10

Synchronous Machines

TOPICS DISCUSSED

- Constructional details of synchronous machines
- Armature winding
- Induced EMF
- Distribution factor and pitch factor
- Open circuit and short-circuit tests
- Synchronous impedance
- Armature reaction
- Voltage regulation
- Parallel operation of synchronous generators
- Synchronous motors
- Effect of change of excitation of synchronous motors
- Applications

10.1 INTRODUCTION

tential energy of water is utilized in running a number of water turbines located at the base of the dam. Large capacity ac generators are coupled with these turbines. When the turbines rotate, electricity is generated in the ac generators which is brought out through wire connections, stepped up to a higher voltage and transmitted through long transmission lines to be taken to places where electricity is required. The ac generators, also called the alternators, used for generation of electricity on a large scale are invariably three-phase ac generators. The generation of voltage is based on the basic principle that when there is relative motion between a conductor and a magnetic field, EMF is induced in the conductor. This is called the generating action. The same machine will work as a motor when electrical energy is the input and mechanical energy is the output. A motor works on the basic principle that when a current carrying conductor is placed in a magnetic field, it experiences a force. Thus, the electro-mechanical energy conversion that takes place in an electrical machine is a reversible process. That is the same machine works as a generator when mechanical energy is converted into electrical energy and as a motor when electrical energy is converted into mechanical output.

10.2 CONSTRUCTIONAL DETAILS OF SYNCHRONOUS MACHINES

In a three phase synchronous generator, a set of coils are placed in slots inside a hollow cylindrical stator. The coils are wound for different number of poles. Magnetic poles are formed on the rotor and are rotated by a prime mover, i.e., a turbine. The rotating poles produce a flux which cuts the stator conductors. Because of the cutting of flux by the coil sides, i.e., conductors, EMF is induced in them.

The poles forming the rotor are rotated at a constant speed, called the synchronous speed so that EMF of constant frequency is generated. Normally the electricity generated is for 50 cycles per second. The relationship between the rotor speed, i.e., synchronous speed, N_S the number of poles, P and the frequency of induced EMF, f is given by

$$N_s = \frac{120f}{P}$$

If the poles for which the machine is made is 2, and the frequency of generated EMF to be 50 Hz, then the turbine speed must be

$$N_S = \frac{120 \times 50}{2} = 3000 \text{ rpm}$$

It can been calculated that for P = 4, N_s = 1500 rpm; for P = 6, N_s = 1000 rpm and so on.

The construction of the rotor forming the magnetic poles which are rotated by the turbine are of two types. One type is of projected pole-type rotor construction where number of poles are made by passing

In hydroelectric generating stations, the speed of the turbines is comparatively lower than the steam turbines used in thermal power stations. For example, the turbine speed in Bhakra Hydroelectric power generating station is only 167 rpm. To generate electricity at 50 Hz, the number of magnetic poles required on the rotor is as many as 36. Projected type of poles are used in the rotors when a large number of poles are to be fixed on the rotor. Such rotors are called salient-type rotors. When P = 36 and the frequency of the induced EMF is to be 50 Hz, then the turbine speed, N_S is

$$N_S = \frac{120 \times 50}{36} = 167 \text{ rpm}$$

In thermal power stations the turbine speed is usually maintained at 3000 rpm so that the number of rotor poles is only 2.

$$N_S = \frac{120 \times 50}{2} = 3000 \text{ rpm}$$

High-speed rotors are made cylindrical type, or non-projected type and are also called non-salient type. Thus, two types of rotor construction are made, one is the salient-type rotor and the other is the non-salient or cylindrical-type rotors. The stator construction is the same in both the cases. Three-phase windings, displaced at 120° apart are made on the stator slots. Cross-sectional view of the two types of synchronous machines are shown in Fig. 10.1. The stator windings that are made on stator slots have not been shown in the figures.

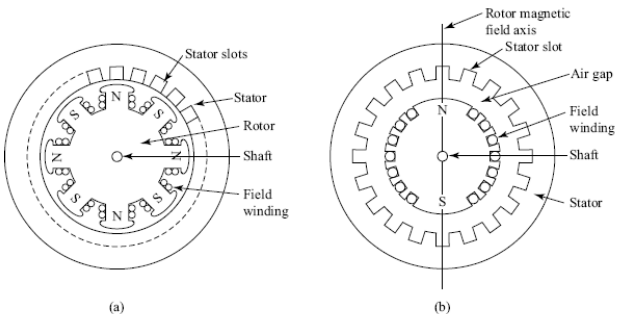

Figure 10.1 (a) Salient-pole-type synchronous machine; (b) cylindrical-type synchronous machine

Direct current supply is provided to the field windings so that the poles are magnetized. Current to the rotating field windings is sup-

supply terminals is to be provided to the rotor field windings through the brush and slip-ring arrangement.

A set of two brushes and slip rings are required to supply dc current to the field windings. Three-phase armature windings are made on the stator slots, and connections from these windings to the load can be taken directly. Thus, we have a three-phase winding placed on the stator slots. Field poles are formed on the rotor which are excited by supplying direct current using two sets of brush and slip rings.

It may be noted that in a dc machine, the armature winding is made on the rotor while the field poles are fixed on the stator. In synchronous machines, the reverse is done, i.e., the armature winding is made on the stator and the field poles are rotated.

10.3 ADVANTAGES OF STATIONARY ARMATURE AND ROTATING FIELD

The field windings get dc supply from a low-voltage dc source of supply, say 250 V. The voltage generated in the armature winding is normally at 11,000 V. If the armature winding is kept stationary, it becomes easy to insulate the conductors. That is why, low voltage field winding is made a rotating member while high-voltage armature winding is kept stationary. Two slip rings of low voltage and current rating will be required in this case. If the armature winding is placed on the rotor, three slip rings insulated for high voltage will be required. The rotor with field poles and windings will have less weight and inertia as compared to armature winding with its iron core on the rotor. Further cooling of the armature windings carrying high currents can easily be done when they are stationary.

10.4 USE OF LAMINATED SHEETS FOR THE STATOR AND THE ROTOR

The stator is made up of thin laminated silicon steel sheets with varnish insulation. These laminated sheets are placed one above the other and are pressed together and held tightly. Loosely held laminations would cause magnetic vibration resulting in humming noise. A large number of slots are made on the inner side of the laminations by punching. After putting an insulated paper or some other insulating sheets on the slots, windings are placed inside the slots. The windings are held tightly inside the slots. The slots could be open type or semi-closed type. Similarly, the rotor is also made of laminated steel sheets.

10.5 ARMATURE WINDINGS

Insulated copper wires are used to form coils which are placed inside the slots made on the stator. The windings are made for a different number of poles depending upon the design. The number of poles for which the stator winding is made and the number of rotor poles are the same. For the generation of three-phase voltages three separate windings are made on the stator and are joined together. The three windings are displaced in space by 120°. For simplicity in Fig. 10.2 (a) we have shown only one coil per phase. The three-phase windings, i.e., R–R′, Y–Y′, B–B′ are shown placed at an angle of 120°. The winding has been made for two poles as in Fig. 10.2 (a) and for four poles as in Fig. 10.2 (b).

The three windings are connected in star by joining R′ Y′ B′ forming the star points and the terminals R, Y, B are brought out for external connections.

rent I_f from a dc voltage source through brush and slip-ring arrangement. When the field system is rotated by a prime mover, which can be a water turbine or a steam turbine, the field flux will cut the winding conductors in sequence, and hence EMF will be induced in them. In the three-phase windings, the alternating voltages will be available. There will be a time phase difference between the voltages induced in the three phases as they are physically displaced at an angle of 120 electrical degrees.

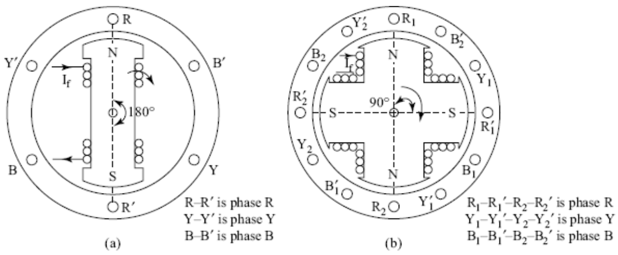

Figure 10.2 (a) Three-phase two-pole stator winding; (b) three-phase four-pole winding

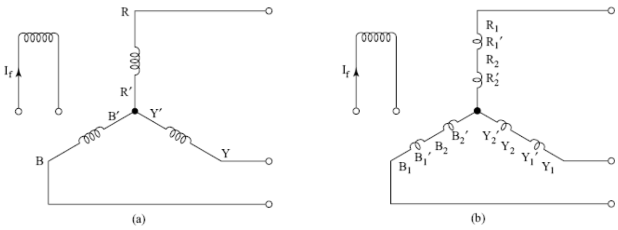

Figure 10.3 Stator windings connected in star: (a) two-pole winding; (b) four-pole winding

10.6 CONCEPT OF COIL SPAN, MECHANICAL, AND ELECTRICAL DEGREES

The angular distance between the two coil sides of a coil is called the coil span. From Fig. 10.2 (a), it can be observed that the angular distance between the two coil sides of coil R–R′ is 180°. The winding is for two poles. From Fig. 10.2 (b) which has a four-pole winding, the angular distance between the coil sides of coil R_1–R_1' is 90°. If we make a winding for eight poles, the coil span will be reduced further to 45°. The change of coil span for windings of a different number of poles has been further illustrated in Fig. 10.4.

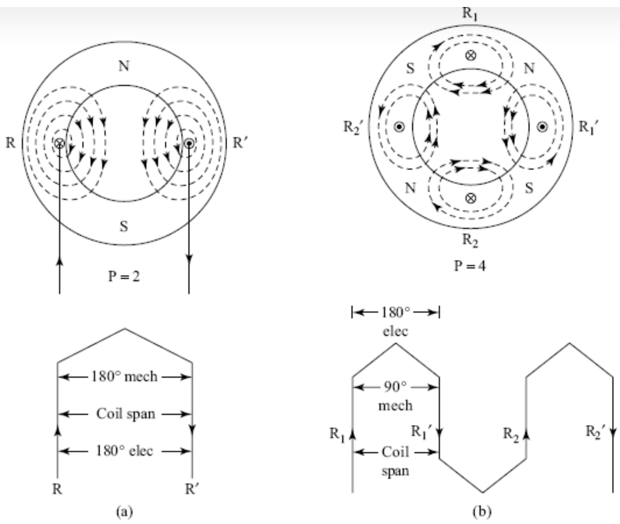

Figure 10.4 (a) Two-pole stator winding; (b) four-pole stator winding

The direction of current flowing through the coils and the flux produced have been shown. It is observed that when the coil span is 180° mechanical, as in Fig. 10.4 (a), two poles are formed. In Fig. 10.4 (b), the coil span has been reduced to 90° mechanical. Two coils have been used to complete the winding distributed throughout the stator. The directions of the flux produced show that four poles are formed in the stator. This shows how by using coils of different spans, a winding can be made for a different number of poles. The students are advised to draw a simple six-pole stator winding by using three coils connected together. The coil span here should be 60° mechanical.

The distance between the two coil sides of a coil is always expressed as 180° electrical irrespective of the number of poles for which the winding is made. For a two-pole winding, the coil span is 180° electrical which is also equal to 180° mechanical. For a four-pole winding, the coil span is again 180° electrical which is equal to 90° mechanical. If the winding is made for six-poles, the coil span will be counted as 180° electrical but will be equal to 60° mechanical.

In general, the relationship between electrical degrees and mechanical degrees is expressed as

$$1^\circ \text{ Mechanical} = \frac{P^\circ}{2} \text{ Electrical}$$

When P = 2, 1° mechanical is equal to 1° electrical or 180° mechanical is equal to 180° electrical.

10.7 TYPES OF WINDINGS

Three-phase windings are made for a different number of poles. Each phase winding generally will have a number of coils connected together. The three-phase windings are displaced in space by 120°. All the coils are placed inside the slots made in the stator periphery

The advantages of distributed winding over concentrated winding are better dissipation of heat generated due to current flow through the windings and better wave form of the generated EMF (better EMF generated means that the shape of the voltage wave should be sinusoidal).

All the coils forming a winding for each phase can be connected in a number of ways. These are called types of windings. They are

1. lap winding;
2. wave winding; and
3. spiral winding.

The windings are also made in *single-layer type* or *double-layer type*. In single-layer type each slot will contain one coil side only. However, each coil will have a large number of turns. In double-layer type, as the name indicates, two coil sides will occupy one slot in the whole of the armature winding. The coils used for winding may be of *full-pitch type* or *short-pitch type.* In a full-pitch coil, the distance between the two coil sides is 180° electrical. The coil span of short-pitch coils is reduced by a certain angle. Windings made with short-pitch coils is called *fractional-pitch winding*. By use of fractional-pitch winding, any specific harmonic present in the generated EMF can be eliminated so that we get a sinusoidal EMF. Fig. 10.5 shows a single-layer distributed stator winding where the windings can be connected in the lap, wave, or spiral form. The connections for only one phase has been shown. The number of coils used per phase is three only. Full-pitch coils have been used in the winding shown in Fig. 10.5 (a).

Use of short-pitch coil improves the wave shape of the induced EMF making it more towards a sine-wave. However, the EMFs induced in the two coil sides when added vectorially in a short-pitch coil will be less than that of a full-pitch coil.

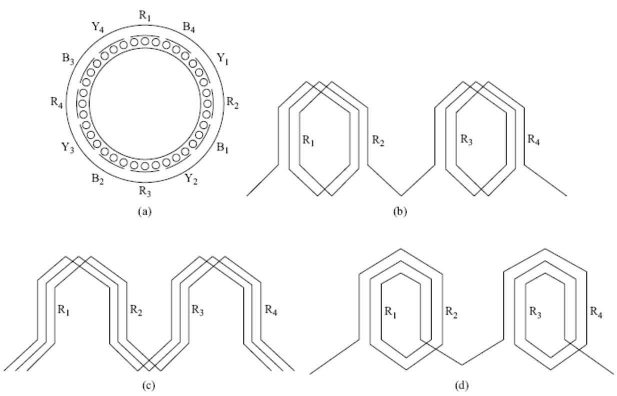

Figure 10.5 (a) Single layer stator winding; (b) lap-type winding; (c) wave-type winding; (d) spiral-type winding

10.8 INDUCED EMF IN A SYNCHRONOUS MACHINE

In synchronous machines, the armature winding is made on the stator. The rotor consists of magnetic poles excited by dc field will have a time phase difference of 120°. Phase difference of 120° degrees corresponds to the time taken by the rotor to rotate by 120 electrical degrees. The generated voltages in the R, Y, and B phases can be expressed as

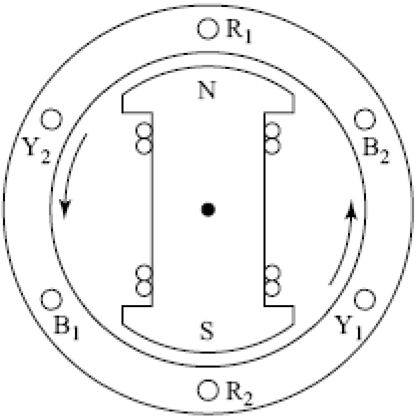

Figure 10.6 EMF is induced in the stator winding due to rotation of poles

$e_R = E_m \sin \omega t$
$e_Y = E_m \sin (\omega t - 120°)$
$e_B = E_m \sin (\omega t - 240°)$

The three EMFs induced in the three-phase windings will be displaced in time phase by 120°. They can be represented by three phasors of equal magnitude but displaced by 120°.

We will now derive the equation of the induced EMF in each of the phases of a synchronous machine.

10.8.1 EMF Equation

Let the rpm of the rotor be N_s. Let ϕ be the flux per pole. For a two-pole machine, the flux cut by a conductor (coil side) in one revolution is 2ϕ W. If P is the number of poles, then flux cut by a conductor in one revolution of the rotor is $P\phi$ webers. The rotor makes N_s revolutions per minute. In terms of seconds, the rotor makes $\frac{N_s}{60}$ resolutions. Thus, the time taken by the rotor to make one revolution is $\frac{60}{N_s}$ seconds. (Since N is the rpm, or $\frac{N_s}{60}$ is the revolutions per second.)

Average value of the induced EMF = flux cut/second

If the number of turns per phase is T, then the total number of conductors Z will be 2T.

Hence, Average EMF induced in each phase $E_{av} = \frac{P\phi N_s 2T}{60}$ V (i)

If, f is the frequency of the induced EMF, the relationship between, f, P, and N_S is given by

$$N_s = \frac{120f}{p} \qquad \text{(ii)}$$

From (i) and (ii) $E_{av} = \frac{PN_s}{120} \times 4\phi T = 4\phi f T$ V

For a sinusoidal wave, the ratio of the rms value to the average value is called the form factor which is equal to 1.11.

$$\frac{E_{rms}}{E_{av}} = 1.11$$
$$E_{rms} = 1.11\ E_{av} = 1.11 \times 4\ \phi f\ T\ \ V$$

If we write E_{rms} = E, the EMF eq. is

$$E = 4.44\ \phi f\ T\ V \qquad (10.1)$$

It is interesting to note that this EMF equation is the same as that developed for transformers where the EMF in the primary and secondary windings were derived respectively as $E_1 = 4.44\ \phi_m f\ N_1$ and $E_2 = 4.44\ \phi_m f\ N_2$.

In the case of the synchronous machine the EMF induced is called the dynamically induced EMF while in the case of the transformer the EMF induced is called statically induced EMF.

In synchronous machines, EMF is induced due to the relative motion the between the rotor flux and the stator conductors. In the case of transformers, EMF is induced in the winding due to the linkage of the time-varying flux with stationary coils.

The EMF equation derived as above is to be multiplied by two factors, namely the *distribution factor*, K_d and the *pitch factor*, K_p. Because of the distribution of the coils in the armature, the EMFs induced in the individual coils cannot be added arithmetically. They

If the whole winding is concentrated in two slots with all the coil sides placed in one slot, then the value of K_d will be 1. That is, there would be no reduction of the total EMF induced due to the use of number of coils to form the winding on the stator.

The pitch factor K_p is due to the use of short-pitch coils. The vector sum of the voltages induced in the two sides of a coil is not equal to the their algebraic sum. With K_d and K_p into consideration, the equation for the induced EMF is

$$E = 4.44\,\phi f\,T K_d K_p \text{ V} \tag{10.2}$$

The factor K_d is used in the EMF equation due to the use of winding being distributed rather than concentrated in two slots. The factor K_p is due to the use of short-pitch coils rather than full-pitch coils.

The values of K_d and K_p are derived as follows.

10.8.2 Distribution Factor

Distribution factor is defined as the ratio of the EMF induced in the distributed winding in a phase to the EMF induced in a concentrated winding. In Fig. 10.7, the stator with a number of slots have been shown. The conductors are placed in the slots. The EMFs induced in the conductors are e_1, e_2, e_3, etc. These EMFs are to be added vectorially as shown in Fig. 10.7.

Let α be the angle between two slots.

$$CA = 2CM = 2\,OC\cos\left(90 - \frac{3\alpha}{2}\right)$$

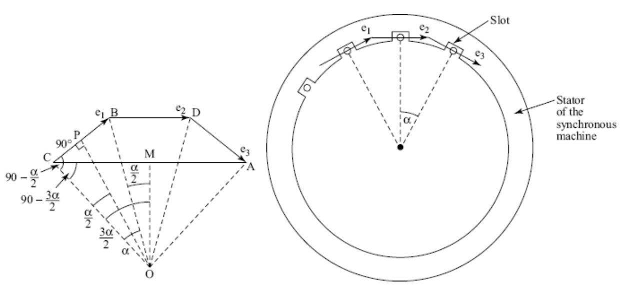

Figure 10.7 Distribution factor of the EMF equation

$$CB = 2CP = 2\,OC\cos(90 - \alpha/2)$$

$$CB = BD = DA = 2\,OC\sin\alpha/2$$

and $$CA = 2\,OC\,\sin\frac{3\alpha}{2}$$

Distribution factor, $K_d = \dfrac{\text{Vector sum of the voltages}}{\ldots} = \dfrac{CA}{\ldots} = \dfrac{CA}{\ldots}$

Here, we have considered three slots per pole per phase. If m is the number of slots per pole per phase, then

Distribution factor, $$K_d = \frac{\sin m\alpha/2}{m \sin \alpha/2} \qquad (10.3)$$

10.8.3 Pitch Factor

The pitch factor is due to the use of short-pitch coils as has been shown in Fig. 10.8. If the winding is made with full-pitch coils then, pitch factor K_p is equal to 1. The pitch factor is defined as the ratio of the EMF induced in a short-pitch coil to the EMF induced in a full-pitch coil. Let β be the angle through which the coil is made less than the full pitch. The pitch factor, K_p is the ratio of the vector sum of the EMFs induced in the coil sides to the algebraic sum of the EMFs.

$K_P = \dfrac{AC}{AB + BC}$ [from Fig. 10.8 (b)]

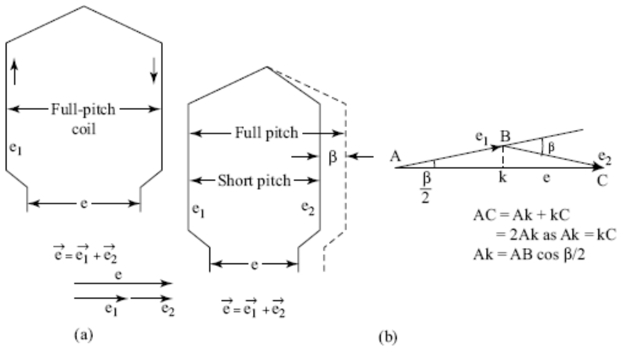

Figure 10.8 Pitch factor due to use of short-pitch coil

or, $$K_p = \frac{2AB \cos\beta/2}{2AB} \quad \text{since } AB = BC$$

Pitch factor, $$K_p = \cos\beta/2 \qquad (10.4)$$

The value of the pitch factor is somewhat less than unity. For example, if the coil is short pitched by an angle say 30°, then β = 30°:

Solution:

Slots are made distributed throughout the whole of stator periphery. The angle between two slots, i.e., slot angle α is calculated as

$$\alpha = \frac{360°}{\text{No. of slots}} = \frac{360°}{36} = 10°$$

Number of slots per pole per phase, i.e., m is calculated as

$$m = \frac{\text{No. of slots}}{\text{No. of poles} \times \text{No. of phases}}$$

$$= \frac{36}{2 \times 3} = 6$$

$$K_d = \frac{\sin m\alpha/2}{m \sin \alpha/2} = \frac{\sin(6 \times 10)/2}{6 \sin 10/2} = \frac{\sin 30°}{6 \sin 5°} = \frac{0.5}{6 \times 0.087}$$

or, $$K_d = 0.958$$

Example 10.2 The stator winding of a three-phase synchronous machine has been wound for four-poles in 36 slots. Each coil span has an eight-slot pitch, i.e., the distance between the coil sides of a coil has been eight slots. Calculate the distribution factor and the pitch factor.

Solution:

$$\alpha = \frac{360}{36} = 10° \text{ mechanical}$$

No. of slots per pole per phase, $m = \dfrac{36}{4 \times 3} = 3$

1° mechanical $= \dfrac{P°}{2}$ electrical. We have to convert all mechanical degrees into electrical degrees.

Since, P = 4,

1° mech = 2° electrical

10° mech = 20° electrical

α = 20°, m = 3

$$K_d = \frac{\sin m\alpha/2}{m \sin \alpha/2} = \frac{\sin(3 \times 20)/2}{3 \sin 20/2} = \frac{\sin 30°}{3 \sin 10°} = \frac{0.5}{3 \times 0.1736}$$

For calculation of pitch factor,

No. of slots per pole $= \dfrac{36}{4} = 9$

This means the coil sides of a full-pitch coil will be at a distance of nine slots. Then the coil sides will lie under opposite poles occupying similar locations under each pole. Since the pole pitch is eight, the slot pitching has been done for one slot angle, i.e., by 20° electrical.

Thus, $\beta = 20°$

$$K_p = \cos\frac{\beta}{2} = \cos 10° = 0.98$$

Example 10.3 The induced EMF in a synchronous machine is 11,000 V with a distributed fractional pitch winding. If a concentrated full-pitch winding were made, what would have been the induced EMFs. Assume the distribution factor and the pitch factor as 0.96 and 0.98, respectively.

Solution:

If concentrated winding and full-pitch coils are used, the EMF induced will be

$$E = 4.44\,\phi f\,T\ \text{V}$$

But with distributed winding and use of short-pitch coils

$$E = 4.44\phi f\,T\,K_d\,K_p\ \text{V}$$

with the given

$$11{,}000 = 4.44\phi f\,T \times 0.96 \times 0.98$$

$$\therefore \qquad E = 4.44\phi f\,T = \frac{11{,}000}{0.96 \times 0.98} = 11{,}692\ \text{V}$$

This shows that due to the distribution of winding throughout the stator periphery and use of short-pitch coils, the EMF induced has been reduced in this case by 692 V. However, the use of distributed winding and short-pitch coils improves the heat dissipation and wave shape of the voltage generated, respectively.

Example 10.4 A three-phase 36-pole synchronous generator is ro-

Solution:

Synchronous speed, $N_s = \frac{120f}{P}$

$$167 = \frac{120 \times f}{36}$$
$$f = 50 \text{ Hz}$$

No. of slots per pole per phase, m is calculated as

$$m = \frac{\text{No. of slots}}{\text{No. of poles} \times \text{No. of phases}} = \frac{324}{36 \times 3} = 3$$

Slot angle = $\frac{360°}{324}$ mechanical

1° mechanical $= \frac{P°}{2}$ Electrical

Here 1° mechanical = $\frac{36}{2}$ = 18° Electrical

Slot angle, α, in electrical degrees is

$$\alpha = \frac{360 \times 18}{324} = 20°$$

Distribution factor, K_d, is calculated as

or,

$$K_d = \frac{\sin m\alpha/2}{m \sin \alpha/2} = \frac{\sin(3 \times 20)/2}{3 \sin 20/2} = \frac{\sin 30°}{3 \sin 10°}$$
$$K_d = \frac{0.5}{3 \times 0.1736} = 0.96$$

Total no. of conductors per phase = $\frac{\text{No. of slots} \times \text{No. of conductors in each slot}}{\text{No. of phases}}$

Number of T will half the number of conductors

K_p = 1 because full-pitch coil has been used.

EMF induced per phase is calculated as

$$E = 4.44\phi f T K_p K_d \text{ V}$$

Substituting all values

$$E = 4.44 \times 20 \times 10^{-3} \times 50 \times 540 \times 1 \times 0.96 \text{ V}$$

or, $$E = 2301 \text{ V}$$

10.9 OPEN-CIRCUIT OR NO-LOAD CHARACTERISTIC

This is the relation between the field current and the induced EMF when the synchronous generator is run on no load.

When a synchronous machine is driven by a prime mover at synchronous speed, N_S, it will generate an induced EMF if its field winding is excited. The field winding is excited by supplying a dc voltage through the brush and slip-ring arrangement. When the field system is rotated at a constant speed N_s and the field current, I_f is gradually increased, keeping the output terminals open as shown in Fig. 10.9, the induced EMF will go on increasing but will have a saturation effect as shown in Fig. 10.9 (b).

The open-circuit characteristic or OCC as shown in Fig. 10.9 is the relationship between the field current and the induced EMF when the rotor is rotated at a constant speed. Since no load is connected across the stator output terminals, the OCC is also called the no-load characteristic.

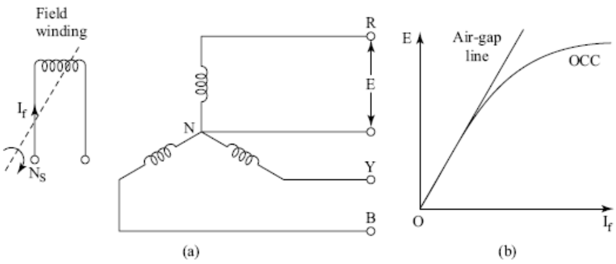

Figure 10.9 Open-circuit characteristic: (a) field system is rotated by prime mover; (b) field current versus EMF-induced characteristic

10.10 SYNCHRONOUS GENERATOR ON LOAD

When a synchronous generator is loaded, current will flow through its winding as well as through the load. Since three-phase currents will flow through the three-phase windings, these currents will develop a resultant rotating magnetic field. This rotating field is due to fields are stationary with respect to each other. The armature field flux and the main field flux produced by the field windings will rotate at the same speed, called the synchronous speed. The air-gap flux will be the resultant of these two fluxes. The effect of the armature field flux on the main field flux is called *armature reaction*. Depending on the power factor of the load, the armature flux will oppose, aid, or distort the main field flux.

If the load is purely inductive, the armature flux will be opposing the main field flux. If the load is purely capacitive, the armature flux will aid the main field flux.

For resistive loads, the armature flux will distort the distribution of the main field flux.

The armature reaction will, therefore, have an effect on the magnitude of the induced EMF. The more is the load current, the more will be the effect of armature reaction. At no load, there is no effect of armature reaction.

When the synchronous generator is loaded, there will be a voltage drop in the windings as well as an armature reaction effect. At unity power factor load, the voltage drop due to loading will be less than at lagging power factor load. For capacitive load, since the armature flux will aid the main field flux, the air-gap flux will increase, and hence the EMF induced will go on increasing as the capacitive loading increases.

10.11 SYNCHRONOUS IMPEDANCE AND VOLTAGE DROP DUE TO SYNCHRONOUS IMPEDANCE

The armature winding, i.e., the stator winding of a synchronous machine has a winding resistance of R_a Ω. When the machine is working as a generator supplying some load, current will flow through the windings causing some I_aR_a voltage drop. Some of the armature flux which does not cross the air gap is called the leakage flux. This leakage flux will lead to leakage reactance, X_1, of the windings. There will be voltage drop due to leakage reactance of the windings. Further, the change in terminal voltage due to the armature reaction effect can also be viewed as a reactance voltage drop. This is a fictitious reactance voltage drop. This reactance due to the armature flux is called X_a. The reactance due to the armature leakage flux is called X_1. The voltage drop due to resistance, R_a is in phase with the armature current, I_a. The reactance voltage drops are in quadrature with the armature current, such that

$$E = V + I_a R_a + j\, I_a (X_l + X_a)$$

where, E is the induced EMF per phase at no-load, I_a is the armature current flowing through each phase, R_a is the armature resistance per phase, X_1 is the leakage reactance of the armature winding due to the leakage flux, and X_a is a fictitious (not real) armature reactance which replaces the effect of armature reaction. Again

$$E = V + I_aR_a + jI_a(X_1 + X_a)$$
$$= V + I_aR_a + jI_aX_s$$
$$= V + I_a(R_a + jX_s)$$
$$= V + I_aZ_s$$

where $X_s = X_a + X_1$ is called the *synchronous reactance* and $Z_s = R_a + jX_s$ is called the *synchronous impedance.*

The vector sum of R_a and X_S is called the synchronous impedance. The effect of armature voltage drop due to armature resistance and synchronous reactance, i.e., synchronous impedance at different power factor load, has been shown in Fig.10.10. It is interesting to note that at leading power factor load the terminal voltage of the synchronous generator increases with increase in load.

Let OS represent the voltage induced at no load, i.e., E. When a load current I_a equivalent to OP flows at a lagging power factor load, the terminal voltage available across the load terminals gets reduced and will be equal to OR which we call as V. The phasor diagram representing E, V, I_a, and voltage drop due to I_aZ_s has been shown in Fig. 10.11 (a). In Fig. 10.11 (b), the phasor diagram has been drawn for leading power factor load.

In the phasor diagram in Fig. 10.11 (a), I_a is shown lagging V by the power factor angle ϕ. Voltage drop in the armature winding resistance R_a is equal to $I_a R_a$. This voltage drop of $I_a R_a$ has been shown parallel to I_a. This is because R_a does not have any direction. Voltage drop across an inductive reactance is shown perpendicular to I_a and leading I_a. Therefore, drops I_aX_1 and I_aX_a have been shown perpendicular to I_a. The sum of $I_a R_a + j I_a (X_1 + X_a)$ is $I_a Z_s$, where $Z_s = R_a + j(X_1 + X_a) = R_a + j X_s$. The sum of V and $I_a Z_s$ is equal to E.

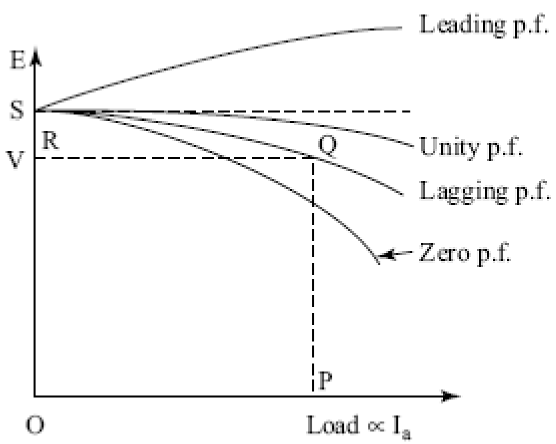

Figure 10.10 Terminal voltage of a synchronous generator under loading condition at different power factors

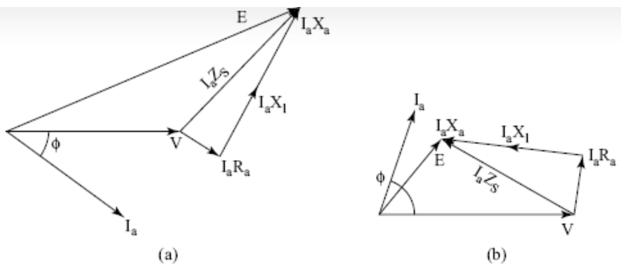

Figure 10.11 (a) Phasor diagram at lagging power factor load; (b) phasor diagram at leading power factor load

In the same way the phasor diagram for leading Power factor load current I_a has been drawn as in Fig. 10.11 (b).

It is interesting to note that for leading power factor load, the terminal voltage V is more than the induced EMF at no load.

10.12 VOLTAGE REGULATION OF A SYNCHRONOUS GENERATOR

Synchronous generators supply power to various loads at a particular terminal voltage. The generator has to maintain its terminal voltage within a specified limit. If there is very large change in the terminal voltage when load on the generator changes, it will give rise to difficulties in operations of various electrical machines and gadgets connected to the system. Voltage regulation tells us about the health of the machine in terms of its voltage stability.

Voltage regulation is defined as the percentage change of the terminal voltage from its no-load condition to its full-load condition as a percentage of full-load voltage. Thus,

$$\text{voltage regulation} = \frac{(E - V)}{V} \times 100$$

The phasor diagram of Fig. 10.11 (a) is redrawn to calculate voltage regulation at a lagging power factor load.

From Fig. 10.12

$$AG^2 = AK^2 + KG^2 = (AD + DK)^2 + (KC + CG)^2$$

or, $$E^2 = (AB\cos\phi + I_aR_a)^2 + (AB\sin\phi + I_aX_s)^2$$

or, $$E^2 = (V\cos\phi + I_aR_a)^2 + (V\sin\phi + I_aX_s)^2$$

or, $$E = \sqrt{(V\cos\phi + I_aR_a)^2 + (V\sin\phi + I_aX_s)^2} \qquad (10.5)$$

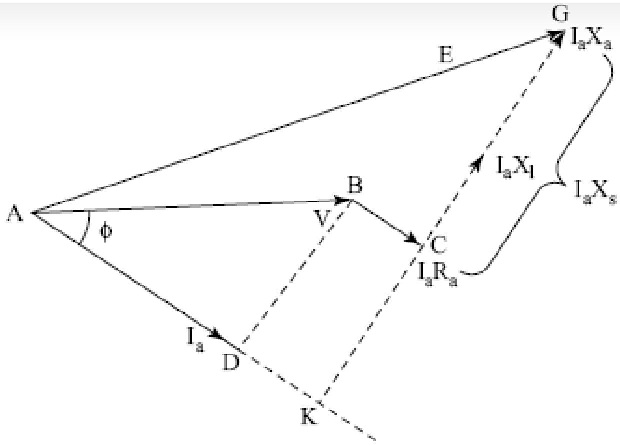

Figure 10.12 Phasor diagram of a synchronous generator at lagging power factor load

For leading power factor load, it will be seen that

$$E = \sqrt{(V\cos\phi + I_aR_a)^2 + (V\sin\phi - I_aX_s)^2} \tag{10.6}$$

To calculate voltage regulation we have to calculate E using the above relation. While V, ϕ, R_a, I_a will be known, the value of synchronous reactance has to be determined. The vector sum of armature resistance and synchronous reactance will give the value of synchronous impedance.

10.13 DETERMINATION OF VOLTAGE REGULATION BY THE SYNCHRONOUS IMPEDANCE METHOD

The direct method of determining voltage regulation is to load the generator and measure its full-load terminal voltage. Then remove the load and measure its no-load voltage, without changing the excitation. Then, calculate voltage regulation using the relation, Volt regulation = $\dfrac{E-V}{V}$.

However, for large machines, it may not be possible to find such loads in the testing laboratory. Further, there will be huge power loss due to loading during the testing time. For these reasons an indirect method of testing is always used.

In the synchronous impedance method, we are required to perform no-load test, i.e., the open-circuit test and short-circuit test on the generator.

For the open-circuit test, the generator is driven at its rated speed by the prime mover. It's field current I_f is gradually increased using a field regulator. The values of I_f and induced EMF, E are recorded and plotted. This will give us the open-circuit characteristic, i.e., the field winding so that the short-circuit current, I_{sc} does not exceed the rated current of the generator. The short-circuit characteristic, SCC is plotted as I_{sc} as a function of I_f by taking a few readings. Both OCC and SCC are drawn as a function of I_f as shown in Fig. 10.13.

At a particular value of field current, say I_f = OP, the open-circuit voltage is PQ Volts. When the output terminals are kept short circuited under the short-circuit test, the voltage E will cause a short-circuit current I_{sc1} to flow. The EMF E_1 on open circuit is regarded as being responsible for circulating a short-circuit current of I_{sc1} through the synchronous impedance Z_s. Thus, Z_s can be calculated as

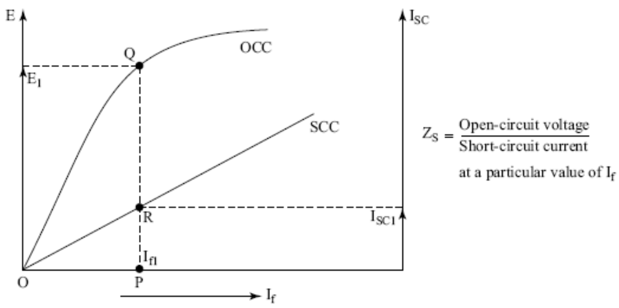

Figure 10.13 Open-circuit and short-circuit characteristics of a synchronous generator

$$Z_s = \frac{\text{OC voltage}}{\text{SC current}} \text{ at a particular } I_f$$
$$= \frac{E_1}{I_{sc1}} \text{ at } I_f = I_{f1}$$

The per-phase armature winding resistance, R_a can be measured by the ammeter voltmeter method. From Z_s the value of X_s can be calculated as X_s = $X_s = \sqrt{Z_s^2 - R_a^2}$.

Voltage regulation for a particular load current and power factor can then be calculated.

Example 10.5 A 3 MVA, 6600 V, three-phase, star-connected synchronous generator has a resistance of 0.2 Ω and synchronous reactance of 3.5 Ω per phase. Calculate the regulation at rated output at 0.8 power factor lagging. The speed and excitation remain constant.

Solution:

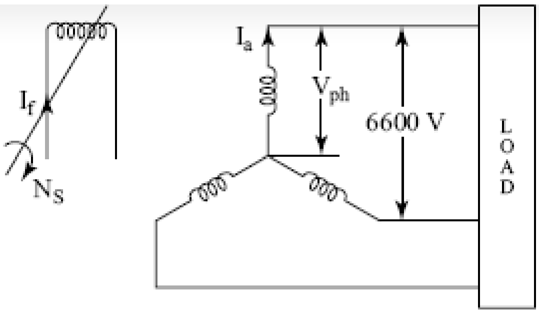

Figure 10.14

Given line voltage = 6600 V

$$\text{phase voltage } V_{Ph} = \frac{6600}{\sqrt{3}}$$
$$= 3810 \text{ V}$$

R_a = 0.2 Ω

X_s = 3.5 Ω, cosϕ = 0.8 lagging, sinϕ = 0.6

Total MVA = 3

Total VA = 3×10^6

This VA is for the three phases. VA per phase will be one-third of the total VA

VA per phase = 1×10^6

Current per phase I_a =
$$\frac{1 \times 10^6}{V_{ph}} = \frac{10,00,000}{3,810} = 262.5 \text{ A}$$

Induced EMF, E =
$$\sqrt{(V\cos\phi + I_a R_a)^2 + (V\sin\phi + I_a X_S)^2}$$

$$= \sqrt{(3810 \times 0.8 + 262.5 \times .2)^2 + (3810 \times 0.6 + 262.5 \times 3.5)^2}$$
$$= 4049.4 \text{ V}$$

Percentage regulation =

$(E - V)$ $(4049.4 - 3810)$

phase. A field current of 50 A produces a short-circuit current of 262 A and an open-circuit EMF of 1200 V between the lines. Calculate voltage regulation of the generator on full load at 0.8 power factor lagging and at 0.8 power factor leading.

Solution:

Total kVA = 1500

$$\text{kVA per phase} = \frac{1500}{3} = 500$$

$$\text{Per-phase voltage } = \frac{V_L}{\sqrt{3}} = \frac{3300}{\sqrt{3}}\text{V} = 1905 \text{ V}$$

Per-phase current,

$$I_a = \frac{500 \times 1000}{3300/\sqrt{3}} = 262 \text{ A}$$

Given that at a field current of 50 A, short-circuit I_a is 262 A and the open-circuit line voltage is 1200 V

Synchronous impedance/phase Z_s

$$= \frac{\text{open-circuit voltage per phase}}{\text{short-circuit current}} = \frac{1200}{\sqrt{3} \times 262} = 2.64\ \Omega$$

R_a per phase = 0.2 Ω

$$\cos\phi = 0.8,\ \phi = 37°,\ \sin\varphi = 0.6$$

At lagging power factor load

$$E_1 = \sqrt{(V\cos\phi + I_a R_a)^2 + (V\sin\phi + I_a X_s)^2}$$

and at leading power factor load

$$E_2 = \sqrt{(V\cos\phi + I_a R_a)^2 + (V\sin\phi - I_a X_s)^2}$$

$$E_1 = \sqrt{(1905 \times 0.8 + 262 \times 0.2)^2 + (1905 \times 0.6 + 262 \times 2.64)^2}$$
$$= 2418 \text{ V}$$

Percentage regulation at full load 0.8 power factor lagging

$$=\frac{(2418-1905)\times 100}{1905}=26.9 \text{ per cent}$$

$$E_2=\sqrt{(1905\times 0.8+262\times 0.2)^2+(1905\times 0.6-262\times 2.64)^2}$$

$$=1640 \text{ V}$$

Percentage regulation at full load 0.8 power factor leading

$$\frac{E_2-V}{1905}\times 100=\frac{(1640-1905)}{1905}\times 100=-13.9 \text{ per cent}$$

This shows that regulation is negative at 0.8 leading power factor load. This is because the full-load terminal voltage is more than the no-load voltage.

10.14 SYNCHRONOUS GENERATORS CONNECTED IN PARALLEL TO SUPPLY A COMMON LOAD

Due to a number of advantages, a group of alternators are installed in the power house instead of a very large single unit. For example, instead of installing a 1000 MVA alternator, we may decide to instal five 200 MVA alternators and connect them in parallel to supply common load. There are a few advantages of parallel connection and operation of number of alternators.

10.14.1 Advantages of Parallel Operation

1. If instead of one very large alternator, a number of smaller units are installed, it is possible to switch off any alternator for repair and maintenance without disrupting the power supply completely.
2. Additional sets can be added depending upon the need.
3. It may not be possible to build generators for very high capacity, i.e., the capacity of a power plant. For example, a thermal power plant near Talwandi Sabo in Panjab is being set up to generate 1980 MW. A single alternator of such a high capacity may be physically difficult to construct and transport to the site.
4. Alternators connected in parallel can be operated near to full load rather than running a big alternator on low load when the demand for electricity changes.

10.14.2 Parallel Connection of Alternators

At the power-generating station, a number of alternators are connected in parallel on a common busbar. The load is supplied from the busbar as shown in Fig. 10.15. The procedure of connection of alternators to the busbar is called synchronization. Although load has been shown connected with the busbar near to the generators, in practise the generated power is sent to the places of its use through high-voltage transmission lines not shown in the figure. Synchronization refers to inter-connection of alternators with a busbar in which a large number of alternators have already been connected. Such busbars are called *infinite busbars*. These days all the generating stations as well as all the loads are interconnected through a

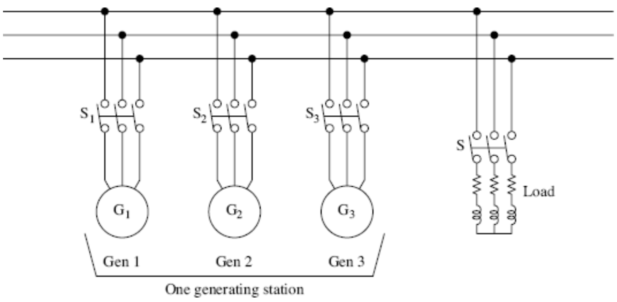

Figure 10.15 Parallel connection of alternators (synchronous generators)

10.14.3 Conditions for Parallel Connection and Synchronization

For satisfactory parallel connection of a synchronous generator to the busbar, the following three conditions must be met:

1. The generated voltage of the incoming machine should be equal to the busbar voltage.
2. The frequency of generated voltage of the incoming generator should be equal to the frequency of the busbar voltage.
3. The phase sequence of the voltages of the incoming generator should be the same as the phase sequence of busbar voltages.

It may be noted that the kVA or MVA rating of the alternators connected in parallel need not be the same.

Synchronization of alternators is done using a synchroscope or synchronizing lamps to make sure that the conditions of parallel operation are met.

Once an alternator is synchronized, it gets connected to the busbar. Now it has to share a portion of the common load. This is called *load sharing*. If load sharing is not done, the generator will simply remain connected to the busbar; this condition is called floating of the generator with the busbar.

After synchronization, two things can be changed: the excitation of the generator or its prime-mover input.

We will study the effect of change of excitation and that of the prime-mover input on load sharing by an alternator.

10.14.4 Load Sharing

Let the incoming generator G_2 be connected to the busbar where one generator G_1 is already connected. See Fig. 10.16. After synchronization, G_2 will simply float on the busbar. It will neither draw any current nor supply any current. For load sharing by the incoming alternator two things can be done. We can change the field current (excitation) or we can change the input to the prime mover driving the generator.

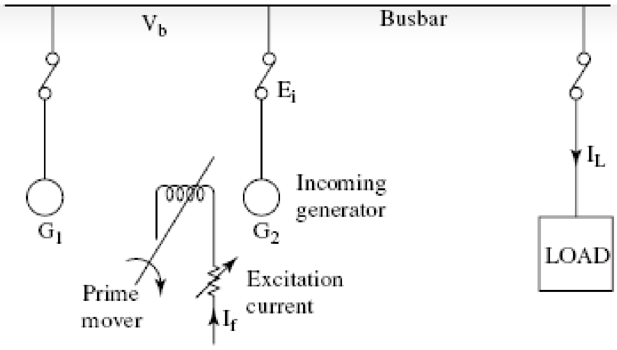

Figure 10.16 Single-line diagram illustrating load sharing by a synchronous generator

(a) Effect of change of excitation

Let V_b represent the busbar voltage and E_1' represent the induced EMF of the incoming generator, G_2. Since the incoming generator is connected in parallel, the two voltages V_B and E_i' are equal and opposite to each other as shown in Fig. 10.17.

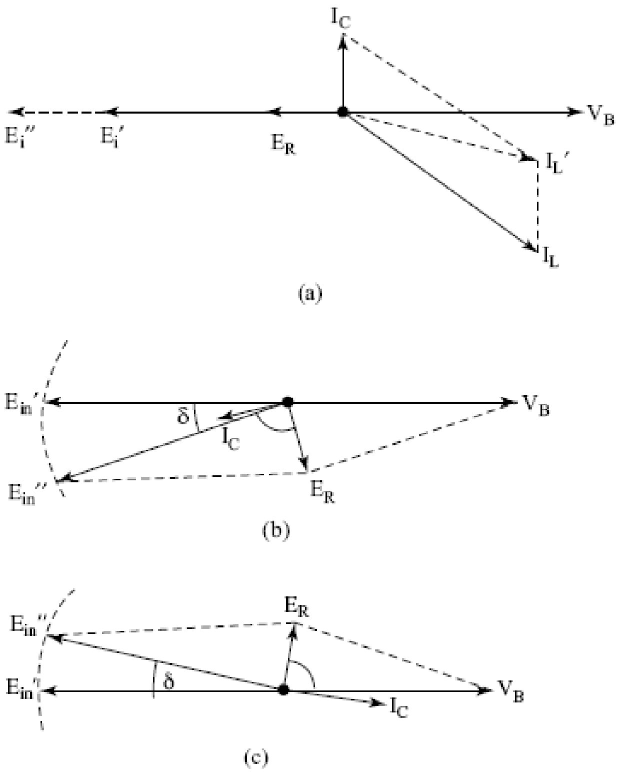

Figure 10.17 (a) Effect of change of excitation; (b) effect of change of prime-mover input

Let us increase the excitation current so that the induced EMF is increased from E_i' to E_i'' as has been shown in Fig. 10.17 (a). A resultant component of the load current so that the load current will change from I_1 to I_1'. Thus, it is seen that change of excitation current of the incoming generator will only cause reactive load sharing but not active load sharing. Change of excitation of the incoming machine will only change the reactive power delivered by the existing machines.

(b) Effect of change of prime-mover input

If the prime-mover input is increased, the effect will be that the rotor of the generator will advance by an angle δ while running at synchronous speed as has been shown in Fig. 10.17 (b):

The induced EMF phasor E_{in} has moved to an advanced position.

Note that phasors are rotating phasors; their relative positions have been shown.

The resultant voltage E_R will circulate a current I_c which will lag E_R by about 90°. It is observed that I_c has a strong in-phase component with E_{in}' so that the machine will be working as a generator supplying load. It will be possible to reduce the prime-mover input to the existing machine. If the prime-mover input to the incoming machine is reduced, the rotor will fall back from synchronizm by an angle, say δ as shown in Fig. 10.17 (c). The resultant voltage E_R will circulate a current I_c which will lag E_R by approximately 90°. Now I_c will have a strong in-phase component with V_B which means that the generators connected with the busbar will have to generate more to compensate for the motoring action of the incoming machine.

To sum up, we can say that the change of excitation of the generator connected to the bus for parallel operation does not affect the sharing of active load. For sharing of active load, the prime-mover input, i.e., for a steam turbine, the steam input has to be increased so that the torque developed is increased.

10.15 SYNCHRONOUS MOTOR

10.15.1 Introduction

A Synchronous generator when synchronized with the busbar, floats on the busbar. That is, it neither draws current nor delivers any current. If the prime mover driving the generator is decoupled, the machine will draw current from the busbar and work as a synchronous motor on no load. Now if some mechanical load is connected to the shaft of the motor, its rotor axis will fall back by some more angle from the axis of the rotating magnetic field created by the current of the stator windings drawn from the busbar voltages. As a result, more current will be drawn by the motor. If, however, a synchronous machine has to start as a motor from its standstill condition, three-phase supply has to be given to the stator windings and dc supply has to be given to the field winding. The principle of working of a synchronous motor and the method of starting are discussed as follows.

10.15.2 Principle of Working of a Synchronous Motor

The stator has a three-phase winding which is fed from a 50 Hz three-phase supply. When a three-phase supply is provided to the stator winding, a rotating magnetic field rotating at synchronous excitation through the brush and slip-ring arrangement. Thus, two magnetic fields are produced; one rotating at a synchronous speed, N_S and the other produced by the field winding. The rotor having the field system should start rotating at the same speed as the rotating magnetic field, N_S. The reason is that two magnetic fields will always try to align with each other. However, due to its inertia, the rotor will not pick up speed. That is why a three-phase synchronous motor is not self-starting. To make it self-starting, a squirrel-cage winding is made on the pole faces so that the rotor will start rotating as an induction motor first, without having the field windings excited.

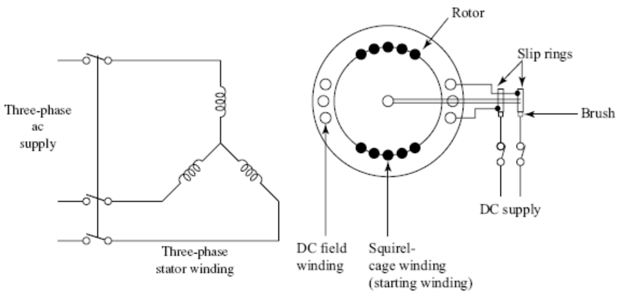

Figure 10.18 Synchronous motor with squirrel-cage winding for self-starting

Once the rotor attains a speed near to synchronous speed like a three-phase induction motor, the dc excitation is provided by switching on the field circuit. The rotor immediately attains synchronous speed and gets locked into synchronizm. Thus, the two magnetic fields become stationary with respect to each other and the rotor continues to develop torque. If load is applied on the rotor shaft, the rotor continues to rotate at synchronous speed, but its axis will fall back by angle δ. As a result, more current is drawn from the supply mains. The more is the load applied on the motor, the more will be the angle of lag, δ. The maximum limit of the angle of lag of the rotor field axis from the stator rotating field axis is 90°. The electromagnetic power developed, P, is expressed as

$$P = \frac{VE}{X_s} \sin\delta$$

where, V is the terminal voltage;

E is the induced EMF;

X_S is the synchronous reactance; and

δ is the angle between V and E, also called the power angle or torque angle.

are excited by the field current fed from a dc supply. When the rotor is rotating, the field flux will cut the stator windings and induce EMF E on the stator windings. When the rotor is rotating at synchronous speed, the magnitude of E will be proportional to the field current. If the field current, I_f, is increased, E will increase; if I_f is decreased, the magnitude of E will decrease. The angle of lag of E with respect to the busbar voltage will depend on the mechanical load applied to the motor shaft. We shall study the effect of change of excitation current I_f on the magnitude of current drawn and the power factor of the motor.

Fig. 10.19 (a) shows a synchronous motor carrying a load. The supply voltage is V and the induced EMF in the stator winding due to field current I_f is E. The phasors V and E have been shown in Fig. 10.19 (b). E has been shown lagging the V axis by an angle δ for a particular load on the motor shaft. The resultant of V and E is E_R. Since the motor windings are highly inductive, I_a drawn by the motor will lag E_R by approximately 90°. The phase angle between V and I_a is the power factor angle θ. The power drawn from the line, i.e., the input power is V $I_a \cos \theta$. As V is constant, $I_a \cos \theta$ = OC will remain constant as long as the mechanical load on the motor remains constant. We can draw a constant power line along XX′ as has been shown in Fig. 10.19 (b). The locus of armature current I_a at a different excitation current I_f will lie on this line. Let excitation current be increased such that E is increased to E′. The resultant of E′ and V is E_R'. Current I_a' lags E_R' by about 90° as shown. The tip of I_a' will lie on line XX′ so that $I_a' \cos\theta_1$ is equal to OC. If excitation current is reduced such that E becomes equal to E″, the resultant of E″ and V is E_R'' and the current which will be lagging E_R'' by about 90° will be I_a''. It is observed that when excitation is increased, the motor draws a leading power factor current and when the excitation is reduced the motor draws a lagging power factor current. At a certain excitation, the current drawn by the motor will be minimum, which will be equal to OC. The current drawn will be at unity power factor as V and I_a will be in phase. The excitation current at which the motor draws unity power factor current is called *normal excitation*. Excitation current higher than the normal excitation current is called *over excitation*. Excitation current lower than the normal excitation is called *under excitation*.

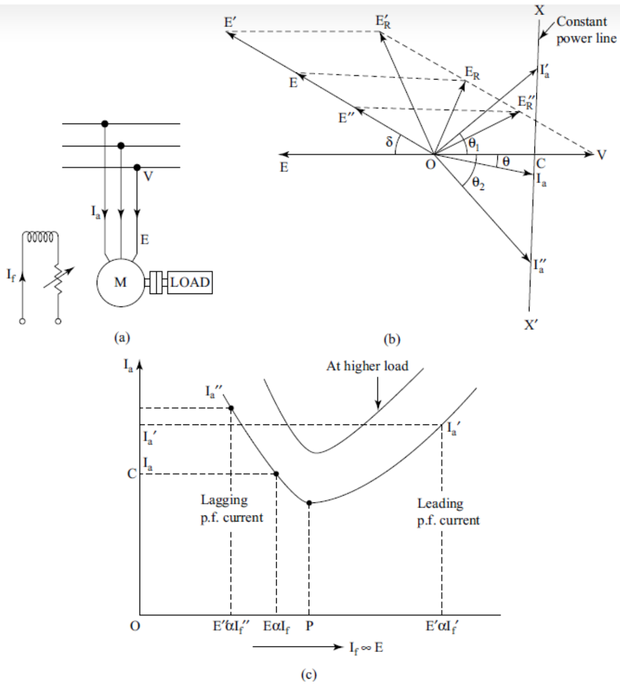

Figure 10.19 Effect of change of excitation on the current drawn by a synchronous motor

The relationship between the excitation current, I_f and the current drawn by the synchronous motor, I_a has been shown in Fig. 10.19 (c). The excitation current OP corresponds to the minimum armature current OC drawn by the motor. Therefore, OP can be called the normal excitation. I_f' is over excitation and I_f'' is under excitation. The graph resembles the letter V of English alphabet, and hence is known as the synchronous motor V-curve. The magnitude of OC will increase if the load on the motor is increased. Keeping that higher load constant, if excitation is changed and values of corresponding armature currents I_a are plotted, another V-curve will be drawn as shown in Fig. 10.19 (c).

10.15.4 Application of Synchronous Motors

We can state that an over-excited synchronous motor draws leading power factor current from the mains. The synchronous motor, therefore, when over excited, in addition to driving some load, will work like a capacitor or condenser. A capacitor draws leading power factor current. An over-excited synchronous motor draws leading power factor current from the mains.

An over-excited synchronous motor is also called a *synchronous condenser*.

Synchronous motors are used as constant-speed drive motors.

Over-excited synchronous motors are used to improve the power factor of electrical loads in industries. Generally, the motor is run on load, and by over excitation the system power factor is also

1. Explain why we use rotating poles and stationary armature in synchronous machines.
2. Distinguish between salient pole and cylindrical pole rotor construction. Why do we use cylindrical rotors in high-speed turbo generators?
3. What do you mean by pole pitch and coil pitch? What is the relationship between mechanical degrees and electrical degrees?
4. What is meant by synchronous speed. Establish the relation $N_s = 120f/P$, where N_s is the synchronous speed, f is the frequency, and P is the number of poles.
5. For a 50 Hz supply what are the possible synchronous speeds?
6. Draw the cross-sectional view of a salient-pole-type and non-salient pole-type synchronous machine. Why do we use laminated sheets for the construction of the stator and the rotor?
7. Draw a simple two-pole and four-pole stator winding for a synchronous machine showing the flux lines and the position of the poles formed.
8. Distinguish between the following three types of stator windings : (i) lap winding; (ii) wave winding; and (iii) spiral winding.
9. Distinguish between a fractional-pitch winding and a full-pitch winding. Mention the advantages and disadvantages (if any) of using fractional-pitch winding over full-pitch winding.
10. Derive the EMF equation for a three-phase synchronous machine taking into consideration the effect of using distributed winding and short-pitch coils.
11. Explain the constructional details of a synchronous machine. Mention the advantages of the stationary armature and rotating field.
12. Derive the expressions for distribution factor and pitch factor.
13. Distinguish between leakage reactance and synchronous reactance of a synchronous machine.
14. Show how the value of synchronous impedance can be calculated from test results.
15. What is meant by armature reaction? What is the effect of armature reaction on the main field flux at lagging and leading power factor loads?
16. Draw phasor diagrams of a synchronous generator at unity power factor load, lagging power factor load, and leading power factor load respectively.
17. Derive an expression for voltage regulation of a three-phase synchronous generator. Can the regulation be negative?
18. Explain how you can determine the regulation of a synchronous generator from open-circuit and short-circuit tests.
19. State the conditions for parallel operation of alternators. For parallel operation is it necessary that the alternators be of the same KVA rating?
20. Explain the effect of change of excitation and prime-mover input on the loading of alternators operating in parallel.
21. Explain the construction and working principle of a synchronous motor.

24. Explain the effect of change of excitation on the armature current of a synchronous motor.
25. What are synchronous motor V-curves? Draw and explain V-curves at different loads.
26. Explain why an over-excited synchronous motor is called a synchronous condensor?
27. Explain how a synchronous motor can be used for system power factor correction.
28. State applications of synchronous motors.

B. Numerical Problems

29. Calculate the EMF induced per phase for a three-phase four-pole synchronous generator having 72 slots on the armature. The number of conductors per slot is 10. The flux per pole is 20 mWb. The alternator is driven at 1,500 rpm. Full-pitch coils have been used for the armature winding.

[Ans 510 V]

30. An eight-pole synchronous generator is running at 750 rpm. What is the frequency of induced EMF? At what speed should the generator be run so that the EMF induced will have a frequency of 60 Hz?

[Ans 50 Hz, 900 rpm]

31. Calculate the distribution factor for a four-pole, three-phase alternator having 36 slots on the slator.

[Ans 0.96]

C. Multiple Choice Questions

1. In synchronous machines
   1. Field system is stationary and the armature windings are made rotating
   2. The armature windings are placed on stator slots and the field system is made rotating
   3. Both the field system and armature windings are rotating at synchronous speed
   4. Both the field system and armature windings are rotating at synchronous speed but in opposite directions.
2. In a synchronous machine the speed of rotation of the magnetic field N_S is
   1. $N_s = \frac{120P}{f}$
   2. $N_s = \frac{120f}{P}$

4. $N_s = \frac{120P^2}{f}$.

3. For a synchronous machine with concentrated winding with full-pitch coil, which of the following is true?
    1. Distribution factor, $K_d < 1$ and pitch factor, $K_p < 1$
    2. $K_d > 1$ and $K_p > 1$
    3. $K_d = 1$ and $K_p = 1$
    4. $K_d = 1$ and $K_p = 0$.
4. With m as the number of slots per pole per phase and a as the slot angle, the distribution factor, K_d is
    1. $K_d = \frac{m \sin \alpha/2}{\sin m\alpha/2}$
    2. $K_d = \frac{\sin \alpha/2}{\sin m\alpha/2}$
    3. $K_d = \frac{\sin m\alpha/2}{m \sin \alpha/2}$
    4. $K_d = \frac{\sin^2 m\alpha/2}{m \sin \alpha/2}$
5. Which of the following statements is not true for a synchronous machine?
    1. The machine can have a cylindrical rotor
    2. The machine can have a salient-type rotor
    3. The machine can have non-salient rotor construction
    4. The machine can have a squirrel-cage-type rotor construction.
6. In a synchronous machine, armature reaction is
    1. The effect of leakage flux on the main field flux
    2. The effect of armature flux on the leakage flux
    3. The effect of armature flux on the main field flux
    4. The effect of reduction of air-gap flux due to large air gap between the field system and the armature.
7. In synchronous machine, armature flux aids the main field flux on
    1. lagging power factor load
    2. leading power factor load
    3. resistive load
    4. resistive-inductive load.
8. When a synchronous generator is loaded, its terminal voltage may increase when the load power factor is
    1. lagging
    2. leading
    3. unity
    4. zero lagging.
9. The voltage regulation of a synchronous generator will always be positive when the load power factor is
    1. leading
    2. lagging
    3. zero leading
    4. above 0.8 leading.
10. The speed regulation of a synchronous machine is
    1. unity
    2. zero
    3. less than unity

    1. $E^2 = (V\cos\phi + I_aR_a)^2 + (V\sin\phi + I_aX_s)^2$
    2. $E = (V\cos\phi + I_aR_a)^2 + (V\sin\phi + I_aX_s)^2$
    3. $E = (V\cos\phi + I_aR_a) + (V\sin\phi + I_aX_s)$
    4. $E = (V\cos\phi + I_aR_a) – (V\sin\phi + I_aX_s)$.
12. For synchronizing an alternator with the busbar which of the following conditions is not applicable?
    1. The generated voltage of the alternator should be equal to the busbar voltage
    2. The frequency of the generated voltage should be equal to the busbar frequency
    3. The phase sequence of the voltage generated should be the same as that of busbar voltage
    4. The KVA rating of the alternator should be equal to the KVA rating of other alternators already connected to the busbar.
13. Sharing of load by two alternators running in parallel can be achieved by
    1. change of excitation
    2. change of speed
    3. change of prime mover input
    4. change of excitation.
14. Which of the following statements is not true for a synchronous motor?
    1. An over-excited synchronous motor draws lagging power factor current
    2. An over-excited synchronous motor draws leading power factor current
    3. At normal excitation the current drawn by a synchronous motor is the minimum
    4. At normal excitation the power factor of the current drawn is unity.
15. In alternators damper windings are used to
    1. prevent hunting
    2. reduced eddy current loss
    3. reduce armature reaction
    4. reduce both eddy current and hysteresis loss.
16. An infinite busbar should maintain
    1. infinite frequency but constant voltage
    2. constant voltage at constant frequency
    3. constant voltage at variable frequency
    4. constant voltage but should possess infinite length.

Answers to Multiple Choice Questions

1. (b)
2. (b)
3. (c)
4. (c)
5. (d)
6. (c)
7. (b)
8. (b)
9. (b)
10. (b)
11. (a)

16. (b)