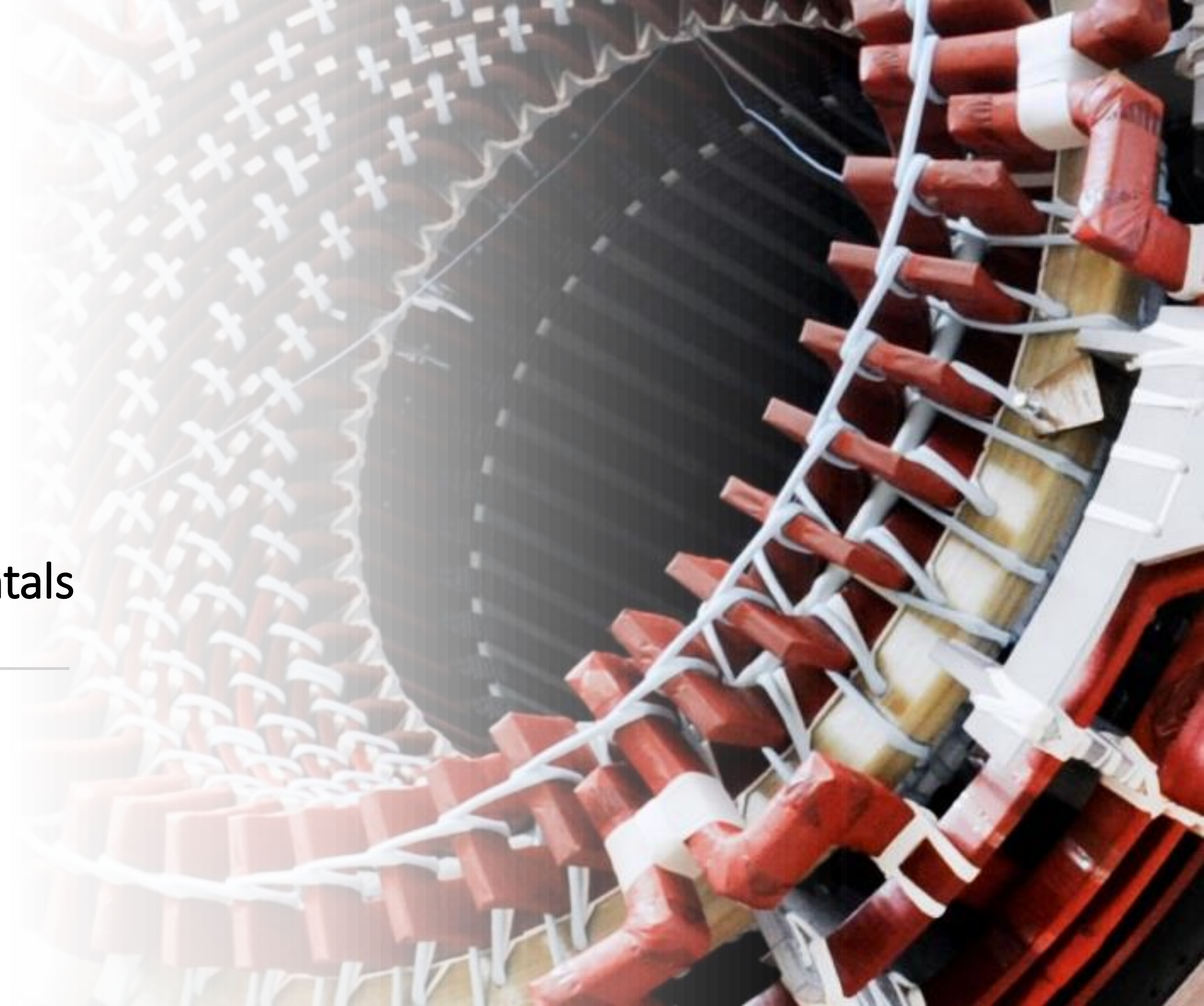
EE3124 Introduction to Electric Machines and Drives



4-AC Machine Fundamentals

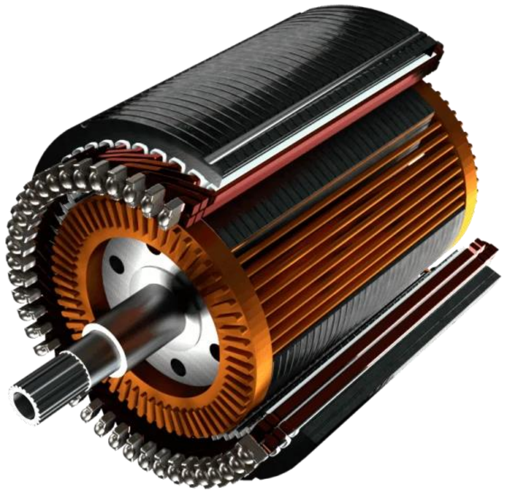
Prof. CQ Jiang

Outline

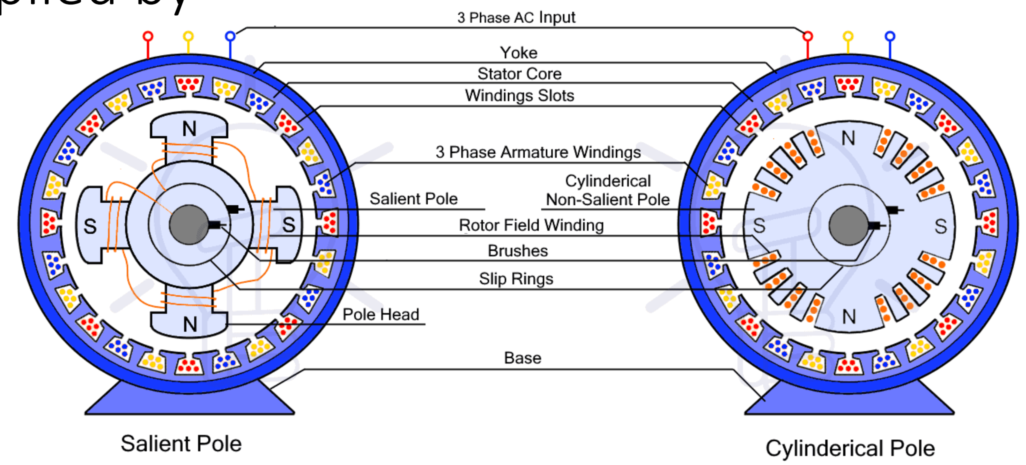
- Two major classes of AC machines
- Rotating Magnetic Field
- Speed of Magnetic Field Rotation
- Poles and Pole-Pair
- Induced Voltage in a Three-phase Set of Coils
- Harmonic Problem

AC Machine Fundamentals

- AC generators convert mechanical energy to AC electrical energy
- AC motor convert AC electric energy to mechanical energy
- Two major classes of AC machines
  - Induction machines
  - Synchronous machines
- Induction machines: magnetic field current is supplied by magnetic induction into their field windings
- Synchronous machines: magnetic field current is supplied by a separate DC power source



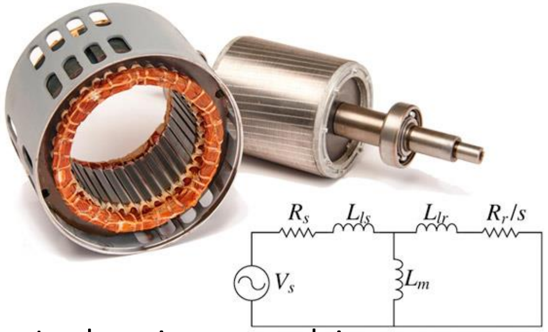
- Induction machines



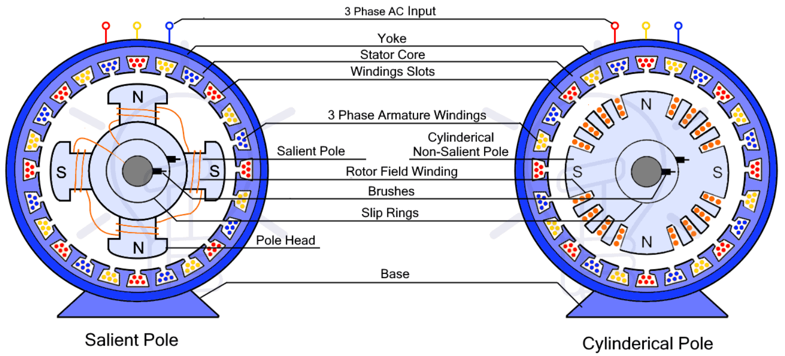
Construction of Synchronous Motor

AC Machine Fundamentals

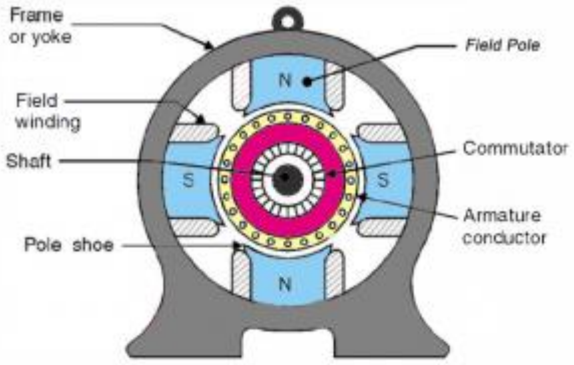
- AC machine differ from DC machines in that their armature windings are almost always located on the stator, while their field windings are located on the rotor.
- Generator: the rotating magnetic field from the rotor field windings of an AC machine induces a three-phase set of ac voltage into its stator armature windings.
- Motor: three-phase set of currents in the stator armature winding produces a rotation magnetic field with interacts with the rotor magnetic field. Producing a torque in the machine



Induction machines



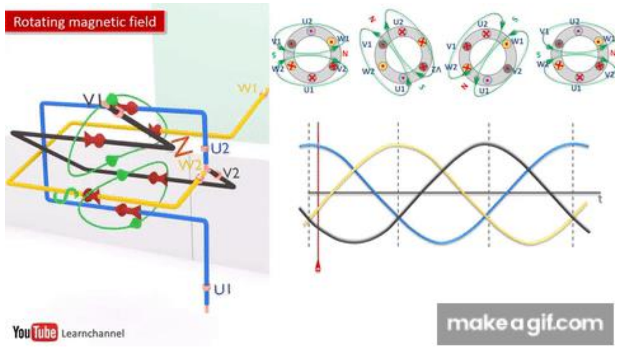
Construction of Synchronous Motor

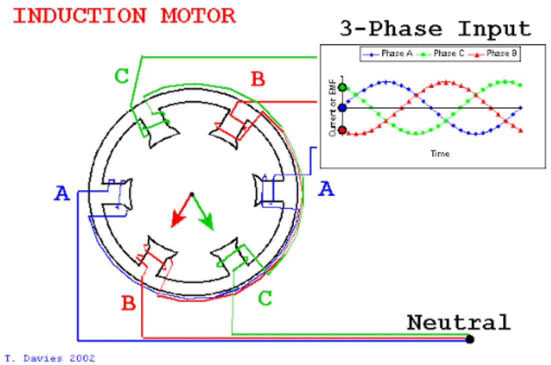


DC machines

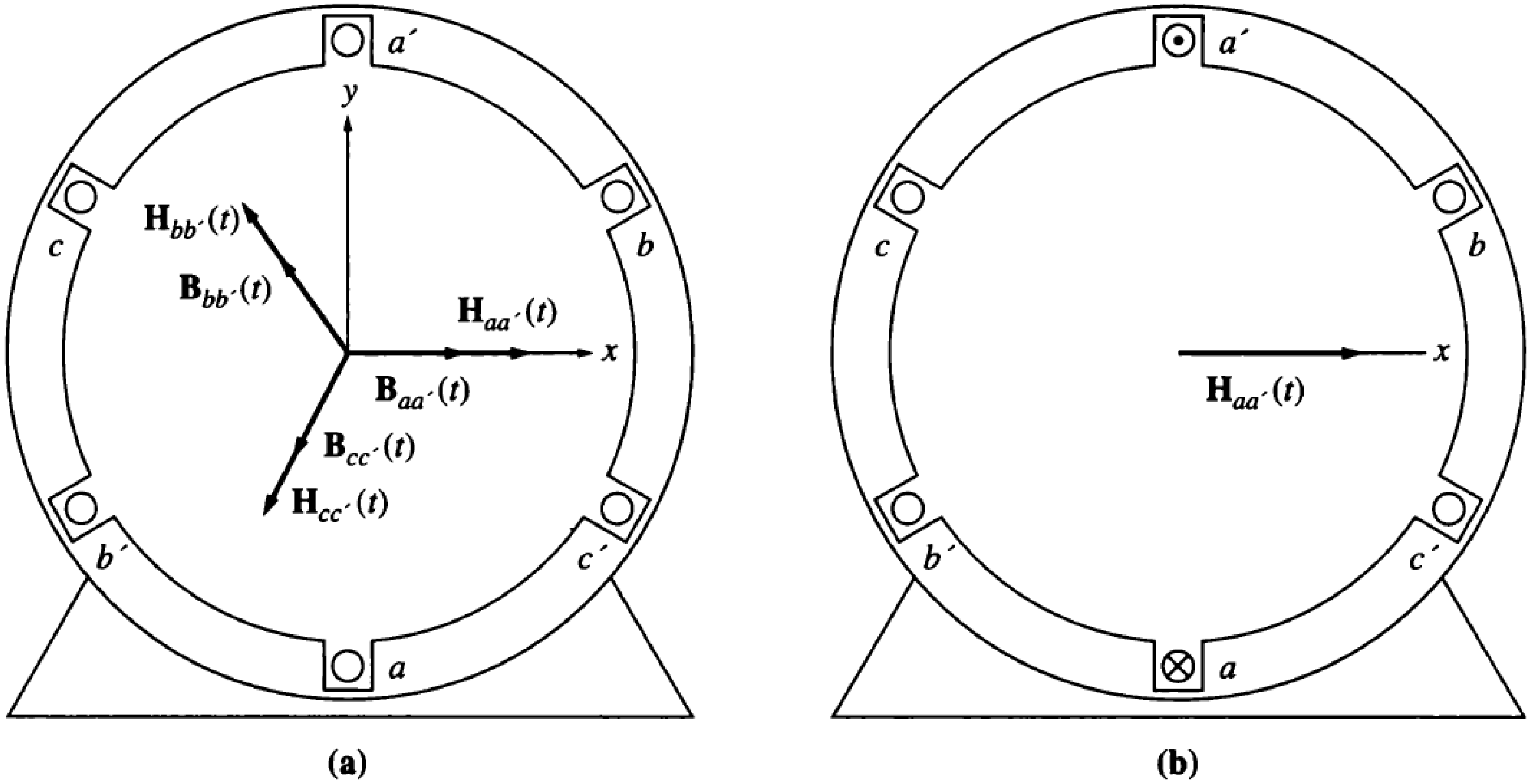
Rotating Magnetic Field

- Principle of AC machine
- 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.
- A three-phase set of currents, each of equal magnitude and differing in phase by 120^{o}, flows in a three-phase winding, then it will produce a rotating magnetic field of constant magnitude.
- The three-phase winding consists of three separate windings spaced 120 degrees apart.





Rotating Magnetic Field



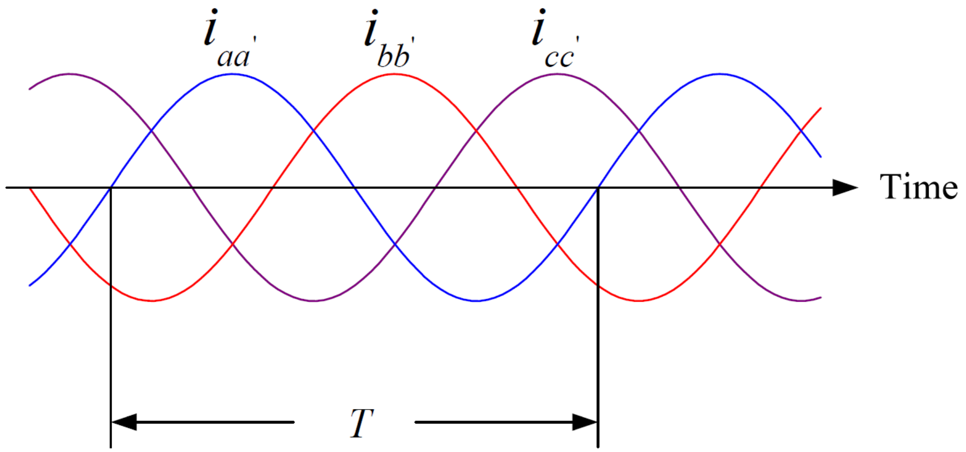
(a) A simple three-phase stator. Currents in this stator are assumed positive if they flow into the unprimed end and out the primed end of the coils. The magnetizing intensities produced by each coil are also shown.

(b) The magnetizing intensity vector $H_{aa'}(t)$ produced by a current flowing in coil aa'

Rotating Magnetic Field

- Assume that the currents in the three coils are given by the equations:

$$i_{aa'}(t) = I_M \sin \omega t \qquad \text{A}$$
$$i_{bb'}(t) = I_M \sin(\omega t - 120^\circ) \qquad \text{A}$$
$$i_{cc'}(t) = I_M \sin(\omega t - 240^\circ) \qquad \text{A}$$

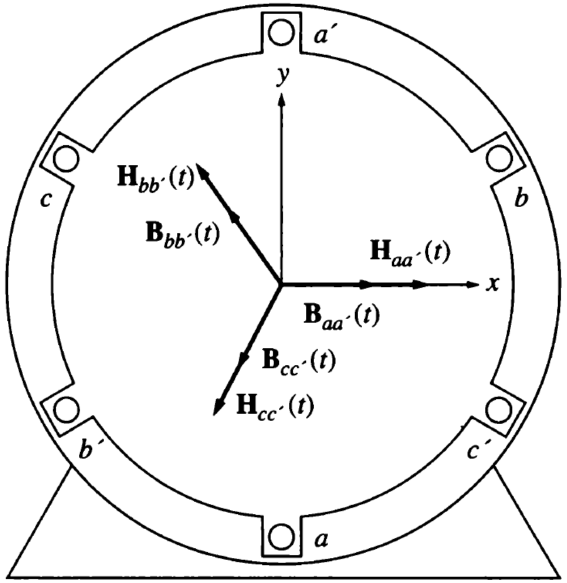


Rotating Magnetic Field

- They produces the magnetic field intensity

$$H_{aa'}(t) = H_M \sin \omega t \ \angle 0^\circ \quad \mathrm{A \cdot turns/m}$$
$$H_{bb'}(t) = H_M \sin(\omega t - 120^\circ) \ \angle 120^\circ \quad \mathrm{A \cdot turns/m}$$
$$H_{cc'}(t) = H_M \sin(\omega t - 240^\circ) \ \angle 240^\circ \quad \mathrm{A \cdot turns/m}$$

- ∠0°, ∠120°,∠240° are the spatial angle of the magnetic field.



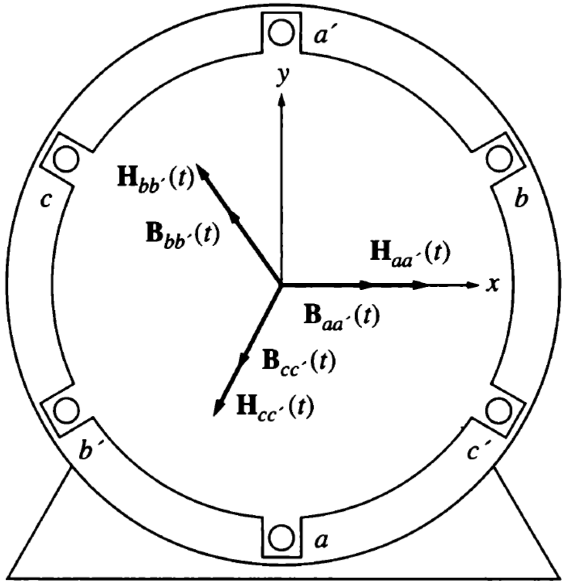
Rotating Magnetic Field

- The flux densities resulting from these magnetic field intensities are given by

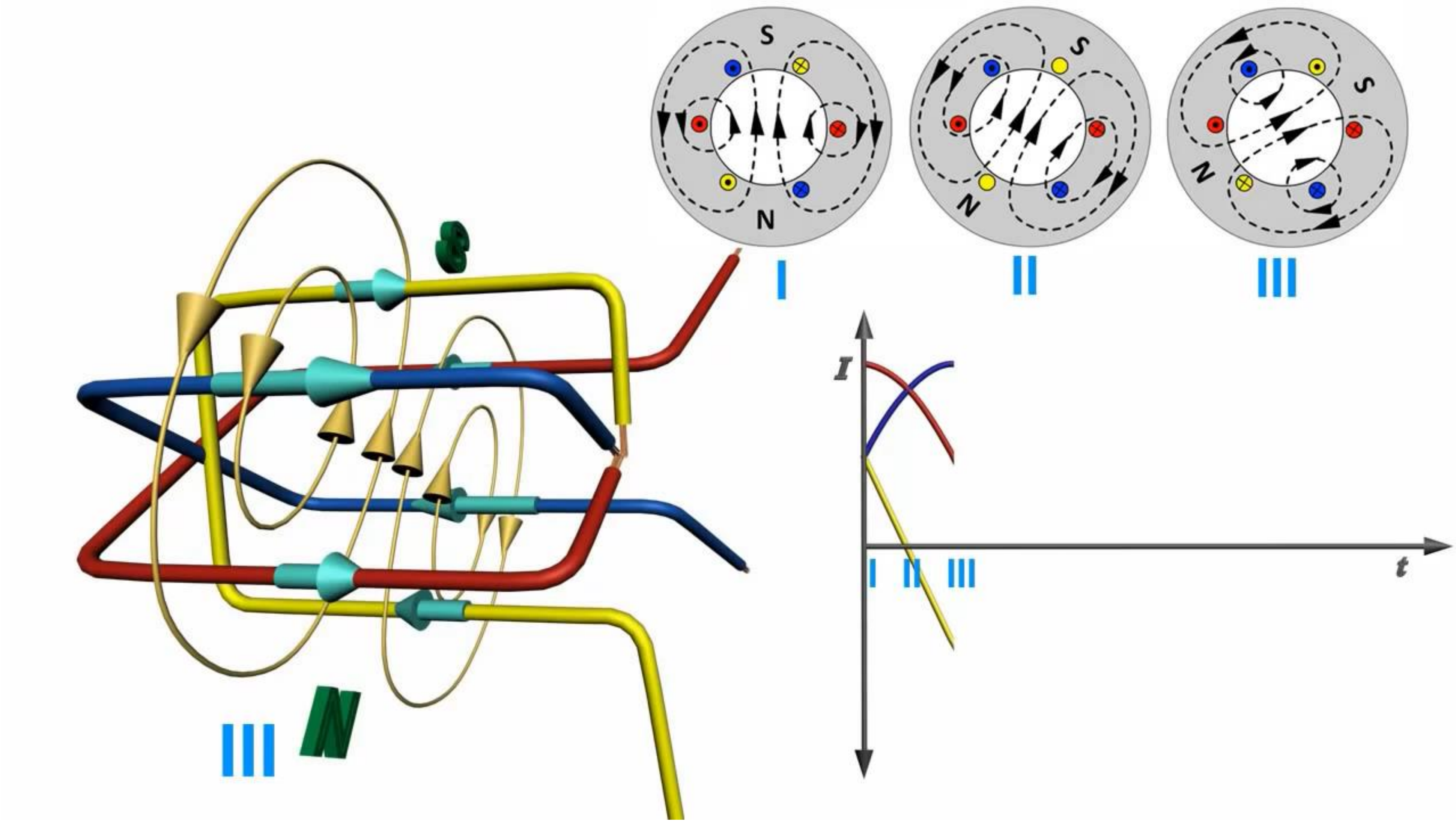
$$B_{aa'}(t) = B_M \sin \omega t \ \angle 0^\circ \qquad \text{T}$$
$$B_{bb'}(t) = B_M \sin(\omega t - 120^\circ) \ \angle 120^\circ \qquad \text{T}$$
$$B_{cc'}(t) = B_M \sin(\omega t - 240^\circ) \ \angle 240^\circ \qquad \text{T}$$

Where $B_M = \mu H_M$

- Now we can examine the flux densities at specific times to determine the resulting net magnetic field in the stator.



Rotating Magnetic Field

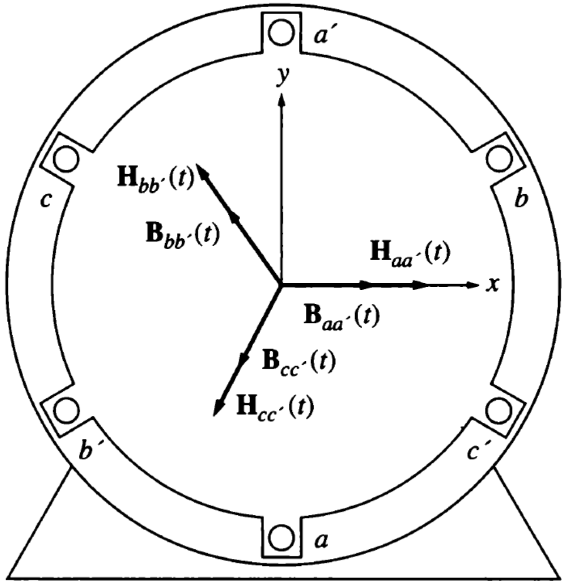


Source: https://www.youtube.com/watch?v=8XF-11MQGQ0

Rotating Magnetic Field

- At time = 0
- The total magnetic field from all three coils added together will be

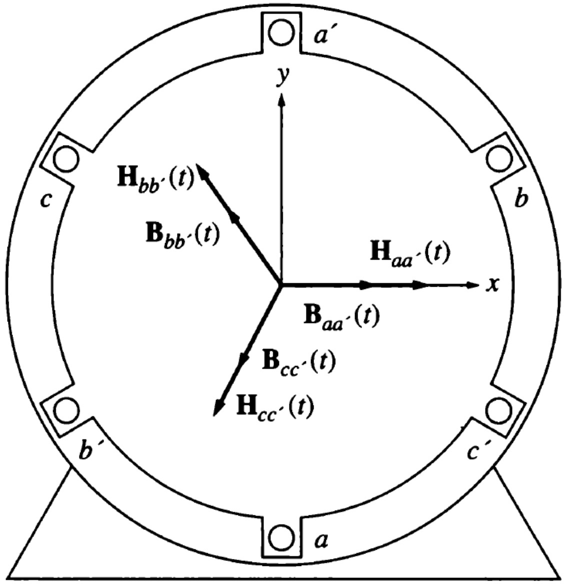
$$
\begin{aligned}
B_{net} &= B_{aa'} + B_{bb'} + B_{cc'} \\
&= 0 + \left(-\frac{\sqrt{3}}{2}B_M\right)\angle 120^\circ + \left(\frac{\sqrt{3}}{2}B_M\right)\angle 240^\circ \\
&= 0 + -\frac{\sqrt{3}}{2}B_M\left[\cos(120)\hat{x} + \sin(120)\hat{y}\right] + \frac{\sqrt{3}}{2}B_M\left[\cos(240)\hat{x} + \sin(240)\hat{y}\right] \\
&= (0 + 0.433\hat{x} - 0.75\hat{y} - 0.433\hat{x} - 7.5\hat{y})B_M \\
&= -1.5B_M\hat{y} \\
&= 1.5B_M\angle -90^\circ
\end{aligned}
$$



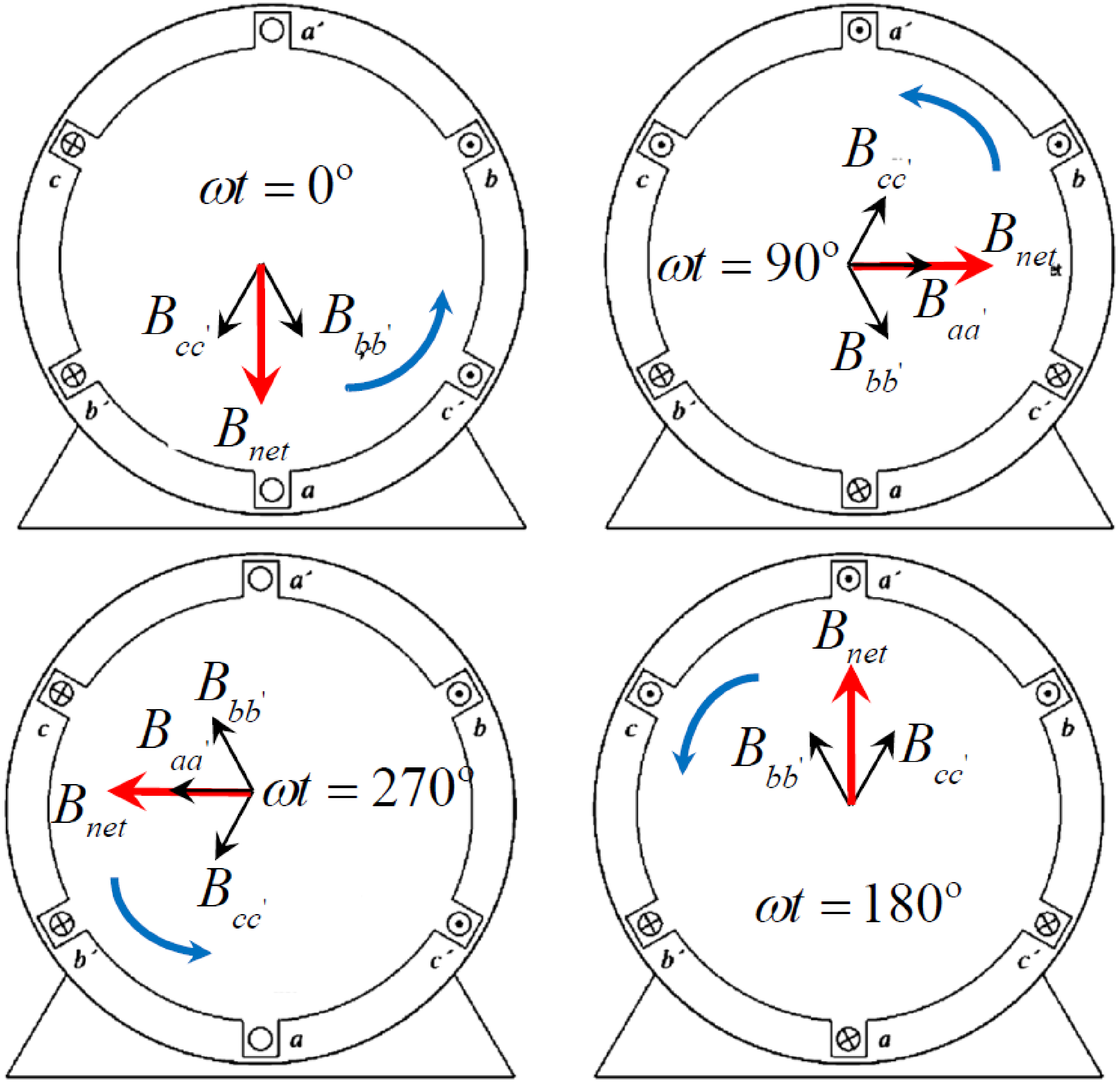
Rotating Magnetic Field

- At time = 90°
- The total magnetic field from all three coils added together will be

$$
\begin{aligned}
B_{net} &= B_{aa'} + B_{bb'} + B_{cc'} \\
&= B_M + (-0.5B_M)\angle 120^\circ + (-0.5B_M)\angle 240^\circ \\
&= B_M - 0.5B_M[\cos(120)\hat{x} + \sin(120)\hat{y}] - 0.5B_M[\cos(240)\hat{x} + \sin(240)\hat{y}] \\
&= (1 + 0.25\hat{x} - 0.433\hat{y} + 0.25\hat{x} + 0.433\hat{y})B_M \\
&= 1.5B_M\hat{x} \\
&= 1.5B_M\angle 0^\circ
\end{aligned}
$$



Rotating Magnetic Field



Rotating Magnetic Field

- If the current in any two of the three coils is swapped, the direction of the magnetic field's rotation will be reversed.
- For instance, phases b and c are swapped.

$$B_{aa'}(t) = B_M \sin \omega t \ \angle 0^\circ \qquad \text{T}$$

$$B_{bb'}(t) = B_M \sin(\omega t - 240^\circ) \ \angle 120^\circ \qquad \text{T}$$

$$B_{cc'}(t) = B_M \sin(\omega t - 120^\circ) \ \angle 240^\circ \qquad \text{T}$$

Rotating Magnetic Field

- At time = 0
- Phase b and c swapped, the total magnetic field from all three coils added together will be

$$
\begin{aligned}
B_{net} &= B_{aa'} + B_{bb'} + B_{cc'} \\
&= 0 + \left(\frac{\sqrt{3}}{2}B_M\right)\angle 120^\circ + \left(-\frac{\sqrt{3}}{2}B_M\right)\angle 240^\circ \\
&= 0 + \frac{\sqrt{3}}{2}B_M\left[\cos(120)\hat{x} + \sin(120)\hat{y}\right] - \frac{\sqrt{3}}{2}B_M\left[\cos(240)\hat{x} + \sin(240)\hat{y}\right] \\
&= (0 - 0.433\hat{x} + 0.75\hat{y} + 0.433\hat{x} + 7.5\hat{y})B_M \\
&= 1.5B_M\hat{y} \\
&= 1.5B_M\angle 90^\circ
\end{aligned}
$$

Rotating Magnetic Field

- At time = 90°
- Phase b and c swapped, the total magnetic field from all three coils added together will be

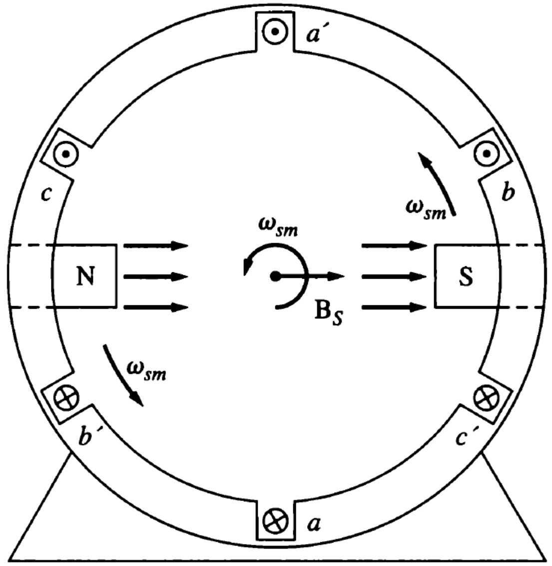
$$
\begin{aligned}
B_{net} &= B_{aa'} + B_{bb'} + B_{cc'} \\
&= B_M + (-0.5B_M)\angle 120^\circ + (-0.5B_M)\angle 240^\circ \\
&= B_M - 0.5B_M[\cos(120)\hat{x} + \sin(120)\hat{y}] - 0.5B_M[\cos(240)\hat{x} + \sin(240)\hat{y}] \\
&= (1 + 0.25\hat{x} - 0.433\hat{y} + 0.25\hat{x} + 0.433\hat{y})B_M \\
&= 1.5B_M\hat{x} \\
&= 1.5B_M\angle 0^\circ
\end{aligned}
$$

Speed of Magnetic Field Rotation

- In this two poles stator, the magnetic poles complete one mechanical rotation around the stator surface for each electrical cycle of the applied current.
- Therefore, the mechanical speed of rotation of the magnetic field in revolutions per second is equal to the electric frequency in hertz.

$$f_e = f_m$$ Two poles (1 pole-pair)

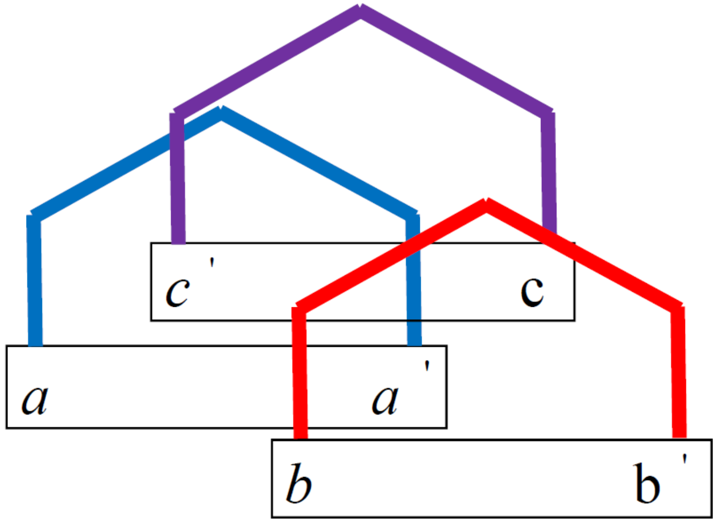
$$\omega_e = \omega_m$$ Two poles (1 pole-pair)

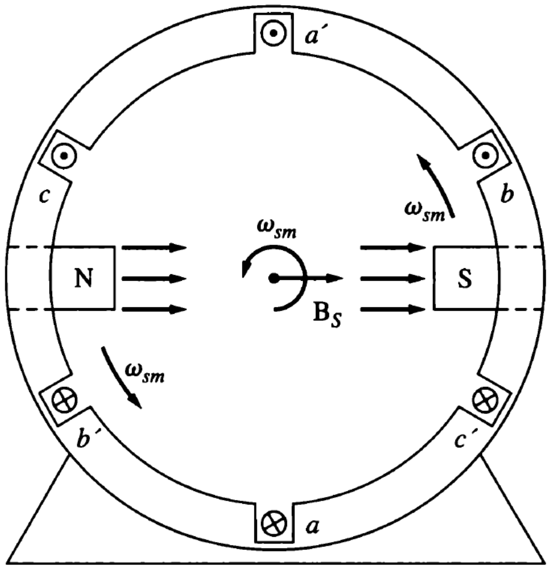


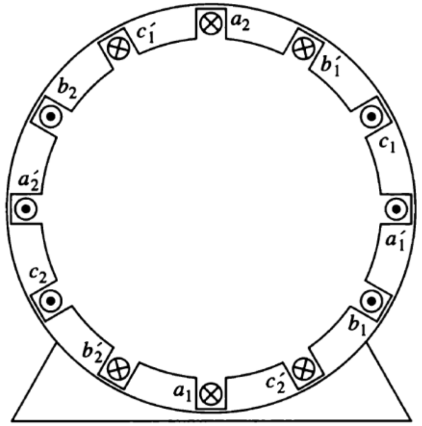
The rotating magnetic field in a stator represented as moving north and south stator poles.

Speed of Magnetic Field Rotation

- The windings on a two-pole stator occur in this order: $a - c' - b - a' - c - b'$





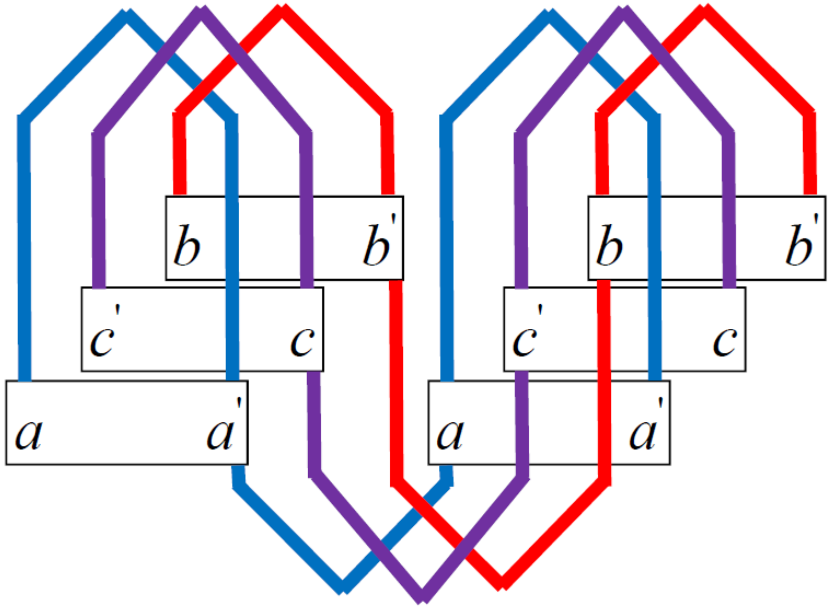


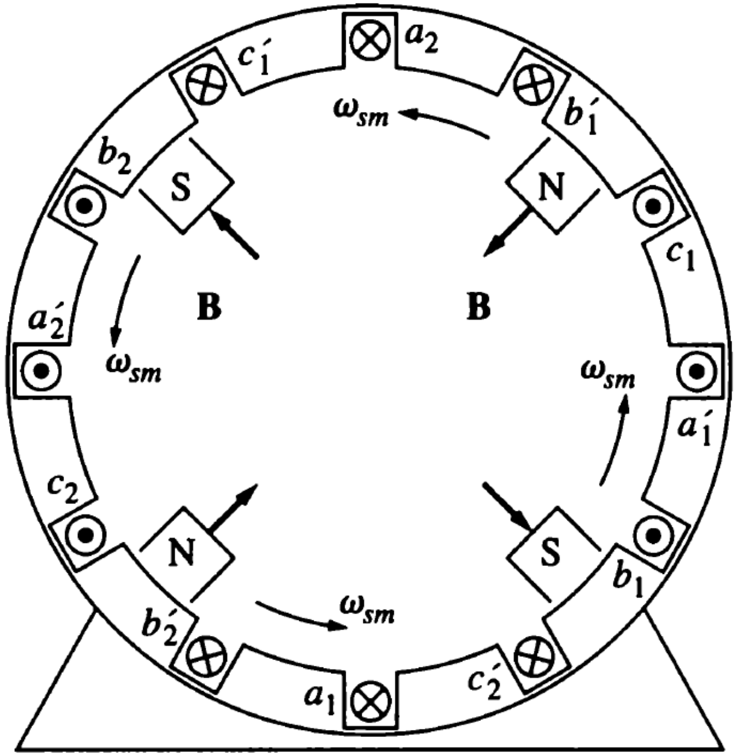
- What would happen in a stator if this pattern were repeated twice within it? i.e.

$$a - c' - b - a' - c - b' - a - c' - b - a' - c - b'$$

Speed of Magnetic Field Rotation

- When a three-phase set of currents is applied to this stator, two north poles and two south poles are produced in the stator winding.
- A pole moves only halfway around the stator surface in one electrical cycle.





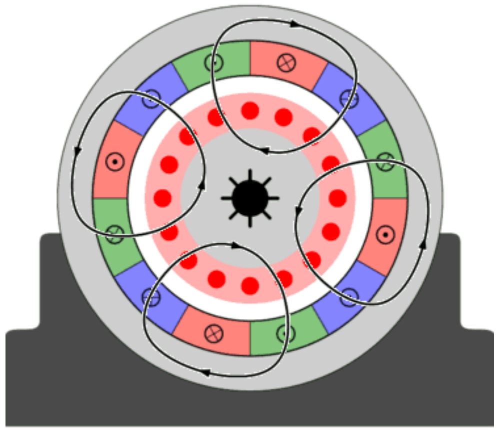
Speed of Magnetic Field Rotation

- Now, the electrical cycle is 360 electrical degrees, and the mechanical motion is 180 mechanical degrees.
- The relationship between the electrical angle and the mechanical angle in this four poles stator is

$$\theta_e = 2\theta_m$$

- If the number of magnetic poles on an AC machine is ***P***, the electrical frequency of the current and the mechanical frequency of rotation is

$$f_e = 2 f_m$$
$$= \frac{P}{2} f_m$$



Speed of Magnetic Field Rotation

- It is possible to relate the electrical frequency in hertz to the resulting mechanical speed (n_m) of the magnetic fields in revolutions per minute (rpm). This relationship is

$$f_e = \frac{P}{2} f_m$$

$$n_m(rpm) = \frac{2 \times f_e}{P} \times 60$$

- What is the mechanical speed of a three-pole pairs machine?

Induced Voltage in a Coil

- Segment ab

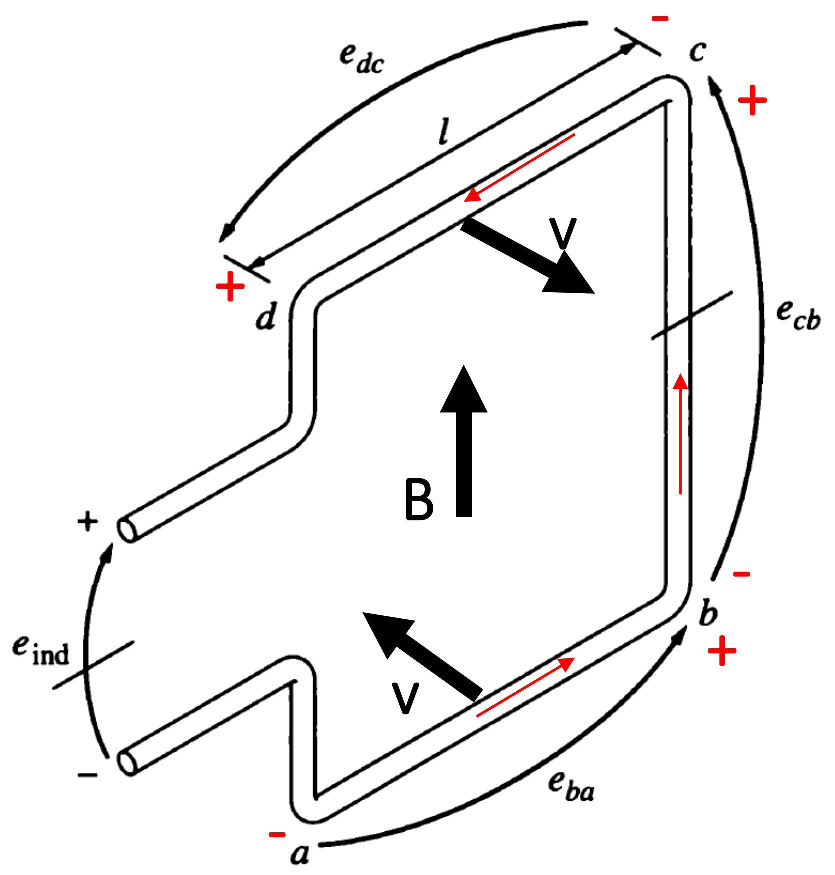
$$e_{ba} = (\mathbf{v} \times \mathbf{B}) \bullet \mathbf{l}$$
$$= vBl \qquad \text{directed out of the page}$$
$$= -v[B_M \cos(\omega_m t - 180°)]l$$
$$= -vB_M l \cos(\omega_m t - 180°)$$

- Segment cb and ad $e_{cb} = (\mathbf{v} \times \mathbf{B}) \bullet \mathbf{l} = 0$

v×B is perpendicular to l

- Segment cd

$$e_{dc} = (\mathbf{v} \times \mathbf{B}) \bullet \mathbf{l}$$
$$= vBl \qquad \text{directed out of the page}$$
$$= v(B_M \cos \omega_m t)l$$
$$= vB_M l \cos \omega_m t$$



Induced Voltage in a Coil

- The total voltage induced in the coil will be the su voltage induced in each of its four segments

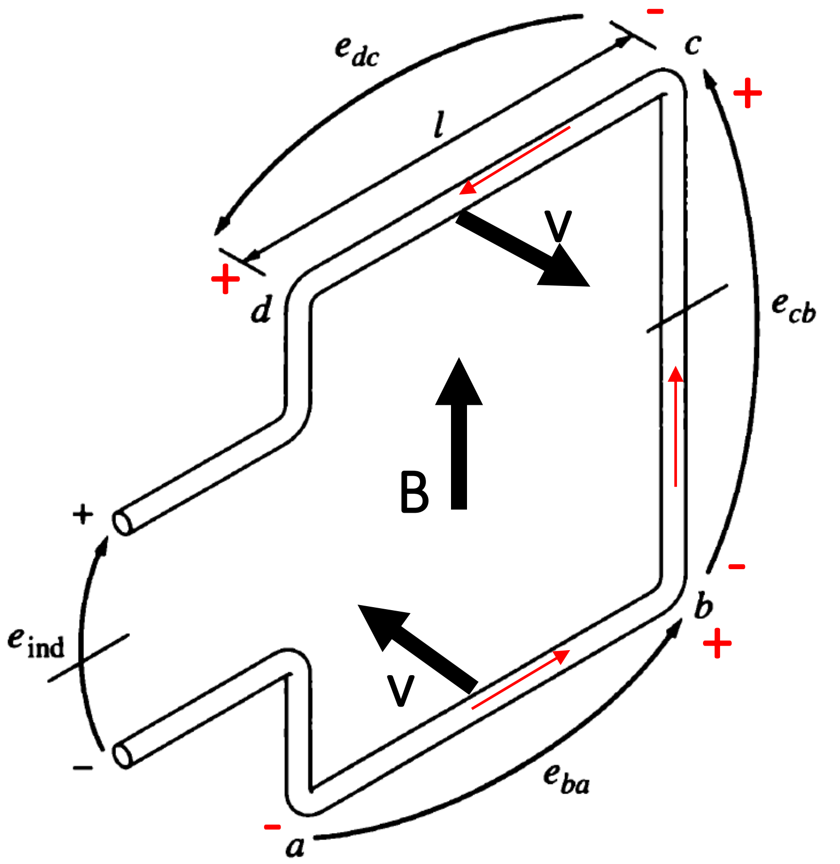
$$e_{ind} = vB_M l \cos \omega_m t + vB_M l \cos \omega_m t$$
$$= 2vB_M l \cos \omega_m t$$

- Since the velocity of the end conductors is given by $v = r\omega_m$, then

$$e_{ind} = 2(r\omega_m)B_M l \cos \omega_m t$$
$$= 2rlB_M\omega_m \cos \omega_m t$$

- Finally, the flux passing through the coil can be expressed as $\phi = 2rlB_m$

$$\boxed{e_{ind} = \phi\omega \cos \omega t}$$



- If the coil in the stator has N_C turns

$$\boxed{e_{ind} = N_C\phi\omega \cos \omega t}$$

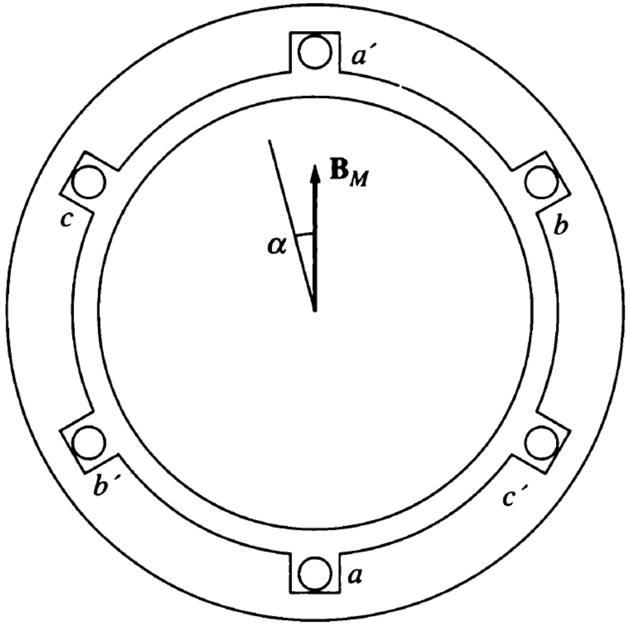
Induced Voltage in a Three-phase Set of Coils

- Voltage induced in each coils is expressed as

$$e_{aa'} = N_c \phi \omega_M \cos(\omega_M t)$$

$$e_{bb'} = N_c \phi \omega_M \cos(\omega_M t - 120^\circ)$$

$$e_{cc'} = N_c \phi \omega_M \cos(\omega_M t - 240^\circ)$$



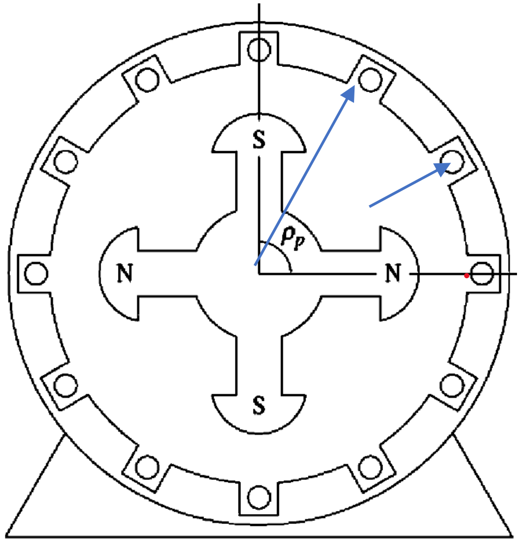
- Summary:

A three-phase set of currents generates a uniform rotating magnetic field in a machine stator, and a uniform rotating magnetic field generates a three-phase set of voltages in the stator.

Pitch of a Coil

- ❑ Pole pitch is the angular distance between two adjacent poles on a machine.

$$\rho_p = \frac{360^\circ}{P}$$



- ❑ A four-pole machine, ρ_p=90
- ❑ If the stator coil stretches across an angle smaller than a pole pitch, it is called a fractional-pitch coil.

Harmonic Problem

- Voltage induced in each coils is expressed as

$$e_{aa'} = N_c \phi \omega_M \cos(\omega_M t)$$

$$e_{bb'} = N_c \phi \omega_M \cos(\omega_M t - 120^\circ)$$

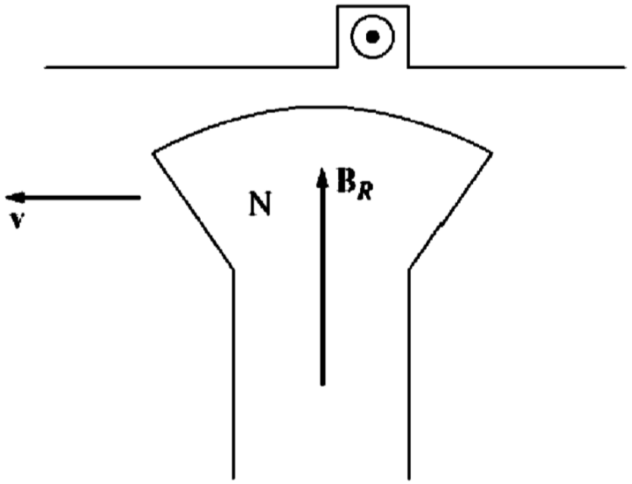
$$e_{cc'} = N_c \phi \omega_M \cos(\omega_M t - 240^\circ)$$

- Summary:

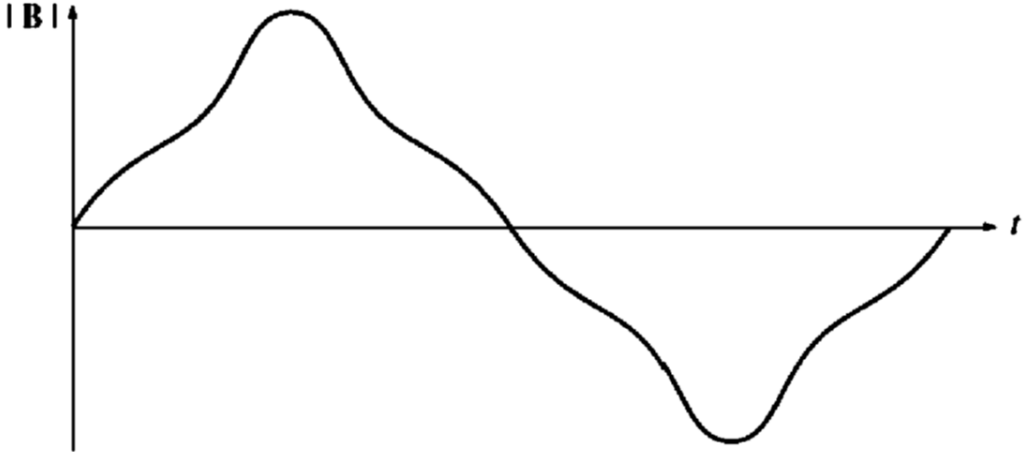
A three-phase set of currents generates a uniform rotating magnetic field in a machine stator, and a uniform rotating magnetic field generates a three-phase set of voltages in the stator.

Harmonic Problem

- Non-sinusoidal flux density distribution in real machines.
- i.e. reluctance of the magnetic field is much lower directly under the center of the rotor (higher flux density) than it is toward the sides.



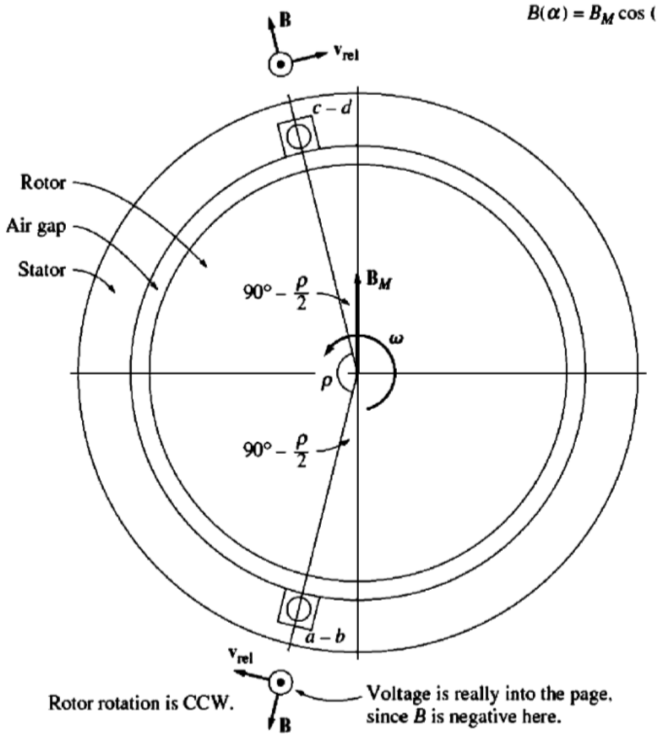
Salient-pole machine

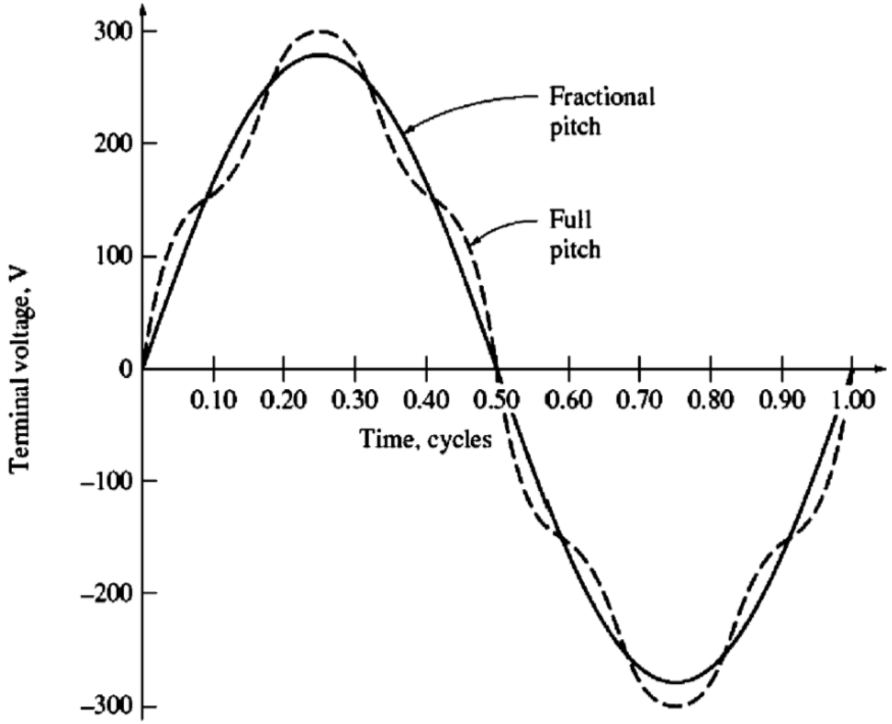


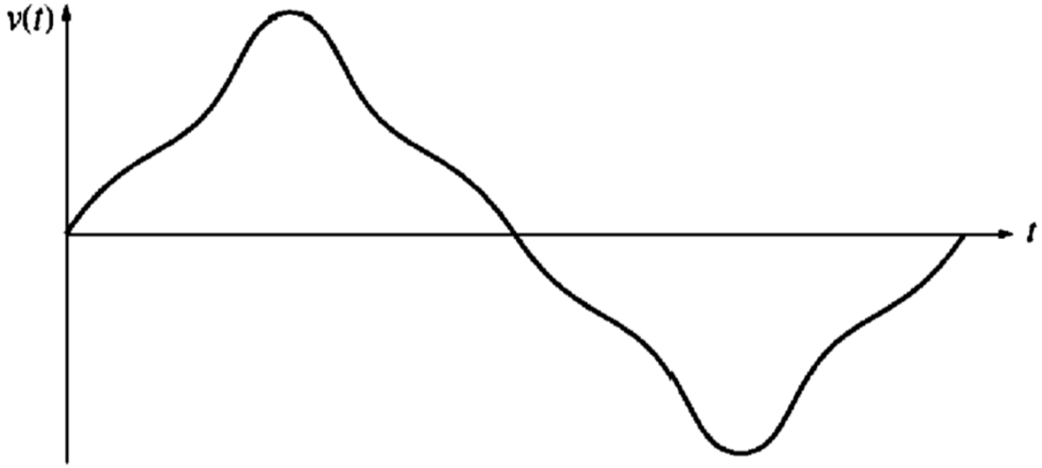
Fourier series

Harmonic Problem

- The induced voltage is not sinusoidal and contains many harmonic frequency components.
- Fractional-pitch windings improve the quality of the induced voltage.

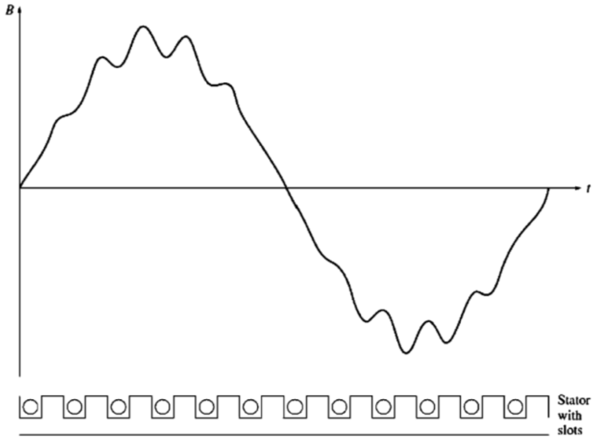




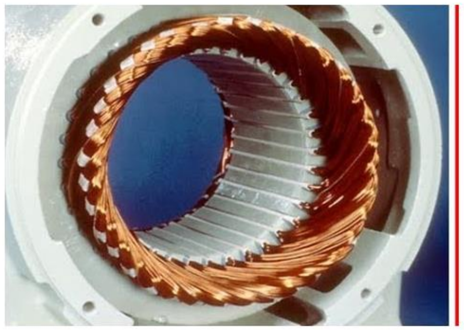


Tooth or Slot Harmonics

- It is impossible to pull all the wires into a single slots. In fact, the windings are distributed among several adjacent pairs of slots.
- Thus, distributed windings introduces harmonic components of voltage.

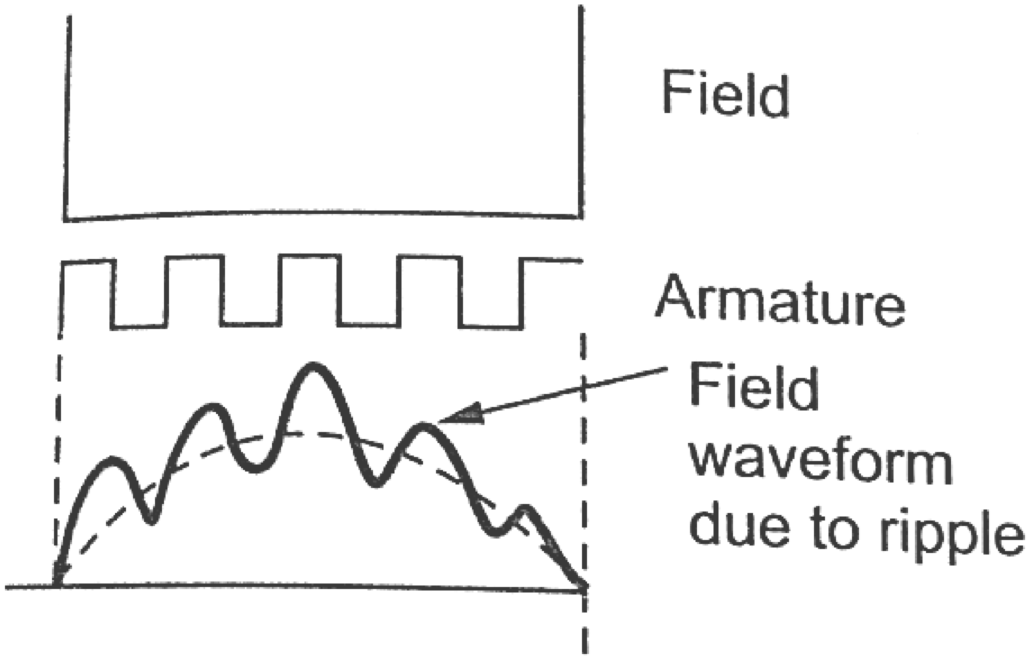


Distributed Winding



Concentrated Winding

electrical4u.net



Example 1: Two-pole Generator

- A simple two-pole generator, the peak flux density of the rotor magnetic field is 0.2T, the mechanical rate of rotation of the shaft is 3600 rpm. The stator diameter of the machine is 0.5m, it coil length is 0.3m, and there are 15 turns per coil. The machine is Y-connected.

  a) What are the three-phase voltage of the generator as a function of time?

  b) What is the rms phase voltage of this generator?

  c) What is the rms terminal voltage of this generator?.

- **Solution**

Flux in this machine

$$\phi = area \cdot B = 0.5 \times 0.3 \times 0.2 = 0.03 \text{ Wb}$$

Velocity of the rotor

$$\omega = 2\pi f = 2\pi \frac{rpm}{60} = 2\pi \frac{3600}{60} = 377 \text{ rad/s}$$

Thus, the peak value of the induced voltage $\hat{E} = N_c \phi \omega_M = 15 \times 0.03 \times 377 = 169.7$

Example 1: Two-pole Generator

- Solution

(a) Three phase voltage as a function of time

$$e_{aa'} = 169.7\cos(377t)$$
$$e_{bb'} = 169.7\cos(377t - 120^\circ)$$
$$e_{cc'} = 169.7\cos(377t - 240^\circ)$$

(b) RMS phase voltage

$$E_{rms} = \hat{E}/\sqrt{2} = 120\text{V}$$

(c) RMS line voltage

$$E_{rms\_LL} = E_{rms}\sqrt{3} = 208\text{V}$$