Lecture 6

Three-Phase Synchronous Machines Construction & Armature Windings

1. Introduction:

Synchronous machine is an ac rotating machine whose speed under steady state condition is proportional to the frequency of the current in its armature. The magnetic field created by the stator currents rotates at the synchronous speed and that created by the field current on the rotor is rotating at the synchronous speed also. The torque is produced due to the interaction between the two magnetic fields. So, these machines are called synchronous machines because they operate at constant speed and constant frequency under steady-state conditions. Synchronous machines are commonly used as generators especially for large power systems, such as turbine generators and hydroelectric generators in the grid power supply. Due to the rotor speed is equal to the synchronous speed of stator magnetic field, synchronous motors can be used in applications where constant speed drive is required. Since the reactive power generated by a synchronous machine can be adjusted by controlling the magnitude of the rotor field current, unloaded synchronous machines are also often installed in power systems for power factor correction or for control of reactive kVA flow. Such machines, known as synchronous condensers, and may be more economical in the large sizes than static capacitors.

Like most rotating machines, synchronous machines are capable of operating both as a motor and as a generator. They are used as motors in constant-speed drives, and where a variable-speed drive is required, a synchronous motor is used with an appropriate frequency changer such as an inverter. As generators, the electric power for everyday use is produced by polyphase synchronous generators. Several synchronous machines are often operating in parallel as in electrical power station. While operating in parallel, the generators share the load with each other. However, at a given time one of the generators may not carry any load. In such a case, instead of shutting down the generator, it is allowed to "float" on the line as a synchronous motor on no-load.

2. Construction of Three-Phase Synchronous Machines:

The synchronous machine has three phase windings on the stator and a DC field winding on the rotor.

A. Stator:

It is the stationary part of the machine and is built up of sheet-steel laminations having slots on its inner periphery. A 3-phase windings is placed in these slots. The armature winding is always connected in star and the neutral is connected to ground. The Three-phase armature winding is placed on the stator. This arrangement has the following advantages:

- It is easier to insulate stationary winding for high voltages, because they are not subjected to centrifugal forces.
- The stationary 3-phase armature can be directly connected to load without going through large, unreliable slip rings and brushes.
- Only two slip rings are required for DC supply to the field winding on the rotor. Since the exciting current is small, the slip rings and brush gear required are of light construction.
- Due to simple and robust construction of the rotor, higher speed of rotating DC field is possible. This increases the output obtainable from a machine of given dimensions.

B. Rotor:

The rotor carries a field winding which is supplied with direct current through two slip rings by a separate DC source. There are two types of rotor according to its construction:

I. Salient (or projecting) pole type rotor.
II. Non-salient (or cylindrical) pole type rotor.

I. **Non-Salient Pole (Cylindrical) Type Rotor:** In this type, the rotor is made of smooth solid forged-steel radial cylinder having a number of slots along the outer periphery. The field windings are embedded in these slots and are connected in series to the slip rings through which they are energized by the d.c. exciter. The regions forming the poles are usually left unslotted as shown in

Figure 1(a). It is clear that the poles formed are non-salient i.e., they do not project out from the rotor surface. High-speed alternators (1500 or 3000 r.p.m.) are driven by steam turbines and use non-salient type rotors due to the following reasons:

- This type of construction has mechanical robustness and gives noiseless operation at high speeds.
- The flux distribution around the periphery is nearly a sine wave and hence a better e.m.f. waveform is obtained than in the case of salient-pole type.

Since steam turbines run at high speed and a frequency of 50 Hz is required, we need a small number of poles on the rotor of high-speed alternators (or turboalternators). We can use not less than 2 poles, and this fixes the highest possible speed. For a frequency of 50 Hz, it is 3000 r.p.m. The next lower speed is 1500 r.p.m. for a 4-pole machine. Consequently, turboalternators possess 2 or 4 poles and have small diameters and very long axial lengths.

II. Salient Pole Type Rotor:

In this type, salient or projecting poles are mounted on a large circular steel frame which is fixed to the shaft of the alternator as shown in Figure 1(b). The individual field pole windings are connected in series in such a way that when the field winding is energized by the DC exciter, adjacent poles have opposite polarities. Low-speed alternators (120 - 400 r.p.m.) such as those driven by water turbines have salient pole type rotors due to the following reasons:

- The salient field poles would cause an excessive windage loss if driven at high speed and would tend to produce noise.
- Salient-pole construction cannot be made strong enough to withstand the mechanical stresses to which they may be subjected at higher speeds.

Since a frequency of 50 Hz is required, we must use a large number of poles on the rotor of slow-speed alternators. Low-speed rotors always possess a large diameter to provide the necessary space for the poles. Consequently, salient-pole type rotors have large diameters and short axial lengths.

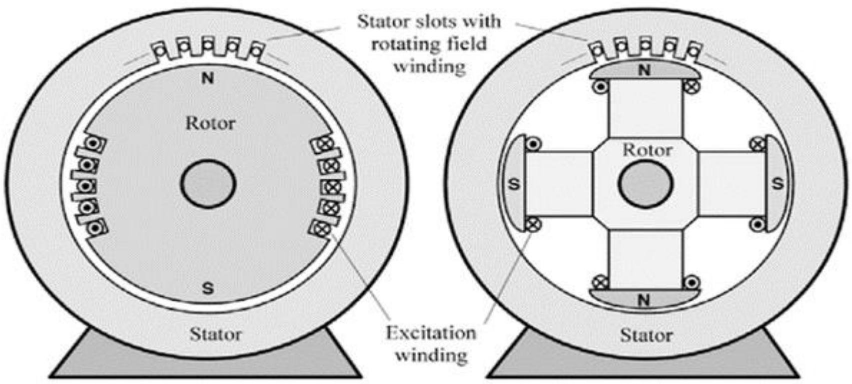

Figure 1 (a) Non Salient Pole Rotor (b) Salient Pole Rotor

C. Excitation Systems:

Since the field winding is on rotor, a special arrangement is necessary to connect DC source to the field circuit. In small size synchronous machines, generally the field winding is excited from a separate DC source through sliprings and brushes. Sliprings are metal rings completely encircling the shaft of the machine but insulated from it. A brush rides and slips over each slipring. The positive end of a DC voltage source is connected to one brush and negative end is connected to another brush. In large machines, various schemes are employed to supply DC excitation to the field winding.

D. Damper Bars:

Under steady state condition, the synchronous machine runs at a constant speed, that is, at synchronous speed. However, like other electric machines, a synchronous machine undergoes transients during starting and abnormal conditions. During transients, the rotor may undergo mechanical oscillations and its speed deviates from the synchronous speed, which is an undesirable phenomenon. To overcome this, an additional set of windings, resembling the cage of an induction motor, is mounted on the rotor. When the rotor speed is different from the synchronous speed, currents are induced in the damper windings. the damper winding acts like the cage rotor of an induction motor, producing a torque to restore the synchronous speed. Also, damper bars provide a means of starting to the synchronous motors, which is otherwise not self-starting. Figure 2 shows the damper bars on a salient pole type rotor.

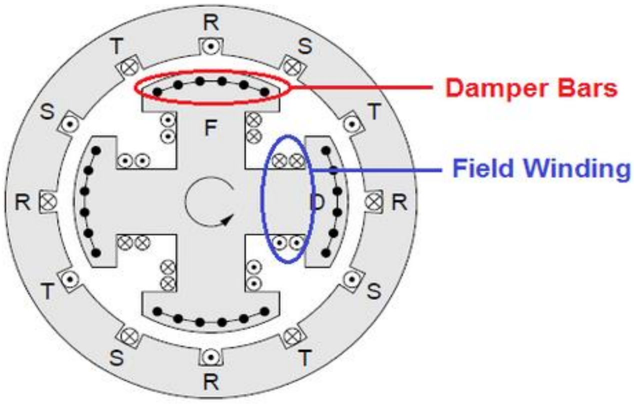

Figure 2 Damper Bars

3. Armature Windings:

The stator windings for alternating current motors and generators are alike. It should be noted that direct current and alternating current windings differ essentially by the former being of the closed-circuit type (through commutator), while alternating-current windings are of the open-circuit type. In most synchronous machines, stationary part is the armature. On the inner periphery of the stator core, number of slots (mostly open parallel sided slots) are provided. In these slots armature winding is placed.

4. Types of Armature Winding:

Various types of winding schemes can be adopted to wound the armature of an alternator, a few of them are given below:

4.1. Single-phase and poly-phase windings: When only one winding is placed on the armature and only one emf is obtained at the output, winding is called single-phase winding. When more than one windings are placed on the armature and emfs induced are more than one, displaced from each other by some angle, the winding is called poly-phase winding. Mostly three-phase winding is provided on the armature.

4.2. Concentrated and distributed windings: When one slot per pole or slots equal to the number of poles are employed, the windings thus obtained are called concentrated windings. Such windings give maximum induced emfs for given number of conductors but the wave form of induced emf is not exactly sinusoidal. When number of slots per poles are more than one, the windings thus obtained are called distributed windings. Such windings give slightly less than maximum induced emf for a given number of conductors but the wave form of induced emf is more sinusoidal.

4.3. **Single layer and double layer windings:** When only one coil side is placed in a slot, the winding is called single layer winding. However, when two coil sides are placed in one slot, one over the other, the winding is called double layer winding.

4.4. **Full pitched and short pitched windings:** When the two coil sides of the same coil are 180 electrical degrees apart, the winding is called full pitch winding. When the two sides of the same coil are less than 180 electrical degrees apart, the winding is called short pitch winding. The emf induced in each coil is maximum with full pitch winding scheme is employed whereas emf induced in the short pitch winding is less than that. However, short pitch winding is preferred over full pitch winding because of the following reasons:

- It decreases the length at the end-connections and thus amount of copper required is saved.
- It reduces the slot reactance and thus improves the wave shape of the generated emf, i.e., the generated emf can be made to approximately sinusoidal more easily by properly chording the winding.
- It reduces or eliminates distorting harmonics in the wave form of generated emf

The only disadvantage of short pitch winding is that a few more turns are used to obtain the same voltage as it would be induced in full pitch winding.

4.5. **Concentric (or spiral), Lap and Wave windings:** When each group of coils under a pole is arranged into a sort of concentric shape i.e., when the current flow is traced through one such properly connected set of coils that the conductors seem to form a spiral around a portion of the core (see Figure 3) the winding is called concentric or chain or spiral winding. This type of winding scheme is preferred for large diameter, low speed synchronous machines.

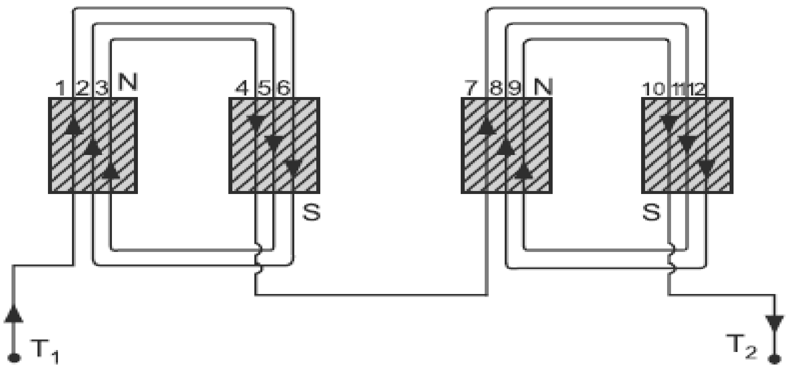

Figure 3 Concentric Winding

In the alternators, the lap and wave windings give the same emf as long as the other conditions are the same. In case of lap winding as shown in Fig. 4, coils or coil sides overlap the other consecutively and connections are made.

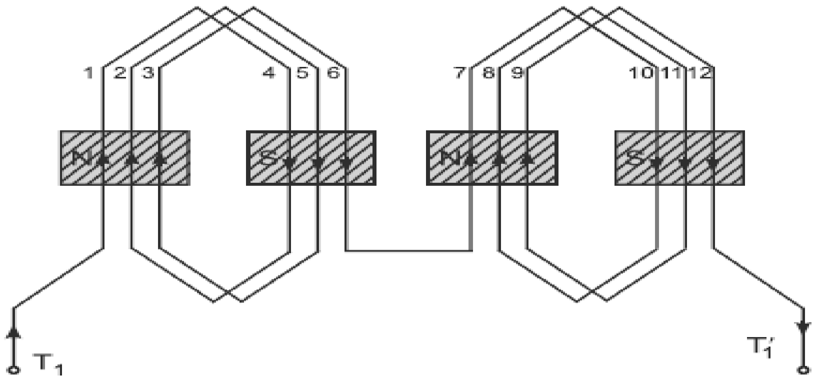

Figure 4 Lap Winding

Whereas in wave winding, as shown in Figure 5, the coils are always forward connected. The connections of a lap winding are simpler to that of the wave winding, therefore, lap winding is exclusively used.

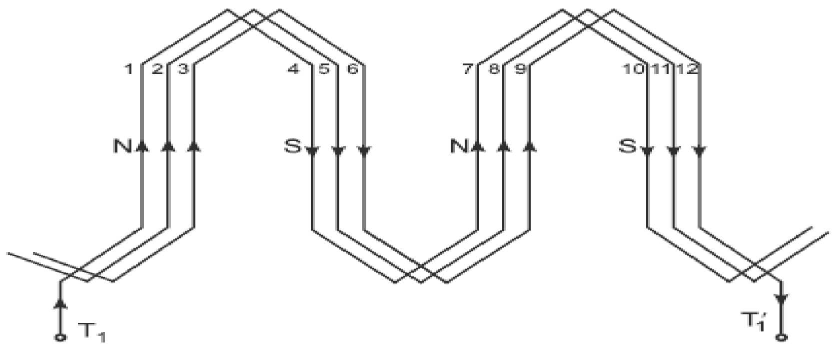

Figure 5 Wave Winding

5. Important Terms About Armature Winding:

Some of the important terms used in the armature winding are given below:

I. **Electrical angle:** When a conductor passes through a pair of poles, one cycle of emf is induced in it. Thus, a pair of poles represents an angle of 360 electrical degrees. There is a perfect relation between electrical and mechanical angle:

Electrical angle = Mechanical angle × Pair of poles.

II. **Pole pitch:** Distance between two neutral axes (or similar points) of adjacent poles is called pole pitch. The pole pitch can be expressed as number of slots per poles or electrical degrees (i.e., 180° elect.), as in figure 7. If **S** is the number of slots on the whole periphery of armature and **P** is the number of poles, Then, **Pole pitch = No. of slots per pole = S/P**.

III. **Coil**: Two conductors placed in the two slots displaced by pole pitch (in full pitch winding) or less than pole pitch (in short pitch winding), connected at one side by the end connections form a single turn coil as shown in Figure 6(a). When number of turns are connected in series and each side (coil side) is placed in the slot, it is called a multi-turn coil as shown in Figure 6(b) and (c). The multi-turn coil is shown in Figure 6(d) by a single line diagram.

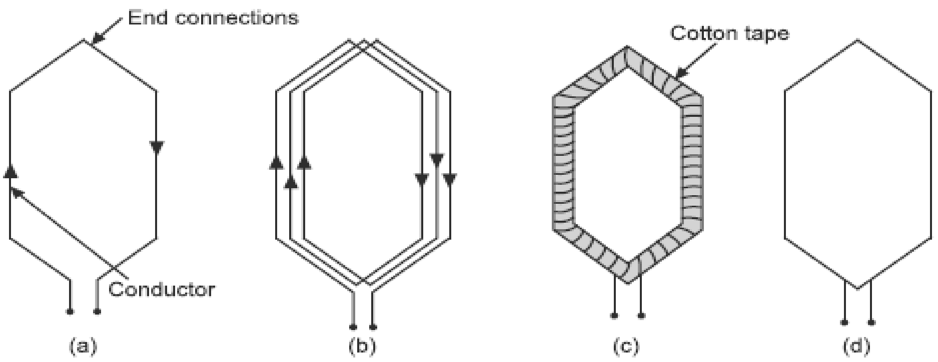

Figure 6 Single and Multi-Turn Coil

IV. **Coil pitch or coil span:** The distance between two active sides of a coil is called coil span. It is expressed in terms of number of slots or electrical degrees (figure 7).

V. **Slot pitch:** The distance between centre points (or similar points) of two consecutive slots or teeth is called slot pitch. It is expressed in electrical degrees (figure 7).

Slot pitch, $\beta = 180^0$ / (No. of slots/pole)

VI. **Phase spread:** The angle or space of pole face over which coil sides of the same phase are spread is called phase spread, as shown in Figure 7 In a distributed winding, the conductors of one phase under one pole are spread in number of slots so that each phase has equal distribution.

In a three-phase winding:

Phase spread = 180 / 3 = 60 electrical degrees

or Phase spread = No. of slots/pole/phase

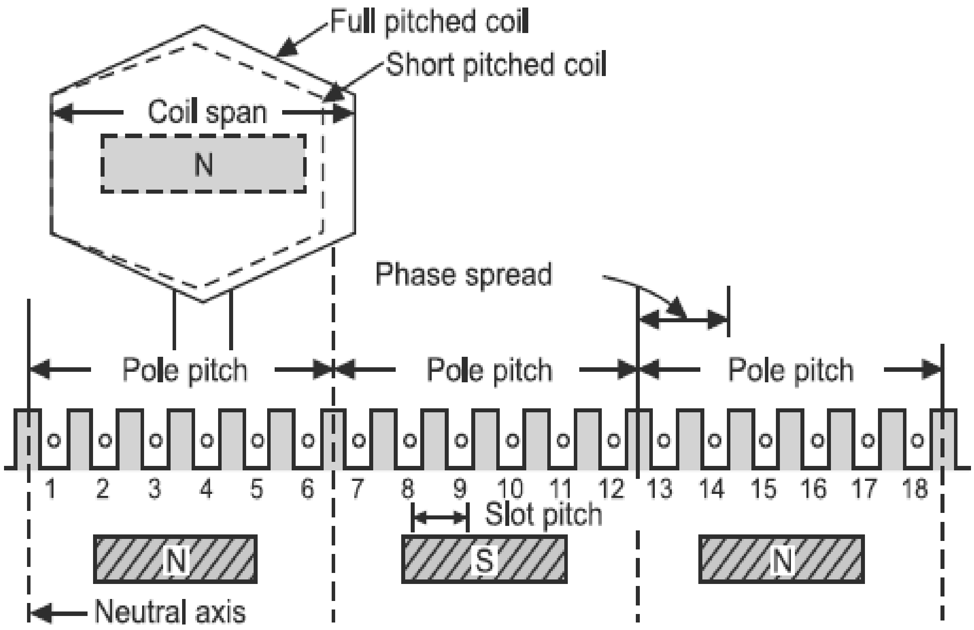

Figure 7 Distributed Windings

6. Windings Factors:

The stator winding of synchronous machine is distributed over the entire stator. The distributed winding produces nearly a sine waveform and the heating is more uniform. Likewise, the coils of armature winding are not full pitched i.e., the two sides of a coil are not at corresponding points under adjacent poles. The fractional pitched armature winding requires less copper per coil and at the same time waveform of output voltage is improved. The distribution and pitching of the coils affect the voltages induced in the coils. We shall discuss two winding factors:

I. Distribution Factor (K_d):

A winding with only one slot per pole per phase is called a concentrated winding. In this type of winding, the e.m.f. generated per phase is equal to the arithmetic sum of the individual coil e.m.f.s in that phase. However, if the coils per phase are distributed over several slots in space (distributed winding), the e.m.f.s in the coils are not in phase (the phase difference between coils e.m.f.s is not zero) but are displaced from each by phase angle equal to the slot angle (**β**) multiplied by the number of slots that the coils are distributed over as shown in figure 8.

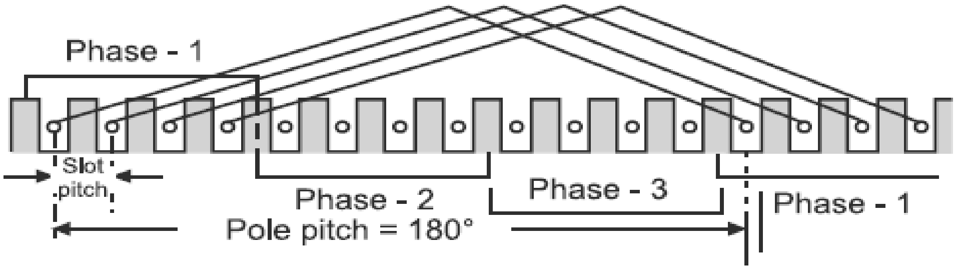

Figure 8 Distributed Windings

The e.m.f. per phase will be the phasor sum of coil e.m.f.s. Thus, the distribution factor can be defined as:

$$K_d = \frac{\text{e.m.f. with distributed winding}}{\text{e.m.f. with concentrated winding}}$$

The final expression for the distribution factor is given below:

$$K_d = \frac{\sin m\beta/2}{m \sin \beta/2}$$

Where, **β** is the slot pitch, **m** is the number of slot per phase per pole.

II. Pitch (Coil Span) Factor (K_p):

In a full pitch winding the coil span or coil pitch is always equal to the pole pitch which is equal to 180 electrical degrees. When the coil span is less than 180 electrical degrees, the winding is called short pitched or fractional pitch or chorded winding as shown in Figure 9. The pitch factor can be defined as:

$$K_p = \frac{\text{e.m.f. induced in short - pitch coil}}{\text{e.m.f. induced in full - pitch coil}}$$

The final expression for the pitch factor is given below:

K_p = **Cos (θ / 2),**

Where, **θ** is an integer multiple of the slot angle **β**.

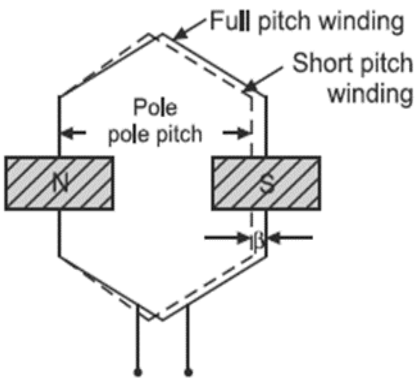

Figure 9 Short Pitch Winding