CHAPTER 4
MAIN FIELD

4.1 Introduction

The operation of dc machines is based on the interaction between the armature conductors and the air gap field, resulting in induced emf and developed torque.

Armature windings were explained in the last chapter, and we shall now study the magnetic field. As explained in section 1.5, coils are placed on the stator poles to produce the required field, which is the subject of the present chapter.

Permanent magnet machines, which have no field coils will not be considered here; they are briefly explained in chapter 10 with other special types of de machines.

Now, the purpose of the armature coils is to produce emf and torque. However, when current flows in them, they will attempt to produce a magnetic field, which is called armature reaction. The overall field in the machine will then be the resultant of the main field produced by the field coils and the armature field produced by the armature coils. In this chapter, we shall study the main field by itself; the armature current is assumed to be zero, so that there is no armature reaction. Armature reaction is considered in the next chapter.

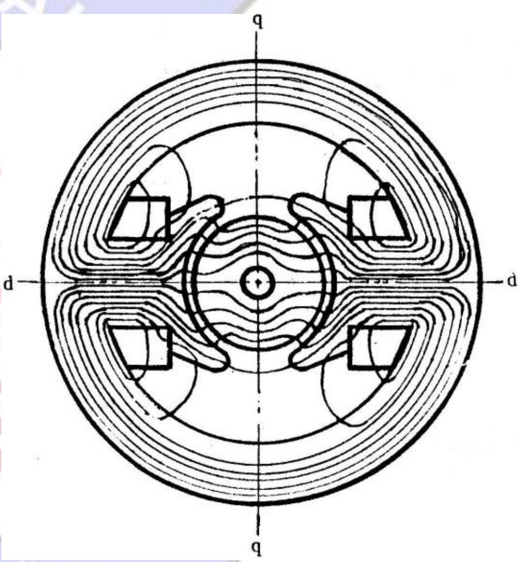


Fig.4.1 Rough sketch of main flux distribution in a 2-pole dc machine.

4. 2 Main Field Distribution

The flux produced by the field coils in a 2-pole machine is distributed approximately as shown in fig. 4.1. Most of the flux in the pole core crosses the air gap to interact with the active conductors at the armature surface; this is the useful flux, Φ in our equations.

However, some flux lines complete their paths without linking the armature conductors; this is the leakage flux, which is not useful because it does not take part in the production of emf and torque. The leakage flux is limited by the high reluctance of the airpaths it follows; usually it does not exceed 10-20 %of the useful flux, which is much less than the amount of leakage shown in fig.4.1

Another approximation in fig. 4.1 is that the flux appears to be uniformly distributed in the air gap between the armature surface and the pole face. This is because the figure assumes the armature surface to be smooth, ignoring the slots and teeth. In fact, the air gap flux has a high density at the teeth, where the air gap is very short and a low density at the slots, where the air gap is much longer, fig.4. 2.

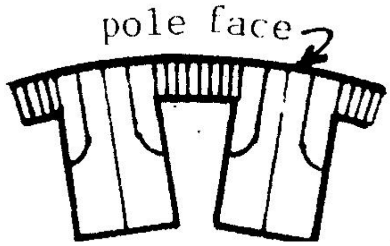


Fig. 4.2 Concentration of air gap flux at teeth.

In a magnetic circuit the flux is determined by the applied magneto motive force, or mmf, and the reluctance in the path of the flux, according to Ohm's law for magnetic circuits:

$$\text{flux} = \frac{\text{mmf}}{\text{reluctance}} \qquad (4.1)$$

The main flux is driven by the mmf coils :if each pole has a coil of N_f turns carrying a current I_f, then the mmf per pole is given by:

$\text{mmf} = N_f \cdot I_f$ ampere-turns/pole. (4.2)

If the machine has two or more coils placed on each pole, then

$\text{mmf} = \Sigma_j N_j \cdot I_j$ Ampere-turns/pole (4.3)

where the summation is, of course, algebraic, and covers the coils on one pole. This mmf acts on the magnetic circuit in the path of the useful flux. From fig. 4.1, it is seen that the path of the useful flux is composed of the following parts in series :stator, yoke , pole core , pole shoe, air gap , armature teeth and slots , and armature core , at low excitation, when I_f and hence mmf are small the iron parts of the path are in the linear regions of their B-H curves, fig. 2.2; the iron permeability is therefore very high, and its reluctance is very small. Thus, at low excitation, the overall reluctance is approximately equal to the air gap reluctance only. However, as the excitation is increased, iron parts begin to saturate so that their reluctance is no longer negligible compared to the air gap reluctance, and has to be included in the overall reluctance of the magnetic circuit. The highest flux density occurs in the armature teeth, fig. 4.2, followed by the pole core, fig. 4.1, and it is these parts which saturate first.

The mmf of the field coil acts on the air gap along the pole face as shown in fig. 4.3a. The resulting flux density distribution in the air gap is shown in fig. 4.3b where it is assumed that the armature surface is smooth. In fact, the slotting effect causes the air gap flux density distribution to look more like fig. 4. 3c; the ripple moves along the curve as the armature rotates. Whatever the precise shape of the flux density distribution b, the average flux density B and the total flux per pole Φ can obtained by integration on as explained in section 1.5, and it is these values that determined the average emf and torque according to the equations derived in sections 1.6, and 3.3.

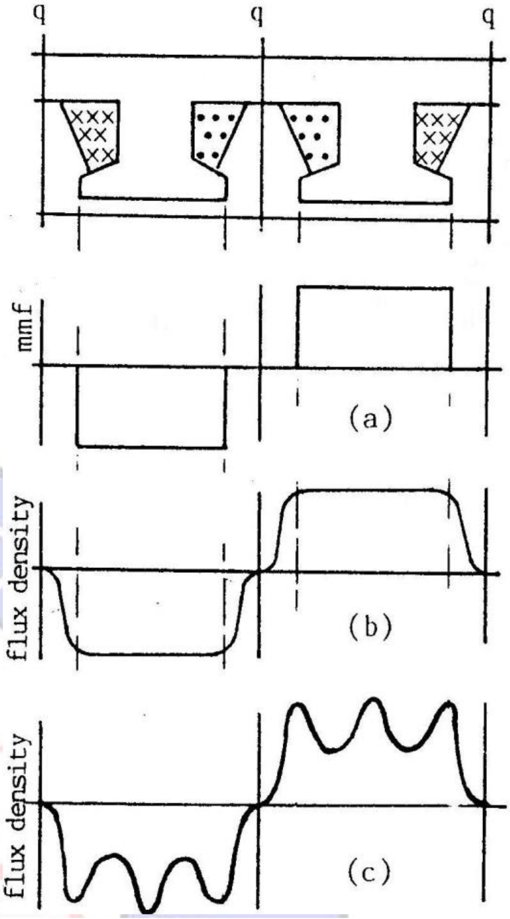


Fig. 4.3 Air gap distributions (a)excitation mmf, (b)flux density assuming smooth armature, and (c)flux density with the slotting effect included.

4.3 Field excitation

The main field is produced by the field coils. The machine may have one set of 2p coils, with one coil placed on each pole; the coils are identical, and are connected in series to form what is called the field winding. Some machines have two or more sets of field coils; the 2p coils of each set are identical to each other (same wire gauge and number of turns), but are generally different from the coil of the other sets. These sets of field coils, or field windings, can be fed with current in a number of different ways. Ina separately-excited machine, fig. 4.4a, the field winding is supplied from a separate source, and there is no connection between the field circuit and the armature circuit.

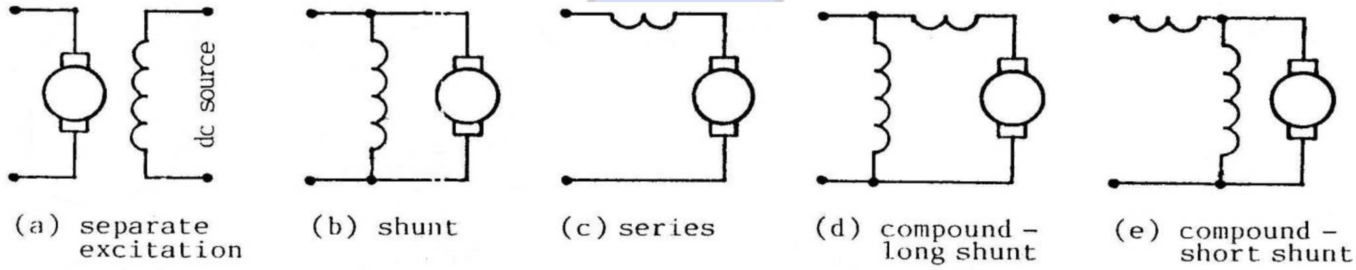


Fig. 4.4 Methods of field excitation in dc machines.

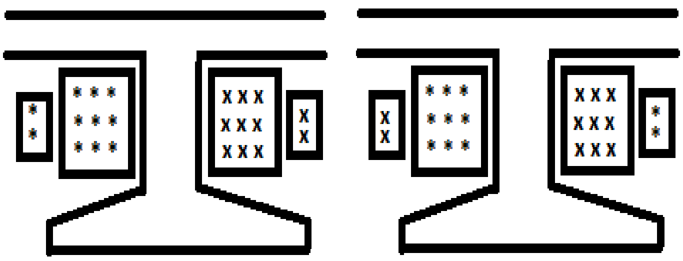
In self-excited machines, on the other hand, the field windings are connected in parallel or in series with the armature, figs. 4.4b-e.

In a shunt machine, the field winding is connected in parallel with the armature, fig. 4.4b. The shunt field coils are made of many turns of thin wire, so that the resistance of the shunt field winding is high, and its current is low; the shunt field current is much smaller than the armature current, usually not exceeding 10 %. The shunt field current can be controlled by means of a variable resistor, or rheostat, connected in series with the shunt field winding. In a series machine, the field winding is connected in series with the armature, fig. 4.4c. The series field coils, are made of few turns of thick wire, so that the resistance, and hence the voltage drop, are low. The series field current can be controlled by means of a diverter, which is a variable resistor connected in parallel with the series field winding.

Compound machines have both shunt and series field windings, that is, two sets of field coils, with two coils on each pole. Compound machines can he connected in long shunt, fig. 4.4d. or in short shunt, fig. 4.4e; there is no major difference between the two connections because, in both cases, the shunt winding voltage is (approximately)equal to the armature voltage, and the series winding current is (approximately)equal to the armature current :the voltage drop in the series winding is small compared to the armature voltage, and the current in the shunt winding is small compared to the armature current. According to eqn. 4.3, the total mmf per pole is given by

$$\text{mmf} = N_f\, I_f \pm N_s\, I_s \qquad (4.4)$$

where N_f and N_s are the shunt and series turn per pole, and I_f and I_s the shunt and series currents, respectively. In general, the shunt winding mmf ($N_f\, I_f$)is much greater than the series winding mmf ($N_s I_s$). Usually, the series mmf aids the shunt mmf so that the compounding is cumulative, fig. 4.5a, and the positive sign is used in eqn. 4.4. If, however the series mmf opposes the shunt, the compounding is said to be differential, fig. 4.5b, and the negative sign is used in eqn. 4.4; differential compounding is seldom used.



(a) Cumulative (b) differential

Fig.4.5 Two ways of compounding.

Some special-purpose dc machines have more than two field windings; each winding is fed from a different controlling signal so that the resultant flux per pole is determined by the overall combination of the controlling signals. Such machines are used in automatic control applications.

The main field can also be excited by means of permanent magnets placed on the stator. The absence of field windings in permanent magnet dc machines means that no supply is needed for the field, and operation is economical because there is no copper loss in the field; moreover, they are compact, and hence are widely used as small motors, fig. 2.9, in such applications as toys.

However, the main field of permanent magnet machines is constant, so that they cannot be used in applications requiring variable field. Their main disadvantage is that permanent magnet materials tend to be expensive and difficult to machine; however, there is continuing progress in the technology of permanent magnets, with consequent reduction in production costs. Section 10.1 discusses permanent magnet dc machines in more detail.

4.4 Magnetization curve

The field coils produce the mmf which acts on the reluctance of the magnetic circuit to produce the flux, eqn. 4.1. The magnetization curve is, basically, the relationship between the applied mmf per pole (M_f) and the resulting flux per pole Φ, fig. 4.6; of course, as M_f is increased, Φ increases, but the relationship is not linear because of the iron in the magnetic circuit. The path of the useful flux per pole is composed of the air gap in series with iron parts as discussed in section 4.1; thus eqn. 4.1 takes the form

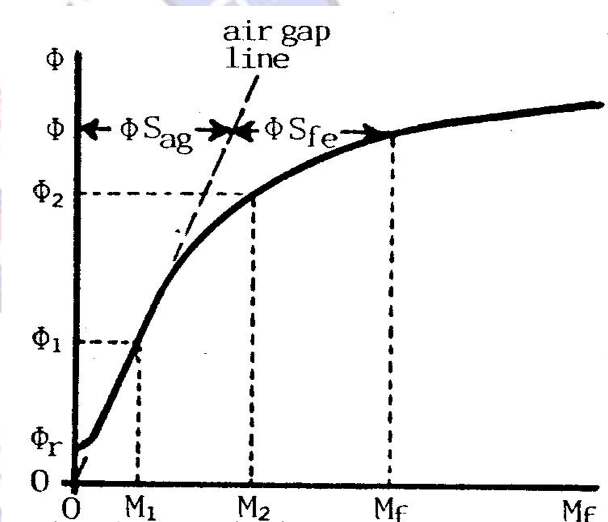


Fig.4.6 Magnetisation curve.

$$\Phi = \frac{M_f}{s_{ag}+s_{fe}} \qquad (4.5)$$

where S_{ag} is the reluctance of the air gap and S_{fe} is the reluctance of the iron parts.

Rearranging eqn. 4.5, we can write

$$M_f = \Phi S_{ag} + \Phi S_{fe} \qquad (4.6)$$

this is similar to voltage division in series electrical circuits :ΦS_{ag} is the mmf drop in the air gap, and ΦS_{fe} is the mmf drop in the iron. The air gap permeability is μ_0, so that the air gap reluctance S_{ag} is constant, ie it does not change as the excitation is varied; this gives the air gap line in fig.4.6, ΦS_{ag} increases linearly with Φ. The iron permeability, on the other hand, is not constant, fig. 2.2, so that the value of S_{fe} changes as the excitation is varied. As discussed in section 4.l, at low excitation the iron reluctance and hence mmf drop are negligible compared to the air gap reluctance and mmf drop; thus, at a low excitation like M_1in fig. 4.6, eqn. 4.6 simplifies to

$$M_1 \approx \Phi_1 \cdot S_{ag}; \qquad (4.7)$$

that is, practically all the applied mmf is consumed in crossing the air gap. Thus, at low excitation, the magnetization curve coincides with the air gap line, as shown in fig. 4.6. However, as the excitation is increased, iron parts enter into saturation so that S_{fe} increases, and is no longer negligible; the magnetization curve thus moves away from the air gap line, and at an excitation like M_2 in fig. 4.6, we have

$$M_2 = \Phi_2 S_{ag} + \Phi_2 S_{fe} \qquad (4.8)$$

As indicated on fig. 4.6, the air gap mmf drop ΦS_{ag} is measured between the vertical axis and the air gap line, while the iron mmf drop ΦS_{fe} is measured between the air gap line and the magnetization curve; at low excitation, $\Phi S_{fe}$is negligible so that the curve and line coincide.

The magnetization curve in fig. 4.6 does not start from the origin; with no current in the field coils, Mf =0, there is a small residual flux Φ_r. This is due to hysteresis in the iron, which remains some of its magnetization when the excitation is brought down to zero. To kill the residual flux completely, the field windings must be excited in reverse.

Now, in a mathematical expression Like y =f(x), the term f(x)is a function or formula in terms of x :if we are given a certain value for the variable x, say x_i, we insert this value in f(), and perform the given algebraic operations to obtain the corresponding value of the variable y, namely $y_i=f(x_i)$. If the magnetization curve is given, we can think of it, and use it, just like a function $\Phi = f(M_f)$:given a value of M_f we can find the corresponding value for Φ from the curve; indeed, we can do the reverse: given a value of Φ we can find the corresponding value for M_f from the curve.

Of course, our operations are now graphical, and not algebraic. Suppose, for example, that we need to calculate the developed torque T_d for a given armature current I_A and a given field excitation M_f; to use eqn. 3.16, we need the value of the flux per pole Φ, and this is obtained graphically from M_f using the magnetization curve. Alternatively, the torque may be given, and we need to determine the necessary field excitation; here we use eqn. 3.16 to find Φ and then the magnetization curve to find M_f.

Engineering calculations often use graphical procedures like the one described here in situations where there are no ready algebraic formulas linking the variables, Φ and M_f in our case.

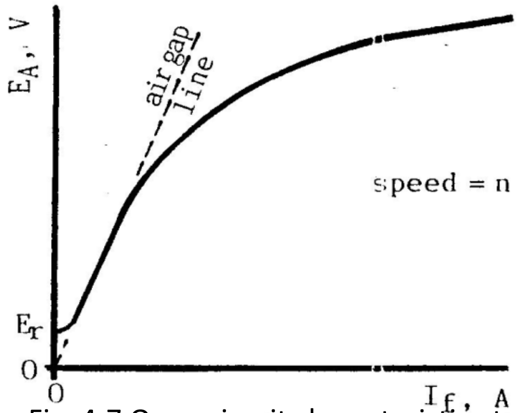


Fig. 4.7 Open circuit characteristic at speed n.

If the machine has one field winding, the mmf per pole M_f is related to the current in the field winding I_f by eqn. 4.2. Since the number of turns per pole N_f is constant, there is direct proportion between M_f and I_f, and the horizontal axis in fig. 4.6 can be scaled in terms of I_f. As an example, let N_f = 500 turns/pole; a point on the horizontal axis marked 2000 A·t/pole can also be marked 4 A of field current; similarly, 3000 A·t/pole becomes 6 A, and so on.

The flux per pole Φ is related to the induced emf E_A by eqn. 3. 12, one form of which is

$$E_A = k_e\, n\, \Phi \quad \rightarrow \quad \Phi = E_A / k_e\, n$$

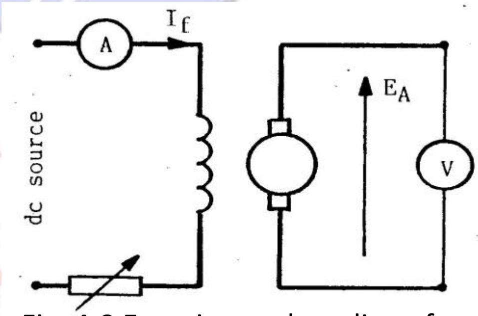


Fig. 4.8 Experimental reading of the OCC. Prime mover rotates armature at constant speed n.

if we consider one constant value of speed n, the factor ($k_e n$)will be constant, resulting in direct proportion between Φ and E_A at that speed; the vertical axis in fig. 4.6 can then be scaled in terms of E_A, but the resulting curve is correct for the specified speed -for a different speed, a different scaling factor ($k_e n$)must be used.

Thus, instead of drawing the magnetization curve as a relationship between the applied excitation M_f and the resulting flux Φ as in fig. 4.6, it can be drawn as a relationship between the exciting field current I_f, and the resulting induced emf E_A (at a specified speed n), as shown in fig. 4.7; in this form, the magnetization curve is called the Open Circuit Characteristic (OCC) of the machine. The OCC can be measured experimentally by the simple test shown in fig. 4.8 :the machine is rotated by means of a prime mover at a constant speed n, usually the rated speed of the machine; the field winding is fed from a separate de source; the exciting field current I_f is varied, by means of n rheostat in the field circuit, or otherwise. The armature circuit is kept open, with no connection to any external load or source; under these open-circuit conditions, a voltmeter connected between the armature terminals as shown will read the induced emf E_A because there is no current, and hence no voltage drops, in the armature circuit -see eqns. 3.13 and 3.14. The emf values are recorded for different values of field current, and the result is plotted as in fig. 4.7. The residual emf E_r is measured when there is no field excitation, ie when the field current I_f is set to zero by disconnecting the field winding from the dc source. Note that in this test the machine is operated as a separately-excited unloaded generator; it does not matter whether the machine is going to be installed as a motor or generator, self-excited or separately-excited, etc. It is also noted that the armature is open-circuited in this test, which is why the resulting characteristic is called the open-circuit characteristic.

Because it can be measured directly, the OCC is the preferred form of the magnetization curve. To scale it back to the original form of fig. 4.6, the horizontal variable I_f is multiplied by N_f, and the vertical variable E_A is divided by (k_en); in practice, however, the constants N_f and k_e are not always known the OCC can still be used, although the original form of fig. 4.6can not be obtained.

Compound machines have two field windings, one in shunt and the other in series, figs. 4.4d and 4.4e. The OCC is obtained with the shunt field winding excited from a separate source as in fig. 4.8, and the series winding left unconnected; this is because the shunt field is the dominant one. Clearly, the horizontal scaling factor N_f represents the shunt turns per pole. But in operation both windings are excited, and the total mmf is their algebraic sum, eqn. 4.4. Given I_f, I_s, N_f, and N_s, the total mmf M_f is computed, and the required point can be located on the horizontal axis of the magnetization curve of fig. 4.6; to locate the corresponding point on the horizontal axis of the OCC of fig. 4.7, M_f must be divided by the scaling factor N_f to obtain an answer in amperes. Dividing M_f in eqn. 4.4 by N_f, we can write

$$\frac{M_f}{N_f} = I_{eq} = I_f \pm \left\{\frac{N_s}{N_f}\right\} I_s \qquad (4.9)$$

where I_{eq} is the required point on the horizontal axis of the OCC; it is an equivalent shunt field current that considers the additional excitation produced by the series field winding. The factor (N_s/N_f) effectively 'refers' the series winding current to the shunt winding :(N_s/N_f)I_s is the current that must flow in the shunt field winding to produce the same mmf produced by I_s flowing in the series field winding.

A given value of field excitation, whether expressed as an mmf M_f or as a field current I_f, produces a specific value of flux per pole Φ, fig. 4.6, but the corresponding emf E_A depends on speed n; this is why the OCC of fig. 4.7 is associated with a particular value of speed :the same value of field current will produce different values of emf at different speeds, although the flux it produces is the same at all speeds. Now suppose the OCC is given at some speed n_1; it is possible to obtain the OCC at any other speed n_2 by simple scaling. Consider a particular value of field current I_o; it produces the mmf M_o and hence the flux Φ_o whose value