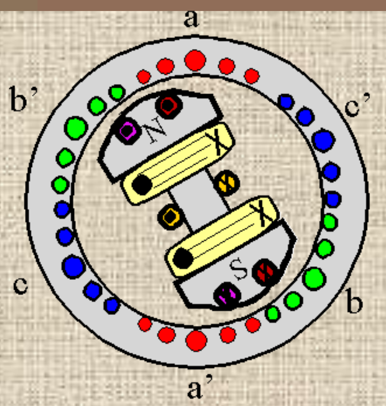
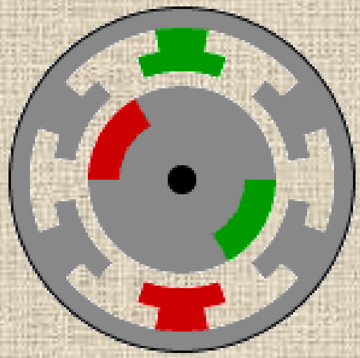
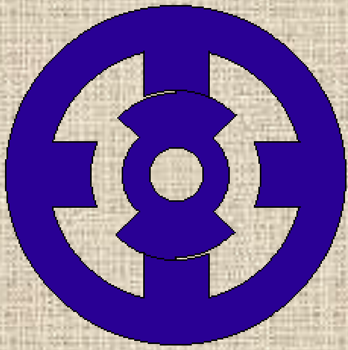
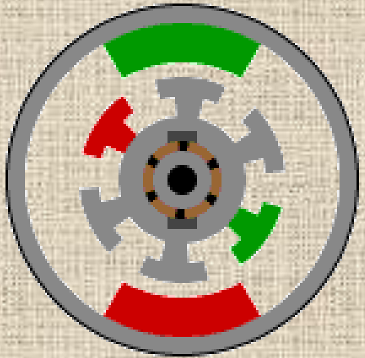
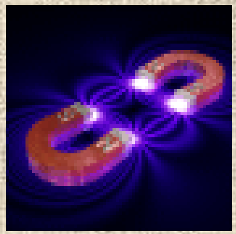
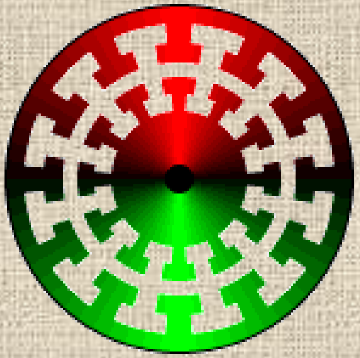
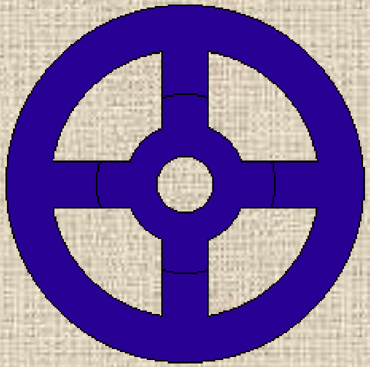
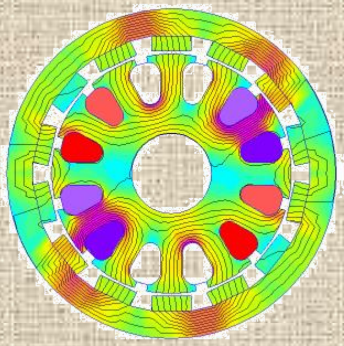
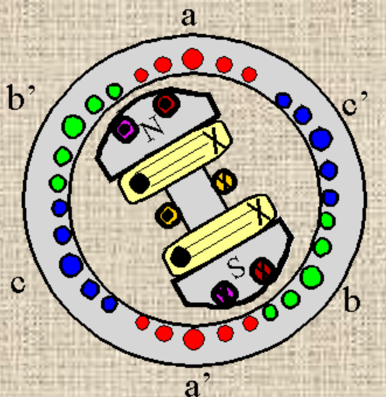


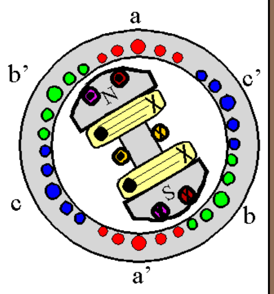
EE552 ELECTRICAL MACHINES III




LECTURE 2

LECTURE NOTES

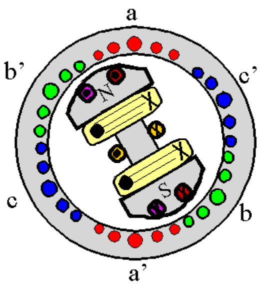


ELECTRICAL MACHINES III

EE552

SPRING 2018

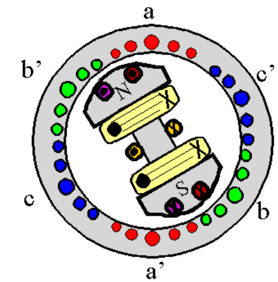
Dr : MUSTAFA AL-REFAI



END LECTURE 2

AC MACHINERY FUNDEMENTALS

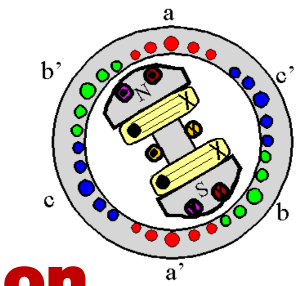
AC MACHINERY FUNDEMENTALS



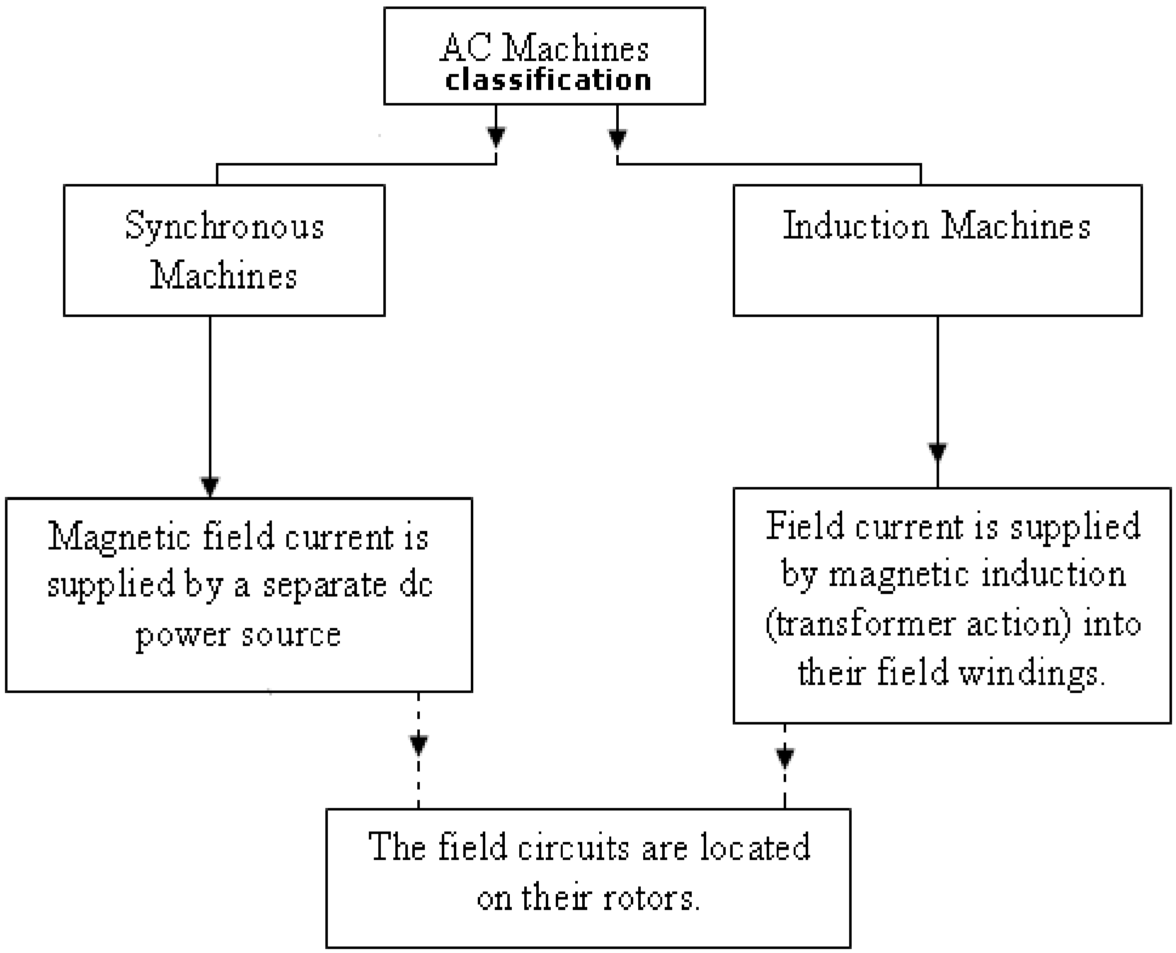
- **AC machines**: convert Mechanical energy to ac electrical energy, as generators & convert ac Electrical energy to mechanical energy as motors

- **Main classes of ac machines:**
  - **(a) synchronous machines:** current for the field (winding) supplied by a separate dc source
  - **(b) induction machine:** current for the field (winding) supplied by magnetic field induction (transformer action)

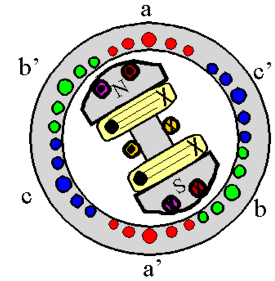
AC MACHINERY FUNDEMENTALS



- **Flowchart of ac Machines Classification**



AC MACHINERY FUNDEMENTALS



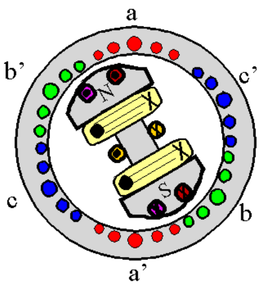
- **A loop of wire in uniform magnetic Field**

Produces a sinusoidal ac voltage

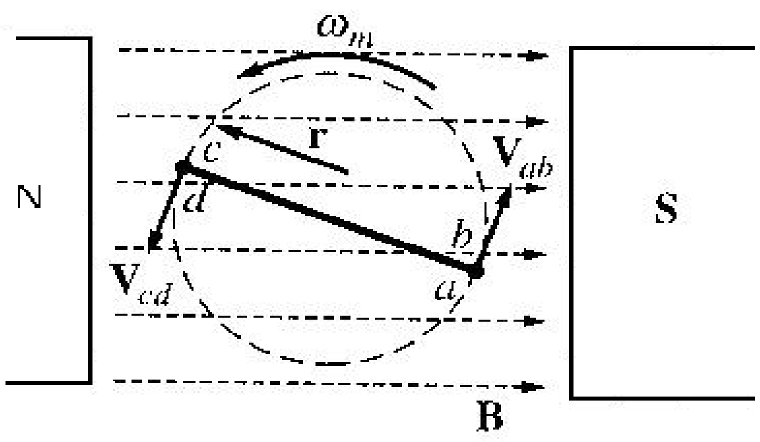
- **This is a simple machine to represent the principles**

(while flux in real ac machines is not constant in either magnitude & direction, however factors that control voltage & torque in real ac machine is the same)

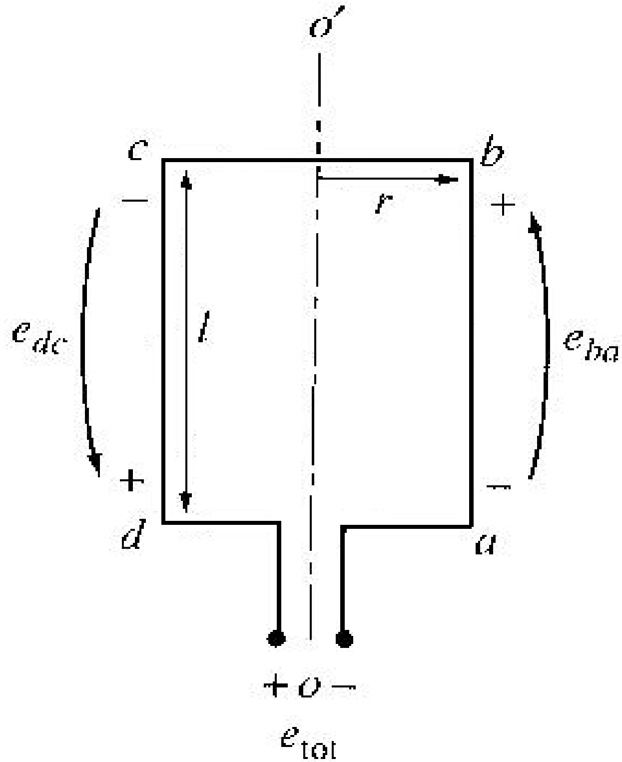
AC MACHINERY FUNDEMENTALS



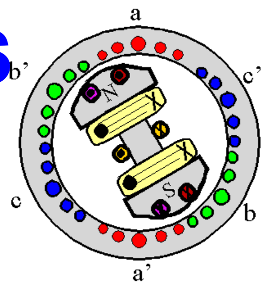
- The following Fig. shows a stationary magnet producing constant & uniform magnetic field & a loop of wire



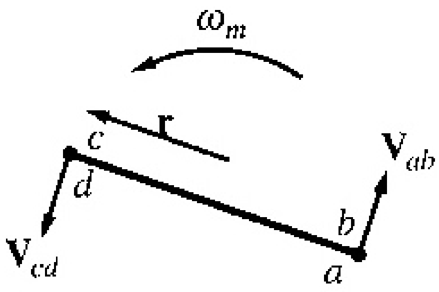
B is a uniform magnetic field, aligned as shown.

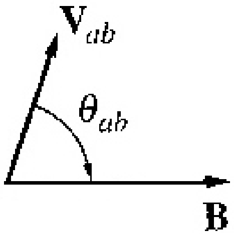


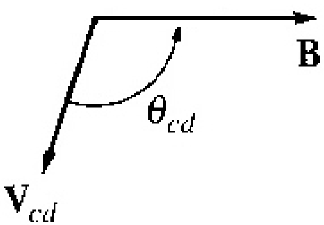
AC MACHINERY FUNDEMENTALS



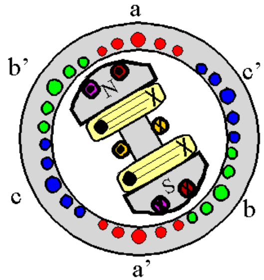
- ❑ Rotating part (the loop of wire) named ***rotor***
- ❑ Stationary part (Magnet) named ***stator***
- Voltage induced in rotor will be determined when it is rotating
- In below ab & cd shown perpendicular to page
- B has constant & uniform pointing from left to right







AC MACHINERY FUNDEMENTALS



- **To determine etot on loop, each segment of loop is examined & sum all voltage components**
- **Voltage of each segment:**

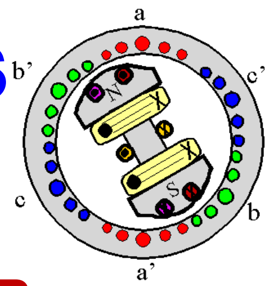
$e_{ind}= (v \times B) \cdot l$

1. segment ab **: velocity of wire, tangential to path of rotation, while B points to right → v X B points into page (same as segment ab direction)**

$e_{ab}=(v \times B) \cdot l = v\, B\, l \sin \theta_{ab}$ **into page**

2. *segment bc* : in 1st half of segment v x B into page, & in 2nd half of segment v x B out of page

AC MACHINERY FUNDEMENTALS

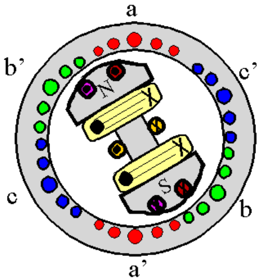


- In this segment, l is in plane of page, v x B perpendicular to l for both portions of segment
- Therefore voltage in segment bc is zero $e_{cb}=0$
- **3. *segment cd:*** *velocity of wire tangential to path of rotation, while B points to right & vxB points out of page, same direction as cd and:*

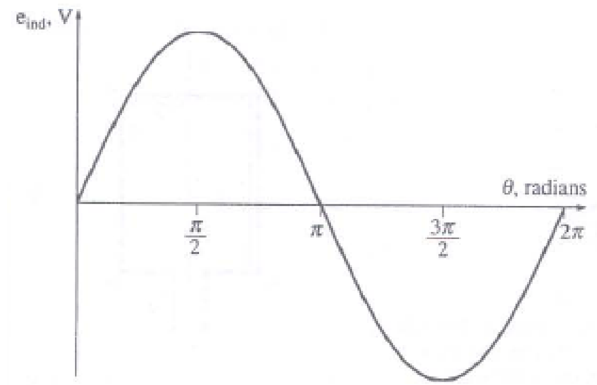
$$e_{cd}=(v \times B)\cdot l = v\,B\,l\,\sin\theta_{cd} \qquad \text{out of page}$$

- ***4. segment da:*** *similar to segment bc, v xB perpendicular to l, voltage in this segment* $e_{ad}=0$
- $e_{ind}= e_{ba}+e_{cb}+e_{dc}+e_{ad}=vBl\,\sin\theta_{ab} + vBl\,\sin\theta_{cd}$
- *Note:* $\theta_{ab}=180^{\circ} - \theta_{cd} \rightarrow e_{ind}=2vBl\,\sin\theta \quad (1)$

AC MACHINERY FUNDEMENTALS

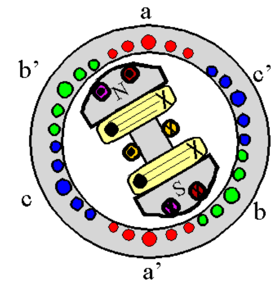


- The resulting voltage eind is a sinusoidal function of θ as shown



- Alternative method to express Equation (1) – which relates behavior of single loop to behavior of larger real ac machine
- If loop rotates at a constant velocity ω,
- θ = ω t   θ=angle of loop
- v = r ω
- r is radius from axis of rotation to one side of loop, and ω is angular velocity of loop

AC MACHINERY FUNDEMENTALS



- Substituting these parameters in Equation (1):

  $e_{ind} = 2r\,\omega B l \sin\omega t$ (2)

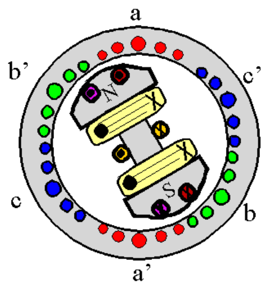
- since area of loop A=2rl, it can be substituted in Eq.(2): $e_{ind} = AB\,\omega \sin\omega t$ (3)
- Max. flux through loop occurs when loop is perpendicular to B: $\varphi_{max} = A\,B$ and Eq.(3) can be written as follows: $e_{ind} = \varphi_{max}\,\omega \sin\omega t$ (4)
- In any real machine the induced voltage depend on :

  1- flux in machine

  2- speed of rotation

  3- A constant representing construction of machine (No. of loops and etc.)

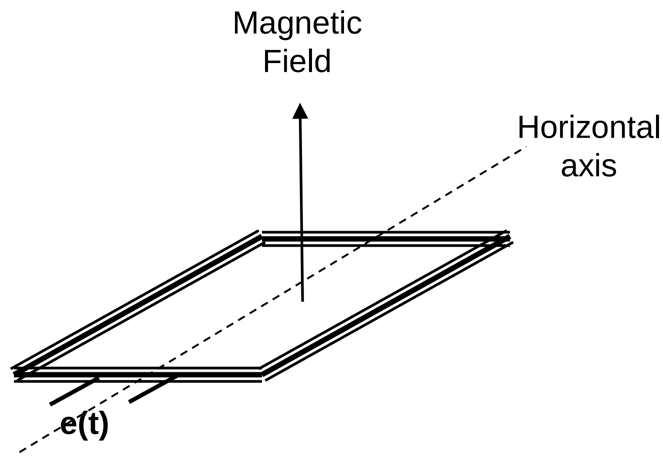
ELEMENTARY CONCEPT



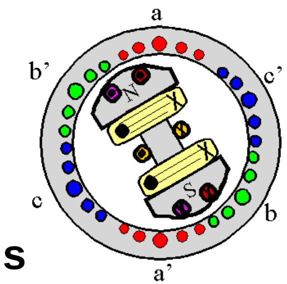
Electromechanical energy conversion occurs when changes in the flux linkages λ resulting from mechanical motion.

$$e(t) = \frac{d\lambda}{dt}$$

Producing voltage in the coil



- **Rotating the winding in magnetic field**
- **Rotating magnetic field through the winding**
- **Stationary winding and time changing magnetic field (Transformer action)**



Armature winding: AC current carrying winding

Synchronous machine
Induction machine
→ Armature winding is stator winding (stationary)

DC machine → Armature winding is on the rotor

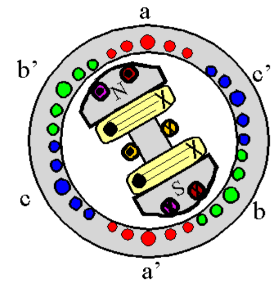
Field winding: DC current carrying winding

DC machine → Field winding is on the stator
Synchronous machine → Field winding is on the rotor

Note: Permanent magnets produce DC magnetic flux and are used in the place of field windings in some machines.

VRM (Variable Reluctance Machines)
Stepper Motors
→ No windings on the rotor (non-uniform air-gaps)

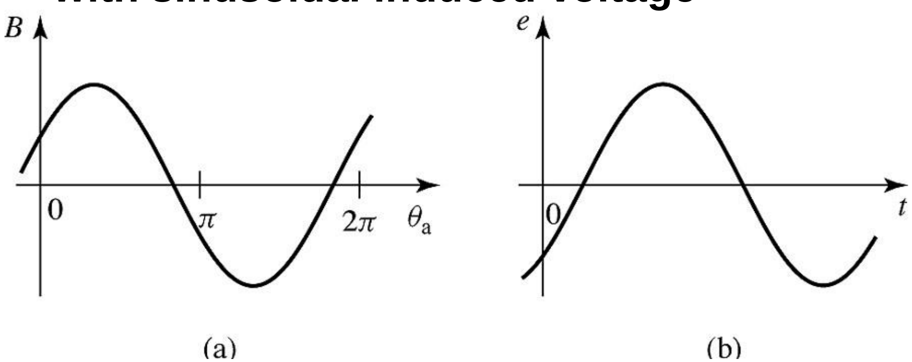
INTRODUCTION TO AC AND DC MACHINES

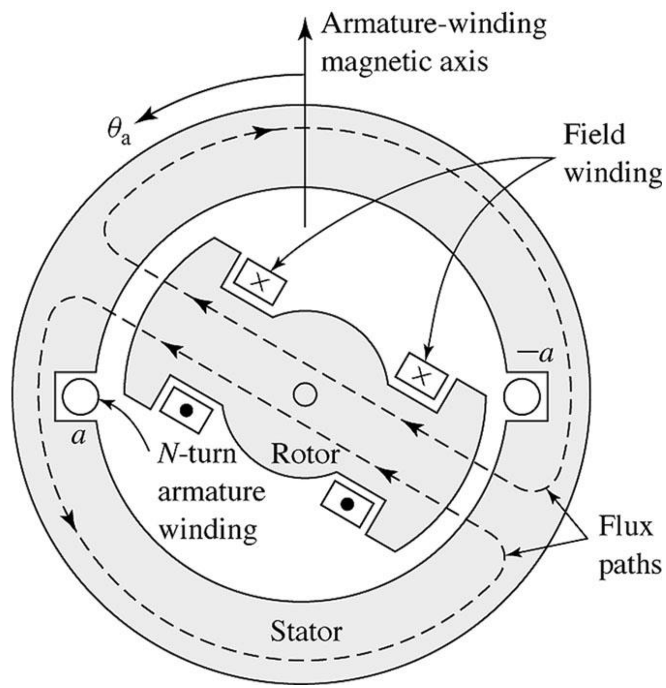


AC Machines: Synchronous Machines and Induction Machines

Synchronous Machines:

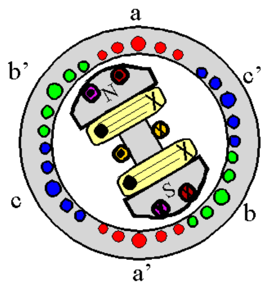
•Two-pole, single phase machine
•Rotor rotates with a constant speed
•Constraction is made such that air-gap flux density is sinusoidal
•Sinusoidal flux distribution results with sinusoidal induced voltage



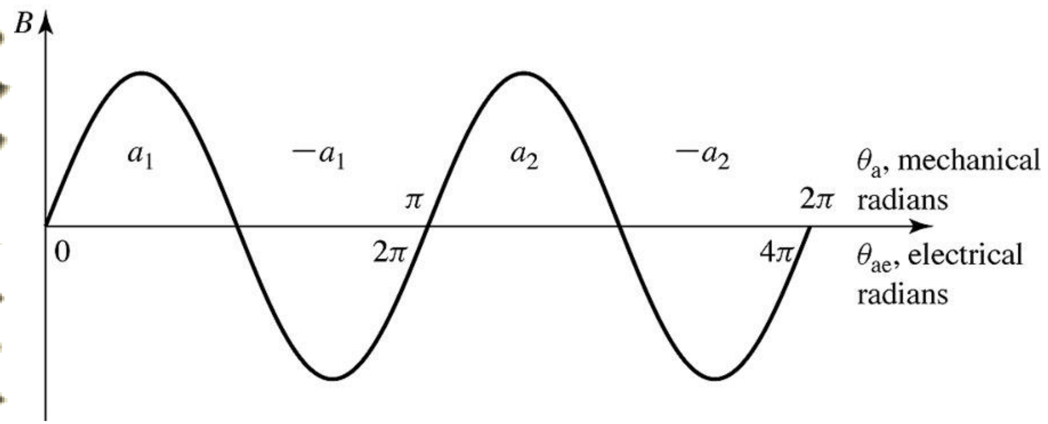


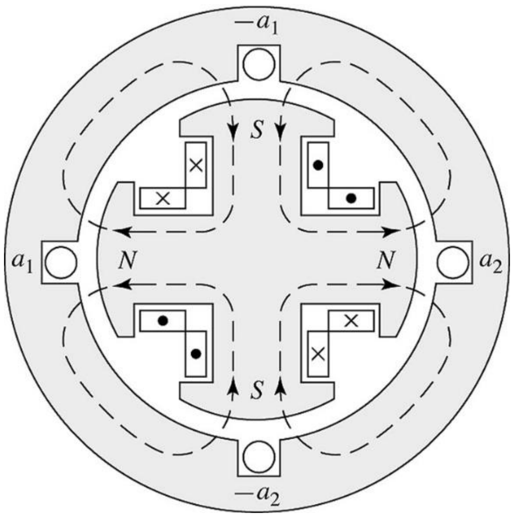
(a) Space distribution of flux density and
(b) corresponding waveform of the generated voltage for the single-phase generator.

Four-pole, single phase machine



- a1,-a1 and a2,-a2 windings connected in series
- The generator voltage goes through two complete cycles per revolution of the rotor. The frequency in hertz will be twice the speed in revolutions per second.



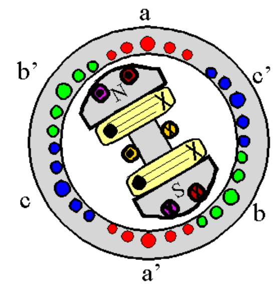


$$\theta_{ae} = \frac{p}{2}\theta_a$$

$$f_e = \frac{p}{2}\frac{n}{60}$$

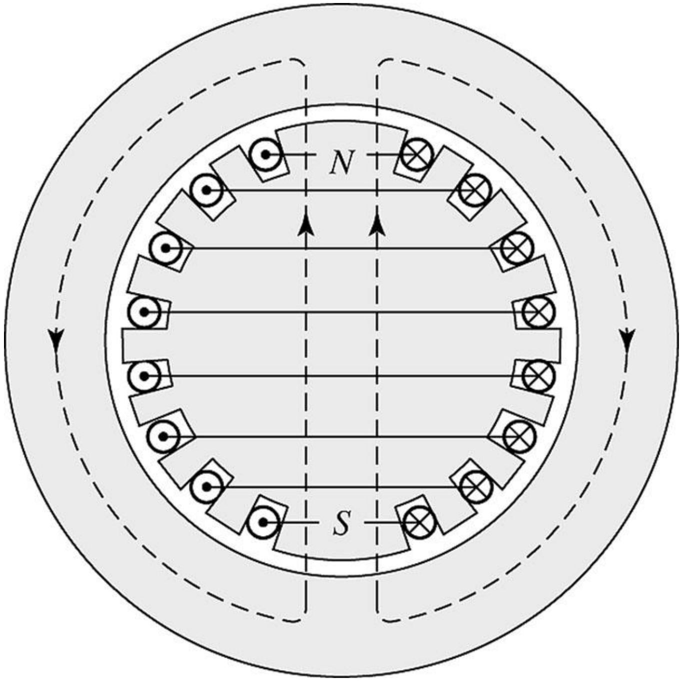
n: rpm
f_e: Hz

Field winding is a two-pole distributed winding Winding distributed in multiple slots and arranged to produce sinusoidal distributed air-gap flux.

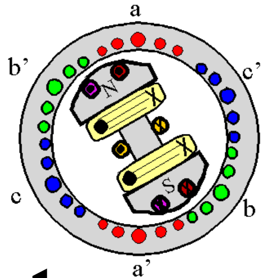


Why some synchronous generators have salient-pole rotor while others have cylindirical rotors?

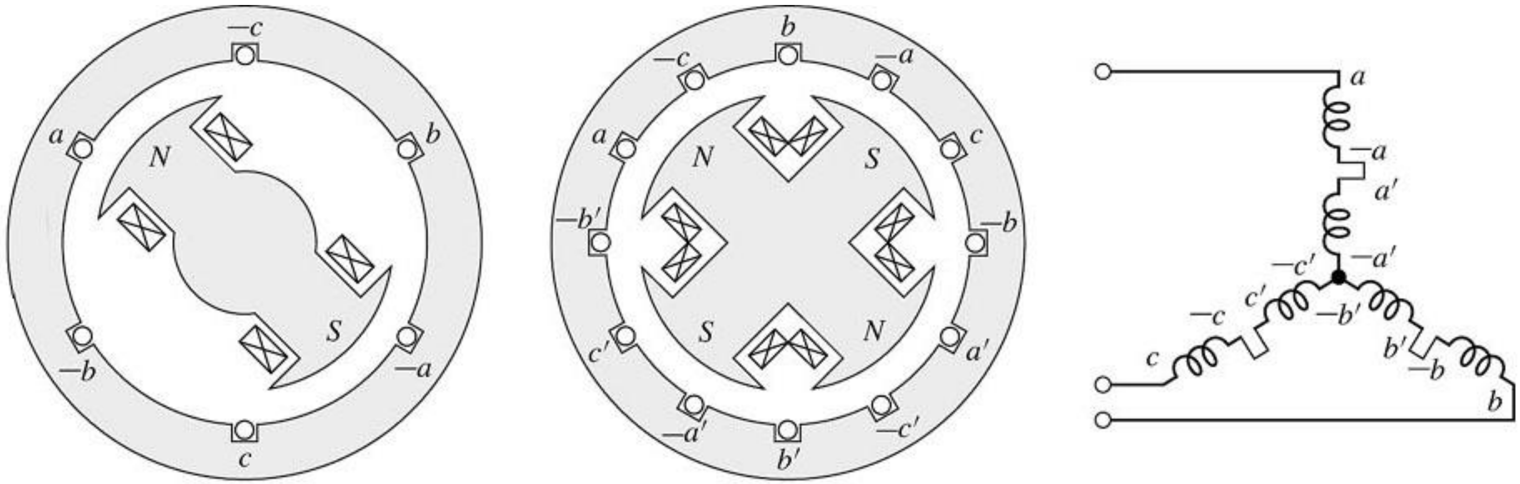
Answer: In salient-pole machines the number of poles can be large therefore they will be able to operate in slow speed to produce 50 Hz voltage.



Elementary two-pole cylindrical-rotor field winding.

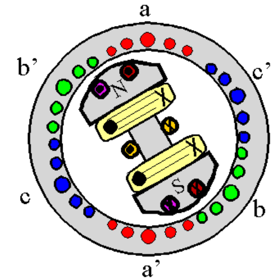


Schematic views of three-phase generators: (a) two-pole, (b) four-pole, and (c) *Y* connection of the windings.



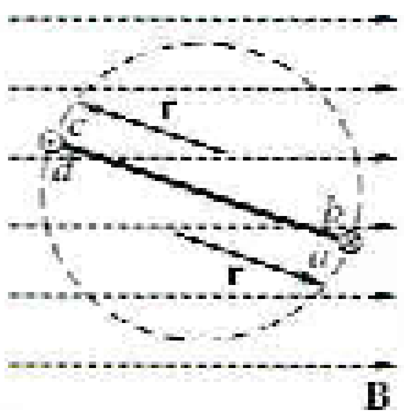
(a) (b) (c)

AC MACHINERY FUNDEMENTALS

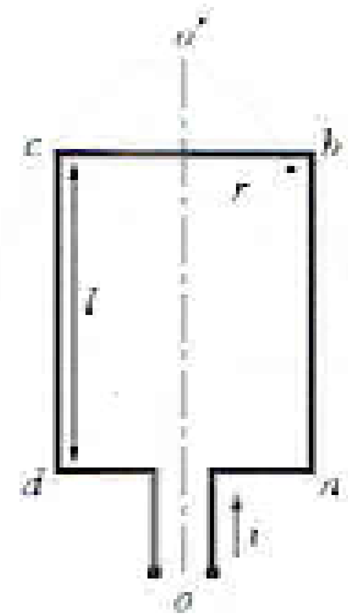


Torque Induced in Current-Carrying Loop

- assume rotor loop makes angle θ w.r.t. B
- “ I ” flowing in loop abcd : (into page & out of page)

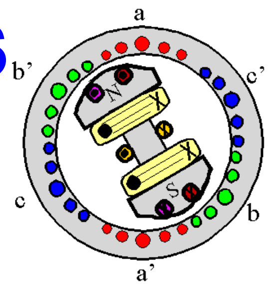


(a)



(b)

AC MACHINERY FUNDEMENTALS



❑ The torque applied on wire loop:

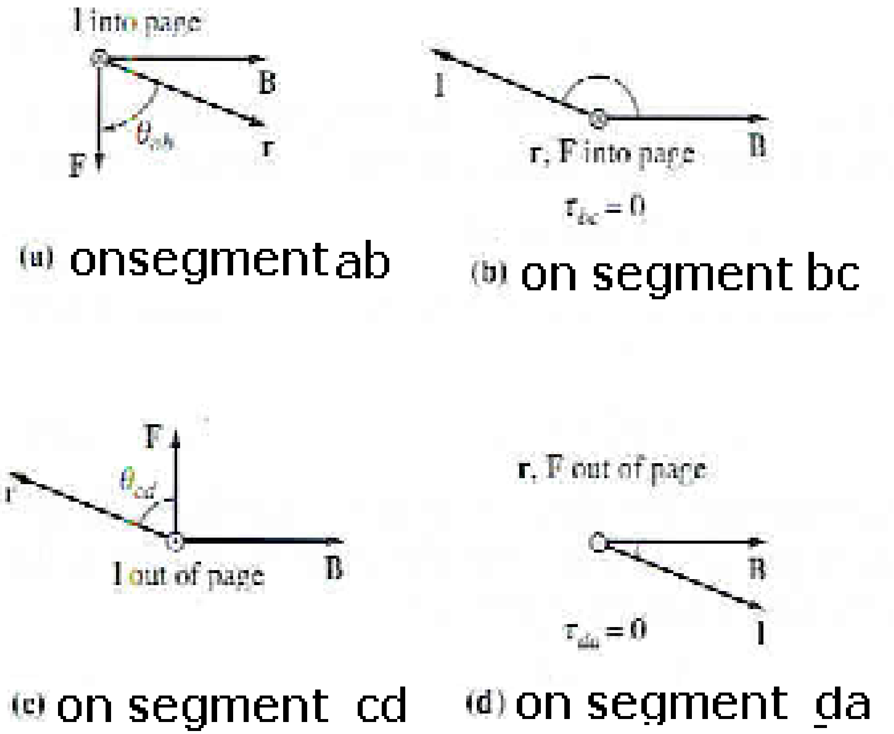
- **Determine direction & magnitude of T on each segment**

F=i (l x B)

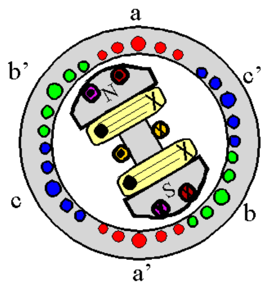
i = mag. of curre

l=length of segm

B=magnetic flux density vect



AC MACHINERY FUNDEMENTALS



- T = (force applied) × (perpendicular distance)=

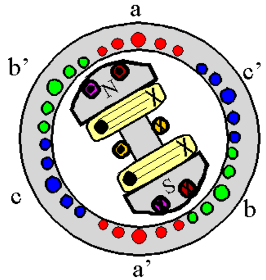
  = (F) × (r sin θ) = r F sinθ

θ: angle between vector r & vector F

direction of T is clockwise → clockwise rotation

& counterclockwise if tend to cause counterclockwise rotation

AC MACHINERY FUNDEMENTALS



1- ***segment ab:*** "I " into page & B points to right → F downward F= i(IxB) = ilB

$T_{ab} = F\ (r\ \sin\theta_{ab}) = rilB\ \sin\theta_{ab}$

clockwise

2- ***segment bc:*** "i" in plane of page, B points to right

→ applied force on segment

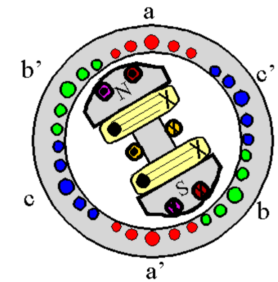
F= i(IxB) =ilB into the page

or $\theta bc=0$

(i.e. for a real machine that axis of rotation is not in plane of loop)

→ $T_{bc} = F\ (r\ \sin\theta_{bc}) = 0$

AC MACHINERY FUNDEMENTALS



3- ***segment cd:*** "i " out of page & B points to right → F upward F= i(lxB) =ilB

T_{ab} = F (r sinθ_{cd}) =rilB sinθ_{cd}

clockwise

2- ***segment da:*** "i" in plane of page, B points to right

→ applied force on segment

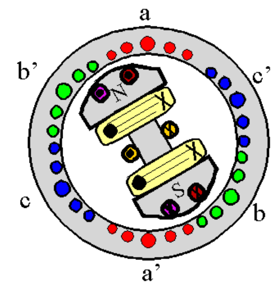
F= i(lxB) =ilB *out of* the page or θ_{da}=0

→ T_{da} = F (r sinθ_{bc}) =0

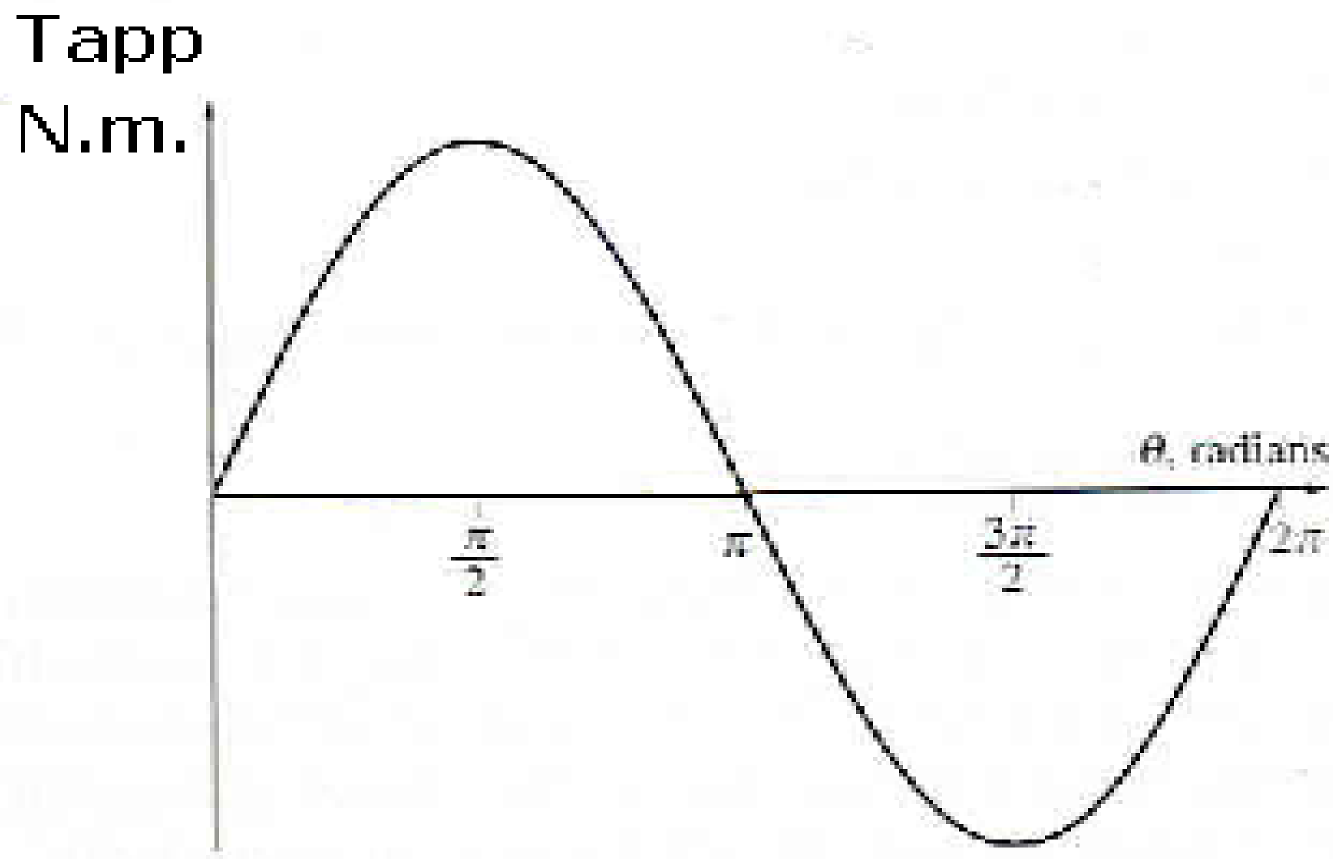
$T_{app}=T_{ab}+T_{bc}+T_{cd}+T_{da}$ =r i l B sin θ_{ab}+ r i l B sin θ_{cd}

Since : $\theta_{ab}=\theta_{cd}$ → T_{app}=2 r i l B sin θ (1)

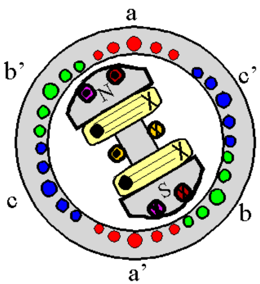
AC MACHINERY FUNDEMENTALS



- Resulting torque as a function of angle θ



AC MACHINERY FUNDEMENTALS



- **Note:**

T is maximum when plane of loop is parallel to B

(θ: angle between perpendicular to B and loop current direction)

T is zero when plane of loop is perpendicular to B

An alternative method to be used for larger, real ac machines is to specify the flux density of loop to be :

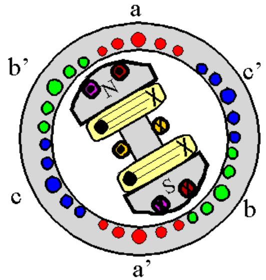
$B_{loop}=\mu i/G$ (G factor depend on geometry).. (2)

Area of loop $A=2rl$ ....(3)

substituting (2) & (3) in (1)→

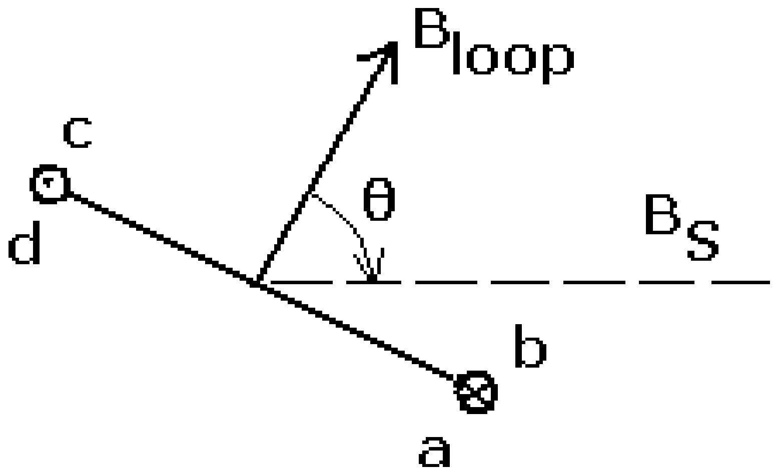
$T_{app}=AG/\mu B_{loop}\ B_s \sin\theta$ ....(4)

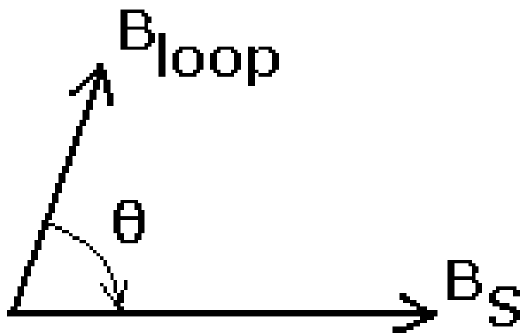
AC MACHINERY FUNDEMENTALS



❑ This can be simplified as :

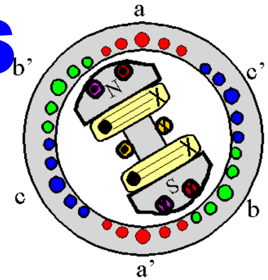
$T_{app} = k\, B_{loop} \times B_S$ ……5





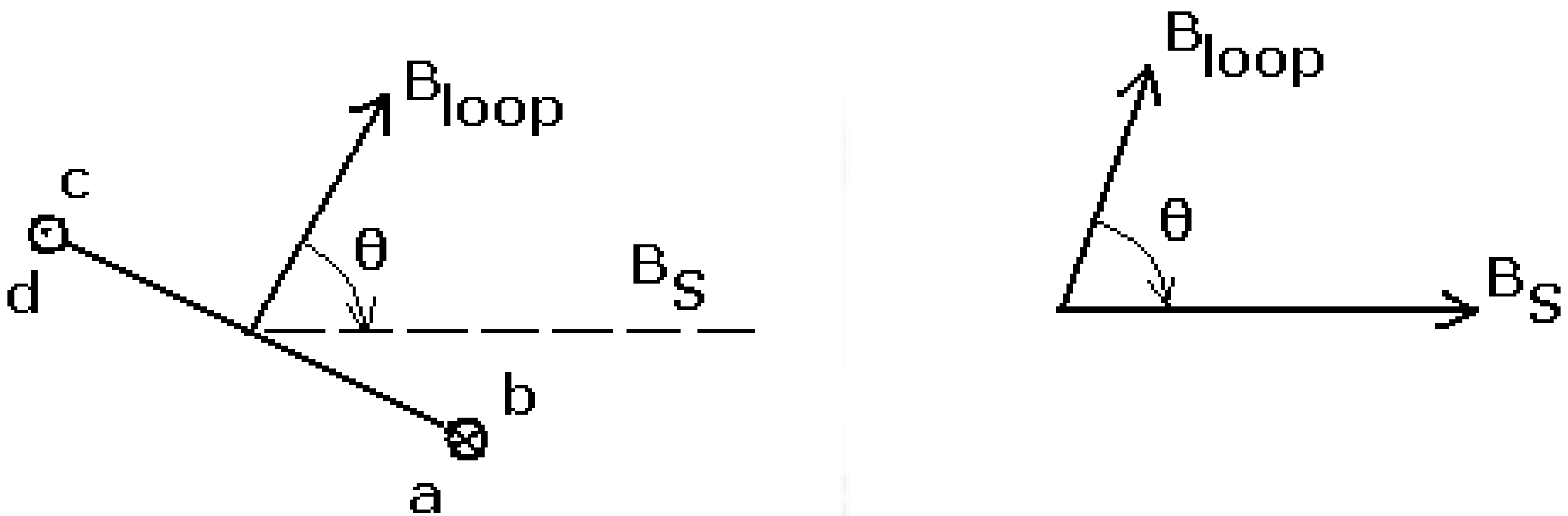
T ~ loop's B & ext. B & sine of angle between them

AC MACHINERY FUNDEMENTALS

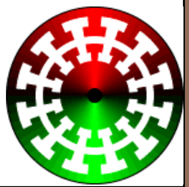


- **This can be simplified as :**

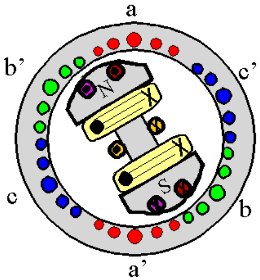
$$T_{app} = k\, B_{loop} \times B_S \quad .....5$$



T ~ loop's B & ext. B & sine of angle between them



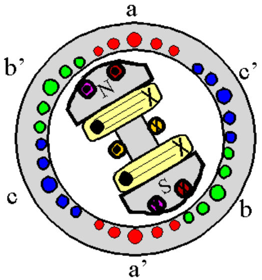
AC MACHINERY FUNDEMENTALS
Rotating Magnetic Field



- if 2 magnetic fields, present in a machine, then a **torque** will be created that tend to **line up** 2 magnetic fields
- If one magnetic field, produced by the stator of an ac machine and the other by the rotor;

  a torque will be applied on rotor which will cause rotor to turn & align itself with stator's B
- → If there were some way to make the stator magnetic field rotate **then the applied T on rotor will cause it to chase the stator Magnetic field**

DEVELOPING MAGNETIC FIELD TO ROTATE

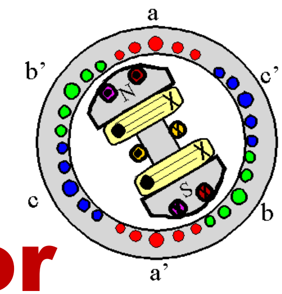


- **Fundamental principle:** ***a 3-phase set of currents , each of equal magnitude and differing in phase by 120º, flows in a 3-phase winding***

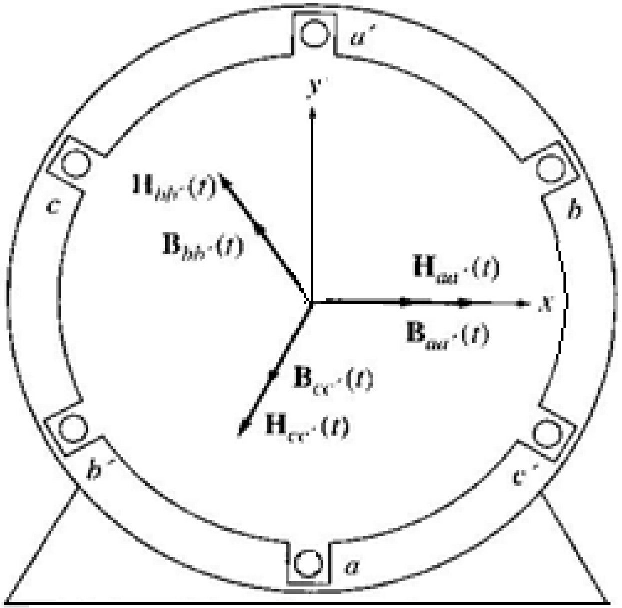
  will produce a rotating magnetic field of constant magnitude

- **The rotating magnetic field concept is illustrated (next slide)– empty stator containing 3 coils 120º apart. It is a 2-pole winding (one north and one south).**

DEVELOPING MAGNETIC FIELD TO ROTATE

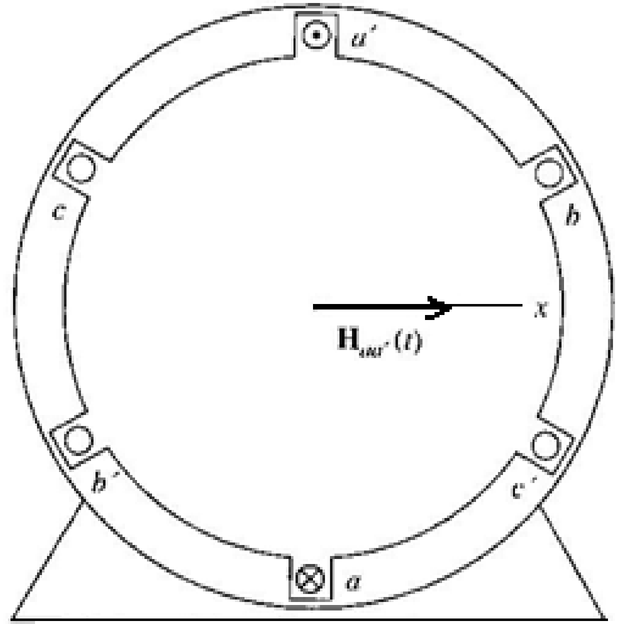


❑ A simple three phase stator



(a)

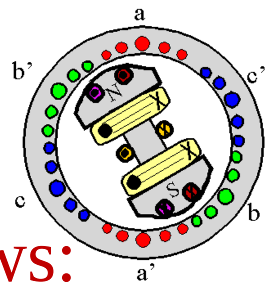
(a) A simple three phase stator. Currents in this stator are assumed positive if they flow into the unprimed end and out the primed end of the coils.



(b)

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

DEVELOPING MAGNETIC FIELD TO ROTATE



- A set of currents applied to stator as follows:

$$i_{aa'}(t) = I_M \sin \omega t \; A$$

$$i_{bb'}(t) = I_M \sin(\omega t - 120°) A$$

$$i_{cc'}(t) = I_M \sin(\omega t - 240°) A$$

- magnetic field intensity:

$$H_{aa'}(t) = H_M \sin \omega t \angle 0° \; A \bullet turns/m$$

$$H_{bb'}(t) = H_M \sin(\omega t - 120°) \angle 120° \; A \bullet turns/m$$

$$H_{cc'}(t) = H_M \sin(\omega t - 240°) \angle 240° \; A \bullet turns/m$$

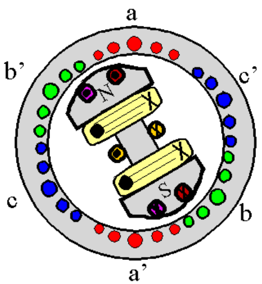
- Flux densities found from B=μH

$$B_{aa'}(t) = B_M \sin \omega t \angle 0° \; T$$

$$B_{bb'}(t) = B_M \sin(\omega t - 120°) \angle 120° \; T$$

$$B_{cc'}(t) = B_M \sin(\omega t - 240°) \angle 240° \; T$$

Rotating Magnetic Field



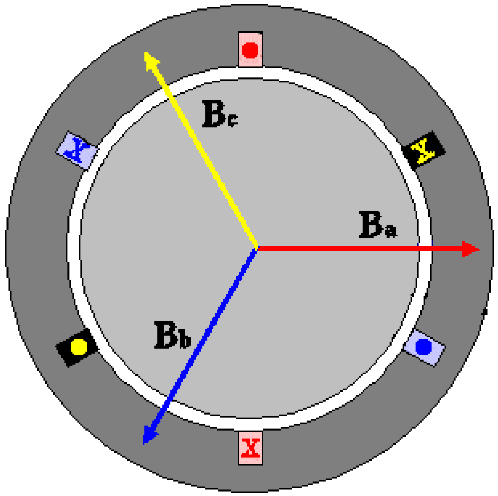
$$B_{net}(t) = B_a(t) + B_b(t) + B_c(t)$$

$$= B_M \sin(\omega t)\angle 0° + B_M \sin(\omega t - 120°)\angle 120° + B_M \sin(\omega t - 240)\angle 240°$$

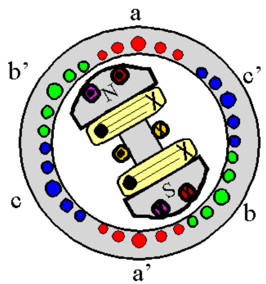
$$= B_M \sin(\omega t)\hat{\mathbf{x}}$$

$$-[0.5B_M \sin(\omega t - 120°)]\hat{\mathbf{x}} - [\frac{\sqrt{3}}{2} B_M \sin(\omega t - 120°)]\hat{\mathbf{y}}$$

$$-[0.5B_M \sin(\omega t - 240°)]\hat{\mathbf{x}} + [\frac{\sqrt{3}}{2} B_M \sin(\omega t - 240°)]\hat{\mathbf{y}}$$



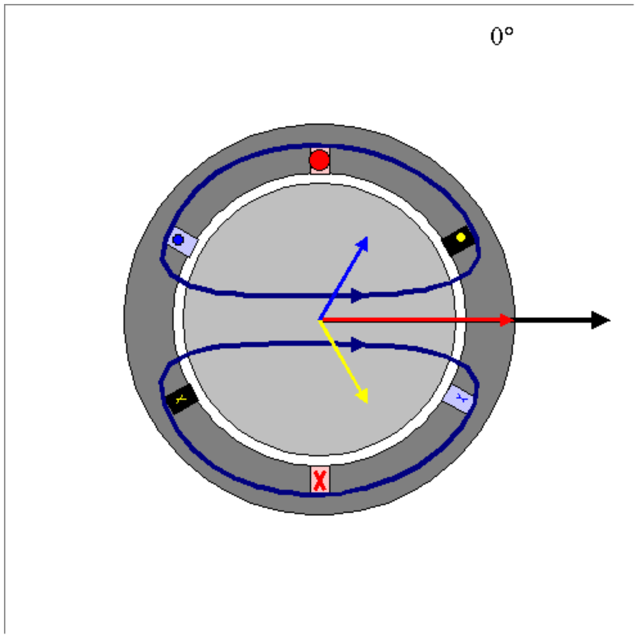
Rotating Magnetic Field



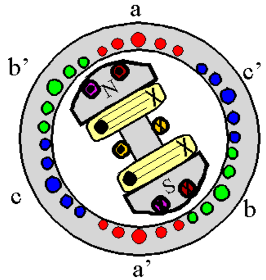
$$B_{net}(t) = [B_M \sin(\omega t) + \frac{1}{4} B_M \sin(\omega t) + \frac{\sqrt{3}}{4} B_M \cos(\omega t) + \frac{1}{4} B_M \sin(\omega t) - \frac{\sqrt{3}}{4} B_M \cos(\omega t)]\hat{\mathbf{x}}$$

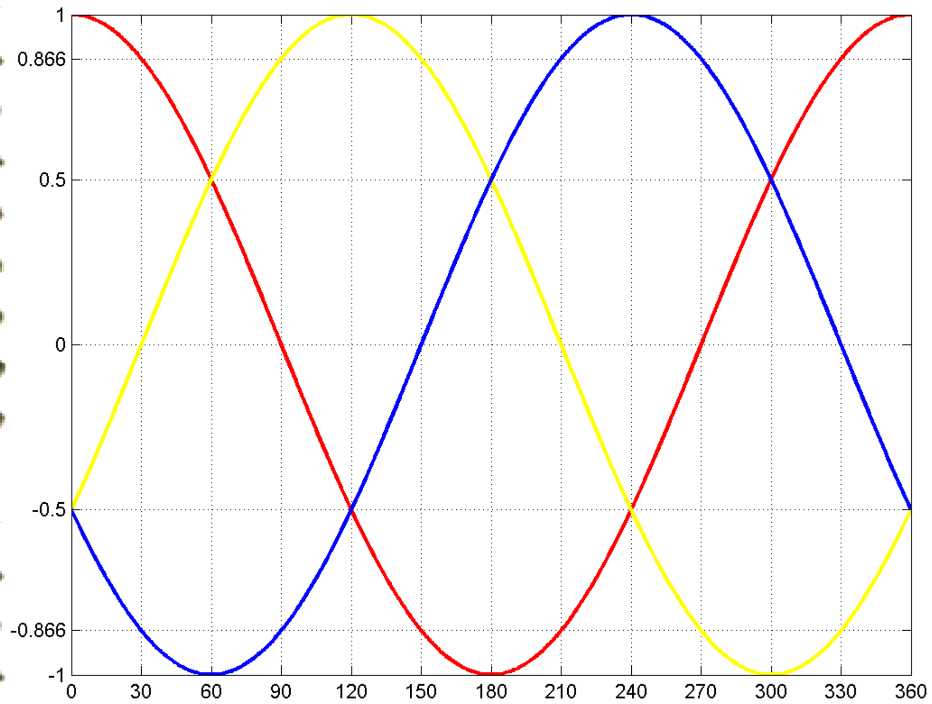
$$+[-\frac{\sqrt{3}}{4} B_M \sin(\omega t) - \frac{3}{4} B_M \cos(\omega t) + \frac{\sqrt{3}}{4} B_M \sin(\omega t) - \frac{3}{4} B_M \cos(\omega t)]\hat{\mathbf{y}}$$

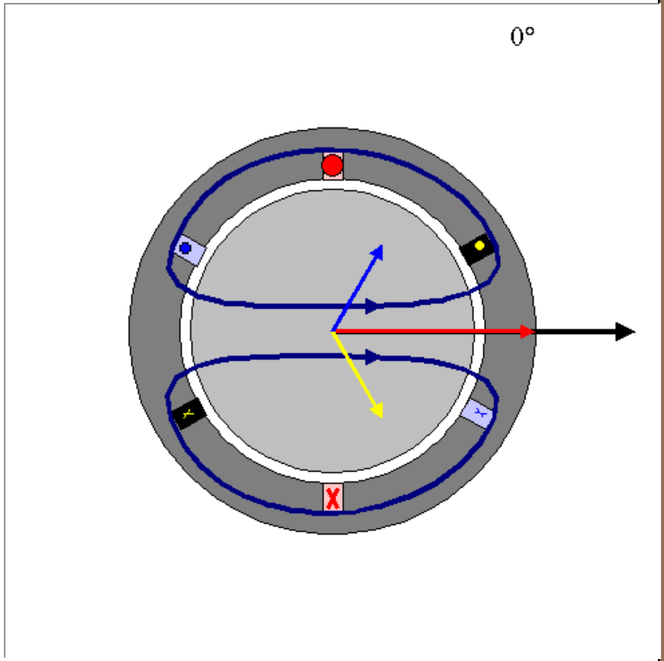
$$= [1.5 B_M \sin(\omega t)]\hat{\mathbf{x}} - [1.5 B_M \cos(\omega t)]\hat{\mathbf{y}}$$



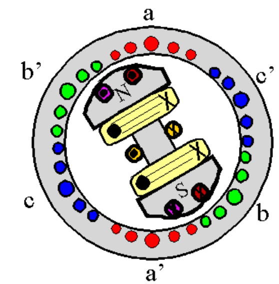
Rotating Magnetic Field







DEVELOPING MAGNETIC FIELD TO ROTATE



❑ Proof of rotating Magnetic Field

$$B_{net}(t) = B_a(t) + B_b(t) + B_c(t)$$

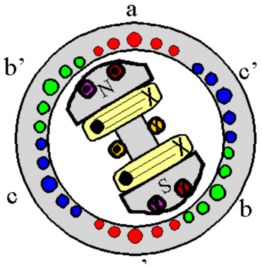
$$B_{net}(t) = B_M \sin \omega t \angle 0° + B_M \sin(\omega t - 120°) \angle 120° + B_M \sin(\omega t - 240°) \angle 240° \ T$$

- $B_{net} = B_M \sin\omega t \,.\, x - [0.5 B_M \sin(\omega t - 120°)] \,.\, x + [\sqrt{3}/2 B_M \sin(\omega t - 120°)] \,.\, y - [0.5 B_M \sin(\omega t - 240°)] \,.\, x + [\sqrt{3}/2 B_M \sin(\omega t - 240°)] \,.\, y =$

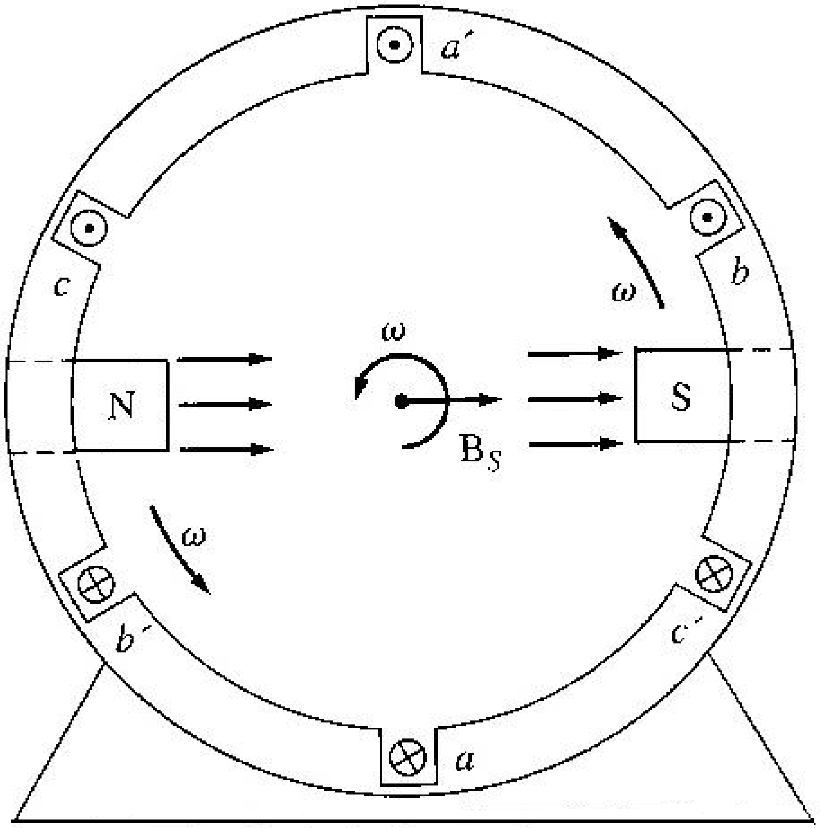
$$= (1.5\ B_M \sin\omega t) \,.\, x - (1.5\ B_M \cos\omega t) \,.\, y$$

- it means the magnitude of flux density is a constant **1.5 B_M** and the angle changes continually in counterclockwise direction at velocity of ω

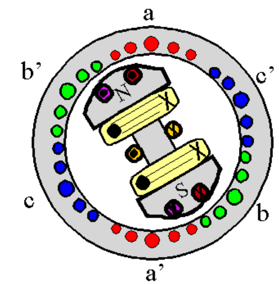
DEVELOPING MAGNETIC FIELD TO ROTATE



- Relationship between Electrical frequency & B rotation speed (2-pole)
- consider poles for stator of machine as N & S
- These magnetic poles complete one physical rotation around stator surface for each electrical cycle of applied current



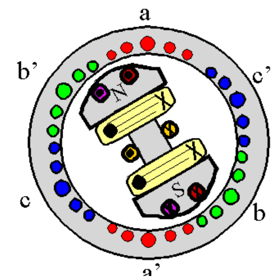
DEVELOPING MAGNETIC FIELD TO ROTATE



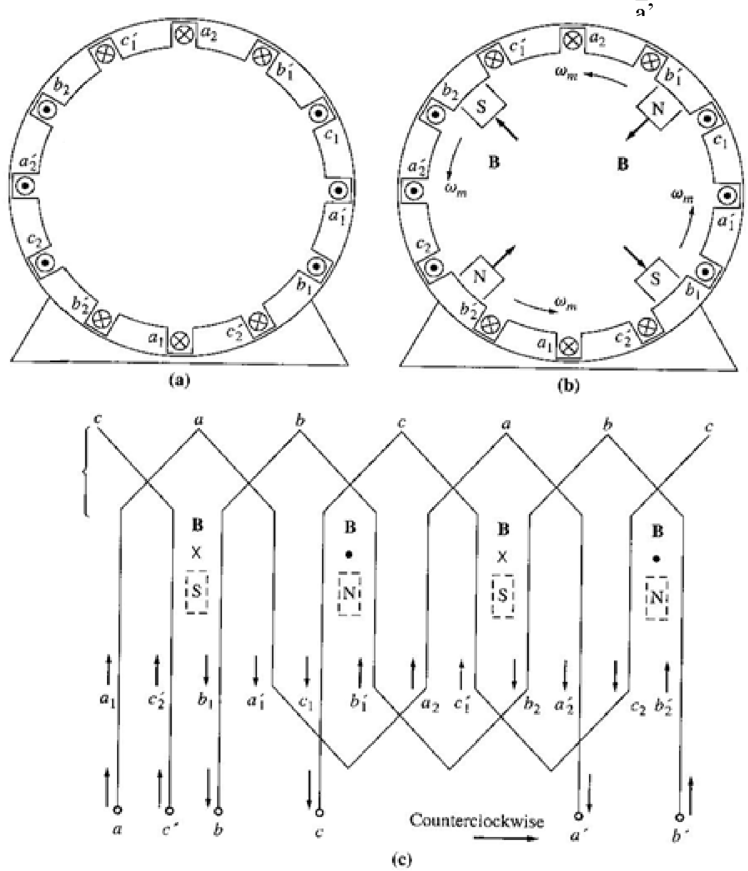
- $f_e = f_m$ two poles
- $\omega_e = \omega_m$ two poles
- f_m and ω_m are mechanical speed in revolutions / sec & radians / sec while f_e and ω_e are electrical speed in Hz & radians/sec
- Note: windings on 2-pole stator in last fig. occur in order (counterclockwise) a-c’-b-a’-c-b’
- In a stator, if this pattern repeat twice as in next Figure, the pattern of windings is:

  a-c’-b-a’-c-b’-a-c’-b-a’-c-b’

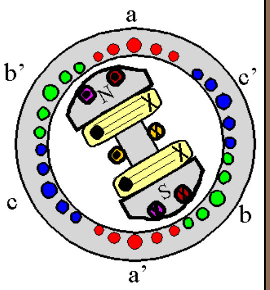
DEVELOPING MAGNETIC FIELD TO ROTATE NUMBER OF POLES



- This is pattern of previous stator repeated twice
- When a 3 phase set of currents applied
- Two North poles & *two* South poles produced in stator winding → Figure



DEVELOPING MAGNETIC FIELD TO ROTATE NUMBER OF POLES



- In this winding, a pole moves ½ way around stator in one electrical cycle
- Relationship between θe & θm in this stator is:

$$\theta_e = 2\theta_m \quad \text{(for 4-pole winding)}$$

- And the electrical frequency of current is twice the mechanical frequency of rotation

$$f_e = 2 f_m \qquad \text{four poles}$$

$$\omega_e = 2\omega_m \qquad \text{four poles}$$

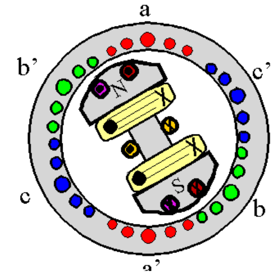
- In general: $\theta_e = P/2\ \theta_m$ for P-pole stator

$$f_e = P/2\ f_m$$

$$\omega_e = P/2\ \omega_m$$

Since : $f_m = n_m/60$ ➔ $f_e = n_m P/120$ n_m:r/min

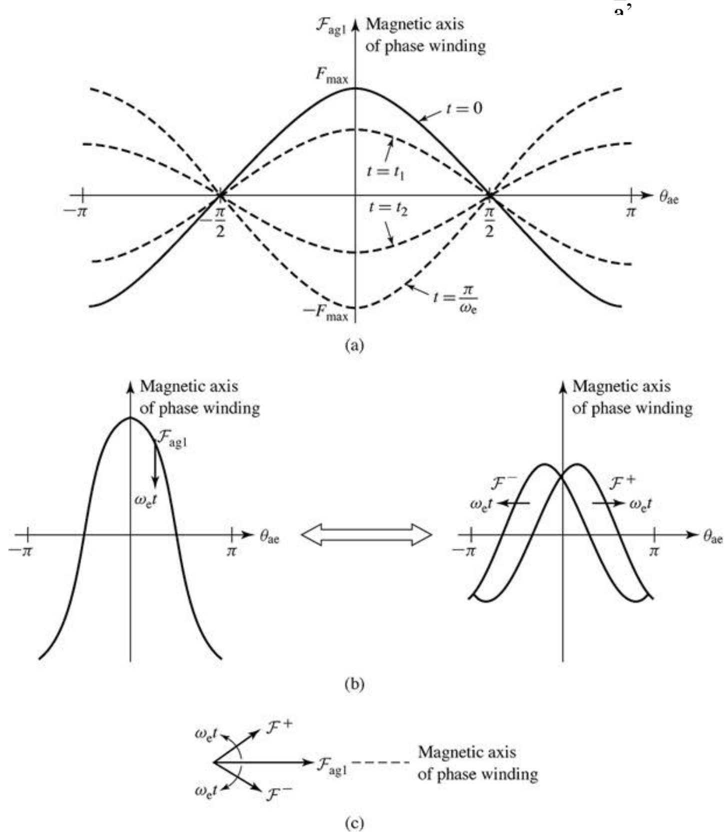
ROTATING MMF WAVES IN AC MACHINES



Single-phase-winding space-fundamental air-gap mmf:
(a) mmf distribution of a single-phase winding at various times;

(b) total mmf F_{ag1} decomposed into two traveling waves F^- and F^+;

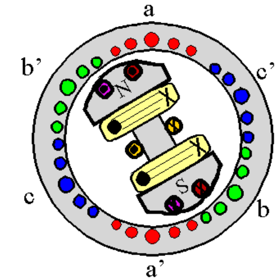
(c) phasor decomposition of F_{ag1}.



$$F_{ag1} = \frac{4}{\pi}\left(\frac{k_w N_{ph}\, i_a}{p}\right)\cos\left(\frac{p}{2}\theta_a\right)$$

$$i_a = I_a \cos\omega_e t$$

MMF Wave of a Polyphase Winding

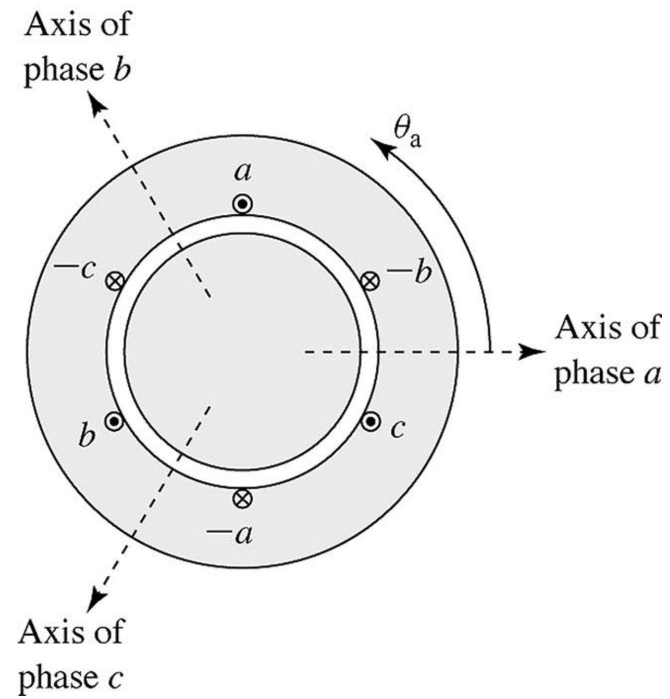


Simplified two-pole three-phase stator winding.

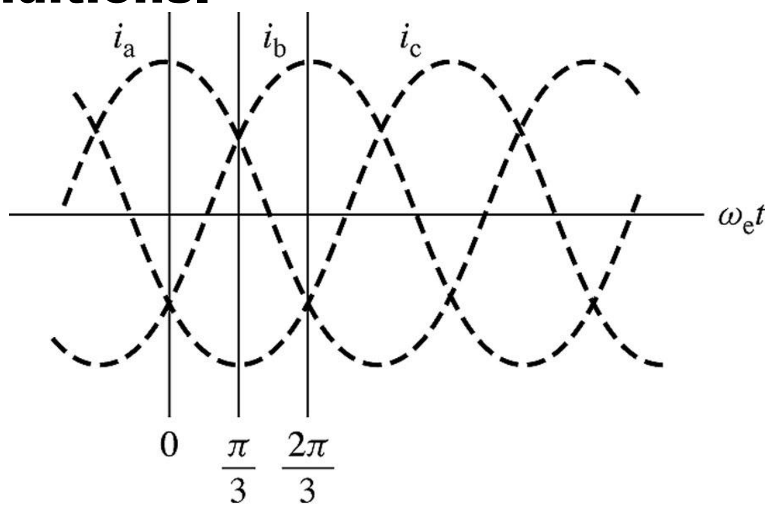
$$i_a = I_m \cos\omega_e t$$

$$i_b = I_m \cos(\omega_e t - 120^0)$$

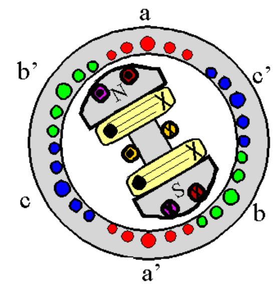
$$i_c = I_m \cos(\omega_e t + 120^0)$$

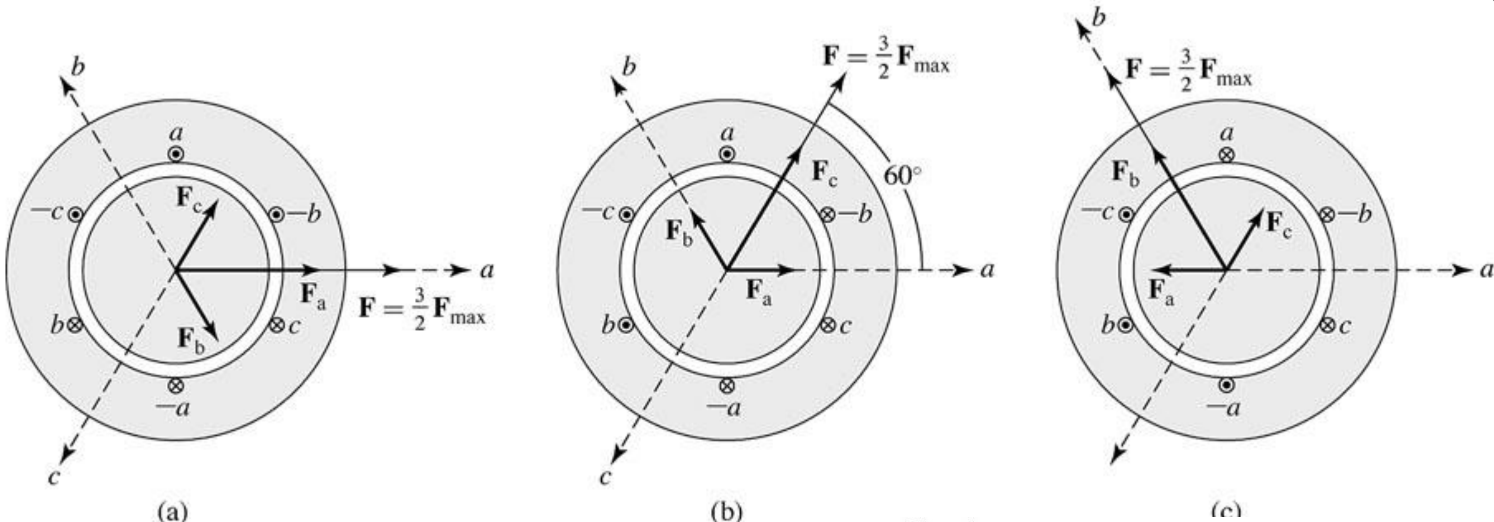


Instantaneous phase currents under balanced three-phase conditions.

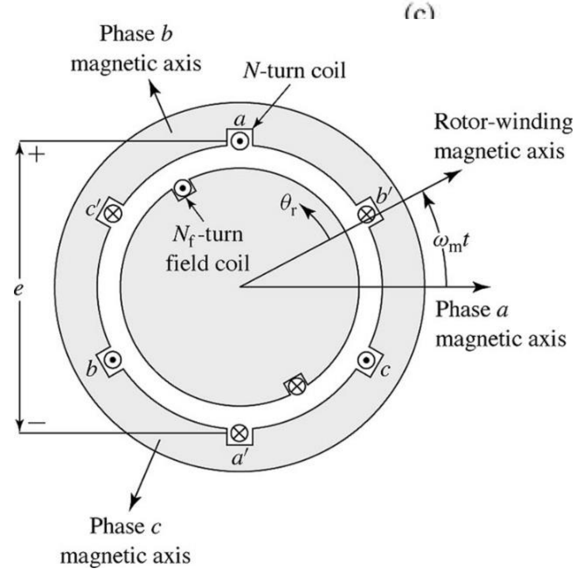


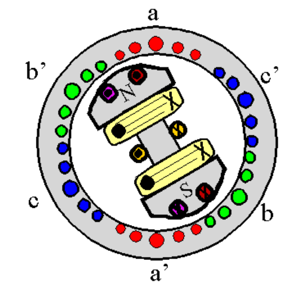
❑ The production of a rotating magnetic field by means of three-phase currents.





❑ Cross-sectional view of an elementary three-phase ac machine.




a
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c’
N
S
c
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a’


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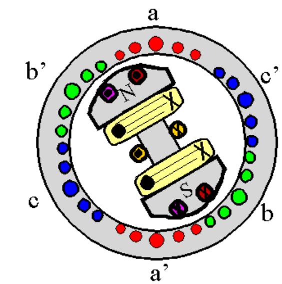
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END OF LECTURE 2