LEC 15

Synchronous Generator

Synchronous generators or alternators are synchronous machines that convert mechanical energy to alternating current (AC) electric energy.

A direct current (DC) is applied to the rotor winding of a synchronous generator to produce the rotor magnetic field. A prime mover rotates the generator rotor to rotate the magnetic field in the machine. A three-phase set of voltages is induced in the stator windings by the rotating magnetic field.

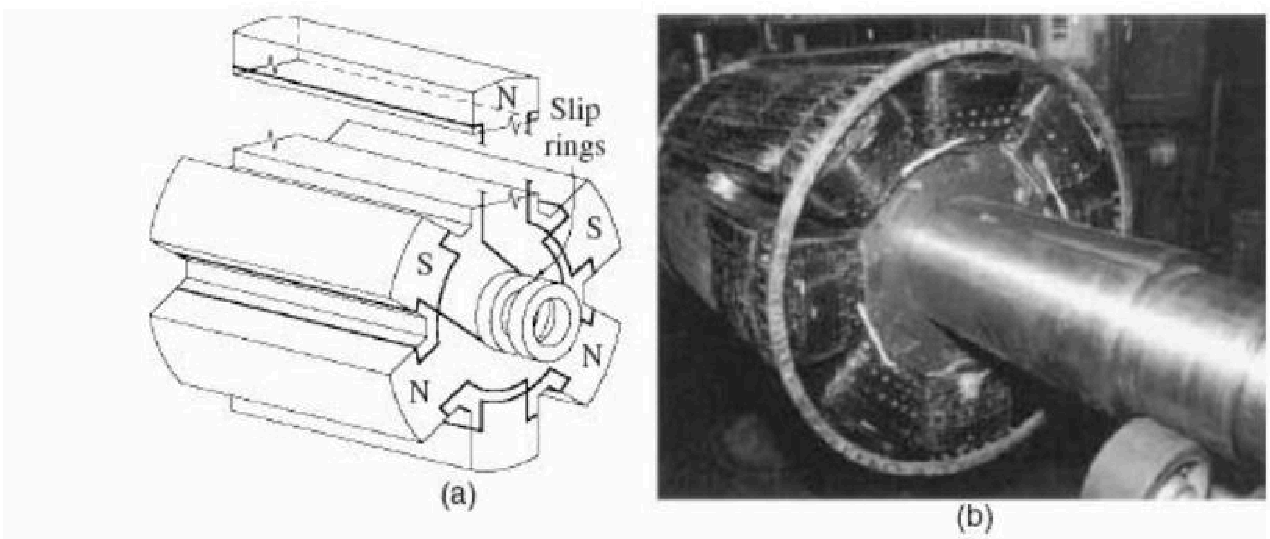
The rotor is a large electromagnet. Its magnetic poles can be salient (protruding or sticking out from the surface of the rotor), as shown in Figure 1, or nonsalient (flush with the surface of the rotor), as shown in Figure 2. Two and four pole rotors have normally nonsalient poles, while rotors with more than four poles have salient poles.

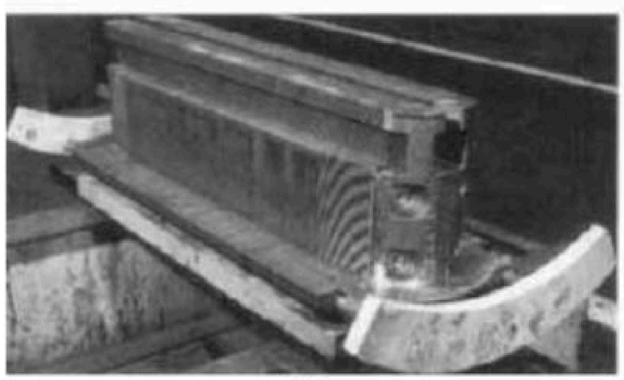
Small generator rotors are constructed of thin laminations to reduce eddy current losses, while large rotors are not constructed from laminations due to the high mechanical stresses encountered during operation. The field circuit of the rotor is supplied by a DC current. The common methods used to supply the DC power are:

1- By means of slip rings and brushes.

2- By a special DC power source mounted directly on the shaft of the rotor.

Slip rings are metal rings that encircle the rotor shaft but are insulated from it. Each of the two slip rings on the shaft is connected to one end of the DC rotor winding and a number of brushes ride on each slip ring. The positive end of the DC voltage source is connected to one slip ring, and the negative end is connected to the second. This ensures that the same DC voltage is applied to the field windings regardless of the angular position or speed of the rotor. Slip rings and brushes require high maintenance because the brushes must be checked for wear regularly. Also, the voltage drop across the brushes can be the cause of large power losses when the field currents are high. Despite these problems, all small generators use slip rings and brushes because all other methods used for supplying DC field current are more expensive.





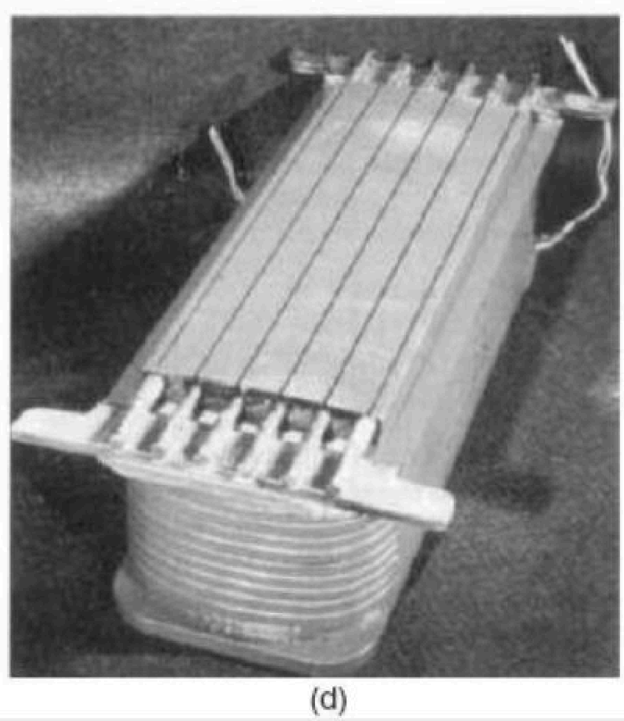


Figure 1 (a) A salient six-pole rotor for a synchronous machine. (b) A salient eight pole synchronous machine rotor showing the windings on the individual rotor poles. (c) A single salient pole from a rotor with the field windings not yet in place. (d) A single salient pole shown after the field windings are installed but before it is mounted on the rotor.

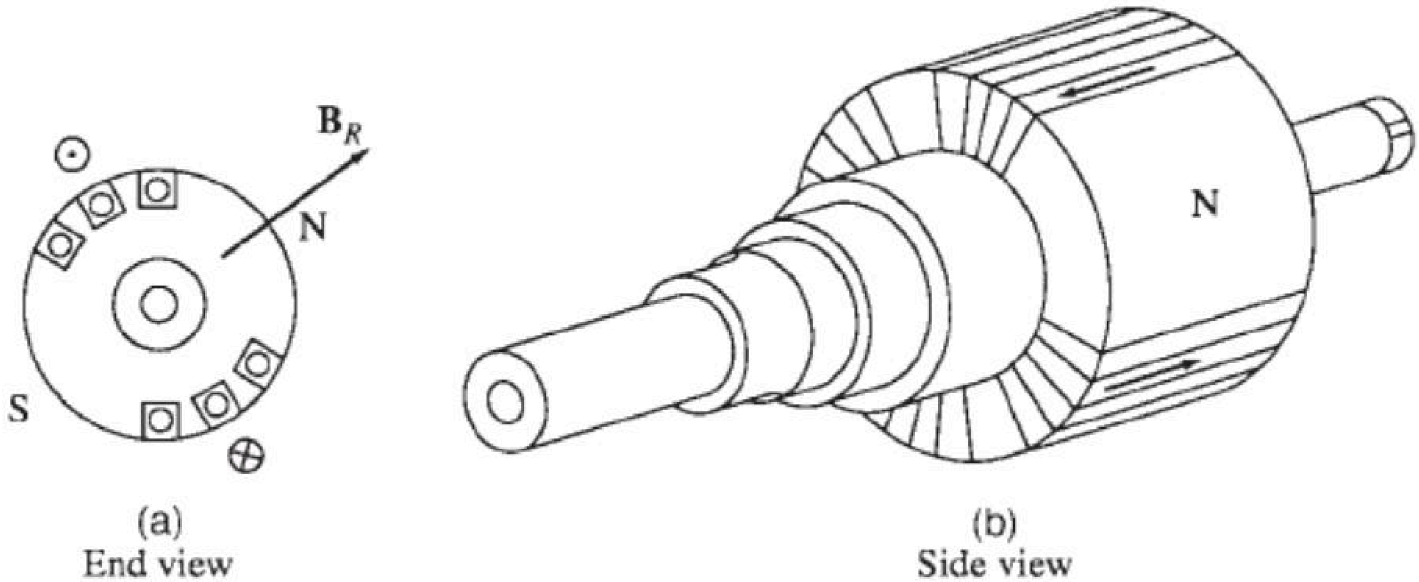


Figure 2 A nonsalient two-pole rotor for a synchronous machine. (*a*) End view; (*b*) side view.

Large generators use brushless exciters for supplying DC field current to the rotor. They consist of a small AC generator having its field circuit mounted on the stator and its armature circuit mounted on the rotor shaft.

The exciter generator output (three-phase alternating current) is converted to direct current by a three-phase rectifier circuit also mounted on the rotor. The DC current is fed to the main field circuit. The field current for the main generator can be controlled by the small DC field current of the exciter generator, which is located on the stator (Figures 3 and 4).

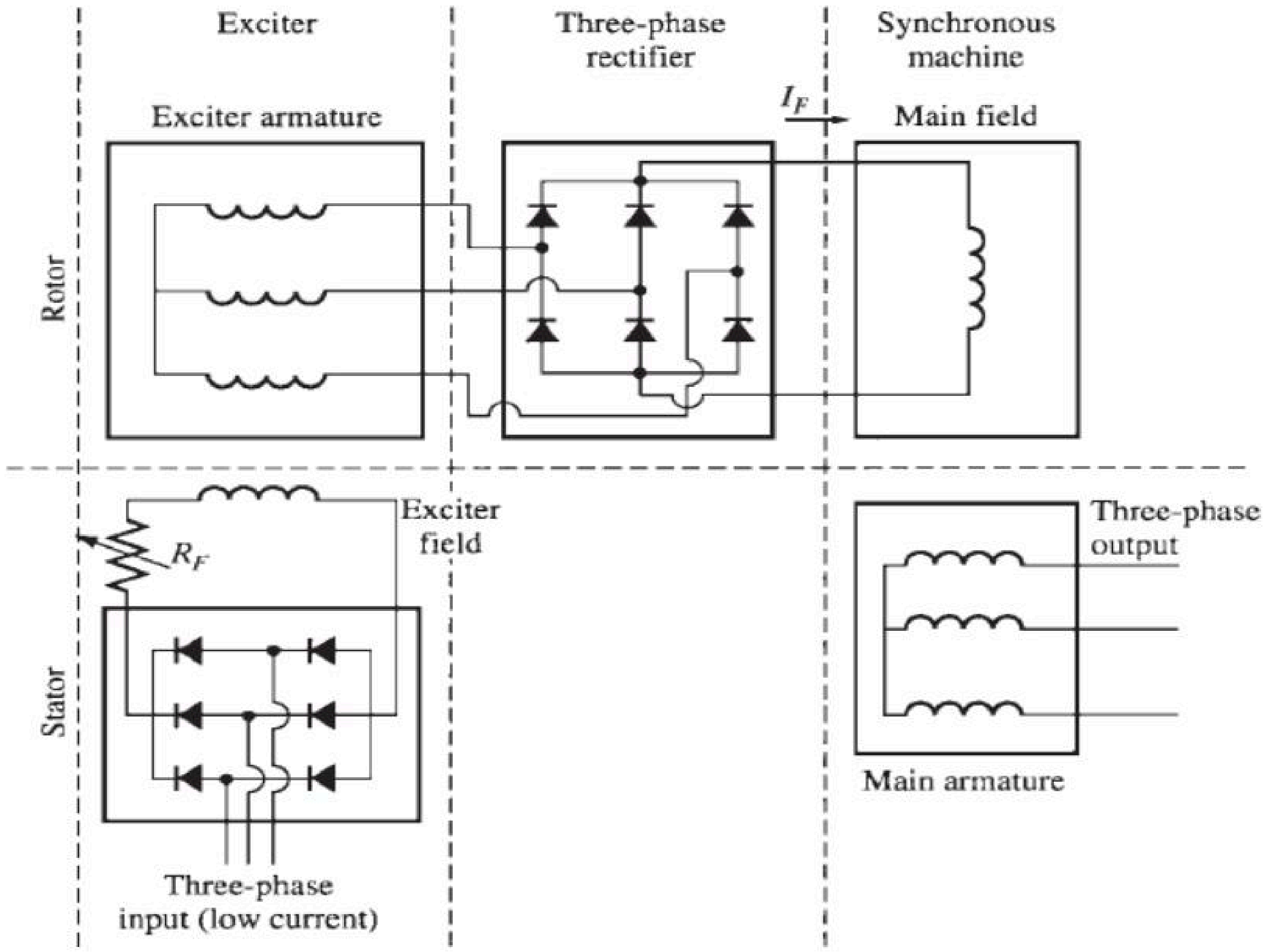


Figure 3 A brushless exciter circuit. A small three-phase current is rectified and used to supply the field circuit at the exciter, which is located on the stator. The output of the armature circuit of the exciter (on the rotor) is then rectified and used to supply the field current of the main machine.

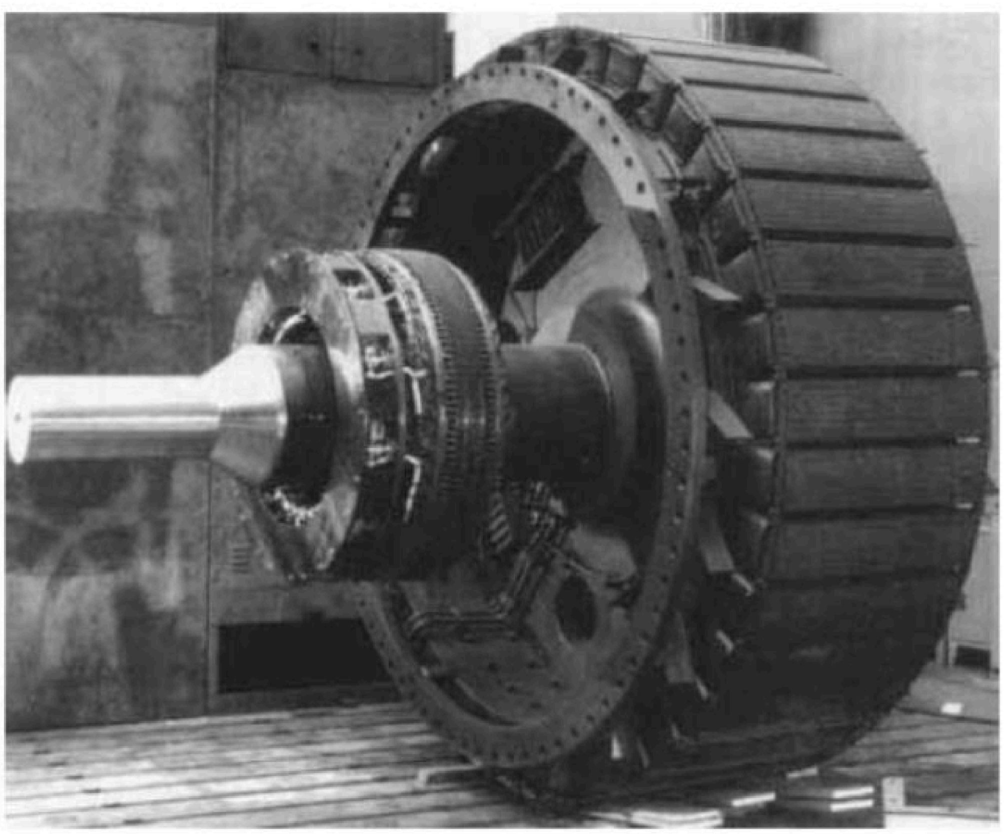


Figure 4 Photograph of a synchronous machine rotor with a brushless exciter mounted on the same shaft.

3.2 The Speed of Rotation of A Synchronous Generator

The electrical frequency of synchronous generators is synchronized (locked in) with the mechanical rate of rotation. The rate of rotation of the magnetic fields (mechanical speed) is related to the stator electrical frequency by:

$$f_e = \frac{n_m P}{120} \tag{1}$$

where f_e = electrical frequency, Hz

n_m = mechanical speed of magnetic field, r/min (= speed of the rotor for synchronous machines)

P = number of poles

For example, a two-pole generator rotor must rotate at 3000 r/min to generate electricity at 50 Hz.

3.3 The Internal Generated Voltage of A Synchronous Generator

The magnitude of the voltage induced in a given stator phase is given by:

$$E_A = K\phi\omega \tag{2}$$

where K is a constant that depends on the generator construction, φ is the flux in the machine, and ω is the frequency or speed of rotation.

Figure 5 (*a*) illustrates the relationship between the flux in the machine and the field current I_F. Since the internal generated voltage E_A is directly proportional to the flux, the relationship between the E_A and I_F is similar to the one between φ and I_F [Figure 5 (*b*)]. The graph is known as the *magnetization curve* or *open-circuit characteristic* of the machine.

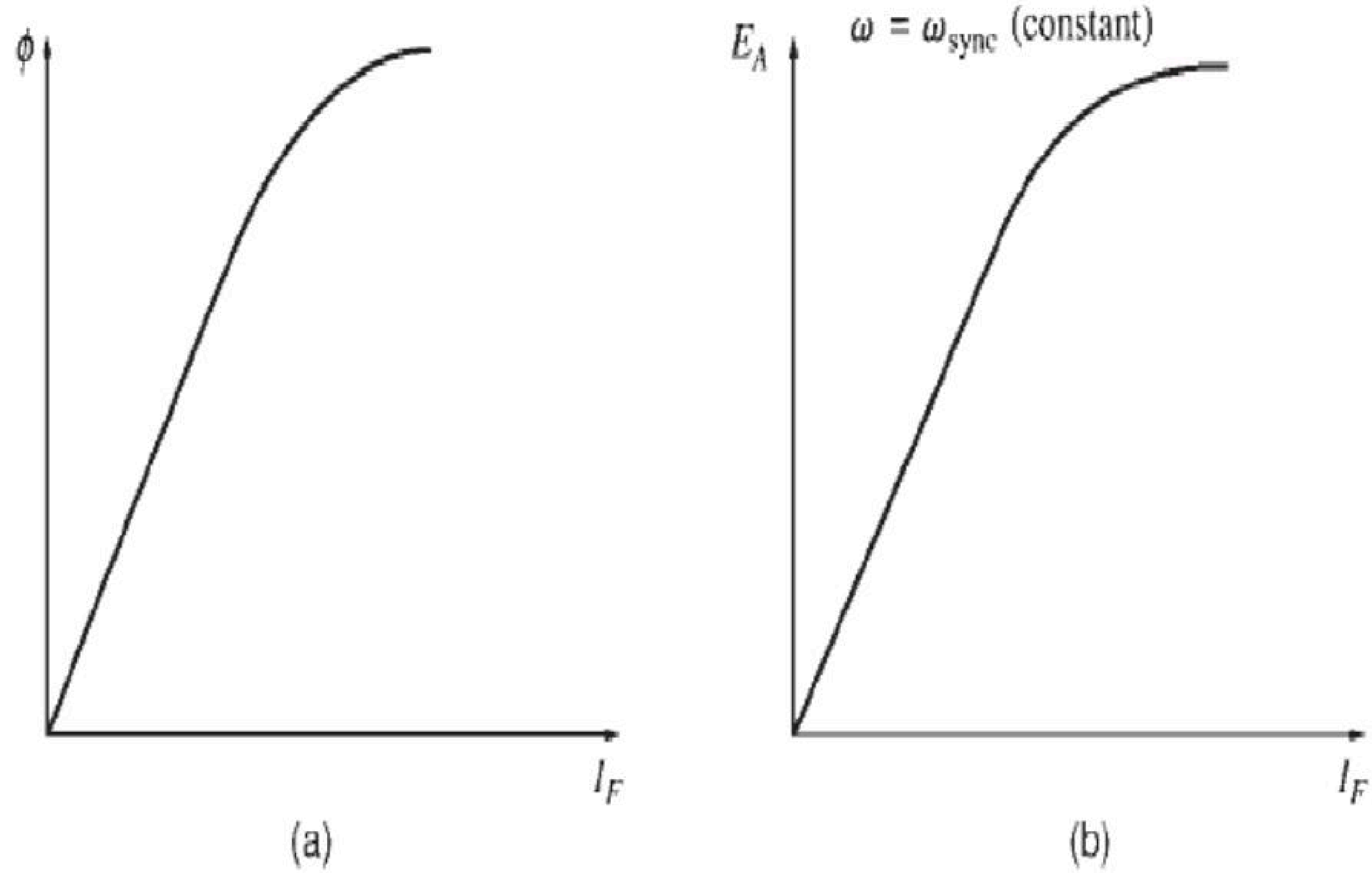


Figure 5 (*a*) Plot of flux versus field current for a synchronous generator. (*b*) The magnetization curve for the synchronous generator.

3.4 The Equivalent Circuit of A Synchronous Generator

The variable E_A is the internal generated voltage induced in one phase of a synchronous generator. However, this is not the usual voltage that appears at the terminals of the generator.

In reality, the internal voltage E_A is the same as the output voltage $V\varphi$ of a phase only when there is no armature current flowing in the stator. The three factors that cause the difference between E_A and $V\varphi$ are:

1-The *armature reaction,* which is the distortion of the air-gap magnetic field by the current flowing in the stator.

2- The self-inductance of the armature (stator) windings.

3- The resistance of the armature windings.

When the effects of the stator windings self inductance L_A (and its corresponding reactance X_A), the armature reaction X and resistance R_A are added, the relationship becomes

$$V_\phi = E_A - jXI_A - jX_AI_A - R_AI_A$$

When the effects of the armature reaction and self-inductance are combined (the reactance's are added), the *synchronous reactance* of the generator is

$$X_S = X + X_A \qquad (3)$$

The final equation becomes

$$V_\phi = E_A - jX_SI_A - R_AI_A \qquad (4)$$

Figure 6 illustrates the equivalent circuit of a three-phase synchronous generator.

The rotor field circuit is supplied by DC power, which is modeled by the coil's inductance and resistance in series. The adjustable resistance R_{adj} controls the field current. The internal generated voltage for each of the phases is shown in series with the synchronous reactance X_S and the stator winding resistance R_A. The three phases are identical except that the voltages and currents are 120° apart in angle.

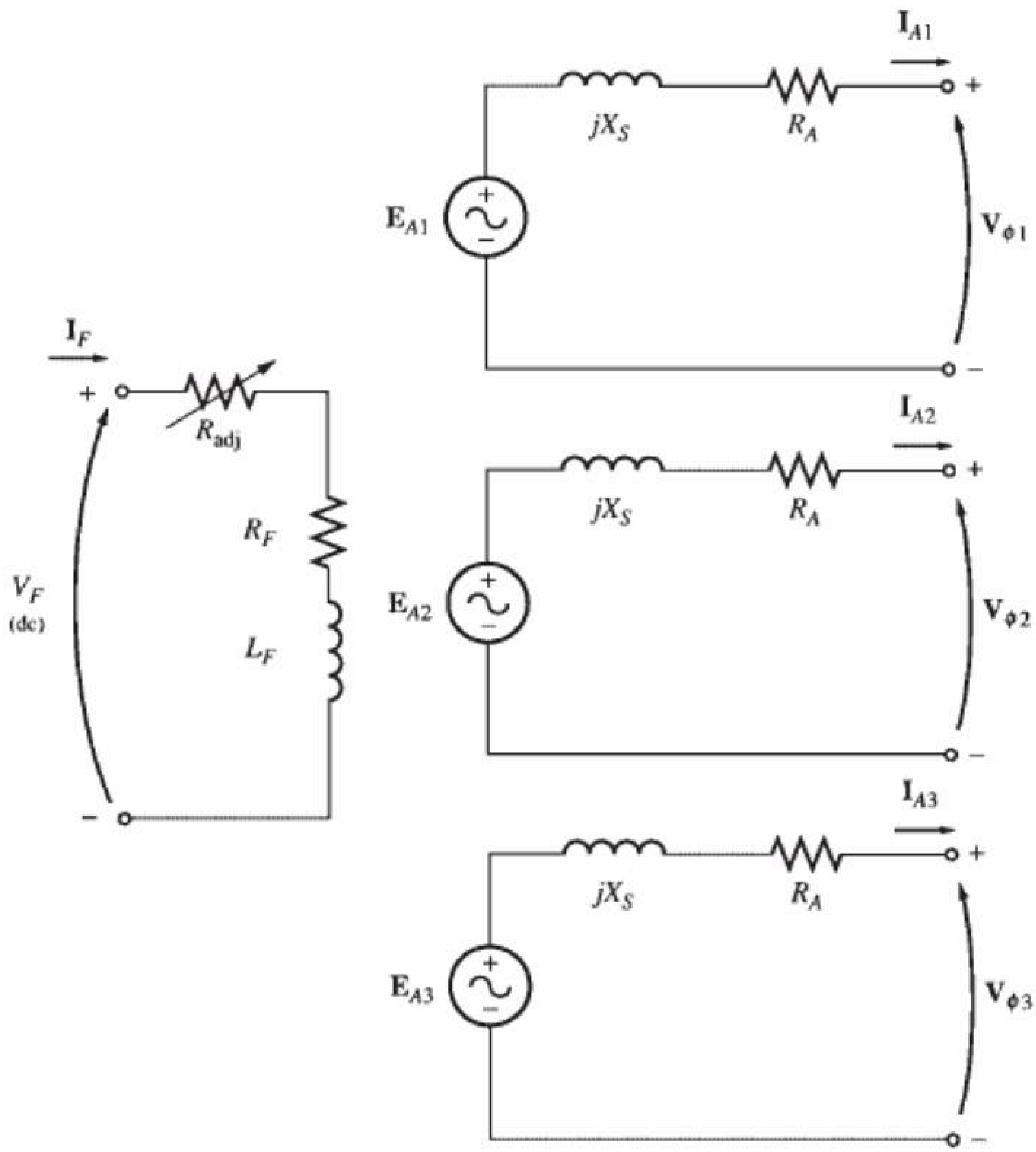


Figure 6 The full equivalent circuit of a three-phase synchronous generator.

Figure 7 illustrates that the phases can be either **Y** or Δ connected. When they are **Y** connected, the terminal voltage V_T is related to the phase voltage $V\varphi$ by

$$V_T = \sqrt{3}\, V_\phi$$

When they are Δ connected, then

$$V_T = V_\phi$$

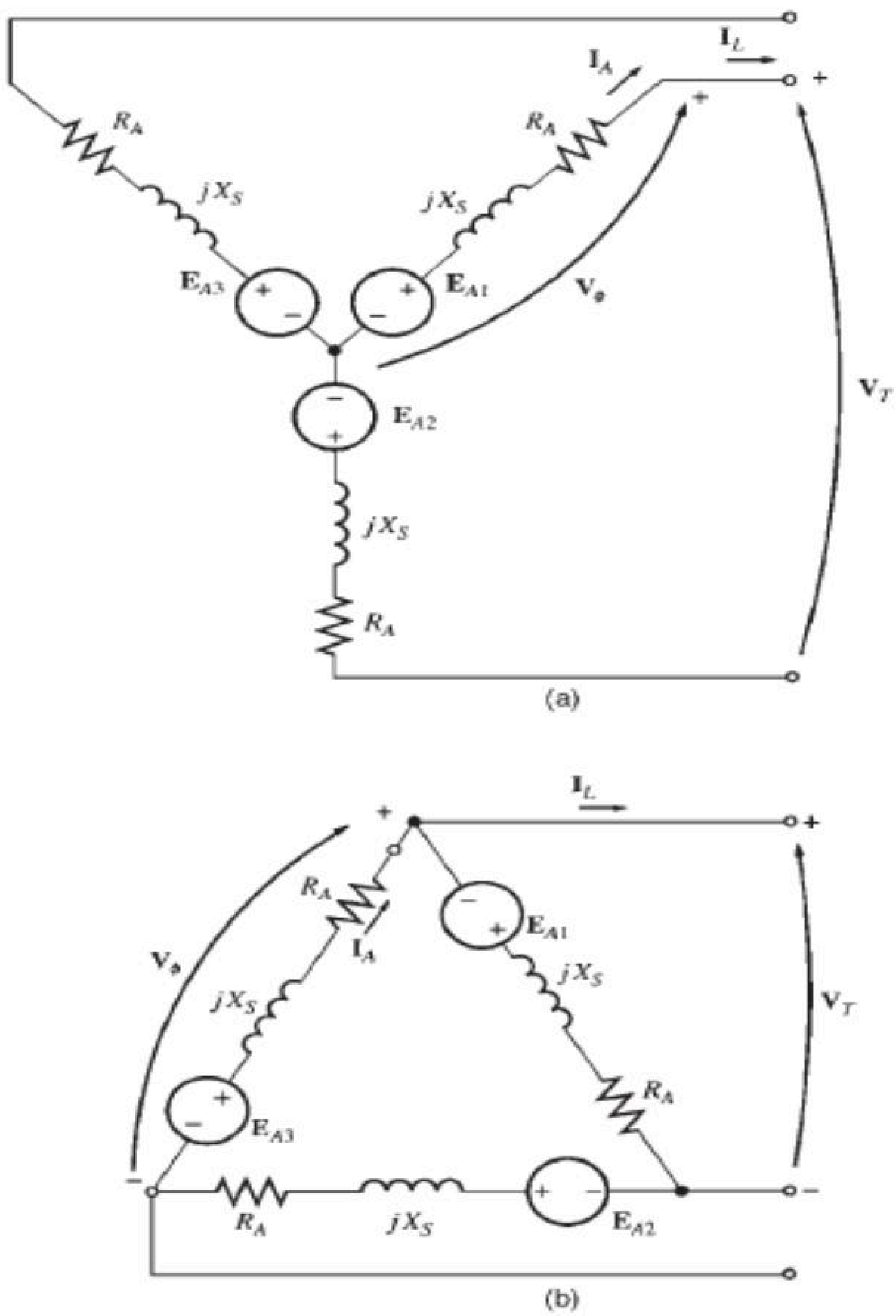


Figure 7 The generator equivalent circuit connected Y in (*a*) and Δ in (*b*).

3.5 The Phasor Diagram of A Synchronous Generator

Phasors are used to describe the relationships between AC voltages. Figure 8 illustrates these relationships when the generator is supplying a purely resistive load (at unity power factor). The total voltage E_A differs from the terminal voltage $V\varphi$ by the resistive and inductive voltage drops. All voltages and currents are referenced to Vφ, which is assumed arbitrarily to be at angle 0°.

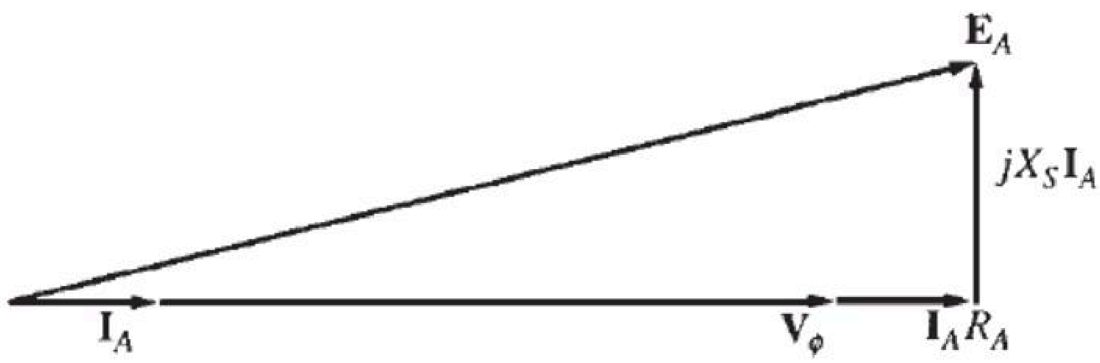


Figure 8 The phasor diagram of a synchronous generator at unity power factor

Figure 9 illustrates the phasor diagrams of generators operating at lagging and leading power factors. Notice that for a given phase voltage and armature current, lagging loads require larger internal generated voltage EA than leading loads. Therefore, a larger field current is required for lagging loads to get the same terminal voltage, because:

$$E_A = K\phi\omega$$

where ω must remain constant to maintain constant frequency. Thus, for a given field current and magnitude of load current, the terminal voltage for lagging loads is lower than the one for leading loads. In real synchronous generators, the winding resistance is much smaller than the synchronous reactance. Therefore, R_A is often neglected in qualitative studies of voltage variations.

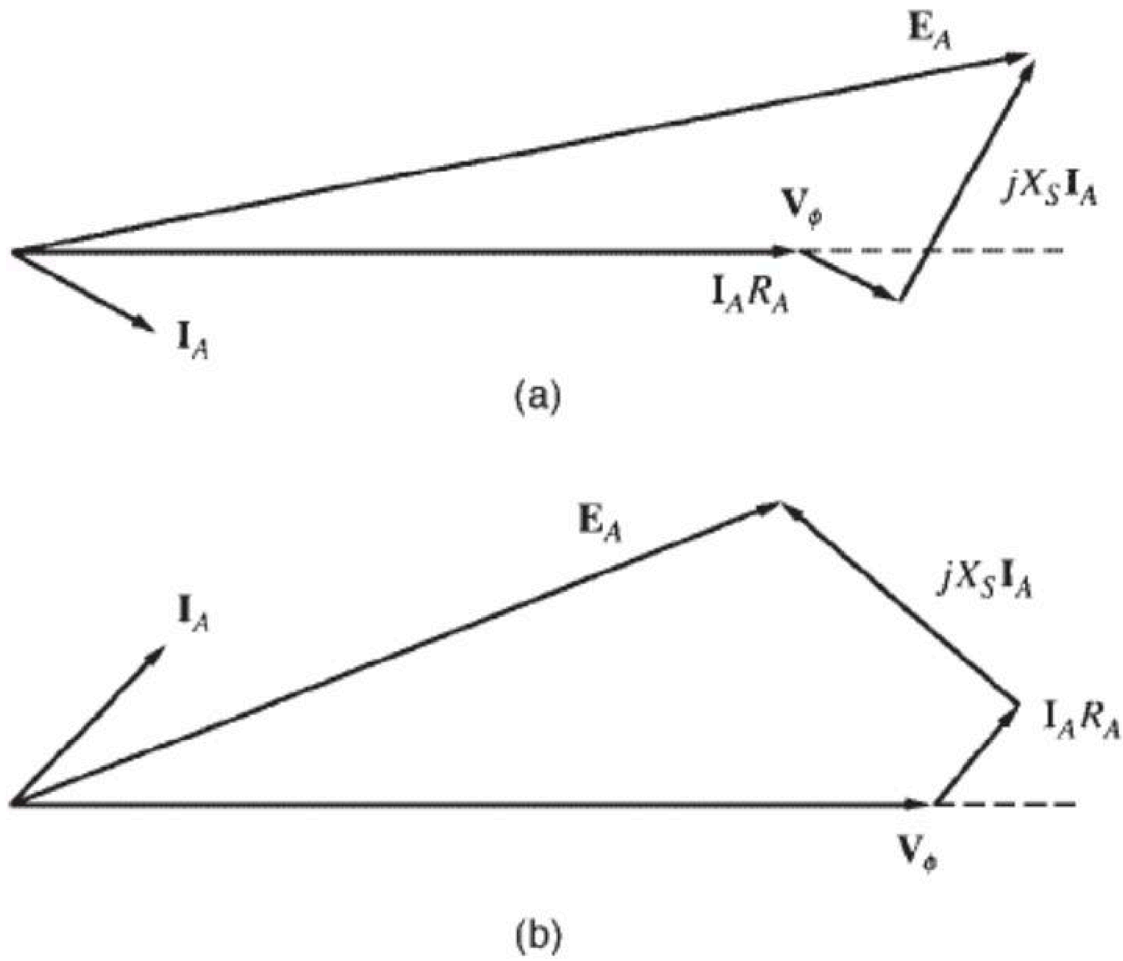


Figure 9 The phasor diagram of a synchronous generator at (*a*) lagging and (*b*) leading power factor.

3.6 Parallel Operation of AC Generators

In most generator applications, there is more than one generator operating in parallel to supply power to various loads.

Three major advantages for operating synchronous generators in parallel are

1. The reliability of the power system increases when many generators are operating in parallel, because the failure of any one of them does not cause a total power loss to the loads.

2. When many generators operate in parallel, one or more of them can be taken out when failures occur in power plants or for preventive maintenance.

3. If one generator is used, it cannot operate near full load (because the loads are changing), then it will be inefficient. When several machines are operating in parallel, it is possible to operate only a fraction of them. The ones that are operating will be more efficient because they are near full load.

3.7 The Conditions Required for Paralleling

Figure 10 illustrates a synchronous generator (G1) supplying power to a load with another generator (G2) that is about to be paralleled with G1 by closing the switch (S1). If the switch is closed at some arbitrary moment, the generators could be severely damaged and the load may lose power. If the voltages are different in the conductor being tied together, there will be *very* large current flow when the switch is closed.

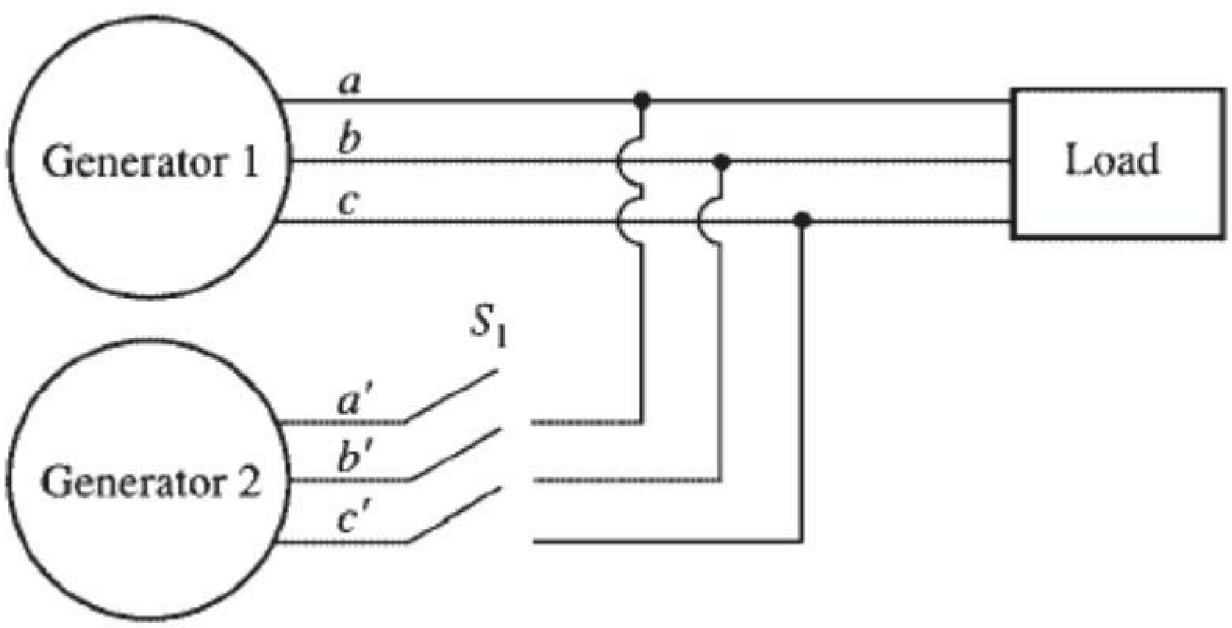


Figure10 A generator being paralleled with a running power system.

This problem can be avoided by ensuring that each of the three phases has the *same voltage magnitude and phase angle* as the conductor to which it is connected. To ensure this match, these four *paralleling conditions* must be met:

1- The two generators must have the same rms line voltages.

2- The *phase sequence* must be the same in the two generators.

3- The two *a* phases must have the same phase angles.

4- The frequency of the *oncoming generator* must be slightly higher than the frequency of the running system.

If the sequence in which the phase voltages peak in the two generators is different [Figure 11], then two pairs of voltages are 120° out of phase, and only one pair of voltages (the *a* phases) are in phase. If the generators are connected in this manner, large currents would flow in phases *b* and *c,* causing damage to both machines.

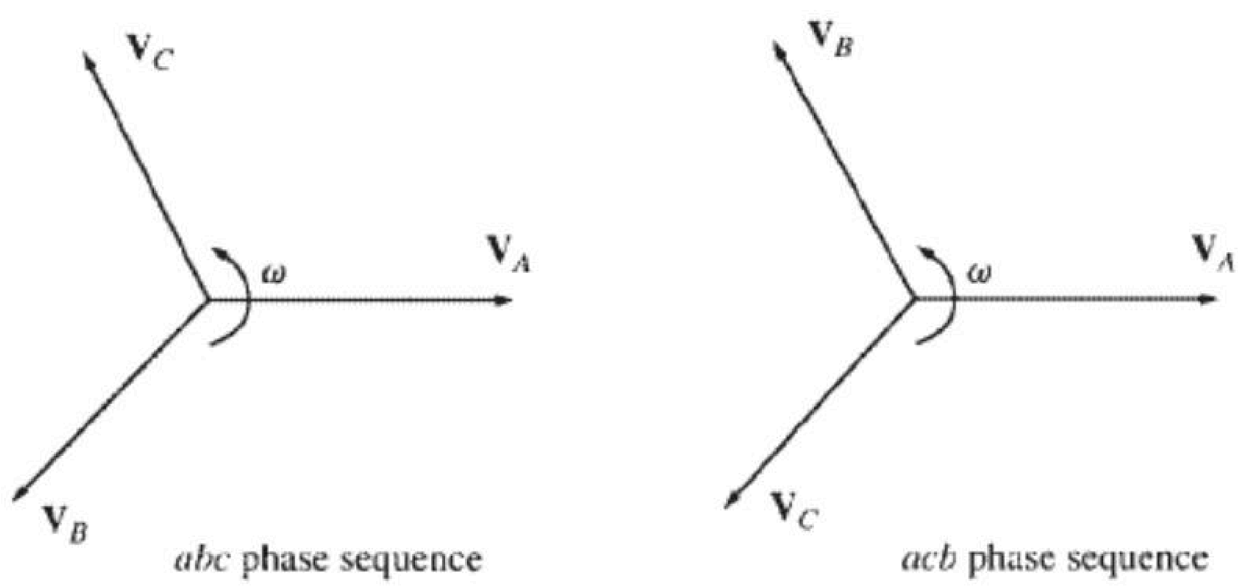


Figure 11 The two possible phase sequences of a three-phase system.

The phase sequence problem can be corrected by swapping the connections on any two of the three phases on one of the generators. If the frequencies of the power supplied by the two generators are not almost equal when they are connected together, large power transients will occur until the generators stabilize at a common frequency. The frequencies of the two generators must differ by a small amount so that the phase angles of the oncoming generator will change slowly, relative to the phase angles of the running system. The angles between the voltages can be observed and switch S_1 can be closed when the systems are exactly in phase and this can be down through three light bulb method as shown in Figure 12.

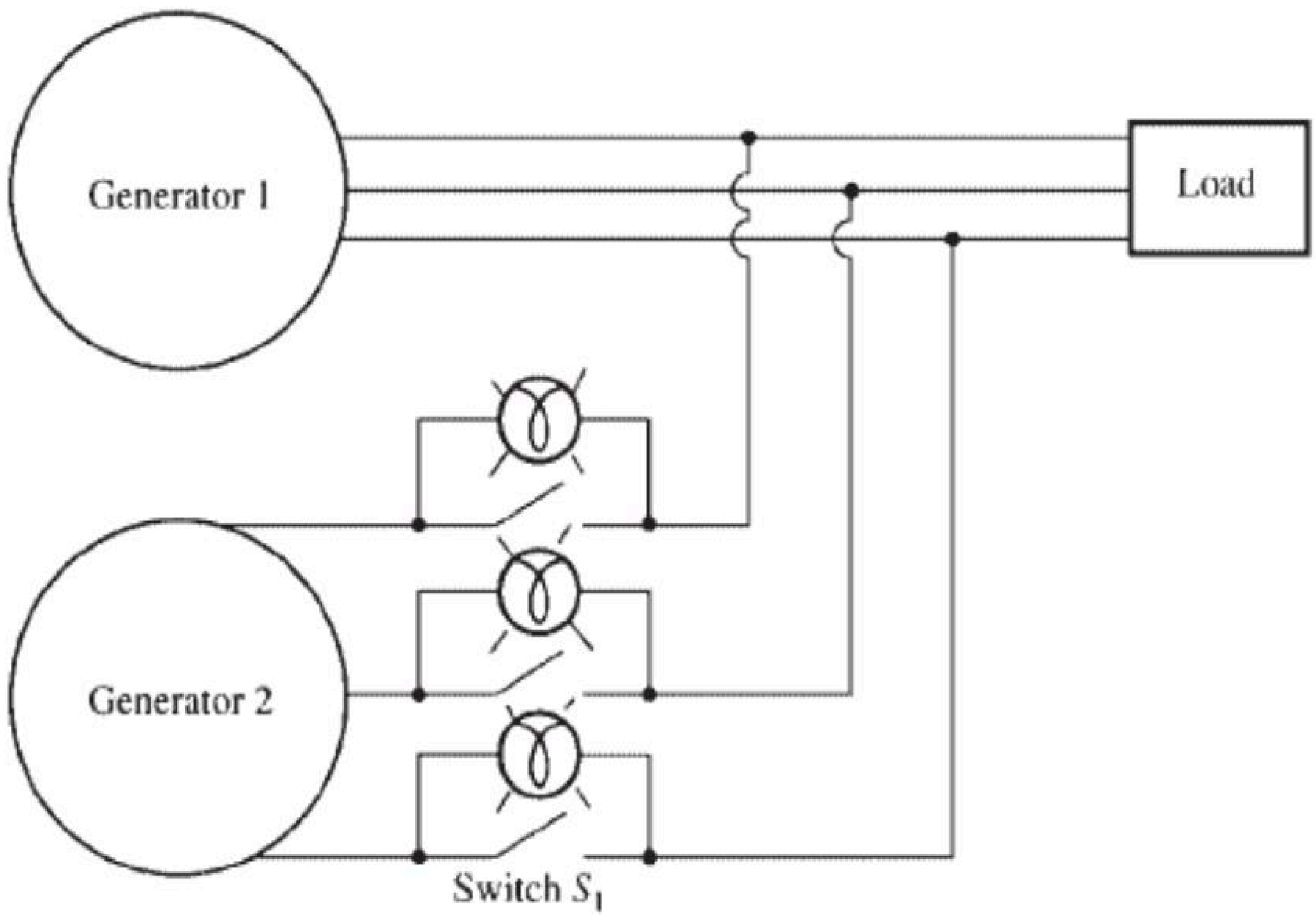


Figure 12 The three-light bulb method for checking phase sequence.

3.8 The Synchronous Machine Modeling

The electrical characteristic equations describing a three-phase synchronous machine are commonly defined by a two-dimensional reference frame. This involves in the use of Park's transformations by using the ***Two-Axis Theorem*** to convert currents and flux linkages into two fictitious windings located 90^0 apart. A typical synchronous machine consists of three stator windings mounted on the stator and one field winding mounted on the rotor. These axes are fixed with respect to the rotor (d-axis) and the other lies along the magnetic neutral axis (q-axis), which model the short-circuited paths of the damper windings.

Electrical quantities can then be expressed in terms of d and q-axis parameters. Figure 13 presents the diagram of d-q axis in the machine.

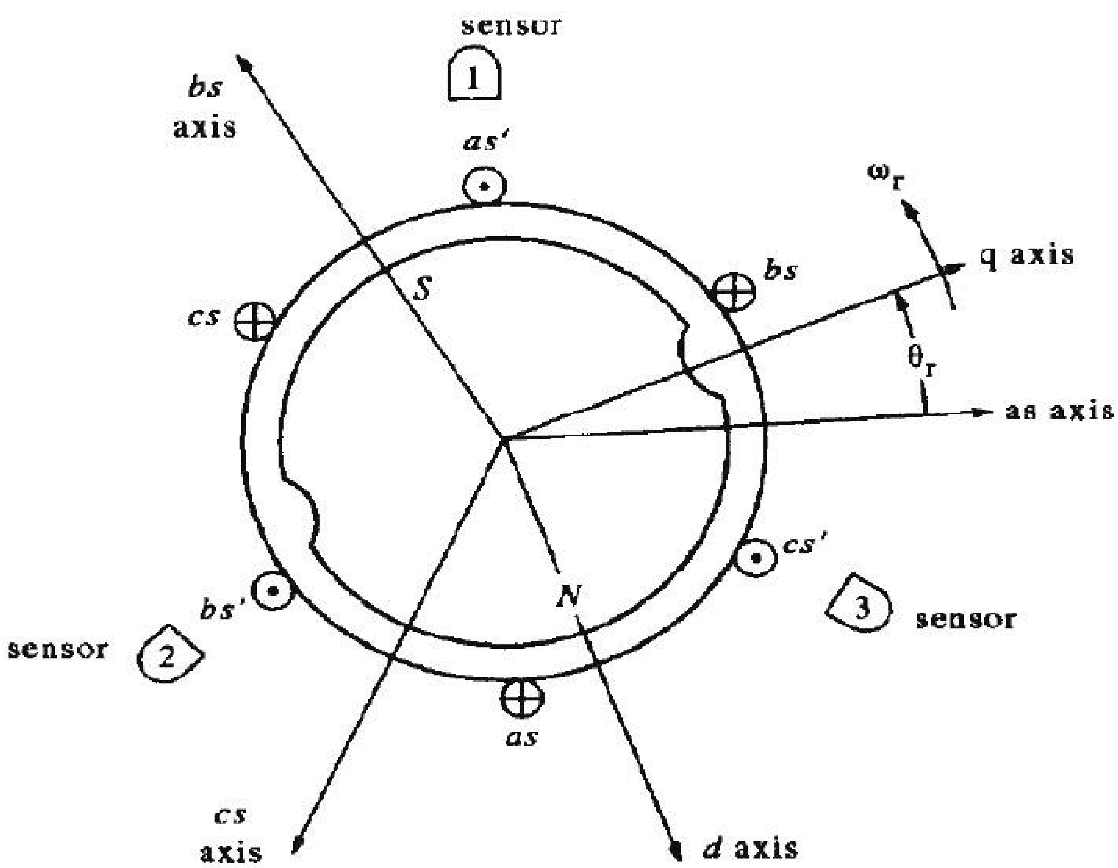


Figure 13 Illustration of the positions of d-q axis on a two-pole machine

There is the need for damper windings to reduce mechanical oscillations of the rotor around the synchronous speed. The damper windings act in both the d-axis and q-axis, however not equally. Illustrated in Figure 14 is the general construction of the damper windings on the poles of the rotor.

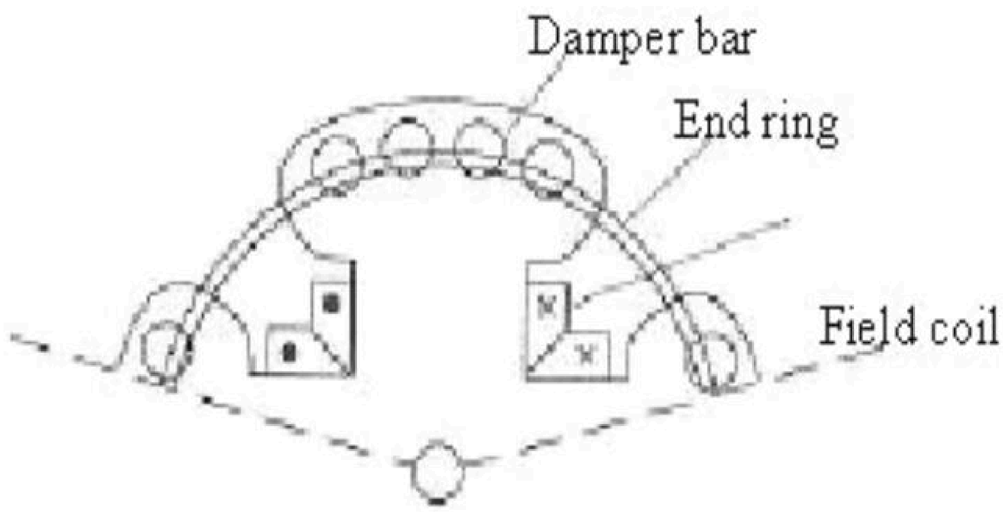


Figure 14 Salient-pole rotor with damper windings

There have been several methods used to determine the parameters of a synchronous machine. All of these methods base their analysis on acquiring the operational inductance obtaining some time constants from the inductance data and then using this to determine the parameters of the machine.

3.8.1 Direct Axis

When a synchronous machine is running at synchronous speed with no field current flowing and with the field winding slip rings short-circuited, the total flux linkages λ_f with the field windings are:

$$\lambda_f = (L_f + M_d)I_f - M_d I_d \tag{5}$$

L_f = leakage inductance of field winding

L_a = leakage inductance of armature winding

Md = mutual inductance between the field and d-axis winding

If = current in field winding

Id = current in d-axis winding

and $R_a = R_f = 0$

These windings are illustrated in Figure 15.

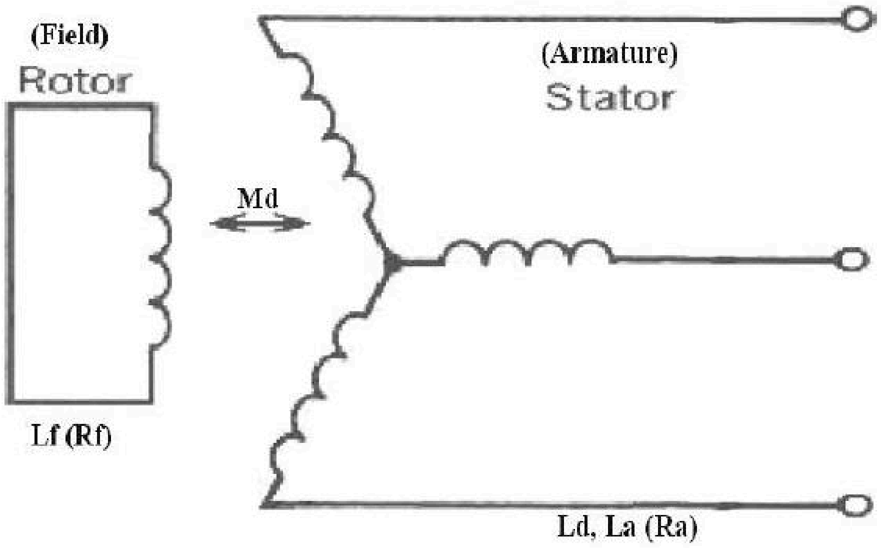


Figure 15 Diagram of windings in the direct axis

With the aid of the diagram shown in Figure 16, the direct axis reactance during transient is not the same as that in the steady state. The value of X_d to be used during transients is called the direct axis transient reactance X'_d.

$$X'_d = X_a + \frac{X_{md} X_f}{X_{md} + X_f} \qquad (6)$$

From this equation, it is obvious that the armature leakage reactance is in series with the parallel combination of X_{md} and X_f. Figure 5 shows the direct axis equivalent circuit including the winding resistances.

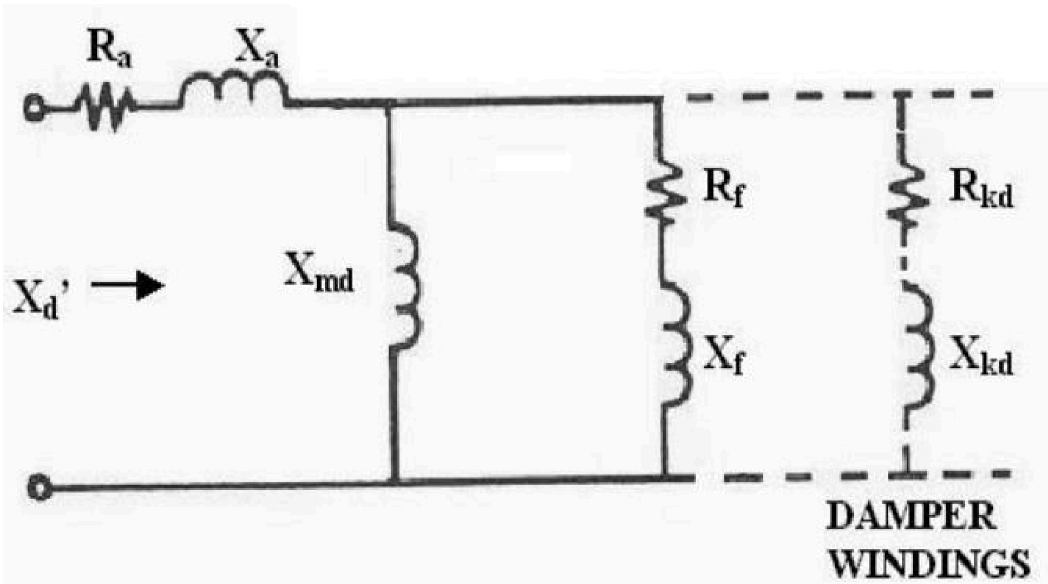


Figure16 Direct axis equivalent circuit

Since during transients the flux linkages with the field winding change, they will also change with any closed circuit on the rotor.

The leakage reactance of damper windings is negligible in the steady state but during sub-transient and transient state, it will be significant as it affects the time constants in those periods. The equation for direct axis sub-transient reactance is:

$$X_d^{''} = X_a + \frac{X_{md} X_f X_{kd}}{X_{md} X_f + X_{md} X_{kd} + X_f X_{kd}} \qquad (7)$$

3.8.2 Quadrature Axis

The quadrature axis equivalent circuit as shown in Figure 17 is similar to direct axis equivalent circuit but it has no field winding.

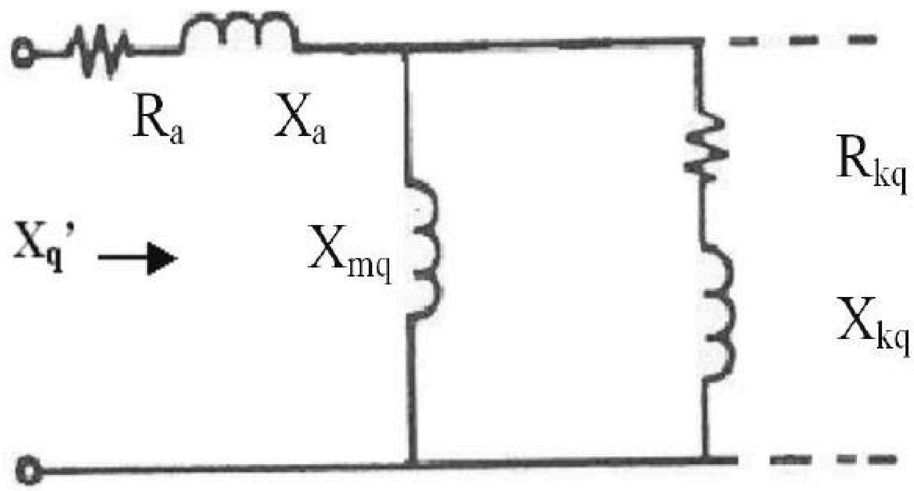


Figure17 Quadrature axis equivalent circuit

$$X_q^{''} = X_a + \frac{X_{mq} X_{kq}}{X_{mq} + X_{kq}} \qquad (8)$$

From Figure 17, the quadrature axis sub-transient reactance can be determined as shown in equation (8).

With the diagram shown in Figure 17, the various time constants can be obtained as follows:

$$T_{do}^{'} = \frac{1}{\omega_o R_f}(X_{md} + X_f) \qquad (9)$$

$$T_d^{'} = \frac{1}{\omega_o R_f}(X_f + \frac{X_{md} X_a}{X_{md} + X_a}) \qquad (10)$$

$$T_{do}^{''} = \frac{1}{\omega_o R_{kd}}(X_{kd} + \frac{X_{md} X_f}{X_{md} + X_f}) \qquad (11)$$

$$T_d^{''} = \frac{1}{\omega_o R_{kd}}(X_{kd} + \frac{X_{md} X_a X_f}{X_{md} X_f + X_{md} X_a + X_f X_a}) \qquad (12)$$

$$T_{qo}^{''} = \frac{1}{\omega_o R_{kq}}(X_{kq} + X_{mq}) \qquad (13)$$

$$T_q^{''} = \frac{1}{\omega_o R_{kq}}(X_{kq} + \frac{X_{mq} X_a}{X_{mq} + X_a}) \qquad (14)$$

$$T_{kd} = \frac{X_{kd}}{\omega_o R_{kd}} \qquad (15)$$