CHAPTER 2
CONSTRUCTION

The essential parts of the dc machine are the poles, where the main field is produced, and the armature conductors, which interact with the field to produce emf and torque. But the actual construction of the machine involves other parts for mechanical support, completion of electric and magnetic circuits, insulation of conductors, etc. This chapter shows how dc machines are constructed, and explains some important factors that influence their design.

2.1 Materials

In general, electrical machines are composed of electrical circuits coupled through magnetic circuits. The dc machine has basically two electric circuits, the field coils and the armature coils, coupled through the magnetic circuit.

Electric circuits must have low resistance to reduce voltage drop and I^2R losses in conductors, and the material most widely used is copper. Thus, field coils, armature coils, and commutator segments are all made from copper. The resistance of copper conductors is discussed in section 1.7.3.

To obtain strong magnetic fields, magnetic circuits are made from iron, which has a high permeability. The permeability is defined as the ratio of the magnetic flux density B to the magnetic field intensity H producing it:

$$\mu = B/H \quad \text{henries/meter} \qquad (2.1)$$

It is useful to think of H as an applied quantity, and B as the resulting quantity which depends not only on the applied H, but also on the permeability of the medium:

$$B = \mu H \qquad (2.2)$$

In principle, the permeability of a given material can be measured as illustrated in fig. 2.1. A ring specimen of the material is made, and a wire is wound around it. Current is passed in the wire to produce flux in the core(applied and resulting quantities respectively). The applied magneto-motive force is defined by $mmf = NI = H\ell$, so that

$$H = NI/\ell \quad \text{Amperes/meter} \qquad (2.3)$$

Where N is the number of turns, and ℓ is the mean length of the, core. The flux density is obtained from

$$B = \Phi/s \qquad (2.4)$$

Where Φ is the flux measured in the core, and s is the cross-sectional area of the core. With Hand B determined from eqns. 2.3 and 2.4, the permeability μ is obtained from eqn. 2.1. For air and copper, the permeability is constant and equal to the free space permeability

$\mu_0 = 4\,\pi\, X\, 10^{-7}$ h /m.

The permeability of iron is not constant because the relationship between B and H is not linear, fig. 2.2. Initially, at low field, the B-H curve has a sharp slope, ie a very high permeability; but as H is increased, the curve goes through a bend, called the 'knee' of the curve, and then enters saturation where even large increases in H produce only negligible increases in B; that is, the flux density B is almost constant when the field is strong enough to saturate the iron. Commercial steels are alloys where the types of additives and their percentages, as well as the manufacturing process, determine the magnetic characteristics, ie the actual B-H curve.

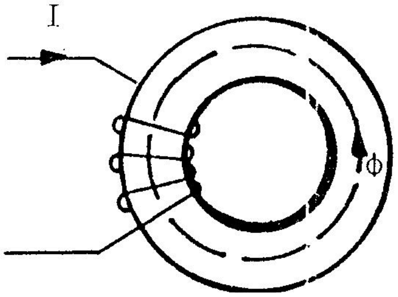

Fig. 2.1 Measurement of the B-H curve using a ring specimen of the material.

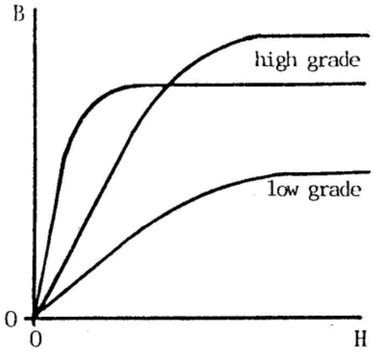

Fig. 2.2 Typical B-H curves of commercial steels.

High grade steels are characterized by a high initial permeability ($\mu_r \geq 1000$), and a high saturated flux density (up to 2 Tesla); they are used for magnetic cores (armature and poles). Low grade steels are used in constructional parts for mechanical support. It is to be noted that different types of steel not only have different magnetic characteristics, but also different mechanical characteristics; of course, all parts should be strong enough to withstand the stresses they are subjected to in addition to copper and iron, electrical machines employ insulating materials to separate cupper conductors from each other and from iron parts.

Different types of insulation are used, including paper and synthetic tapes which may be impregnated in resins etc; commutator segments are insulated from each other by solid mica insulators. A main feature of all insulating materials is their sensitivity to temperature rise : beyond a certain temperature different for each type of material, the insulator breaks down allowing current to flow between the conductors it is supposed to separate. Such 'short circuits' are the most common type of fault that occurs in electrical machines.

2.2 Temperature Rise

When an electrical machine is working, it tends to heat up because some of the input energy is converted to heat energy instead of useful output; that is, the process or electromechanical power conversions accompanied by some loss in power. Obviously, such power loss is undesirable because it represents waste. But more importantly, it is undesirable because the heat generated raises the temperature of the various parts of the machine; temperature rise is most critical to insulating materials :their insulation deteriorates at around 100 °C, and ultimately breaks down causing short circuits and possibly total machine failure.

Losses cannot be eliminated, but machines are designed to make them as small as possible, and also to limit the temperature rise by efficient heat dissipation and ventilation. As we shall see later, certain features of the practical construction of machines are intended specifically to limit the temperature rise.

Losses are generated in a number of ways. We have already seen in section1.7 that current flow in conductors produces I^2R loss; this is called copper loss, and occurs in armature coils as well as field coils.

The rotation of the armature produces mechanical losses due to friction. Losses also occur in iron cores due to hysteresis and eddy currents. Hysteresis loss can be kept small by using steels whose hysteresis loops are thin since the loss is proportional to the area enclosed by the loop. Eddy currents in the armature iron are driven by the emf induced due to rotation in the magnetic field; current flow, of course, produces I^2R loss in the iron itself. The eddy current loss is reduced by effectively increasing the iron resistance in the path of current flow, which is done by constructing cores using stacks of steel laminations instead of solid steel. Laminations are sheets 0.5 -1.0 mm thick, with their surfaces electrically insulated using suitable coatings; the laminations are stacked and pressed together to form the required core, fig. 2.3. The laminations are arranged so that the insulated interfaces are in the path of the induced emf and current, but not in the path of the magnetic flux so as not to increase the reluctance; that is, the flux paths should be in the plane of the laminations.

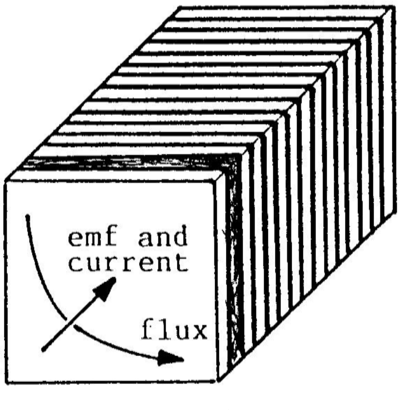

Fig. 2.3 Laminated iron part.

The total length of the armature block includes both iron and insulation; the effective length of the armature includes only the iron, because the insulation as the permeability of free space μ_0The stacking factor is defined as the ratio of the useful effective length to the total length:

$$\text{Stacking factor} = \frac{effectivelength}{totallength}$$

The stacking factor ranges from 90 %to 97 .%

Copper losses and core losses generate heat inside conductors and iron cores respectively. The heat is removed by contact with air at the surfaces of the material blocks. When the machine is working, the temperature rises until the rate of heat removal is equal to the rate of heat generation; the temperature then remains constant. The machine is designed so that the various materials can withstand their steady-state temperatures; that is, the temperature in any part of the machine does not rise beyond the permissible value for the materials in that part. To improve the rate of heat removal, and hence limit temperature rise, the contact surfaces with the cooling air aloe increased, for example by drilling ducts through iron cores, or attaching metal fins to external surfaces; note that the external surfaces or copper conductors are in immediate contact with insulating materials which are particularly sensitive to temperature rise. The machine design should also provide for good ventilation, that is the flow of the heated air outside the machine, and its replacement by fresh cooling air.

2.3 Machine Rating

DC machines are manufactured in many sizes, and operate on different voltages with different current and speeds. For each machine there are, in principle, specified values of voltage, current, speed, torque, power, etc. which are called the 'rated values', ie rated voltage, rated current., etc. Usually there is a small p1ate attached to the cover of the machine on which the rated values are written, together with additional information such as type of machine, manufacturer name, serial number, etc; this is called the nameplate of the machine. The specification of rated values does not mean that the machine has to be operated at these values all the time; for example, a machine rated at1200 rpm may be rotated at 1000 rpm, 1500 rpm, or even 2000 rpm. The concept of rating may be understood as a sort of contract between the manufacturer and the user :if the user operates the machine according to its rating, then the manufacturer guarantees that it will give satisfactory service over its specified lifetime, say 20 or 30 years; if, however, the user operates the machine outside its rating, then its useful life is shortened. In severe cases where the user attempts to operate the machine far outside its rating (for example, rotating a 1200 rpm machine at 5000 rpm), the machine may break down.

The design details of the machine are determined by the intended rated values. Current determines conductor cross-sectional areas :higher currents require thick conductors to limit copper loss and to increase surface area for heat exchange. Voltage determines core size recalling eqn. 1.13c, the average air gap flux density B does not exceed 0.8 T in practice (corresponding to 2 Tin the core -see section 2.1); to increase the voltage for a given speed ω and a given number of turns N, the designer has to increase the armature diameter D, its length L, or both -see fig. 1.26. The voltage also determines the amount of insulation between conductors. Speed determines mechanical aspects of the design: the armature and its parts should withstand the centrifugal forces caused by rotation, and vibration should be as small as possible.

Insulating materials determine the maximum allowable temperature rise, which in turn, determines the limits on the allowable losses in the various parts of the machine and the measures taken to aid heat dissipation.

Operating the machine according to its rating means that the electrical, mechanical, and thermal stresses in all parts of the machine are within acceptable values for the materials used. Operating the machine, a little bit outside its rating for short intervals has little effect, although it may shorten the machine's lifetime slightly. Operating the machine far outside its rating for long intervals can cause severe deterioration, or damage to parts that have been driven outside their acceptable limits (for example, insulation breakdown due to severe overvoltage or temperature rise, mechanical breakdown due to severe over-speed, etc). Implicit in this discussion is an economic factor: better materials and parts can withstand higher stresses, but are, of course, more expensive.

The nameplate of the machine usually gives its continuous rating; that is, the machine can be operated continuously at the rated values listed. The current and power rated values correspond to full load applied continuously; if the load on the machine is reduced, the current and power will be less than their rated values, which is acceptable. In certain cases, the rating is given as a range of values; for example, motors required to operate at different speeds have the allowable speed range specified, say 1000-2000 rpm (the lower limit is determined by the requirements of ventilation). For certain applications the nameplate gives short-time rating; for example, a generator may have a continuous current rating of 5 A, but a short-time rating of, say, 10 A for 2 minutes; this means that the temperature does not rise to a dangerous level in 2 minutes. Intermittent rating is similar to short-time rating, but also gives the minimum time interval allowed between successive applications of the high value; this interval allows the machine to cool down.

On the electrical side, the power of the machine is the product of voltage and current. As we have seen, higher rated voltages require larger cores, while higher currents require thicker conductors. In general, then, higher power ratings require bigger machines; that is, the physical overall size of machines tends to increase with their power ratings.

Machines are usually manufactured in standard frame sizes to facilitate their installation. They also come in different enclosures to suit various environmental conditions. For example, standard enclosures are for dry environments; however, if the machine is to be installed in a wet environment, the enclosure should protect the machine; manufacturers can supply machines that are drip-proof, splash-proof, or even totally submersible.

To select a suitable machine for a given application, the user must know the requirements of his system, such as the available voltage supply, the required torque and speed, the environmental conditions, etc. He then studies manufacturers' proposals, and chooses the most economical machine that meets his specifications.

2.4 Main Parts of The Dc Machine

All rotating electrical machines have a stationary part called the stator, and a rotating part called the rotor; the two are separated by a small clearance, the air gap, to allow relative motion between them. In dc machines, the poles, where the field is produced, are placed on the stator, while the armature, whose coils interact with the field, is placed on the rotor. The dc machine also has a commutator attached to the rotor and rotates with it; the brushes are stationary, being attached to the stator. Fig. 2.4 shows the main constructional features of dc machines; actual machines can differ greatly in the details of construction.

2.4.1 Stator:

The cylinder enclosing the machine is called the yoke; the poles are fixed to it, usually by means of bolts. The yoke provides a return path for the magnetic flux. Each pole is composed of a core, around which the field coils are placed, and a shoe, which is the part facing the armature. The pole shoe has tips extending beyond the core which serve to improve the flux density distribution in the air gap, fig. 2.5.

The pole tips increase the effective area of the air gap, thus reducing its reluctance to the magnetic flux. The tips also provide mechanical support for the field coils. The pole shoes are usually made from laminated steel because the rotating armature slots and teeth cause the air gap field to fluctuate, resulting in eddy current losses in the pole shoes. The pole care mayor may not be laminated, but in modern motors operating from solid state drives, even the yoke is laminated.

The field coils provide the main working flux. In certain machines, there are two coils on each pole :one coil has many turns of fine wire, and the other coil has few turns of thick wire. Identical coils are placed on all poles, and the coils of each set are connected in series. Permanent magnet machines have no field coils; the poles are permanent magnets, with the flux path completed through the yoke.

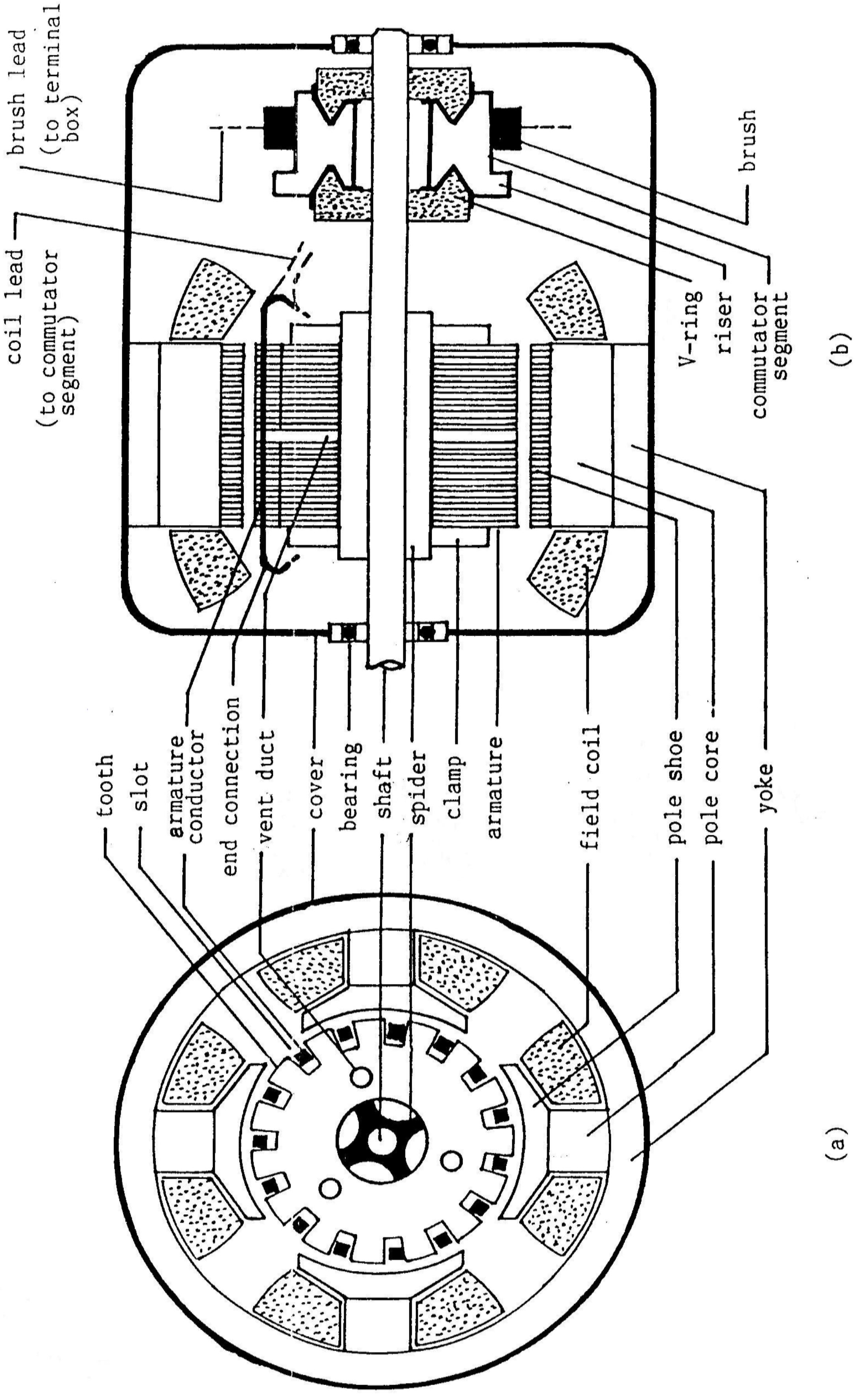

Fig. 2.4 Typical dc machine :(a)cross section; (b)longitudinal section

2.4.2 Rotor

The armature is made from circular laminations, punched with holes for slots, vent ducts, and a central bore for the shaft. The laminations are stacked together, and clamped to form a rigid cylinder. In small machines, the armature is mounted directly on the shaft; in large machines, the armature is mounted on a spider, and the spider is mounted on the shaft. The spider is a mechanical fixture, and does not need to be made from high grade magnetic steel. The shaft rotates in bearings or bushings fitted to the machine cover which is attached to the stator. Axial vent ducts are formed by holes punched in the laminations, fig. 2.4a; radial ventilation in large machines is achieved by stacking the armature laminations in packets, with space between packets for air flow, fig. 2.4b.

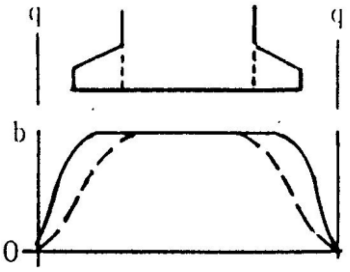

Fig. 2.5 Improvement of air gap flux density distribution due to pole

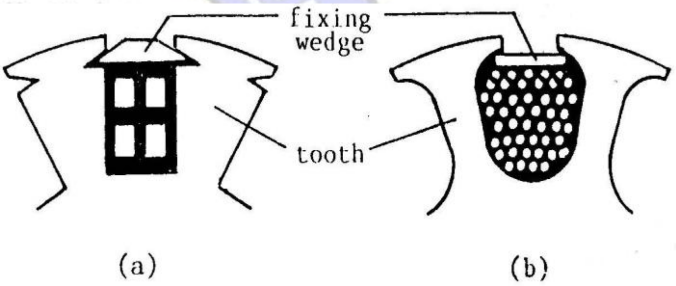

Fig. 2.6 Typical armature slots.

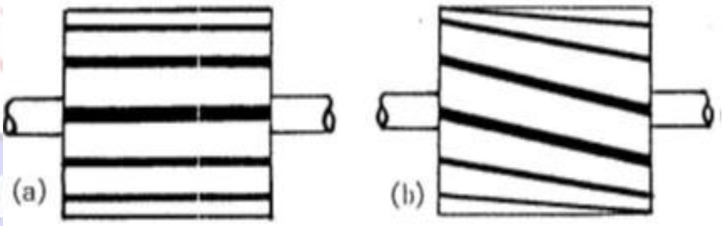

Fig. 2.7 Armature side view with (a) straight slots, and (b)skewed slots.

The armature coils are placed in slots around the periphery; the end connections (see fig. 1.5) extend outside the iron cylinder of the armature, fig. 2.4b. The coil leads are taken to the commutator, and the terminals are soldered to its segments. Typical slot shapes are shown in fig. 2.6; the iron between adjacent slots forms a 'tooth'. The fixing wedge helps keep the conductors in position in the slot against the centrifugal forces arising from rotation. In large machines, where currents are high, the armature coils are made from thick and rigid copper strap, fig. 2.6a; the coils are formed outside the armature, then placed in the slots. In small machines, the currents are small, and the coils are made from relatively thin flexible wire, fig. 2.6b; they may be pre-formed outside the slots, or they may be wound directly on the armature. The insulation occupies a larger proportion of the slot area in small machines than in big machines. The slots may be straight as in fig. 2.7a, or they may be skewed as in fig. 2.7b. Skewing is done by a slight rotation of consecutive laminations during stacking; the total skew between the two ends of the armature is usually one slot. Skewing helps reduce noise and vibration by allowing the active conductors of the armature to enter smoothly under the poles during rotation; however, it increases the length of the coil, and hence its resistance, without any increase in induced emf or torque.

2.4.3 Air gap

The air gap is the space between the pole face and the armature surface; such clearance is necessary to allow relative motion between the two. The air gap also helps in heat removal from the armature surface, and in ventilation. However, it introduces a high reluctance in the path of the magnetic flux, and is therefore made as short as possible, typically 0.5-5.0 mm. The armature surface and the pole shoe facing it require precise machining to ensure symmetry and avoid vibration.

2.4.4 Commutator

The commutator is mounted on the shaft, so that it rotates with the armature, fig. 2.8. It is made up of copper segments insulated from each other and forming a cylinder. The insulation between segments is mica or micanite of thickness 0.5 -1.0 mm; it is undercut below the copper surface, also by0.5 -1.0 mm. The number of segments is equal to the number of coils in the armature; the terminals of each coil are soldered to two different segments.

Each segment has a riser in which the coil terminals are placed and soldered. The segments of the commutator are held together by means of two V-rings. Which are mounted on the shaft, fig. 2.4b; the V-rings clamp the segments, but are electrically insulated from them. The brushes are made from carbon or graphite; they are mounted in stationary holders, with spring pressure to maintain good electrical contact with the rotating segments. Sparking and friction between brushes and commutator cause the brushes to wear out, so that they should be replaced

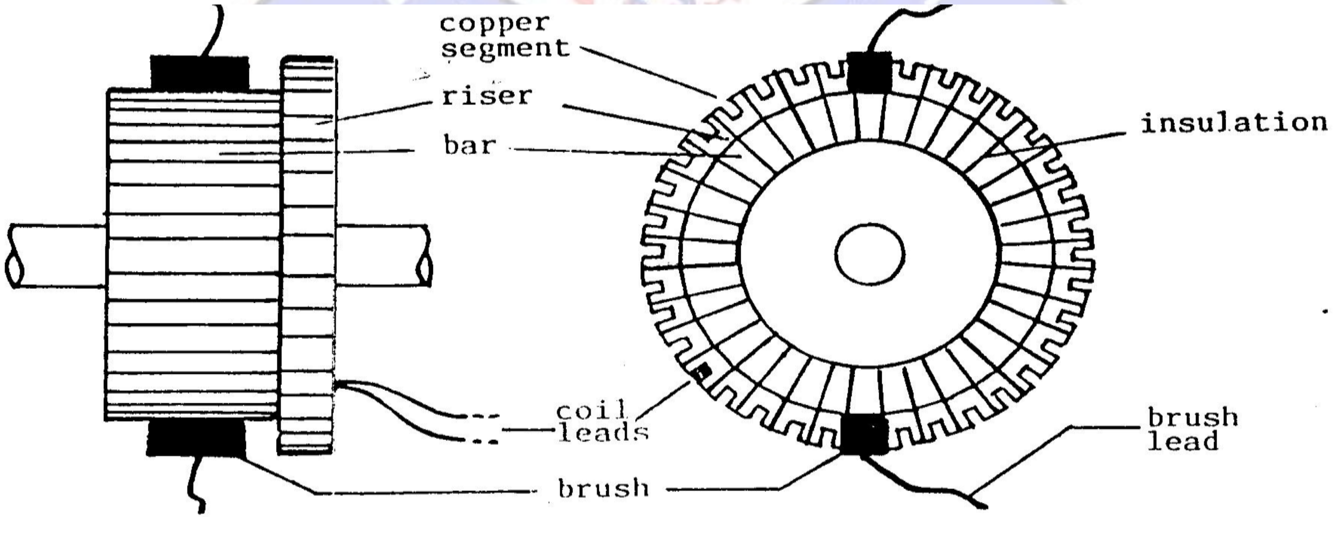

Fig. 2.8 Commutator and brushes

regularly. The commutator also requires regular maintenance to remove carbon filings and dirt that tend to accumulate on it, especially between segments.

2.5 Miscellaneous items

Section 2.4 explained the main parts of the dc machine; in this section we look at some of the other items that may be found in the machine.

The machine is protected by a metal cover that gives it the overall shape of a cylinder. The cover mayor may not extend over the stator yoke, but it has caps that protect the commutator on the right of fig. 2.4b and the end connections on the left. The cover has windows to aid ventilation; it also has removable plates in the region of the commutator to allow servicing of commutator and brushes.

The shaft carries all the rotating parts of the machine, and transmits torque into the machine or out of it; these mechanical stresses determine the diameter of the shaft. At the two ends of the machine, the shaft rests in bearings or bushings fixed to the cover; friction in these mountings is minimized by greasing. At one end, the shaft extends outside the cover to allow external coupling, which may be through pulley and belt, through gears, or direct. In many machines, a fan is mounted on the shaft to improve ventilation.

Heavy machines usually have one or more lifting eyes fixed to the yoke. The machine may also have a base, or some other fixture, for installation.

The leads from the main electrical circuits inside the machine are brought to a terminal box fixed to the outside of the machine to allow external connections. In the box, there are two terminals for the brushes, which provide the connections to the armature; there are also two terminals for each set of field coils.

The armature of very small dc machines, called miniature machines, may have only three slots and three teeth as shown in fig. 2.9; the slot pitch (see exercise 1.3) is two-thirds the pole pitch. The commutator has three segments, and the terminals of each coil are soldered to adjacent segments. The cover at the commutator end carries a pair of metal-carbon brushes on spring strips which are also the terminals. The field in fig. 2.9is an annular 2-pole permanent magnet. Such miniature motors run on small batteries, and their power rating is typically around five watts; they are used in toys, tape recorders, etc. Miniature motors similar to that shown in fig. 2.9 are also constructed with five slots.

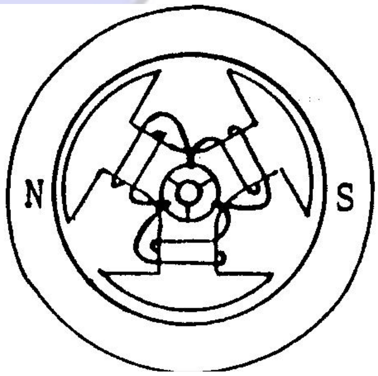

Fig. 2.9 Miniature permanent-magnet dc motor (actual size).

2.6 Exercises

2.1 List the main types of materials found in dc machines, and explain why each is used.

2.2 Discuss the effect of saturation on the permeability of iron.

2.3 Why are armature coils not made from silver? from iron?

+2.4 a. Explain how hysteresis arises in the armature iron.

b. The iron in pole shoes undergoes minor hysteresis loops; discuss.

2.5 Explain why the effective length is less than the total length of a laminated armature. Which value should be used for L in eqns. 1.13and 1.24? Which value should be used in resistance calculations?

+2.6 Explain why the armature laminations are clamped together without any bolts going tight through them.

2.7 Does the use of laminations reduce hysteresis loss?

2.8 Sketch a laminated iron cylinder, and indicate the directions of eddy current flow and magnetic flux. Why are the laminations arranged to be parallel to the flux paths and not perpendicular to them?

2.9 Laminating iron parts increases their resistance, and hence reduces eddy currents. Reducing the emf induced in iron also reduces eddy currents. How can the emf in iron be reduced? and why is this not considered to be a good method for reducing eddy currents?

2.10 a. A dc generator is rated at 150 V and 9 KW. What is the rated current?

b. A 25 hp motor is rated at 1200 rpm. What is the rated torque ?

2.11 A machine is rated at 1500 rpm. What damage is to be expected if it is rotated at 3000 rpm? at 300 rpm ?

2.12 List in sequence the parts of the machine in the closed path of magnetic flux.

+2.13 With reference to fig. 2.6, discuss the advantages and disadvantages of

a. using metallic fixing wedges; b. making the teeth thin.

+2.14 Skewing the armature increase the conductor length in the slot. Why then does skewing not increase emf and torque, both of which are proportional to the active length, eqns. 1.13 and 1.24 ?

2.15 Why does insulation occupy a larger fraction of the slot cross-sectional area in smaller machines?