therefore, the machine can be considered stator fed, and, depending on the rotor type, the rotor is called either a squirrel cage rotor or a wound rotor. In DC machines, the function of a rotor armature winding is to perform the actual power transmission, the machine being thus rotor fed. Field windings do not normally participate in energy conversion, double-salient-pole reluctance machines possibly being excluded: in principle, they have nothing but magnetizing windings, but the windings also perform the function of the armature. In DC machines, commutating and compensating windings are windings the purpose of which is to create auxiliary field components to compensate for the armature reaction of the machine and thus improve its performance characteristics. Similar to the previously described windings, these windings do not participate in energy conversion in the machine either. The damper windings of synchronous machines are a special case among different winding types. Their primary function is to damp undesirable phenomena, such as oscillations and fields rotating opposite to the main field. Damper windings are important during the transients of controlled synchronous drives, in which the damper windings keep the air-gap flux linkage instantaneously constant. In the asynchronous drive of a synchronous machine, the damper windings act like the cage windings of asynchronous machines.

The most important windings are categorized according to their geometrical characteristics and internal connections as follows:

- phase windings;
- salient-pole windings; and
- commutator windings.

Windings in which separate coils embedded in slots form a single- or poly-phase winding constitute a large group of AC armature windings. However, a similar winding is also employed in the magnetizing of nonsalient-pole synchronous machines. In commutator windings, individual coils contained in slots form a single or several closed circuits, which are connected together via a commutator. Commutator windings are employed only as armature windings of DC and AC commutator machines. Salient-pole windings are normally concentrated field windings, but may also be used as armature windings in for instance fractional slot permanent magnet machines and in double-salient reluctance machines. Concentrated stator windings are used as an armature winding also in small shaded-pole motors.

In the following, the windings applied in electrical machines are classified according to the two main winding types, namely slot windings and salient-pole windings. Both types are applicable to both DC and AC cases, Table 2.1.

2.1 Basic Principles

2.1.1 Salient-Pole Windings

Figure 2.1 illustrates a synchronous machine with a salient-pole rotor. To magnetize the machine, direct current is fed through brushes and slip rings to the windings located on the salient poles. The main flux created by the direct current flows from the pole shoe to the stator and back simultaneously penetrating the poly-phase slot winding of the stator. The dotted lines in

Table 2.1 Different types of windings or permanent magnets used instead of a field winding in the most common machine types

	Stator winding	Rotor winding	Compensating winding	Commutating winding	Damper winding
Salient-pole synchronous machine	Poly-phase distributed rotating-field slot winding	Salient-pole winding	—	—	Short-circuited cage winding
Nonsalient-pole synchronous machine	Poly-phase distributed rotating-field slot winding	Slot winding	—	—	Solid-rotor core or short-circuited cage winding
Synchronous reluctance machine	Poly-phase distributed rotating-field slot winding	—	—	—	Short-circuited cage winding possible
PMSM, $q > 0.5$	Poly-phase distributed rotating-field slot winding	Permanent magnets	—	—	Solid-rotor or short-circuited cage winding, or, for example, aluminium plate on rotor surface
PMSM, $q \leq 0.5$	Poly-phase concentrated pole winding	Permanent magnets	—	—	Damping should be harmful because of excessive losses
Double-salient reluctance machine	Poly-phase concentrated pole winding	—	—	—	—
IM	Poly-phase distributed rotating-field slot winding	Cast or soldered cage winding, squirrel cage winding	—	—	—
Solid-rotor IM	Poly-phase distributed rotating-field slot winding	Solid rotor made of steel, may be equipped with squirrel cage	—	—	—
Slip-ring asynchronous motor	Poly-phase distributed rotating-field slot winding	Poly-phase distributed rotating-field slot winding	—	—	—
DC machine	Salient-pole winding	Rotating-field commutator slot winding	Slot winding	Salient-pole winding	—

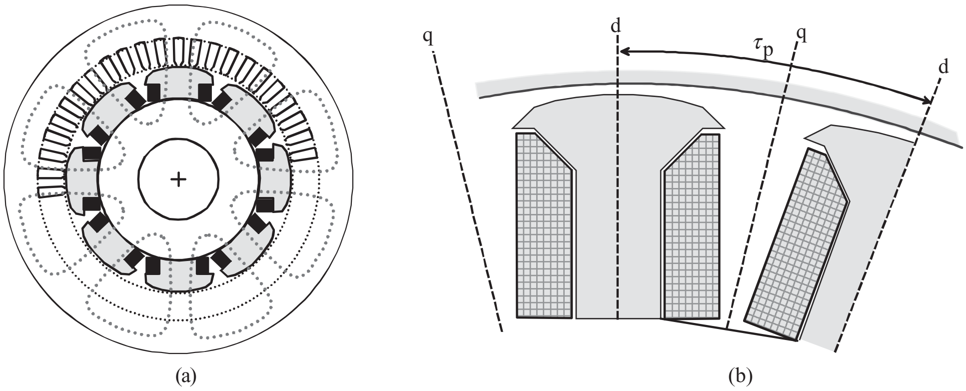

Figure 2.1 (a) Salient-pole synchronous machine ($p = 4$). The black areas around two pole bodies form a salient-pole winding. (b) Single poles with windings: d, direct axis; q, quadrature axis. In salient-pole machines, these two magnetically different, rotor-geometry-defined axes have a remarkable effect on machine behaviour (this issue will be discussed later)

the figure depict the paths of the main flux. Such a closed path of a flux forms the magnetic circuit of a machine.

One turn of a coil is a single-turn conductor, through which the main flux travelling in the magnetic circuit passes. A coil is a part of winding that consists of adjacent series-connected turns between the two terminals of the coil. Figure 2.1a illustrates a synchronous machine with a pole with one coil per pole, whereas in Figure 2.1b the locations of the direct (d) and quadrature (q) axes are shown.

A group of coils is a part of the winding that magnetizes the same magnetic circuit. In Figure 2.1a, the coils at the different magnetic poles (N and S alternating) form in pairs a group of coils. The number of field winding turns magnetizing one pole is N_{f}.

The salient-pole windings located on the rotor or on the stator are mostly used for the DC magnetizing of a machine. The windings are then called magnetizing or sometimes excitation windings. With a direct current, they create a time-constant current linkage Θ. The part of this current linkage consumed in the air gap, that is the magnetic potential difference of the air gap $U_{\mathrm{m},\delta}$, may be, for simplicity, regarded as constant between the quadrature axes, and it changes its sign at the quadrature axis q, Figure 2.2.

A significant field of application for salient-pole windings is double-salient reluctance machines. In these machines, a solid salient pole is not utilizable, since the changes of flux are rapid when operating at high speeds. At a simple level, DC pulses are fed to the pole windings with power switches. In the air gap, the direct current creates a flux that tries to turn the rotor in a direction where the magnetic circuit of the machine reaches its minimum reluctance. The torque of the machine tends to be pulsating, and to reach an even torque, the current of a salient-pole winding should be controllable so that the rotor can rotate without jerking.

Salient-pole windings are employed also in the magnetizing windings of DC machines. All series, shunt and compound windings are wound on salient poles. The commutating windings are also of the same type as salient-pole windings.

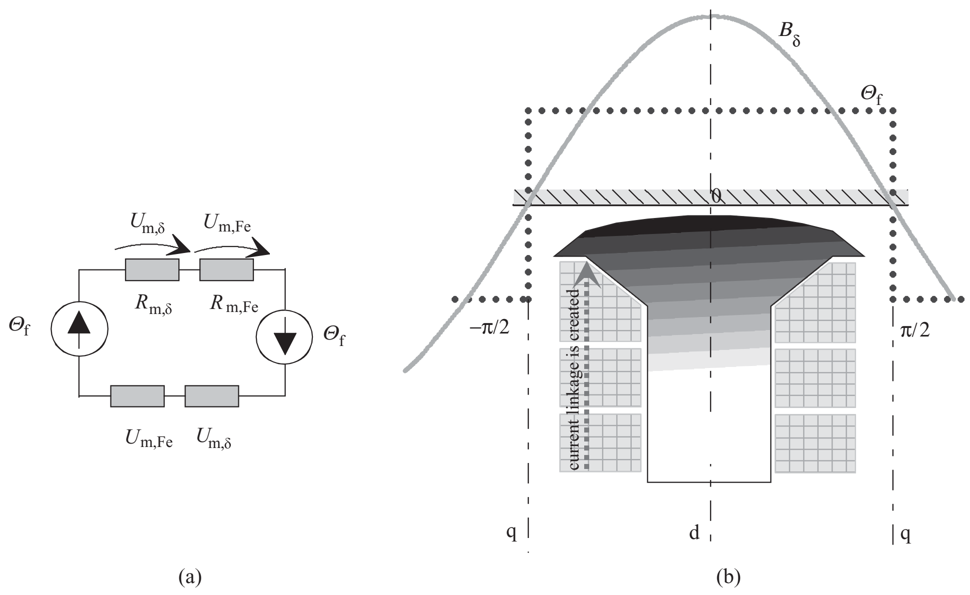

Figure 2.2 (a) Equivalent magnetic circuit. The current linkages Θ_f created by two adjacent salient-pole windings. Part $U_{m,\delta}$ is consumed in the air gap. (b) The behaviour of the air-gap flux density B_δ. Due to the appropriate design of the pole shoe, the air-gap flux density varies cosinusoidally even though it is caused by the constant magnetic potential difference in the air gap $U_{m,\delta}$. The air-gap magnetic flux density B_δ has its peak value on the d-axis and is zero on the q-axis. The current linkage created by the pole is accumulated by the ampere turns on the pole

Example 2.1: Calculate the field winding current that can ensure a maximum magnetic flux density of $B_\delta = 0.82\,\mathrm{T}$ in the air gap of a synchronous machine if there are 95 field winding turns per pole. It is assumed that the air-gap magnetic flux density of the machine is sinusoidal along the pole shoes and the magnetic permeability of iron is infinite ($\mu_{Fe} = \infty$) in comparison with the permeability of air $\mu_0 = 4\pi \times 10^{-7}$ H/m. The minimum length of the air gap is 3.5 mm.

Solution: If $\mu_{Fe} = \infty$, the magnetic reluctance of iron parts and the iron magnetic potential difference is zero. Now, the whole field current linkage $\Theta_f = N_f I_f$ is spent in the air gap to create the required magnetic flux density:

$$\Theta_f = N_f I_f = U_{m,\delta} = H_\delta \delta = \frac{B_\delta}{\mu_0}\delta = \frac{0.82}{4\pi \cdot 10^{-7}} 3.5 \cdot 10^3 \mathrm{A}$$

If the number of turns is $N_f = 95$, the field current is

$$I_f = \frac{\Theta_f}{N_f} = \frac{0.82}{4\pi \cdot 10^{-7}} 3.5 \cdot 10^{-3} \frac{1}{95} \mathrm{A} = 24\ \mathrm{A}$$

It should be noted that calculations of this kind are appropriate for an approximate calculation of the current linkage needed. In fact, about 60–90% of the magnetic potential difference in electrical machines is spent in the air gap, and the rest in the iron parts. Therefore, in a detailed design of electrical machines, it is necessary to take into account all the iron parts with appropriate material properties. A similar calculation is valid for DC machines, with the exception that in DC machines the air gap is usually constant under the poles.

2.1.2 Slot Windings

Here we concentrate on symmetrical, three-phase AC distributed slot windings, in other words rotating-field windings. However, first, we discuss the magnetizing winding of the rotor of a nonsalient-pole synchronous machine, and finally turn to commutator windings, compensating windings and damper windings. Unlike in the salient-pole machine, since the length of the air gap is now constant, we may create a cosinusoidally distributed flux density in the air gap by producing a cosinusoidal distribution of current linkage with an AC magnetizing winding, Figure 2.3. The cosinusoidal distribution, instead of the sinusoidal one, is used because we want the flux density to reach its maximum on the direct axis, where $\alpha = 0$.

In the case of Figure 2.3, the function of the magnetic flux density approximately follows the curved function of the current linkage distribution $\Theta(\alpha)$. In machine design, an equivalent air gap δ_e is applied, the target being to create a cosinusoidally alternating flux density in the air gap

$$B(\alpha) = \frac{\mu_0}{\delta_e}\Theta(\alpha). \tag{2.1}$$

The concept of equivalent air gap δ_e will be discussed later.

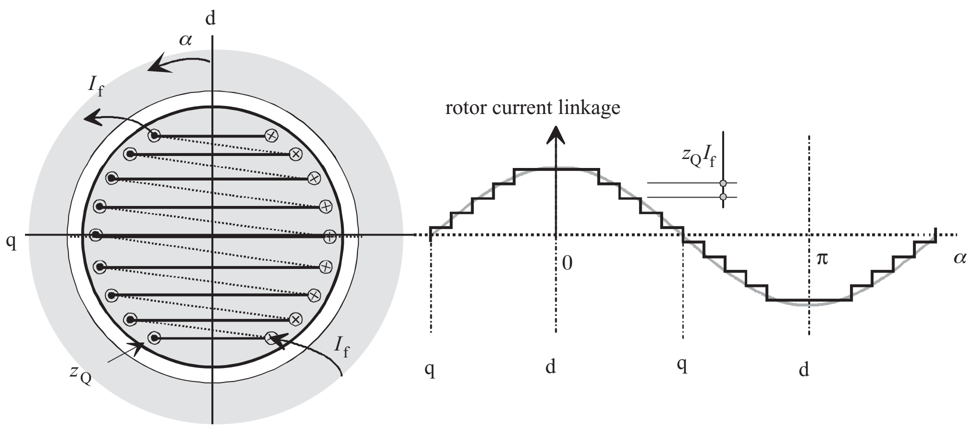

Figure 2.3 Current linkage distribution created by two-pole nonsalient-pole winding and the fundamental of the current linkage. There are z_Q conductors in each slot, and the excitation current in the winding is I_f. The height of a single step of the current linkage is $z_Q I_f$