DC Machines

The armature winding of a dc machine is on the rotor with current conducted to it by means of carbon brushes. The field winding (励磁绕组) is on the stator and is excited by direct current. A cutaway view of a dc motor is shown in figure 1.

Consider a very elementary two-pole dc generator as is shown in figure 2. The armature winding, consisting of a single coil of N turns, is indicated by the two coil sides(元件边) a and $-a$ placed diametrically opposite points on the rotor with the conductors parallel to the shaft. The rotor is normally turned a constant speed by a source of mechanical power connected to the shaft.

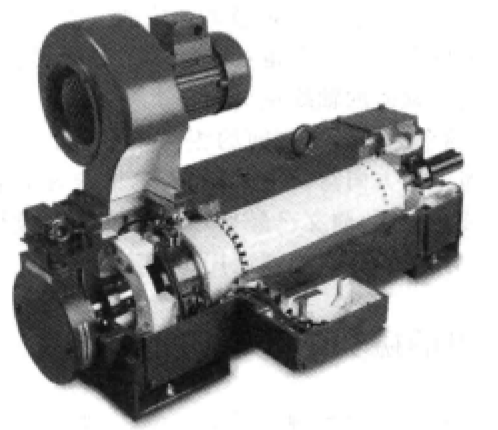

Figure 1 Cutaway view of a 25-hp, 1750 -rpm, 500-v dc motor.

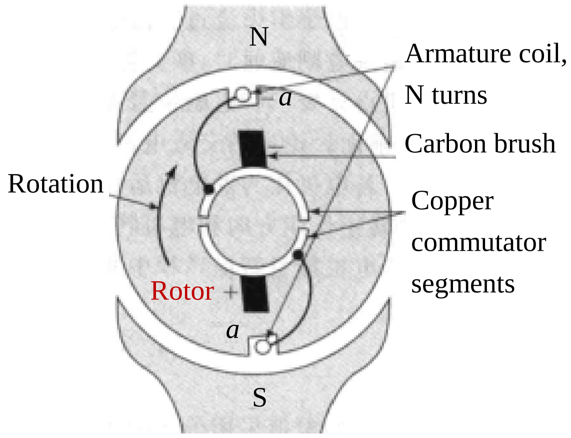

Figure 2 Elementary dc machine with commutator. The rotor, armature coil, and commutator rotate while the brushes remain stationary.

The air-gap flux distribution usually approximates a **flat-topped** wave, rather than the sine wave found in ac machines, and is shown in figure 3. Rotation of the coil, shown schematically in figure 3(a), generates a coil voltage which is a time function having the same waveform as the spatial flux-density distribution.

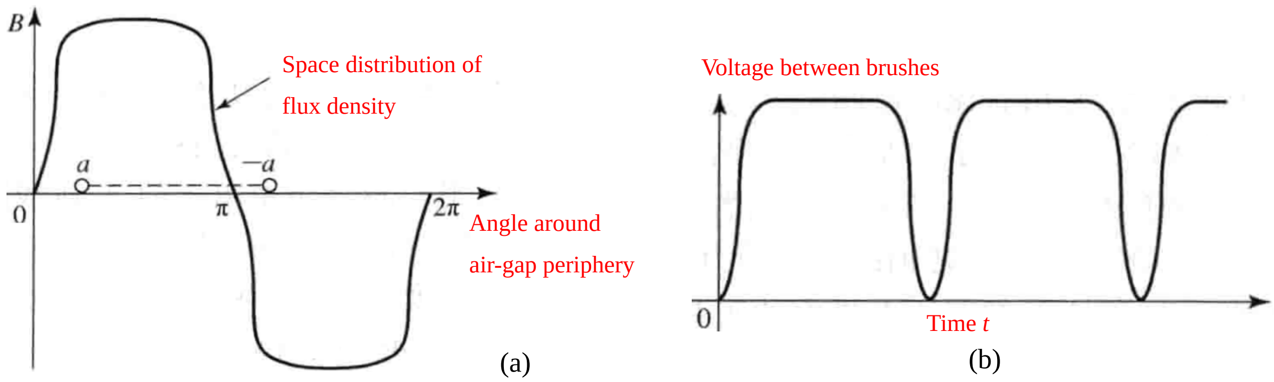

Figure 3 Space distribution of air-gap flux density in an elementary dc machine

The function of a dc generator is the production of dc voltage and current. Thus the ac voltage and currents induced in the armature winding must be rectified. In a dc machine, rectification is produced mechanically by means of a commutator which is a cylinder formed of copper segments to which the armature coils are connected. These segments are otherwise insulated from each other by mica or some other insulating material and mounted on, but insulted from, the rotor shaft. Stationary carbon brushes held against the commutator surface connect the winding to the external winding to the external armature terminals. The commutator and brushed can readily be seen in figure 1 and a simple two-segment commutator is shown in figure 2. The need for commutation is the reason why the armature windings of dc machines are found on the rotor.

For the elementary dc generator, the commutator takes the form shown in figure 2. To understand its function as a rectifier, note that the commutator at all times connects the coil side which is closest to South Pole to the positive brush and the coil side closet to the North Pole is connected to the negative brush. Thus, each half rotation of the rotor, the brushes switch their polarity with respect to the coil polarity. As a result, although the coil voltage is an alternating voltage similar in form to the air-gap flux distribution shown in figure 3(a), the commutator provides full-wave rectification, transforming the coil voltage to the voltage between brushes of figure 3(b) and marking available a unidirectional voltage to the external circuit. The dc machines of figure 2 is, of course, simplified to the point of being unrealistic in the practical sense, and later it will be essential to examine the action of more realistic commutators.

The direct current in the field winding of a dc machine creates a magnetic flux distribution which is stationary with respect to the stator. Similarly, the effect of the commutator is such that when direct current flows through the brushes, the armature creates a magnetic flux distribution which is also fixed in space and whose axis, determined by the design of the machine and the position of the brushes, is typically perpendicular to the axis of the field flux.

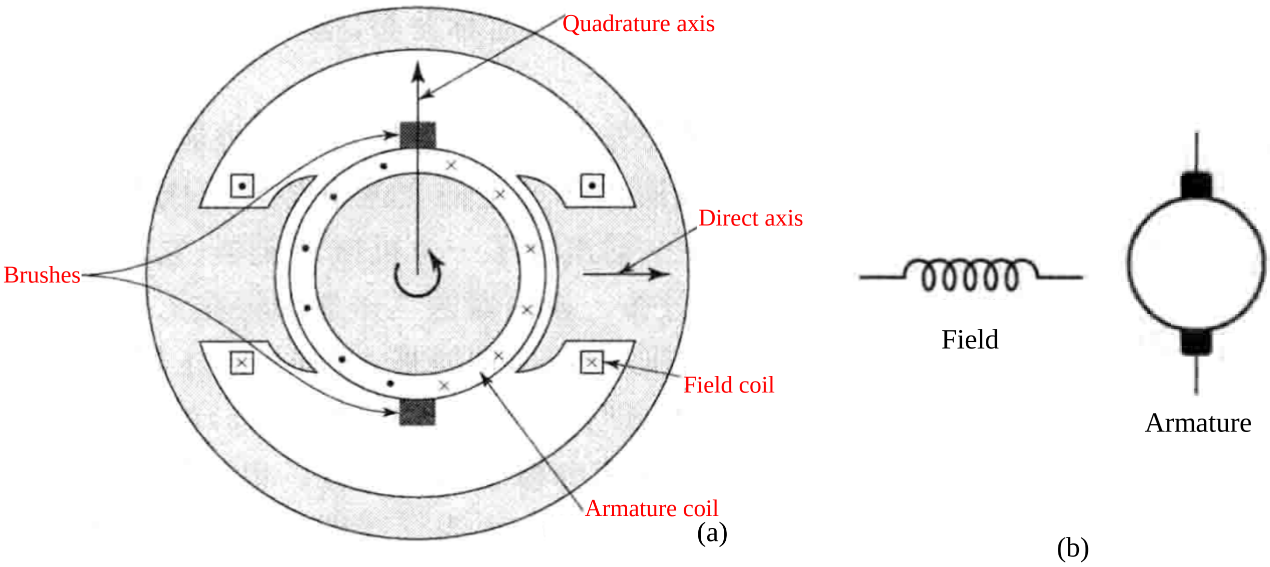

Figure 4 Schematic representations of a dc machine

The essential features of a dc machine are shown schematically in figure 4. The stator has salient poles and is excited by one or more field coils. The air-gap flux distribution created by the field windings is symmetric about the center line of the field poles. The axis is called the field axis or direct axis.

The brushes are located so that commutation occurs when the coil sides are in the neutral zone, midway between the field poles. The axis of the armature-mmf wave the is 90 electrical degrees from the axis of the field poles, i.e., in the quadrature axis. In the schematic representation of figure 4a, the brushed are shown in the quadrature axis because this is the position of the coils to which they are connected. The armature-mmf wave then is along the brush axis, as shown. (The geometric position of the brushes in an actual machine is approximately 90 electrical degrees from their position in the schematic diagram because of the shape of the end connections to the commutator.) For simplicity, the circuit representation usually will be drawn as figure 4b.

The electromagnetic torque T_e can be expressed in terms of the interaction of the direct-axis air-gap flux per pole Φ. $T_e=C_T\Phi I_a$

Where I_a= Current in external armature circuit.

C_T= a constant determined by the design of the winding.

The rectified voltage E_a between brushes, known also as the speed voltage, is $E_a=C_e\Phi n$.

$$P_e = E_a I_a = T_e \Omega \tag{1}$$

Noting that the product of torque and mechanical speed is the mechanical power, this equation simply say that the instantaneous electric power associated with the speed voltage equals the instantaneous mechanical power associated with the magnetic torque, the direction of power flow being determined by whether the machine is acting as a motor or generator.

The outstanding advantages of dc machine arise from the wide variety of operating characteristics which can be obtained by selection of the method of excitation of the field windings. Various connection diagrams are shown in figure 5. The method of excitation profoundly influences both the steady-state characteristics and the dynamic behavior of the machine in control systems.

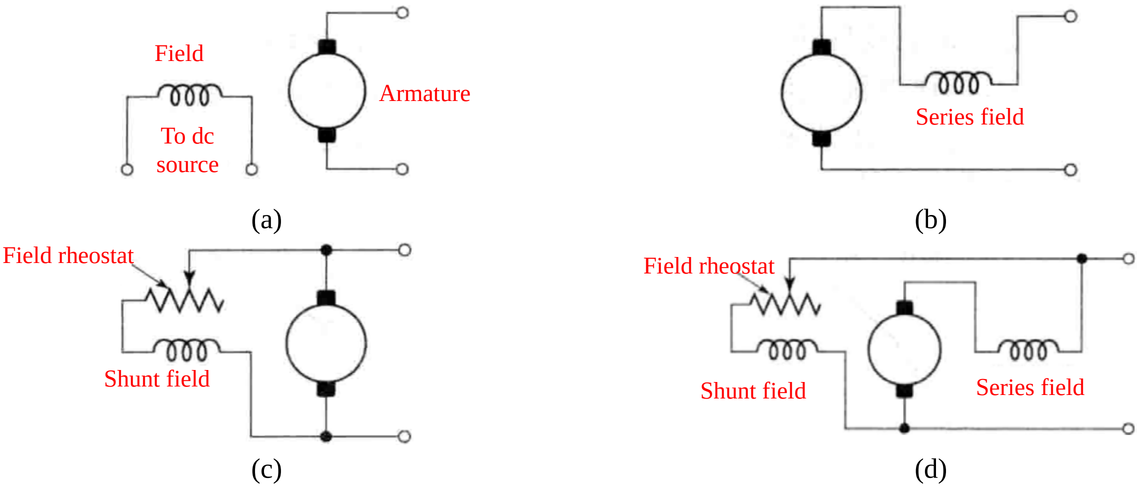

Figure 5 Field-circuit connections of dc machines: (a) separate excitation;(b) series, (c) shunt, (d) compound.

Consider first dc generators. The connection diagram of a separately excited generator is given in figure 5. The required field current is a very small fraction of the rated armature current, on the order of 1 to 3 percent in the average generator. A small amount of power in the field circuit may control a relatively large amount of power in the armature circuit; i.e., the generator is a power amplifier. Separately excited generators are often used in feedback control systems when control of the armature voltage over a wide range is required.

The field windings of self-excited generators may be supplied in three different ways. The field may be connected in series with the armature (Figure 5b), resulting in a series generator. The field may be connected in shunt with armature (Figure 5c), resulting a shunt generator, or the field may be in two sections (Figure 5d), one of which is connected in series and the other in shunt with armature, resulting in a compound generator. With self-excited generators, residual magnetism must be present in the machine iron to get the self-excitation process started.

The relation between the steady-state generated emf Ea and the armature terminal voltage U is

$$U = E_a - I_a R_a \tag{2}$$

where I_a is the steady-state armature current output and R_a is the total armature circuit resistance including the winding and brushes. In a generator, E_a is larger than U, and the electromagnetic torque T_e is a counter torque opposing rotation.

Any of methods of excitation used for generators can also be used for motors. It is assumed that the motor terminals are supplied from a constant-voltage source. In a motor the relation between the emf E_a generated in the armature and the armature terminal voltage U is

$$U = E_a + I_a R_a \quad \text{or} \quad I_a = (U - E_a)/R_a \tag{3}$$

Where I_a is now the armature-current input to the machine. The generated emf E_a is now smaller than the terminal voltage U, the armature current is in the opposite direction to that in generator and the electromagnetic torque T_e is the direction to sustain rotation of the armature.

EFFECT OF ARMATURE MMF

Armature mmf has definite effects on both the space distribution of the air-gap flux and the magnitude of the net flux per pole. The effect on flux distribution is important because the limits of successful commutation are directly influenced; the effect on flux magnitude is important because both generated voltage and the torque per unit armature current are influenced thereby. These effects and the problems arising from them are described in this section.

The armature-mmf wave can be closely approximated by a sawtooth, corresponding to the wave produced by a finely distributed armature winding or current sheet. For a machine with brushed in the neutral position, the idealized mmf wave is shown by the dashed sawtooth in figure 6, in which a positive mmf ordinate denotes flux lines leaving the armature surface. Current directions in all windings other than the main field are indicated by black and cross-hatched bands. Because of the salient-pole field structure found in almost all dc machines, the associated space distribution of flux will not be triangular. The distribution of air-gap flux density with only the armature excited is given by the solid curve of figure 6. As can be readily by seen, it is appreciably decreased by the long air path in the interpole space.

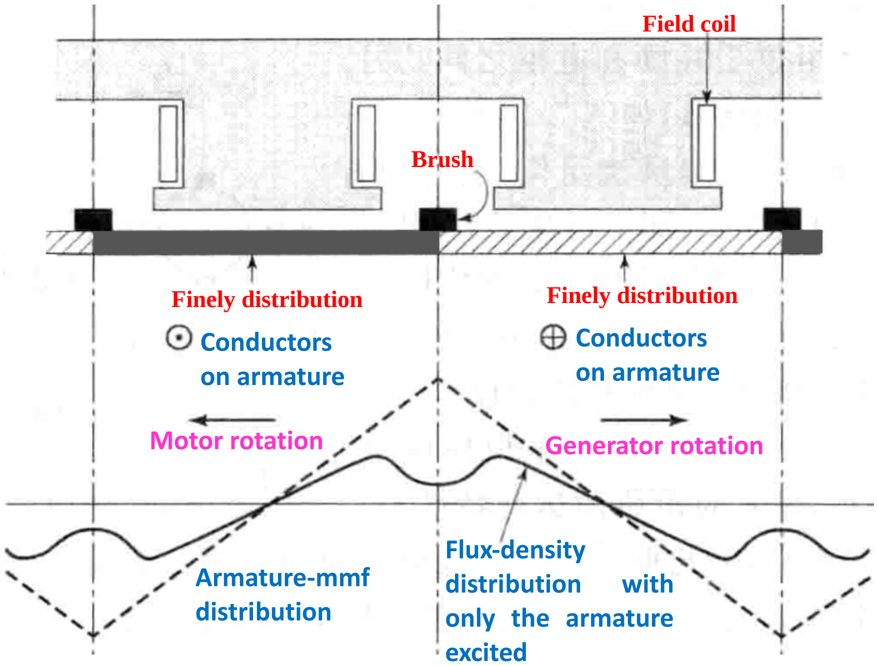

Figure 6 Armature-mmf and flux-density distribution with brushed on neutral (几何中性线) and only the armature excited.

The axis of the armature mmf is fixed at 90 electrical degrees from the main-field axis by the brush position. The corresponding flux follows the paths shown in figure 7. The effect of the armature mmf is seen to be that of creating flux crossing the pole faces; thus its path in the pole shoes crosses the path of the main-field flux. For this reason, armature reaction of this type is called ***cross-magnetizing armature reaction*** and it causes a decrease in the resultant air-gap flux density under one half of the pole and an increase under the other half.

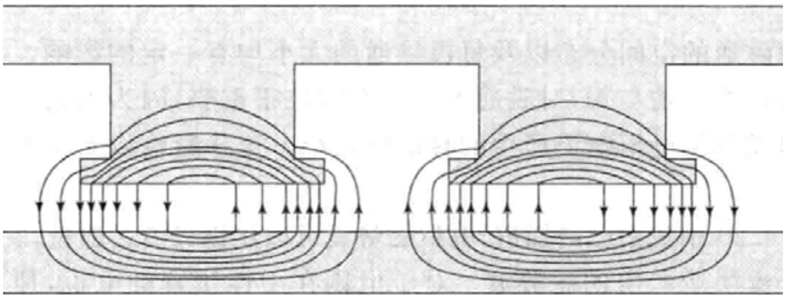

Figure 7 Flux with only the armature excited and brushes on neutral.

When the armature and field windings are both excited, the resultant air-gap flux-density distribution is of the form given by the solid curve of figure 8. Superimposed on this figure are the flux distributions with only the armature excited (long-dash curve) and only the field excited (short-dash curve). The effect of cross-magnetizing armature reaction in decreasing the flux under one pole tip and increasing it under the other can be seen by comparing the solid and short-dash curves. In general, the solid curve is not the algebraic sum of the two dashed curves because of the nonlinearity of the iron magnetic circuit. Because of saturation of the iron, the flux density is decreased by a greater amount under one pole tip than it is increased under the other. Accordingly, the resultant flux per pole is lower than would be produced by the field winding alone, a consequence known as the ***demagnetizing effect of cross-magnetizing armature reaction***. Since it is caused by saturation, its magnitude is a nonlinear function of both the field current and the armature current. For normal machine operation at the flux densities used commercially, the effect is usually significant, especially at heavy loads, and must often be taken into account in analyses of performance.

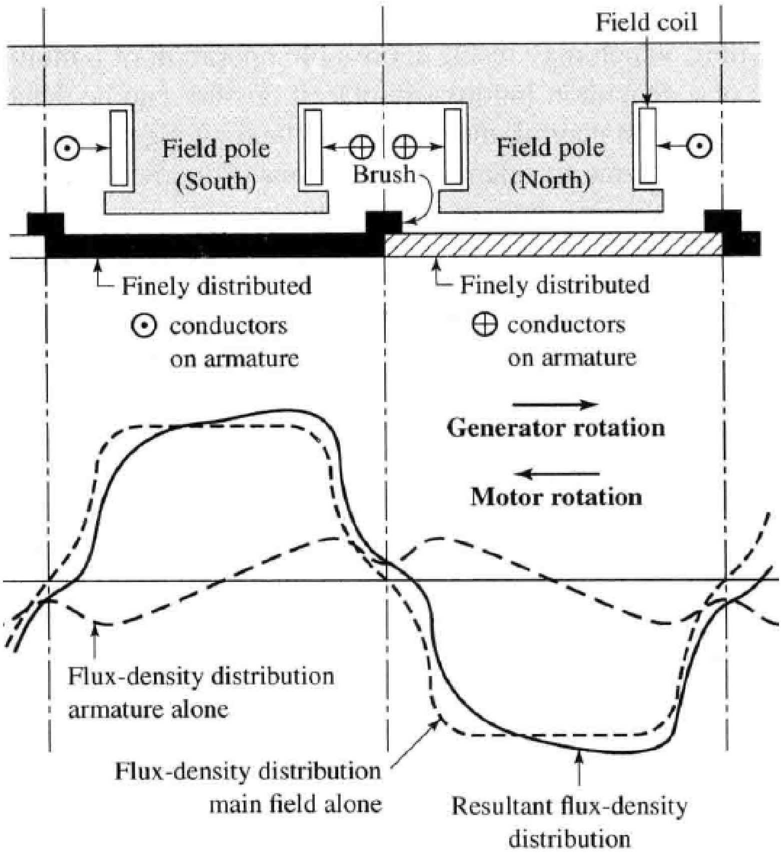

Figure 8. Armature, main-field, and resultant flux-density distributions with brushes on neutral

The distortion of the flux distribution caused by cross-magnetizing armature reaction may have a detrimental influence on the commutation of the armature current, especially if the distortion becomes excessive. In fact, this distortion is usually an important factor limiting the short-time overload capability of a dc machine, such as a shunt motor, where the field excitation remains substantially constant while the armature mmf may reach very significant proportions at heavy loads. The tendency is least pronounced in a series-excited machine, such as the series motor, for both the field and armature mmf increase with load.

The effect of cross-magnetizing armature reaction can be limited in the design and construction of the machine. The mmf of the main field should exert predominating control on the air-gap flux, so that the condition of weak field mmf and strong armature mmf should be avoid. The reluctance of the cross-flux path (essentially the armature teeth, pole shoes, and the air gap, especially at the pole faces, by avoiding too small an air gap, and by using a chamfered or eccentric pole face, which increases the air gap at the pole tips. These expedients affect the path of the main flux as well, but the influence on the cross flux is much greater. The best, but also the most expensive, curative measure is to compensate the armature mmf by means of a winding embedded in the pole faces.

If the brushes are not in the neutral position, the axis of the armature mmf wave is not 90° from the main-field axis. The armature mmf then produces not only cross magnetization but also a direct-axis demagnetizing or magnetizing effect, depending on the direction of brush shift. Shifting of the brushes from the neutral position is usually inadvertent due to incorrect positioning of the brushes or a poor brush fit. Before the invention of interpoles, however, shifting the brushes was a common method of securing satisfactory commutation, the direction of the shift being such that demagnetizing action was produced. It can be shown that brush shift in the direction of rotation in a generator of against rotation in a motor produces a direct-axis demagnetizing mmf which may result in unstable operation of a motor or excessive drop in voltage of a generator. Incorrectly placed brushes can be detected by a load test. If the brushes are on neutral, the terminal voltage of a generator or the speed of a motor should be the same of identical conditions of field excitation and armature current when the direction of rotation is reversed.