CHAPTER 5
ARMTURE REACTION

5.1 Introduction

The last chapter explained the magnetic field produced by the field coils, with no current in the armature. In normal operation, however, there will be current in the armature; its flow in the armature conductors produces an mmf called the armature reaction. The actual flux in the machine is thus produced by the mmf of the field coils and the mmf of the armature acting together. The effect of the armature mmf is to distort the field distribution in the machine; the distortion has a number of adverse effects on the operation of the machine. This chapter explains armature reaction and its effects.

5.2 Distributed armature mmf

When current flows in the armature conductors, it tends to set up a magnetic field. Fig. 5.1 shows the flux distribution in a 2-pole machine due to the currents in the armature conductors acting alone, ie with the field winding unexcited. The conductors form a single 'pseudo-coil', with currents going in at the right and coming out at the left; the axis of the pseudo-coil is therefore the q-axis, and application of the right-hand rule will give the flux direction shown in the figure. Comparing with fig. 4.1, it is seen that the armature field is perpendicular to the main field :whereas the main field acts on the d-axis, the armature field acts on the q-axis. Over a pole pitch corresponding to one pole, the armature flux is directed from the armature to the pole over half the pitch, and from the pole to the armature over the other half pitch; therefore, it tends to aid the main field over half a pole, and oppose it over the next half pole.

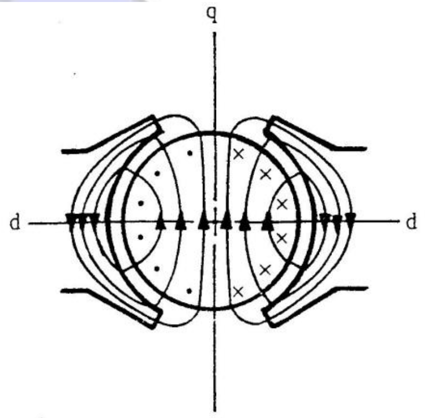

Fig. 5.1 Magnetic field due to armature current acting alone in a 2-pole machine.

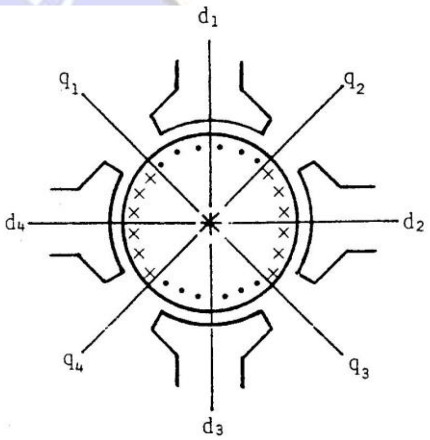

Fig. 5.2 Armature current distribution in a 4-pole machine

Instead of a single pseudo-coil, it is convenient to think of the armature conductors of fig. 5.1 as forming two pseudo-coils :one in the top half of the armature acting to produce a flux directed out of the armature surface, and the other in the bottom half acting to produce a flux directed into the armature.

Going up to the case of 4-pole machine :fig.5.2. we can distinguish four such pseudo-coils : for example, the conductors enclosed between d_1 and $d_2$actto produce a flux directed out of the armature surface in this region; the axis of this pseudo-coil is q_2Similarly, the conductors between d_2 and $d_3$act to produce a flux directed into the armature, and their axis is q_3; and so on for the remaining two pseudo-coils.

The pseudo-coils act on the q-axes, while the main field coils act on the d-axes. The mechanical angle between adjacent q -and d-axes is 45° in the4-pole machine of fig. 5.2, but the electrical angle is 90°. Thus, electrically, the armature field is perpendicular to the main field; this is true for any number of poles since the angle between adjacent q -and d-axes is always 90 electrical degrees.

Fig. 5.3 shows a developed diagram of the pseudo-coil between d_1 and d_2 in fig. 5.2, or, equally well, the upper pseudo-coil of fig.5.1. This pseudo-coil attempts to produce a flux directed out of the armature surface, ie upward sin fig. 5.3. The mmf ma represents the action of the conductors of the pseudo-coil in their attempt to produce the flux. The sides at positions 1 and 6 act on the region from 1 to6; the sides at positions 2 and 5 act on the region from 2 to 5; and the sides at 3 and 4act on the region from 3 to 4. By superposing these mmf's, we obtain the overall mmf of the pseudo-coil which has the staircase shape shown:in the regions 1-2 and 5-6, the mmf is produced by the sides at 1 and 6 only; in the regions 2-3and 4-5, the mmf is produced by the coil sides at 1 and 6 as well as the coil sides at 2 and 5; in the region 3-4, the mmf is produced by all the sides, and is therefore maximum, M_{am}. It is convenient to approximate the actual stepped mmf distribution by the triangular distribution shown dotted in fig.5.3. The maximum value M_{am} occurs at the center of the pseudo-coil, ie at the q-axis.

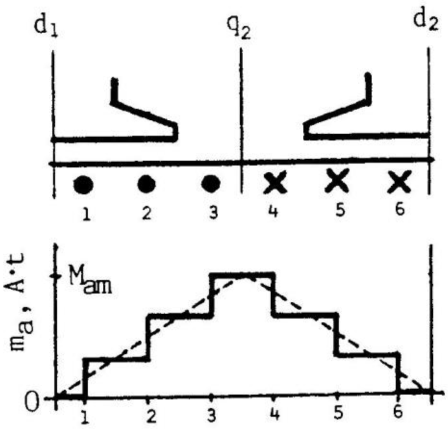

Fig. 5.3 Distributed mmf of armature pseudo-coil

Since M_{am} is produced by all the conductors in the pseudo-coil, it is equal to the total number of turns of the pseudo-coil multiplied by the current in theconductors. The total number of turns is equal to the number of conductors in one side of the pseudo-coil, which is the number of conductors in half a pole pitch, $\frac{1}{2}(Z/2p)$; the current in the conductors is the path current $I_A/2a$. Thus

$$M_{am} = \frac{1}{2}\left(\frac{Z}{2p}\right)\cdot\left(\frac{I_A}{2a}\right) = \frac{Z}{8pa}I_A = \frac{NC}{4pa}I_A \qquad (5.1)$$

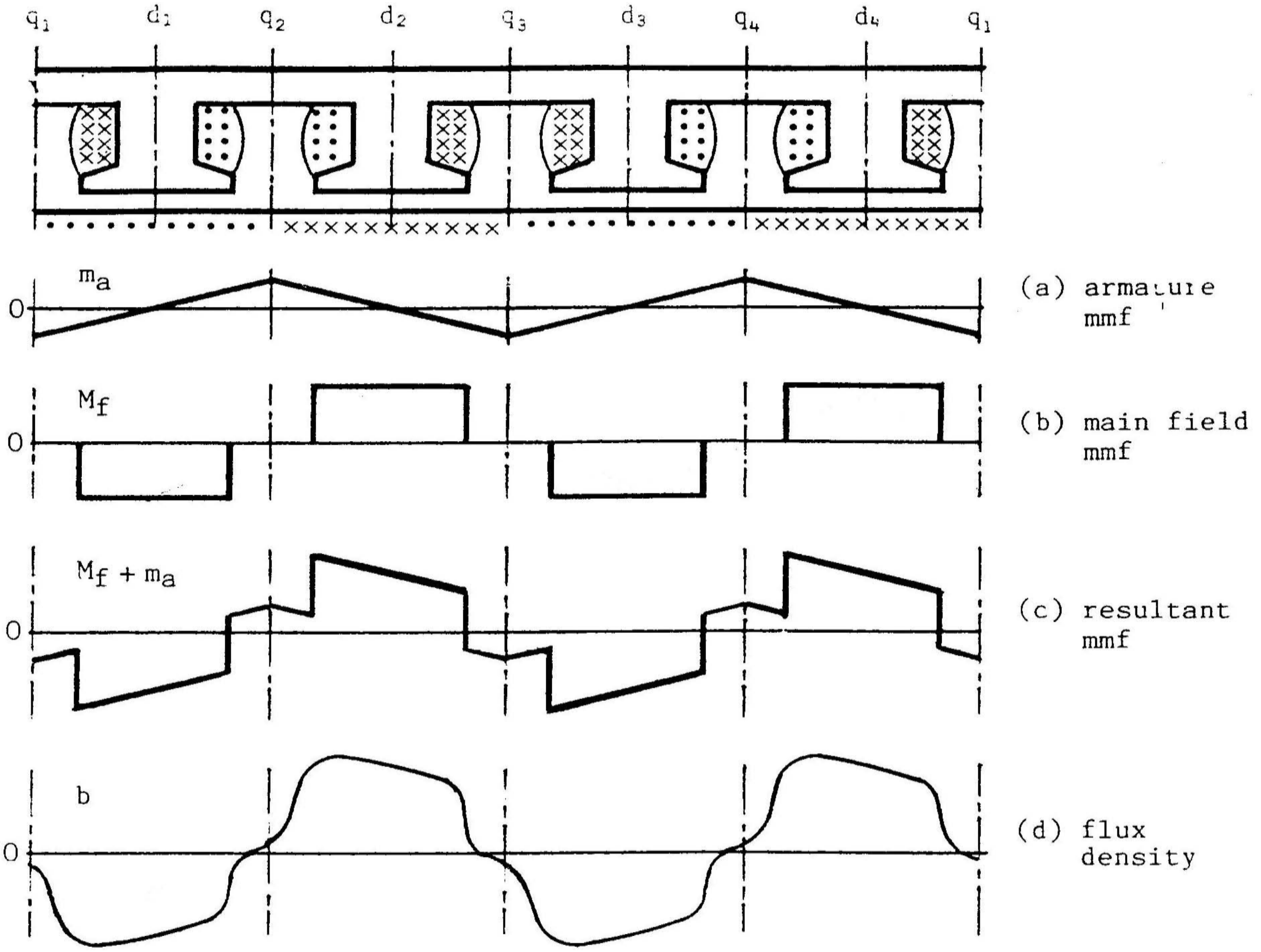

Fig. 5.4 The mrnf distributions acting on the air gap and the resulting air gap flux density distribution.

The stepped distribution approach the triangular distribution as the number of steps is increased, that is, as the number of slots is increased.

Clearly, then, the mmf of an armature pseudo-coil is distributed over the entire pole pitch covered by the pseudo-coil; the statement that "the pseudo-coil acts on the q-axis "simply means that its maximum mmf occurs at the q-axis.

Consecutive pseudo-coils act in opposite directions :one attempts to produce a field directed out of the armature surface :and the next one attempts to produce a field directed into the armature, figs. 5.1 and 5.2. Therefore, if the mmf of one pseudo-coil is taken to be positive, the mmf of the following pseudo-coil must be considered negative. The overall mmf distribution of the armature will thus have the triangular wave-shape shown in fig. 5.4a. Note that the armature mmf is zero at the d-axes.

5.3 Resultant field

In normal operation, there is current in the armature conductors, and the field winding is excited; the respective mmf's, acting on the air gap, are shown in figs. 5.4a and 5.4b. Adding the two mmf distributions point by point gives the resultant mmf distribution shown in fig.5.4c. This resultant mmf acts on the air gap to produce the flux density distribution shown in fig. 5.4d. The flux density wave follows the resultant mmf wave approximately, and not exactly, because the flux is determined not only by the mmf but also by the reluctance, and the air gap reluctance is not constant around the armature periphery :in the region of the d-axis, ie under the pole face, the air gap is short and hence the reluctance is small; in the region of the q-axis, ie between poles, the air gap is long, and hence the reluctance is large. The non-uniform reluctance, and the resulting fringing near the tips of pole shoes, cause the flux density distribution in the air gap to be somewhat different from the mmf distribution producing it. Note, for example, how the wave is rounded at the pole tips due to fringing. Also note that the flux density at the q-axis, although no longer zero, is still very small because of the high reluctance there.

Comparing the resultant mmf and flux density of figs. 5.4c and 5.4d with the main field mmf and flux density of figs. 4.3a and 4.3b, it is seen that armature reaction generally distorts the distributions in the air gap. The distortion is apparent both in the region of the d-axis under the pole, and in the region of the q-axis between poles. Under the pole, the armature mmf aids the main field mmf over half the pole, and opposes it over the other half; the resultant flux density is no longer uniform under the pole, being strengthened at one tip, and weakened at the other tip. Consequently, the instantaneous emf and torque in the armature conductor, which are proportional to b, undergo change as the conductor moves under the pole. Between poles, armature reaction applies an mmf so that the flux density is no longer zero at the q-axis; the point at which b passes through zero is shifted slightly from the q-axis. The presence of a magnetic field at the q-axis means that the emf and torque in a conductor passing through the q-axis are no longer zero; they are still very small because b is very small due to the large air gap, and hence high reluctance, at the q-axis.

Fig. 5.4 includes a developed diagram of the machine showing the sources of the resultant magnetic field, ie the currents in the field coils and in the armature conductors. Application of the right-hand rule indicates that the forces on the armature conductors are towards the right; that is, the torque is in the clockwise direction for the current directions assumed. Therefore, if the motion is also to the right, then the machine is a motor; if, on the other hand, motion is to the left, then the machine is a generator.

In general, then, armature reaction 'pulls' the flux in the direction of rotation in generators, and in the direction opposite to rotation in motors. The distorted flux distribution in a 2-pole machine is shown in fig. 5.5; as in fig.5.4, rotation is clockwise for motor operation, and counterclockwise for generator operation. Compare the resultant flux distribution of fig. 5.5 with the main field distribution of fig. 4.1; note, in particular, that the flux density is no longer uniform around the air gap.

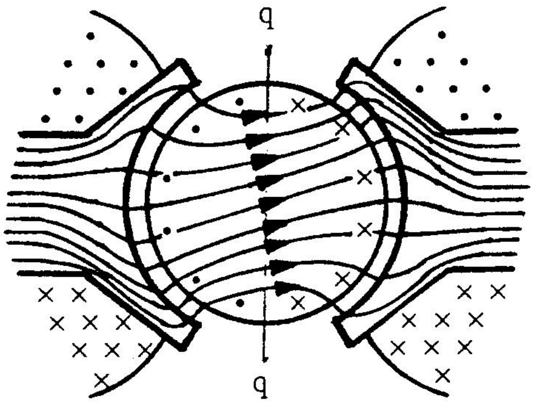

Fig.5.5 Resultant flux distribution in a 2-pole machine, showing distortion due to armature reaction.

5.4 Effects of Armature Reaction

The last section explained how armature reaction distorts the field in the machine. The distortion has three main harmful effects on machine operation; these will now be explained.

5.4.1 Demagnetizing Effect

The armature mmf aids the main field mmf over half the pole, and opposes it over the other half; the increase in mmf in the first half is equal to the decrease in the second half. We might therefore expect the flux per pole Φ to remain unchanged, the increase compensating for the decrease. In fact, however, there is a net decrease in Φ caused by the nonlinearity of Iron: in the region where the field is strengthened, the pole tip and armature teeth are driven deep into saturation, fig. 5.5, so that the increase in flux density there is less than the decrease in flux density in the region where the field is weakened.

Thus, although the increase and decrease in mmf are equal, the resulting increase and decrease in flux density are not, with the increase being less than the decrease. Armature reaction therefore leads to a slight demagnetization of the machine; that is, it reduces the magnetic field in the machine. Usually the reduction is small enough to be neglected, but can become significant for large armature currents, especially under overload or short circuit conditions.

Recalling eqns. 3.12 and 3.16, it is seen that any reduction in the flux per pole Φ results in corresponding reductions in the average armature emf E_A and developed torque T_d.

The OCC is measured with the armature open-circuited so that there is no armature current and hence no armature reaction; let E_o represent the emf under open-circuit conditions. Under normal operating conditions with nonzero armature current, the actual emf E_A may be somewhat less than E_o due to the demagnetizing effect of armature reaction; the difference

$$\Delta E = E_o - E_A \qquad (5.2)$$

thus represents the demagnetizing effect of armature reaction as a reduction-in induced emf. The effective magnetization curve on load, where $I_A \neq 0$, lies below the OCC, and is lower for higher armature currents, fig. 5.6. The curves merge at the air gap line because there is no saturation at low excitation. The difference between the OCC and the effective magnetization curve on load is ΔE, which is a complicated and nonlinear function of both field and armature mmf's, and hence of field and armature currents; in practice, ΔE is much smaller than suggested by fig. 5.6. At a field current I_f and zero armature current, we have

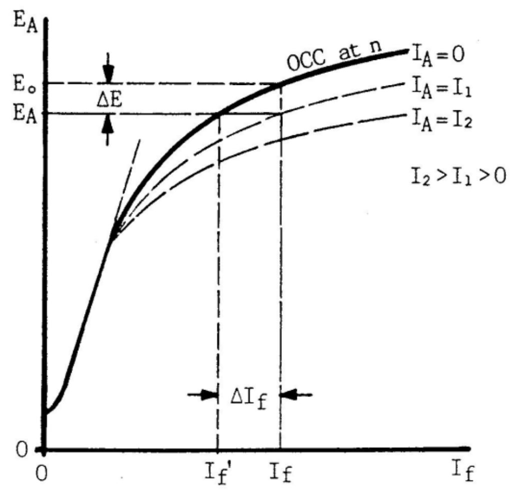

Fig. 5.6 Representation of the demagnetising effect of armature reaction

$$V_A = E_A = E_o \qquad (5.3)$$

At the same field current I_f, but with a nonzero armature current I_A, Kirchhoff's voltage law and eqn. 5.2 yield

$$V_A = E_A \pm (I_A R_A + V_b) = (E_o - \Delta E) \pm (I_A R_A + V_b)$$

$$= E_o \pm (I_A R_A + V_b \mp \Delta E) \qquad (5.4)$$

where, according to fig. 3.15 and eqns. 3.13 and 3.14, the upper sign applies for motor operation, and the lower sign for generator operation. If the demagnetizing effect of armature reaction is negligible, ΔE is dropped from eqn. 5.4, which then simplifies to eqn. 3.13 or 3.14, depending on the mode of operation.

At a given field current I_f and armature current I_A, the point (I_f, EA) represents actual values : If is the actual current flowing in the field winding, and E_A is the actual emf induced in the armature. This point does not lie on the OCC, as can be seen from fig. 5.6; however, it can be associated with two points that do lie on the OCC. The first is the point (I_f, Eo) lying vertically up, and the second is (I_f', E_A) lying horizontally to the left I_f' can be viewed as the effective field current that would give the actual emf E_A on the OCC; the difference

$$\Delta I_f = I_f - I_f' \qquad (5.5)$$

represents the demagnetizing effect of armature reaction as a reduction in field excitation. Thus, the small triangle in fig. 5.6 represents the demagnetization in two ways :the vertical side gives the reduction in emf ΔE, and the horizontal side gives the reduction in effective field current ΔI_f.

5.4.2 Shift of The Magnetic Neutral Axis

The point on the armature surface at which the air gap flux density passes through. zero defines the magnetic neutral axis, or mna. If the main field acts alone, the mna coincides with the q-axis, fig. 4.3. Armature reaction causes the mna to move away from the q-axis, as can be seen in fig. 5.4d. Thus, the flux density at the q-axis is no longer zero, although it is still very small because of the large air gap, and hence high reluctance, at the q-axis. The small field induces a small emf in the coil side passing through the q-axis; this coil side is part of a coil undergoing commutation, ie a coil whose current is being reversed by a brush short circuit -see section 3.2. Thus, the shift of the mna from the q-axis produces a nonzero emf in the coil undergoing commutation.

Another effect of the mna shift is best understood by considering one pole pitch, such as that enclosed between q_1 and q_2 in fig. 5.4d. In this pole pitch, most of the flux is directed downwards, but is reversed in the small region between the mna and q_2; therefore, the conductors passing through this small region will have their emfs and torques opposite to what they should be, resulting in a slight reduction of the overall armature emf and torque. This effect is quite small because the region in question is very small, and the flux density in that region is itself very small.

5.4.3 Flashover

In each pole pitch, armature reaction tends to concentrate the flux at one pole tip, as can be seen in fig. 5.4. Section 5.3.1 explained that this redistribution of the flux can cause a slight reduction in the average emf, and that this reduction is often negligible. Its effect on the instantaneous coil emfs, on the other hand, can be quite significant :a coil whose sides are passing under tips where the field is strengthened will have a high emf induced in it. The coil sides are near the q-axis, which means that the coil is connected to commutator segments that are near the brushes, where the air is highly ionized due to normal sparking between brush and commutator. The high coil voltage is applied between segments, ie it is applied to the ionized air in the region, which may thus break down, resulting in arcing between segments. The heat of the arc can melt holes in the segments. Moreover, the arc may itself cause further ionization and hence further arcing between segments; in severe cases, the arc may extend from brush to brush, which is called flashover.

Flashover is a very serious condition because the heat from the arc can melt the commutator segments, thus causing total machine failure. The machine must therefore be designed to minimize the possibility of flashover. Under normal operating conditions, the coil voltages are unlikely to be high enough to cause flashover. However, under severe overload or short circuit conditions, the distortion caused by armature reaction may be so sharp as to lead to flashover of the commutator.

5.5 Treatment of Armature Reaction

In normal operation, the distortion caused by armature reaction is relatively small, fig. 5.7a. The distortion can become quite sharp if the armature current becomes too high, fig. 5.7b, or if the main field is allowed to become too weak, fig. 5.7c. The adverse effects of armature reaction discussed in the last section place limits on the acceptable operating conditions of the machine; in severe cases, flashover can occur, causing total machine failure, section 5.4.3. Therefore, the design and construction of dc machines must aim at reducing armature reaction and its effects; below we explain some of the treatments used to counter armature reaction.

The machine is designed to have a strong main field; that is, the main field mmf M_f is much greater than the maximum armature mmf M_{am}. The distortion due to armature reaction is then relatively small as in fig. 5.7a; otherwise, the field may be distorted as in fig. S.7c where the shift of the magnetic neutral axis is particularly notable.

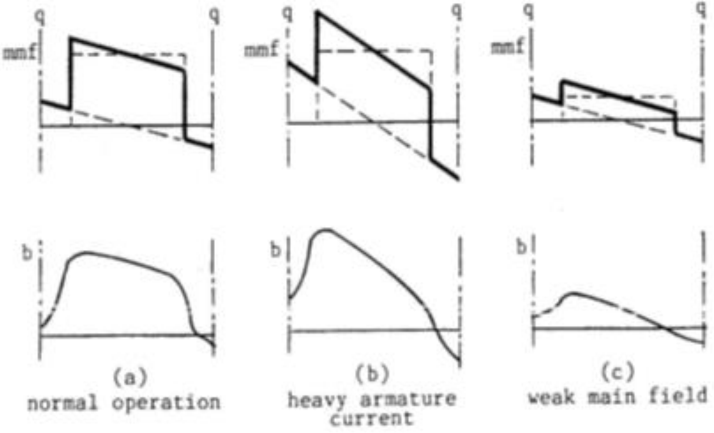

Fig. 5.7 Distortion due to armature reaction under various operating conditions.

Under the pole face, the armature mmf is highest at the pole tips, figs.5.3 and 5.4a. Its effect can therefore be reduced by increasing the reluctance of the magnetic circuit in the region of the pole tip. This may be done by constructing the poles with alternate laminations as in fig.5.8a so that the effective length of the iron in the pole tip is half that in the pole core; with the area seen by the flux in the tip reduced, the reluctance of the air gap under the pole tips is effectively increased. Alternatively, the air gap is made longer under the pole tip by constructing the poles with eccentric faces as in fig. 5.8b, or by chamfering the pole faces as in fig. 5.8c. These methods of increasing the reluctance at the tips are intended to reduce the effect of the armature mmf; of course the increased reluctance also reduces the flux produced by the main field mmf, ie by the main field coils, but the reduction in the main field is much smaller than the reduction in the armature field :In the magnetic circuit seen by the main field, fig. 4.1, the reluctance at the pole tips is in parallel with the reluctance at the d-axis, so that its increase has only a small effect on the overall reluctance seen by the main field; in the magnetic circuit seen by the armature field, fig.5.1, the reluctance at the pole tips is the main series component in the path, so that its increase has a major effect on the overall reluctance seen by the armature field.

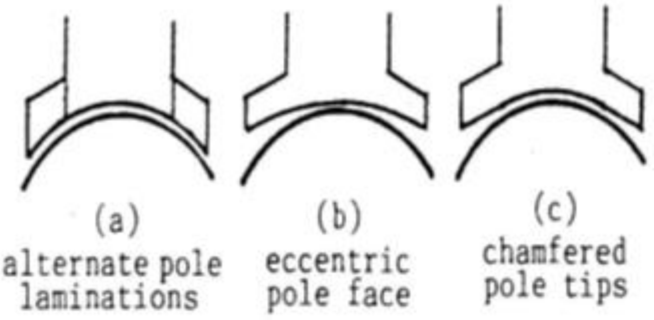

Fig.5.8 Increasing the reluctance at pole tips:((a)each pole lamination has only one tip, and the laminations are stacked alternately; (b)the arc of the pole face is off center with respect to the armature; (c)the pole face is cut straight at the tip.

Section 5.4.3 explained that the ionized air near the brushes breaks down if the voltage between segments becomes too high. Experience indicates that the breakd9wn of air can be avoided if the maximum instantaneous voltage between adjacent segments is not allowed to exceed 30-40 volts; the corresponding average voltage is 20 -30 volts. The machine must therefore be designed in such a way that the average voltage between segments does not exceed 20 -30 volts.

The voltage between segments is directly related to the coil voltage :in a simple lap winding, the voltage between adjacent segments is equal to the coil voltage, and in a simple wave winding, it is equal to p times the coil voltage; in general, then, the voltage between adjacent segments is equal to V_{coil} x p/a.

The design must therefore ensure that $E_{coil}xp/a < 20$ -30 volts; otherwise, the machine may experience flashover, resulting in total failure.

In some machines, the poles are made with slots in which an additional winding is placed, fig.5.9a; the winding is called the compensating winding or pole-face winding. The currents in the conductors of the compensating winding are opposite to the currents in the armature conductors, fig. 5.9a,so that the corresponding mmf's also oppose, figs. 5.9b and 5.9c; ideally, the two mmf's cancel out under the pole face, leaving only a small mmf acting in the inter polar region, fig. 5.9d. The resultant mmf is then as shown in fig.5.9.e, producing the air gap flux density distribution shown in fig. 5.9f :the distortion under the pole face has been eliminated, as may be verified by comparison with fig. 5.4d; in this way, the compensating winding prevents flashover.

The compensating winding also reduces the flux density at the q-axis and the shift in the magnetic neutral axis; it cannot eliminate them completely because it has no conductors in the inter-poles region, figs. 5.9a and 5.9c.

The compensating winding is connected in series with the armature, fig.5.10, so that the current in its conductors is I_A. The maximum mmf of the compensating winding is

$$M_{cm} = \frac{1}{2} N_c I_A \tag{5.6}$$

Where N_c is the number of conductors in each pole face. For full compensation as in fig. 5.9, the maximum mmf of the compensating winding must equal the armature mmf at the pole tips, that is

$$M_{cm} = \alpha M_{am} \tag{5.7}$$

Whereα is the pole arc /pole pitch ratio, fig. 1.41. Substituting for M_{am} from eqn.5.1 and for M_{cm} from eqn. 5.6and rearranging, we get

$$N_c = \frac{\propto Z}{4pa} = \frac{\propto NC}{2pa} \tag{5.8}$$