Induction Motors

- Most of the motors used in industry is 3-phase induction motors. These machines are robust, cheap and requires less maintenance. Their power range is between a few watts and 10000 HP. High power induction motors (>5 kW) are designed in 3-phase in order to load the network symmetrically. Low power induction motors are usually designed as single-phase.
- The speed of induction motors is almost constant. There is very small difference between the speeds at full load and no-load. However, they have some certain disadvantages as well:

1. Their speed cannot be controlled easily.
2. At small loads, they have small lagging power factor.
3. The starting current can be as big as 5-7 times of the nominal current.

- Although it is possible to use an induction machine as either a motor or a generator, it has many disadvantages as a generator and so it is only used as a generator in special applications. For this reason, induction machines are usually referred to as induction motors.
- There are two different types of induction motor rotors which can be placed inside the stator. One is called a *cage rotor, while the other is called a wound rotor.*
- Figure 1 shows rotors of the cage induction motor. Rotor of a cage induction motor consists of a series of conducting bars laid into slots carved in the face of the rotor and shorted at either end by large *shorting rings. This design is referred* to as a cage rotor.
- In this rotor structure there is no slip rings and carbon brushes. If it is carefully examined, the rotor bars are not parallel to the machine axis. This is because; more uniform torque is obtained and the noise is reduced during operation.

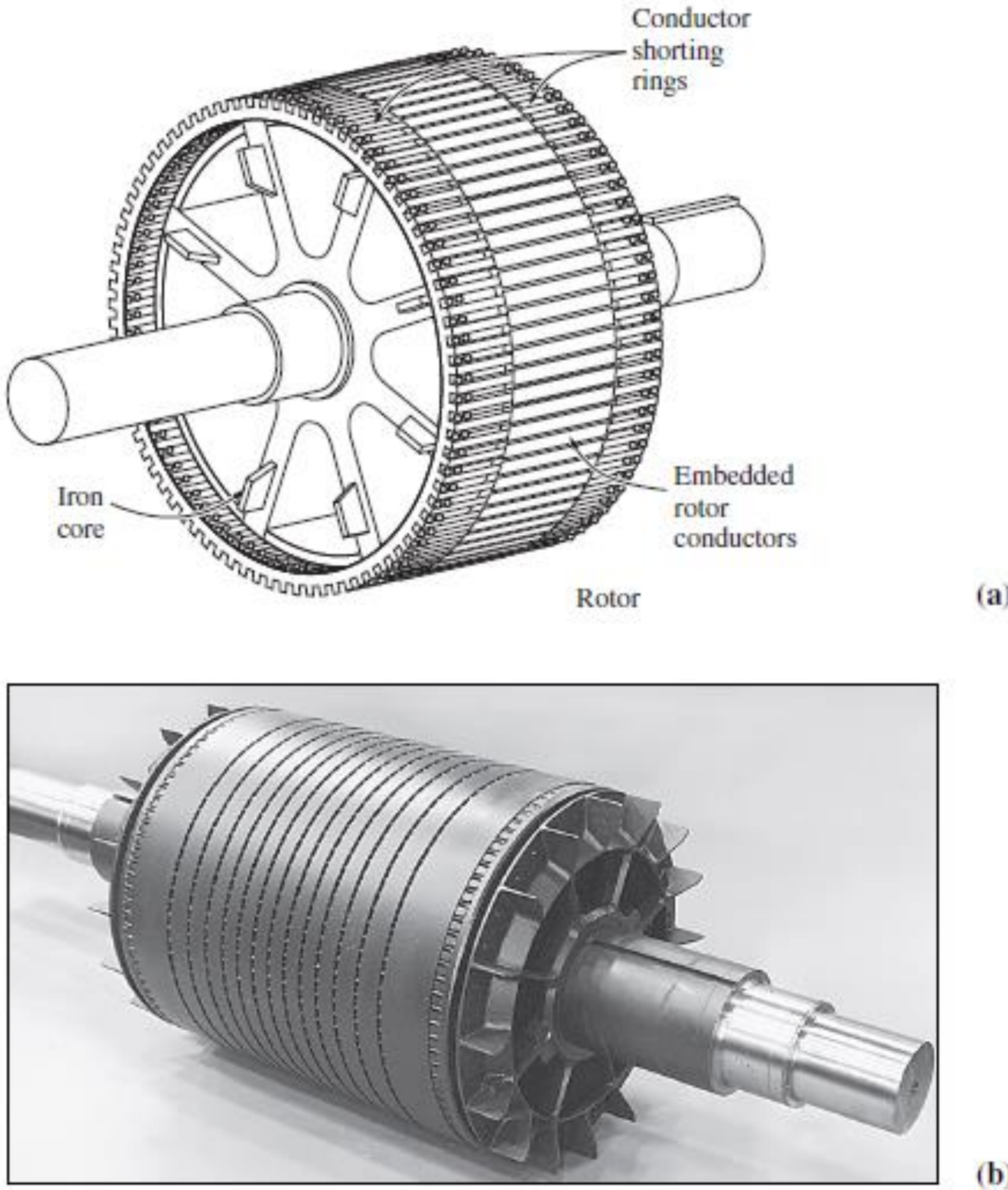
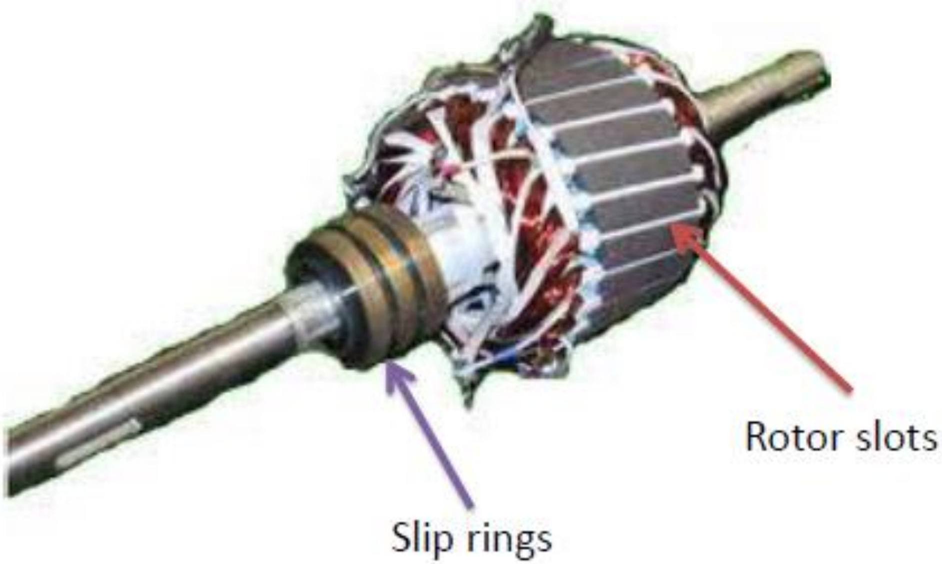
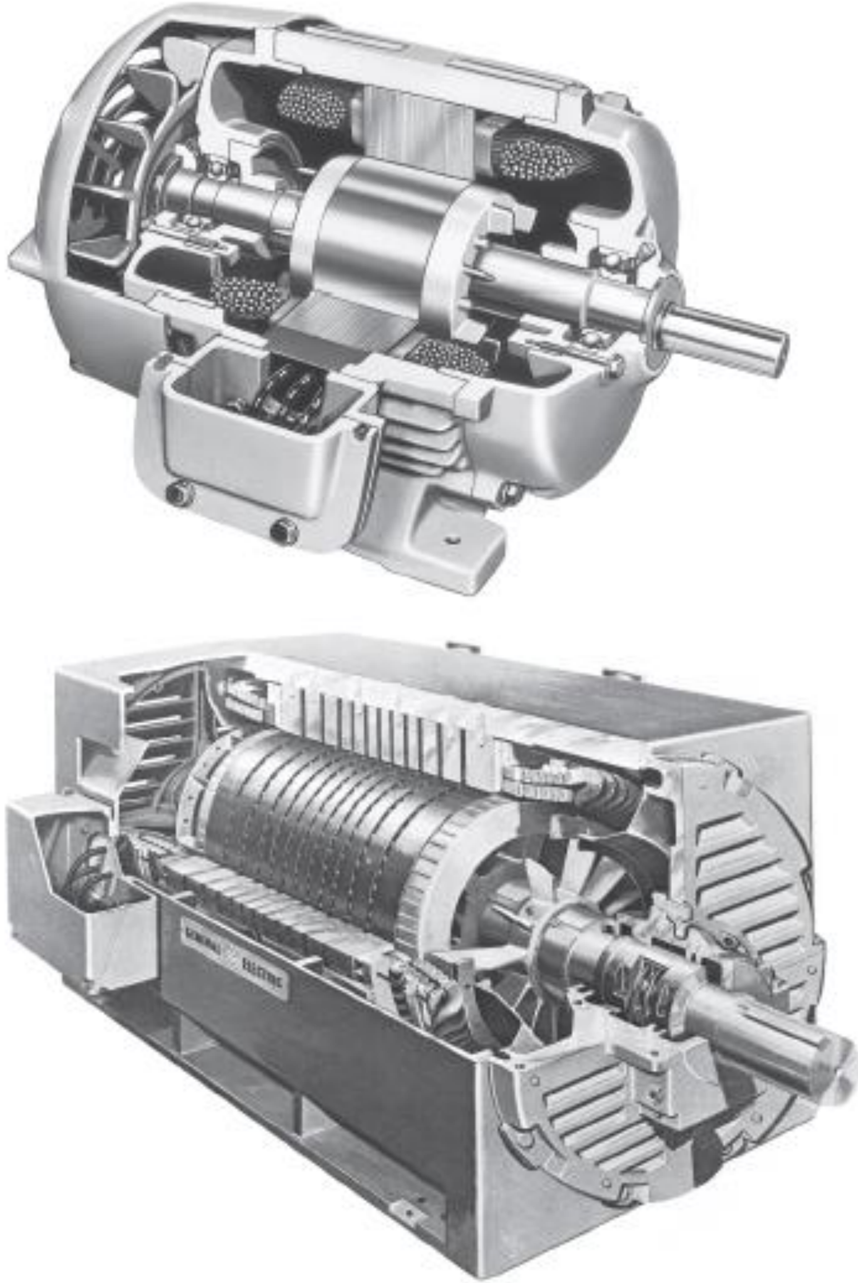


FIGURE 1
(a) Sketch of cage rotor. (b) A typical cage rotor.

Wound Rotor

- Aluminium or copper windings are located in rotor slots.
- There are three slip-rings and brushes used for energy transfer.





(a)

(b)

FIGURE 2
(a) Cutaway diagram of a typical small cage rotor induction motor.
(b) Cutaway diagram of a typical large cage rotor induction motor.

While the rotor bars are cut by the stator field, an emf is induced on the bars because of the transformer operation. A current will flow through the short-circuited rotor bars. Therefore, a torque will be developed because of these currents and the stator rotating field. Form and number of the rotor bars are determined according to the required motor characteristics. Air-gap of this kind of the motors is very small.

- The other type of rotor is a wound rotor. A *wound rotor has a complete set* of three-phase windings that are similar to the windings on the stator. The three phases of the rotor windings are usually Y-connected, and the ends of the three rotor wires are tied to slip rings on the rotor's shaft. The rotor windings are shorted through brushes riding on the slip rings. Wound-rotor induction motors therefore have their rotor currents accessible at the rotor brushes, where they can be examined and where extra resistance can be inserted into the rotor circuit. It is possible to take advantage of this feature to modify the torque–speed characteristic of the motor.

- Wound-rotor induction motors are more expensive than cage induction motors, and they require much more maintenance because of the wear associated with their brushes and slip rings. As a result, wound-rotor induction motors are rarely used. A complete wound-rotor induction motor is shown in Figure 3.

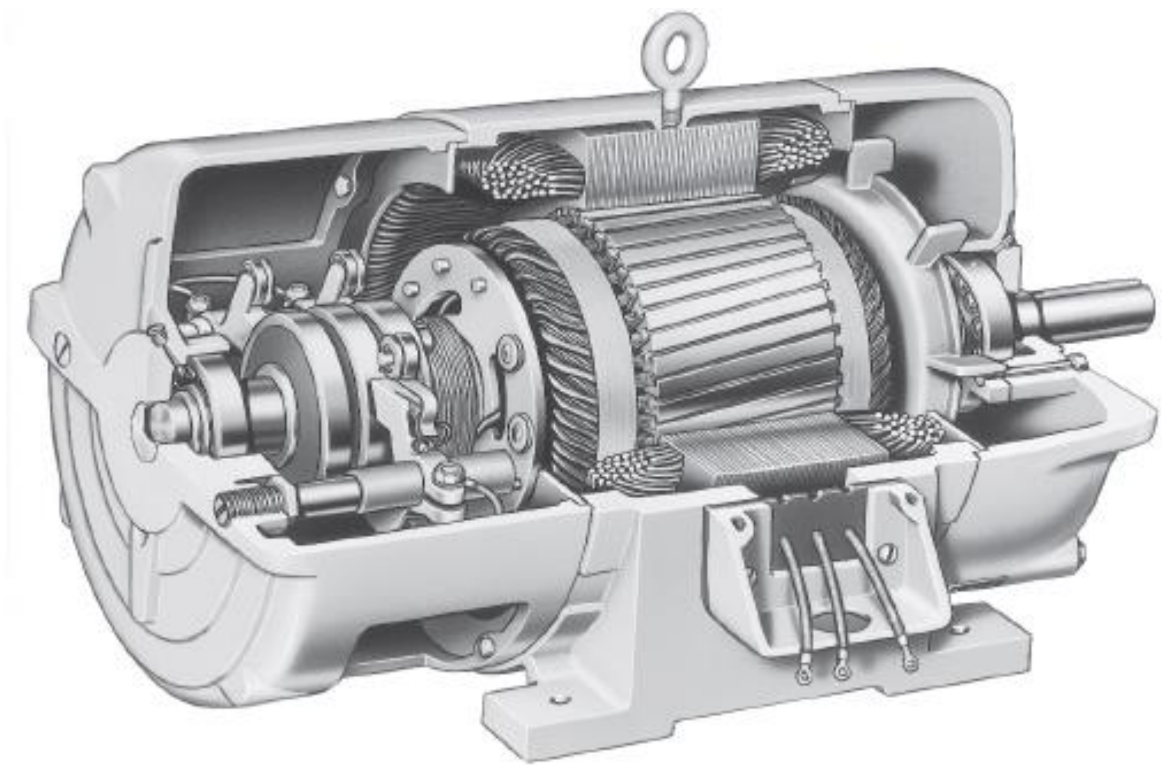
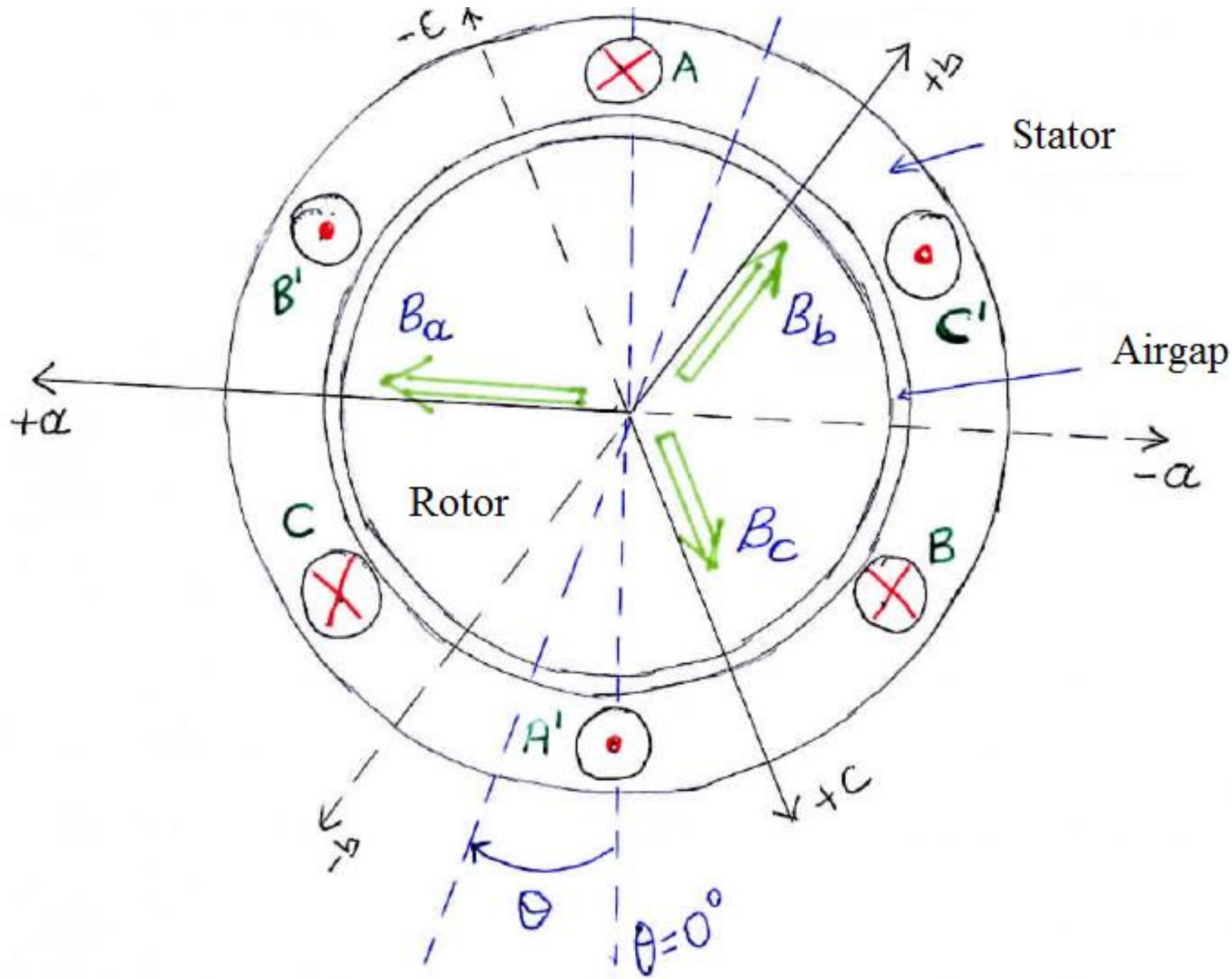


FIGURE 3
Cutaway diagram of a wound-rotor induction motor. Notice the brushes and slip rings. Also notice that the rotor windings are skewed to eliminate slot harmonics.

- Independently from the rotor structure, rotor currents are induced because of the rotating stator magnetic field. These induced currents constitute motor operating principle. For this reason, it is important to know how a rotating magnetic field is obtained from static 3-phase stator windings.

The Rotating Magnetic Field

- If one magnetic field is produced by the stator of an ac machine and the other one is produced by the rotor of the machine, then a torque will be induced in the rotor which will cause the rotor to turn and align itself with the stator magnetic field.
- If there were some way to make the stator magnetic field rotate, then the induced torque in the rotor would cause it to constantly "chase" the stator magnetic field around in a circle. This is the basic principle of all ac motor operation.
- The fundamental principle of ac machine operation is that *if a three-phase set of currents, each of equal magnitude and differing in phase by 120°, flows in a three-phase stator winding, then it will produce a rotating magnetic field of constant magnitude. The three-phase* winding consists of three separate windings spaced 120 electrical degrees apart around the surface of the machine.



- **Figure 4:** Schematic representation of the stator, rotor, phase winding and axis of the magnetic fields

- The rotating magnetic field concept is illustrated in the simplest case by an empty stator containing just three coils, each 120° apart (see above figure). Since such a winding produces only one north and one south magnetic pole, it is a two pole winding.
- To understand the concept of the rotating magnetic field, we will apply a set of currents to the stator and see what happens at specific instants of time. Assume that the currents in the three coils are given by the equations;

$$i_a(t) = I_m.\sin(\omega t) \rightarrow B_a(t) = B_m.\sin(\omega t)$$

$$i_b(t) = I_m.\sin(\omega t - 2\pi/3) \rightarrow B_b(t) = B_m.\sin(\omega t - 2\pi/3)$$

$$i_c(t) = I_m.\sin(\omega t - 4\pi/3) \rightarrow B_c(t) = B_m.\sin(\omega t - 4\pi/3)$$

- Each phase current will produce a magnetic field at its own direction.

- Sum of the magnetic fields occurred on the ±a, ±b and ±c field axis can be expressed as sum of the projection of the magnetic fields at any axis;

$$B_{a\theta}(t) = B_a(t).\sin(\theta) = B_m.\sin(\omega t).sin\theta$$

$$B_{b\theta}(t) = B_b(t).\sin(\theta - 2\pi/3) = B_m.\sin(\omega t - 2\pi/3).\sin(\theta - 2\pi/3)$$

$$B_{c\theta}(t) = B_c(t).\sin(\theta - 4\pi/3) = B_m.\sin(\omega t - 4\pi/3).\sin(\theta - 4\pi/3)$$

- Therefore, the total flux density is;

$$B(t,\theta) = B_{a\theta}(t) + B_{b\theta}(t) + B_{c\theta}(t)$$

$$B(t,\theta) = B_m.\sin(\omega t).sin\theta + B_m.\sin(\omega t - 2\pi/3).\sin(\theta - 2\pi/3) + B_m.\sin(\omega t - 4\pi/3).\sin(\theta - 4\pi/3)$$

If the last expression is rearranged;

$$B(t,\theta) = \frac{3}{2} B_m . \cos(\omega t - \theta)$$

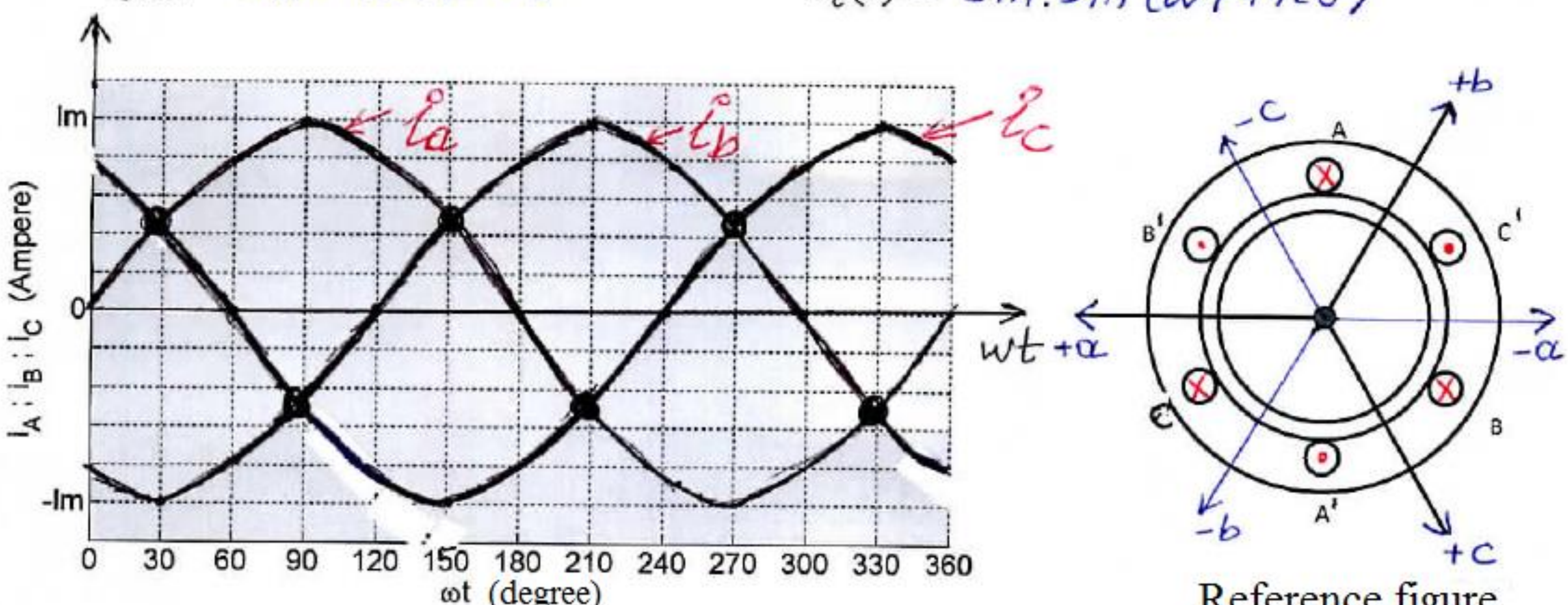
This result shows that the magnetic field in the airgap is a rotating magnetic field. As can be seen, the total magnetic field is 3/2 times of the maximum magnetic field created by one phase winding.

- It can be also shown graphically that the generated magnetic field is a rotating magnetic field.

$$i_A(t) = I_m \sin(\omega t) \Longrightarrow B_a(t) = B_m \cdot \sin(\omega t)$$

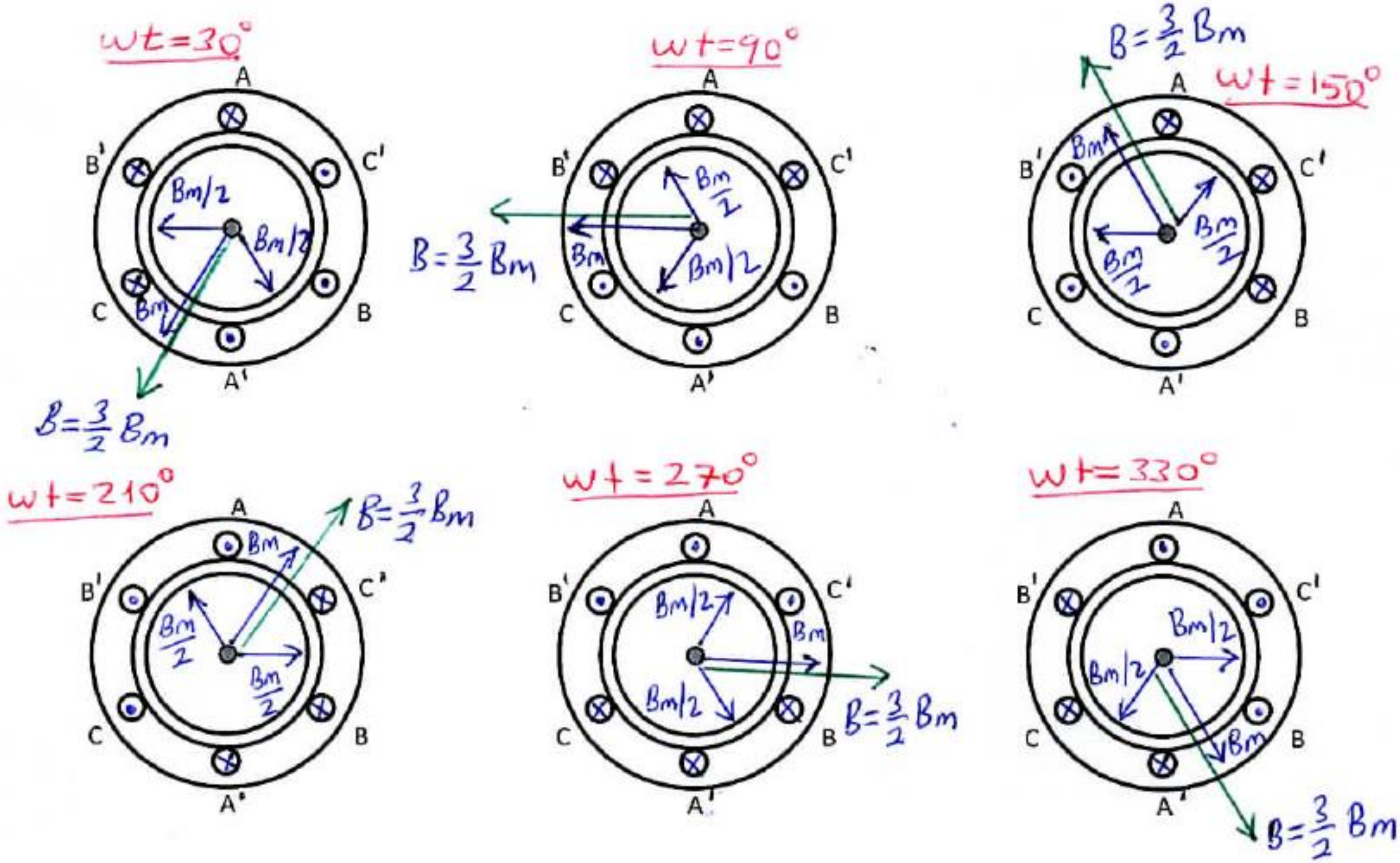
$$i_B(t) = I_m \sin(\omega t - 120^\circ) \Longrightarrow B_b(t) = B_m \sin(\omega t - 120^\circ)$$

$$i_C(t) = I_m \sin(\omega t + 120^\circ) \Longrightarrow B_c(t) = B_m \cdot \sin(\omega t + 120^\circ)$$



Reference figure

	i_A (A)	i_B(A)	i_C(A)	B_a(T)	B_b(T)	B_c(T)
30°	$I_m/2$	$-I_m$	$I_m/2$	$B_m/2$	$-B_m$	$B_m/2$
90°	I_m	$-I_m/2$	$-I_m/2$	B_m	$-B_m/2$	$-B_m/2$
150°	$I_m/2$	$I_m/2$	$-I_m$	$B_m/2$	$B_m/2$	$-B_m$
210°	$-I_m/2$	I_m	$-I_m/2$	$-B_m/2$	B_m	$-B_m/2$
270°	$-I_m$	$I_m/2$	$I_m/2$	$-B_m$	$B_m/2$	$B_m/2$
330°	$-I_m/2$	$-I_m/2$	I_m	$-B_m/2$	$-B_m/2$	B_m



- Here, pole number of the motor is taken as 2. Therefore, for one period change of the current ($2\pi/\omega$), the rotating field vector turns one revolution. If the motor had 4 poles then, the rotating field would move on half cycle for one period change of the current. For this reason, the rotating field speed is inversely proportional with number of pairs of the pole.
- In addition, as $\omega=2\pi f$, for 2 pole machine, if f=1 Hz, the magnetic field vector will rotate one revolution in 1 second ($T=2\pi/\omega = 2\pi/2\pi.f = 1$ second). If the frequency is increased to 50 Hz then, the magnetic field vector will rotate one revolution in 0,02 seconds (T=1/50). In other words, the magnetic field will turn 50 revolution per second or 3000 revolution per minute (rpm) (60*50=3000). That is; speed of the field vector will be 3000 rpm for 50 Hz. However, for 1 Hz it will be 1*60=60 rpm.

- Therefore, speed of the rotating field is proportional with the frequency. Hence, speed of the rotating field in rpm is;

$$n_s = \frac{f}{P/2}.60 \rightarrow n_s = \frac{120.f}{P} \ (rpm)$$

- Where; P is the pole number. Speed of the rotating field is also known as the synchronous speed.

Induced Voltage

Consider an AC machine. Ideally the flux density seen by coil *aa'* is expressed as

$$B_a(t,\theta) = B_m \cos\theta \cos\omega t$$

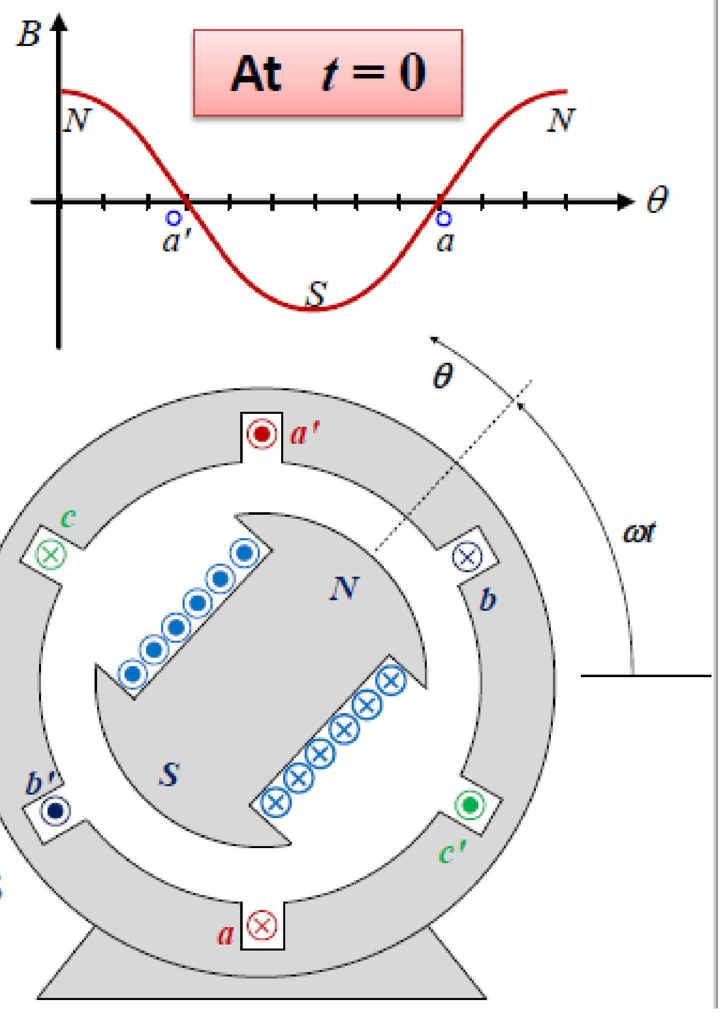
The corresponding air-gap flux is

$$\phi(t) = \int_A B \cdot dA \Rightarrow \phi_a(t) = \int_0^L \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} B_a \cdot r dl d\theta$$

$$\boxed{\phi_a(t) = 2LrB_m \cos\omega t}$$

$$\phi_a(t) = \phi_m \cos\omega t \qquad \phi_m = 2LrB_m$$

where L is the stator axial length and r is the stator inner radius



$$\boxed{\phi_a(t) = \phi_m \cos \omega t} \qquad \phi_m = 2LrB_m$$

The induced voltage in coil *aa'* with N turns is

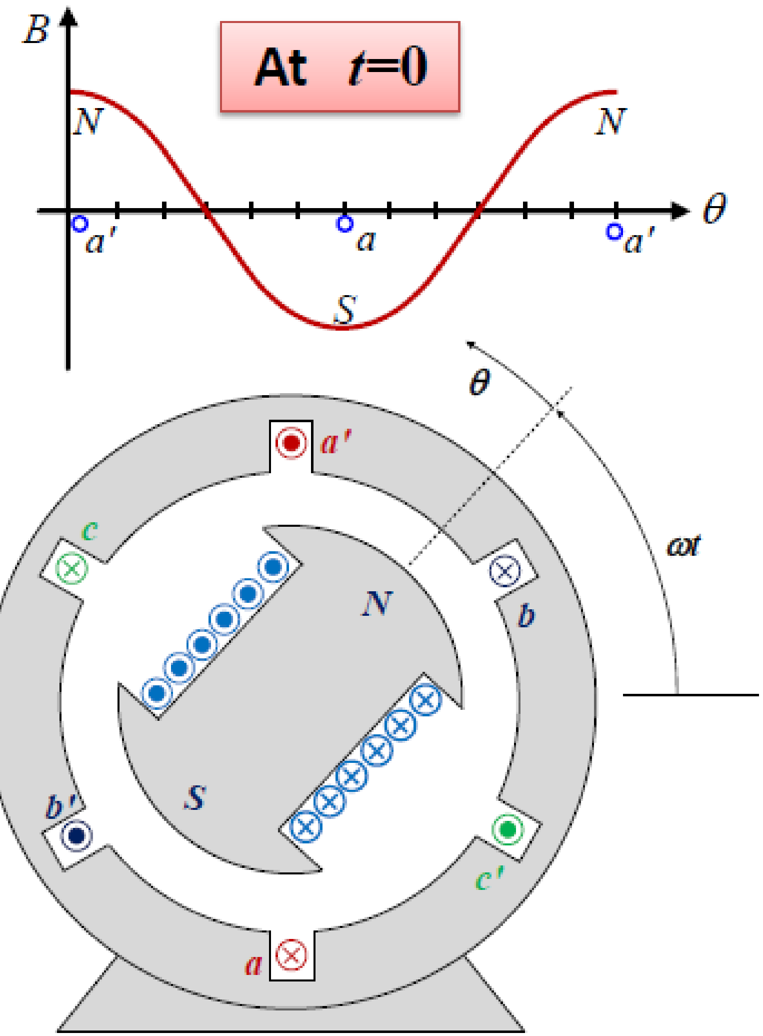
$$e_a(t) = -N\frac{d\phi_a}{dt}$$

$$\Rightarrow \quad e_a(t) = N\phi_m \omega \sin \omega t$$

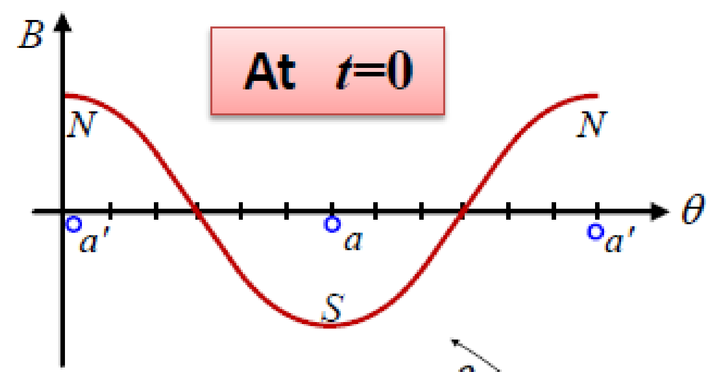
$$e_b(t) = N\phi_m \omega \sin(\omega t - 120^\circ)$$

$$e_c(t) = N\phi_m \omega \sin(\omega t + 120^\circ)$$

$$\boxed{E_{rms} = \frac{N\phi_m \omega}{\sqrt{2}}}$$



$$E_{rms} = \frac{N\phi_m \omega}{\sqrt{2}} \Rightarrow E_{rms} = \frac{N\phi_m 2\pi f}{\sqrt{2}}$$

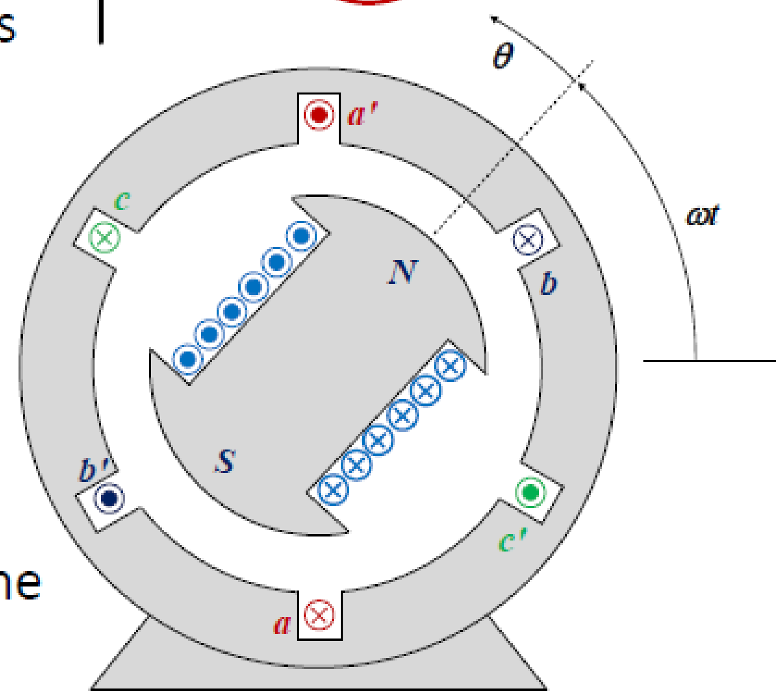


The RMS induced voltage in each phase having N turns in series with **concentrated** and **full pitch** windings is

$$E_{rms} = 4.44 N\phi_m f$$

For machines with **distributed** and/or **short pitch** windings the RMS induced voltage is

$$E_{rms} = 4.44 N\phi_m f\, k_p k_d$$



Where k_p is the pitch factor and k_d is the distribution factor.