

Chapter 18

Synchronous Machines

The following chapters study principles of operation, construction, mathematical model, and basic characteristics of synchronous machines. Along with induction machines, synchronous machines belong to the group of AC machines. Their operating principles are different. The rotor of induction machines revolves at the speed slightly lower than the synchronous speed, thus their name *asynchronous* machines. The rotor of synchronous machines revolves at the synchronous speed.

In both induction and synchronous machines, revolving magnetic field is created by AC currents in the three-phase windings of the stator. The stator magnetic circuits and the stator windings of induction and synchronous machines are very much the same. In both cases, three-phase system of stator currents creates rotating magnetomotive force and rotating field of magnetic inductance. The field revolves at the speed which is determined by the angular frequency of the stator currents, also called power supply frequency. Synchronous machines and induction machines have different construction of their rotors. The rotor winding in most induction machines is a short-circuited cage made of aluminum bars which are placed in the rotor slots. Rotor in synchronous machines may have excitation winding or permanent magnets. The rotor with excitation winding is supplied with DC currents that create the rotor magnetomotive force and the rotor flux. Instead of excitation windings, rotor of synchronous machines may have permanent magnets built into the rotor magnetic circuit. In this case, the rotor does not have any windings.

The principles of operation of induction machines have been described in Chap. 14. The rotor windings of an induction machine are short-circuited. When the rotor of an induction machine falls behind the revolving field by the amount of slip, the electromotive forces are induced in short-circuited rotor windings, and the rotor currents appear as a consequence. By joint action of the induced rotor currents and magnetic field, induction machine generates the electromagnetic torque, proportional to the slip. The torque generation process requires the rotor to revolve somewhat slower than the field, so that the revolving field advances with respect to the rotor by the amount of slip. Certain amount of slip is required in order to change the rotor flux and create electromotive forces and electrical currents in rotor bars.

It has been shown in [Chap. 14](#) that electromagnetic torque of an induction machine depends on the angular frequency of rotor currents $\omega_{slip} = \omega_e - p\Omega_m$, which is determined by the rotor lagging with respect to revolving field. In rated operating conditions, the rotor of an induction machine does not rotate synchronously with the field. Therefore, induction machines are also called *asynchronous machines*.

Rotor in synchronous machines is either an electromagnet or a permanent magnet. Position of the rotor flux is uniquely defined by the position of the rotor. In rated operating conditions, the rotor revolves synchronously with the stator field. Electromagnetic torque is proportional to the vector product of the stator and rotor flux vectors. The synchronous rotation of the rotor is the reason for this type of electrical machines to be called *synchronous machines*.

In this chapter, basic operating principles of synchronous machines are introduced and explained. The torque generation is discussed for the machines with an excitation winding on the rotor and for the machines with permanent magnets. The construction of stator windings and stator magnetic circuit is rather similar to that of the induction machine. It is reinstated briefly, along with generation of the revolving magnetic field of the stator winding. The rotor construction is explained in more detail. The available methods of supplying the DC excitation current to rotors with an excitation winding are introduced, explained, and discussed, including the sliding rings with brushes and the transformer with revolving secondary and rectifier circuit on the rotor. This chapter reviews most significant characteristics of permanent magnet materials. Two different ways of inserting permanent magnets into the rotor magnetic circuits are explained and discussed. Magnetic and electrical properties of synchronous machines with buried magnets and surface-mounted magnets are studied. In particular, the difference in self-inductance of the stator windings is discussed and explained for buried magnet machines and surface-mounted magnet machines.

18.1 Principle of Operation

Like induction machines, synchronous machines have AC currents in stator windings. Stator currents create the stator magnetomotive force F_S which revolves at the speed $\Omega_e = \omega_e/p$, also called synchronous speed. The synchronous speed is determined by the angular frequency ω_e of stator currents and by the number of pole pairs p . The stator magnetomotive force creates the stator flux $\Phi_S = F_S/R_\mu$, which depends on magnetic resistance R_μ . The flux Φ_S rotates at the same speed Ω_e as the magnetomotive force. Rotor in synchronous machines may have permanent magnets built into magnetic circuit or excitation windings supplied by DC current. In both cases, the rotor flux Φ_R has the course and direction determined by the rotor position. The flux vector Φ_R rotates at the rotor speed Ω_m . With $\Omega_m = \Omega_e$, both the stator flux vector Φ_S and the rotor flux vector Φ_R revolve at the same speed. They do not change their relative position and maintain the angle between the two vectors constant. The torque and power of electromechanical conversion are dependent on

the vector product of the two flux vectors. The vector product depends on the angle between the two vectors. With $\Omega_m = \Omega_e$, the two flux vectors do not change their relative position. The electromagnetic torque is proportional to the product of the two flux amplitudes and to the sine of the angle between the two flux vectors. With constant flux amplitudes and constant relative position between the two flux vectors, the electromagnetic torque remains constant. The operation of synchronous machines and the torque development require synchronous rotation ($\Omega_m = \Omega_e$) of the stator field, created by the stator currents, and the rotor field, created by excitation winding or permanent magnets.

18.2 Stator Windings

Stator of a synchronous machine is very much the same as the stator of an induction machine. Current circuits on the stator side have three separate parts called stator phase windings or stator phases. Each phase is obtained by connecting a number of turns in series. Relevant conductors are distributed along the machine circumference and placed into slots. The stator slots are carved into the inner side of the stator magnetic circuit, facing the air gap. Distribution of stator conductors along the machine circumference is quasisinusoidal. That is, an attempt is made to achieve sinusoidal change of the conductor density along the circumference. Ideal sinusoidal distribution cannot be achieved due to a finite number of slots. Conductors cannot be placed in an arbitrary position. They have to be placed in one of the slots. Hence, there are a limited number of discrete locations for the placement of stator conductors. For this reason, sinusoidal distribution of stator conductors along the machine circumference cannot be achieved in full. Yet, the windings are made in such way that the distribution of conductors gets as close to sinusoidal as possible. Each of the three-phase windings has two terminals. One end of each phase winding is connected to the three-phase voltage source which supplies the stator windings. Stator terminals of synchronous generators may be connected to three-phase electrical loads. Remaining ends of the three-phase windings are wired together into the node called *star point*. This way of connecting the stator phases is called *star connection*. With the sum of the three-phase currents equal to zero, $i_a(t) + i_b(t) + i_c(t) = 0$, there is no need to connect the star point to the source; thus, no return line is required. Most machines¹ have their star points disconnected from the power

¹Electrical machines supplied the mains with line voltages $U < 1$ kV are also called low-voltage machines. Most low-voltage machines have star connected stator windings with floating star point. Namely, the star connection of the three phases is not connected to any other node. In most cases, the star point is even inaccessible, namely, it is not made available to the user. Machines with stator voltages in excess to 1 kV may have their star point connected to the neutral or to the ground by means of a series impedance. This connection reduces the overvoltage stress. In most cases, the impedance used for grounding the star point has a minor effect on the equation $i_a + i_b + i_c = 0$.

supply (floating). In some cases, the three phases of the stator winding are connected in triangle, and this way of connecting the phase windings is called *delta connection*. There is no star point in a delta connection.

Each phase winding creates magnetomotive force which is determined by the number of turns of the phase winding and by the electrical current of the phase winding. Each phase winding with AC currents creates variable magnetomotive force. Currents i_a , i_b и i_c in individual phases of the stator winding create magnetomotive forces F_a , F_b , and F_c . Corresponding magnetomotive force vectors are positioned along magnetic axis of each phase winding. Magnetic axes of the phases that make a two-pole winding system are displaced by $2\pi/3$. Resulting stator magnetomotive force F_S is obtained by vector summation of the three magnetomotive forces, F_a , F_b , and F_c , created by the three-phase windings.

18.3 Revolving Field

Magnetic axes of the stator phases as well as magnetomotive forces F_a , F_b , and F_c are displaced in space by $2\pi/(3p)$, where p is the number of pairs of magnetic poles. The stator winding can be arranged so as to produce magnetic field with more than two magnetic poles. Example of four-pole stator winding has been explained in Chap. 17.

Revolving magnetic field with two magnetic poles is established by AC currents in two-pole stator windings. With phase currents of the same amplitude I_m and frequency ω_e , and with their initial phases displaced by $2\pi/3$, a two-pole stator winding creates two-pole stator field which revolves at the speed $\Omega_e = \omega_e/p = \omega_e$, also called synchronous speed. With stator windings that create magnetic field with more than one pair of magnetic poles ($p > 1$), the stator field revolves at the speed $\Omega_e = \omega_e/p$.

Magnetomotive forces of the three-phase windings are given in (Fig. 18.1), assuming that the currents have the same amplitude I_m , the same angular frequency ω_e , and the initial phases mutually shifted by $2\pi/3$. It is assumed that each phase winding has N_s turns:

$$\begin{aligned} F_a &= N_s I_m \cos \omega_e t, \\ F_b &= N_s I_m \cos \left(\omega_e t - \frac{2\pi}{3} \right), \\ F_c &= N_s I_m \cos \left(\omega_e t - \frac{4\pi}{3} \right), \end{aligned} \quad (18.1)$$

By summing the magnetomotive forces of individual phases, one obtains the resultant magnetomotive force of the stator winding, represented by the vector F_S in Fig. 18.2. This vector revolves at synchronous speed. Calculation of the amplitude

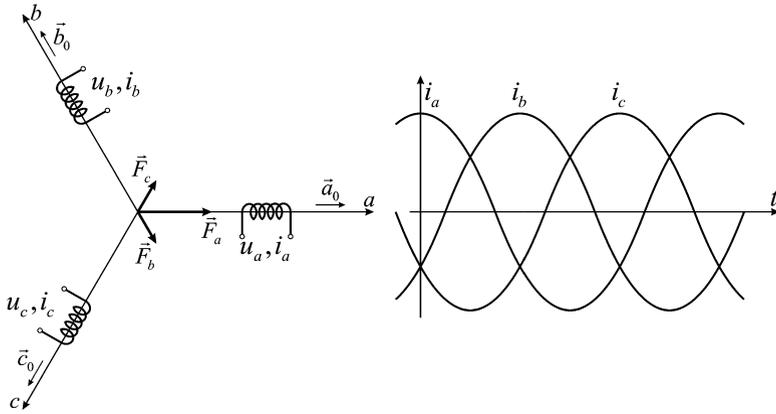


Fig. 18.1 Three-phase stator winding of synchronous machine

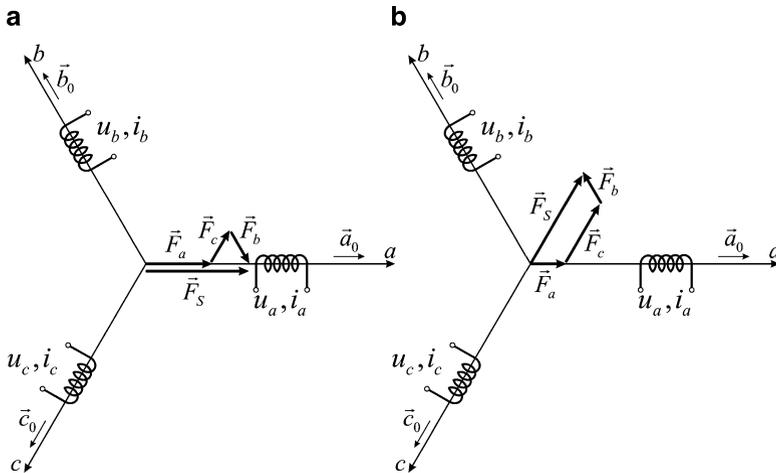


Fig. 18.2 Spatial orientation of the stator magnetomotive force

and spatial orientation of the magnetomotive force created by three-phase stator windings is explained in Chap. 15. Considering (18.1), magnetic field revolves at the speed $\Omega_e = \omega_e/p$ and maintains a constant amplitude.

Initial phase of stator currents determines the spatial orientation of the stator magnetomotive force F_S at instant $t = 0$. At steady state, the vector F_S in synchronous machines has to revolve in synchronism with the rotor. The torque depends on the sine of the angle between the rotor flux vector and the vector F_S of the stator magnetomotive force. When the stator field F_S/R_μ revolves in synchronism with the rotor, synchronous machine develops a constant torque and constant power.

Magnetomotive force vectors of individual phases are oriented along magnetic axes of respective phase windings. With two-pole stator winding, the axes are

displaced by $2\pi/3$. Amplitudes of magnetomotive forces F_a , F_b и F_c are determined by the phase currents $i_a(t)$, $i_b(t)$ и $i_c(t)$, and by the number of turns N_S in each phase winding. The resultant magnetomotive force F_S is the vector sum of magnetomotive forces of individual phases. The quotient F_S/R_μ of the magnetomotive force and magnetic resistance R_μ gives the vector of the stator flux Φ_S . The flux Φ is the surface integral of the magnetic inductance B , and it represents the flux in one stator turn. The stator flux Φ_S is the vector sum of flux vectors F_a/R_μ , F_b/R_μ , and F_c/R_μ .

The winding flux Ψ represents the flux of all the turns of the winding. It depends on the number of turns N . In cases where the winding is concentrated, all conductors of the winding are placed in two diametrical slots. Then, the winding flux Ψ is the product of the flux Φ in one turn and the number of turns, $\Psi = N\Phi$.

In most cases, the stator conductors are distributed along the air gap circumference with a quasisinusoidal line density of conductors. Therefore, not all the turns of the phase winding are in the same place, and they do not have the same flux. The flux in individual turns depends on the position, and it is expressed as $\Phi_S(\theta)$, where the angle θ represents the position of the turn. The winding flux cannot be obtained by multiplying the flux in one turn by the number of turns. Instead, it has to be calculated by integration, as explained in introductory chapters. For the phase winding with quasisinusoidal distribution of conductors, with N_S turns, and with the maximum value of the flux in one turn equal to Φ_m , the winding flux is determined by $\Psi = (\pi/4)N_S\Phi_{Sm}$.

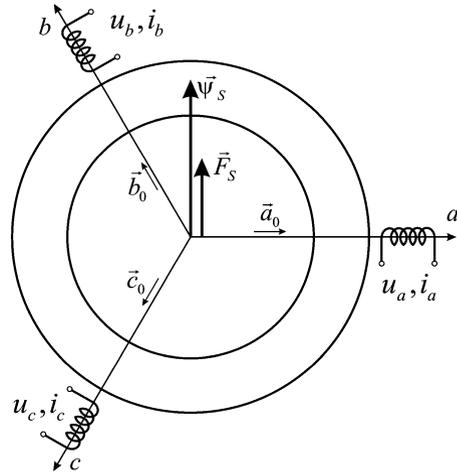
The stator flux revolves at the speed Ω_e , which is determined by the angular frequency of the stator phase currents. One part of the stator flux encircles the stator conductors, but it does not pass through the air gap and does not reach the rotor magnetic circuit. This component of the flux is called *leakage flux*, and it has the same nature as the leakage flux described in chapters discussing induction machines. The remaining part of the stator flux passes through the air gap and reaches the rotor magnetic circuit. This component is called *mutual flux* or *air gap flux*. Along with the contribution from the rotor, it makes up the total air gap flux of the machine.

The electromagnetic torque is created by joint action of the stator and rotor flux vectors. Rotor of synchronous machine may have permanent magnets which create the rotor flux. There are also synchronous machines with an *excitation winding* on the rotor. DC currents in excitation winding create the rotor magnetomotive force and the rotor flux.

The flux of the stator winding system comprising three-phase windings is defined in (18.2), where R_μ is magnetic resistance and N_S is the number of turns per phase. The stator flux vector is denoted by Ψ_S . It is obtained by dividing the magnetomotive force F_S by magnetic resistance, and it is shown in Fig. 18.3. The flux linkages of individual phases are denoted by Ψ_a , Ψ_b , and Ψ_c , and they depend on the amplitude of the flux vector Ψ_S and its relative position with respect to magnetic axis of relevant phase winding:

$$\vec{\Psi}_S = N_S \frac{\vec{F}_S}{R_\mu}. \quad (18.2)$$

Fig. 18.3 Vectors of the stator magnetomotive force and flux



18.4 Torque Generation

With permanent magnets built into the rotor magnetic circuit, the rotor generates the flux which moves along with the rotor. The same way, the rotor with an excitation winding creates the rotor magnetomotive force and the rotor flux which moves with the rotor. Hence, the rotor flux vector has the position which is equal to position of the rotor. At the same time, the stator currents create the magnetomotive force F_S and the stator flux Ψ_S . For both stator and rotor flux vectors, corresponding magnetic poles are identified as the regions where the lines of magnetic field enter or exit the iron parts of magnetic circuit. Regarding the stator flux, position of corresponding magnetic poles is defined by direction of the revolving magnetomotive force F_S , created by the stator currents. Magnetic poles of the rotor flux are defined by the rotor position. Electromagnetic forces tend to bring the opposite stator and rotor magnetic poles in close vicinity (Fig. 5.3). When the stator field rotates in such way that the north stator pole leads and remains ahead of the south rotor pole, there is a constant electromagnetic torque which tends to increase the rotor speed. Considering vectors shown in Fig. 18.4, the torque acts toward bringing the rotor flux Ψ_R closer to the vector F_S . The torque can be expressed as the vector product between the stator magnetomotive force and the rotor flux:

$$\vec{T}_{em} = k_t \vec{\Psi}_R \times \vec{F}_S.$$

Developing constant torque and performing continuous electromechanical conversion require that relative position of the stator and rotor vectors remains unchanged. This condition is met when the rotor revolves at synchronous speed Ω_e , which is the angular speed of the stator field F_S .

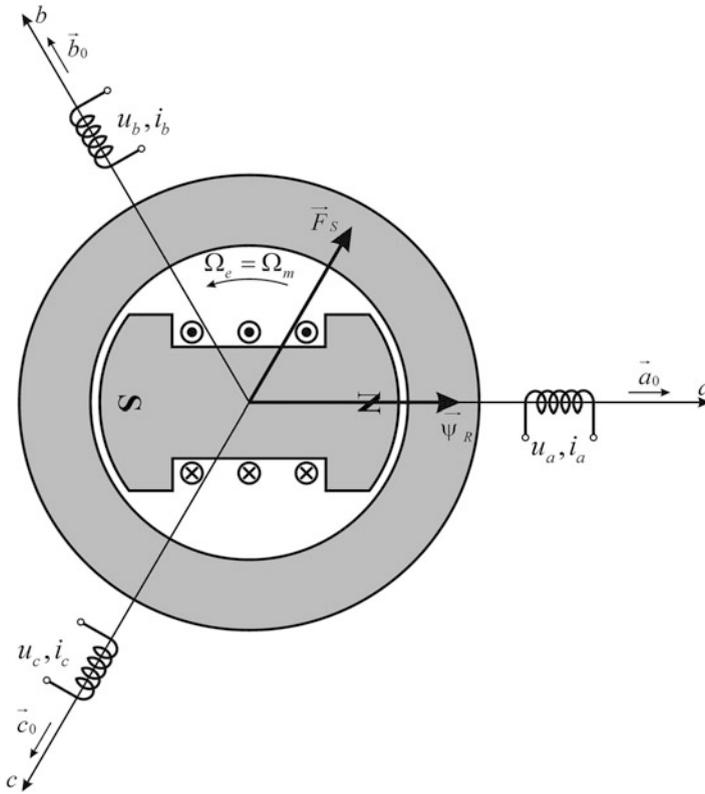


Fig. 18.4 Position of rotor flux vector and stator magnetomotive force

Dividing the vector F_S by the number of turns N_S , one obtains the vector with course and direction of F_S , and with the amplitude equal to the stator current. In further considerations, the vector F_S/N_S is called *stator current vector*. The torque can be expressed as the vector product of the rotor flux Φ_R and the vector of the stator current, $T_{em} = k_t N_S \Phi_R \times i_S = k_t N_S |\Phi_R| |i_S| \sin(\xi)$, where ξ denotes the angle between the rotor flux vector and the stator current vector, while $|i_S|$ denotes the amplitude of the stator current.

For the given rotor flux, required torque can be obtained with different pairs of values $(|i_S|, \xi)$. The amplitude of the stator current required to obtain desired torque is lower when $\sin(\xi)$ is higher, and it reaches the minimum in cases where the relevant vectors are orthogonal. With $\xi = \pm\pi/2$ and with the smallest possible $|i_S|$, corresponding copper losses in the stator winding reach their minimum. Condition $\xi = \pm\pi/2$ provides the possibility to obtain the maximum torque for the given current amplitude $|i_S|$. In other words, it maximizes the *torque-per-Ampere* ratio $T_{em}/|i_S|$.

In order to maximize the torque-per-Ampere ratio in synchronous machines, it is necessary to establish the phase currents i_a , i_b , and i_c so as to obtain the stator

magnetomotive force vector F_S which is perpendicular to the rotor flux. Hence, whatever the rotor speed or position, the vector F_S is to be locked to the rotor position, advancing with respect to the rotor flux by $\pi/2$. In such cases, the electromagnetic torque is determined by the amplitude of the stator current, $T_{em} = k_t N_S |\Phi_R| |i_S|$. Negative values of the torque are obtained when the vector F_S falls behind the rotor flux by $\pi/2$. This approach is used in controlling the torque of permanent magnet synchronous machines used in motion control applications. These synchronous machines are also called synchronous servomotors, and they are distinguished by low inertia of the rotor and high ratio of the peak torque and the rated torque. In motion control applications, each synchronous servomotor is supplied from a separate three-phase inverter which supplies the motors with the phase currents required for generating the set torque. By using the current regulator with pulse width modulation control, the stator voltages are adjusted so as to obtain desired phase currents i_a , i_b , and i_c . Three-phase inverters with pulse width modulation and with current regulator are also called *current regulated pulse width modulated inverters* or CRPWM inverters.

Question (18.1): Consider two induction machines with short-circuited rotor cage and with the same dimensions of stator and rotor magnetic circuits. One of these is a two-pole induction machine while the other is a four-pole machine. The rotors of both machines are taken out of their stators. A new machine is made by inserting the rotor of the second machine into the stator of the first machine. Is it possible for the new machine to develop any torque?

Answer (18.1): The torque development is based on interaction of the stator and rotor magnetic fields. In order to obtain the electromagnetic torque, it is necessary that the rotor and stator fields have the same number of magnetic poles. Magnetic field of the stator of an induction machine is created by magnetomotive forces caused by electrical currents in the stator windings. The stator windings of the first machine generate a two-pole magnetic field, while the stator windings of the second machine create a four-pole magnetic field. The latter has two north magnetic poles and two south magnetic poles. In both machines, magnetic field of the rotor depends on the currents induced in the rotor conductors. The rotor currents appear as a consequence of electromotive forces induced in the rotor cage. Electromotive forces depend on magnetic induction in the air gap, and they also depend on the slip speed. The change in amplitude and direction of the rotor electromotive forces and currents reflects the change of the air gap inductance B . Therefore, the number of magnetic poles of consequential rotor flux is the same as the number of poles of the stator magnetic field. Hence, one and the same rotor creates a two-pole field while operating within a two-pole stator and a four-pole field when operating in a four-pole stator. Therefore, the machine made by combining the stator of the first machine with the rotor of the second machine will be capable of running as a proper induction machine, and it will develop the torque.

Question (18.2): Consider two synchronous machines, each with permanent magnet rotor. Both machines have equal dimensions of their rotor and stator magnetic

circuits. The first machine is a two-pole machine while the second is a four-pole machine. A new machine is made by inserting the rotor of the second machine into the stator of the first machine. Would this new machine be able to develop any torque?

Answer (18.2): Unlike induction machines, synchronous machines have the rotor flux created by an excitation winding on the rotor or by permanent magnets build into the rotor magnetic circuit. With permanent magnet excitation, the number of magnetic poles depends on configuration of the permanent magnets. With an excitation winding, the excitation current is not induced from the stator side. Instead, it is provided from a separate source of DC current. The way of making the excitation winding determines the number of magnetic poles of the rotor field. Hence, with both permanent magnet excitation and with excitation winding, the number of magnetic poles of the rotor field of synchronous machines depends on the rotor design. In other words, the number of magnetic poles of the rotor field does not depend on the number of poles of the stator field, which was the case with induction machines. Synchronous machine operates properly and develops electromagnetic torque only in the case when the stator and rotor have the same number of magnetic poles. A combination of a two-pole stator with a four-pole rotor would not develop any electromagnetic torque.

18.5 Construction of Synchronous Machines

Synchronous machines have stator with three-phase windings and rotor with either excitation winding or with permanent magnets. The stator terminals are connected to a symmetrical system of three-phase voltages and currents. The stator currents create revolving magnetic field in the air gap of the machine. For the proper operation of synchronous machine, the stator field has to revolve at the same speed as the rotor. Electromagnetic torque is created from interaction of the two magnetic fields. Synchronous machines can be made in the form of discs or cylinders; they can have hollow rotor, and there are also linear synchronous machines which perform translation rather than rotation. Synchronous machines are mostly cylindrical machines (Fig. 18.5).

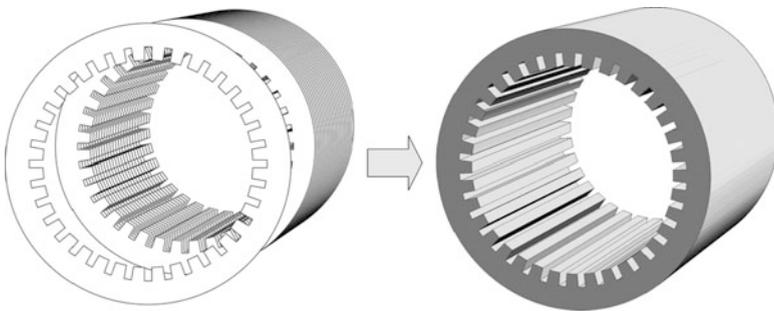


Fig. 18.5 Stator magnetic circuit is made by stacking iron sheets

18.6 Stator Magnetic Circuit

Stator of cylindrical synchronous machines is a hollow cylinder which accommodates the rotor. The main parts of the stator are magnetic circuit and current circuits, also called phase windings. Magnetic circuit is made of ferromagnetic materials, usually iron alloys, while the current circuits consist of insulated copper conductors.

Stator of synchronous machines is entirely the same as the stator of an induction machine. Magnetic induction B in the stator magnetic circuit changes due to rotation of the magnetic field with respect to the stator core. Induction B varies with the frequency ω_e , which is the angular frequency of the stator currents. Variation of magnetic induction causes eddy current losses and hysteresis losses in conductive ferromagnetics. The losses due to eddy currents are proportional to the square of the frequency, while the losses due to hysteresis are proportional to the frequency. In synchronous machines supplied from the mains, magnetic induction in the stator magnetic circuit pulsates at the frequency of $f_e = 50$ Hz (60 Hz). In order to reduce losses in the stator magnetic circuit, it is made by stacking the iron sheets. The sheets are separated by a thin layer of electric insulation.

The iron sheets are actually made of iron alloys comprising small quantities of manganese and other elements. Lamination of magnetic circuit does not reduce the hysteresis losses, but it suppresses the eddy currents and reduces the overall iron losses in magnetic circuit caused by the pulsation of magnetic induction. Since the magnetic field revolves with respect to the stator, magnetic induction in stator magnetic circuit changes direction. For this reason, it is essential for the iron sheets to have the same magnetic properties in all directions. Such sheets are obtained by *hot rolling* of steel, and they are called *hot rolled sheets*. On the other hand, magnetic circuits used in power transformers have the field which is always directed along the same path. Therefore, it is important to have improved magnetic properties along the flux path, while the properties in directions perpendicular to the path are of lesser importance. In such cases, it is beneficial to use anisotropic² material, optimized to provide a low magnetic resistance along the flux path. The sheets with such properties are obtained by cold rolling. Hence, the iron sheets used in power transformers are *cold rolled sheets*. Cold rolling results in reduced magnetic resistance in direction of rolling, which should correspond to the flux path within power transformer.

By stacking the sheets, one obtains a hollow cylinder with slots on the inner surface which faces the air gap. The slots are intended for placing conductors of the stator winding. Parts of the stator magnetic circuit between the slots are called teeth. The flux passing toward the air gap is directed through the teeth, made of iron of high-permeability and low magnetic resistance. The flux does not pass through the slots, where permeability is μ_0 and where magnetic resistance is high. Therefore, magnetic induction inside teeth is higher compared to the rest of the stator magnetic circuit, which results in increased teeth iron losses.

² Anisotropic – having different properties in different directions. For example, anisotropic ferromagnetic may have different permeability in direction of axes x , y , and z .

18.7 Construction of the Rotor

The rotor of synchronous machines with permanent magnets built into magnetic circuit is shown in the part (A) of Fig. 18.6. Permanent magnets are ferromagnetic materials capable of providing the rotor flux without an excitation winding. Magnetizing characteristic $B(H)$ of permanent magnets has a relatively high remanent induction B_r . In absence of rotor windings, there is no rotor magnetomotive force $F = NI$; thus, there are no external means to create and control the rotor flux but the permanent magnets. With sufficient remanent induction of permanent magnets, it is possible to achieve significant values of the rotor flux. By inserting permanent magnets into the rotor magnetic circuit, the rotor flux is obtained in a lossless manner, without a need of making the rotor windings. This simplifies the machine construction, reduces the losses, and increases efficiency. One shortcoming of this solution is the lack of possibility to change the rotor flux. Without the flux control, the field-weakening operation of permanent magnet synchronous machines is virtually impossible.

The part (b) of Fig. 18.6 shows the rotor with electromagnetic excitation. This rotor has an excitation winding with N_R turns carrying DC current i_R . The magnetomotive force of the excitation winding $F_R = N_R i_R$ determines the excitation flux $\Phi_R = N_R i_R / R_\mu$ and the flux of the excitation winding $\Psi_R = N_R \Phi_R = (N_R^2 / R_\mu) i_R = L_R i_R$. There is a small amount of the rotor flux which encircles the excitation winding, but it does not

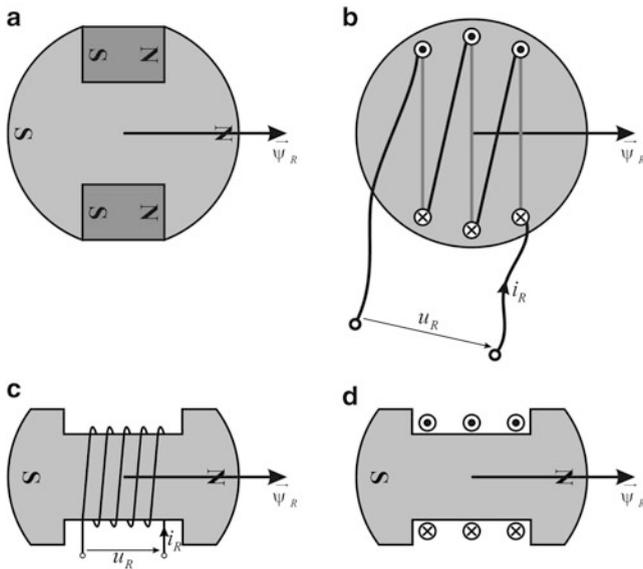


Fig. 18.6 (a) Rotor with permanent magnets. (b) Rotor with excitation winding. (c) Rotor with excitation winding and salient poles. (d) Common symbol for denoting the rotor in figures and diagrams

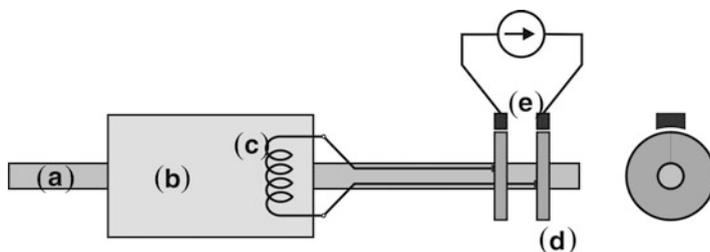


Fig. 18.7 Passing the excitation current by the system with slip rings and brushes. (a) Shaft. (b) Magnetic circuit of the rotor. (c) Excitation winding. (d) Slip rings. (e) Brushes

pass through the air gap and does not reach the stator magnetic circuit and the stator windings. This flux is called excitation leakage flux. Major part of the excitation flux encircles both the rotor and stator winding; it contributes to the mutual flux Ψ_m and it is denoted by Ψ_{mR} . This flux is the bases for the process of electromechanical energy conversion and for creation of the electromagnetic torque.

Magnetic core of the rotor with excitation winding may have *salient poles*, and one such case is shown in Fig. 18.6c. Salient pole rotors have a small air gap and a low magnetic resistance along the path of the excitation flux, while the air gap in direction perpendicular to the flux is larger, causing a larger magnetic resistance.

Commonly used symbol that represents the rotor in figures and diagrams is shown in Fig. 18.6d. Although it resembles a salient pole rotor, it is also used as a simplified representation of cylindrical rotors, such as the one in Fig. 18.6b, which have the same air gap and the same magnetic resistance along the circumference.

Advantage of electromagnetic excitation over permanent magnet excitation is that the latter allows variation of the excitation flux by varying the excitation current i_R . Shortcomings of this solution are increased losses and more complex construction of the machine, owing to the need to feed DC current i_R to the winding which is mounted on the rotor. The excitation voltage u_R supplied to the terminals of the excitation winding needs to be wired to an external DC source. This source is placed on the stator side, the side that does not move, while the excitation winding resides on the rotor which revolves with respect to the stator. This brings up the problem of passing the excitation current to the moving part of the machine (Fig. 18.7).

18.8 Supplying the Excitation Winding

Supplying the excitation winding can be performed by means of the slip rings fastened to the rotor shaft. The two terminals of the excitation winding can be wired to a pair of slip rings, both of them with mutual electrical insulation and insulated from the shaft. Two conductive brushes can be fastened to the stator and pressed against respective slip ring, providing in this way an electrical access to the excitation winding. While the rotor is in motion, the brushes slide against

the rings and maintain electrical contact. DC current fed to the brushes passes to the slip rings and gets to the terminals of the excitation winding. Prescribed method of supplying the excitation winding from the stator side passes the DC current from an external source to the excitation winding. It works both with the rotor in motion and with the rotor at standstill. By changing the excitation voltage, the excitation current can be adjusted so as to provide the rotor flux that corresponds to desired operating mode of the machine.

Large hydrogenerators that operate in hydroelectric power plants as well as turbogenerators that operate in thermal power plants have electromagnetic excitation that includes the excitation winding on the rotor. Electrical current in excitation winding is adjusted so as to obtain desired voltage across the stator terminals. The stator electromotive force determines the stator voltage. At the same time, the electromotive force is proportional to the rotor flux. Hence, the stator voltage of synchronous generators can be increased or decreased by changing the excitation current. Variation of generator voltages is required in order to compensate for variable voltage drops between the power plants and electrical consumers. As the consumption of electrical power at the consumer side increases, the generator load increases as well as the stator current. An increased current produces larger voltage drops in transmission lines, power transformers, and distribution cables. In order to keep the consumer voltages constant, it is necessary to increase the voltage of synchronous generators. This increase is required to compensate for the increased voltage drops in transmission and distribution. The goal is achieved by increasing the excitation current of synchronous generators.

One shortcoming of the excitation system with slip rings is that the excitation current passes through the contact between the brushes and slip rings. The rotor motion makes the contact surfaces slide against each other. With unsteady electrical contact, electric arc may appear in the course of rotation. Sporadic arcing presents the fire risk and increases electromagnetic interference. Besides, arcing and friction contribute to wear of the sliding rings and brushes. This in turn requires repairs and maintenance. Besides, the presence of slip rings increases the axial length of the machine.

18.9 Excitation with Rotating Transformer

The transfer of the excitation power to the rotor without mechanical contact can be accomplished by using a rotating transformer, the principles of which are depicted in Fig. 18.8. Primary winding of this transformer is on the stator side of the machine, along with one half of the transformer magnetic circuit. Both transformer parts are attached to the stator and do not move. The stator side of the transformer magnetic circuit has the shape of a ring. Along the circumference, a slot is carved into the inner surface of the ring, and the primary winding is placed into this slot. The other part of the transformer magnetic circuit is attached to the rotor shaft, and it moves with the rotor. It has the shape of a ring of a smaller diameter so that it fits into the stator part of the transformer magnetic circuit. A slot

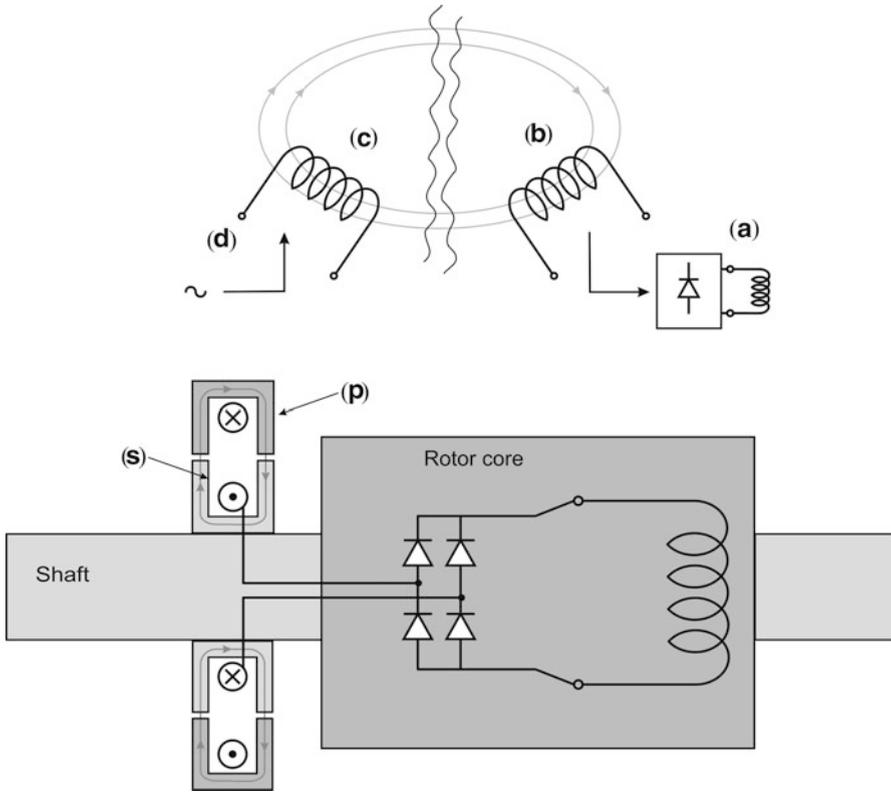


Fig. 18.8 Contactless excitation system with rotating transformer. (a) Diode rectifier on the rotor side. (b) Secondary winding. (c) Primary winding. (d) Terminals of the primary fed from the stator side. (P) Stator part of the magnetic circuit. (S) Rotor part of the magnetic circuit

is carved into the outer side of this ring, and it houses the secondary winding of the rotating transformer. It is observed in Fig. 18.8 that conductors of primary and secondary windings of the rotating transformer have tangential direction. Namely, they are wound around the shaft. The circumstance that one part of the magnetic circuit rotates with respect to the other part does not preclude establishing the mutual flux of the transformer. This flux couples the primary and secondary windings and provides for customary transformer function of passing the electrical energy from the primary to the secondary side. The field lines that represent the mutual flux are shown in Fig. 18.8.

Primary winding of the rotating transformer is supplied by an external source of AC current with the frequency ranging from several hundred Hz to several kHz. Due to magnetic coupling between the primary and secondary windings, the AC currents are transferred from the primary to the secondary side of the transformer. In this way, the secondary winding provides the source of AC currents that are made available at the rotor side of the machine. In order to supply the excitation winding

with DC currents, the rotor has a diode bridge. This bridge rectifies AC currents of the secondary winding and obtains DC current which is fed to the excitation winding. The excitation current can be varied by changing the amplitude of the primary AC current. Described excitation system uses a contactless transfer of the excitation power to the rotor. It does not involve any friction or mechanical wear. Therefore, it offers high reliability and low maintenance. When applying a rotating transformer with a diode rectifier built into the rotor, the rotor temperature has to be limited to 125–150°C so as to avoid damage to semiconductor diodes.

18.10 Permanent Magnet Excitation

By inserting permanent magnets into the rotor magnetic circuit, synchronous machine obtains the rotor flux without any excitation winding and with no rotor currents. In rare cases, the whole rotor is made of permanent magnets. In majority of cases, only one part of the rotor volume is filled with permanent magnet materials while the remaining, larger part of the rotor magnetic circuit is made of ferromagnetic materials such as iron sheets. The quantity of magnets is determined so as to produce sufficient rotor flux for the operation of the machine. The iron part of the rotor has dedicated holes for the insertion of magnet modules (Fig. 18.9).

During regular operation of synchronous machine, the rotor revolves in synchronism with the stator field. Therefore, there is no variation of magnetic induction in the rotor magnetic circuit and no iron losses.³ In absence of rotor windings and absence of iron

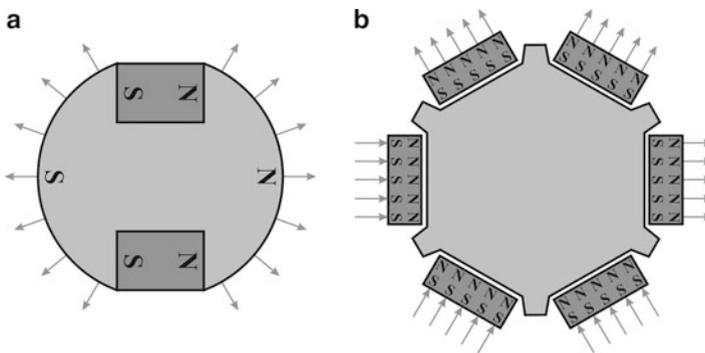


Fig. 18.9 (a) Rotor with interior magnets. (b) Surface-mounted magnets

³ In synchronous motors supplied from three-phase inverters with pulse width modulation, there is a certain current ripple, a high-frequency component of the stator current with an amplitude of $0.02 \dots 0.03 I_n$ and with the frequency which is equal to the switching frequency of power transistors. Due to this nonsinusoidal supply, there are some small, high-frequency variations of the magnetic induction within the rotor circuit, notwithstanding the fact that the fundamental flux component revolves in synchronism with the rotor.

losses in rotor magnetic circuit, there is no heat generated within the rotor. As a consequence, there is no need to devise any particular measures for cooling of the rotor. Without the rotor heat, cooling of the stator winding and the stator magnetic circuit is easier to achieve in synchronous machines than in induction machines. For this reason, there is a certain margin to increase the current and flux densities in synchronous machine. With increased current density and increased magnetic induction, synchronous machines can deliver more torque and more power from the same volume. Alternatively, for the given torque and given power, synchronous machines can be designed with lower size and lower weight than equivalent induction machines. Hence, specific torque⁴ and specific power of synchronous permanent magnet machines are higher compared to induction machines.

The problem of synchronous machines with permanent magnets is the absence of possibility of changing the rotor flux. For this reason, permanent magnet machines have difficulties operating in field-weakening mode. Permanent magnets can be built on the surface of the rotor magnetic circuit (*surface mount*) or within the interior part of the magnetic circuit (*interior magnet* or *buried magnet*). The way of inserting the magnets has significant impact on the machine parameters and characteristics. It mostly affects the stator inductance L_s . The winding inductance is inversely proportional to the magnetic resistance, and the latter is greatly affected by the method of inserting the magnets. In synchronous machines with interior magnets, magnetic resistance is relatively small. The winding inductance has relative value that ranges from 0.1 up to 0.5. In machines with surface mount magnets, relative value of the winding inductance ranges from 0.01 up to 0.1.

Synchronous machines with permanent magnets have virtually no rotor losses, and their efficiency is higher compared to other kinds of electrical machines. Comparing the power balance of permanently excited synchronous machines to the power balance of induction machines, it has to be noted that the synchronous machine does not have the rotor losses sP_δ . With the rotor revolving at synchronous speed, relative slip s of synchronous machines is equal to zero. The absence of rotor losses contributes to a significant increase in the efficiency of synchronous machines.

Question (18.3): Efficiency of a two-pole induction motor running at the rated speed of $n_n = 2,850$ rpm is 90%. It is known that the iron losses are relatively small compared to copper losses. Make an estimate of efficiency of a permanent magnet synchronous motor of the same rated speed, same power, voltage, current, and dimensions.

Answer (18.3): Based on the problem formulation, the iron losses can be neglected in both machines. Mechanical losses are relatively small and similar in both cases. Therefore, they can be neglected in making an estimate of the efficiency. Required estimate should be made considering copper losses alone.

⁴ Specific torque is the ratio T_{em}/m , the quotient of the torque, and mass of the machine. Alternatively, specific torque can be defined as T_{em}/V , the quotient of the torque and volume.

In synchronous machines, there are copper losses in the stator winding only. Compared to synchronous machines, induction machines have the rotor losses as well, and their amount is $sP_\delta = P_{Cu2}$. The stator and rotor currents in induction machines have approximately the same amplitude. At the same time, the cross section of the stator and rotor slots is also similar, as well as the current density. Therefore, it is reasonable to assume that the copper losses in stator are comparable to the copper losses in rotor of induction machines. The rotor losses $s_r P_{\delta r}$ are close to $(3,000-2,850)/3,000 = 5\%$ of the rated power. Hence, a rough estimate of the stator losses of synchronous machine is 5%. Efficiency of an equivalent synchronous machine is close to 95%.

18.11 Characteristics of Permanent Magnets

Magnetizing characteristic of permanent magnet material is shown in Fig. 18.10. The abscissa represents the external field H , that is, the field brought into the considered domain by means of the factors outside the magnet. In most cases, external field is created by electrical currents in coils or windings placed in close vicinity of the magnet. Remanent induction B_R exists with no external field, with $H = 0$, and it may exceed 1 T. Smaller values of remanent induction such as 0.3 T are encountered with ferrite magnets. Majority of ferromagnetic materials such as iron have a small level of remanent inductance, which appears due to tendency of oriented magnetic dipoles to retain their direction after removing the external field (Fig. 18.11). A certain remanent induction exists even in iron sheets which are used in making magnetic circuits of electrical machines. This value has rather small remanent induction of $B_R < 50$ mT, which is readily reduced to zero by an external magnetic field H of opposite direction or by exposing magnetic material to elevated temperatures.

Relation between the magnetic induction within permanent magnet and the external field H is given in Fig. 18.10. By introducing an external magnetic field H of moderate intensity ($H > -H_c/2$) and direction opposite to remanent induction,

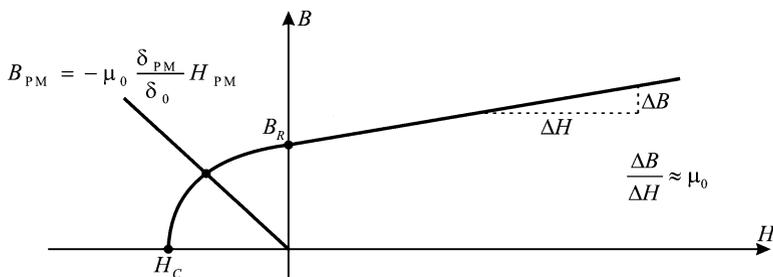


Fig. 18.10 Magnetizing characteristic of permanent magnet

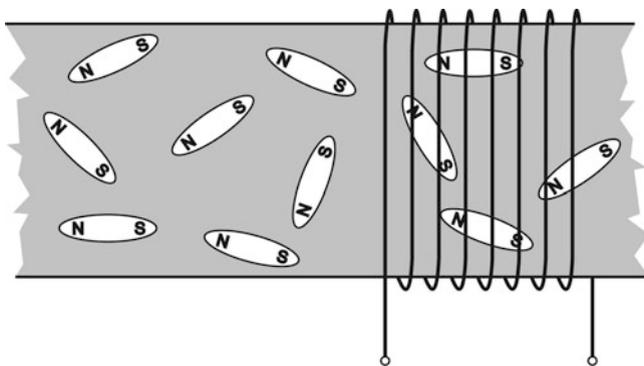


Fig. 18.11 Ferromagnetic material viewed as a set of magnetic dipoles

the operating point moves from $(0, B_R)$ toward the left, which results in some decrease of magnetic induction. Upon removing demagnetizing field H , the operating point returns to the initial position, to the point $(0, B_R)$ in Fig. 18.10.

In cases where the external field H reaches the value of *coercitive field* $-H_c$, magnetic induction drops to zero. This may cause permanent damage to the magnet. Namely, starting from the point $(-H_c, 0)$ and removing the field $-H_c$ does not necessarily bring the operating point back to $(0, B_R)$. Instead, the operating point may return to the point $(0, B_{R1})$ with much lower remanent induction $B_{R1} < B_R$. In such cases, the original remanent induction cannot be restored, and the damage to the magnet remains permanent. The remanent induction can be reduced by a factor of two or three. Damage to the magnet can be evaluated after removing the demagnetizing field $H < 0$.

In majority of permanent magnet materials, characteristic $B(H)$ has a point of inflection in the second quadrant called the *knee point*, where the external field $H < 0$ makes the magnetic induction reduce at an increased rate. The field strength at the knee point is approximately $H = -H_c/2$. In most cases, permanent damage to the magnet occurs when the operating point passes the knee point and proceeds the left, reaching the zones with $H < -H_c/2$.

Larger values of remanent induction B_R have positive impact on characteristics of synchronous machines with permanent magnets, since the rotor flux is proportional to B_R and the torque is proportional to the rotor flu. It is also beneficial to have a large coercitive field H_c , which delineates the magnet capability to withstand demagnetizing field. Quality of permanent magnets is measured by the product $B_R H_c$, which has dimensions of energy density. Magnets with *higher energies* have larger values of remanent induction and larger values of coercitive fields. They are more robust with respect to external fields, that is, they could operate with larger demagnetizing fields H without suffering any damage. This property helps the operation of permanent magnets built into the rotor magnetic circuit, where they get exposed to demagnetizing fields. The stator currents of synchronous machines produce considerable magnetomotive forces. These magnetomotive forces produce

relatively large magnetic field H within permanent magnets. In most cases, direction of this field opposes to magnetic induction of the magnet and causes demagnetization. For this reason, it is of interest to select permanent magnets with an adequate $B_R H_c$ product, that is, with an adequate *energy*. This choice is particularly important in synchronous servomotors where the peak torque and the peak stator current exceed their rated values by an order of magnitude, causing exceptionally large demagnetizing fields.

In the first quadrant of the $B(H)$ characteristic, all magnetic dipoles inside the magnet are already oriented in the direction of the field, and they already make their full contribution to magnetic induction. There are no magnetic dipoles that are not oriented. Any further increase of the field H cannot find any disoriented magnetic dipoles and cannot get them aligned with the field. In such conditions, any further increase ΔB of magnetic induction is equal to $\mu_0 \Delta H$. Therefore, differential permeability $\Delta B / \Delta H$ of permanent magnets in the first quadrant is close to μ_0 . In other words, the permanent magnet response ΔB to an external field ΔH is equal to that of the air or vacuum, $\Delta B = \mu_0 \Delta H$. Considering magnetic resistance to external field, permanent magnet behaves as the air. Magnetic resistance R_μ to an external magnetomotive force does not change by inserting permanent magnet into the air-filled space, nor does it change by extracting permanent magnet from the magnetic circuit.

18.12 Magnetic Circuits with Permanent Magnets

It is of interest to analyze magnetic circuits that comprise permanent magnets. As an example, magnetic circuit in Fig. 18.12 is studied in order to obtain the values of the field H and magnetic induction B in different parts of the circuit. The circuit has permanent magnet of the length δ_{PM} , an air gap δ_0 , and an iron part of magnetic

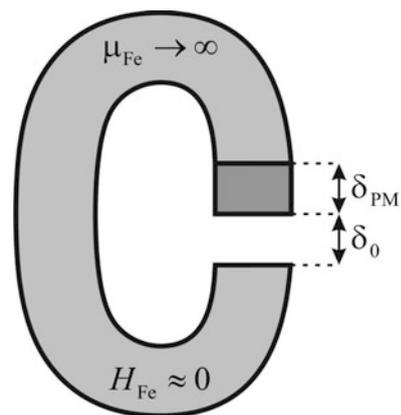


Fig. 18.12 Magnetic circuit comprising a permanent magnet and an air gap

circuit of permeability μ_{Fe} which is very large. Therefore, magnetic field H_{Fe} in iron is neglected.

Considered structure does not have any windings; thus, $Ni = H_{PM}\delta_{PM} + H_0\delta_0 = 0$. All parts of the circuit have the same cross section S . Considering the flux conservation law $\Phi_{PM} = \Phi_0 = \Phi_{Fe}$, one obtains that $B_{PM} = B_0 = B_{Fe}$. Since $H_0 = B_0/\mu_0 = B_{PM}/\mu_0$, relation between magnetic induction B_{PM} and field H_{PM} is given by expression $B_{PM} = -\mu_0(\delta_{PM}/\delta_0)H_{PM}$. The intersection of nonlinear magnetizing characteristic $B(H)$ of permanent magnet material and the line $B_{PM} = -\mu_0(\delta_{PM}/\delta_0)H_{PM}$ gives the operating point of considered magnetic circuit. Coordinates of this intersection represent the values of magnetic induction and magnetic field within the magnet. In B - H diagram, the intersection is located in the second quadrant, where magnetic induction is positive while magnetic field H is negative.

In cases where magnetic circuit does not contain any air gap, the field $H_{PM} = B_{PM}(\delta_0/\delta_{PM})/\mu_0$ inside the magnet is equal to zero, while the magnetic induction is equal to remanent induction B_R of permanent magnet material. By increasing the air gap, the slope of the straight line $B_{PM} = -\mu_0(\delta_{PM}/\delta_0)H_{PM}$ decreases. The intersection with the curve $B(H)$ assumes smaller value of magnetic induction, while the field H_{PM} assumes negative value. Hence, when the magnet is placed in magnetic circuit with an air gap, magnetic induction B_{PM} and field H_{PM} within the magnet are of opposite direction.

18.13 Surface Mount and Buried Magnets

Permanent magnets can be mounted on the rotor surface or buried within the rotor magnetic circuit. Example of permanent magnets mounted on the rotor surface is given in Fig. 18.13.

The lines of magnetic field pass from the stator teeth into the air gap δ_0 ; they proceed and enter the permanent magnet of thickness δ_{PM} and then pass to the iron parts of the rotor magnetic circuit. Passing through the rotor core and getting to the opposite magnetic pole of the rotor, the field lines return from the rotor into the stator passing through the iron parts of the rotor, then through the permanent magnet, proceeding through the air gap, and reaching the stator teeth.

Resultant flux of the stator winding has the component Ψ_{mR} that comes from permanent magnets and the component $L_S i_S$ caused by the stator currents, the latter proportional to the stator self-inductance L_S . Stator self-inductance L_S depends on magnetic resistance R_μ encountered along the path of the stator flux. Permeability in iron is very large ($\mu_{Fe} \sim \infty$), making magnetic field H_{Fe} in iron parts of magnetic circuit negligible. Therefore, magnetic resistance on the path of the stator flux reduces to the air gap resistance and the resistance of permanent magnets:

$$R_\mu = \frac{2\delta_0}{\mu_0 S} + \frac{2\delta_{PM}}{\mu_{PM} S}. \quad (18.3)$$

Fig. 18.13 Surface-mounted permanent magnets. (a) Air gap. (b) Permanent magnet

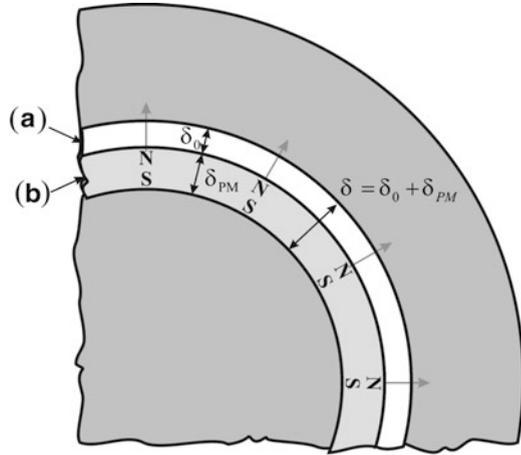
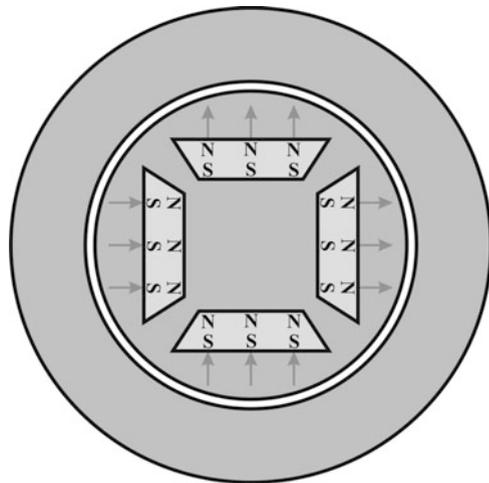


Fig. 18.14 Permanent magnets buried into the rotor magnetic circuit



In the first quadrant of $B-H$ plane, differential permeability of permanent magnet materials $\mu_{PM} = \Delta B/\Delta H$ is equal to μ_0 . In the presence of the stator magnetomotive force, behavior of permanent magnets of thickness δ_{PM} is the same as behavior of an additional air gap δ_{PM} . Therefore, the equivalent magnetic gap δ is equal to the sum of the two,

$$\delta = \delta_0 + \delta_{PM}, \tag{18.4}$$

where δ_0 represents the actual mechanical air gap, that is, the distance between the stator and rotor, while δ_{PM} represents the thickness of the magnet. For the purposes of L_S calculation, the magnet can be replaced by an additional air gap of the thickness δ_{PM} . Thickness of the magnet is many times larger than the air gap. For this reason,

magnetic resistance on the path of the stator flux is significantly larger in synchronous machines with surface-mounted magnets. Hence, the stator self-inductance L_S is very low. Synchronous machines with surface-mounted magnets have the stator inductance of the order 1%. The stator inductance of synchronous machines with interior magnets has the values ranging from 10% up to 70%.

A small inductance L_S reduces the reactance of the machine $X_S = \omega_e L_S$. Synchronous machines are usually supplied from three-phase transistor inverters with pulse width modulation, where reduced inductance of the stator winding results in an increased current ripple ΔI . In inverter supplied machines, pulse width-modulated pulses of the amplitude E repeat across the stator terminals with commutation frequency $f_{PWM} = 1/T \approx 10\text{--}20$ kHz, and they create oscillations of the stator current around the fundamental component. These oscillations are called *ripple*. The amplitude of current ripple is roughly $\Delta I \approx ET/(4L_S)$. With low stator inductance L_S of synchronous machines with surface-mounted magnets, the ripple ΔI is increased. Therefore, in order to contain the stator current ripple in synchronous servomotors, it is necessary to increase the commutation frequency of three-phase transistor inverters and to operate with $f_{PWM} > 10$ kHz.

Rather than being mounted on the surface, permanent magnets can be inserted into dedicated openings made within inner iron parts of the rotor magnetic circuit (Fig. 18.14). These openings can be placed further away from the rotor surface, in deeper areas of the rotor core and closer to the shaft. Hence, the magnets are *buried* into the rotor core. With buried magnets, the stator teeth do not face the permanent magnets across the air gap. Instead, the stator flux passes from the stator teeth into the iron parts of the rotor magnetic circuit. The lines of magnetic field caused by the stator currents pass through the air gap and enter the surface parts of the rotor magnetic circuit which are made of iron having a very high permeability. Because of this, the equivalent magnetic gap $\delta = \delta_0 + \delta_{PM}$ is equal to the air gap δ_0 , and it is much smaller than the equivalent magnetic gap with surface-mounted magnets. Therefore, magnetic resistance along the stator flux path is considerably smaller, and the stator inductance L_S is considerably higher. With buried magnets, relative value of stator inductance ranges from 10% up to 70%.

18.14 Characteristics of Permanent Magnet Machines

Surface-mounted magnets result in a very small stator inductance L_S . The rate of change of the stator current $di_a/dt = (u_a - e_a)/L_S$ is very high and approaches the value of $di_a/dt \approx 7,000 [I_n/s]$,⁵ allowing a very high rate of change of the electromagnetic torque T_{em} , which depends on the rotor flux and the stator current, $T_{em} = k|\Psi_{Rm} \times i_s|$. With surface-mounted magnets, the torque rise time from zero up to the rated value can be achieved in 100–200 μ s. For this reason,

⁵ Starting from zero, the rated current I_n can be reached in 1/7,000 s.

synchronous motors with surface-mounted magnets are used in motion control applications such as the industry automation and robotics, where the closed loop speed and position control depend on the ability to effectuate very fast torque changes.

One shortcoming of synchronous machines with surface-mounted magnets is their limited ability to operate in the field-weakening region, where the rotor speed exceeds the rated speed, increasing as well the electromotive force $j\omega_e\Psi_S$ induced in the stator windings. Above the rated speed, the stator flux Ψ_S has to be reduced in order to maintain the electromotive force $j\omega_e\Psi_S$ within the rated limits, $|j\omega_e\Psi_S| \leq U_n = \Psi_n\omega_n$. To this aim, the flux $\Psi_S = \Psi_{Rm} + L_S i_S$ should be decreased according to the law $\Psi_S(\omega_e) = \Psi_n(\omega_n/\omega_e)$. The flux Ψ_{Rm} of permanent magnets cannot be altered, and the flux reduction requires a demagnetizing component of the stator current i_S . The amount of demagnetizing stator current depends on the stator inductance. For machines with very small inductance $L_S \sim 1\%$, very high stator currents are required in order to reduce the flux. Therefore, the operation of synchronous machines with surface-mounted magnets in the zone of flux weakening is not feasible. Hence, synchronous machines with surface-mounted magnets are used in motion control applications that require high peak torque capability, fast torque changes, and low inertia.

There are applications of synchronous machines that do not require fast torque changes, but they do require the field-weakening operation. In such cases, synchronous machines are used with permanent magnets built into interior⁶ parts of the rotor magnetic circuit. With stator teeth facing the iron parts of the rotor magnetic circuit, magnetic resistance is decreased while the stator self-inductance is increased. With elevated L_S , reduction of the stator flux $\Psi_S = \Psi_{Rm} + L_S i_S$ can be performed with relatively low stator currents. In absence of losses in the rotor, synchronous machines with buried magnets are applied in all cases where the efficiency is of particular importance. Some of these examples are renewable energy sources and autonomous electrical vehicles.

⁶Synchronous machines with permanent magnets that are not placed on the rotor surface, and do not face the air gap, but reside instead in dedicated holes and chambers carved within inner regions of the rotor magnetic circuits, located further away from the surface and closer to the shaft are called *buried magnet* or *interior magnet* machines.