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## OKERENKOKO, DELTA STATE, NIGERIA

FILE TITLE

### FACULTY OF ENGINEERING
### DEPARTMENT OF ELECTRICAL ENGINEERING

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ELECTRICAL MACHINES II

is found on the rotating part, referred to as the rotor. The armature winding of a DC machine consists of many coils connected together to form a closed loop. As the rotor rotates a mechanical contact (split ring commutator) is used to supply current to the armature winding.

Synchronous and DC machines typically have two sets of windings. Apart from the armature windings they have a second set of windings which carry DC current and which produce the main operating flux in the machine. This second winding is typically called field winding. While the field windings of a synchronous machine is found on the rotor that of the DC machine is found on the stator. Since the field windings of the synchronous machine is found on the rotor current must be supplied winding by means of a rotating mechanical contact (slip rings). Since permanent magnets also produce DC magnetic flux they can be used in place of field windings.

The stator and rotor of rotating machines is made of magnetic material (mostly electrical steel) and the windings are placed in slots on the stator and rotor structures. The magnetic materials used are of very high relative permeabilities and serve the following purposes;

1. They maximize the coupling between stator and rotor coils
2. They increase the magnetic energy availably in the coupling field for electromechanical energy conversion.
3. They also help the machine designer to shape and distribute the magnetic fields to suit each particular machine

The time varying flux present in the armature structures induces eddy currents in the armature structure. The effect of eddy currents can significantly reduce the machine performance. These eddy currents are reduced by building the armature structure from thin laminations of electrical steel which are insulated from each other

In some machines such a variable reluctance machines and stepper motors, there are no windings on the rotor. The operation of such machines depend on the non-uniformity of air-gap reluctance associated with variations in the position of the rotor in relation to the time varying currents applied to their stator windings. In such machines since both the stator and rotor are subjected to time varying magnetic flux both may require laminations to reduce eddy current effects.

## 1.2. Introduction to AC Machines

Traditionally, AC machines fall into one of two categories: Synchronous or induction. It would be seen that a major distinguishing feature between these two categories of AC machines is that in synchronous machines rotor winding currents are supplied directly from the stationary frame through a rotating contact whereas in induction machines rotor currents are induced into the rotor windings by a combination of the time varying stator currents and the motion of the rotor relative to the stator.

# Synchronous Machines

To understand the performance and operation of a synchronous machine, let us consider a very much simplified two-pole salient pole sychronous generator shown in figure 1.1.

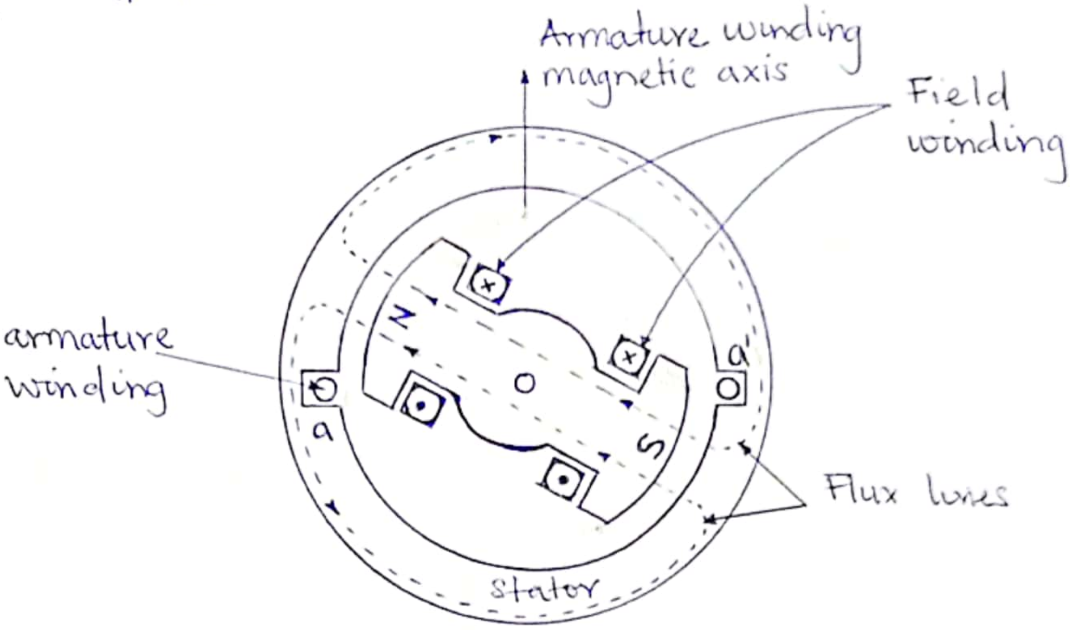



Fig. 1.1. Schematic view of a simplified, two-pole single phase synchronous genenerator.

As seen in figure 1.1 the armature winding of a synchronous machine is mostly found on the stator and the field winding is placed on the rotor. The field winding is excited by DC conducted to it by means of stationary carbon brushes which contact rotating slip rings. It is practically more advantageous to have the low power, single phase field winding on the rotor while the high power, multi-phase armature winding is placed on the stator.

Figure 1.1. shows the cross-section of the armature winding consisting of a single coil of N-turns, represented by two coil sides a and a' on the inner surface of the stator.

The rotor is turned at a constant speed by a source of mechanical power connected to the shaft. Since armature winding is assumed to be open circuited the flux in this machine is produced by the field winding alone.

The ideal model of this machine assumes a sinusoidal distribution of magnetic flux in the air gap as seen in figure 1.2 (a).

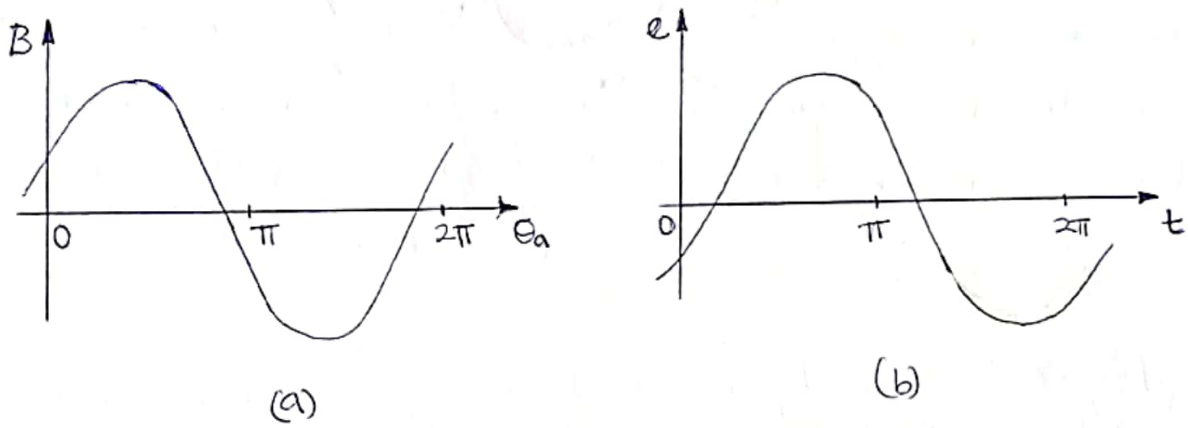



Fig. 1.2. (a) Space distribution of flux density
(b) Waveform of the corresponding generated voltage for the single phase generator of figure 1.1.

As the rotor rotates, the flux linkages of the armature winding change with time. Assuming a sinusoidal flux distribution and constant rotor speed, the resultant induced voltage, e, will be sinusoidal as shown in figure 1.2 (b). Thus it is seen that the voltage induced in the coil completes a cycle for each revolution of the two-pole machine of fig. 1.1. Its frequency in Hz (cycles per second) is same as the speed of the rotor in revolutions per second. The electrical frequency of the generated voltage is thus synchronized with the mechanical speed of rotation, hence the name "Synchronous" machine. It is therefore seen, for example, that a two-pole synchronous machine must revolve at 3000 revolutions per minute to produce a 50 Hz voltage.

In practice most synchronous machines have more than two poles. When a machine has more than two poles, it is convenient to concentrate on a single pole pair bearing in mind that the electric, magnetic and mechanical conditions of every other pole pair are repetitions of those for the pair under consideration. Fig. 1.3 presents a four pole single phase synchronous generator.

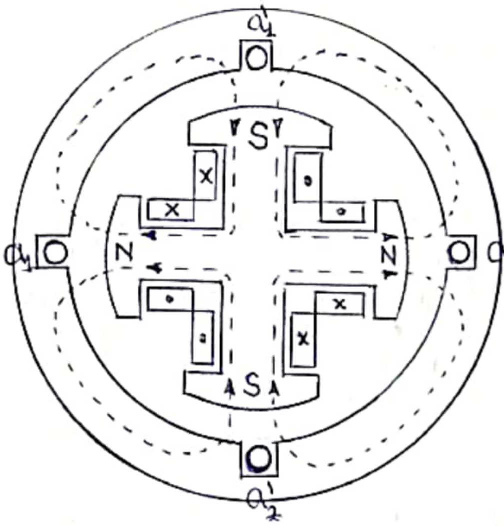



Fig. 1.3. Schematic of a simple, four-pole, single phase synchronous generator

As seen in figure 1.3 the field coils are connected so that the poles are of alternate polarity. In this arrangement there are two complete wavelengths, or cycles per complete revolution of the field as illustrated by figure 1.4. The armature windings now contains two coils $a_1, a_1'$ and $a_2, a_2'$, connected in series by their end connections. As seen in figure

1.4 the generated voltage now goes through two complete cycle per revolution of the rotor. The frequency in hertz will thus be twice the mechanical speed in revolutions per second.

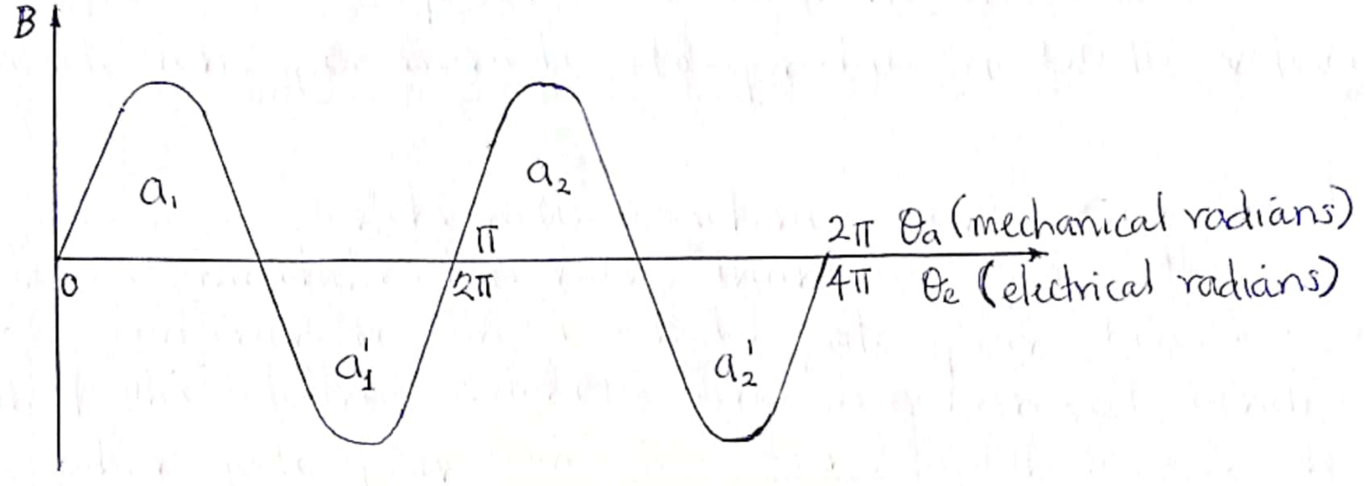



Fig. 1.4. Space distribution of the air-gap flux density in an ideal four-pole, single phase synchronous generator

It is convenient to express angles in electrical degrees or electrical radians rather than in physical units. The relationship between electrical radians and mechanical radians is gotten by noting that one complete pair of poles rotation or one cycle of flux distribution equals 360 electrical degrees or 2π electrical radians. Since there are no. of poles/2 complete wavelengths, or cycles in one complete revolution, it follows that

$$\text{Electrical degrees, } \theta_e = \left(\frac{\text{no. of poles}}{2}\right)\theta_a \qquad 1.1$$

Where $\theta_a$ is the spacial angle (in mechanical degrees). This same relationship holds for all angular measurements in a multipole machine. The electrical units equivalent will be equal (no. of poles/2) times the equivalent spacial values. From the waveform of induced voltage in a multipole machine it is seen that the coil voltage passes through a complete cycle every time a pair of poles sweeps by, or (no. of poles/ 2) times each revolution. The electrical frequency of the induced voltage in a synchronou machine is therefore

$$f = \left(\frac{\text{no. of poles}}{2}\right)\frac{n}{60} \text{ Hz} \qquad 1.2$$

Where n is the mechanical speed in revolutions per minute, and n/60 is the speed in revolutions per second. The electrical frequency in radians per second is given as

$$\omega_e = \left(\frac{\text{no. of poles}}{2}\right)\omega_m$$

Where $\omega_m$ is the mechanical speed in radians per second.

The rotor of a synchronous machine can be constructed in two main forms; salient or projecting poles, having concentrated windings (figures 1.1 and 1.3) and nonsalient poles or cylindrical rotor, having distributed windings as illustrated in figure 1.5.

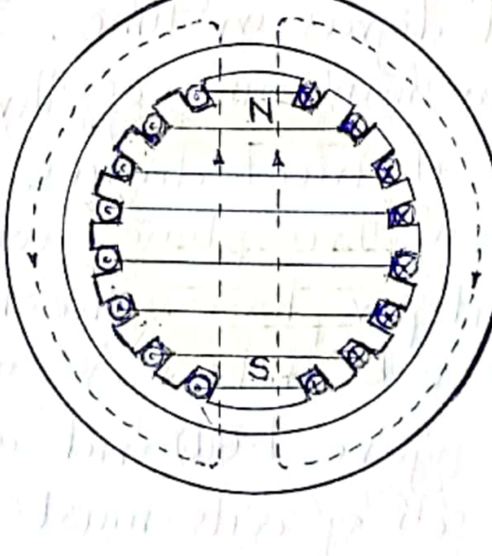


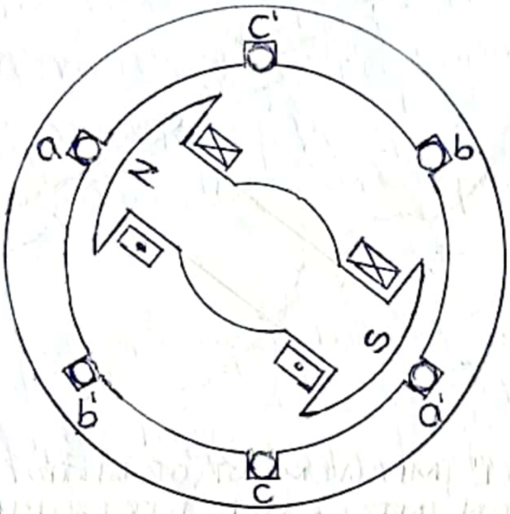

Fig. 1.5. Elementary two-pole synchronous machine, showing Cylindrical rotor having distributed windings.

As seen in figure 1.5 the coil sides are arranged into multiple slots around the rotor surface. This distributed arrangement produces an approximately sinusoidal distribution of flux around the air gap.

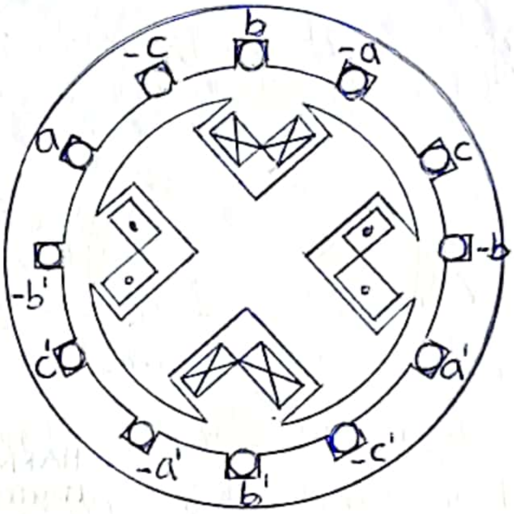
Most power systems in the world operate at either 50 or 60Hz frequency. Power generating systems (such as hydroelectric generators) which employ hydraulic turbines that operate at relatively low speeds would require a relatively large number of poles to achieve the desired frequency. Such generators therefore make use of salient-pole rotors. Steam and gas turbines on the other hand operate best at relatively high speeds and such systems commonly make use of two or four-pole cylindrical rotors.

## Three Phase Synchronous Machines

The discussion so far has centered on single phase synchronous machines. However, most of the worlds power systems are three phase systems and as a result most synchronous generators are three phase machines. Three phase generators produce a set of three voltages phase-displaced by 120 electrical degrees in time. To produce a set of such voltages require a minimum of three coils, phase displaced in space by 120 electrical degrees. Figure 1.6(a) presents a simplified view of a three phase, two-pole synchronous machine with one coil per phase. The three phases are represented by the letters a, b and c. A simple four pole machine is illustrated in figure 1.6(b) and as can be seen a minimum of two such sets of coils must be used. From the foregoing it follows that in an elementary multipole machine the number of sets of coils is given by half the number of poles.




(a)




(b)

Fig. 1.6. Simplified schematics of three-phase generators (a) two-pole (b) four-pole

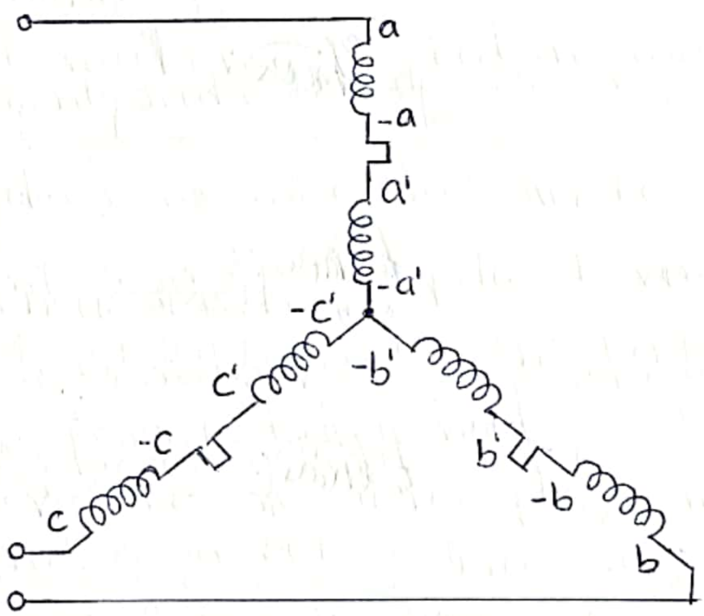



Fig. 1.7. Star (Y) connection of the windings.

As seen in figure 1.7 the two coils in each phase are connected in series so that their voltages add and the three phases are then connected in star (Y). However since the coil voltages in each phase are same a parallel connection is possible and the three phases can also be connected in Δ (delta.

When a synchronous generator is supplying power to a load current will flow through its armature windings to the load. This armature current creates a rotating magnetic field in the air gap which rotates at synchronous speed The interaction between this armature flux and the field flux results in an electromechanical torque due to their tendency to align. This electromechanical torque is the mechanism through which the synchronous generator converts mechanical to electrical energy. In a generator this electromechanical torque opposes rotation of the rotor and external mechanical torque must be applied from a prime mover to maintain rotation.

In the operation of a synchronous motor, on the other, hand while alternating current is supplied to the armature winding on the stator, DC excitation is supplied to the field windings located on the rotor. The current flowing in the armature creates a magnetic field which rotates at synchronous speed. The DC current flowing in the field windings also creates a rotating magnetic field. The interaction between the stator and rotor fields creates an electromechanical torque which causes rotation in the rotor.

To produce a steady electromechanical torque the magnetic fields produced in the stator and rotor must be of constant amplitude and stationary relative to each other. This steady state speed in a synchronous motor is determined by the number of poles and frequency of the armature current.

Therefore, a synchronous motor which is operated from a constant frequency AC source will produce a steady electro-mechanical torque which in turn translates to a constant steady-state speed in the rotor.

## Induction Machines

The induction machine presents a second type of AC machine. Like in the sychronous machine the stator winding is excited by AC. However, in contrast to the synchronous machine alternating current also flows in the rotor of an induction machine, but by induction (transformer action). The induction machine may thus be regarded as a generalized transformer in which electric power is transformed between stator and rotor with a change in frequency and a flow of mechanical power

At this point it is worthy of note that induction machines are commonly deployed as induction motors and seldom used as generators. This is because the performance of the induction gen is unsatisfactory for most applications. However, recently it was found well suited for wind power application and it may also be used as a frequency changer.

In construction, the induction motor 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, since current is induced by transformer action from the stator winding

As in a synchronous motor, the armature flux in the induction motor leads that of the rotor thus producing an electromagnetic torque. However, unlike the synchronous machine the rotor of the induction machine not rotate synchronously. Induction motors, thus operate at speeds less than synchronous mechanical speeds. Figure 1.8 presents a typical speed-torque characteristic of an induction motor.

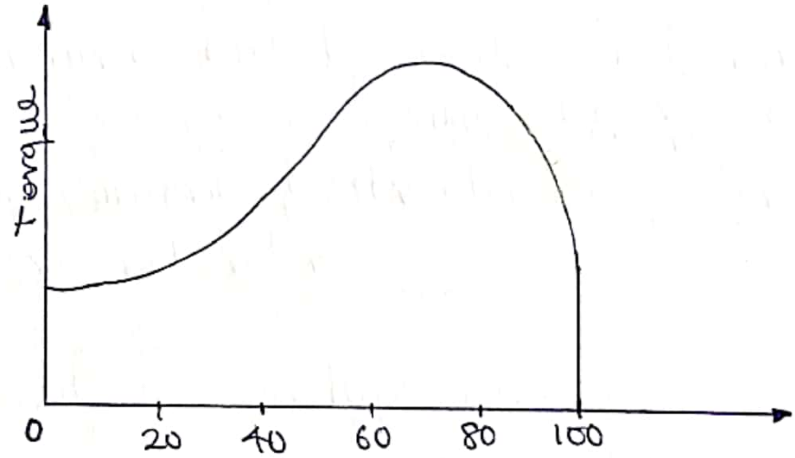



Figure 1.8. Typical induction motor speed-torque characteristics.