Chapter 4

Synchronous Machines

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4-1 INTRODUCTION

Conventional electric motors and generators, called *electric machines,* convert energy by means of rotational motion. Electric motors are built in sizes from a small fraction of horsepower to thousands of horsepower. Ratings of several hundred thousand kilowatts are not uncommon for present-day electric generators. Simplicity of construction and compactness of design as well as the nature of the connected apparatus (in the case of the generator, the prime mover and in the case of a motor, the driven load) dictate rotary motion for electric generators and most motors.

Electric power generated by the power industry is converted from *mechanical power* usually supplied to the electric generators by means of steam and water turbines and in a few cases internal-combustion engines. Because of the large quantities of energy involved in the energy-conversion process, economy of operation as well as reliability of the equipment are extremely important. Efficiency and economics of power demand require the use of very large generators; as a result ac generators rated in excess of 1000 MVA† are in use. Large generators have high efficiency—in fact, at ratings greater than 50,000 kW, the efficiency usually exceeds 98 percent. Generally, the higher the rating of a machine, for a given speed, the greater is the efficiency. Electric motors also have high efficiencies, in some cases greater than 80 percent for ratings as low as 1 hp or even less.

† Features of a 1200-MW generator are presented by A. Abolins and F. Richter. "Test Results of the World's Largest Four-Pole Generator with Water-Cooled Stator and Rotor Windings," *Trans. IEEE Power Apparatus and Systems* PAS-94, No. 4 (July–August 1975):1103–1108.

By way of contrast, acoustical devices such as microphones are extremely sensitive and respond to such small amounts of power as a few microwatts, while loudspeakers may have input ratings exceeding 50 W, generally with an efficiency of less than 50 percent. Such values of power are practically insignificant when compared with the ratings of large rotating machines and transformers.

Electric machines consist of a magnetic circuit, one or more electric circuits and mechanical supports, with at least one winding. For a motor such a winding is energized from an electrical source of energy and for a generator such a winding (if there is only one) is a source of electrical energy. The magnetic circuit contains iron interrupted by an air gap between the stationary member or stator and the rotating member or rotor. Magnetic cores subjected to alternating magnetic fluxes or fluxes that undergo rapid time variations are usually laminated to ensure low eddy-current losses and rapid responses. However, smaller devices, with magnetic circuits of complex configurations, generally have laminated structures to reduce manufacturing costs, whether the excitation is ac or dc.

The turns in the windings of small machines consist of round wire. In larger machines the conductor material has rectangular cross section for more compact nesting in the space occupied by the winding. The most common conductor material is copper, although aluminum has come into limited use.

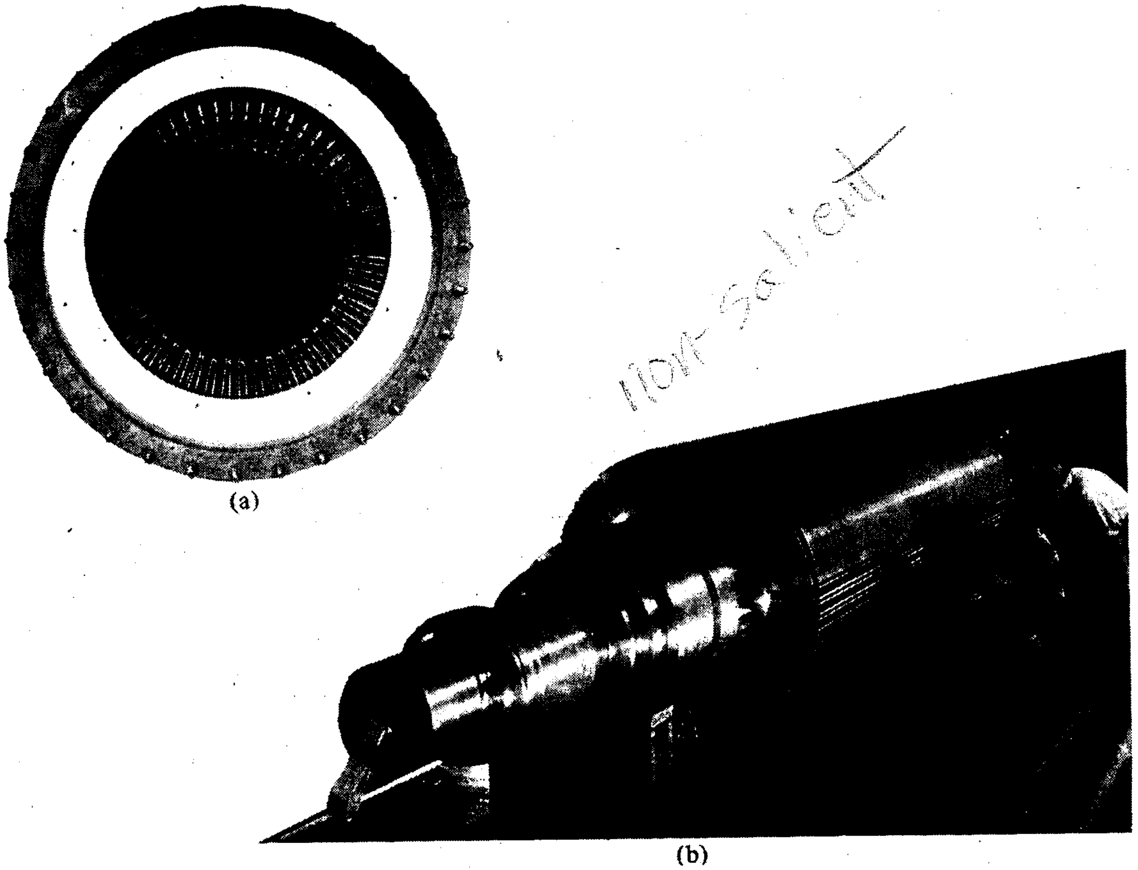
Conventional systems of the power industry are supplied by three-phase synchronous generators which fall into two general classifications—cylindrical-rotor machines and salient-pole machines. The cylindrical-rotor construction is peculiar to synchronous generators driven by steam turbines and which are also known as *turboalternators* or *turbine generators.* The stator core and rotor iron of a four-pole turbine generator are shown in Fig. 4-1, and the stator with its three-phase winding of a smaller machine is shown in Fig. 4-2. Steam turbines operate at relatively high speeds, 1800 and 3600 rpm being common for 60 Hz, accounting for the cylindrical-rotor construction, which, because of its compactness, readily withstands the centrifugal forces developed in the large sizes at those speeds. In addition, the smoothness of the rotor contour makes for reduced windage losses and for quiet operation.

Salient-pole rotors are used in low-speed synchronous generators such as those driven by waterwheels. They are also used in synchronous motors. Because of their low speeds salient-pole generators require a large number of poles as, for example, 72 poles for a 100-rpm 60-Hz generator. This follows from the fact that in one revolution a voltage undergoes $P/2$ cycles and the relationship between frequency and speed is

$$\boxed{f = \frac{Pn_{\text{syn}}}{120}} \qquad \text{(4-1a)}$$

where P = number of poles and n_{syn} = synchronous speed in rpm.

In the terminology applied to rotating electric machines, an angle has the same value in electrical measure as in mechanical measure for two-pole machines because the voltage induced in the armature coil by a constant field flux goes through one cycle or 2π radians per revolution of the armature. However, in a



(a)

(b)

non-salient

Figure 4-1 (a) Stator core for an ac turbine generator. (b) Four-pole turbine generator rotor. (Courtesy of Siemans-Allis, Inc.)

machine that has P poles (i.e., one or more pair of poles), the armature coil generates $P/2$ cycles or $P\pi$ radians in electrical measure while the armature makes one revolution which corresponds to 2π radians in mechanical measure. Accordingly,

$$\boxed{\theta = \frac{P}{2}\,\theta_m} \tag{4-1b}$$

where θ is in electrical measure and θ_m in mechanical measure.

Figure 4-3 shows a hydrogenerator or waterwheel generator being assembled at the site of its installation. A synchronous motor is shown in Fig. 4-4. The salient-pole structure is simpler and more economical to manufacture than would be a cylindrical one with a large number of poles.

In contrast with the dc machine, the field winding, instead of the armature winding of conventional synchronous machines, is carried by the rotor, because the field winding is less massive than the armature winding, operating as it does at lower voltage with smaller current. In addition, the field winding is excited with direct current, requiring it to terminate in only two slip rings as are evident on the rotor shown in Fig. 4-4. If on the rotor, the armature winding would require at least three slip rings and in most cases a fourth for the neutral of the three-phase winding which is generally connected in wye. Slip rings and brushes are eliminated in synchronous machines with brushless excitation systems. These

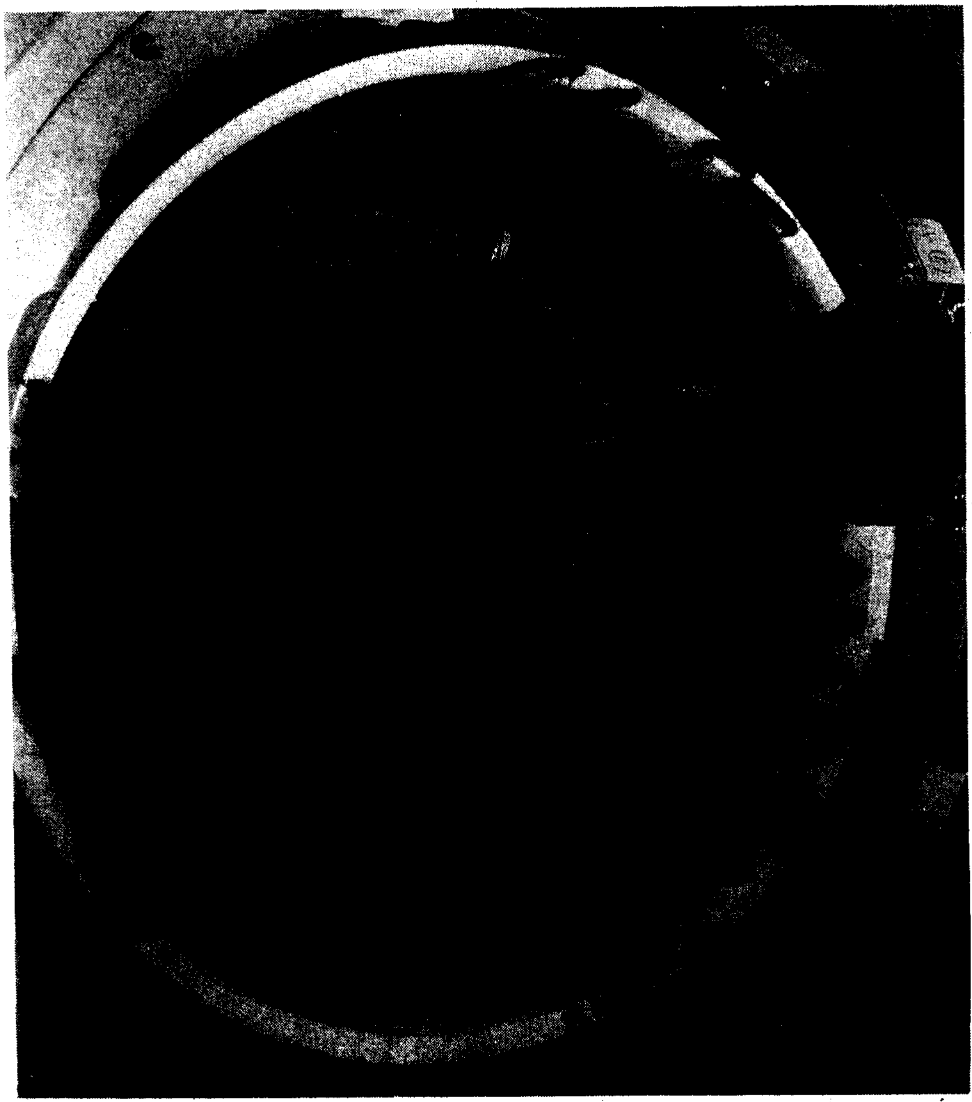


Figure 4-2 Stator with three-phase winding. (Courtesy General Electric Company.)

require the field winding to be on the rotor. For example, a certain 432,000-kVA 22-kV three-phase 1800-rpm 60-Hz generator has a rated armature current of 11,340 A, while the field is rated at 500 V and 1940 A.

4-2 WAVEFORM

Conventional three-phase generators deliver practically sinusoidal voltage under normal conditions. Features that contribute to the production of good waveform are the use of distributed armature windings (i.e., among several slots per phase and pole), fractional-pitch armature coils (i.e., coils that span less than 180° in electrical measure), distribution of the field winding among several slots per pole in cylindrical rotors, and by shaping the pole shoes of salient-pole rotors so that the air gap is shortest under the pole center and increasing in length toward the pole tips.

Figure 4-5 illustrates two- and four-pole cylindrical rotors along with a developed view of the field winding for one pair of poles. One pole and its

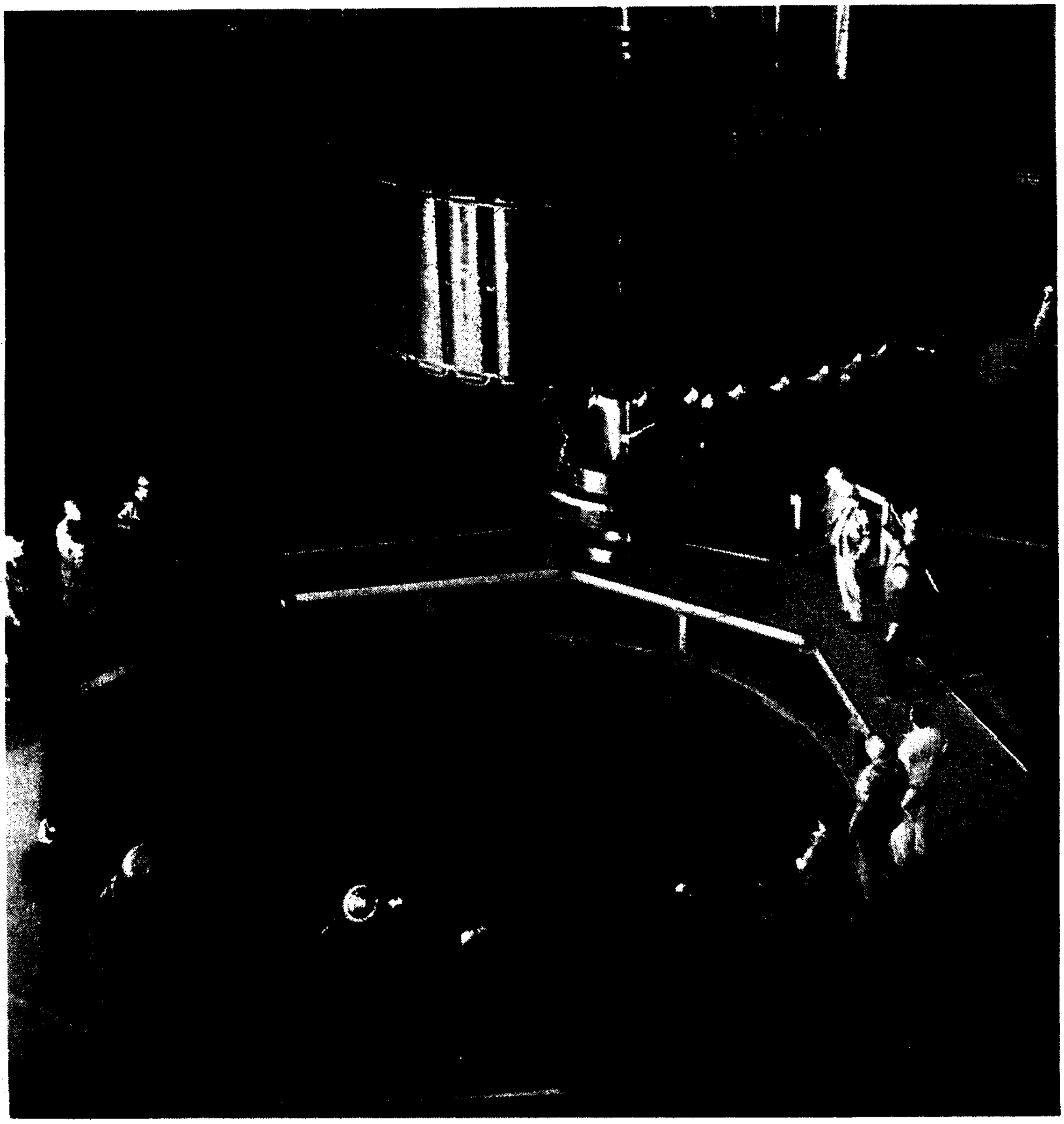


Figure 4-3 Salient-pole rotor being lowered into the stator of a hydrogenerator. (Courtesy General Electric Company.)

associated field coil of a salient-pole rotor is shown in Fig. 4-5(d). The stator slots in which the armature winding is embedded are not shown for reasons of simplicity. The approximate path taken by the field flux, not including leakage flux, is indicated by the dashed lines in Fig. 4-5(a), (b), and (d). The field coils in Fig. 4-5(c) are represented by filaments but actually (except for the insulation between turns and between the coil sides and the slot) practically fill the slot more nearly in keeping with Fig. 4-6.

The stepped curve in Fig. 4-6 represents the waveform of the mmf produced by the distributed field winding if the slots are assumed to be completely filled by the copper in the coil sides instead of containing current filaments. The shape of the mmf wave may be verified for this assumption by taking line integrals of **H** around appropriate paths. The sinusoid indicated by the dashed line in Fig. 4-6 represents approximately the fundamental component of the mmf wave.

The air gap in cylindrical-rotor machines is practically of uniform length

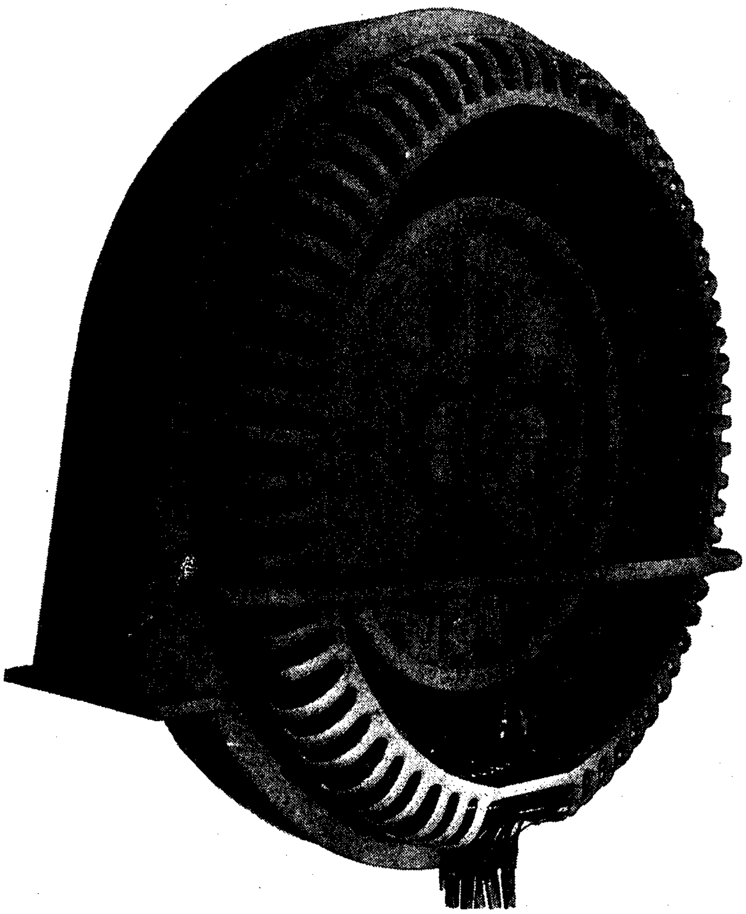


Figure 4-4 Synchronous motor. (Courtesy Westinghouse Electric Corporation.)

except for the slots in the rotor and in the stator, and when the effect of the slots and the tangential component of **H**†—which is quite small for the low ratio of air-gap length to the arc subtended by one pole in conventional machines—are neglected, the stepped mmf wave in Fig. 4-6 produces a flux-density space wave in which the corners of the steps are rounded due to fringing. The flux-density waveform is therefore more nearly sinusoidal than the mmf waveform when the effect of the slots is neglected. However, saturation of the iron in the region of maximum mmf tends to flatten the top of the flux-density wave.

4-3 AC ARMATURE WINDINGS

The armature winding of an ac machine is the source of the induced voltage, and for that reason some of the more elementary aspects of ac windings are treated in this chapter.

Armature windings are generally comprised of one or more turns and are so interconnected that their electric and magnetic effects are cumulative. The coils may have full pitch or fractional pitch. A full-pitch coil spans 180° in

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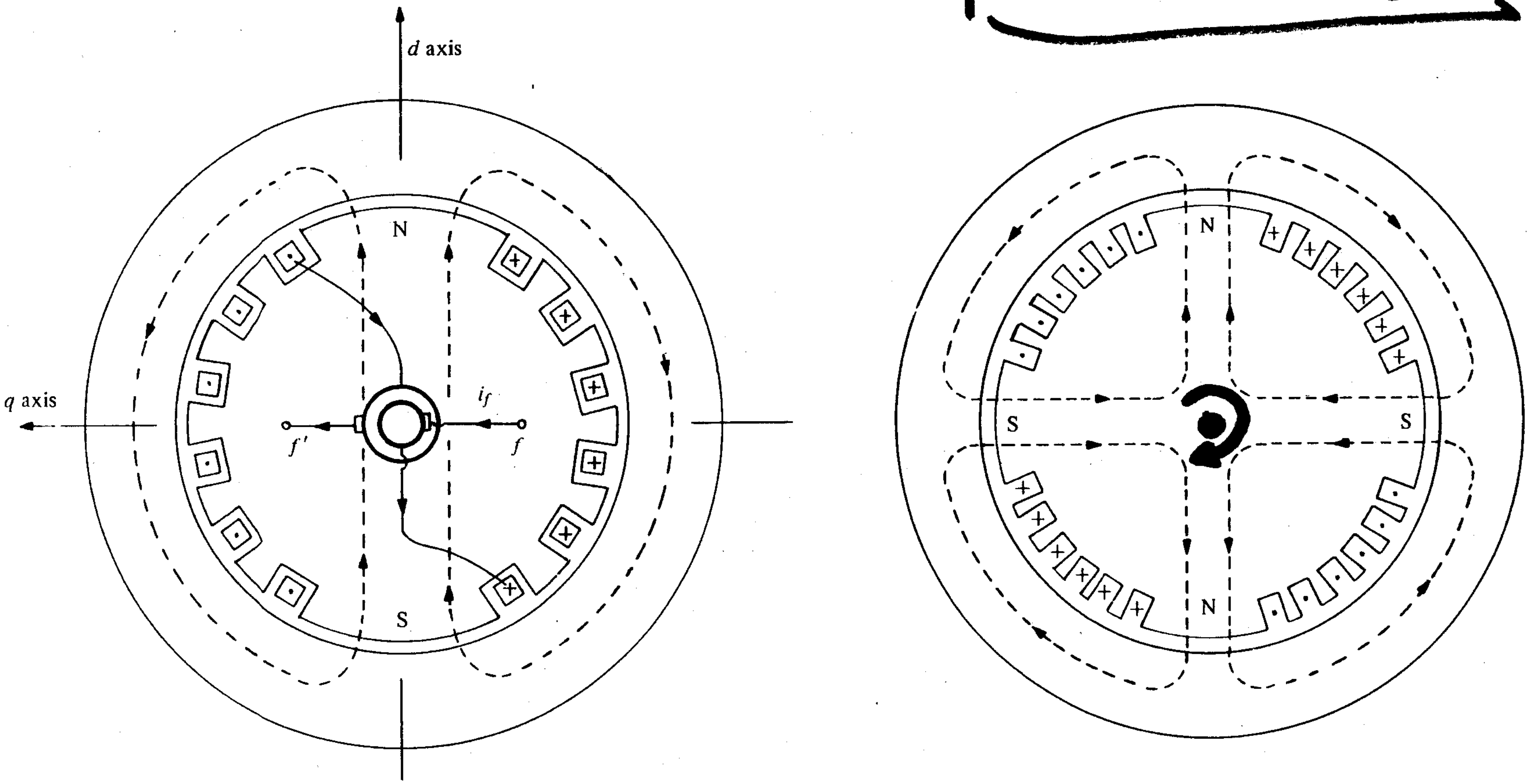
† For a rigorous treatment of **H** due to current filaments in air gaps, see B. Hague, *The Principles of Electromagnetism Applied to Electrical Machines* (New York: Dover Publications, Inc.,

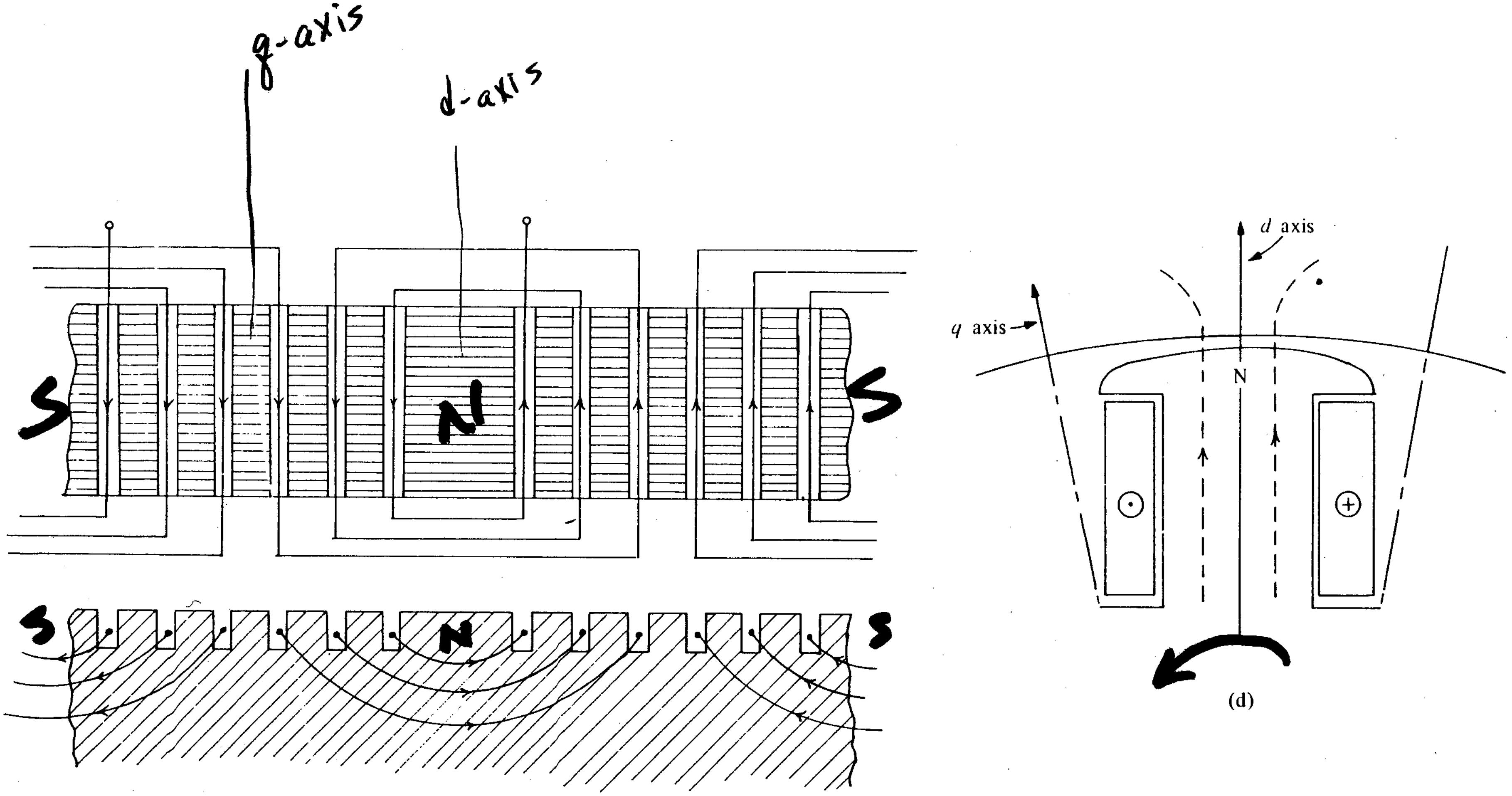
$$\boxed{\delta_e = \delta_m \frac{N_p}{2}}$$



(a)

(b)

Figure 4-5 Synchronous machines with stator slots and armature winding omitted. (a) Two-pole and (b) four-pole cylindrical rotors. (c) Developed view of two-pole cylindrical rotor field structure. (d) Salient pole and field coil. (cont'd on page 162)



(c)

(d)

Figure 4-5 (Continued)

Field Winding arrangement

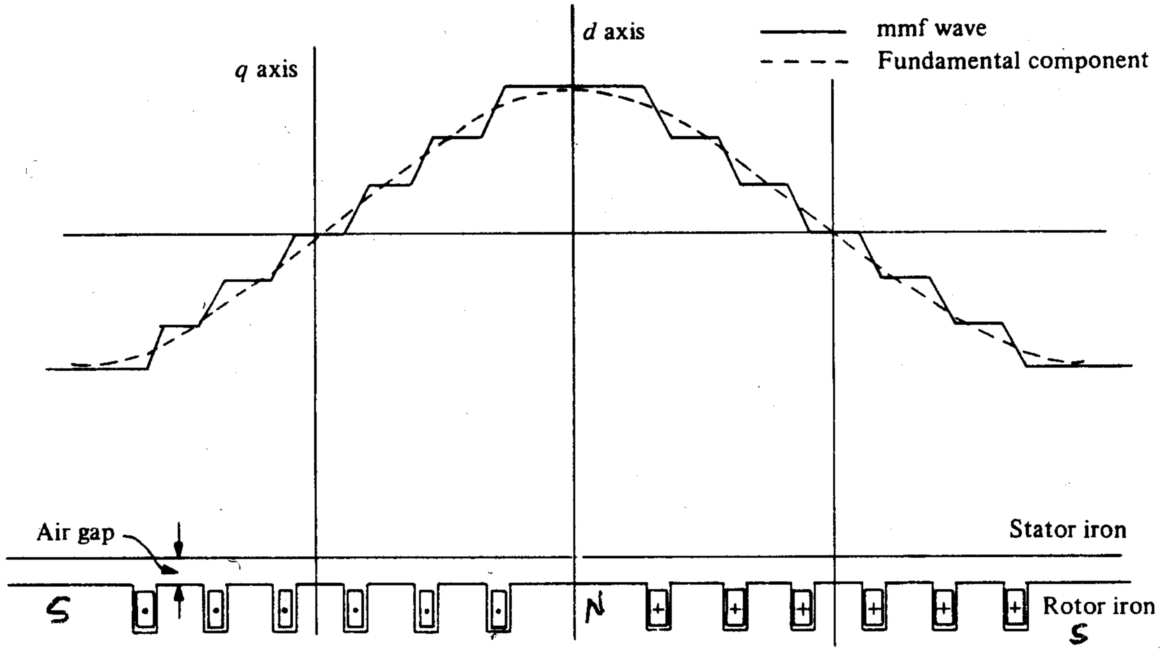


Figure 4-6 Cylindrical-rotor mmf wave and its fundamental of a synchronous machine.

electrical measure and a fractional-pitch coil spans less than 180° but seldom less than 120°. Full-pitch and fractional-pitch coils are shown in Figs. 4-7 and 4-8.

The armature in Fig. 4-7 has three slots per pole, which corresponds to one slot per phase and pole for a three-phase winding. The three coils that are shown belong to one phase arbitrarily designated as a phase, hence the letter designation a_1, a_2, and a_3. These three coils may be connected in series to form a single-circuit winding or they may be connected in parallel, resulting in a three-circuit winding. A developed view of the single-circuit connection is shown in Fig. 4-7(b), and a side view of the coil sides in the slots is shown in Fig. 4-7(c). Only the simplest of a large variety of armature windings used in three-phase machines are treated in this text.† However, the principles underlying the characteristics of these simple windings are basic, with minor modifications also for the more complex arrangements.

A three-phase winding results from the addition of another two sets of armature coils displaced 120° and 240° in electrical measure from the first phase to produce a system of three voltages equal in magnitude and displaced from each other by 120°. A three-phase full-pitch winding is shown in Fig. 4-9(a), (b), and (c) in which b phase is displaced from a phase by two slots in the direction of rotation, with c phase similarly displaced from b phase. Since each slot corresponds to 60° in electrical measure, the windings are displaced so that b-phase and c-phase voltages lag a-phase voltage by 120° and 240°, respectively, as shown by the phasor diagram in Fig. 4-9(d). This phase sequence (a-b-c) is called *positive*

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† For a more complete treatment of armature windings in ac machines, see M. Liwschitz-Garik, *Winding Alternating-Current Machines* (New York: D. Van Nostrand Company, Inc., 1950); C. S. Siskind, *Alternating-Current Armature Windings* (New York: McGraw-Hill Book Company, 1951); A. M. Dudley, *Connecting Induction Motors,* 3d ed. (New York: McGraw-Hill Book Company, 1936).

phase sequence. A reversal in the direction of rotation results in *negative-phase sequence* (*a-c-b*) as shown by the phasor diagram in Fig. 4-9(e). The winding in Fig. 4-9 has one-half as many coils as there are slots or one coil side per slot. The more common arrangement of two coil sides per slot is shown in Fig. 4-10, with only one phase shown in Fig. 4-10(a) and (b). A side view of the slots and the coil sides for all three phases is shown in Fig. 4-10(c). A comparison of Fig. 4-10(c) with Fig. 4-9 shows that the former has two layers of coil sides in the slots and the latter has one layer, hence the terms *two-layer* and *single-layer* windings. Although single-layer windings are not common, they are sometimes used in induction motors of 10 hp or less. The chief advantage of the two-layer winding is that of accommodating fractional-pitch coils which have shorter end turns or end connections than full-pitch coils and as a result have lower resistance without a proportionate decrease in their flux linkage. Fractional pitch also assists in improving the waveform of the induced emf and the armature mmf. Three coils of a $\frac{2}{3}$-pitch winding are illustrated in Fig. 4-11, and a $\frac{5}{6}$-pitch winding is shown in Fig. 4-12.

The windings treated in this chapter are called *integral-slot windings,* since they occupy a structure in which the number of slots per pole is an integer. A more common arrangement for ac machines is the fractional-slot winding† for which the number of slots per pole is a fraction. The analysis of integral-slot windings is simpler than that of fractional-slot windings and yet serves to bring out the basic principles regarding the mmfs and inductances of armature windings. Fractional-slot windings have two advantages: (1) it is possible to use the same stator laminations, with resulting lower investment in dies, for salient-pole structures with a variety of a number of poles, and (2) the contribution toward good waveform is equivalent to that of an integral-slot winding with a larger number of slots per pole. Fractional-slot windings are also used to some extent in induction motors.

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4-4 INDUCED ARMATURE VOLTAGE

A phasor diagram‡ which includes voltage-, current-, and flux-linkage phasors facilitates the analysis of steady-state synchronous machine-behavior. In order to relate the phase of flux linkage to the voltage that results from its time variation, it is necessary to establish conventions regarding the sign of the induced voltage in a generator and in a motor with regard to assumed current direction and the time phase of the flux linkage.§ Therefore, consider the magnetic circuit and

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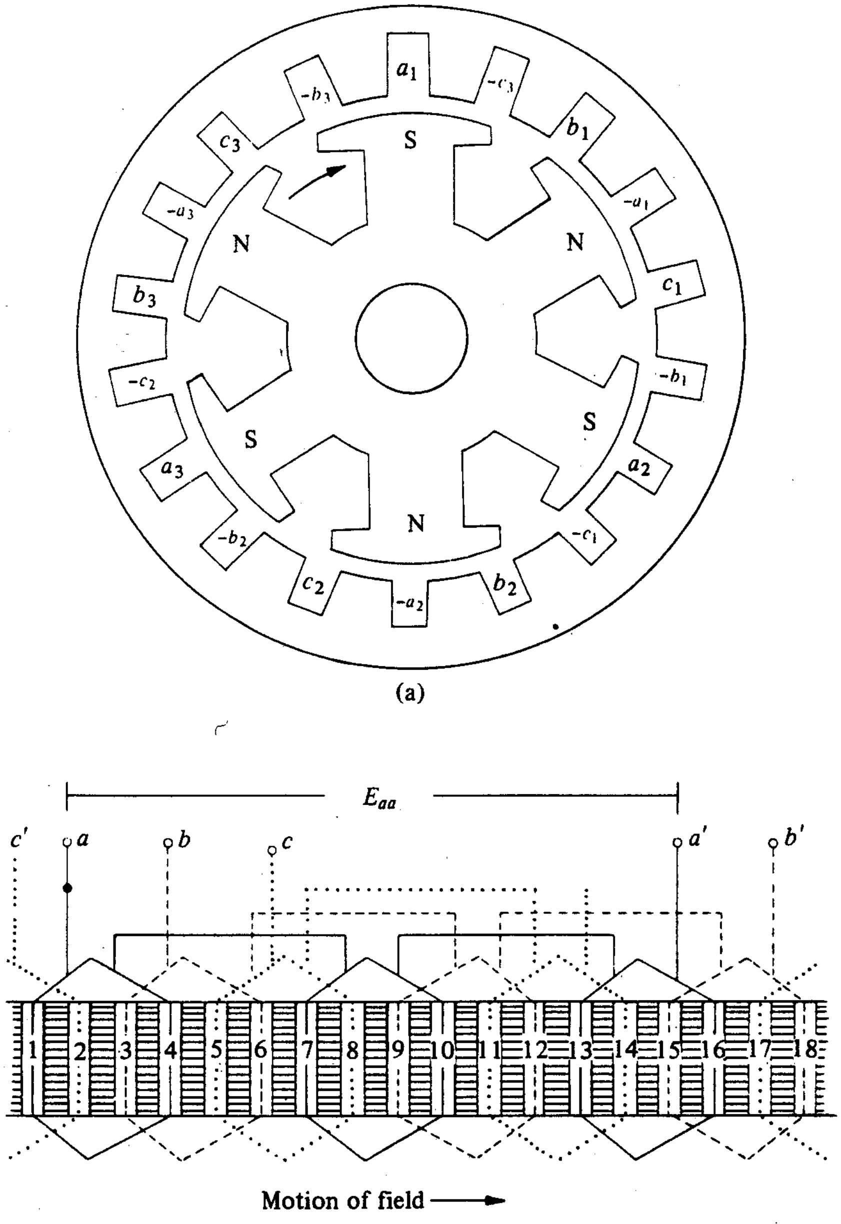
† See M. Liwschitz-Garik and C. C. Whipple, *Alternating-Current Machines,* Vol. II (New York: D. Van Nostrand Company, Inc., 1961).

‡ D. B. Harrington, "Recommended Phasor Diagram for Synchronous Machines." *IEEE Paper No. TP 143-PWR.* Presented at IEEE Winter Power Meeting, New York, January 1969.

§ For a more complete discussion, see W. A. Lewis, "Simplicity in Three-Phase System Circuit Conventions and Concepts," *Elec. Eng.* October 1958: 937–939; November 1958: 1038–1040; December 1958: 1126–1128.



(a)

(b)

full-pitch

Figure 4-9 Three-phase six-pole machine. (a) Arrangement of coil sides in stator slots. (b) Developed view of armature winding. (c) Developed side view of slots. (d) Positive-sequence voltage phasors. (e) Negative-sequence voltage phasors. (f) Wye and delta connections.

$$\boxed{v_{an} = -r_a i_a - \underline{p}\lambda_a} \qquad p = \frac{d}{dt} \tag{4-3}$$

By similar reasoning, Fig. 4-13(c) shows the same circuit when representing one phase of a motor and for which the applied terminal voltage is expressed by

$$\boxed{v_{an} = r_a i_a + \underline{p}\lambda_a} \tag{4-4}$$

However, λ_a results from both the mmf of the armature current and that of the field current. In the motor the direction of the field mmf relative to that of the armature is opposite that in the generator, which is in agreement with Fig. 4-27(a) and (b). The value of λ_a is therefore different in the generator [Fig.