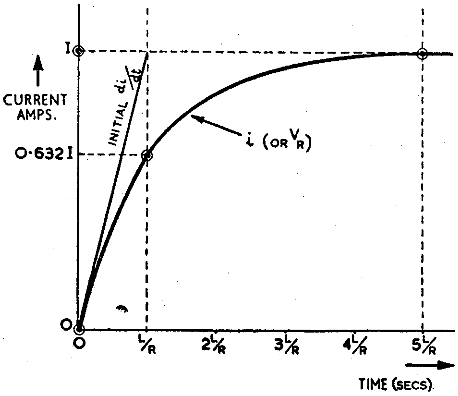


Fig. 4.—GROWTH OF CURRENT.

Decay of Current in an Inductive Circuit

12. Consider the circuit shown in Fig. 5.

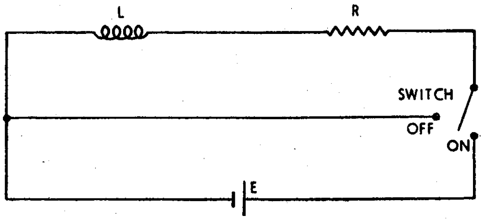


Fig. 5.—SIMPLE INDUCTIVE CIRCUIT, DECAY OF CURRENT.

With the circuit switched on, the current in the coil will rise exponentially towards its maximum value $I = \frac{E}{R}$ amps, reaching this value in a time of approximately $5\frac{L}{R}$ seconds after closing the switch. Assume maximum current to be now established in the coil ; since it is a steady current, the back e.m.f. across the coil will have fallen to zero and the p.d. across the resistance will equal the supply e.m.f. If the circuit is switched off under these conditions, the coil is shunted by the resistance, and the current will tend to fall to zero. It cannot do so instantly, however, because as soon as the current starts to fall a back e.m.f. is produced across the coil ; this back e.m.f. will endeavour to maintain the current in the circuit. Thus, in the same way that the current in an inductive circuit rises in an exponential manner, so it will now fall or decay. The curve of the decay of current can be obtained from an experiment similar to the one described in Paras. 3 to 6. A stop-watch is started at the instant of disconnecting the supply and readings of the current i taken at regular intervals of time. From a set of such readings the required graph can be plotted.

13. (*a*) For purpose of accurate calculation the current in the circuit at any instant t after opening the switch and allowing the current to decay is given by :—

$$i = I.\epsilon^{-\frac{R}{L}t} \text{ (amps)} \quad .. \quad .. \quad .. \quad (4)$$

where all the terms have the same significance as in equation (1)

(*b*) From Ohm's law, the p.d. developed across R at any instant after opening the switch is :—

$$V_R = i\,R \text{ (volts)} \quad .. \quad .. \quad .. \quad .. \quad .. \quad (5)$$

(*c*) From Kirchhoff's second law, the sum of the p.d.s across R and across L must at any instant equal the e.m.f. acting in the circuit. If the supply is disconnected, the e.m.f. is zero. Thus :—

$$V_R + V_L = O$$
$$\therefore V_L = - V_R \text{ (volts)} \quad .. \quad .. \quad .. \quad (6)$$

14. A graph can be plotted showing the variation in i, V_R, or V_L with respect to the time t seconds after disconnecting the supply. Either of the two methods described in Para. 9 can be used to obtain such a graph, and again three instants of time are significant :—

(*a*) *At the instant of disconnecting the supply* ($t = o$).

$i = I \;:\; V_R = E \;:\; V_L = —E$

(*b*) *At* $t = \frac{L}{R}$ *seconds after disconnecting the supply.*

$i = 0{\cdot}368I : V_R = 0{\cdot}368E : V_L = —0{\cdot}368E$

(*c*) *at* $t = 5\frac{L}{R}$ *seconds after disconnecting the supply.*

$i \simeq O \;:\; V_R \simeq O \;:\; V_L \simeq O$

15. These three instants of time are used to

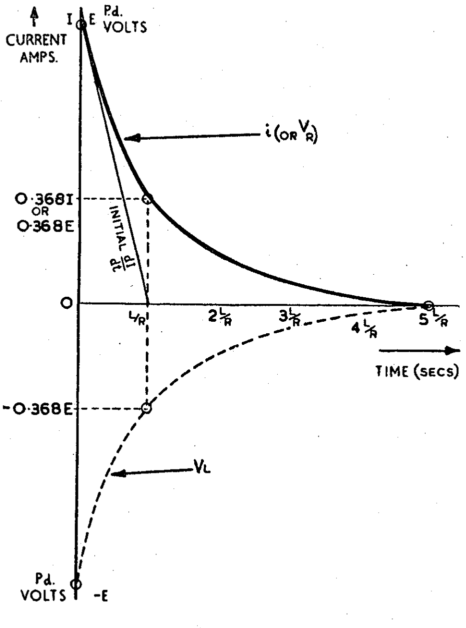


Fig. 6.—DECAY OF CURRENT.

plot the graph showing the variations in i, V_R and V_L with respect to the time t seconds after disconnecting the supply (Fig. 6).

Time Constant

16. The time $t = \frac{L}{R}$ seconds is termed the **time constant** of an inductive circuit and has been referred to in Paras. 6. It is defined as follows :—

> *The time constant $t = \frac{L}{R}$ is the time taken for the current in an inductive circuit to rise to 63·2% (approximately two-thirds) of its maximum value when connected to a supply, or to fall by 63·2% of its maximum value when disconnected from a supply. Alternately, it is the time taken for the current to reach its* **maximum** *value in the first case, or to fall to* **zero** *in the other, provided the* **initial** *rate of change of current is maintained.*

(The latter is shown in the graphs although it cannot apply in practice).

17. In theory, the current in an inductor would take an infinitely long time to reach its maximum value or to fall to zero. However, after a time of $5\frac{L}{R}$ seconds the growth or decay is so nearly complete as to be considered so for practical purposes.

Practical Example

18. In the circuit shown in Fig. 7, L = 1H, R = 10 Ω, and E = 10V. The circuit is switched on for one second and then switched off. It is required to sketch a graph to indicate how the current in the circuit varies with time.

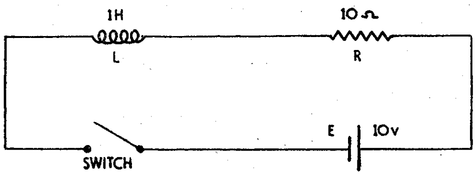


Fig. 7.—EXAMPLE.

19. (*a*) The time constant $t = \frac{L}{R} = \frac{1}{10} = 0{\cdot}1$ second.

(*b*) The maximum current $I = \frac{E}{R} = \frac{10}{10} =$ 1 amp.

	Time (Seconds)	0	$\frac{L}{R} = 0{\cdot}1$	$5\frac{L}{R} = 0{\cdot}5$
Growth of current	i (amps)	0	0·632	1
Decay of current (after 1 sec.)	i (amps)	1	0·368	0

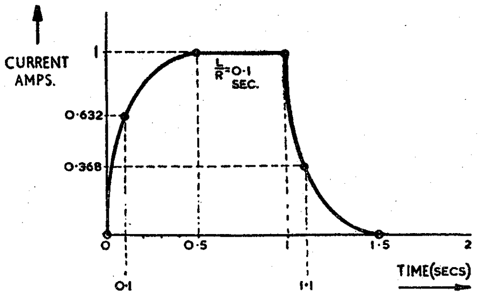


Fig. 8.—GROWTH AND DECAY OF CURRENT.

(*c*) The current at the relevent instants of time is given in the table.

(*d*) The graph of the growth and decay of the current is shown in Fig. 8. The graph of the p.d.s across R and across L could be obtained from equations (2) and (3) during growth, and from equations (5) and (6) during decay.

Square Waves Applied to an Inductive Circuit

20. Although the effect of switching a coil across a d.c. supply is important, in some radio equipments it is more important to consider the effect of applying a square wave of voltage. One simple method of producing such a square wave would be merely to switch the circuit shown in Fig. 9 on and off alternately for definite periods of time. If the periods of time for which the circuit is switched on and off are equal, a *symmetrical* square wave of voltage is produced, as shown. The practical methods for producing square waves are fully dealt with in Part 3.

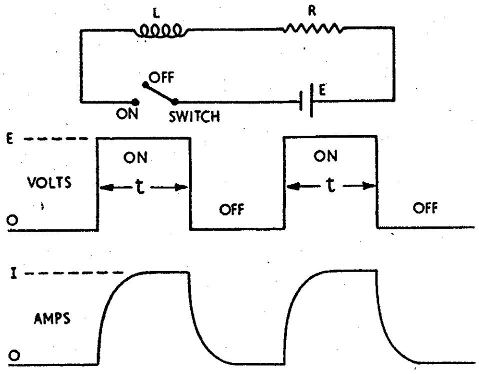


Fig. 9.—SQUARE WAVES APPLIED TO AN INDUCTIVE CIRCUIT.

21. Provided the periods of time for which the supply is switched on and off are long in relation to the time constant of the circuit, the current in the coil will rise and decay exponentially as explained in Para. 19 and as shown in Fig. 9. The corresponding variations in the p.d.s across R and across L are as shown in Fig. 10.

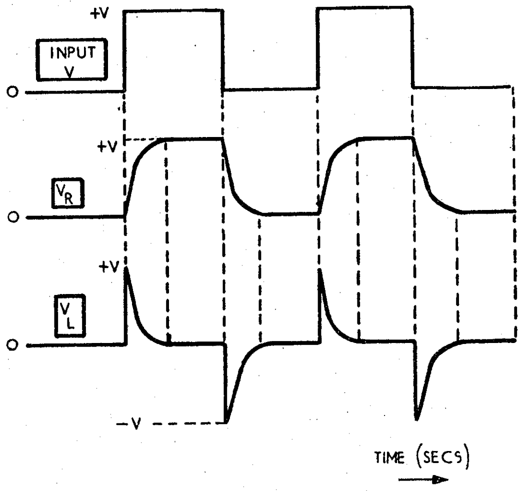


Fig. 10.—VARIATION IN V_R AND V_L WITH TIME

SECTION 2

CHAPTER 4

CONSTRUCTION OF INDUCTORS

PART 1, SECTION 2, CHAPTER 4

CONSTRUCTION OF INDUCTORS

Introduction

1. Inductors have a wide application in radio ; they vary in size and value from large iron-cored inductors for use at low frequencies to very small inductors for use at the higher frequencies. This Chapter gives an outline of the basic construction of such inductors.

Eddy Currents

2. Consider a coil wound over an iron core. When the current in the coil changes, the magnetic flux linking with the iron core changes, and (according to Faraday's law) an e.m.f. is induced in the *core* as well as in the coil. Such an induced e.m.f. in the core gives rise to circulating currents—these currents being termed **eddy currents.**

3. The direction of the flow of eddy currents in the core will be given by Fleming's right-hand rule, the effective " *motion* " of the core being the reverse of the direction in which the field is moving. In Fig. 1, the current in the coil is assumed to be increasing and the field is moving outwards. Thus, the effective " motion " of the core is *inwards.* Applying Fleming's right-hand rule to the core shows that the eddy currents, at this instant, are circulating in the manner indicated. If the current in the coil is now decreased, the field tends to collapse inwards and the eddy currents will circulate in the reverse direction.

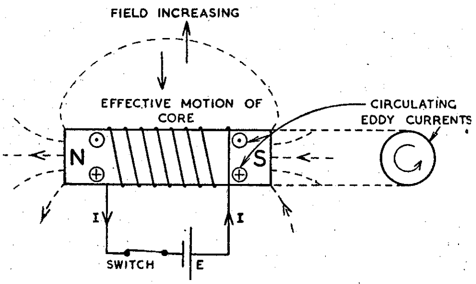


Fig. 1.—EDDY CURRENTS.

4. Eddy currents in the core of a coil have several effects, the two most important being :—

(*a*) The core becomes hot, and the conversion of electrical energy into heat energy constitutes an energy loss termed **eddy current loss.** (This is in addition to any hysteresis loss in the core as discussed in Chapter 1).

(*b*) The eddy currents produce a flux of their own and, since this will be in opposition to the main flux, a reduction in the main flux results.

5. In order to reduce the effects of eddy currents it is usual to " *laminate* " the core. The core is cut up into very thin slices or **laminations** ; each lamination is insulated from the next by a thin film of shellac or other insulator. The path to the flow of eddy currents is thus broken up and the increase in resistance reduces the eddy currents. The thinner the laminations, the smaller is the loss from eddy currents. For the laminations to be effective, they must be in the correct direction relative to the field and to the eddy currents as shown in Fig. 2.

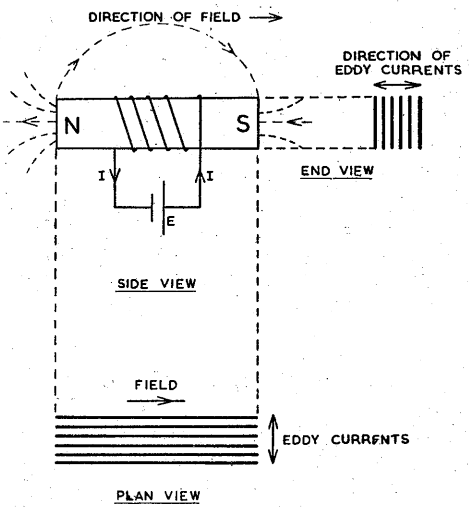


Fig. 2.—LAMINATIONS.

Iron-cored Inductors

6. It was shown in Chapter 2 that the self-inductance of a coil is given by :—

$$L = N^2 \frac{\mu a}{l} \text{ (henrys)}$$

Thus, where a large value of inductance is required, the coil will :—

(*a*) consist of a large number of turns ;

(*b*) be wound over an iron core ;

(*c*) have a high ratio of area to length.

7. Normally the coil will consist of several layers of good quality copper wire, covered by a cotton braiding or by an enamel coating, wound on an iron core which is laminated to reduce eddy current losses. The core will be constructed from a magnetic material, such as Stalloy, which gives a low hysteresis loss.

8. Such coils will give values of inductance up to 100 henrys, and are used to provide effective opposition to slow changes in the current flowing through them—i.e., they are used at low frequencies only, as audio frequency (A.F.) chokes and smoothing chokes. Where a high d.c. value of current is also present, the magnetic circuit will have an *air gap* to prevent magnetic saturation.

9. Laminated iron cores can be used to increase the inductance of a coil only up to frequencies of the order of 20 kc/s. Above this frequency, the high eddy current and hysteresis losses prohibit their use. Above 20 kc/s, iron-dust cores can be used. These are cores in which the iron has been reduced to a very fine dust, mixed with an insulating mica binder, and compressed to form a solid mass. The result is an extremely fine " laminated " core which gives low eddy current losses up to very high frequencies of the order of 60 Mc/s. Above this frequency, the eddy current loss again becomes excessive and air-cored coils are used.

Radio Frequency Chokes

10. Radio frequency (R.F.) chokes are used to provide effective opposition to rapid changes in the current flowing in them—i.e., they are used at high frequencies. Values of inductance from a few micro-henrys to 100 milli-henrys may be required. Air-cored coils are normally used for this. Since the value of inductance depends on the number of turns, the smaller inductors will use a single layer winding for the higher radio frequencies, and the larger inductors multi-layer windings for the lower radio frequencies. Various methods of winding are used.

(*a*) **Single layer.** The coil, of good quality copper wire, is wound on a bakelite or other insulated former, with a considerable spacing between the turns. This gives inductance values up to 100 micro-henrys.

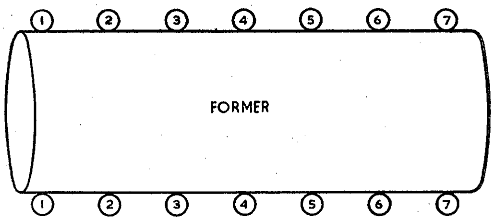


Fig. 3.—SINGLE LAYER COIL

(*b*) **Simple multi-layer.** As shown in Fig. 4, the layers are wound one on top of the other on a bakelite former. Each turn is insulated from the next by a cotton brading or by an enamel coating on the conductor. This method of winding has the disadvantage that turns near each other in adjacent layers (say, 1 and 17) have a high p.d. existing between them ; this may give rise to losses through leakage (capacitive) currents (see Sect. 4). This type of winding gives inductance values up to 100 milli-henrys, but losses are high.

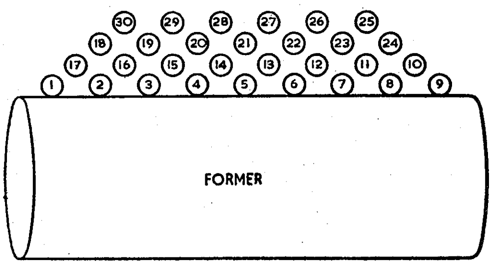


Fig. 4.—SIMPLE MULTI-LAYER COIL.

(*c*) **Bank winding.** This is a multi-layer coil of low loss (Fig. 5). It is wound such that turns near each other in adjacent layers are also near each other in potential. The losses through leakage are then small.

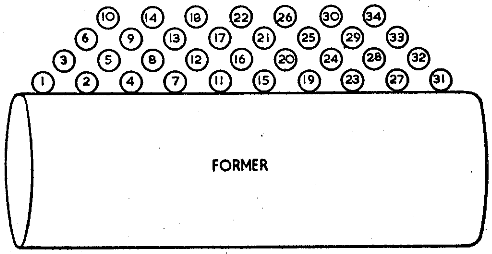


Fig. 5.—BANK-WOUND COIL.

(*d*) **Honeycomb or wave winding.** In this type of multi-layer coil, only a few turns are wound per layer, and the winding is formed in much the same way as a ball of string. The resultant coil is waxed to make it rigid and self-supporting. The p.d. between adjacent turns is small and the losses through leakage are reduced to a minimum to give a low-loss inductor.

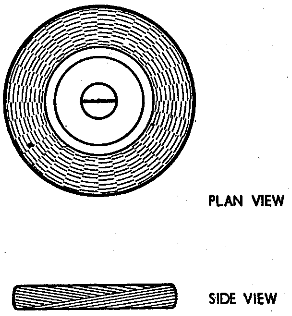


Fig. 6.—HONEYCOMB WINDING.

(*e*) **Pie-winding.** This coil consists of a number of honeycomb windings, all connected in series, and spaced as shown in Fig. 7. The losses through leakage are small, and the result is a low-loss inductor of inductance values up to 100 milli-henrys.

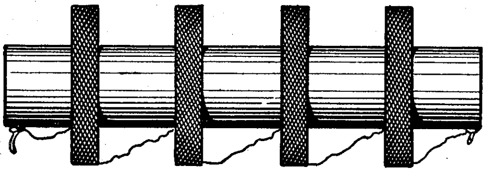


Fig. 7.—PIE-WOUND COIL

Tuned Circuit Coils

11. These are radio frequency coils used in conjunction with a capacitor to form a *tuned circuit* (see Sect. 5). At the higher radio frequencies, small values of inductance are required and a single layer coil will be used ; at the lower frequencies a multi-layer bank-wound coil is normal.

12. It is often necessary to be able to vary the inductance in a tuned circuit. This can be done in two ways :—

(*a*) By "tapping off" the value of inductance required as shown in Fig. 8(*a*).

(*b*) By using a variable iron-dust core inside the coil as in Fig. 8(*b*). When the core is fully "in", the inductance will be a maximum, and *vice versa.*

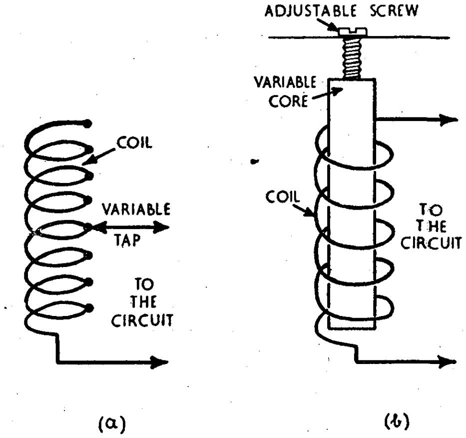


Fig. 8.—VARIATION OF INDUCTANCE.

Skin Effect

13. When a conductor is carrying a direct current, the current is distributed evenly throughout the cross section of the conductor; the magnetic field associated with this current is as shown in Fig. 9. If the current in the conductor is alternating, the changing magnetic field will induce a back e.m.f. in the conductor such as to oppose the change in current. Since all the flux lines build up from, and collapse into, the *centre* of the conductor, the back e.m.f. will be greatest at the centre. The result is that the current tends to flow nearer the surface of the conductor. This is termed **skin effect.**

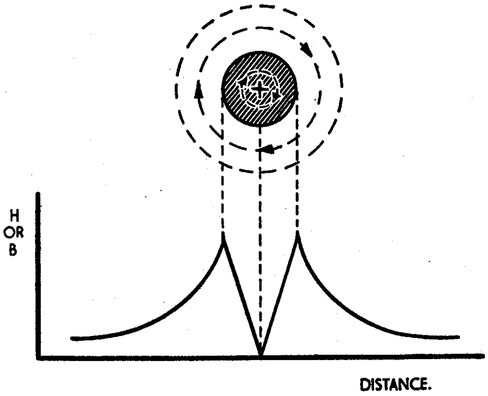


Fig. 9.—CONDUCTOR CARRYING A DIRECT CURRENT.

14. Skin effect becomes more pronounced as the frequency increases because of the increased rate of change of flux. Further, since the effective cross-sectional area of the conductor has been reduced by skin effect, the resistance of the conductor increases with frequency (since $R = s\frac{1}{a}$).

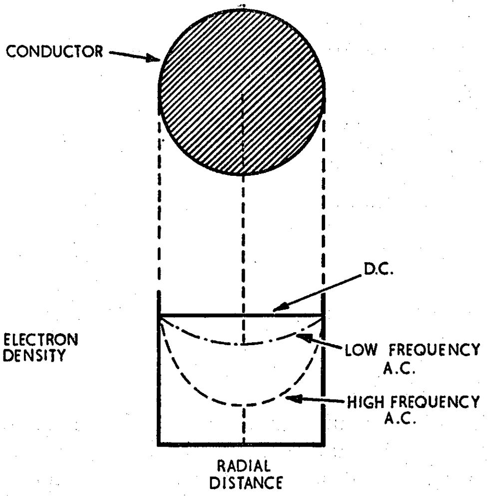


Fig. 10.—SKIN EFFECT.

15. To reduce the high frequency (H.F.) resistance of a conductor, two methods are used :—

(*a*) A special wire, known as "Litzendraht" or "Litz wire" can be employed. This is made up of a number of small diameter, enamelled strands joined in parallel at each end. The strands are thoroughly interwoven so that each strand will, on the average, link with the same number of flux lines as every other strand. Thus, the current divides evenly among the strands ; the effective cross-sectional area is increased and the H.F. resistance decreased. This wire is useful only up to frequencies of 3 Mc/s. Above this, certain leakage effects between the strands give excessive losses.

(*b*) Tubular copper conductors, which have been silver-plated, can be used. The resistivity at the skin is, therefore, reduced and since the electron density is greatest in this region, a reduction in the H.F. resistance results. This method is popular in self-supporting inductors for use at high frequencies.

Proximity Effect

16. When two or more adjacent conductors are carrying current, the current distribution in any one conductor is affected by the magnetic flux produced in adjacent conductors as well as by its own flux. This **proximity effect** is merely an increased case of skin effect and increases the H.F. resistance of inductors used at radio frequencies. Increasing the spacing between turns will reduce proximity effect. Note that maximum current flows in any conductor where it is linked by minimum flux.

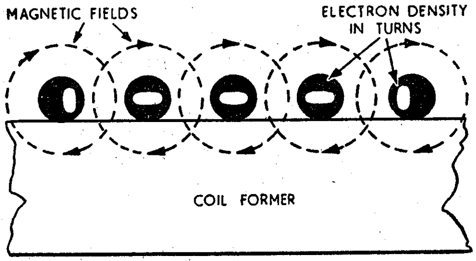


Fig. 11.—PROXIMITY EFFECT.

Non-inductive windings

17. In Sect. 1, Chap. 3 it was noted that wire-wound resistors, being wound in the form of a coil, had inductance as well as resistance. To obtain a pure resistance, the length of insulated wire to be used in the resistor winding is first doubled back on itself and then wound on a former. The current in adjacent turns is flowing in opposite directions so that the magnetic fields around these turns effectively neutralize each other, and the self-inductance becomes negligible.

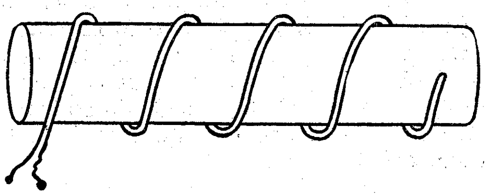


Fig. 12.—A NON-INDUCTIVE WINDING.

Summary

18. Table 1 summarizes the main points on the inductors discussed in this Chapter. Fig. 13 shows a selection of the various types of inductors used in radio.

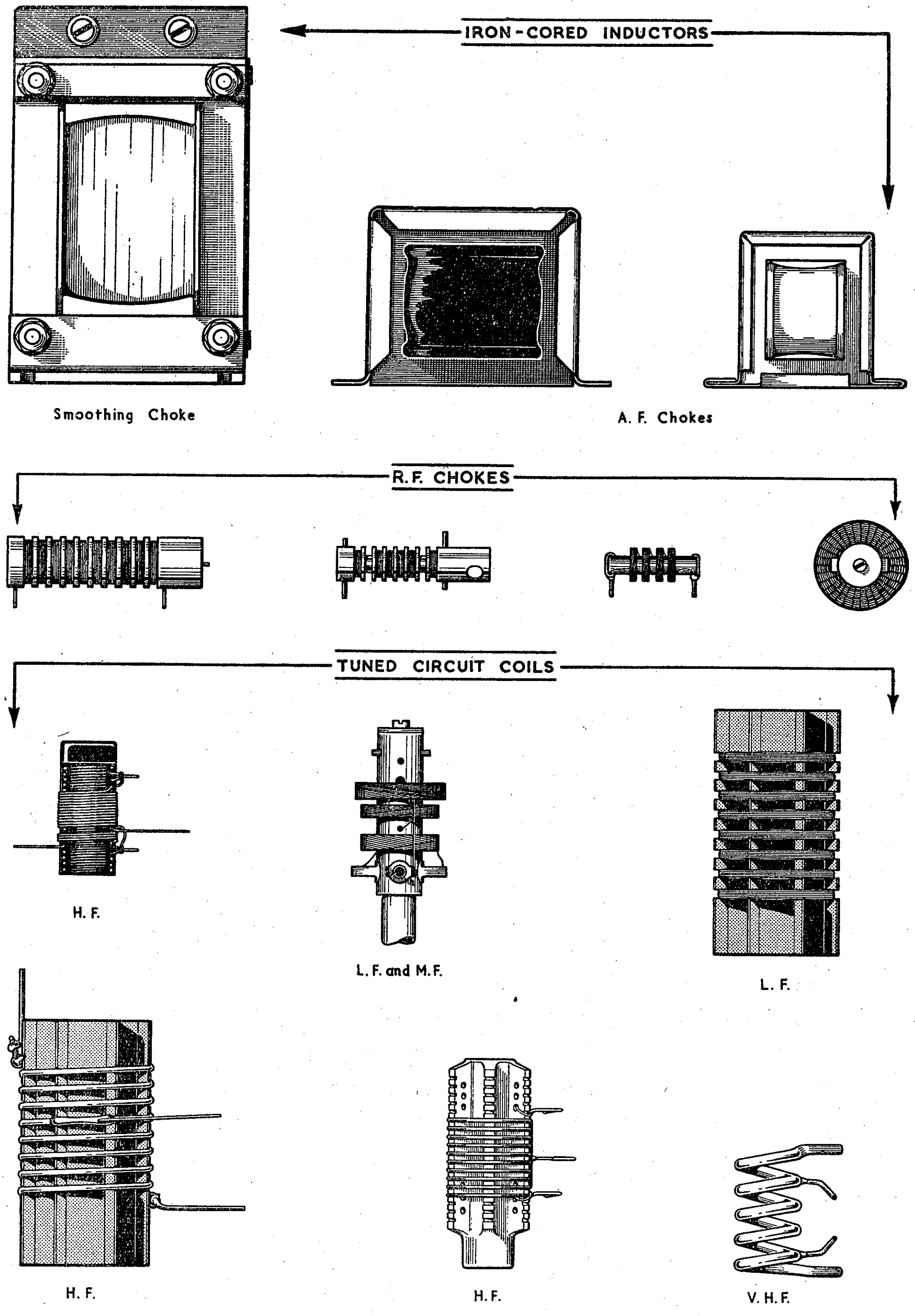


Fig. 13.—TYPICAL INDUCTORS USED IN RADIO.

Type	Frequency	Inductance	Winding	Core
Smoothing choke	Power frequencies, e.g., 50 c/s	1H to 100H	Multi-layer	Laminated iron or stalloy with air gap
A.F. choke	20 c/s to 20 kc/s	0·1H to 100H	Multi-layer	Laminated iron or stalloy with air gap
R.F. choke	L.F. and M.F. H.F. V.H.F.	100μH to 100mH 50μH to 100μH $0{\cdot}25\mu$H to 50μH	Multi-layer Single layer Single layer	Air or iron-dust core Air Air
Tuned circuit coils	← As for R.F. choke →			Normally iron-dust or other core, variable for tuning purposes

TABLE 1—INDUCTORS USED IN RADIO

SECTION 1

BASIC ELECTRICITY

SECTION 1

CHAPTER 1

ELECTRIC CURRENT, E.M.F. AND P.D.

FUNDAMENTAL UNITS *Paragraph*

ELECTRIC CURRENT

E.M.F. AND P.D.

PART 1, SECTION 1, CHAPTER 1

ELECTRIC CURRENT, E.M.F. AND P.D.

FUNDAMENTAL UNITS

Introduction

1. Both electrical and radio engineering are based upon the same fundamental principles, and for a sound knowledge of the techniques of radio it is essential to have an understanding of these principles. Electricity may be used to make things move, to generate heat and light, to set the diaphragm of a telephone vibrating as a source of sound, and in many chemical manufacturing processes. The study of electricity is thus closely linked with that of a number of other branches of engineering and, as a result, many electrical units are defined in terms of mechanical units. It is, therefore, necessary to know something of fundamental mechanical terms like "force", "power", and "energy" before their use in electrical and radio engineering can be appreciated.

Definitions

2. **Force** is any push or pull which alters or tends to alter the state of a body, whether of rest or of uniform motion in a straight line. The practical interpretation of this definition is that the application of force to a body will change or tend to change its **velocity** (or speed) in some way. If the body is at rest and free to move it will do so ; if moving in a straight line at a constant speed it will be deflected or alter its speed. When the velocity of a body is increasing the body is said to undergo **acceleration** and this is measured by the rate at which the velocity is changing.

3. When a force moves the body to which it is applied, **work** is done, the amount of work being equal to the product (force X distance moved in the direction of the force). Thus, in lifting a pencil work is done by the person on the pencil. This can be accomplished quickly or otherwise, and the *rate* of doing work is termed **power.**

4. Any body which has the ability to do work possesses **energy.** When work is done by one body on another, energy is transferred from the one to the other. In lifting a pencil energy is transferred from the person to the pencil. While held above the table, the pencil has *potential* energy which can be regarded as work stored for future use. When the pencil is allowed to fall the potential energy is converted to *kinetic* energy or energy of motion. Energy exists in various forms, and although it can be converted from one form to another, it cannot be created or destroyed.

Units

5. The units in which the above quantities are measured depend on the fundamental units used for length, mass, and time. In accordance with modern practice in radio the unit of length is the *metre* (m) ; that of mass, the *kilogramme* (kg) ; and that of time, the *second* (sec.) Measurement of quantities derived from these are said to be made in *metre-kilogramme-second* (*m.k.s.*) units.

6. (*a*) Velocity or speed is measured in *metres per second* (m/sec.)

(*b*) If the velocity of a body is increasing at the rate of one metre per second every second, the acceleration is *one metre per second per second* (m/sec^2).

(*c*) The unit of force is the *newton.* One newton is that force which gives one kilogramme mass an acceleration of one metre per second per second.

(*d*) The unit of work is the *joule* (J). One joule is the work done when a force of one newton acts through a distance of one metre.

(*e*) The unit of energy is the same as that of work—the *joule* (J). When one joule of work is done by one body on another, one joule of energy is transferred from the one to another.

(*f*) The unit of power is the *watt* (W). One watt is the power developed when work is done at the rate of one joule per second.

ELECTRIC CURRENT

Structure of Matter

7. The study of electricity has grown up during the past two hundred years, keeping pace with the growth of knowledge of

chemistry and of the nature of the substances (called matter) found in the world. It should be realized that chemical actions and electrical effects both happen because matter is made up in a certain way, and to understand what is meant by "an electric current" it is necessary to have an elementary knowledge of the atomic structure of matter.

8. (*a*) **Matter** is defined as anything which occupies space and is acted upon by gravitational forces ; it can exist in three states—solid, liquid, or gaseous.

(*b*) All matter is constructed from **molecules**—the smallest particles into which a substance may be divided while still retaining the chemical properties of the substance.

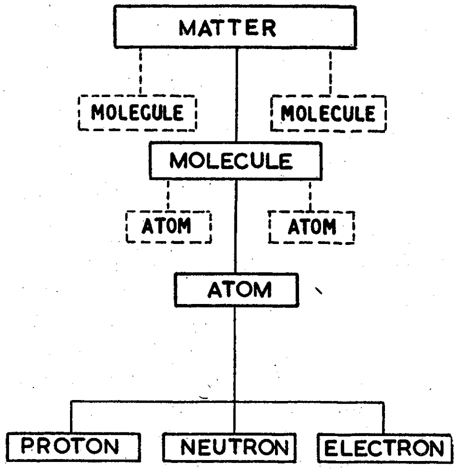


FIG. 1 — THE CONSTRUCTION OF MATTER

(*c*) Molecules are made up of **atoms**—the smallest particles of matter which can enter into chemical combination or which are obtainable by chemical separation, e.g., two hydrogen atoms and one oxygen combine to form a molecule of water.

(*d*) An **element** is a substance whose molecules are made up of the same kinds of atoms, e.g., iron, copper, and nickel.

(*e*) A **compound** is a substance whose molecules are made up of different kinds of atoms, e.g., water, salt, and lime.

Atomic Structure

9. An atom in any material contains three fundamental particles in close association:—

(*a*) **Proton.** The elementary particle of *positive* electricity or charge.

(*b*) **Electron.** The elementary particle of *negative* electricity ; its charge is equal and opposite to that on a proton.

(*c*) **Neutron.** A particle having mass approximately equal to that of a proton but having zero electric charge.

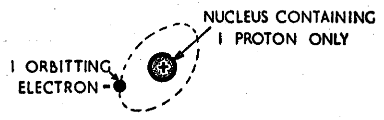
10. The protons and neutrons, comprising almost all the mass of the atom, are confined to the central core or nucleus of the atom; the electrons rotate at high speed in orbits of various sizes around the nucleus, like the planets round the sun.

11. The number of planetary electrons in an atom varies with the element and gives the *atomic number* of the element. The atomic number of hydrogen is 1, indicating that it has one electron ; that of uranium is 92. At the present day the number of known elements (and hence, of different kinds of atoms) is 98, although research indicates that this may well be extended. Table 1 gives a short list of some of the better-known elements.

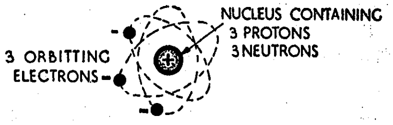
Atomic Number	Element	Symbol	Atomic Number	Element	Symbol
1	Hydrogen	H	33	Arsenic	As
6	Carbon	C	47	Silver	Ag
8	Oxygen	O	50	Tin	Sn
13	Aluminium	Al	74	Tungsten	W
26	Iron	Fe	79	Gold	Au
28	Nickel	Ni	82	Lead	Pb
29	Copper	Cu	92	Uranium	U

TABLE 1. SOME WELL-KNOWN ELEMENTS

12. An atom, under normal conditions, is electrically neutral. The numbers of electrons and protons are *equal*, and since the negative charge on an electron is neutralized by the equal positive charge on a proton, the atom as a whole has zero charge. The neutron increases the mass of the atom without contributing to the charge. Fig. 2 gives a simple idea of the construction of a hydrogen atom and of a lithium atom (atomic number 3).



• HYDROGEN ATOM



LITHIUM ATOM

Fig. 2.—THE ATOMIC STRUCTURE

Ionisation

13. Normally, the electron orbits are maintained by attractive forces between the negative charge on the electron and the positive charge in the nucleus. However, under certain conditions, one or more of the planetary electrons in the outer orbits can be detached from the atom. Such an atom, having " lost " a negative charge, is termed a **positive ion.** The electron so stripped off may attach itself to a neighbouring atom which then becomes a **negative ion.** The process whereby atoms are caused to lose or gain electrons is termed **ionisation.** During the time that an electron remains unattached to any atomic system it is termed a **free electron.**

Conductors and Insulators

14. A **conductor** is a substance in which there is a constant random movement of free electrons between atoms. Pure metals are good conductors, silver being the best and copper ranking second.

15. An **insulator** is a substance in which there is practically no random movement of free electrons. In this case, the outer orbital electrons are tightly bound to their parent nuclei and will not normally break away. Examples of good insulators are dry air, rubber, mica, ebonite, and porcelain.

16. No rigid line can be drawn between conductors and insulators. Copper is a very good conductor ; mica is a very good insulator. Between these extremes lies a group of materials which are neither good conductors nor good insulators. Some of these materials are termed **semi-conductors** and have important special properties which will be dealt with in Section 8.

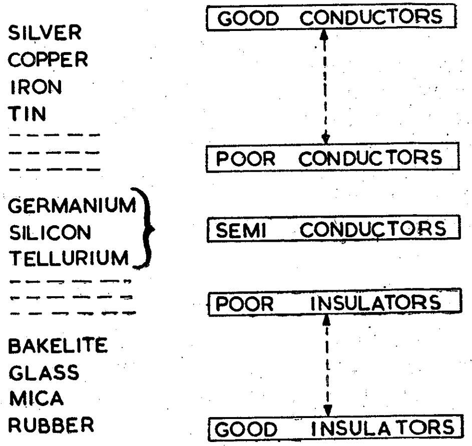
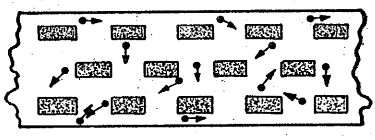


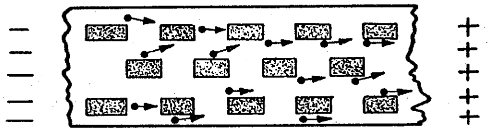
Fig. 3.—CONDUCTORS AND INSULATORS

Electric Current

17. An electric current is an average movement of electric charges through a material in one general direction. The electric charges can be electrons, ions, or both. For instance, in a conductor under normal conditions there is a continual random movement of free



RANDOM MOVEMENT – NO CURRENT



GENERAL MOVEMENT — ELECTRIC CURRENT

▨ = HEAVY POSITIVE IONS

● = FREE ELECTRONS

Fig. 4.—CONDUCTION CURRENT

electrons between the static atoms. This does not constitute a current. Under certain conditions, however, (such as that shown in Fig. 4) the free electrons can be caused to move through the conductor in one general direction towards a point which is positive and, therefore, attracts them. This constitutes a **conduction current,** which occurs in conductive circuits and in a vacuum, e.g., in a thermionic valve.

18. By convention, the *direction* of an electric current is from positive to negative. This was assigned as the direction of current before the discovery of the electron and the result is that a large number of electrical laws are defined in terms of this **conventional current,** notwithstanding the fact that electrons move in the reverse direction in a conductive circuit.

Effects of an Electric Current

19. The more important effects observed when an electric current is flowing are :—

(*a*) **The heating effect.** A movement of electrons through a conductor always causes the conductor to become hot. This effect is used in devices such as electric fires, electric irons, electric lamps, and fuses. Consideration must always be given to the heat produced in radio instruments by electric currents.

(*b*) **The chemical effect.** An electric current through an electrolyte causes a change in the chemical composition of the electrolyte and of any electrodes immersed in the solution. This effect is used in battery charging and in electroplating.

(*c*) **The magnetic effect.** An electric current through any medium always produces a magnetic field (see Section 2). This cause and effect are inseparable and are put to use in devices such as electric bells, relays, electric motors, and transformers.

Unit of Charge

20. The charge on an electron (or a proton) is extremely small and is inconvenient for practical measurements. The practical unit of charge or quantity of electricity (symbol Q) is the **coulomb.** A charge of one coulomb is equal to the charge on $6{\cdot}29 \times 10^{18}$ electrons. This rather awkward figure arose from the fact that the coulomb was assigned as the unit of charge before the discovery of the electron.

Unit of Current

21. The practical unit of current (symbol I) is the **ampere.** If, in any circuit, the quantity of electricity passing a given point in one second is one coulomb, the current will be one ampere.

22. Since one ampere equals a rate of flow of one coulomb per second :—

$$\text{Current, I amperes} = \frac{\text{Quantity or charge, Q coulombs}}{\text{Time, t seconds}}$$

$$\text{i.e. } I = \frac{Q}{t} \text{ (Amperes)} \quad — \quad — (1)$$

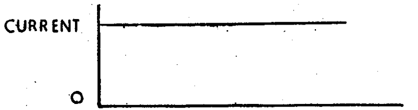
Constant and Varying Currents

23. The rate of flow of electrons in a circuit (i.e., the current) can be in one of the following forms :—

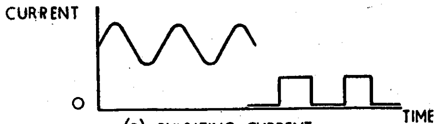
(*a*) **Direct current, d.c.** An electric current flowing continuously in one direction at a steady rate.

(*b*) **Pulsating current.** An electric current which flows in one direction but which undergoes regular, recurring variations in magnitude.

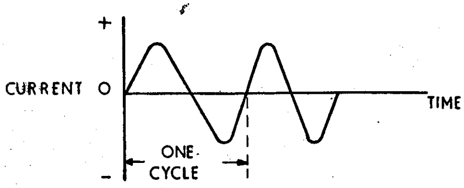
(*c*) **Alternating current, a.c.** An electric current which alternately reverses its direction in a circuit in a regular manner. One *cycle* is a complete variation as shown in Fig. 5. The number of such cycles occurring in one second is termed the *frequency* and is given in cycles per second or c/s (see Sections 3 and 5).



(A) D.C.



(B) PULSATING CURRENT



(C) A.C.

Fig. 5.—TYPES OF CURRENT

E.M.F. AND P.D.

Electrical Energy

24. When an electric current flows in a conductor, the conductor becomes hot, i.e., energy is dissipated in the conductor in the form of heat. Electrons during their passage through the conductor collide with the molecules and give up some of their kinetic energy to them. The molecules, already in a state of agitation, move faster and further from one another. This results in both heat and expansion of the conductor.

25. As energy can neither be created nor destroyed, this heat energy must be derived from some other form of energy—in this case, **electrical energy.**

26. By conversion, electrical energy may be obtained from other forms of energy. The more practical methods are :—

(*a*) **Chemical.** The electric cell.

(*b*) **Thermal.** Thermionic emission.

(*c*) **Electromagnetic.** The electric generator.

(*d*) **Thermo-electric.** The thermo-junction.

(*e*) **Photo-electric.** The photo-electric cell.

Electromotive Force (E.M.F.) and Potential Difference (P.D.)

27. Consider a simple closed electric circuit, such as a conductor connected between the terminals of a battery. There are two energy transformations going on concurrently. Chemical energy is being converted to electrical energy by the battery, and electrical energy is being converted to heat energy in the conductor. These two processes provide the basis of two important ideas in the description of electrical phenomena :—

(*a*) Whenever there is introduced in any part of an electric circuit any form of energy capable of being converted into electrical energy, an **electromotive force (e.m.f.)** is said to be acting in that circuit. Thus, in the simple circuit described above, the battery supplies an e.m.f., as chemical energy is there being converted to electrical energy.

(*b*) If between any two points in an electric circuit it is possible to convert electrical energy into any other form, a **potential difference (p.d.)** is established between the two points. In the simple circuit described above, between any two points on the conductor electrical energy is being converted to heat energy ; there is, therefore, a p.d. between any two points on the conductor.

Unit of E.m.f. and P.d.

28. The unit of e.m.f. is the **volt.** The e.m.f. of a supply is one volt if the amount of energy converted into electrical energy is one joule for each coulomb of electricity passing.

$$\text{E.m.f., E volts} = \frac{\text{Energy or work, W joules}}{\text{Quantity or charge, Q coulombs}}$$

$$\text{i.e., } E = \frac{W}{Q} \text{ (volts)} \quad — \quad — \quad — \quad (2)$$

29. The unit of p.d. is the **volt.** The p.d. between two points in a circuit is one volt if the amount of electrical energy converted into some other form is one joule for each coulomb which passes between the two points.

$$\text{P.d., V volts} = \frac{\text{Energy or work, W joules}}{\text{Quantity or charge, Q coulombs}}$$

$$\text{i.e., } V = \frac{W}{Q} \text{ (volts)} \quad — \quad — \quad — \quad (3)$$

Potential

30. For practical purposes the earth is regarded as being electrically neutral (i.e. zero charge). Any point having a deficiency of electrons has then a positive **potential** with respect to the earth ; between the two a p.d. will exist. Conversely, a point having a surplus of electrons has a negative potential with respect to earth.

31. Any point in an electric circuit can be taken as a reference point ; any other point will then have a potential (either positive or negative) *with respect to* the reference point and a p.d. will exist between the two. In Fig. 6 :—

(*a*) "A" is at a potential of one volt positive with respect to "B", and *two* volts positive with respect to "C". A p.d. of one volt exists between "A" and "B", and two volts between "A" and "C".

(*b*) "C" is at a potential of one volt negative with respect to "B", and *two* volts negative with respect to "A". A p.d.

of one volt exists between "C" and "B", and two volts between "C" and "A".

(*c*) "B" is at a potential of one volt *negative* with respect to "A", and one volt *positive* with respect to "C". Between "A" and "B", and between "B" and "C" p.d.s of one volt exist.

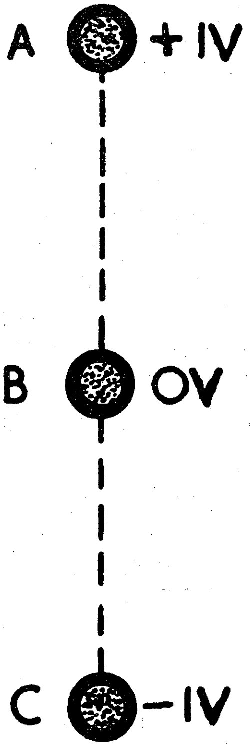


Fig. 6.—POTENTIAL AND POTENTIAL DIFFERENCES

Expressions for Electrical Energy and Power

32. Electrical energy is the ability or the capacity of an electrical system for doing work. The practical unit is the **joule** (see Para. 6(*e*)). The work done when a charge of Q coulombs moves through a p.d. of V volts is given by equation (3) :—

$$W = V.Q \text{ (joules)}$$

From equation (1) :—

$$Q = I.t \text{ (coulombs)}$$

By substitution :—

$$W = V.I.t \text{ (joules)} \quad — \quad — \quad (4)$$

33. Electrical power is the *rate* at which work is done. The practical unit is the **watt**—the rate of working when one joule of energy is transformed per second. Thus:—

$$\text{Power, P watts} = \frac{\text{Energy or work, W joules}}{\text{Time, t seconds}}$$

$$\text{i.e., } P = \frac{W}{t} = \frac{V.I.t.}{t} = V.I. \text{ (watts)} \quad (5)$$

34. From Paras. 32 and 33 it is seen that if a current of one ampere is established in a circuit where the p.d. is one volt, a power of one watt is developed. If this condition is maintained for one second, the energy expended is one joule.

SECTION 1

CHAPTER 2

RESISTANCE AND OHM'S LAW

RESISTANCE AND OHM'S LAW

KIRCHHOFF'S LAWS

PART 1, SECTION 1, CHAPTER 2

RESISTANCE AND OHM'S LAW

Introduction

1. Chapter 1 has shown that when a source of e.m.f. is acting in a circuit such as to cause a p.d. to be developed across a conductor, a current is established in that conductor. It is now necessary to find the relationship between the current in the conductor and the p.d. across it.

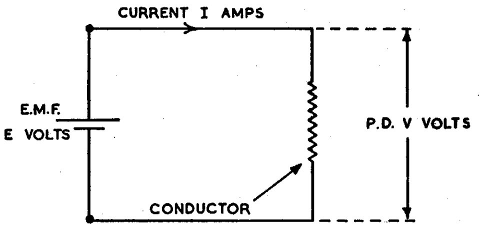


Fig. 1.—SIMPLE ELECTRIC CIRCUIT

Ohm's Law

2. This states :—

> " In any given conductor, provided the temperature remains constant, the ratio of the p.d. across the conductor to the current established in the conductor is a constant."

$$\text{Thus :—}\frac{\text{P.d., V volts}}{\text{Current, I amperes}} = \text{Constant}$$

$$\text{i.e., } \frac{V}{I} = \text{Constant} \quad — \quad — \quad (1)$$

3. Ohm's law is a **linear** law,—i.e., plotting a graph of current in the conductor for various values of p.d. across it results in a straight line through the origin. Fig. 2 shows such a graph for two different conductors.

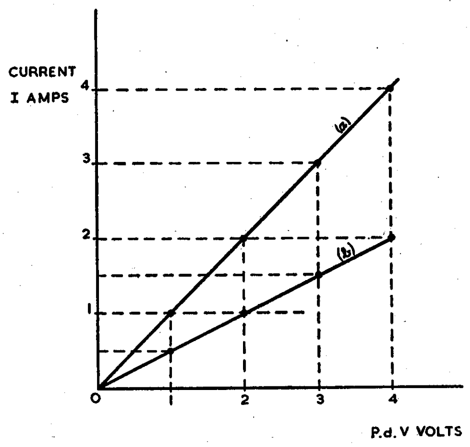


Fig. 2.—GRAPH TO SHOW OHM'S LAW

In graph (*a*) :—

$$\frac{V}{I} = \text{Constant} = 1$$

In graph (*b*) :—

$$\frac{V}{I} = \text{Constant} = 2$$

4. Any material which gives a linear graph through the origin as in Fig. 2 is said to obey Ohm's law. Any device which does not obey Ohm's law is termed a **non-linear device**,—e.g., a thermionic valve.

Resistance

5. The constant of Paras. 2 and 3 is termed the **resistance** of the conductor (symbol R). The unit of resistance is the ohm (symbol Ω). A conductor has a resistance of one ohm if a p.d. of one volt across the conductor establishes a current of one ampere. Equation (1) can now be re-written :—

$$\frac{\text{P.d., V volts}}{\text{Current, I amps}} = \text{Resistance, R ohms}$$

$$\text{i.e., } \frac{V}{I} = R \text{ (ohms)} \quad — \quad — \quad — \quad (2)$$

Thus, if a p.d. of 5 volts across a conductor establishes a current of 50 milli-amperes (mA), the resistance of the conductor is :—

$$R = \frac{V}{I} = \frac{5}{50 \times 10^{-3}} = 100 \text{ ohms.}$$

6. The resistance of a material varies from a very low value for a good conductor to a very high value for a good insulator.

Factors Affecting Resistance

7. The resistance of a material is directly proportional to its length (l) and inversely proportional to its cross-sectional area (*a*) :—

$$R = \rho\frac{l}{a} \quad — \quad — \quad — \quad — \quad (3)$$

8. In this expression, ς is called the **resistivity** or the **specific resistance** of the material and is defined as the resistance between the opposite faces of a specimen of that material of unit length and unit cross-sectional area ;

that is, of unit cube. The value of ρ depends on the units chosen and is generally given in ohms per cm. cube.

Temperature Coefficient of Resistance.

9. The resistivity (and hence the resistance) of a material varies with temperature. The resistance of pure metals increases with temperature rise, while the resistance of insulators decreases. Pure metals change more than alloys, some of which actually decrease in resistance as the temperature rises. The resistances of carbon and electrolytes decrease with a rise in temperature. A material whose resistance increases with a rise in temperature has a *positive temperature coefficient* ; those whose resistances decrease with a rise in temperature have *negative temperature coefficients.*

10. For the purposes of calculation, the formula

$$R_t = R_o (1 + \alpha t) \text{ ohms} \quad — \quad — \quad (4)$$

is used, where R_t stands for the resistance at t°C, R_o for the resistance at 0°C and α for the temperature coefficient taking 0°C as standard.

Conductance

11. In direct current circuits, the **conductance** of a material (symbol G) is the reciprocal of its resistance. The unit of conductance is the **mho.** Thus :—

$$\text{Conductance, } G = \frac{1}{R} \text{ (mhos)} \quad — \quad — \quad (5)$$

Resistors in Series

12. When a conductor is specially constructed to provide resistance it is termed a **resistor,** and as such is used extensively in radio.

Resistors are "in series" when they are connected end to end in such a manner that only one path is provided for the current, the same current flowing through each resistor. This is shown in Fig. 3.

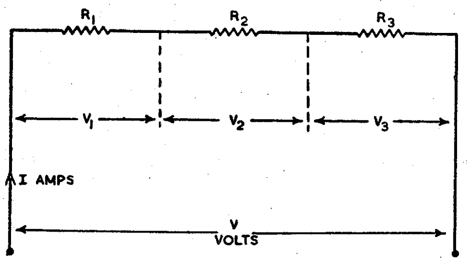


Fig. 3.—RESISTORS IN SERIES

13. The p.d. across each resistor is obtained by applying the general formula for Ohm's law, i.e., V = I.R (volts). From this it is seen that the p.d. across individual resistors connected in series is the same only if their resistance values are the same. The total resistance of several resistors connected in series is the sum of the individual resistances:-

$$R_T = R_1 + R_2 + R_3 + — \text{ (ohms)} —(6)$$

Resistors in Parallel

14. Resistors are "in parallel" when they are connected in such a manner that they provide alternative paths for the current, the p.d. across each resistor being the same. The current through each resistor will be the same only if the resistors are equal in value. This is shown in Fig. 4.

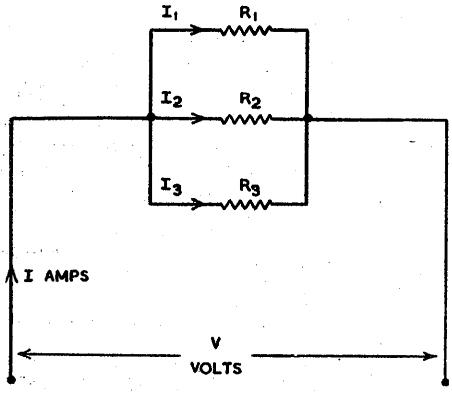


Fig. 4.—RESISTORS IN PARALLEL

15. By applying Ohm's law to the circuit it is found that :—

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \quad — \quad — \quad (7)$$

i.e., the reciprocal of the total resistance is the sum of the reciprocals of the individual resistances ; the total resistance is always less than the smallest individual resistance.

16. Since conductance is the reciprocal of resistance in d.c. circuits, equation (7) may be written :—

$$G_T = G_1 + G_2 + G_3 + \text{ (mhos)} \quad — (8)$$

Resistors in Series-Parallel

17. The procedure for solving a circuit consisting of combinations of resistors in

series and parallel is to reduce any parallel combination to a single equivalent resistance, and add to any resistance which may be in series in that arm, repeating the procedure as necessary.

Internal Resistance

18. When a current of I amperes flows through a resistance of R ohms, a p.d. or "volts drop", given by $V = I.R$ (volts) is developed across the resistance. Any source of supply (e.g., a battery) must have some "internal resistance" and when a current flows in the circuit a volts drop is developed across this internal resistance.

19. In the circuit shown in Fig. 5, the internal resistance of the supply is 0·5 ohms. The total resistance is :—

$$R_T = R_1 + R_2 = 0{\cdot}5 + 5{\cdot}5 = 6 \text{ ohms.}$$

$$\therefore\ I = \frac{E}{R_T} = \frac{12}{6} = 2 \text{ amps.}$$

This current flows through the two resistances in series developing a volts drop across each. The volts drop across the internal resistance is :—

$$V = I.R = 2 \times 0{\cdot}5 = 1 \text{ volt.}$$

The polarity is as shown and is such as to *subtract* from the e.m.f. of the supply. The terminal p.d. of the supply across AB is, thus:—

$$12 - 1 = 11 \text{ volts.}$$

The conclusion is that when a current is taken from a supply, the terminal p.d. is less than the e.m.f. by the volts drop developed across the internal resistance of the supply.

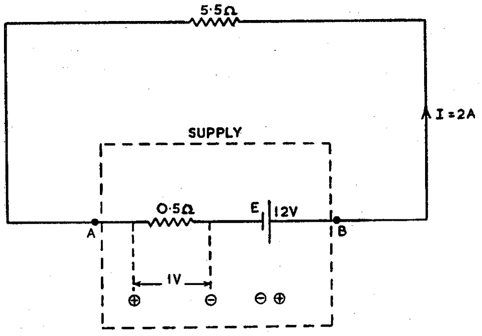


Fig. 5.—INTERNAL VOLTS DROP

Expressions for Power and Energy

20. It has been shown in Chap. 1 that :—

Energy, $W = V.I.t$ (joules)
Power, $P = V.I$ (watts).

By substitution for V or I from Ohm's law relationship $\frac{V}{I} = R$, other expressions for energy and power are obtained :—

$$\text{Energy, } W = V.I.t = I^2.R.t = \frac{V^2}{R}.t \quad \text{(joules)} \text{ — — — — } (9)$$

$$\text{Power, } P = V.I = I^2.R = \frac{V^2}{R} \quad \text{(watts)} \text{ — — — } (10)$$

Maximum Power Transfer Theorem

21. This states :—

> "Maximum power is transferred from a source of supply to an external circuit when the resistance of the external circuit is equal to the internal resistance of the supply".

22. In the circuit shown in Fig. 6, to find that value of load R for which maximum power will be transferred from the supply to the load :—

(*a*) Let $R = 2\Omega$; then $R_T = 3 + 2 = 5\Omega$

$$\therefore I = \frac{E}{R_T} = \frac{12}{5} = 2{\cdot}4A$$

The power developed across the load is :—

$$P = I^2R = (2{\cdot}4)^2 2 = 11{\cdot}52W$$

(*b*) Let $R = 3\Omega$; then $R_T = 3 + 3 = 6\Omega$

$$\therefore\ I = \frac{12}{6} = 2A$$

And $P = (2)^2\ 3 = 12W.$

(*c*) Let $R = 4\Omega$; then $R_T = 3 + 4 = 7\Omega$

$$\therefore\ I = \frac{12}{7} = 1{\cdot}7A$$

And $P = (1{\cdot}7)^2\ 4 = 11{\cdot}56W$

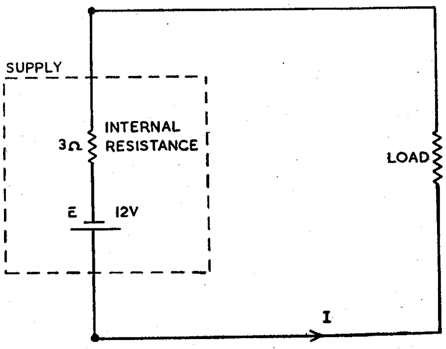


Fig. 6.—MAXIMUM POWER TRANSFER

(*d*) A graph of the power P developed across the load for several values of load R is shown in Fig, 7. This proves the theorem.

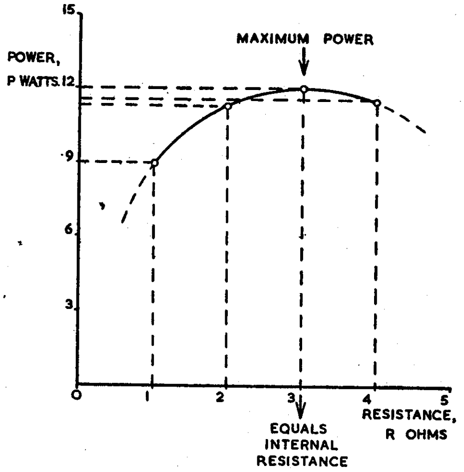


Fig. 7.—GRAPH TO SHOW MAXIMUM POWER TRANSFER CONDITIONS

The Potential Divider

23. The fact that a volts drop is developed across a resistance when a current flows through it can be used to give a division of potential in a circuit.

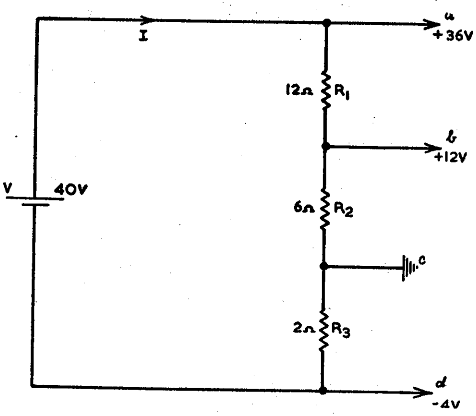


Fig. 8.—A POTENTIAL DIVIDER

24. Consider Fig. 8. The p.d. across each resistor is found by applying Ohm's law to the circuit. Point "c" is at earth potential. The p.d. across R_3 is 4 volts, so that point "d" is at a potential of 4 volts *negative* with respect to earth. Similarly point "b" is at a potential of 12 volts *positive* with respect to earth. Point "a" is at a potential of $24 + 12 = 36$ volts *positive* with respect to earth. These potentials can be applied to various parts of a system. In any potential divider of this type, the p.d. across any resistor R is :—

$$V_R = \frac{\text{Total p.d.} \times R}{\text{Total Resistance}} = \frac{V \times R}{R_T} \text{ (volts)} \quad — \quad — \quad — \quad — \quad (11)$$

KIRCHHOFF'S LAWS

Kirchhoff's Laws

25. Circuits which do not come within the category of simple series or parallel circuits can be solved by means of Kirchhoff's laws :—

(*a*) **First Law.** " The algebraic sum of currents meeting at any point in a circuit is zero ". Thus, at any junction in a circuit, the current entering that junction must equal the current leaving it.

(*b*) **Second law.** " In any closed circuit, the algebraic sum of the e.m.f.s is equal to the algebraic sum of the p.d.s." Thus, if all the p.d.s in a circuit are added (with due regard to their polarity) the sum will equal the e.m.f. acting in that closed circuit.

Application of Kirchhoff's Laws

26. To demonstrate the method by which Kirchhoff's laws are applied consider Fig. 9.

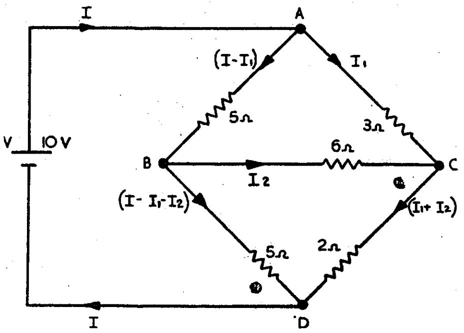


Fig. 9.—APPLICATION OF KIRCHHOFF'S LAWS

It may be necessary to find the current in the centre (6 ohms) arm. To obtain this, the sequence is as follows :—

(*a*) Apply Kirchhoff's first law to the circuit and annotate the currents at various parts of the circuit. For instance, the current entering A is I. This is also the current leaving A so that if I_1 is established between AC, the current established between AB is $(I - I_1)$, since $I_1 + (I - I_1) = I$. By similar reasoning the currents established at other parts of the circuit will be as shown.

(*b*) Three unknown quantities I, I_1, and I_2 are thereby produced, and to obtain the value of any one of them, three simultaneous equations are obtained and solved in the usual manner.

(*c*) To obtain such equations, Kirchhoff's second law is applied to three of the closed circuits (one containing the battery e.m.f.). For instance, mesh ACB is a closed circuit where the e.m.f. acting is zero. The algebraic sum of the p.d.s must, therefore, be zero. The correct polarity of the p.d. across each resistor must be observed, a minus sign indicating that the p.d. is negative when taken against the conventional flow of current. Thus :—

$$3I_1 - 6I_2 - 5(I - I_1) = 0$$
$$\therefore 5I - 8I_1 + 6I_2 = 0$$

(*d*) A further two simultaneous equations may be obtained in a similar manner by considering circuits BCD and ACD (and battery). The three equations are then solved to give I_2 — the current in the centre arm.

Wheatstone's Bridge

27. The bridge arrangement of resistors shown in Fig. 10 is used extensively in radio for a variety of applications, including the measurement of component values. The principle of Wheatstone's bridge is simple. If there is no reading in the galvanometer (an instrument used to indicate that current is flowing in a circuit) the bridge is said to be "balanced". If no current is flowing between B and C these points must be at the same potential ; the current flowing in the other branches will then be as indicated in Fig. 10.

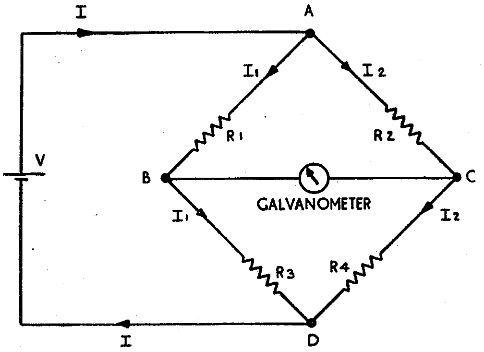


Fig. 10.—WHEATSTONE'S BRIDGE

28. (*a*) For the points B and C to be at the same potential, the p.d. across AB must equal that across AC.

i.e., $I_1R_1 = I_2R_2$

$$\therefore \frac{I_1}{I_2} = \frac{R_2}{R_1} \quad \text{— — — — — —} \quad \text{(i)}$$

(*b*) Similarly, the p.d. across BD must equal that across CD.

i.e., $I_1R_3 = I_2R_4$

$$\therefore \frac{I_1}{I_2} = \frac{R_4}{R_3} \quad \text{— — — — — —} \quad \text{(ii)}$$

(*c*) From equations (i) and (ii) :—

$$\frac{I_1}{I_2} = \frac{R_2}{R_1} = \frac{R_4}{R_3}$$

$$\therefore \frac{R_1}{R_2} = \frac{R_3}{R_4} \quad \text{— — — — —} \quad (12)$$

This gives the condition under which the bridge is balanced.

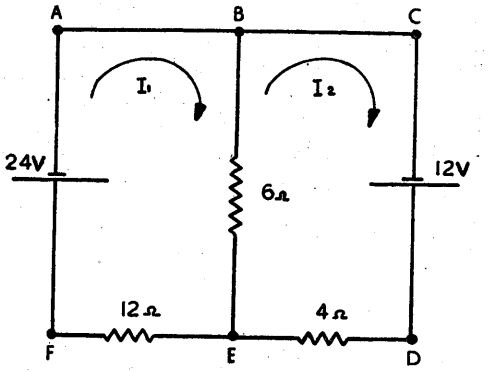
29. The normal arrangement in a Wheatstone's bridge used for resistance measurement is for two resistors (say R_1 and R_2) to be fixed and known in value ; R_3, say, to be variable and calibrated ; R_4 is then the unknown resistor whose resistance is to be measured. For adjustment, R_3 is varied until there is no deflection in the galvanometer. The bridge is then balanced and from equation (12) :—

$$R_4 = \frac{R_2\,R_3}{R_1} \text{ (ohms).}$$

30. In a Wheatstone's bridge, at balance, there is no p.d. across BC for any voltage applied across AD. The converse is also true. In either case, however, a p.d. is developed across any single resistor in the bridge. These facts are used in practice where it is required to prevent two voltages, which feed into a common circuit, from affecting each other.

Maxwell's Circulating Currents

31. In the circuit shown in Fig. 11, two currents I_1 and I_2 are assumed to flow in a



11.—MAXWELL'S CIRCULATING CURRENTS

clockwise direction round each loop. Kirchhoff's second law is applied to each loop and the simultaneous equations so obtained are solved to give the required result.

The Superposition Theorem

32. With this theorem, each battery is considered to be short-circuited in turn and two separate calculations are made by applying Ohm's law to each circuit. The separate answers are then superposed to give the final result. Fig. 11 can be redrawn in accordance with the superposition theorem to give Fig. 12.

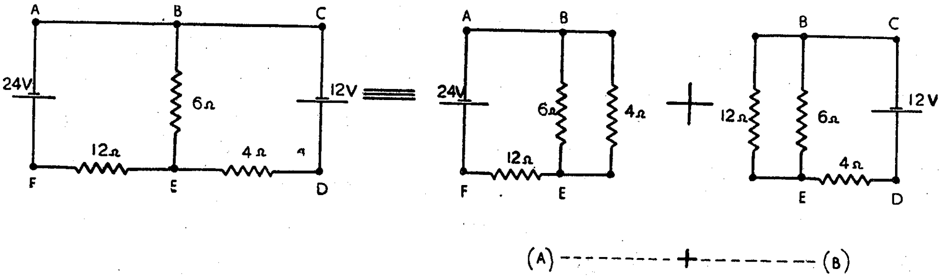


Fig. 12.—THE SUPERPOSITION THEOREM

SECTION 1

CHAPTER 3

RESISTOR CONSTRUCTION

RESISTOR CONSTRUCTION

Introduction

1. A modern radar equipment may contain as many as 5,000 resistors, each used for a specific purpose such as to provide a p.d. from a current flowing through it, or to form part of a potential divider network.

2. Values of resistance from a fraction of an ohm to several million ohms are used. Methods of resistor construction include :—

(*a*) Carbon composition type.
(*b*) Cracked carbon film type.
(*c*) Wire-wound type.
(*d*) Metal film type.

Carbon Composition Resistors

3. The method of construction of this type varies considerably. The following method is typical :—

Powdered carbon dust with a filling material and a binder of resin, are mixed together, moulded to shape, and then fired at a high temperature. The resultant composition rod forms the resistor whose resistance varies according to the carbon content. Connection is made to the resistor either by metal caps clamped at each end of the rod, or by wires firmly wound round the ends of the rod. The resistor is then varnished, or placed inside a ceramic tube, and colour-coded.

4. This type of resistor has a very poor stability. The resistance value varies considerably with temperature, load, and even with shelf life. Consequently, it can only be used where a quite large change in resistance is of no importance to the operation of the equipment. In addition, the power that can be developed in this type of resistor is relatively small (of the order of 2 watts).

Cracked Carbon Film Resistors

5. In this type, a hard carbon film is deposited on to a ceramic rod and the required resistance obtained by cutting a spiral track through the film. This rod is then varnished, or placed inside a ceramic tube, and colour-coded. The stability in this type is much better than that in the carbon composition type.

Colour Code

6. (*a*) The colour code used to indicate the resistance value on carbon composition and cracked carbon film types of resistors is given in Table 1. Two of the more common methods of marking the resistor are shown in Fig. 1.

Colour	1st Band or Body, 1st Figure	2nd Band or Tip, 2nd Figure	3rd Band or Spot, Multiplying Factor	4th Band, Tolerance
Black	0	0	1	—
Brown	1	1	10	± 1%
Red	2	2	100	± 2%
Orange	3	3	1,000	± 3%
Yellow	4	4	10,000	± 4%
Green	5	5	100,000	—
Blue	6	6	1,000,000	—
Violet	7	7	10,000,000	—
Grey	8	8	—	—
White	9	9	—	—
Gold	—	—	0·1	± 5%
Silver	—	—	0·01	± 10%
No Colour	—	—	—	± 20%

TABLE I—COLOUR CODE

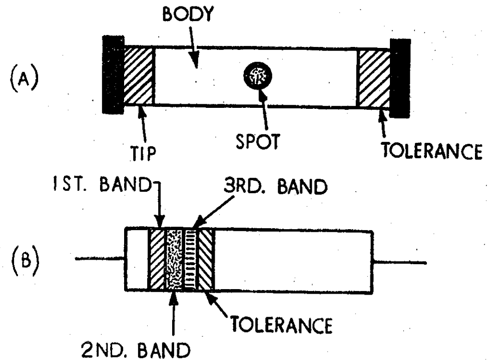


Fig. 1.—COLOUR CODING

Example. (i) Body = Yellow (4)
Tip = Violet (7)
Spot = Orange (3)
∴ Resistance = 47,000 ± 20% (ohms)

(ii) 1st Band = Blue (6)
2nd Band = Grey (8)
3rd Band = Red (2)
4th Band = Gold
∴ Resistance = 6,800 ± 5% (ohms).

(*b*) The accuracy of a resistance value is indicated by a tolerance marking as shown in Fig. 1. Because a tolerance of ± 20% is more common in carbon composition type resistors, manufacturers produce a limited range of resistors which, by the tolerance variation, can cover the whole range of resistance, e.g., 10, 15, 22, 33, 47, 68, 100 (all ± 20%). These are known as " preferred values ".

Wire-Wound Resistors

7. In this type, wire of nickel-chrome or copper-nickel is wound on a ceramic former. These wires have a high resistivity and the small amount of wire required for a particular resistance gives a resistor of reasonable size. In addition, the temperature coefficient of resistance is low, and therefore resistivity remains fairly constant with variations in temperature. This type has the best stability characteristics. The resistor is finished with a coating of vitreous enamel so that high temperatures will not oxidise the wire. The value of resistance in ohms is stencilled or stamped on the resistor.

8. Wire-wound resistors suffer from the disadvantage that the wire is wound in the form of a coil and, unless special precautions are taken, they may be unsuitable for many applications in radio (see Sect. 2, Chap. 4).

Metal Film Resistors

9. These combine the stable characteristics of the wire-wound type with the simplicity of the cracked carbon film type. The metal film type resistor is constructed as follows :—

(*a*) A thin film of platinum-gold compound is coated on to a glass plate or tube.

(*b*) This is fired to about 400°C.

(*c*) The resistance value is adjusted by etching a spiral track through the film.

(*d*) The resistor is then fired to about 700°C. to give in effect, a wire-wound resistor with each individual " wire " bonded to the glass base.

(*e*) The whole element is finally sealed in an outer tube which gives complete protection from the atmosphere and ensures the long term stability of the resistor.

Variable Resistors

10. These are termed rheostats and potentiometers.

(*a*) A **rheostat** is a variable resistor which is inserted in series with other devices in a circuit. Its value can be varied to alter the current in the circuit. It has only two connections, as shown in Fig. 2.

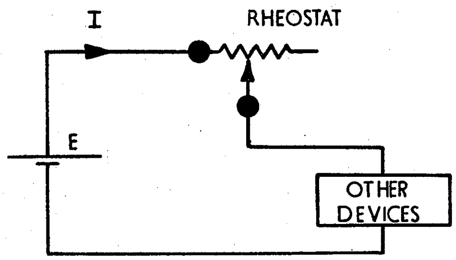


Fig. 2.—USE OF A RHEOSTAT.

(*b*) A **potentiometer** is a variable resistor arranged in such a manner that a certain proportion of the applied voltage can be " tapped off " for application to another part of the circuit. A typical use is as a volume control in a radio receiver. The potentiometer has three connections. It is seen from Fig. 3 that

V_1 is variable between 0% and 100% of E.

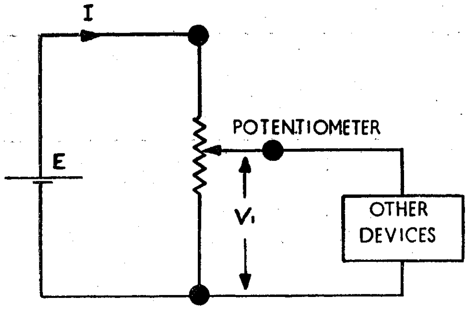


Fig. 3.—USE OF A POTENTIOMETER

(*c*) Variable resistors are constructed as carbon composition, cracked carbon film, or wire-wound types depending on the stability and power requirements. A potentiometer consists of an incomplete ring (either wire on a ceramic former, or a carbon track) the ends of which are taken out to two terminals. A wiper arm, operated by a shaft, bears on this ring and is connected to the centre terminal. As the wiper arm is moved, the resistance value between either of the end terminals and the centre terminal is varied. The whole is enclosed in a sealed bakelite or metal container.

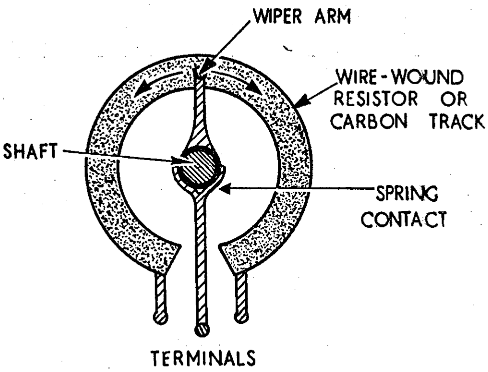


Fig. 4.—CONSTRUCTION OF A POTENTIOMETER

Summary of Resistors

11. The main characteristics of the resistors discussed in this Chapter are given in Table 2. Fig. 5 shows a selection of these resistors.

Type	Wattage Rating	Resistance	Remarks
Carbon Composition, fixed.	$\frac{1}{16}$W to 3W.	10Ω to 25 MΩ	Used in low power circuits, at all frequencies, where stability is not important.
Cracked Carbon Film, fixed.	$\frac{1}{8}$W to 2W	10Ω to 10MΩ	Used in low power circuits where greater stability is required.
Wire-wound, fixed.			
(*a*) Precision	$\frac{1}{4}$W to 3W	0·1Ω to 5MΩ	Used in low power circuits where consistent accuracy in critical applications is essential.
(*b*) Power	1W to 300W	0·5Ω to 400kΩ	Used in circuits where reliability under all conditions is necessary and where a high dissipation of power is to be achieved.
Metal Film, fixed.	$\frac{1}{8}$W to 2 W	1Ω to 1 MΩ	Used in low power circuits where greater stability is required than that obtainable with a cracked carbon resistor. This type is smaller than a wire-wound resistor of comparable ohmic value.

TABLE 2—COMPARISON OF RESISTORS

Type	Wattage Rating	Resistance	Remarks
Carbon Composition, variable.	½W to 2W	10 Ω to 2M Ω	Used in low power circuits where stability is not important.
Wire-wound, variable.	1W to 100W	1 Ω to 100k Ω	Used in circuits where a good stability is required or where a high dissipation of power is to be achieved.

TABLE 2—COMPARISON OF RESISTORS

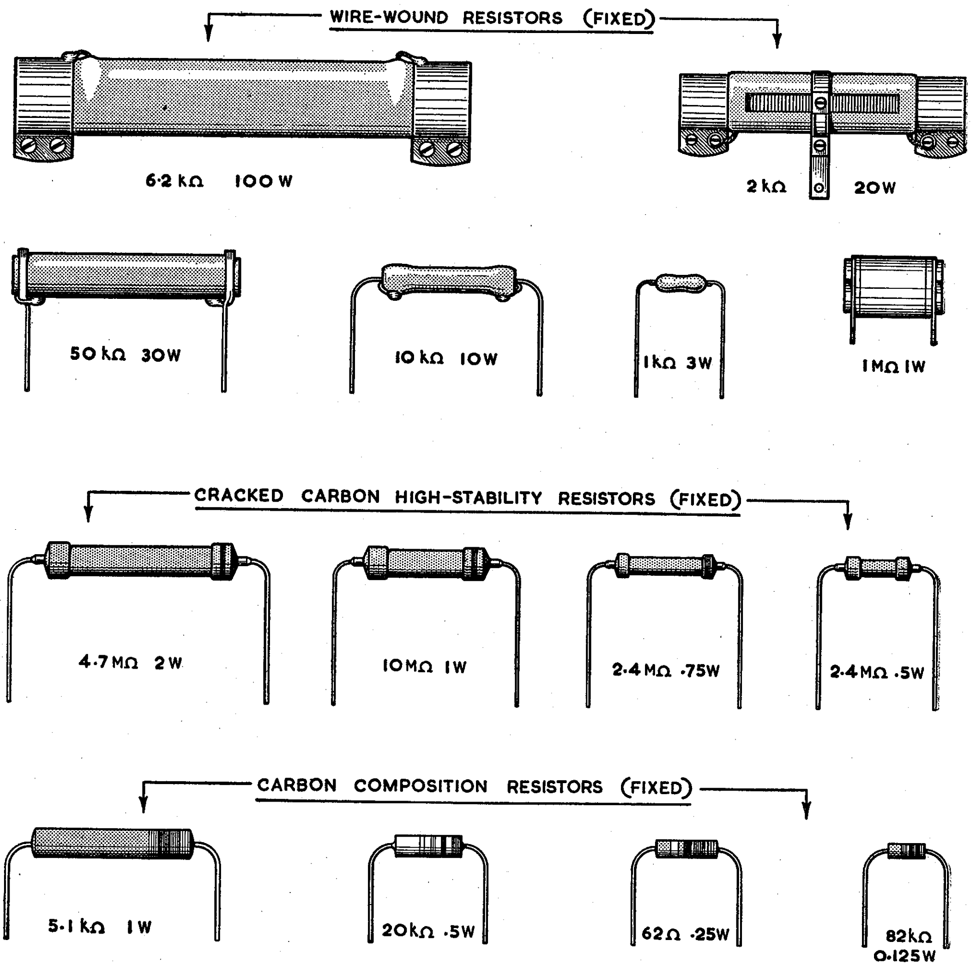


Fig. 5—TYPICAL RESISTORS USED IN RADIO

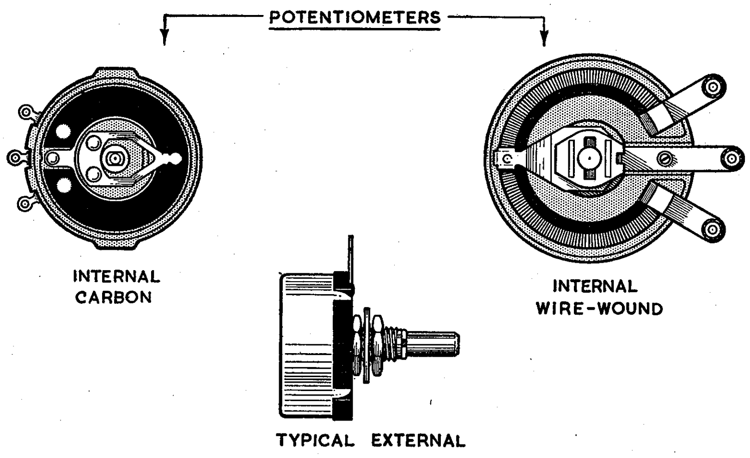


FIG. 5—TYPICAL RESISTORS USED IN RADIO

CONTENTS

PRELIMINARIES

SECTIONS

(*A detailed contents list is given at the beginning of each Section and Chapter*)

This leaf is issued with A.L. 6

STANDARD TECHNICAL TRAINING NOTES

FOR THE

RADIO ENGINEERING TRADE GROUP (FITTERS)

FOREWORD

1. These Notes are issued to assist airmen and apprentices under training as Fitters in the Radio Engineering Trade Group. They are not intended to form a complete text book, but are to be used in conjunction with lectures and demonstrations given at the Radio Schools. They are also intended to assist airmen on continuation training at other R.A.F. establishments.

2. There are four broad classifications in the advanced (Fitter) trades of the Radio Engineering Trade Group :—

(*a*) **Air Radar Fitter.** Employed in the servicing of all types of aircraft radar equipment (where servicing implies inspection, repair, re-conditioning, and modification).

(*b*) **Air Wireless Fitter.** Employed in servicing aircraft radio communication and inter-communication equipment, specified navigational aids, and miscellaneous wireless equipment.

(*c*) **Ground Radar Fitter.** Employed in servicing all types of ground radar equipment.

(*d*) **Ground Wireless Fitter.** Employed in servicing all types of ground communication equipment.

Note. The term "Radio Fitter" signifies an airman who has dual (Wireless and Radar) qualifications.

3. Before the duties described in Para. 2 can be carried out, a "thorough knowledge of the electrical and radio principles, and the elementary mathematics appropriate to the theory of the specified equipment in the trade" is required (see A.P. 3282A, Vol. 2). These Notes are in six Parts. The first four Parts deal with the theory, the basic principles, and the practice of radio to the standard demanded of the Radio Fitter Trades. Parts 5 and 6 give a summary of the equipments which the Fitter may meet in practice. These latter Parts are not intended to supersede existing Air Publications which should be consulted on specific equipment as necessary.

4. These Notes can only be issued on temporary loan to each trainee ; they must be handled with care and returned at the end of the course. A number of copies will also be available in Royal Air Force reference libraries ; these may be issued, as required, to airmen on continuation training.

5. No alterations to these Notes may be made without the authority of official Amendment Lists which will be issued from time to time.

LIST OF AIR PUBLICATIONS ASSOCIATED WITH THE TRADE

Principles and Techniques

A.P. 1093	R.A.F. Signal Manual, Part 2 (Radio Communication)
A.P. 1093E	Interservices Radar Manual—Radar Techniques
A.P. 1093F	Radar Circuit Principles, with Aerials and Centimetric Techniques
A.P. 1093G	Radio Circuitry Supplement
A.P. 1093H	Suppressed Aerials
A.P. 1186V	C.V. Register of Electronic Valves
A.P. 2521A	V.H.F. Ground Station Aerial Systems
A.P. 2867	Interservices Standard Graphical Symbols
A.P. 2867A	Interservice Glossary of Terms used in Telecommunications
A.P. 2867B	Interservice Glossary of Terms used in Telecommunications (Radar)
A.P. 2878C	H.F. and M.F. Aerials for Ground Stations
A.P. 2900C	Handbook of Electronic Test Methods and Practices
A.P. 3158C	R.A.F. Technical Services Manual
A.P. 3214 (Series)	The Services Textbook of Radio.

Equipment

Air Publications applicable to specific radio equipment are listed in:—

A.P. 2463	Index to Radio Publications

INSTRUCTIONAL FILMS

Title	Reference
Current of Electricity	14L/52
Nuts and Bolts	14L/178
Micrometer Calipers	14L/273
Vernier Scale	14L/413
Hammers, Chisels, Punches and Drifts	14L/1605
Files and Filing	14L/1606
Spanners, Screwdrivers and Pliers	14L/1636
Taps, Dies and Reamers	14L/1727
Hacksaws, Shears, and Vice Clamps	14L/1728
Locking Devices	14L/1729
Measuring and Marking—Precision Instruments	14L/1730
Transmission Lines—Maintenance of Coaxial Cables	14L/3280
Transmission Lines and Waveguides	14L/3288

This leaf issued with A.L. 13

Title	Reference
Vacuum Tubes—Electronic Diode	14L/3953
Cathode Ray Tube	14L/4268
Electricity and Magnetism	14L/4708
Magnetism	14L/5557
Electrical Terms	14L/5607
What is Electricity?	14L/5609
Electricity and Heat	14L/5610
Electricity and Movement	14L/5611
Electrochemistry	14L/5612
Putting Free Electrons to Work	14L/5614
A.C. and D.C.	14L/5615
The Generation of Electricity	14L/5616
The Transmission of Electricity	14L/5617
Aircraft First Line Servicing	14L/5656
Audio Oscillator	14L/5666
Volts—Ohm Meter Operation	14L/5667
Radio Shop Technician	14L/5668
First Line Servicing, Fighter Aircraft	14L/5768
Radio Antennae Fundamentals, Parts 1 and 2	14L/5780–1
R.D.F. to Radar	14L/5826
Waveguides, Parts 1 to 5	14L/5958–5962
Tuned Circuits	14L/6037
Ground Handling of Aircraft	14L/6338
The Doppler Principle in Airborne Navigation Aids	14L/6388
Centimetric Oscillators, Parts 1 to 3	14L/6397
Servomechanisms	14L/6435
Radar Techniques, Part 1—Waveform Response of C.R. Circuits	14L/6500
Radar Techniques, Part 2—Multivibrator	14L/6502
Radar Techniques, Part 3—Miller Timebase	14L/6504
Radar Techniques, Part 4—Pulse Forming by Delay Lines	14L/6506
Radar Techniques, Part 5—Flip Flop	14L/6508
Problems of Radio and Electronic Fault Finding	14L/6594
Principles of the Transistor	14L/6620

INSTRUCTIONAL FILM STRIPS

Title	Reference
Primary Cells	14J/154
Time Constant	14J/155
Distribution of Electricity	14J/194
Electricity—its Production	14J/195
Uses of Electricity	14J/196
Radiation	14J/197
Thermionic Valve	14J/198
Electrical Measuring Instruments	14J/203
The D.C. Motor	14J/204
Basic Radio Trouble-shooting, Parts 1 to 5	14J/239–243
The Internal Combustion Engine	14J/369
Elementary Principles of Cathode Ray Oscillograph	14J/370
The Cathode Ray Tube	14J/404
Magnetism and Electricity	14J/407
Waveguide Theory	14J/495–511
Waveguide Theory	14J/512–517
Introduction to Control Engineering Theory	14J/578
Introduction to Electronics	14J/586
Electronic Devices—Electron Tubes	14J/587
Basic Valve Circuits, Parts 1 to 4	14J/588–9
The Meaning of Valve Characteristics	14J/590
Telecommunication Principles	14J/606

STANDARD TECHNICAL TRAINING NOTES FOR THE RADIO ENGINEERING TRADE GROUP (FITTERS)

LAYOUT OF A.P.

LIST OF SYMBOLS AND ABBREVIATIONS

TABLE 1

Greek Letters Used in the Text

Letter			Letter		
Small	**Capital**	**Name**	**Small**	**Capital**	**Name**
α	—	Alpha	λ	—	Lamda
β	—	Beta	μ	—	Mu
γ	—	Gamma	π	—	Pi
δ	Δ	Delta	ρ	—	Rho
ϵ	—	Epsilon	σ	—	Sigma
η	—	Eta	ϕ	Φ	Phi
θ	—	Theta	ω	Ω	Omega
κ	—	Kappa			

TABLE 2

Meaning of Symbols Used in the Text

Letter	Meaning	Letter	Meaning
A	Ampere, Amplification	i	Instantaneous current
B	Magnetic flux density, Susceptance, Bandwidth	j	Vector operator $=\sqrt{-1}$
		k	Coupling factor, Kilo—(prefix)
C	Capacitance	l	Length
D	Electric flux density, Distance	m	Modulation factor, Metre, Mass, Milli—(prefix)
E	Electromotive force, Electric field strength	n	Number
F	Farad, Factor	p	Pico—(prefix)
G	Conductance	q	Instantaneous charge
H	Magnetic field strength, Henry	r	Length (in polar co-ordinates)
I	Electric current	r_a	Anode slope resistance

(*continued overleaf*)

J	Joule
L	Inductance
M	Mutual inductance, Mega—(prefix)
N	Number, Noise factor
P	Power
Q	Quantity or charge of electricity, Coil amplification factor
R	Resistance
S	Magnetic reluctance
T	Temperature (Absolute), Period, Transit Time
V	Potential difference, Volt, Volume
W	Energy or work, Watt
X	Reactance
Y	Admittance
Z	Impedance
a	Area
c	Velocity of light, Cycle
e	Instantaneous e.m.f., Electron charge
f	Frequency
g_c	Valve conversion conductance
g_m	Valve mutual conductance

(*continued overleaf*)

s	Second
t	Time, Temperature
u	Velocity
v	Instantaneous potential difference
x	Distance, Length
y	Length
α	Angle, Number
β	Number
γ	Propagation constant
δ	Small increment
ϵ	Base of natural logs = 2·71828
η	Efficiency
θ	Angle
κ	Dielectric constant
κ_0	Permittivity of free space
λ	Wavelength
μ	Permeability, Valve amplification factor
μ_o	Permeability of free space
μ_r	Relative permeability
π	Ratio of circumference to diameter of a circle = 3·14159
ρ	Specific resistance
ϕ	Angle
Φ	Magnetic flux
ω	Angular velocity = $2\pi f$
Ω	Ohm

TABLE 3

Prefixes for Multiples and Sub-multiples

Multiple or sub-multiple	Name	Prefix	Multiple or sub-multiple	Name	Prefix
$1{,}000{,}000 = 10^6$	Mega-	M	$\frac{1}{1{,}000{,}000} = \frac{1}{10^6} = 10^{-6}$	Micro-	μ
$1{,}000 = 10^3$	Kilo-	k			
$\frac{1}{1{,}000} = \frac{1}{10^3} = 10^{-3}$	Milli-	m	$\frac{1}{10^{12}} = 10^{-12}$	Micro-micro- or Pico	μμ or p

AL11

TABLE 4

Abbreviations of Units

Unit	Abbreviation	Unit	Abbreviation
Ampere	A	Henry	H
Ampere-hour	Ah	Joule	J
Cycles per second	c/s	Metre	m
Decibel	db	Ohm	Ω
Degree	°	Second	s or sec.
Electron-volt	eV	Volt	V
Farad	F	Watt	W
Gramme	g		

RESTRICTED

A.P. 3302

STANDARD TECHNICAL TRAINING NOTES
FOR THE
RADIO ENGINEERING TRADE GROUP
(FITTERS)

PART I
ELECTRICAL AND RADIO FUNDAMENTALS

RESTRICTED