11 Synchronous Machines

LEARNING OBJECTIVES

After completing this chapter, you will be able to understand:

- Classifications of synchronous machines.
- Construction and operation of synchronous machines.
- The emf generated and voltage regulation in synchronous machines.
- Power and torque in synchronous generators.
- Applications of synchronous machines.

11.1 Introduction

A synchronous machine is an AC rotating machine whose speed under steady-state condition is constant which is known as synchronous speed. We have seen that this speed is given by

$$N_s = \frac{120 f_s}{p}$$

Here, f_s is the frequency of armature current in Hz and p is the number of stator poles.

11.2 Classification

Synchronous machines can be classified into the following based on their applications:

1. Synchronous generators or alternators: These are electromechanical devices that convert mechanical energy received from a prime mover such as steam turbine, diesel engine, etc. to electrical energy. Most commonly used generators for large power systems are basically of two types: turbine generators and hydroelectric generators in the grid power supply. As large quantities of energy are involved in this energy conversion process, the economy of operation as well as the reliability of the equipment is important. The efficiency and economy of the power demand requires the use of large generators. Generally, the higher the rating of the machine for a given speed, the greater is the efficiency.
2. Synchronous motors: These machines receive electrical energy from AC supply main and drive mechanical load. Synchronous motors are available in the market from small fraction of the horse power to thousands of horse power. They are generally used for constant speed drive applications.

Synchronous machines consist of the following parts:

1. **Stator:** The armature winding of a conventional synchronous machine is usually placed on the stator and is a three-phase winding. The stator has various parts such as frame, stator core, stator winding and cooling arrangement. The frame may be of cast iron for small size machines and welded steel type for large size machines. In order to reduce hysteresis and eddy current losses, the stator core is assembled with high-grade silicon steel laminations.
2. **Rotor:** The field winding on the rotor is usually excited by DC current or permanent magnets. The DC power required for exciting the field winding is supplied by a DC generator known as *exciter*. The exciter is often mounted on the same shaft as the synchronous machine. Large turbine generators use various excitation systems using AC exciter and solid state devices. The conventional system of the power industries supplied by the three-phase synchronous generators falls into two classifications:
   (a) **Cylindrical rotor:** Cylindrical rotor structure is used for high-speed synchronous machines such as steam turbine generators, which is otherwise known as *turbo alternators* or *turbine generators*. Figure 11.1 shows a cylindrical rotor structure with armature windings placed in the slots. These types of rotors have long axial length and small diameter. This type of rotor construction limits the centrifugal forces and has greater mechanical strength. Hence, it is suitable for high-speed operation. Cylindrical rotors have following special features:
      i. They have small diameter and long axial length.
      ii. Less windage losses.
      iii. High operating speed (3000 rpm).
      iv. Robust construction and noiseless operation.

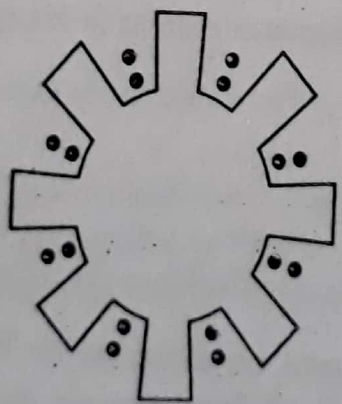

Figure 11.1 Cylindrical pole rotor.

   (b) **Salient pole rotor:** The salient pole structure is used for low-speed applications such as hydroelectric generators. They have the following special features:
      i. They have large diameter and short axial length.
      ii. The pole shoes cover about two-thirds of the pole pitch.
      iii. They are suitable for low-speed operation (100–375 rpm). Hence, they are used in hydraulic turbines.

Figure 11.2 shows a rotor of a hydroelectric generator.

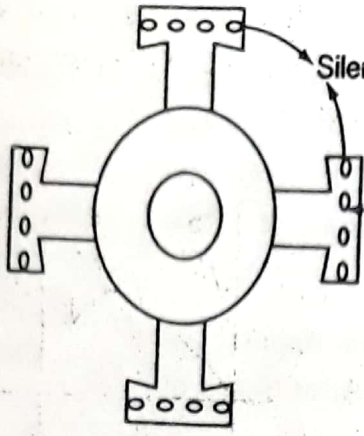

Figure 11.2 Silent pole rotor.

The armature winding is placed on the stator because it operates at high voltages (as high as 11 kV). It is difficult to place the armature winding on the rotor because of the following reasons:

1. High voltage requires larger insulation, which would make the rotor bulky, causing a reduction in the torque/weight ratio.
2. Taking out connection from the rotating body at high voltage would be difficult.

The synchronous machine houses the windings as shown in Fig. 11.3.

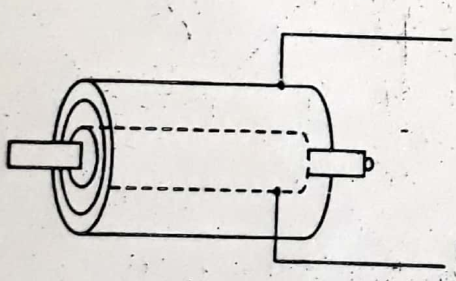

Figure 11.3 Placement of windings in synchronous machines.

11.4 Principle of Operation

11.4.1 Principle of Operation of Generator

The DC field winding, placed on the rotor, develops fixed electromagnetic poles in it. The construction of both machine types (i.e., salient pole and cylindrical rotor types) is such that when DC is given to the rotor, a nearly sinusoidal field is created in the air gap between the stator and the rotor. This is achieved by the typical shape of the pole shoes as shown in Fig. 11.4(a). The rotor is rotated at synchronous speed by a mechanically coupled prime mover (turbine/engine). When this nearly sinusoidally rotating flux of rotor cuts the armature winding, a three-phase AC emf gets induced in the latter placed on the stator. The factors responsible for induction of three-phase AC emf in armature winding are explained in Fig. 11.4.

1. The shape of the rotor poles is such that the emf induced in each armature coil is sinusoidal. This is described in Fig. 11.4(a).

2. The distribution of three-phase AC winding on the stator is shown in Figs. 11.4(b) and (c). The top-most diagram of Fig. 11.4(c) corresponds to the position of rotor in Fig. 11.4(b) when it is aligned with the phase "a" of the armature.

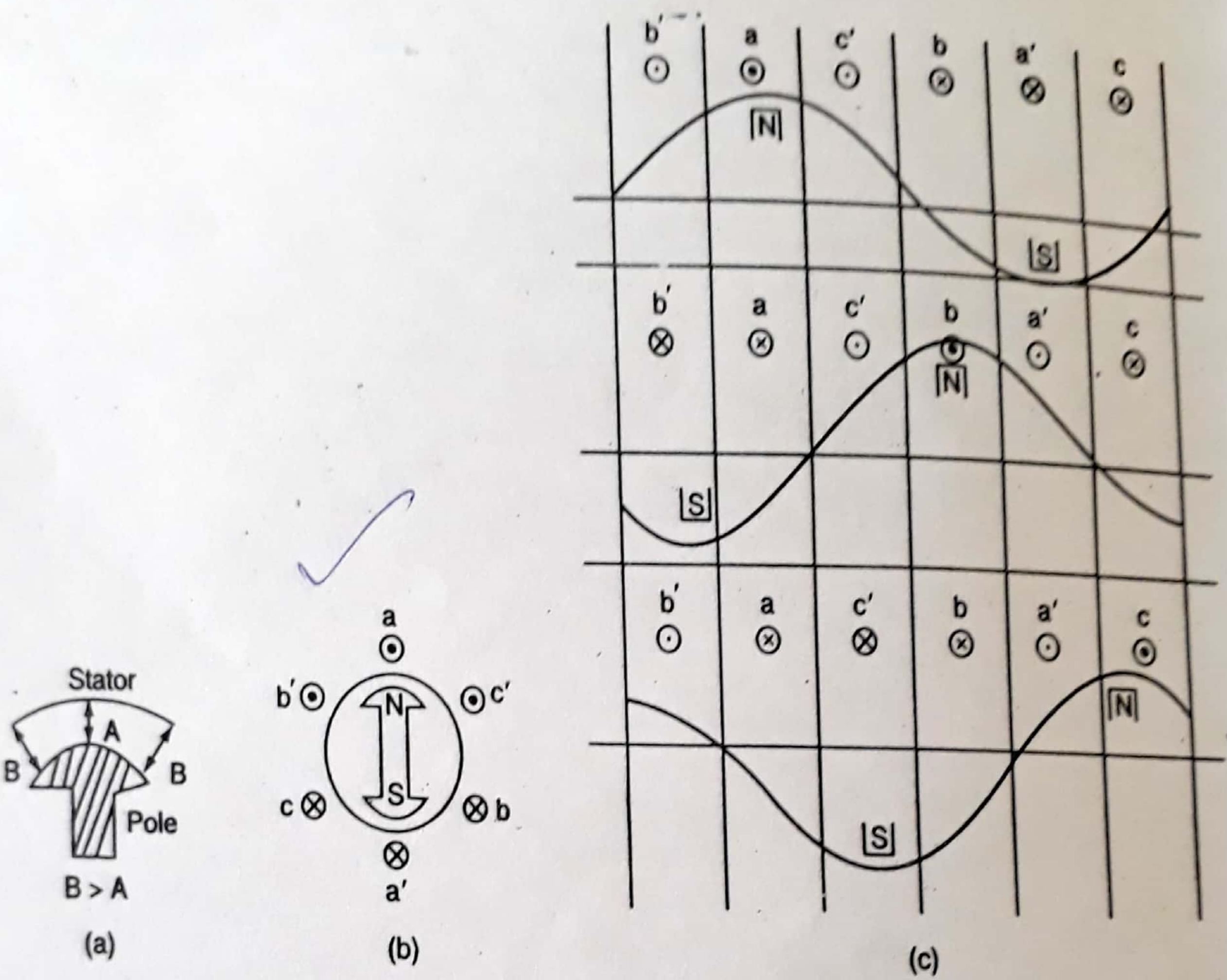

Figure 11.4 Sinusoidal emf in armature winding.

The rotor of alternator is rotated at a constant (synchronous) speed "N_s" rpm. The design and layout of the armature winding is such that when the DC flux (due to "P" number of poles of the rotor, rotating at N_s rpm) cuts this winding, three-phase AC emf gets induced in it. This emf, having frequency of f_s Hz, becomes available at the armature winding terminals.

11.4.2 Principle of Operation of Synchronous Motor

The three-phase AC armature winding, placed at stator, when energized by a three-phase AC supply, develops a rotating magnetic field in the air gap. This rotating magnetic field is similar to P number of fictitious poles rotating in the air gap at synchronous speed (see Fig. 11.5). The rotor contains DC field winding, which creates electromagnetic poles on the rotor. The rotor poles, when get aligned and locked with the stator fictitious poles, make the rotor rotate in the direction of the stator's rotating magnetic field.

The synchronous motors are inherently ***non-self-starting*** motors. At the time of starting, when the rotor is stationary, the fictitious poles, due to stator field, change their polarity f times per second (where f is the frequency of the input AC supply to the armature). Thus, with rapidly changing polarities (100 times for a 50 Hz supply), the stator poles seem to be sweeping over the rotor poles. When a

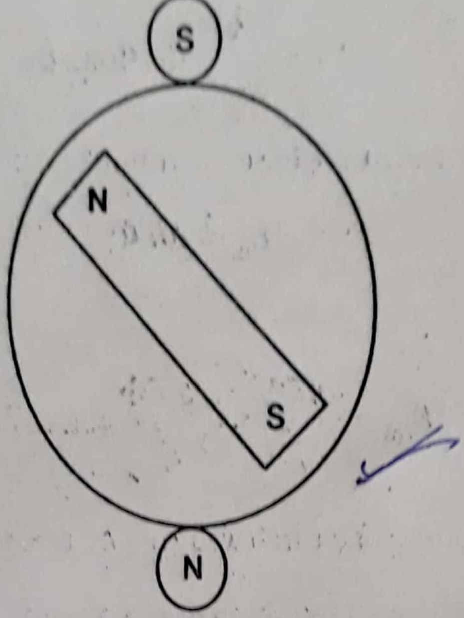

Figure 11.5 The interaction of the fictitious stator poles with the fixed polarity rotor poles in a synchronous motor.

stator's S pole passes over the rotor's N pole, the rotor tries to align itself with it. The stationary rotor's inertia is high. Hence it takes some time to begin the movement. By this time, the stator's N poles come over the same N pole of the rotor. Now this rotor's N pole gets repelled by the stator's N pole. In a very short span of time, the rotor's N pole experiences attraction and repulsion by the stator's S and N poles, respectively. Thus, alternately the N and S poles of the stator field quickly pass over the stationary rotor poles, and the rotor fails to get aligned and locks itself with the stator field. The rotor, thus, fails to rotate, thereby making the synchronous motor non-self-starting.

In order to make it self-starting, a special winding called the ***damper winding*** is put in the rotor (along with the already existing DC winding). This special winding is made up of copper bars that are short-circuited at both ends (and thus are closed circuit electrically). Hence it helps start the motor like a three-phase induction motor. The rotor field winding is initially kept open-circuited. The supply is fed to the armature winding, which results in the development of a rotating magnetic field in the air gap. On the principle of induction motor, a current starts flowing in the short-circuited copper bars at the rotor. Thus, the motor starts as an induction motor and the rotor poles soon get rotating at a speed close to the stator's rotating magnetic field (i.e. the synchronous speed). At this point, if the DC supply to the rotor field winding is switched ON, the rotor quickly catches the speed of the stator field and gets locked with it. Once the rotor starts rotating at the synchronous speed, it continues to do so throughout for complete range of loads.