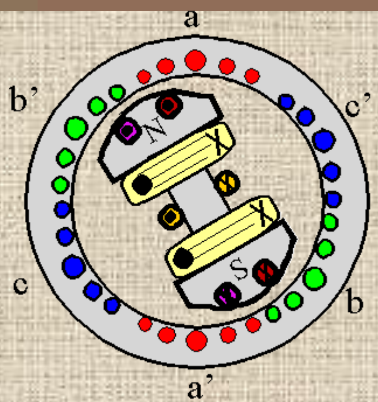
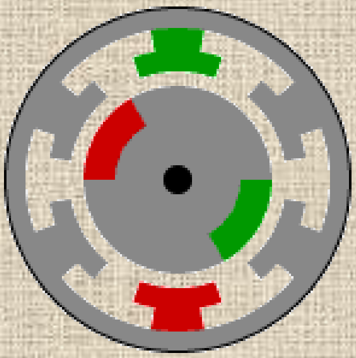
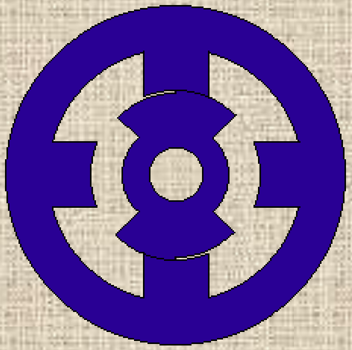
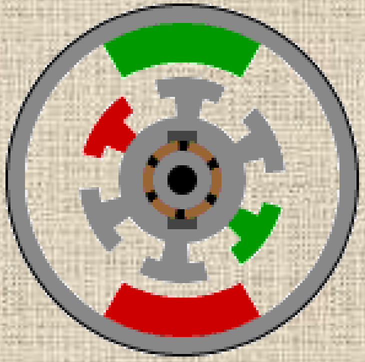
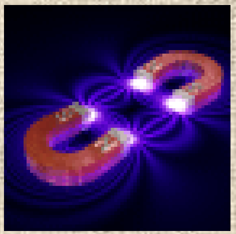
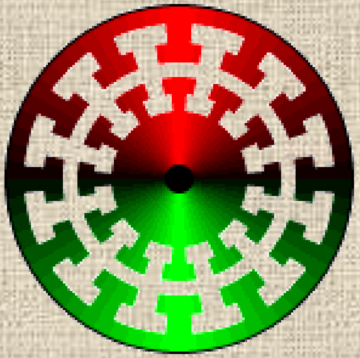
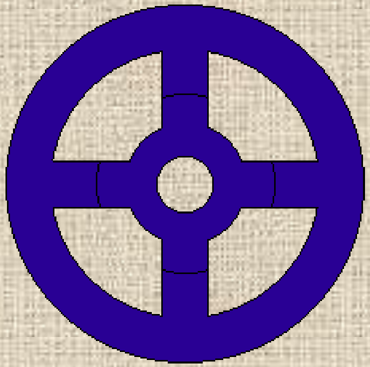
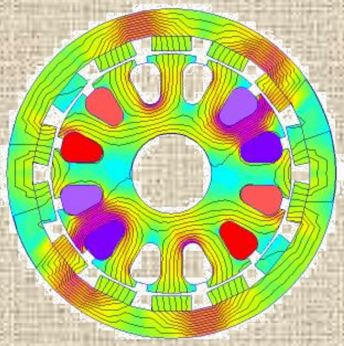
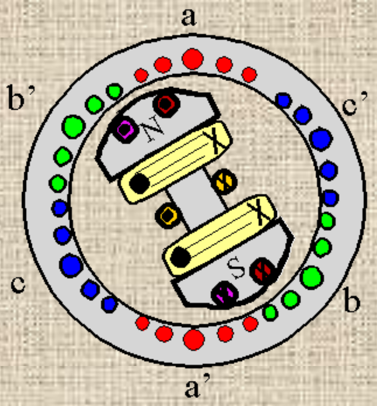


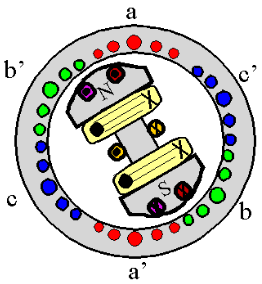
EE552 ELECTRICAL MACHINES III




LECTURE 3

LECTURE NOTES

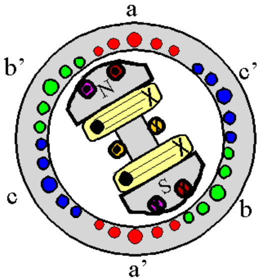


ELECTRICAL MACHINES III

EE552

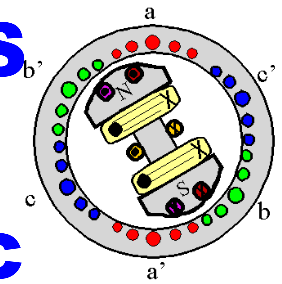
SPRING 2018

Dr : MUSTAFA AL-REFAI



LECTURE 3

AC MACHINERY FUNDEMENTALS



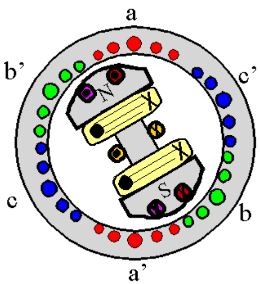
Producing Rotating Magnetic Field

- **Reversing Direction of Magnetic Field Rotation**
  - if current in any 2 of 3 coils is swapped, direction of magnetic field's rotation will be reversed
  - This means it is possible to reverse the direction of rotation of ac motor by switching connections on any 2 of 3 coils
- **This will be verified here**

$$B_{net}=B_{aa'}(t)+B_{bb'}(t)+B_{cc'}(t)=B_{max}\sin\omega t \angle 0^\circ + B_{max}\sin(\omega t-240^\circ)\angle 120^\circ + B_{max}\sin(\omega t-120^\circ)\angle 240^\circ$$

- **Now each of the 3 components of magnetic fields can be broken down into x & y components**

AC MACHINERY FUNDEMENTALS
Producing Rotating Magnetic Field

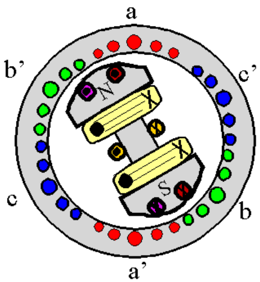


- $B_{net}=B_{max}\sin\omega t \,.\, x - [0.5B_{max}\sin(\omega t-240)].x + [\sqrt{3}/2\, B_{max}\sin(\omega t-240)].y - [0.5\, BM_{max}\sin(\omega t-120)].x - [\sqrt{3}/2\, B_{max}\sin(\omega t-120)].y =$

  $= (1.5\, B_{max}\sin\omega t).x + (1.5\, B_{max}\cos\omega t).y$

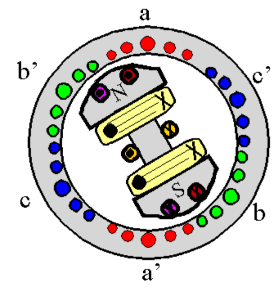
- Means: by swapping 2 of the 3 coils, B has same magnitude while rotating in a clockwise direction

AC MACHINERY FUNDEMENTALS
MMF & B Distribution on ac machines

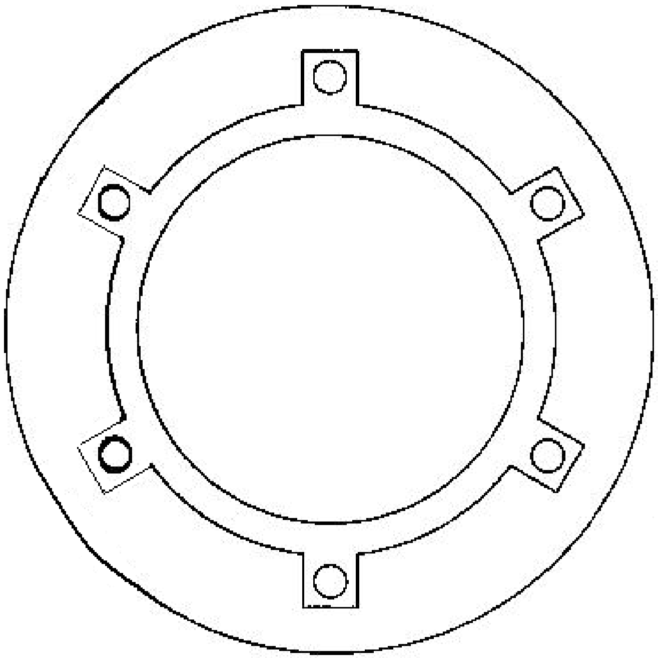


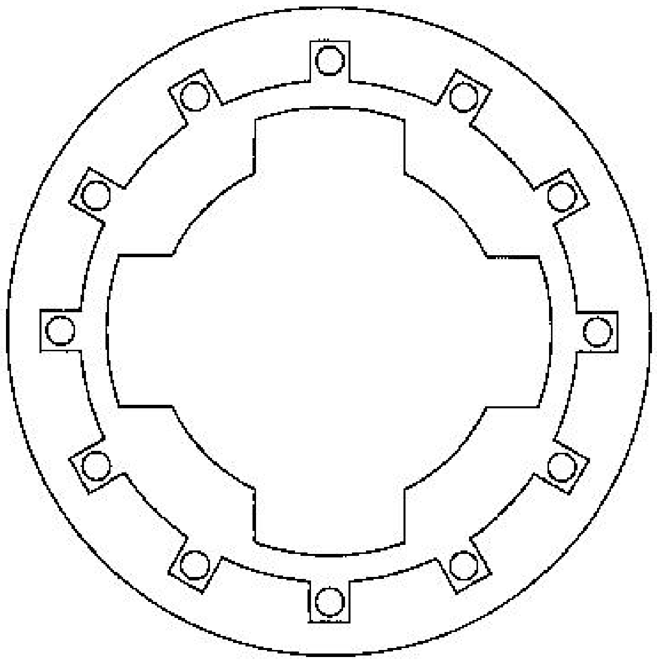
- In previous demonstration of 3 phase stator, B direction produced by coil wire assumed perpendicular to plane of coil (B direction by R.H.R. & in free space)
- B in a real machine doesn't behave in simple manner assumed, since ferromagnetic rotor is in center of machine with a small air gap in between
- Rotor can be cylindrical , with non-salient poles or with salient poles

AC MACHINERY FUNDEMENTALS
MMF & B Distribution on ac machines

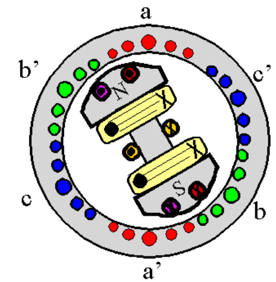


- An ac machine with: cylindrical rotor & salient-pole


(a)


(b)

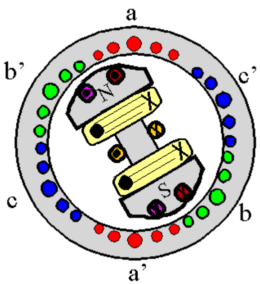
AC MACHINERY FUNDEMENTALS
MMF & B Distribution on ac machines



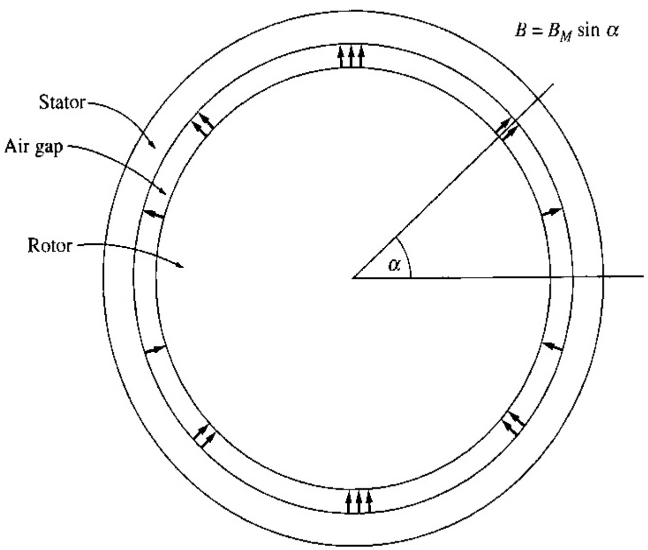
- Discussion here is restricted to cylindrical rotors
- Reluctance of air gap in this machine >> Reluctance of either rotor or stator,

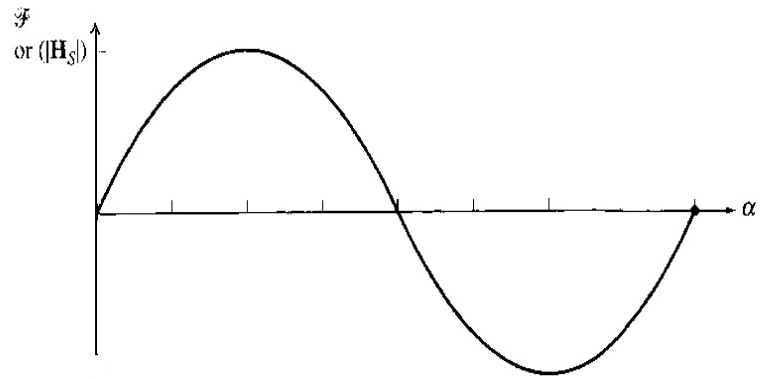
  → B takes shortest possible path across air gap & jumps perpendicularly between rotor & stator
- To develop a sinusoidal voltage in this machine, B should vary sinusoidally along the surface of air gap
- it needs **H** to vary sinusoidally,
- Easiest way is to distribute turns of winding among the slots around surface of machine in a sinusoidal manner

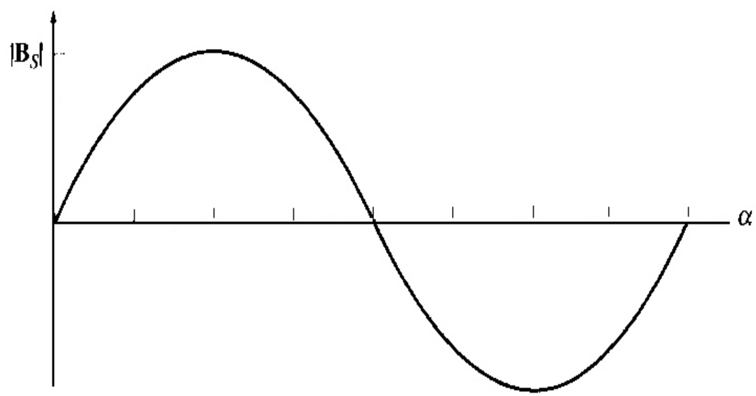
AC MACHINERY FUNDEMENTALS
MMF & B Distribution on ac machines



- ❑ A cylindrical rotor with sinusoidal varying B

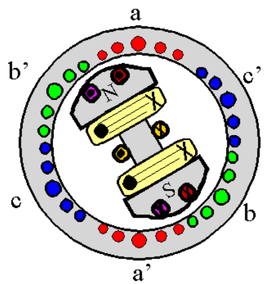






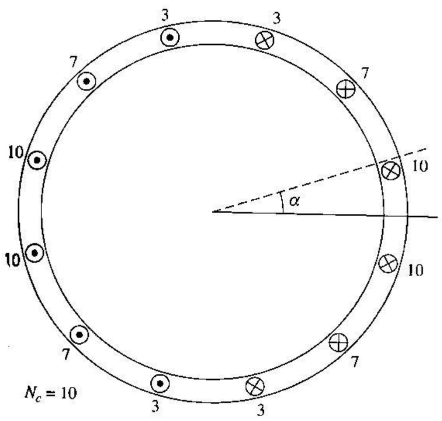
AC MACHINERY FUNDEMENTALS

MMF & B Distribution on ac machines

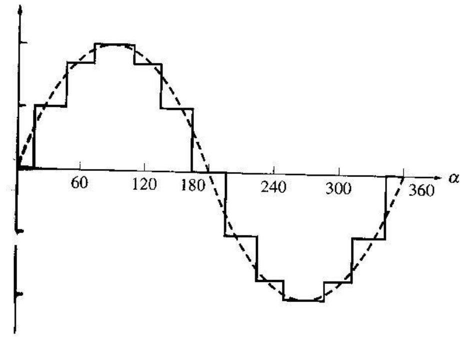


- Figure show such a winding, ➔
- While No. of conductor/slots

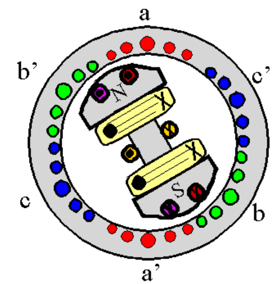
  nC=Nc cosα



- NC=number of conductors at an angle of 0◦ Nc=10 ➔
- As higher the No. of slots around the surface, and as more closely the slots are located a better approximation achieved mmf distribution➔



AC MACHINERY FUNDEMENTALS
MMF & B Distribution on ac machines



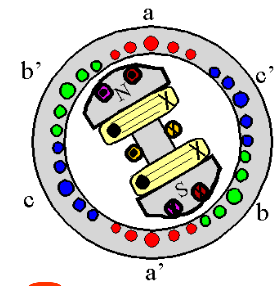
- In practice can not distribute windings exactly in accordance to last equation, since No. of slots is limited & only integral No. of conductors are available in each slot

  → The Resultant mmf approximately sinusoidal
  →some higher order harmonic components present
- Fractional-pitch windings employed to suppress unwanted harmonic components.
- full pitch: if stator coils stretches across an angle same as pole pitch (360/p).
- In design convenient to include equal number of conductors in each slot rather than varying them.

  →Then stronger higher order harmonics are present in comparison to original designs
- There are special harmonic-suppression
- techniques to be employed.

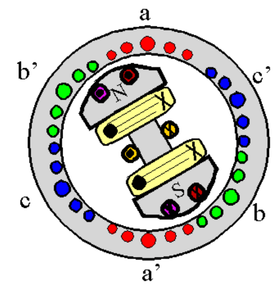
AC MACHINERY FUNDEMENTALS

Induced Voltage in ac Machines



- ❑ As a 3 phase set of currents in a stator → rotating magnetic field
- ❑ A rotating magnetic field → a 3 phase set of voltages in coils of a stator.
- ❑ Equations governing induced voltage in 3 phase stator winding developed in this section.
- ❑ Starting with a single turn coil and expanding it to a general 3 phase stator.

AC MACHINERY FUNDEMENTALS
Induced Voltage in ac Machines

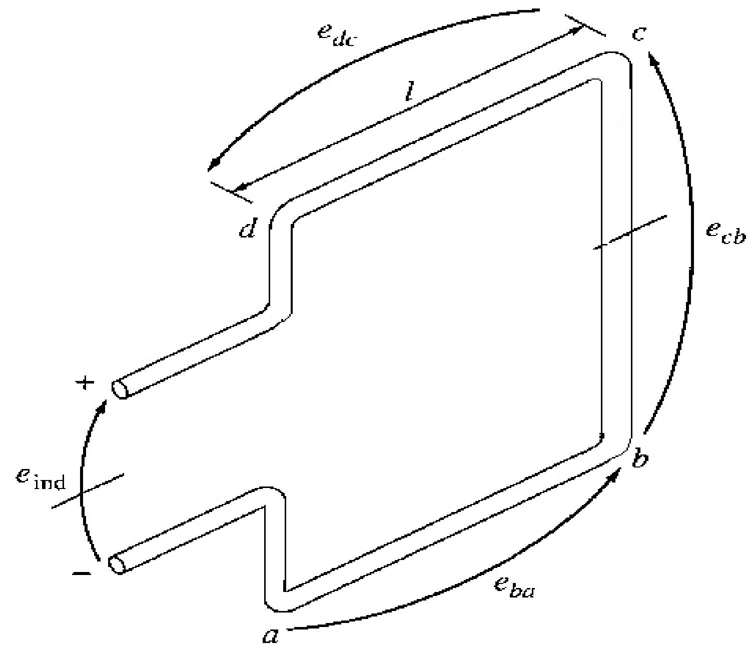


- **Induced voltage in a coil on a 2 pole stator**
- **Figure in Next slide show a rotating rotor with a sinusoidally distributed B, Its stationary stator coil →**

  *** reverse of having a stationary magnetic fiel & rotating loop**

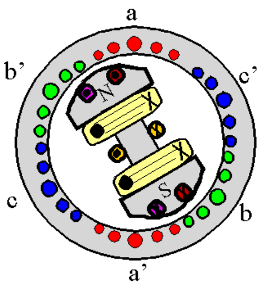
  velocities shown w.r.t. a frame of reference in which B is stationary

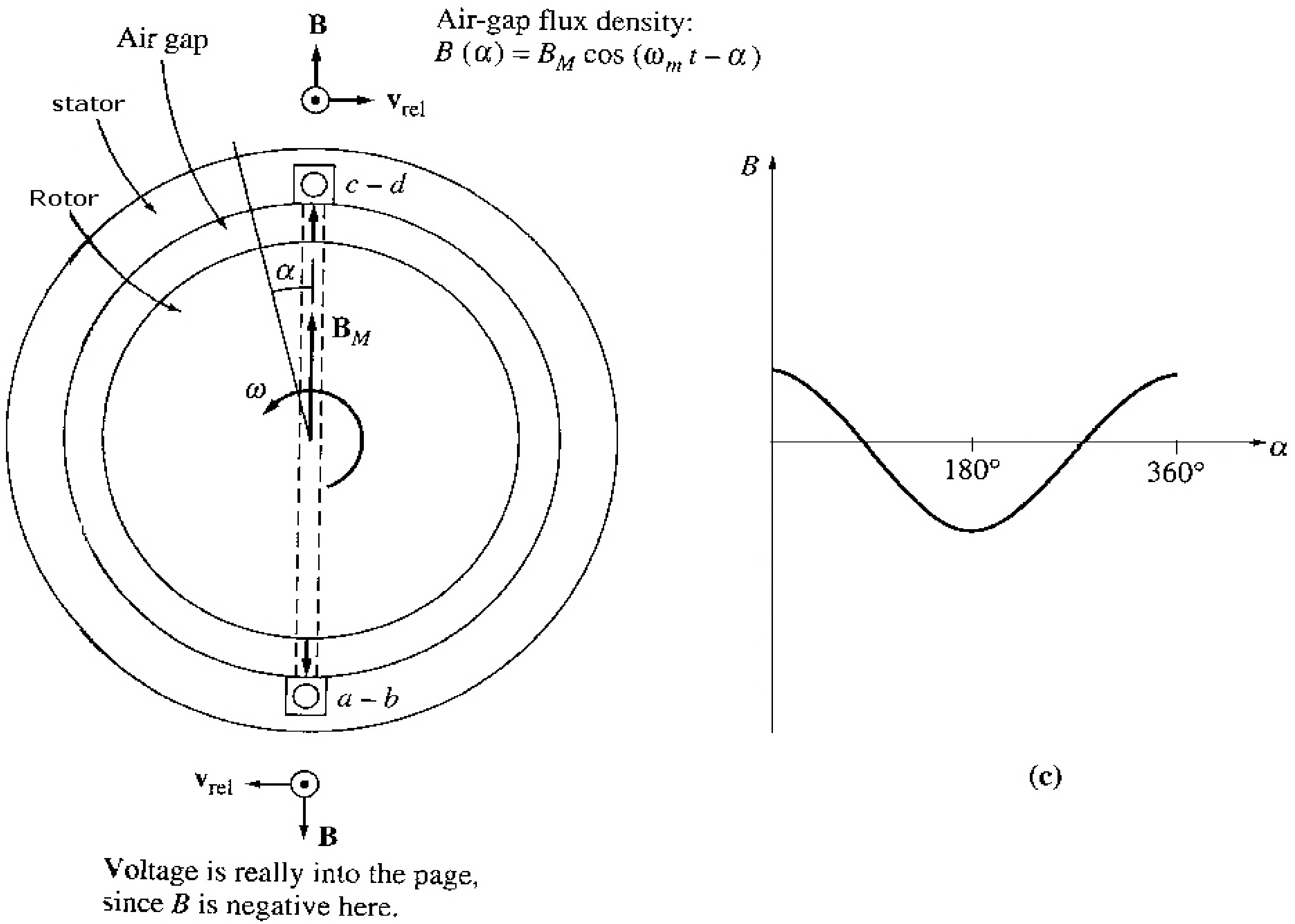
  (i.e. a frame rotating with the same speed as rotating field)



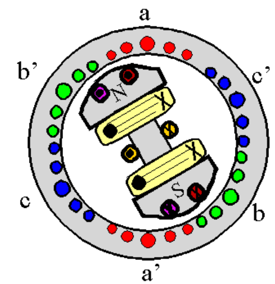
(a)

AC MACHINERY FUNDEMENTALS
Induced Voltage in ac Machines





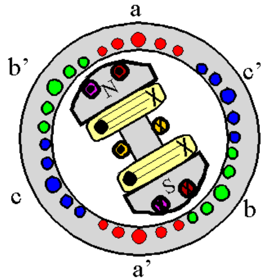
AC MACHINERY FUNDEMENTALS
Induced Voltage in ac Machines



- **Assuming magnitude of B produced by rotor in air gap varies sinusoidally with mechanical angle**
  - **B always radially outward,**
  - **α angle measured from direction of peak rotor B**
  - **$B = B_{max} \cos \alpha$**
  - **Note: in some locations would be toward rotor when its value is negative**
  - **since rotor is rotating at an angular velocity ω_m , magnitude of B at any angle α around stator as function of time is:**

$$B = B_{max} \cos (\omega_m t - \alpha)$$

AC MACHINERY FUNDEMENTALS
Induced Voltage in ac Machines



- **The induced voltage is :**

  e=(v x B) . l

  v= velocity

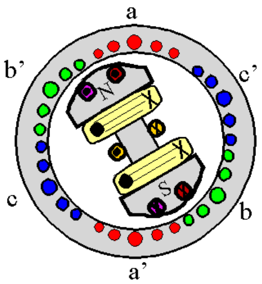
  B= magnetic flux density vector

  l= length of conductor in the magnetic field

  Derived for moving wire in stationary magnetic field

- **Here the wire is stationary & magnetic field is moving, a v_{rel} can be employed (using the magnetic field as reference frame)**

AC MACHINERY FUNDEMENTALS
Induced Voltage in ac Machines

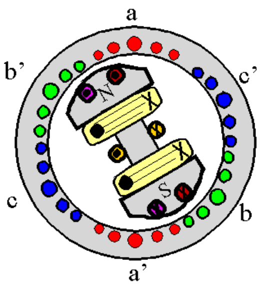


- **Total voltage induced in coil, is sum of voltages induces in each of four sides:**
- ***Segment ab*: *For ab $\alpha=180^\circ$* Assuming B directed radially outward from rotor, angle between v & B in segment ab is 90° while vxB is in direction of l, so:**
- **$e_{ba} = (v \times B) \cdot l = vBl$ directed out of page**

$$= -v\,[B_{max}\cos(\omega_m t - 180^\circ)]\,l$$

$$= -v\,B_{max}\,l\cos(\omega_m t - 180^\circ)$$

AC MACHINERY FUNDEMENTALS
Induced Voltage in ac Machines



- ***segment bc***: **since v x B for this segment is perpendicular to l, voltage on this segment is zero** **ecb=(v x B) . l=0**
- ***segment cd***: **for this segment α=0◦, and B directed outward from rotor, angle between v and B in segment cd is 90◦, while quantity vxB is in direction of l,**
- **edc = (vxB).l**

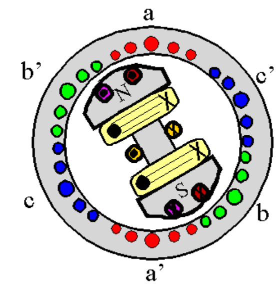
  =vBl directed out of the page

  =v (Bmax cosωmt) l =v Bmax l cosωmt
- ***segment da*** **: voltage on segment da is zero, since vector quantity vxB perpendicular to l ead=(vxB).l=0**
- **Eind = eba+edc=**

-vBmaxlcos(ωmt-180◦)+vBmaxlcosωmt=2 vBmax lcosωmt=

$= 2(r\omega_m)B_m\, l \cos \omega_m t = 2\, r\, l\, B_m\, \omega_m \cos\omega_m t$

AC MACHINERY FUNDEMENTALS
Induced Voltage in ac Machines



- flux passing through coil is $\varphi = 2rlB_{max}$, while $\omega_m = \omega_e = \omega$ for a 2 pole stator
- induced voltage can be expressed as:

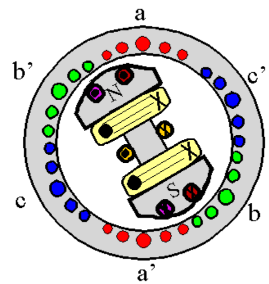
$e_{ind} = \varphi\ \omega \cos\omega t$ in a single turn

if stator has Nc turns of wire

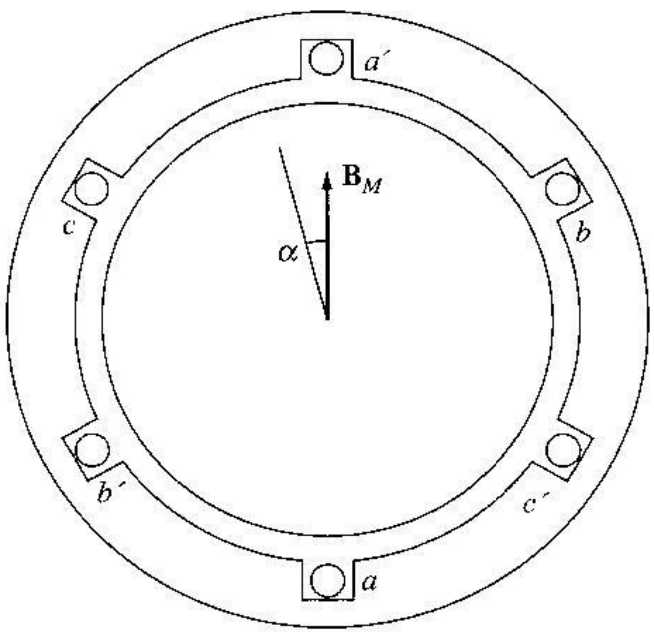
$e_{ind} = N_c\ \varphi\ \omega \cos\omega t$

Next: induced voltage in a 3 phase set of coils computed

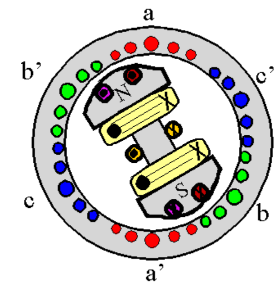
AC MACHINERY FUNDEMENTALS
Induced Voltage in a 3 ph set of coils



- 3 coils, each of Nc turns, placed around rotor
- Voltage induced equal magnitude, 120◦ different in phase



AC MACHINERY FUNDEMENTALS
Induced Voltage in a 3 ph set of coils

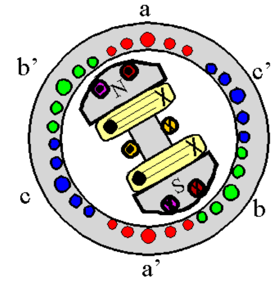


- e_{aa} =Nc φωsinωt V
- e_{bb} =Nc φωsin(ωt-120°) V
- e_{cc} =Nc φωsin(ωt-240°) V
- **Therefore:**

  a 3 ph. currents generate uniform rotating magnetic field in stator air gap

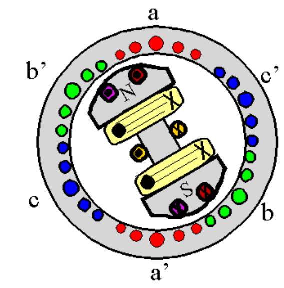
  and a uniform rotating magnetic field can generate a 3 ph. Set of voltages in stator
- The RMS Voltage in 3 ph. Stator
- **Peak voltage** in any phase of this 3 ph. Stator is: Emax=Nc φ ω & since ω=2πf → **Emax=2 π Nc φ f**

AC MACHINERY FUNDEMENTALS
Induced Voltage in a 3 ph set of coils



- **rms voltage of each phase is:** $E_A = \sqrt{2}\pi N_C \varphi f$
- **rms voltage at terminals of machine depend on whether stator is Y or Δ connected**
- **Terminal voltage for Y connected $\sqrt{3}\, E_A$ and for Δ connected is E_A**

AC MACHINERY FUNDEMENTALS
Induced Voltage in a 3 ph set of coils



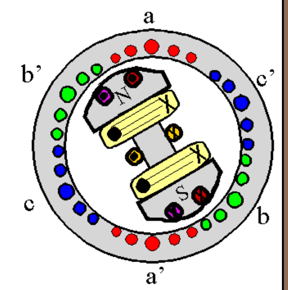
- **Example:**
- **For a simple 2 pole generator, $B_{max\text{-}rotor}=0.2T$, $\omega_m=3600$ r/min**
- **Stator diameter 0.5 m, its coil length 0.3 m, and there are 15 turns per coil**
- **Machine is Y connected**

(a) what are 3 ph. Voltages of gen. as function of time

(b) what is rms ph. Voltage of gen. ?

(c) what is rms terminal voltage of generator?

AC MACHINERY FUNDEMENTALS
Induced Voltage in a 3 ph set of coils



- **Solution:**
- φ=2.r.l.B=d.l.B
- d= diameter , l=length of coil loop
- Flux in machine: φ=(0.5)(0.3)(0.2)=0.03 Wb
- Speed of rotor is: ω=(3600)(2π)(1 min/60)=377 rad/s

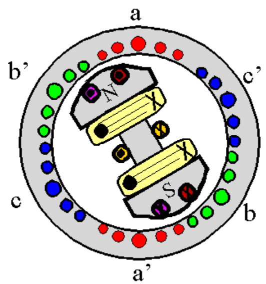
(a) Emax=NC$\varphi\omega$=(15)(0.03)(377)=169.7 V

3 ph. Voltage: eaa'=169.7 sin 377t V, ebb'=169.7 sin (377t-120°) V, ecc'=169.7 sin (377t-240°) V

(b) rms phase Voltage of generator:
EA=Emax/√2 = 169.7/√2 =120 V

(c) Since generator is Y connected :
VT=√3EA= √3(120)=208 V

AC MACHINERY FUNDEMENTALS
Applied Torque in ac machine



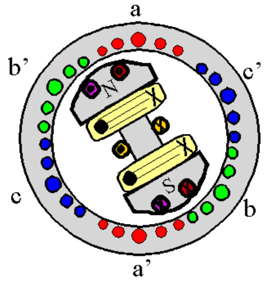
- **2 magnetic fields present in a ac machine under normal operating conditions:**

(a) a magnetic field from rotor circuit

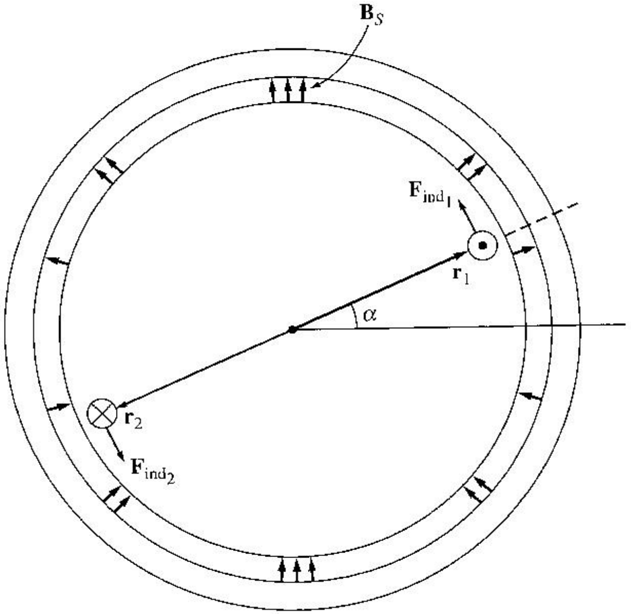
(b) another magnetic field from stator circuit

- **Interaction of 2 magnetic fields produces torque in machine**
- **similar as 2 permanent magnets near each other will experience a torque causes them to line up**

AC MACHINERY FUNDEMENTALS
Applied Torque in ac machine

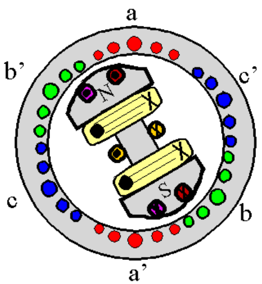


- **Fig. shows a simplified ac machine, with:**
  - a sinusoidal stator flux distribution peaks in upward direction &
  - a single coil or wire mounted on rotor
- **stator flux distribution** $Bs(\alpha)=Bs \sin\alpha$
- **assuming: when Bs positive, B points radially outward from rotor surface to stator surface**



$|\mathbf{B}_S(\alpha)| = B_S \sin\alpha$

AC MACHINERY FUNDEMENTALS
Applied Torque in ac machine



- **applied force on each conductor of rotor:**

force on conductor 1 located perpendicular to page:

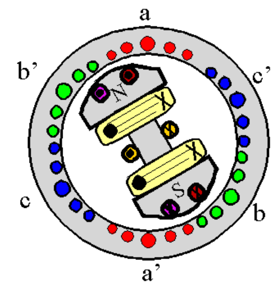
$F=i(l \times B)=ilB_s \sin\alpha$ direction shown in last figure

torque :$T_{applied}=(r \times F)=r.i.l.B_s \sin\alpha$ counterclockwise

therefore: Torque on rotor loop is:

$T_{applied}=(r \times F)=2rilB_s \sin\alpha$ counterclockwise

AC MACHINERY FUNDEMENTALS
Applied Torque in ac machine



- **Alternatively this equation can be determined through below figure also:**

1- i flowing in rotor coil produces $H_R = C\ i$

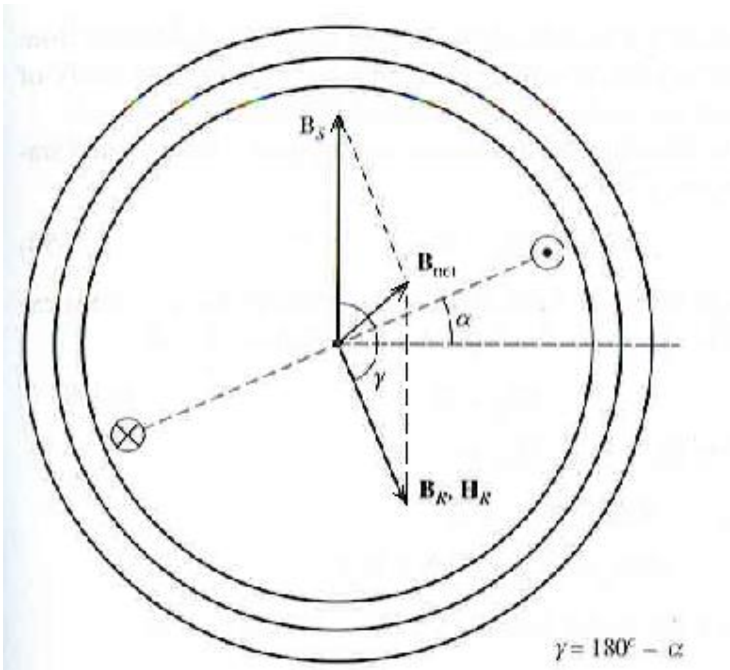
C : a constant

2- angle between peak of B_S & peak of H_R is γ and

$\gamma=180-\alpha$, $\sin\gamma=\sin(180-\alpha)=\sin\alpha$

- **Combining these 2 observations: Torque on loop is:**
- **$T_{app}=K\ H_R\ B_S \sin\alpha$**

counterclockwise



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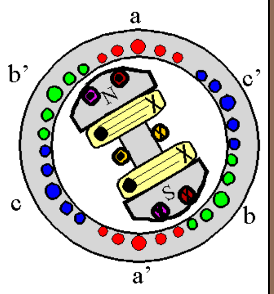
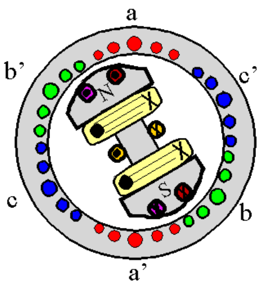
Applied Torque in ac machine



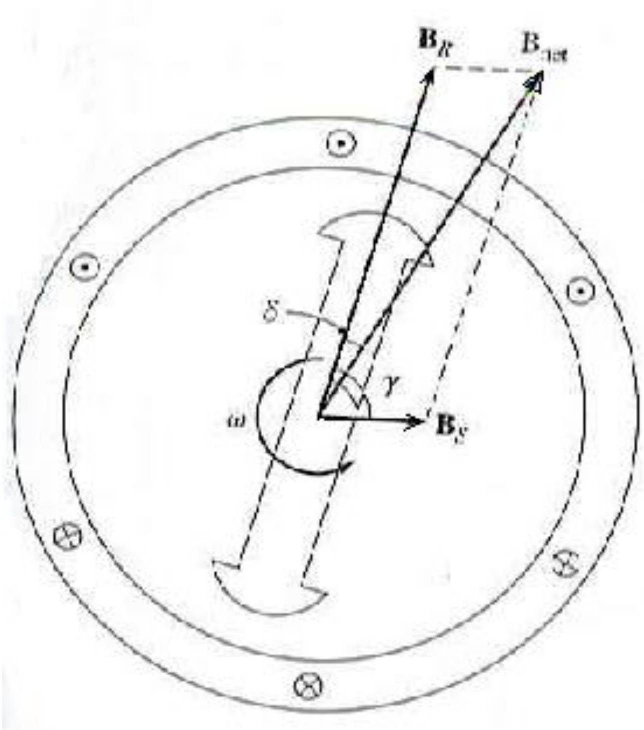
- **where:**

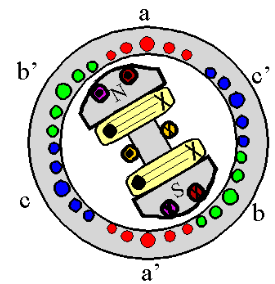
  K, constant dependent on machine construction
- $T_{app} = K\ (H_R \times B_S)$
- since $B_R = \mu\ H_R$ it can be reordered as :
- $T_{app} = k\ (B_R \times B_S)$ (where: $k = K/\mu$)
- The net flux density in machine:
- $B_{net} = B_R + B_S \rightarrow B_S = B_{net} - B_R$
- $T = k\ B_R \times (B_{net} - B_R) = k(B_R \times B_{net}) - k(B_R \times B_{Rapp})$
- The 2nd term is always zero →
- $T_{app} = k\ B_R \times B_{net}$ or $T_{app} = k\ B_R\ B_{net} \sin\delta$
- δ: angle between B_R and B_{net}

AC MACHINERY FUNDEMENTALS
Applied Torque in ac machine



- **Figure: is an example of one application**
- **Its magnetic fields rotating in counterclockwise direction, shown through direction of rotation**
- **While the direction of applied torque on machine by applying Right Hand Rule to the last equation is clockwise or opposite to direction of rotation**
- **Conclusion: Machine must be acting as a Generator**



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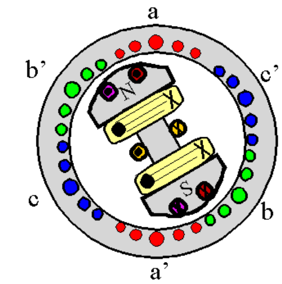
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END OF LECTURE 3