AC machines

Traditional ac machines fall into one of two categories: synchronous and induction. In synchronous machines, rotor-winding currents are supplied directly from the stationary frame through a rotating contact. In induction machines, rotor currents are induced in the rotor windings by a combination of the time-variation of stator currents and the motion of the motion of the rotor relative to the stator.

Synchronous Machines

A preliminary picture of synchronous-machine performance can be gained by discussing the voltage induced in the armature of the very much simplified salient-pole ac synchronous generator shown schematically in figure 1. The field-winding of this machine produces a single pair of magnetic poles (similar to that of bar magnet), and hence this machine is referred to as a two-pole machine.

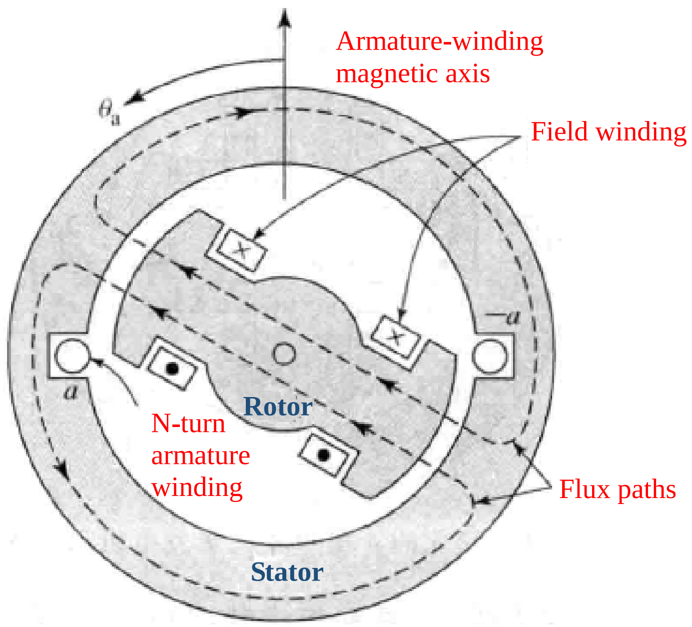
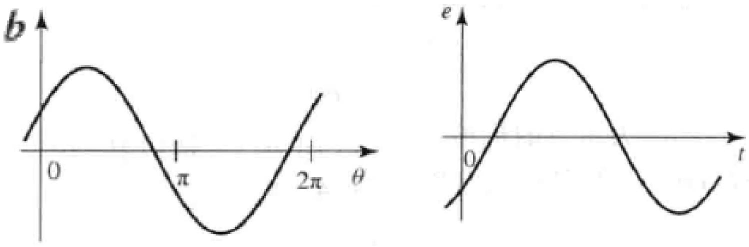


Figure 1 Schematic view of a simple, two-pole, single-phase synchronous generator.

With rare exceptions, the armature winding of a synchronous machine is on the stator, and the field winding is on the rotor, as is true for the simplified machine of figure 1. The field winding is excited by direct current, typically conducted to it by means of stationary carbon brushes which contact rotating slip rings or collector rings although in some cases the field winding may be supplied from a rotating excitation system, typically referred to as a brushless excitation system. Practical factors usually dictate this orientation of the two windings: It is advantageous to have a single, low-power field winding on the rotor while having the high-power, typically multiple-phase, and armature winding on the stator.

The armature winding, consisting here of only a single coil of N turns, is indicated in cross section by the two coil sides a and $-a$ placed in diametrically opposite narrow slots on the inner periphery of stator of figure 1. The conductors forming these coil sides are parallel to the shaft of the machine and are connected in series by end connections (not shown in the figure). The rotor is turned at a constant speed by a source of mechanical power connected to its shaft. The armature winding is assumed to be open-circuited and hence the flux in this machine is produced by the field winding alone. Flux paths are shown schematically by dash lines in figure 1.

A highly idealized analysis of this machine would assume a sinusoidal distribution of magnetic flux in the air gap. The resultant idealized radial distribution of air-gap flux density b is shown in figure 2a as a function of the spatial angle θ (measured with respect to the magnet axis of the armature winding) around the rotor periphery. In practice, the air-gap flux-density of practical salient-pole machines can be made to approximate a sinusoidal distribution by properly shaping the pole faces.



(a) (b)

Figure 2 (a) Idealized sinusoidal space distribution of the air-gap radial flux density and (b) corresponding wave form of the generated voltage for the single-phase generator of figure1.

As the rotor rotates, the flux-linkages of the armature winding change with time. Under the assumption of a sinusoidal flux distribution and constant rotor speed, the resulting coil voltage will be sinusoidal in time as shown in figure 2b. The coil voltage passes through a complete cycle for each revolution of the two-pole machine of figure 1. Its frequency in cycles per second (Hz) is the same as the speed of the rotor in revolutions per second: the electric frequency of generated voltage is synchronized with the mechanical speed, and this is the reason for the designation “synchronous” machine. Thus a two-pole synchronous machine must revolve at 3600 revolutions per minute to produce a 60-Hz voltage.

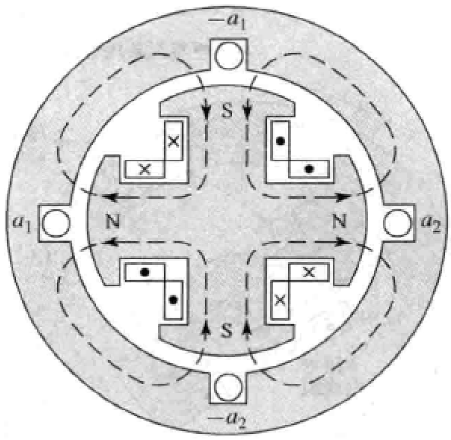


Figure 3 Schematic view a simple, four-pole, single-phase synchronous generator.

A great many synchronous machines have more than two poles. As a specific example, Figure 3 shows in schematic form a four-pole single phase generator. The field coils are connected so that the poles are of alternate polarity. There are two complete wavelengths, or cycles, in the flux distribution around the periphery, as shown in figure 4. The armature winding now consists of two coils a_1,- a_1 and a_2, - a_2 which be connected either in series or parallel. The span of each coil is one wavelength of the rotor. The frequency in herz will be twice the speed in revolutions per second.

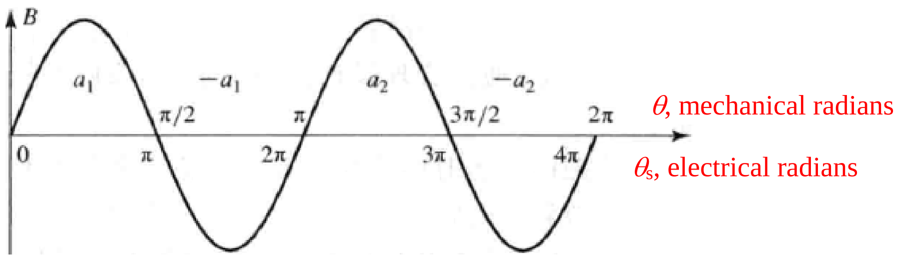


Figure 4 Space distribution of the air gap flux density in an idealized, four-pole synchronous generator

When a machine has more than two poles, it is convenient to concentrate on a single pair of poles and to recognize that the electric, magnetic, and mechanical conditions associated with every other pole pair are repetitions of those for the pair under consideration. For this reason, it is convenient to express angles in *electrical degree* or *electrical radians* rather than in physical units. One pair of poles in a multi-pole machine or one cycle of flux distribution corresponds to 360 electrical degrees or 2π electrical radians. The pair number p of magnetic pole is equal to poles/2. Since there are p complete wavelengths, or cycles, in one complete revolution, it follows, for example, that $\theta_s = p\theta$ (1)

where θ_s is the angle in electrical units, θ is the spatial angle. This same relationship applies to all angular measurements in a multi-pole machine; their values in electrical units will be equal to p times their actual spatial values.

The coil voltage of a multi-pole machine passes through a complete cycle every time a pair of poles sweeps by, or p times each revolution. The electrical frequency f of the voltage generated in a synchronous machine is therefore: $f=pn/60$.

Where n is the mechanical speed in revolutions per minute, and hence $n/60$ is the speed in revolutions per second. The electrical frequency of the generated voltage in radians per second is

$\omega = 2\pi f = p\Omega = p2\pi n/60$ (2)

Where Ω is the mechanical speed in radians per second.

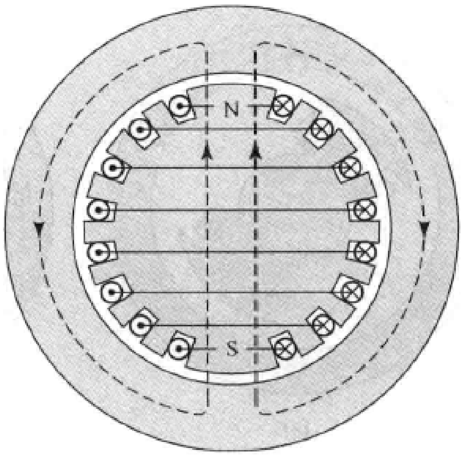
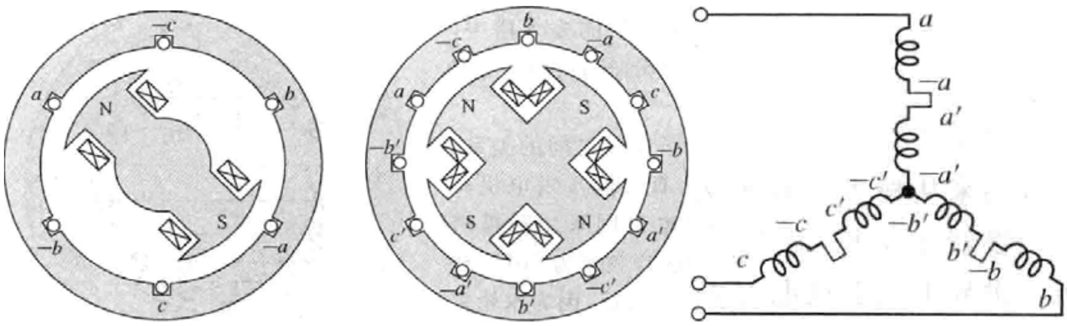


Figure 5 Elementary two-pole cylindrical-rotor field winding

The rotors shown in figure 1 and 3 have salient, or projecting, poles with concentrated windings. Figure 5 shows diagrammatically a nonsalient-pole, or cylindrical, rotor. The field winding on the rotor is a two-pole distributed winding; the coil sides are distributed in multiple slots around the rotor periphery and arranged to produce an approximately sinusoidal distribution of radial air-gap flux.

The relationship between electrical frequency and rotor speed of $f=pn/60$ can serve as a basis for understanding why some synchronous generators have salient pole rotor structures while others have cylindrical rotors. Most power systems in the world operate at frequencies of 50 or 60 Hz. A salient-pole construction is characteristic of hydroelectric generators because hydraulic turbines operate at relatively low speeds, and hence a relatively large number of poles is required to produce the desired frequency; a salient-pole construction is better adapted mechanically to this situation. Steam turbines operate best at relatively high speeds, and turbine-driven alternators or turbine generators are cylindrical-rotor machines.



(a) (b) (c)

Figure 6 Schematic views of three-phase generators: (a) two-pole, (b) four-pole, (c) Y connection of the windings.

Most of the world’s power systems are three-phase systems and, as a result with very few exceptions, synchronous generators are three-phase machine. For the production of a set of three coils phase-displaced by 120 electrical degrees in time, a minimum of three coils phase-displaced 120 electrical degrees in space must be used. A simplified schematic view of a three-phase, two-pole machine with one coil per phase is shown in figure 6a. The three phases are designated by the letters a, b, and c. In an elementary four-pole machine, a minimum of two such sets of coils must be used, as illustrated in figure 6b; in an elementary multi-pole machine, the minimum number of coil sets is given by one half the number of poles.

The two coils in each phase of figure 6b are connected in series so that their voltages add, and the three phases may then be either Y- or Δ- connected. Figure 6c shows how the coils may be interconnected to form a Y connection. Note however, since the voltages in the coils of each phase are identical, a parallel connection is also possible, e.g., coil(a,-a) in parallel with coil (a',-a'), and so on.

The counterpart of the synchronous generator is the synchronous motor. Alternating current is supplied to the armature winding on the stator, and dc excitation is supplied to the field winding on the rotor. The magnetic field produced by the armature currents rotates at synchronous speed. A steady electromechanical torque is produced when the rotor rotates in synchronism with the magnetic field produced by the armature currents. Hence the steady-state speed of a synchronous motor is determined by the number of poles and the frequency of the armature current and a synchronous motor operated from a constant-frequency ac source will operate at a constant steady-state speed.

In a motor the electromechanical torque is in the direction of rotation and balances the opposing torque required to drive the mechanical load. The flux produced by currents in the armature of a synchronous motor rotates ahead of that produced by the rotor field winding, thus pulling on the field winding (and hence on the rotor) and doing work. This is the opposite of the situation in a synchronous generator, where the field does work as its flux pulls on that of the armature. In both generators and motors, in addition to an electromechanical torque, a speed voltage (emf) is induced in the armature by the rotating field winding.

Induction machines

A second type of ac machine is the induction machine. In an induction machine, the stator windings are essentially the same as those of a synchronous machine. However, the rotor windings are electrically short-circuited and frequently have no external connections; currents are induced by transformer action from the stator winding. Here the rotor “windings” are actually solid aluminum bars which are cast into the slots in the rotor and which are shorted together by cast aluminum rings at each end of the rotor. This type of rotor construction results in induction motors which are relatively inexpensive and highly reliable, factors contributing to their immense popularity and widespread application.

In contrast to a synchronous machine in which a field winding on the rotor is excited with dc current and the rotor rotates in synchronism with the flux wave produced by ac armature currents, the rotor windings of an induction machine are not excited by an external source. Rather, currents are induced in the shorted rotor windings as the rotor slips past the synchronously-rotating armature flux wave. Thus, induction machines are asynchronous machines and produce torque only when the rotor speed differs from synchronous speed.

Interestingly, although the rotor operates asynchronous, the flux wave produced by the induced rotor currents rotates in synchronism with the stator flux wave. This in fact is a requirement for, and consistent with, the ability of an induction machine to produce net torque. Induction motors operate at speeds less than the synchronous mechanical speed, in which case the armature flux in the induction motor leads that of the rotor and produces and electromechanical torque which pulls on the rotor just as is the case in a synchronous motor.

Because rotor currents are by produced by induction, an induction machine may be regarded as a generalized transformer in which electric power is transformed between rotor and stator together with a change of frequency and a flow of mechanical power. Although induction machines are primarily used as motors, in recent years induction generators have been found to be well suited for some wind-power applications.