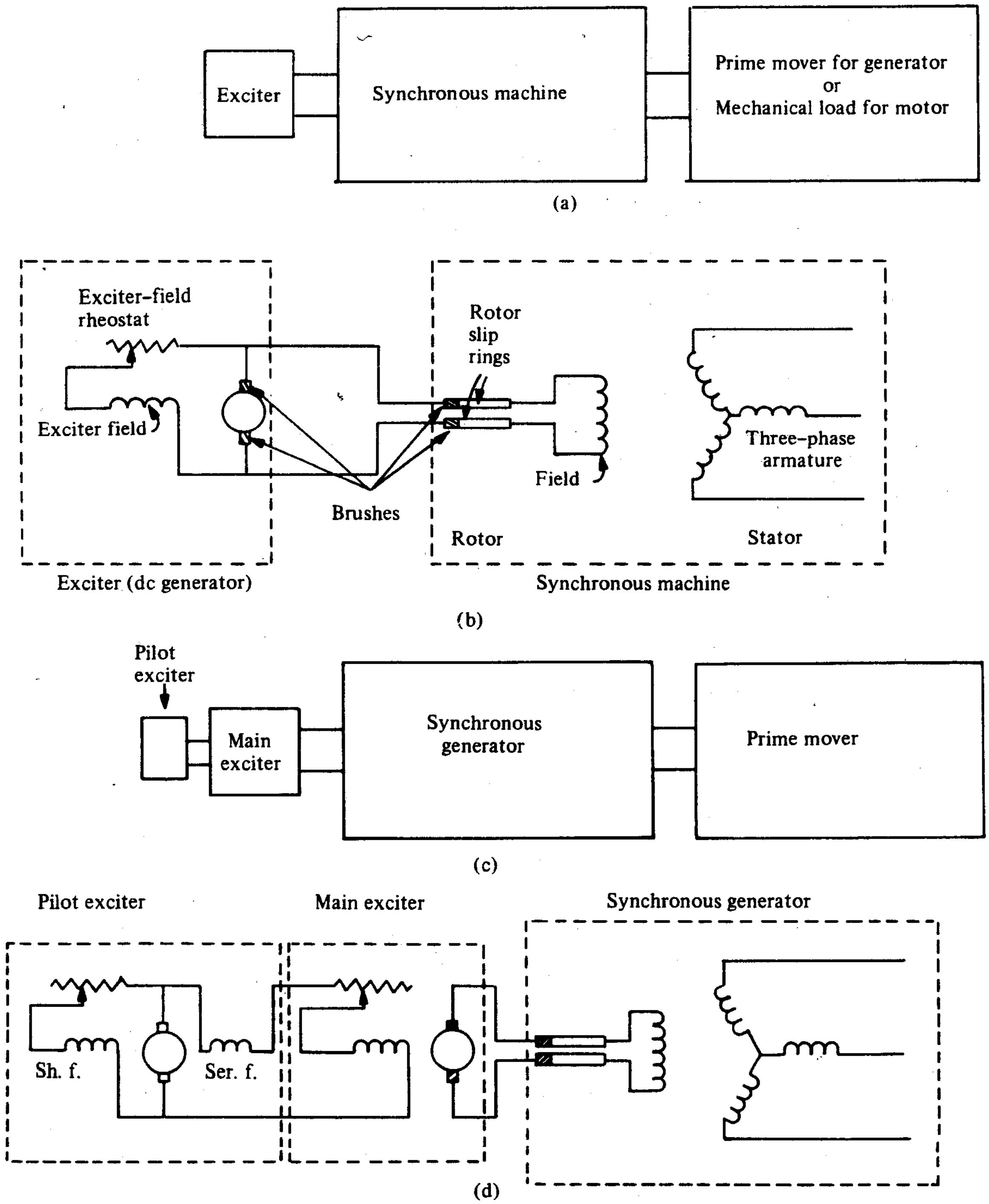

Figure 4-37 Conventional excitation systems for synchronous machines. (a) Physical arrangement. (b) Circuit diagram for shaft-mounted exciter. (c) Physical arrangement. (d) Circuit diagram for shaft-mounted exciter and pilot exciter.

4-17 DIRECT-AXIS AND QUADRATURE-AXIS SYNCHRONOUS REACTANCE IN SALIENT-POLE MACHINES—TWO-REACTANCE THEORY

While the air gap in synchronous machines of the cylindrical-rotor construction is practically of uniform length, that of the salient-pole machine is much longer

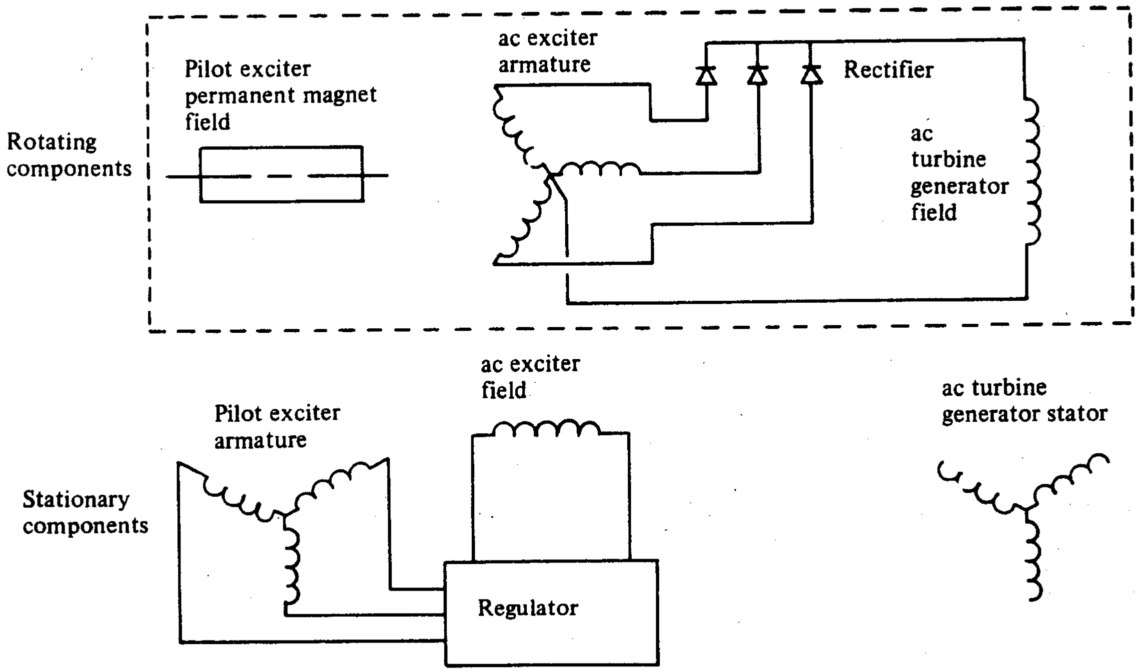

Figure 4-38 Brushless excitation system.

in the quadrature axis (i.e., in the region midway between poles) than in the direct axis or at the pole centers, as is evident from Fig. 4-7. Since the air gap is of minimum length in the direct axis, a given armature mmf directed along that axis produces a maximum value of flux, and the same armature mmf directed along the quadrature axis where the air gap has its greatest length produces a minimum value of flux. The synchronous reactance associated with the direct axis is therefore a maximum and is known as the *direct-axis synchronous reactance,* x_d. The minimum synchronous reactance x_q is called the *quadrature-axis synchronous reactance.* In addition, because of the nonuniform length of air gap, a sinusoidal mmf wave with its amplitude in the direct axis produces a distorted flux-density wave somewhat as shown in Fig. 4-39(a), while the same sinusoidal mmf will produce a flux density wave of a different shape, about as shown in Fig. 4-39(b), when the amplitude is in the quadrature axis. Flux-density waves of other shapes are produced when the sinusoidal armature mmf reacts

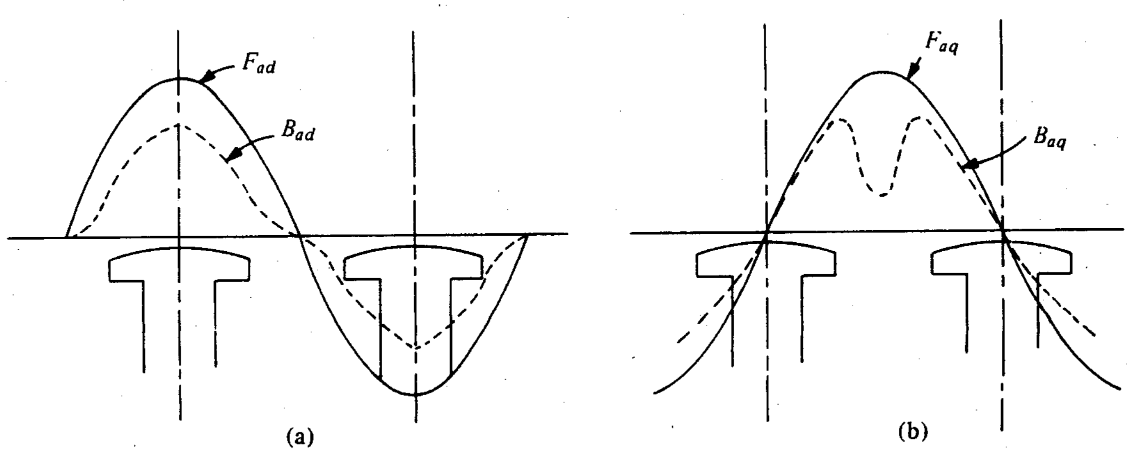

Figure 4-39 Sinusoidal armature mmf wave and resulting flux-density wave. (a) d axis. (b) q axis.

along an axis that lies between the direct and quadrature axes. These complications of variable reactance and of waveform for different locations of the magnetic axis of armature mmf relative to that of the field poles make a rigorous treatment of the salient-pole machine along the lines of cylindrical-rotor theory too cumbersome to be practical.

Cylindrical-rotor theory when modified to take waveform into account could be applied to the salient-pole machine if the armature current were 90° out of phase with the generated emf $\mathbf{E}_{af}$ or if it were in phase with $\mathbf{E}_{af}$. In the first case the armature mmf would react along the direct axis and the direct-axis synchronous reactance x_d would apply. A phasor diagram for a salient-pole generator with the current lagging the generated emf by 90° is shown in Fig. 4-39(a). Since the mmf produced by the armature, in this case, reacts entirely along the direct axis, the armature current is designated as $\mathbf{I}_d$, the direct-axis current. And for this condition the phasor relation between generated emf terminal voltage, and impedance is expressed by

$$\mathbf{E}_{af} = \mathbf{V} + (r_a + jx_d)\mathbf{I}_d \tag{4-106}$$

In the second case the armature mmf reacts along the quadrature axis and the quadrature-axis synchronous reactance x_q is used as shown in Fig. 5-46(b), and the armature current is therefore designated as $\mathbf{I}_q$, the quadrature-axis current. The synchronous reactance associated with this current is x_q and the voltages are related to each other in accordance with

$$\mathbf{E}_{af} = \mathbf{V} + (r_a + jx_q)\mathbf{I}_q \tag{4-107}$$

The phasor relations for Eqs. 4-106 and 4-107 are illustrated in Fig. 4-40, in which λ_{af} is the fundamental component of flux linkage due to the field current and λ_{ad} is produced by $\mathbf{I}_d$ while λ_{aq} is the fundamental quadrature-axis flux linkage due to $\mathbf{I}_q$.

The armature current in synchronous generators and in synchronous motors is normally displaced from the generated voltage $\mathbf{E}_{af}$ by some angle lying between 0° and 90° and may then be divided into the two components $\mathbf{I}_d$ and $\mathbf{I}_q$ as shown in Fig. 4-40(a). Then in keeping with Eqs. 4-106 and 4-107, it follows that the generated voltage of the salient-pole generator is

$$\mathbf{E}_{af} = \mathbf{V} + (r_a + jx_q)\mathbf{I}_q + (r_a + jx_d)\mathbf{I}_d$$

and since

$$\boxed{\begin{aligned} \mathbf{I}_d + \mathbf{I}_q &= \mathbf{I} \\ \mathbf{E}_{af} &= \mathbf{V} + r_a\mathbf{I} + jx_q\mathbf{I}_q + jx_d\mathbf{I}_d \end{aligned}} \tag{4-108}$$

The components $\mathbf{I}_q$ and $\mathbf{I}_d$ are usually not given, since the only known quantities are $\mathbf{V}$, $\mathbf{I}$, the load power-factor angle θ, r_a, x_d, and x_q. The current components $\mathbf{I}_d$ and $\mathbf{I}_q$ may, however, be readily obtained by making use of the known quantities to establish the angle δ in Fig. 4-41(b), and we then have

$$I_d = I \sin(\theta + \delta) = I \sin \theta_i$$

and

$$I_q = I \cos(\theta + \delta) = I \cos \theta_i \tag{4-109}$$

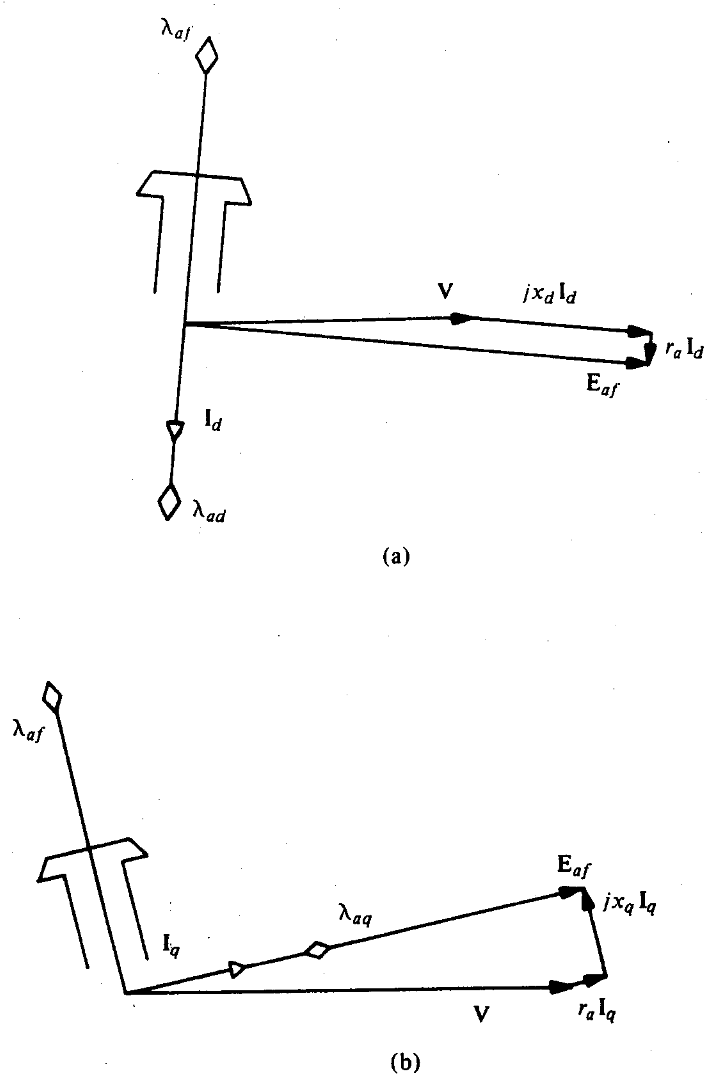

Figure 4-40 Phasor diagram for salient-pole generator with the armature mmf. (a) d axis. (b) q axis.

The phasor diagram in Fig. 4-42 affords a basis for determining the value of δ. Assume the current components $\mathbf{I}_d$ and $\mathbf{I}_q$ to be known. Then if the currents $\mathbf{I}_d$, $\mathbf{I}_q$, and $\mathbf{I}$ are multiplied by jx_q, the voltage triangle ABC that is similar to the current triangle abc is obtained and the phasor $jx_q\mathbf{I} = \mathbf{AC}$ terminates at point C on the phasor $\mathbf{E}_{af}$, so

$$\mathbf{aC} = \mathbf{V} + (r_a + jx_q)\mathbf{I}$$

and

$$\tan \delta = \frac{\text{Im } \mathbf{aC}}{\text{Re } \mathbf{aC}}$$

$$= \frac{AC \cos \theta - r_a I \sin \theta}{V + r_a I \cos \theta + AC \sin \theta}$$

$$= \frac{x_q I \cos \theta - r_a I \sin \theta}{V + r_a I \cos \theta + x_q I \sin \theta} \tag{4-110}$$

Hence,

$$\mathbf{E}_{af} = [aC + (x_d - x_q)I_d]\underline{/\delta} \tag{4-111}$$

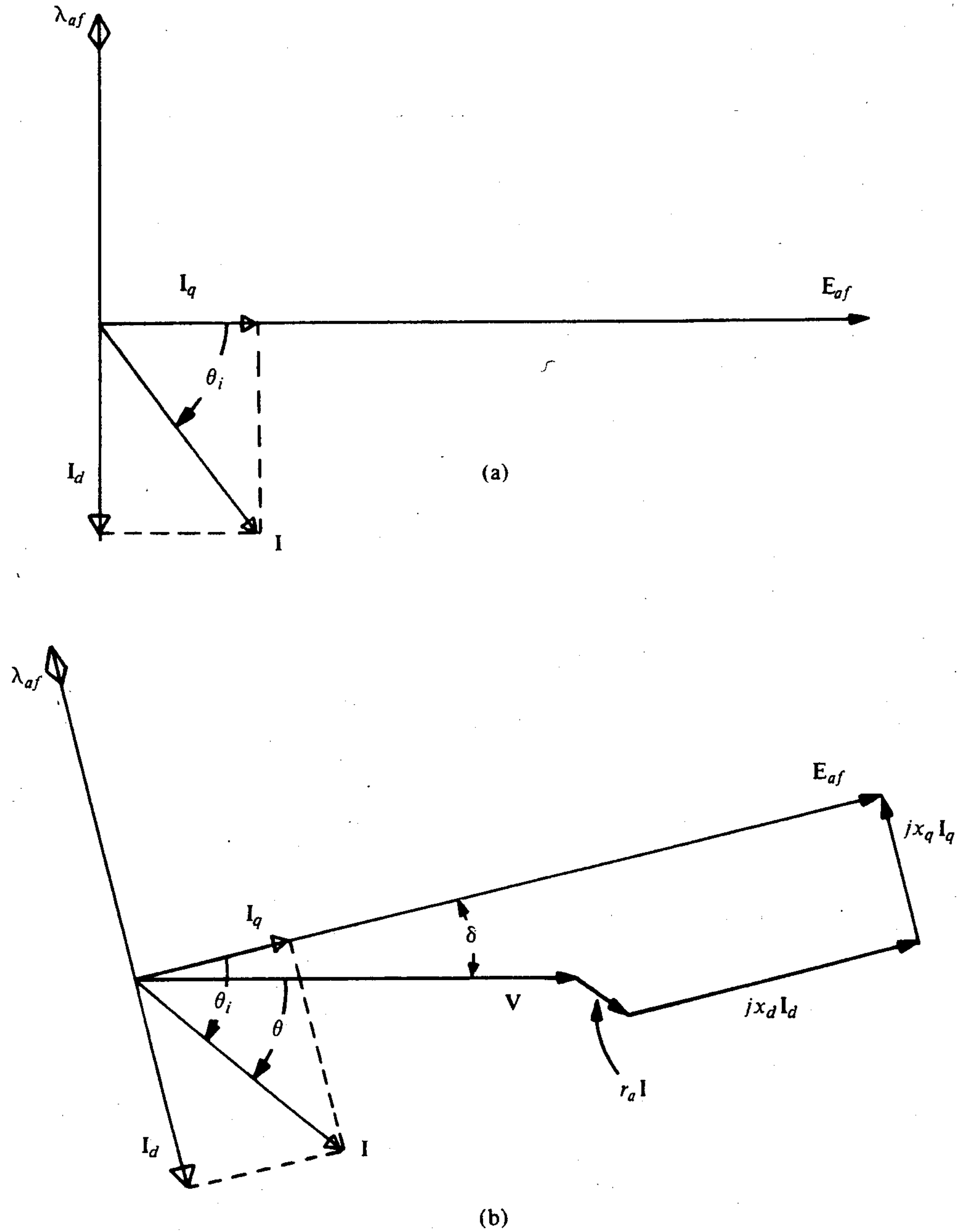

Figure 4-41 Phasor diagrams for salient-pole generator. (a) Angular relationships of currents and induced voltage. (b) Terminal voltage and impedence drops included.

The armature resistance can generally be neglected and

$$\boxed{\tan \delta = \frac{x_q I \cos \theta}{V + x_q I \sin \theta}} \quad \text{if } R_A = 0 \tag{4-112}$$

A phasor diagram of flux-linkage components for an overexcited salient-pole generator is shown in Fig. 4-43. The expressions for inductance derived in Sec. 4-6 can be applied to salient-pole machines by use of multiplying factors that take into account the effects of saliency.† However, the self-inductance of

† See L. A. Kilgore, "Calculations of Synchronous Machine Constants," *Trans. AIEE* 5, No. 4 (1931): 1201–1213.

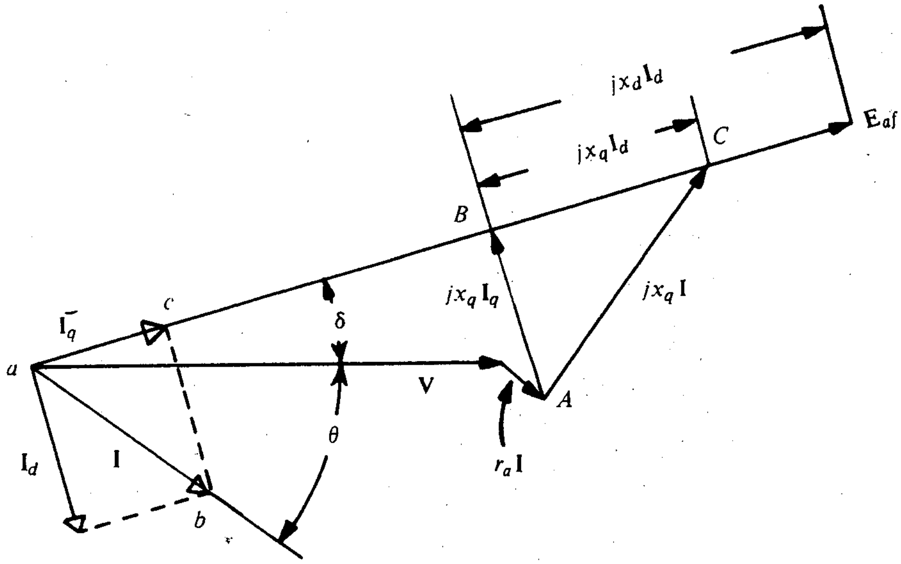

Figure 4-42 Phasor diagram as a basis for determining δ.

each phase by itself and the mutual inductance between phases are functions of rotor position (i.e., of σ).

-END 34

4-18 ZERO-POWER-FACTOR CHARACTERISTIC AND POTIER TRIANGLE

While the open-circuit and short-circuit characteristics yield the unsaturated value of synchronous reactance and a rough approximation of the saturated values, closer approximations of the saturated synchronous reactance can be obtained for cylindrical-rotor as well as for salient-pole machines from their zero-power-factor and open-circuit characteristics.

In the zero-power-factor test the generator is loaded with an inductive load of low power factor. An unloaded synchronous motor of about the same rating as the generator can be used as a load. The field of the synchronous motor is underexcited and that of the generator is overexcited so as to produce rated current at various values of terminal voltage. A diagram of connections is shown in Fig. 4-44(a).

It is generally not necessary to obtain a complete zero-power-factor curve, as two points usually suffice for most practical purposes—one is near rated terminal voltage and the other at zero terminal voltage (i.e., short circuit). In that case, the first point may be obtained by connecting the generator or motor to supply a three-phase bus that operates at or somewhat above the rated voltage to assure saturation. The real-power output of the generator is made approximately zero by adjusting the output of its prime mover, or the machine may be operated as an unloaded synchronous motor. The field is overexcited so that the machine supplies its rated value of current to the bus. The zero-terminal voltage point is obtained from the short-circuit characteristic.

Two results are achieved by means of zero-power-factor load. One is that the magnetic circuit is saturated in the presence of armature current, whereas