

SECTION 6, CHAPTER 4

D.C. GENERATORS AND MOTORS

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ELEMENTARY GENERATOR PRINCIPLES

Introduction

1. Mechanical energy can be converted into electrical energy by dynamically inducing an e.m.f. and applying this e.m.f. to a closed circuit, thereby setting up an electric current. Any machine which converts mechanical energy into electrical energy in this manner is known as a generator; if the current set up in the external circuit is unvarying in its direction the machine is termed a direct current generator.

2. The simplest form of generator (Fig. 1) consists of a single loop of wire, formed into a rectangular shape and able to rotate in the space between the poles of a horseshoe permanent magnet. Connection is made to the external circuit by brushes pressing on two slip rings connected to the ends of the loop.

E.M.F. Induced in a Rotating Loop

3. During rotation the sides of the loop move across the magnetic field which exists between the poles of the magnet, i.e., they cut across the lines of force, and an e.m.f. is

consequently induced in each of the straight sides. By applying Fleming's Right Hand Rule it will be seen that the e.m.f.s. so induced are opposite in direction, but as the

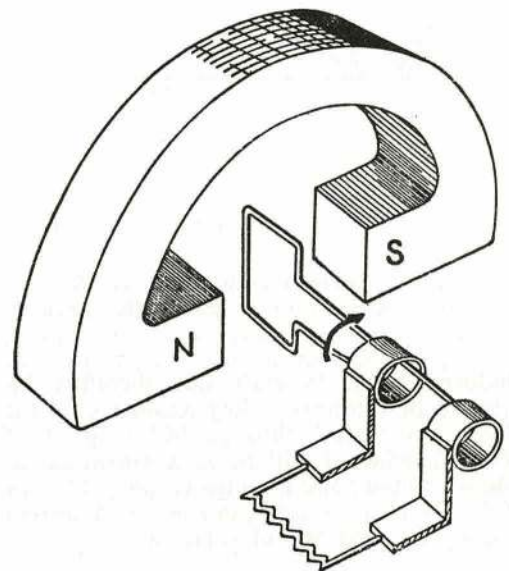


Fig. 1. SINGLE-LOOP PERMANENT-MAGNET GENERATOR.

(A.L. 12, Oct. 62)

two sides are joined together at the distant ends the two e.m.fs. will combine, forcing current through the external circuit.

4. The magnitude of the e.m.f. varies during rotation according to the number of lines cut by the sides of the loop in a given time. This number will depend on three factors, viz. the speed of rotation, the density of the field and the angle at which the sides of the loop are moving across the lines of force. If the speed of rotation is constant, the e.m.f. will be directly related to the position of the loop in the magnetic field.

5. In Fig. 1 of Fig. 2, the loop is shown as having just reached the vertical position. In this position the motion of each side is parallel to the lines of force, and no lines are being cut; no e.m.f. is therefore induced in the cell. This is represented on the graph of e.m.f. induced and current flowing in the external circuit by the point O.

until, at 180° (Fig. 3 of Fig. 2), they are again moving parallel with the lines, and cutting has ceased. The induced e.m.f. consequently decreases, during the second 90° of rotation, from maximum P to zero Q. Thus for 180° of rotation the e.m.f. (and the current in the external circuit) have risen from zero to maximum and then declined again to zero.

8. As rotation continues beyond 180° the sides of the loop again begin to cut the lines of force at an increasing rate, but the relative motion of each side of the loop and the field is reversed. The induced e.m.f. begins to rise again, but in the opposite direction, until after 270° of rotation (Fig. 4 of Fig. 2) it is once more at a maximum, as shown by the point R on the graph.

9. The fourth quadrant of rotation (270° to 360°) will again result in a decreasing rate of cutting lines of force until, at 360° (Fig. 5 of

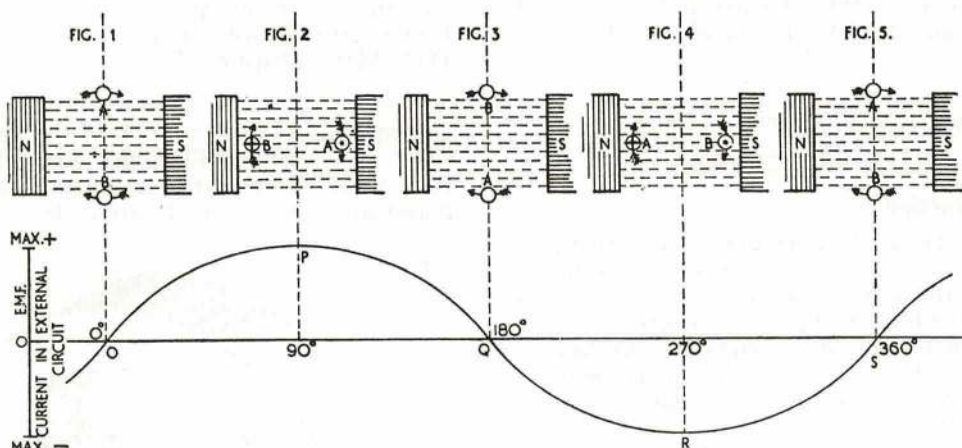


Fig. 2. E.M.F. INDUCED IN A ROTATING LOOP

6. As the rotation continues, the sides of the loop begin to cut across the lines of force at a continually increasing angle, cutting the lines at an increasing rate. The induced e.m.f. in each side therefore increases in a corresponding manner until the loop has turned through 90° (Fig. 2 of Fig. 2), when it will be at a maximum as shown by the point P on the graph. The line OP shows the variation in e.m.f. and current during the first 90° of rotation.

7. After turning 90° the sides of the loop cut the lines of force at a decreasing rate

Fig. 2), cutting has ceased and the e.m.f. has again declined to zero as shown by point S on the graph. Further movement will produce a second reversal of e.m.f. with subsequent rise and fall, reversal, etc., as a second complete revolution of the loop is accomplished.

10. To summarize this sequence, it can be said that:—

(a) The polarity of the slip rings reverses as the sides of the loop move alternately under the influence of a north and south pole.

(b) The current in the external circuit changes its direction as the slip ring polarity reverses, and is known as an alternating current.

Production of Direct Current

11. The current supplied to the external circuit by the simple slip-ring single-loop generator just described reverses its direction at regular intervals, and although such current can be used effectively for lighting, heating, and operating certain types of motors, etc., it is not suitable for electrolytic processes such as battery charging, electroplating, metal refining, etc. These processes require a current which flows in one direction only, i.e. a direct current.

12. Direct current in the external circuit can be obtained by substituting a form of automatic reversing switch, known as a commutator, for the slip rings. The commutator automatically reverses the connections between loop and external circuit as the e.m.f. in the loop reverses, thus maintaining the direction of current in the external circuit. A simple form of commutator suitable for the single loop generator consists of the two halves of a split ring suitably insulated from each other. Each end of the loop is connected to a segment of the slip ring, and the external circuit is connected to the loop by brushes placed on opposite sides of the commutator, as shown in the illustration (Fig. 3).

13. In Fig. 1 of Fig. 3 the sides of the loop are moving parallel to the magnetic field, no e.m.f. is induced in the loop, and no current flows in the external circuit. In this position both brushes are bridging the two segments of the commutator. As the loop rotates in a clockwise direction an e.m.f. is induced in it, causing current to flow in the external circuit in the direction indicated. Each brush is now in contact with one commutator segment only. This state of affairs continues while the loop rotates through 180° , maximum e.m.f. being induced at 90° (Fig. 2 of Fig. 3). At 180° (Fig. 3 of Fig. 3) the sides of the loop are again moving parallel to the magnetic field, and no e.m.f. is induced; current therefore ceases to flow in the external circuit. In this position both brushes are again bridging the segments.

14. Further rotation of the loop causes a reversed e.m.f. to be induced; it also causes the commutator segments to move under opposite brushes as the e.m.f. reverses. The brushes therefore maintain their original polarity, and current flows again in the external circuit in the original direction. Maximum e.m.f. and current is attained at 270° rotation (Fig. 4 of Fig. 3), and at 360° rotation (Fig. 5 of Fig. 3) the e.m.f. and current again decline to zero, with the segments coming under opposite brushes again as reversal of e.m.f. in the loop occurs. Thus the current in the external circuit is unidirectional, although continually varying in magnitude, while one brush is always positive and the other always negative. Fig. 6 of Fig. 3 shows the variation of brush voltage and external circuit current during one complete revolution of the loop.

15. The voltage at the brushes and the current in the external circuit of a single-loop d.c. generator falls to zero twice during each revolution. A more constant brush voltage and a smoother flow of current can be obtained by placing additional loops symmetrically round the axis of rotation. 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 declining, and the e.m.f. in the succeeding loop is still 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; as only one loop can be in the zero-e.m.f. position at any one time, it follows that the brush voltage will never sink to zero, and the former fluctuation becomes a ripple, as shown in Fig. 4.

Magnitude of Induced E.M.F.

16. The e.m.f. induced in a single loop of wire in a permanent magnetic field is extremely small, since a conductor must cut 10^8 lines of force per second to induce an e.m.f. of one volt. A higher e.m.f. can be obtained by substituting a coil of wire for the loop, the coil consisting of a fairly large number of turns. The e.m.f.s. induced in the separate turns are all in the same direction, the total e.m.f. induced in the coil is therefore the sum of all the individual e.m.f.s. induced in each turn of the coil. Each side of each turn of the coil is contributing to the total e.m.f. of the coil, and each side is termed an "effective conductor". Thus a

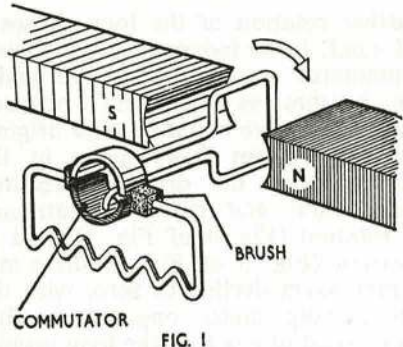


FIG. 1

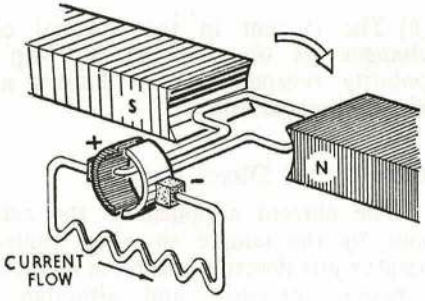


FIG. 2

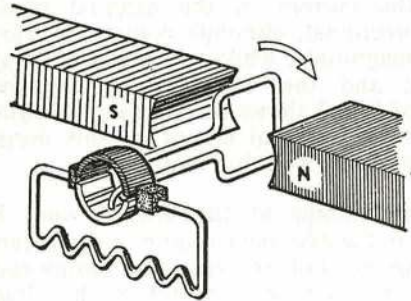


FIG. 3

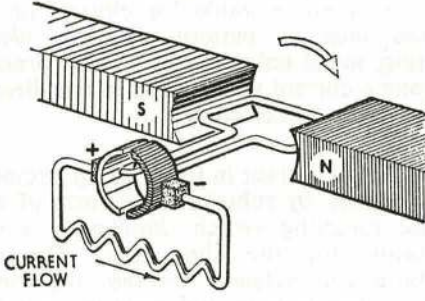


FIG. 4

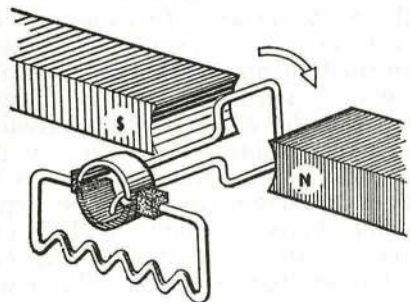


FIG. 5

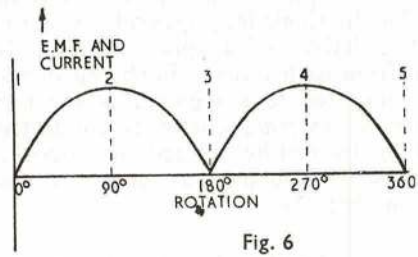


Fig. 6

Fig. 3. PRODUCTION OF DIRECT CURRENT.

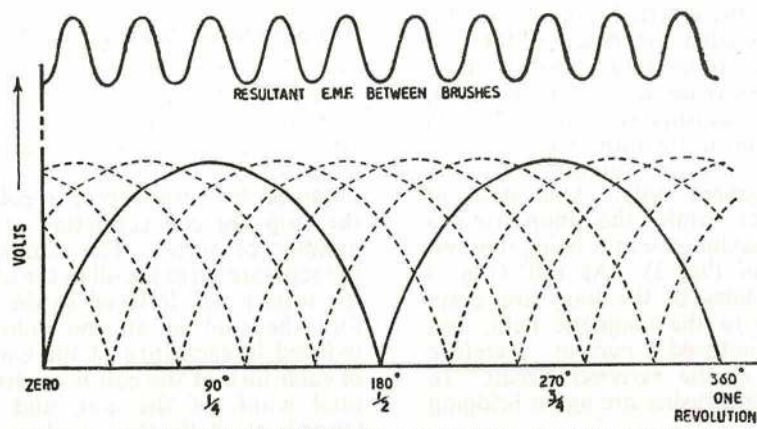


Fig. 4. RESULTANT E.M.F. PRODUCED BY FIVE COILS.

coil of 250 turns of wire has 500 effective conductors.

17. The induced e.m.f. of a generator therefore depends on the number of effective conductors, the speed of rotation, and the field strength. In practice the number of conductors is fixed, while the speed is usually constant (except in the case of M.T. or aircraft generators). Any control of e.m.f. must consequently be obtained through the variation of field strength. This is obviously impossible with a field derived from permanent magnets, but is easily achieved by substituting electromagnets for permanent magnets. The e.m.f. can then be controlled by varying the field strength by means of a variable resistance in series with the windings of the electromagnet.

CONSTRUCTION OF D.C. MACHINES

Introduction

18. A d.c. machine, whether intended for use as a generator or as a motor, consists of two main assemblies, viz. the stator or fixed portion, and the rotor or armature assembly. The stator is the supporting carcase of the machine, and has the general shape of a thick-walled cylinder. It carries the field magnet system, the brush gear, and the housings for the bearings which support the rotor. The latter is likewise cylindrical in shape and carries the coils in which the e.m.f. is induced (if used as a generator), the commutator, and in many cases a series of

fan blades to assist in cooling. Generally speaking, the stator of a high speed machine is long compared with its diameter, while low speed machines have relatively short stators. The appearance and arrangement of the main components of a d.c. machine is shown in Fig. 6.

The Magnetic Field System

19. Except for very small machines the magnetic field is supplied by electromagnets arranged in such a way that the conductors pass under North and South poles alternately. The number of poles is therefore always an even number; small machines may have 2 poles, but the number tends to increase with the size and output of the machine. The intense magnetic field through which the conductors move must be obtained for the minimum expenditure of electrical energy in the magnet windings; this is achieved by winding the magnet coils on cores of high permeability material and arranging the magnetic circuit so that it has the least possible reluctance. Ferromagnetic materials are naturally employed for constructional purposes, and the air gap through which the conductors move is kept as small as possible. The diagram (Fig. 5) shows the magnetic circuit of a four-pole d.c. machine. The component parts of the magnetic field system are described in subsequent paragraphs.

20. **The Yoke.** This is the cylindrical frame of the machine, and forms a path of low

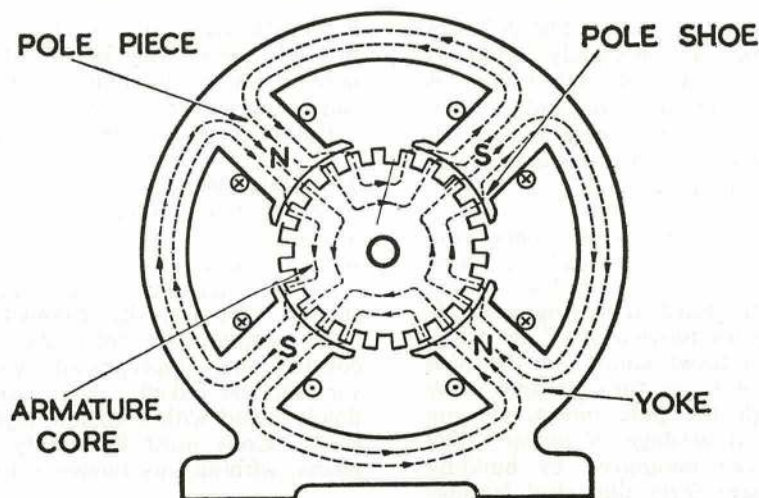


Fig. 5. MAGNETIC CIRCUIT OF 4-POLE D.C. MACHINE.

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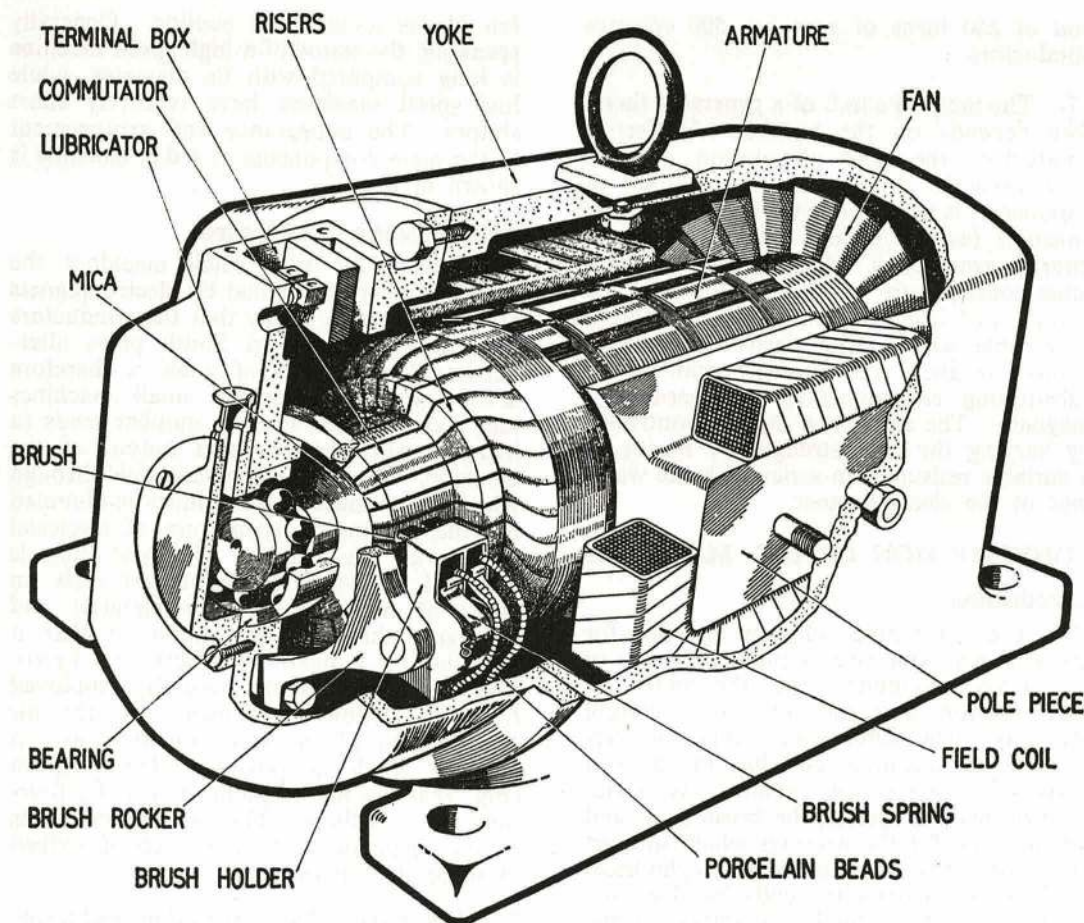


Fig. 6. CONSTRUCTION OF TYPICAL D.C. MACHINE.

reluctance between the poles. The yokes of modern machines are normally made of rolled steel, particularly if high output is required with minimum size and weight. Cast steel or even cast iron may be used for stationary machines in which size and weight are not of great importance.

21. Pole Pieces. These components form the cores of the magnet coils, and are bolted to the inside of the yoke. The faces of the pole pieces are subjected to varying magnetic fields caused by the movement of the rotor, giving rise to induced e.m.fs. in the pole faces. These e.m.fs. in turn produce eddy currents through the pole pieces, causing local heating and wastage of power. The eddy currents are minimized by building up the pole pieces from thin steel laminations, 0.04 in. to 0.10 in. thick, the surface of the laminations being oxidized to give

them high electrical resistance. Alternatively the pole pieces may be of solid steel, with pole shoes of laminated form, since the eddy currents are restricted to the *faces* of the pole pieces adjacent to the rotor.

22. Field Windings. These windings are pre-formed coils mounted on the pole pieces in such a way that, when current passes through them, the polarity of the main poles is alternately North and South. Insulated wire (usually enamelled) is used; after winding the coils are covered with cotton tape, impregnated with insulating varnish, and baked. After baking they are finally taped with a double layer of Empire cloth. Coils must fit closely on the pole pieces, without any tendency to move.

23. Armature Core. The armature core not only carries the main winding of the

machine; it also forms an essential part of the magnetic system by affording a path of low reluctance to the magnetic flux. As the flux through the various portions of the armature core is constantly reversing, it is essential that the material used should have a narrow hysteresis loop. Special sheet steel is used for this purpose, and the core is built up of laminations, with one side of each lamination lacquered, to minimize eddy currents in the core. The laminations are mounted on a cast steel spider keyed to the rotor shaft, and they are slotted on the outer edge to take the main winding.

The Armature Assembly

24. The armature assembly or rotor comprises the main shaft, spider, armature core and main winding (these are known collectively as the armature), the commutator, fan blading, and bearings. The armature is the practical application of the rotating loop of wire, and is driven, in the case of the generator, by a prime mover, i.e. a heat engine (steam, gasoline, diesel, etc.), electric motor, water turbine, or even a windmill.

25. Confusion may be caused, when dealing with electrical machines, by such terms as conductor, coil, and winding. These can be defined as follows:—

- (a) **Conductor.** An individual effective wire or bar, such as one side of a rectangular single loop.
- (b) **Coil.** A continuous length of wire formed into a series of loops.
- (c) **Winding.** The complete assembly of coils on an armature or in a field system.

26. **Armature Windings.** The individual coils which make up an armature winding are all identical, i.e. every coil is alike in size, shape, number of turns, length and gauge of wire, etc. The general shape of each coil is that of a lozenge (Fig. 7), with two straight sides running parallel to each other, then converging to a point at each end. The distance between the two straight sides is approximately the distance between the centre lines of the adjacent poles of the machine. Coils for small machines are wound with insulated wire on an accurate

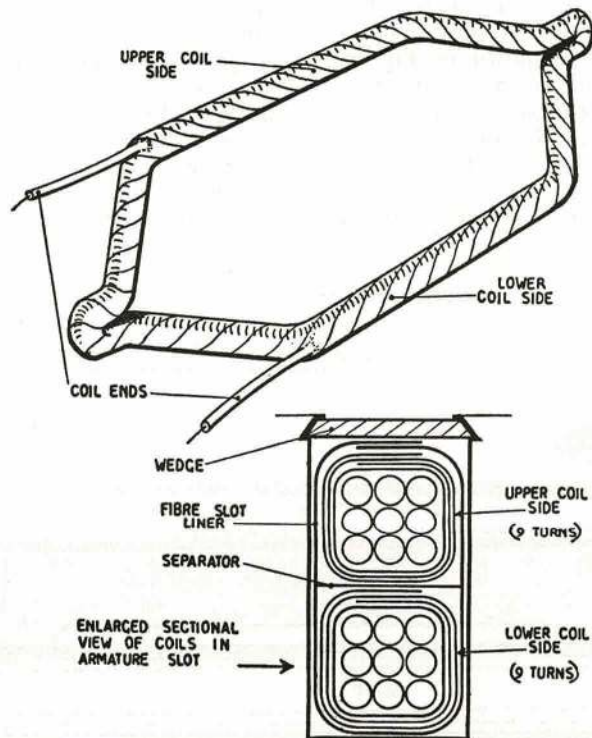


Fig. 7. ARMATURE COIL AND SLOT.

former; after being taped and impregnated they are then pressed into a shape which will permit them to lie snugly in the armature core slots. For larger machines it is usual to use copper strip instead of wire. After shaping, the coils are fitted into the armature slots and are secured by wedges of insulating material. Additional security against displacement of the coils by centrifugal force is given by binding or lapping the circumference of the armature with steel wire or thin steel strip. 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 (not necessarily an adjacent coil). The complete winding thus forms a closed circuit.

27. The Commutator. This is mounted towards one end of the shaft, and in most machines is built up of hard drawn copper segments of wedge section, insulated from each other by thin sheets of mica or micanite. The assembled segments and separators are clamped firmly between the flange of a hub and an end clamp ring by clamping bolts, and the hub is shrunk on to the shaft. The construction of a typical commutator for a medium size machine is shown in Fig. 8. Commutators for small machines are produced by moulding the segments and mica separators into a plastic hub which is pressed on to the shaft. The ends of the coils are generally soldered into lugs or "risers", formed on the end of the commutator

segments, although in large machines with heavy segments the connection is often made by soldering into a slot cut in the end of the segment.

28. Bearings. Ball bearings are widely used for small and medium size machines, while roller bearings are often employed for heavy duties. A common combination is a roller bearing at the drive end of the shaft with a ball bearing at the dead end. Plain bearings lubricated by oil rings dipping into an oil reservoir are occasionally encountered, usually on old-type machines, while certain heavy machines have large plain-journal bearings with forced lubrication. When oil is used as a lubricant for bearings it is essential that efficient oil-baffles are fitted to prevent oil reaching the commutator, windings, brush gear, etc. Fractional h.p. machines of modern design are often fitted with self-lubricating bearings; these are of plain type, with the shaft supported in a bush whose semi-porous walls are impregnated with lubricant at the time of manufacture.

29. Cooling. Heat is generated in the windings of a machine by the passage of current through them, while eddy currents in pole shoes and armature core also tend to raise the temperature. Heat is also developed in the steel or iron of the magnetic system due to flux changes. If the heat so generated is not dispersed, it will tend to carbonize the insulation of windings, etc., and will eventually lead to short circuits

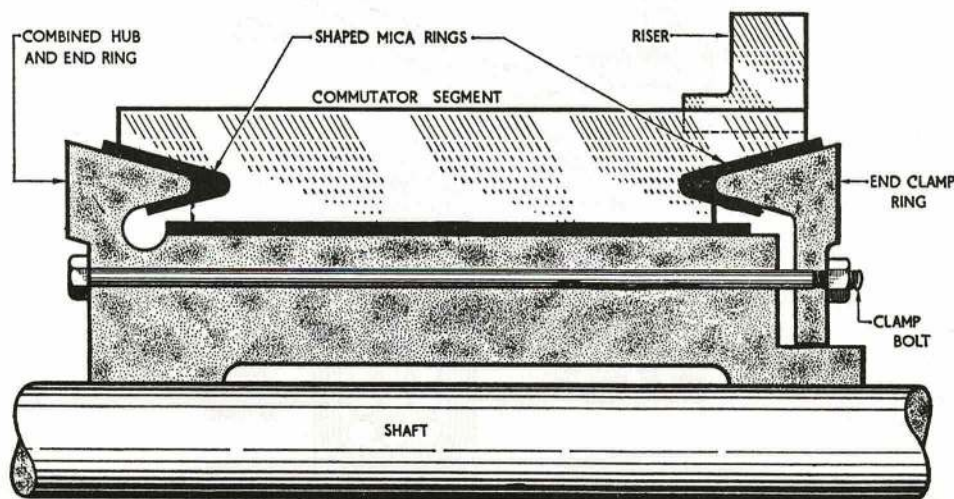


Fig. 8. COMMUTATOR CONSTRUCTION.

and a complete burn-out of the machine. The ability to dissipate heat as it is generated is one of the most important factors which limit the output of a generator. Some machines are built with open-ended stators to allow free passage of air; where enclosure is necessary a fan is usually assembled on the rotor shaft, remote from the commutator, with inlet and outlet grilles or louvres at the ends of the stator. Machines having a high output relative to their size, such as aircraft generators, are often cooled by an independent supply of air forced through the machine at pressure; such machines are said to be blast-cooled. In many cases the laminations of the armature core are perforated to give an axial flow of air through the interior of the armature.

Brushgear

30. The main or armature winding of the machine is connected to the external circuit by rubbing contact between stationary brushes and the surface of the commutator. The complete assembly of brushes, with the necessary equipment for holding each brush at the proper angle and in the correct position, is generally referred to as the brush gear.

31. **Brushes.** Operating conditions in various types of d.c. machines differ so much that a wide range of brushes, each with distinctive properties of its own, is necessary. The main classes of brush are as follows:—

(a) Purely graphitic brushes, made from natural graphite, are self-lubricating and cause little commutator wear. They are suitable for high speed machines, but require constant attention as they wear very rapidly.

(b) Hardened graphitic brushes, in which natural graphite is hardened by heat treatment, are more durable but still retain much of the self-lubricating quality of natural graphite. They are produced in various grades of hardness, and are suitable for the majority of machines which operate at moderate voltages and currents.

(c) Blended graphitic brushes have copper or bronze dust added to the natural graphite in varying proportions to increase the current-carrying capacity of the brush. They are particularly suitable for machines operating with relatively high current, but their low resistance is responsible for rather

heavy reactive sparking. Their use is consequently restricted to low voltages d.c. machines.

(d) Electrographitic brushes are made from artificial graphite produced by subjecting carbon to extremely high temperatures. These brushes are tough and hard, have long life and cause little commutator wear; they are available in many grades, and are used in most Service machines.

(e) Carbon brushes are brittle and have a high resistance; their use is limited to high-voltage low-current machines, where their high resistance minimizes reactive sparking.

(f) Copper brushes, of compressed copper gauze or moulded copper dust, are occasionally used in low-voltage heavy-current machines intended for intermittent use. They cause considerable commutator wear, and reactive sparking tends to be heavy on account of their low resistance.

32. **Brush Holders.** The brushes are carried in small open-ended boxes, whose inside surfaces are machined to the size of the brush, plus a slight clearance so that the brush may slide freely without tilting or rocking. Pressure is applied to the top of the brush by an adjustable spring which maintains the rubbing contact with a pressure of 2 lbs. to 3 lbs. per square inch of contact-surface.

33. **Brush Rocker.** The brush holders are bolted, through insulating sleeves, to a steel ring mounted on the end of the frame of the machine. In many cases this ring is adjustable for position, and can be rotated through a few degrees to alter the position of the brushes. A moveable ring of this type is known as a brush rocker, and it enables the brush position to be varied to give the best possible commutation. The normal position is usually indicated by marks on the brush rocker and the end frame.

34. **Brush Connections.** In small machines using low current the contact between brush sides and the brush holder is often good enough to ensure satisfactory operation, although contact is improved by copper-plating the brushes. In larger machines the brushes are fitted with connectors or "pig-tails" of flexible copper braid moulded into

the brush during manufacture. The free ends of the pigtails terminate in spade or plate terminal eyes for connecting to the brush holder arm, which in turn is connected to the appropriate terminal of the machine. Springs are adversely affected by current passing through them, and in some types of brush gear this is prevented by fitting an insulating pad or roller at the end of the spring arm where it bears on the top surface of the brush.

35. Brush Arrangement. When four or more brush holder arms are fitted to the machine they are alternatively positive and negative, those of similar polarity being connected together by copper bar connecting links. The size of individual brushes is limited by practical considerations; in large machines each brush holder arm carries a line of relatively small brushes, each in its individual holder. The lines of brushes of similar polarity are slightly off-set so that the unswept portion of commutator surface between individual brushes of one line is swept by the brushes of the next line of similar polarity. This ensures even wearing of the commutator, without the formation of ridges between brush tracks. Off-setting of adjacent lines (i.e. positive and negative) is useless, as the rate of wear differs under positive and negative brushes. The off-setting must be between lines of the same polarity.

36. Brush Angle. When the armature of a d.c. machine is required to turn in either direction (i.e. the machine is reversible), the brushes must be set radially to the commutator. (In this position a line drawn through the centre of the brush passes through the centre of the commutator.) Where rotation is in one direction only (i.e. the machine is non-reversible), the brushes are set with a trailing angle of 8° to 10° ; this gives much steadier mechanical operation of the brush than is possible with radial setting.

ELEMENTARY MOTOR PRINCIPLES

Introduction

37. An electric motor is a machine for converting electrical energy into mechanical energy, its function being the reverse 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, etc., are found in both types of machine. Provided it is of suitable design as regards brush-gear, etc., a d.c. machine can be used either as a motor or as a generator; dual-purpose machines of this type are found in certain electrical servicing trolleys, where the generator is also used as the starter-motor for the engine of the unit.

Action of a Motor

38. A motor depends for its operation on the force exerted upon current-bearing conductors situated in a magnetic field. When an external supply is connected to the terminals of a d.c. machine, current flows through the armature winding and the field winding. The current-bearing conductors of the armature are therefore situated in a magnetic field, and the force exerted upon them produces motion. The direction of the motion is found by applying Fleming's Left-Hand Rule.

39. Consider a simple permanent magnet motor connected to a battery as shown in the illustration (Fig. 9). By applying Fleming's Left-Hand Rule it will be seen that side A of the armature loop (under the N. pole) tends to move upward, while side B of the loop (under the S. pole) tends to move downward. The forces acting on the two sides of the loop are thus cumulative in their effect, and tend to turn the armature in a clockwise direction.

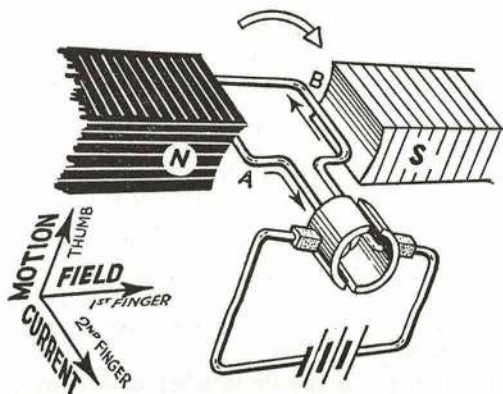


Fig. 9. D.C. MOTOR PRINCIPLE.

40. 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 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 downward, and on side B upward. The mechanical force on the armature is thus continued in the original direction, and rotation continues so long as the supply is connected.

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