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شابتري

CH3 Fundamentals of Ac Machinery.

a+1+10+8 +5+

Ac (Motor) →

A c electrial energy | Ac Machine | Mechanical Energy

← Ac (generator)

* Types of Ac Machines :-

1. Synchronous Machines: They are generator or Motors whose magnetic field current is supplied by separate Dc source.

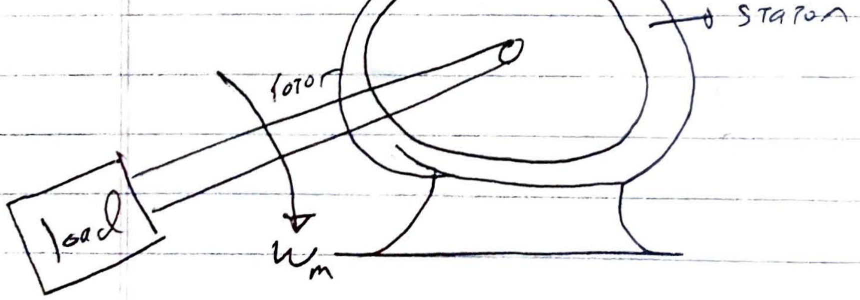
2. Inductions Machines :- They are Motors or generator whose magnetic field current is supplied by Magnetic Induction (Transformer action)

* Construction of Ac Machines :-

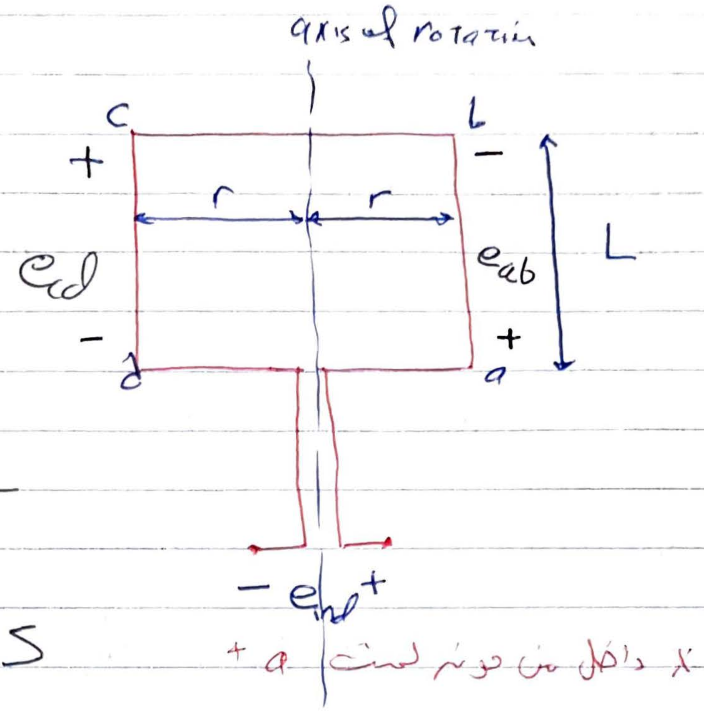
The Ac machine consits of two main parts :-

1. Stator :- it's the stationary part and it carry high current.

2. Rotor :- it's the rotating part in the machine.

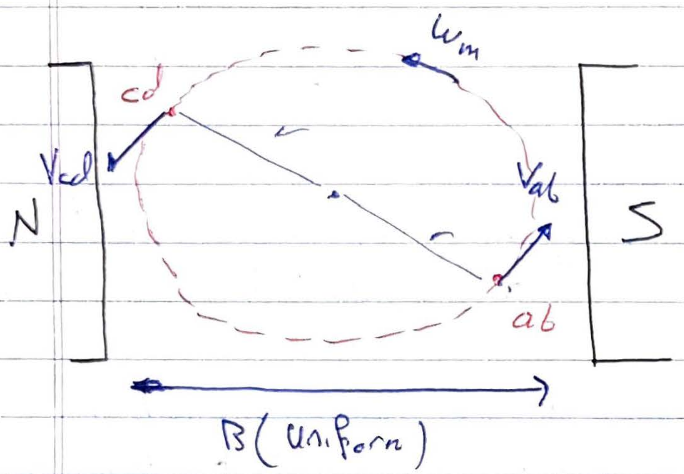


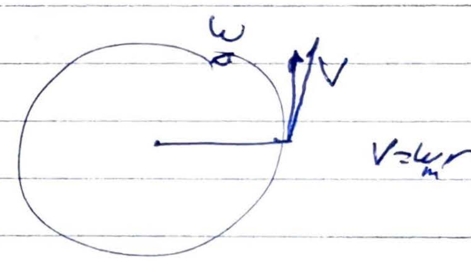
⊛ Voltage induced in a simple loop rotating in a uniform magnetic field



Induced Voltage $= (\vec{V} \times \vec{B}) \cdot L$

V: velocity of conductor
B: Magnetic flux density
L: Length of conductor



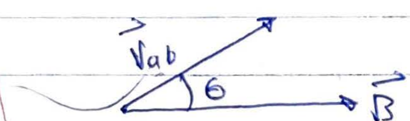


⊛ segment ab

$$e_{ab} = (\vec{V}_{ab} \times \vec{B}) \cdot \vec{L}_{ab}$$

$\vec{V}_{ab} \times \vec{B}$

into the page



$$e_{ab} = (VB\sin\theta)\, L\cos(0)$$

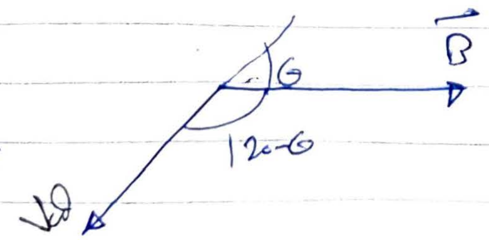
$$e_{ab} = V \cdot B\, L \sin\theta$$

segment cd

$$e_{cd} = (V_{cd} \times B) \cdot L_{cd} \quad , \quad L_{cd} = L$$

$\vec{V}_{cd} \times \vec{B}$

out of the page



$$e_{cd} = (VB\sin(120-\theta))\, L\cos(0)$$

$$e_{cd} = VBL\sin\theta$$

Note $\sin(A \mp B) = \sin A \cos B \mp \cos A \sin B$
$\cos(A \mp B) = \cos A \cos B \mp \sin A \sin B$

* Segment bc

$e_{bc} = (\vec{V}_{bc} \times \vec{B}) \cdot L$, $(V_{bc} \times B) \perp L(2r)$ $= \boxed{e_{bc} = 0}$

* Segment ad

$e_{da} = (\vec{V}_{da} \times \vec{B}) \cdot L$, $(\vec{V}_{da} \times \vec{B}) \perp L(da)$ $\Rightarrow \boxed{e_{da} = 0}$

* The total induced voltage is given by "KVL":

$e_{ind} = e_{ab} + e_{bc} + e_{cd} + e_{da} = e_{ab} + e_{cd}$

$e_{ind} = 2VBL\sin\theta$

$w = \frac{d\theta}{dt}$ $\Rightarrow \boxed{\theta = w_m t}$

$e_{ind} = 2(w_m r)BL\sin\theta = (2rL)(B w_m \sin(w_m t))$

$e_{ind} = AB\, w_m \sin(w_m t)$

where: $A = 2rL \Rightarrow$ Area

$e_{ind} = \phi\, w_m \sin(w_m t)$, $\phi = BA$ (flux)

* For [n] coil the induced voltage is given by: $\boxed{e_{ind} = n\phi w_m \sin(w_m t)}$

In general, the induced voltage is:

$e_{ind} = K\phi\, w_m \sin(\theta)$

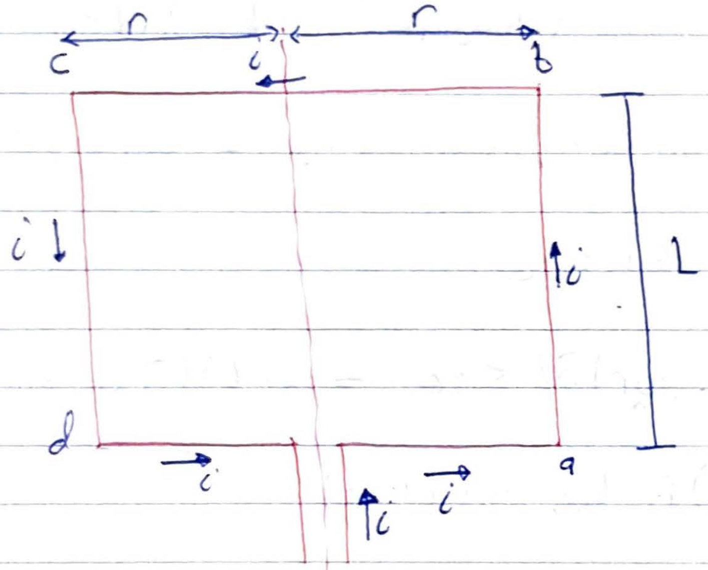
The induced Voltage depend on:..

1) Magnetic flux of the machine
2) speed of machine
3) constant represents the construction of machine (Numbers of turns and its shape).

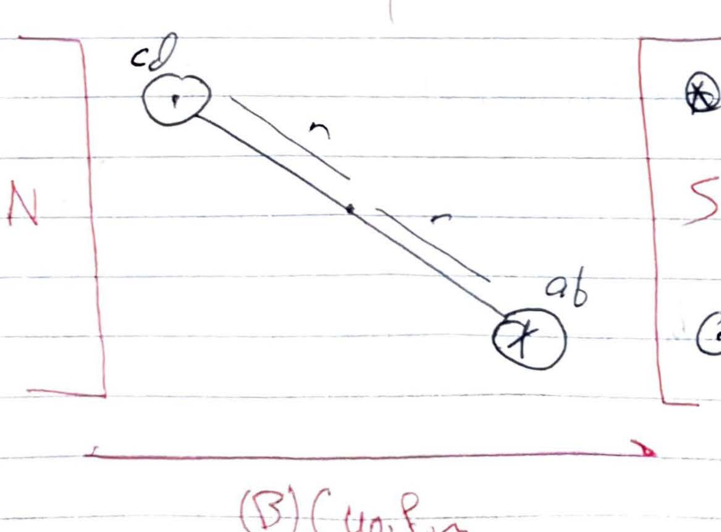
⊗ Torque induced in current carrying loop in a uniform magnetic field

Induced force $\longrightarrow F_{ind} = i \vec{L} \times \vec{B}$

Induced Torque $\longrightarrow T_{ind} = \vec{r} \times \vec{F}_{ind}$



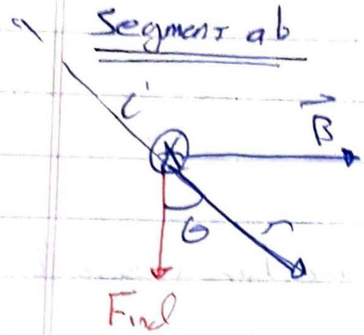
Axis of Rotation



⊗: means that the current is flowing into the Page

⊙ means that the current ---

Segment ab

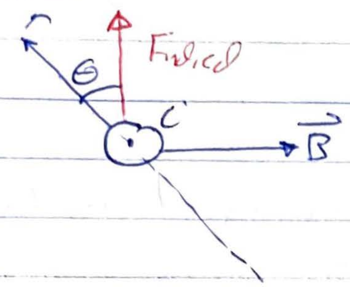


$$F_{ind,ab} = i L_{ab} \times B = iLB\sin 90 = iLB$$

$$\tau_{ind,ab} = \vec{r} \times \vec{F}_{ind,ab} = r F_{ind,ab} \sin\theta$$

$\tau_{ind,ab} = r i L B \sin(\theta)$ "clockwise"

Segment cd



$$F_{ind,cd} = i \vec{L}_{cd} \times \vec{B} = iLB\sin(90°) = iLB$$

$$\tau_{ind,cd} = \vec{r} \times \vec{F}_{ind,cd} = r F_{ind,cd} \sin\theta$$

$$\tau_{ind,cd} = r i L B \sin\theta$$

Segment bc

$F_{ind,bc} = i L_{bc} \times \vec{B} =$

$\vec{r}$ is parallel $F_{ind,bc} \Rightarrow \tau_{ind,bc} = 0$

$\tau_{ind} = \vec{r} \times \vec{F}_{ind,bc}$

Segment da

$\vec{F}_{ind,da} = i \vec{L}_{da} \times \vec{B}$, $\vec{r}$ is Parallel with $F_{ind,da}$, $\tau_{ind,da} = 0$

The Total Induced torque is:

$$\tau_{ind} = \tau_{ab} + \tau_{bc} + \tau_{cd} + \tau_{da}$$

$A = 2rL$
$=$ Area.

$$= 2ri LB\sin\theta = (2rL) B i \sin\theta = ABi\sin\theta$$

$\tau_{ind} = \phi i \sin\theta$, $\phi = BA$

For n coils, the net Induced Torque is o

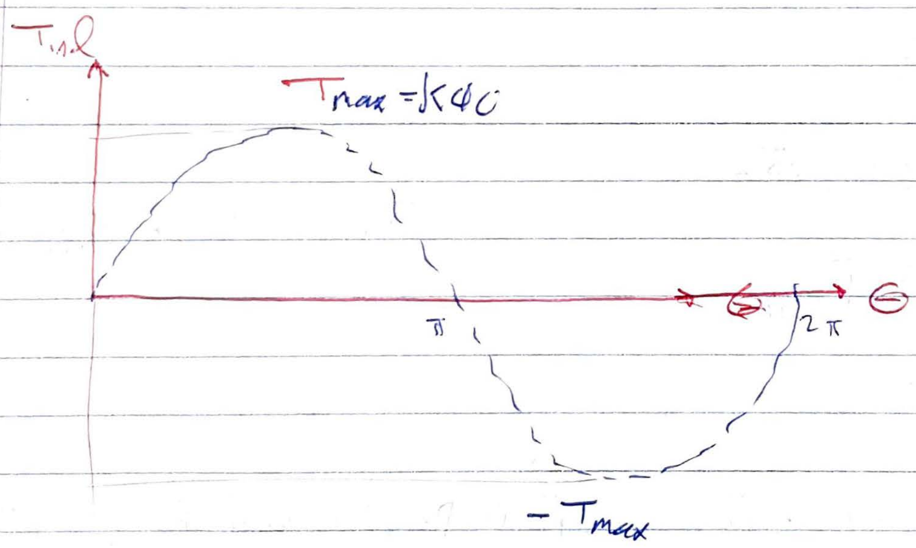
$$T_{ind} = n\phi i \sin\theta$$

In general, the Torque induced in the machine is given by o

$$T_{ind} = K\phi i \sin(\theta)$$

The torque developed by the machine depends on o

1) magnetic flux
2) Machine current
3) Constant depends on the construction of the machine such as its geometry and Numbers of ~~Ratio~~ Turns.



any current flows in the loop, it will produces a Magnetic field, B_{Loop}, "Ampers Law"

$$\oint H \cdot dl = I_{enc}$$

$$H\theta = i$$

$H = \frac{i}{G}$; G : is a factor depends on geometry of the loop.

* The Loop magnetic flux density $B_{loop} = \mu H = \frac{\mu i}{G}$

$B_{Loop} = \frac{\mu i}{G}$ OR $i = \frac{G B_{Loop}}{\mu}$

$i = \frac{G B_r}{\mu}$; $B_r = B_{loop}$ → Rotor magnetic field.

(B) is the external or stator magnetic field ($B = B_s$)

Recall, the induced Torque equation →

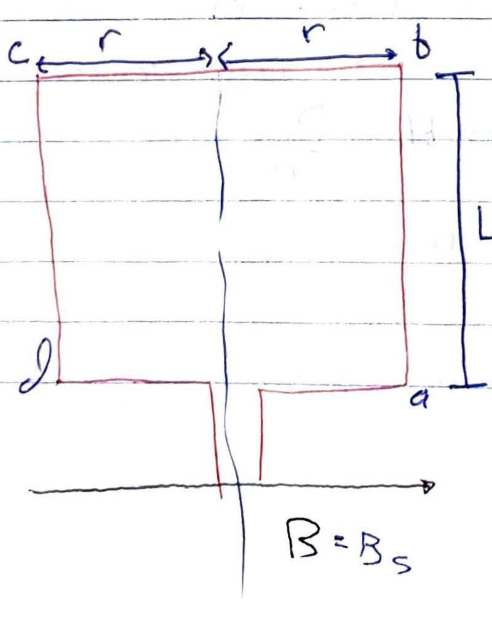
$$T_{ind} = A B_s i \sin\theta = A B_s \left(\frac{G B_r}{\mu}\right) \sin\theta$$

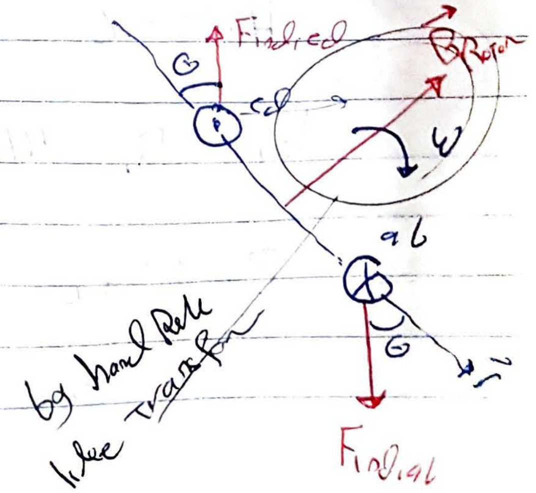
$$T_{ind} = \frac{AG}{\mu} B_r B_s \sin\theta$$

Video *

$$\boxed{T_{ind} = K \vec{B_r} \times \vec{B_s}}$$

* Torque induced in a simple rotating loop in a uniform magnetic field





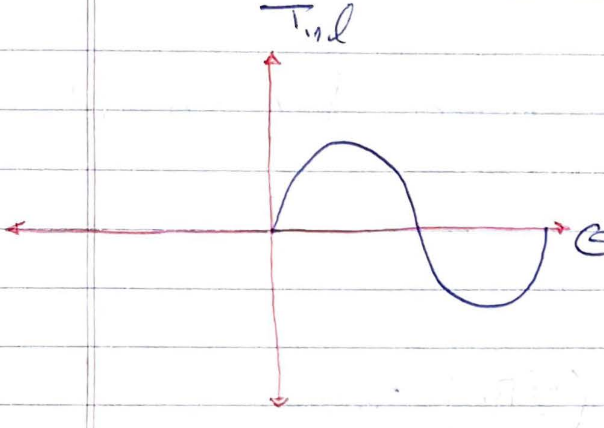
$T_{ind} = 2 i l B_S \sin\theta$ —— ①

$T_{ind} = A B_S i \sin\theta$, $A = 2rL$ $\Rightarrow T_{ind} = \phi i \sin\theta$

⊗ for n loop, the torque developed is $T_{ind} = n \phi i \sin\theta$

In general, the induced is so $T_{ind} = K \phi i \sin\theta$

constant depends on the construction of the machine



⊗ Alternative way to express the induced torque.

Any current flows in the loop, it will generate a magnetic field "Ampere law"

$\oint H_r \cdot dl = I_{enc}$, where H_r is the rotor magnetic field intensity.

لانه الشكل مش لازم يكون دائري

$H_r G = i$, where G is the factor depend on the loop geometry.

but $B_r = \mu H_r \Rightarrow H_r = \dfrac{B_r}{\mu}$

$\dfrac{B_r}{\mu} G = i$ —— ②

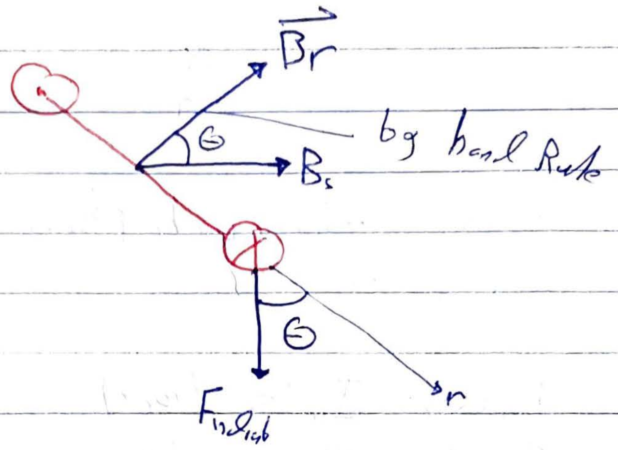
by substituting equation ② in ①.

$$T_{ind} = 2\left(\frac{B_r G}{\mu}\right) L B_s r \sin\theta$$

where B_s is the stator magnetic flux density.

$$T_{ind} = \left(\frac{2GLr}{\mu}\right) B_r B_s \sin\theta$$

In general $T_{ind} = K B_r B_s \sin\theta$



The Torque induced:

$$\vec{T_{ind}} = K \vec{B_r} \times \vec{B_s}$$

⊛ The Torque induced depends on:

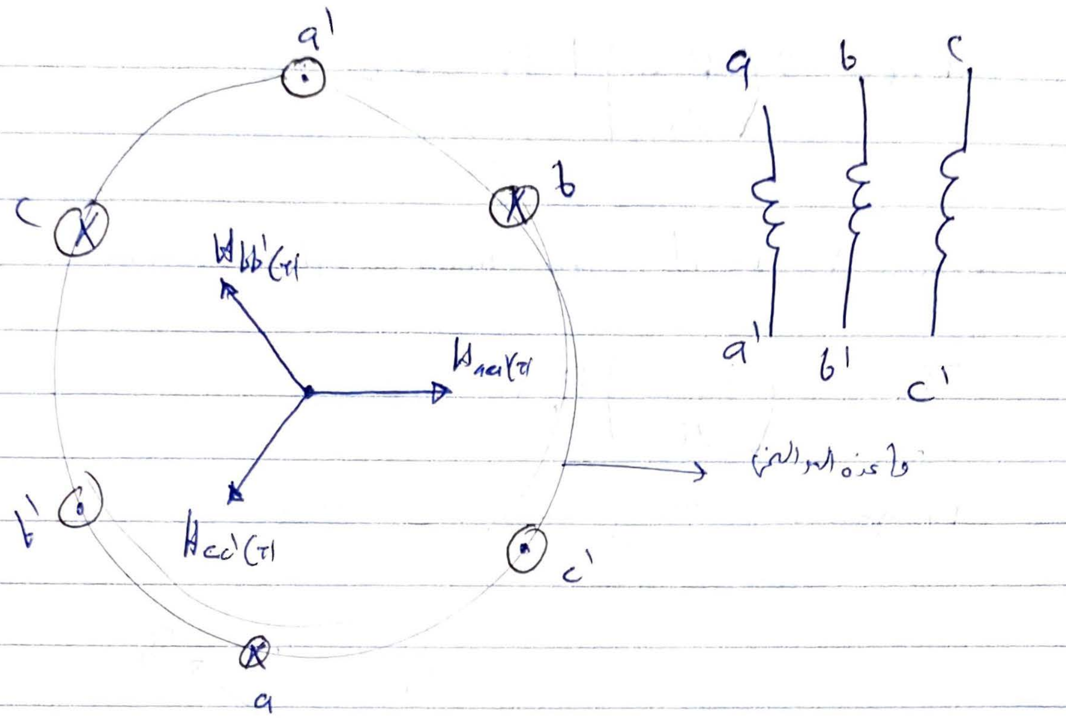
1) The strength of rotor magnetic field.
2) The strength of stator magnetic field.
3) Sine of angle between $\vec{B_r}$ & $\vec{B_s}$.
4) constant representing the construction of the machine (# of Turns, sizes, shape)

Note: $\vec{B_r}$ & $\vec{B_s}$ tend to align (line up) themselves with each other.

⊛ Rotating Magnetic field:

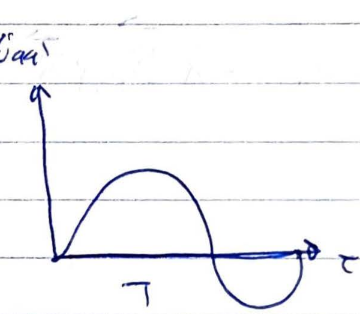
⊛ if $\vec{B_s}$ is rotating, the Rotor will chase it and it rotates

⊛ Assume that, we have 3-phase winding shifted electrically from each other by 120°



* Assuming that, the phases currents applied to the stator winding are

$i_{aa'}(t) = I_m \sin(\omega_e t)$
$i_{bb'}(t) = I_m \sin(\omega_e t - 120°)$
$i_{cc'}(t) = I_m \sin(\omega_e t + 120°)$



$f_e = \frac{1}{T} \Rightarrow \omega_e = 2\pi f_e$

* where ω_e is the electric radian frequency
The magnetic field intensities are.

$\vec{H}_{aa'}(t) = H_m \sin(\omega_e t) \angle 0°$

$\vec{H}_{bb'}(t) = H_m \sin(\omega_e t - 120) \angle 120°$

$\vec{H}_{cc'}(t) = H_m \sin(\omega_e t + 120) \angle -120°$

* The magnetic flux densities are:

$B = \mu H$

$\vec{B}_{aa'} = B_m \sin(\omega_e t) \angle 0$
$\vec{B}_{BB'} = B_m \sin(\omega_e t - 120°) \angle 120°$
$\vec{B}_{cc'} = B_m \sin(\omega_e t + 120) \angle -120°$

The net magnetic field is ...

$$\vec{B}_{net} = \vec{B}_s = \vec{B}_{aa'} + \vec{B}_{bb'} + \vec{B}_{cc'}$$

At $\omega_e t = 0°$

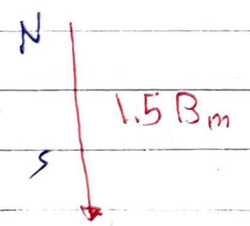
$$\vec{B}_{aa'} = 0 \angle 0°$$
$$\vec{B}_{bb'} = -\frac{\sqrt{3}}{2} B_m \angle 120°$$
$$\vec{B}_{cc'} = \frac{\sqrt{3}}{2} B_m \angle -120°$$

$$\vec{B}_s (\omega_e t = 0) = B_{aa'} + B_{cc'} + B_{bb'}$$

$$\vec{B}_s(\omega_e t = 0) = \left(-\frac{\sqrt{3}}{2} \cancel{B_m} \angle 120° + \frac{\sqrt{3}}{2} \angle -120°\right) B_m$$

$$\vec{B}_s(\omega_{e}(t) = 0) = \left[-\frac{\sqrt{3}}{2}\left(-\frac{1}{2} + j\frac{\sqrt{3}}{2}\right) + \frac{\sqrt{3}}{2}\left(-\frac{1}{2} - j\frac{\sqrt{3}}{2}\right)\right] B_m$$

$$= -j1.5 B_m = 1.5 \angle -90°$$



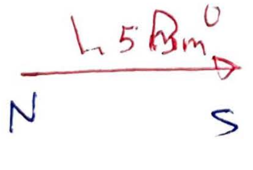
from 3φ causes make Rotating Magnetic

At $\omega_e t = 90°$

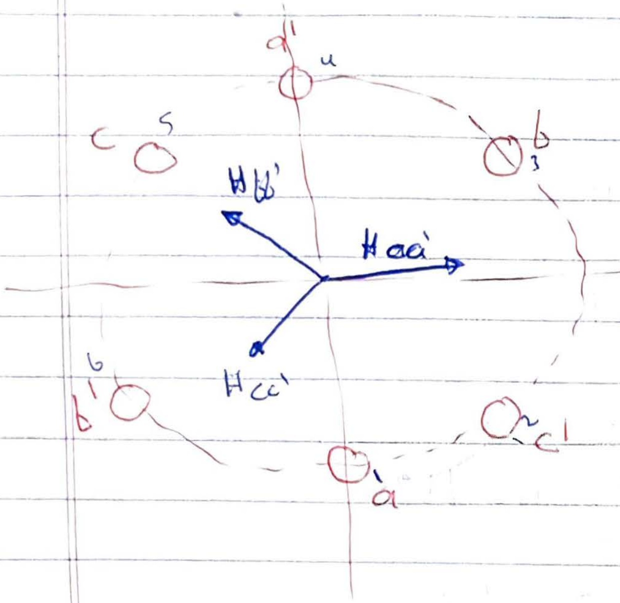
$$B_{aa'} = B_m \angle 0°$$
$$B_{bb'} = -\frac{1}{2} B_m \angle 120°$$
$$B_{cc'} = -\frac{1}{2} B_m \angle -120°$$

$$B_s = B_m + -\frac{1}{2} B_m\left(-\frac{1}{2} + j\frac{\sqrt{3}}{2}\right) - \frac{1}{2} B_m\left(-\frac{1}{2} - j\frac{\sqrt{3}}{2}\right)$$

$$B_s = 1.5 B_m \angle 0$$



Rotating Magnetic field



The net magnetic field is given by

$$\vec{B}_{net} = \vec{B}_{aa'}(t) + \vec{B}_{bb'}(t) + \vec{B}_{cc'}(t)$$

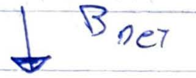
when $B_{aa'} = B_m \sin(\omega t) \angle 0^\circ$

$B_{bb'} = B_m \sin(\omega t - 120^\circ) \angle 120^\circ$

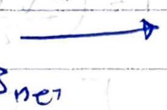
$B_{cc'} = B_m \sin(\omega t + 120^\circ) \angle -120^\circ$

$$\vec{B}_{net} = 1.5\, B_m \sin(\omega t)\, \hat{x} - 1.5\, B_m \cos(\omega t)\, \hat{y}$$

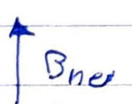
$\omega t = 0 \Rightarrow \vec{B}_{net} = -1.5\, B_m \hat{y}$



$\omega t = 90 \Rightarrow B_{net} = 1.5\, B_m \hat{x}$



$\omega t = 180 \Rightarrow B_{net} = 1.5\, B_m \hat{y}$



* The Relation between electric frequency & speed of magnetic field

* winding sequence is $a c' b a' c b'$

* Number of poles $= P = 2$ or number of pole pair $= \frac{P}{2} = 1$

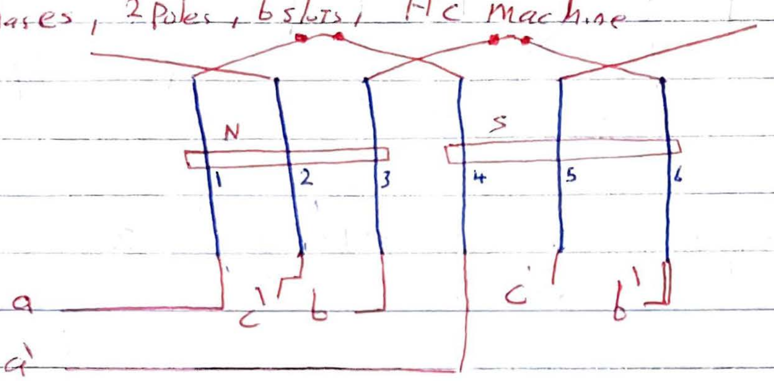
$\Theta_e = \Theta_m$ where Θ_e: electric angular position

Θ_m: mechanical angular position

$\omega_e = \omega_m$ where ω_e : electric radian frequency ($\omega_e = 2\pi f_e$)
ω_m : Mechanical speed (speed of rotating magnetic field)

⊗ Winding diagram : توزيع ملف وترنس slots الكامل على Rotating Magnetic field

⊗ 3-phases, 2 poles, 6 slots, Ac machine



ه° اكهرن اصابع
معدل ملف

$$\text{phase difference} = \frac{120^\circ}{360} \times \frac{\text{Number of slots}}{(\text{Number of pole Pairs} = P/2)}$$

$$= 1/3 \times \frac{6}{1} = 2$$

phase - a ⟶ 1
phase - b ⟶ 3
phase - c ⟶ 5

⊗ if the sequence of stator winding was repeated, then we will get a 4-pole Ac machine.

⊗ winding sequence : $a_1 c_1' b_1 a_1' c_1 b_1' - a_2 c_2' b_2 a_2' c_2 b_2'$

in this case, the net magnetic flux density will move half a cycle per each electric cycle

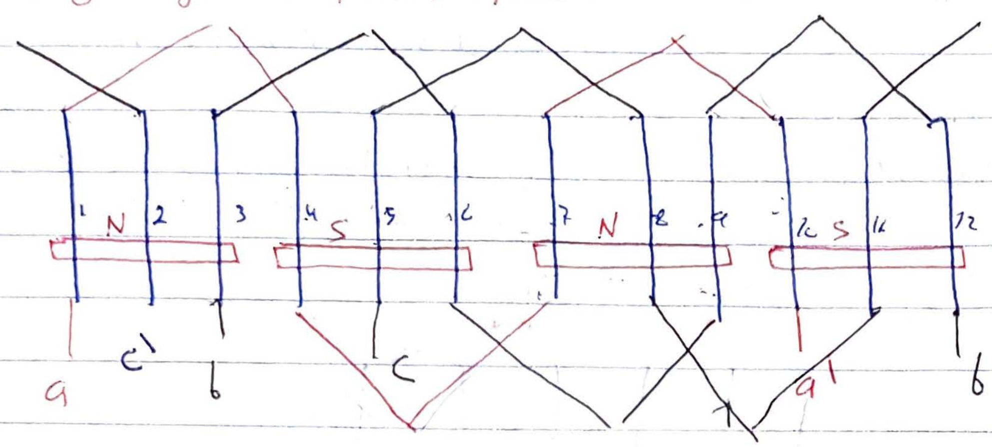
$$\theta_m = \frac{\theta_e}{2} \Rightarrow \omega_m = \frac{\omega_e}{2}$$

Note: B_{net} will move a complete cycle per each electric cycle

For $\theta_e = \theta_m$
$\omega_e = \omega_m$

external Peaper.

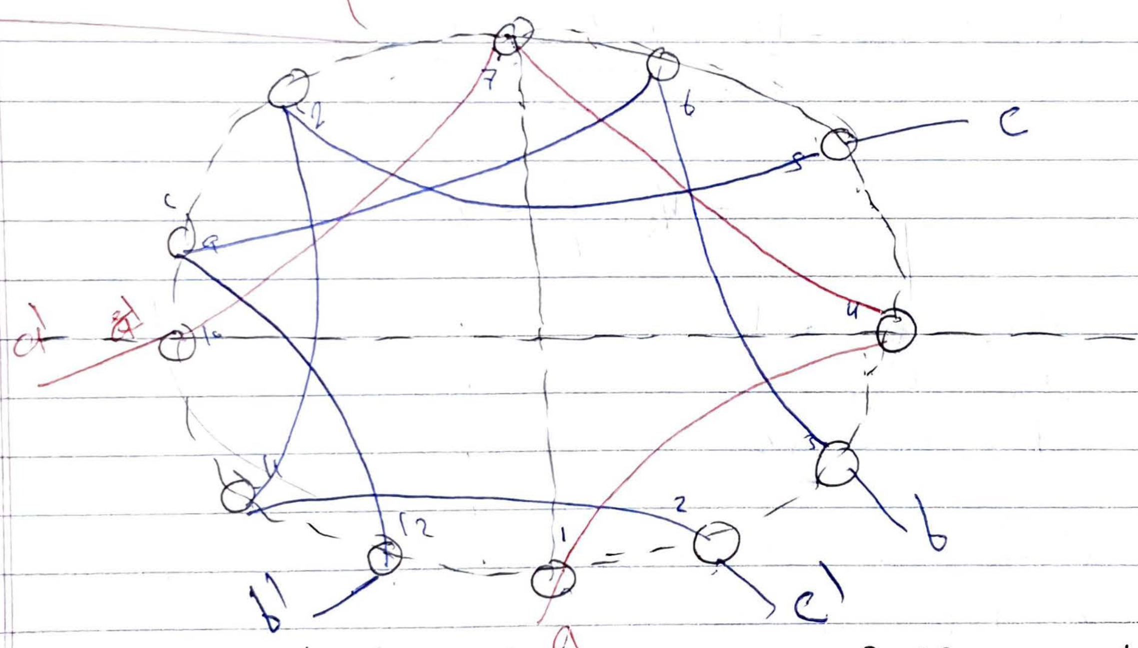
winding diagram, 3 phase, 4 poles, 12 slots



phase difference = $\frac{120}{360} \times \frac{\#\text{ of slots}}{\#\text{ of pole}} = \left(\frac{12}{2}\right)\left(\frac{120}{360}\right) = 2$

phase a → 1
phase b → 3
phase c → 5

* draw it from Video



In general, the speed of rotating magnetic field is given by eq

$$\omega_m = \frac{\omega_e}{(P/2)} \quad \text{OR} \quad \omega_m = \frac{2}{P}(2\pi f_e) = \frac{4\pi f_e}{P}$$

* The speed of rotating magnetic field in rpm, n_m is given by

$$n_m = \frac{60}{2\pi}\omega_m = \frac{30}{\cancel{\pi}}\left(\frac{4\cancel{\pi} f_e}{P}\right) \Rightarrow \boxed{n_m = \frac{120}{P} f_e}$$

Induced Voltage in three phase - set of coils.

Assuming that the rotor is rotating at angular speed ω_m and it has a uniform magnetic flux density, then the magnetic flux density in the air-gap between the stator & Rotor varies sinusoidally with a mechanical angle α.

الهدف : الحصول على end حسب العلاقة $N_c \phi \omega_m \sin$
ولكن بعدم حركة Stator دائما تتغير بجعل الـ B
يتغير Sinusoidally ، وذلك يعطي نفس العلاقة .

$$B = B_m \sin \alpha$$

if the numbers of turns in each coil is N_c, then the induced voltages at phase a, b, c are given by

$$e_{aa'} = N_c \phi \omega \sin(\omega t) \quad \text{Volt}$$
$$e_{bb'} = N_c \phi \omega \sin(\omega t - 120) \quad \text{Volt},$$
$$e_{cc'} = N_c \phi \omega \sin(\omega t + 120) \quad \text{Volt},$$

- The Peak value of Induced Voltage is:

$$E_{peak} = N_c \phi \omega = 2\pi N_c \phi f$$

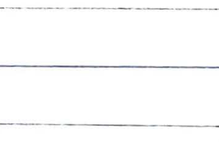
- The RMS value of the induced voltage or phase rms voltage is given by

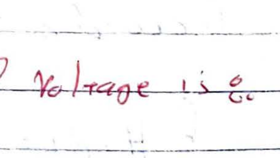
$$E_{RMS} = \frac{E_{peak}}{\sqrt{2}} = \sqrt{2}\, \pi N_c \phi f$$

- the line-line RMS value of Induced Voltage is:

$$E_{L-L} = \sqrt{3}\, E_{RMS} \quad \text{Y-connected winding}$$

$$E_{L-L} = E_{RMS} \quad , \Delta \text{ connec}$$



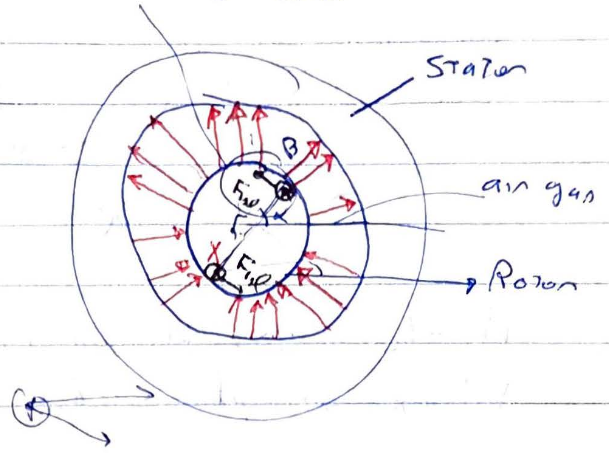


Induced Torque in AC Machine

* Assume that the field distribution of stator is given by:

$$B_{stator} = B_S \sin\alpha$$

direction by $i \times B$



Induced forces:

$$F_{ind,1} = iLB_S \sin\alpha$$
$$F_{ind,2} = iLB_S \sin\alpha$$

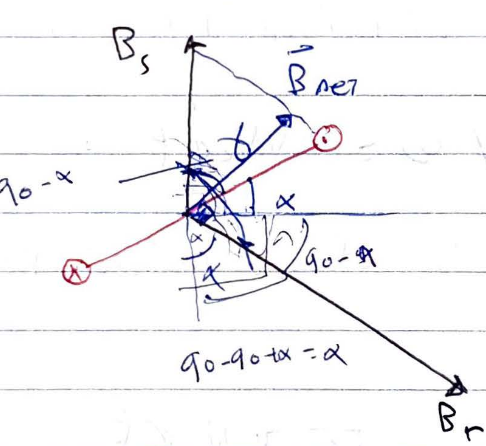
Induced Torques:

$$\tau_{ind,1} = rLiB \sin\alpha$$
$$\tau_{ind,2} = rLiB_S \sin\alpha$$

The net Induced Torque is:

$$\tau_{ind} = 2rLiB_S \sin\alpha.$$

$\alpha = \pi - \delta$



According to Amperes law

$$\oint H_R \cdot dl = i \Rightarrow H_r = Ci \quad , C \text{ is constant}$$

$$B_r = \mu H_r = \mu Ci \Rightarrow \boxed{i = \frac{B_r}{\mu C}}$$

$$\tau_{ind} = 2rL\left(\frac{B_r}{\mu C}\right) B_S \sin\alpha$$

$$= KB_r B_S \sin\alpha = KB_r B_S \sin(180-\delta)$$

$$= K B_r B_s \sin\delta \quad , \quad T_{ind} = K \vec{B}_r \times \vec{B}_s$$

$$\vec{B}_{net} = \vec{B}_r + \vec{B}_s$$

$$B_s = \vec{B}_{net} - \vec{B}_r$$

$$\boxed{T_{ind} = K \vec{B}_r \times \vec{B}_{net}}$$

⊗ T يأتي من تداخل B_r و B_s ، اذا T_{ind} مع Motor
عكس Generator

Note: The ~~actual~~ direction of rotation magnetic field is reversed by switching the phase currents of any two coil.
مهم

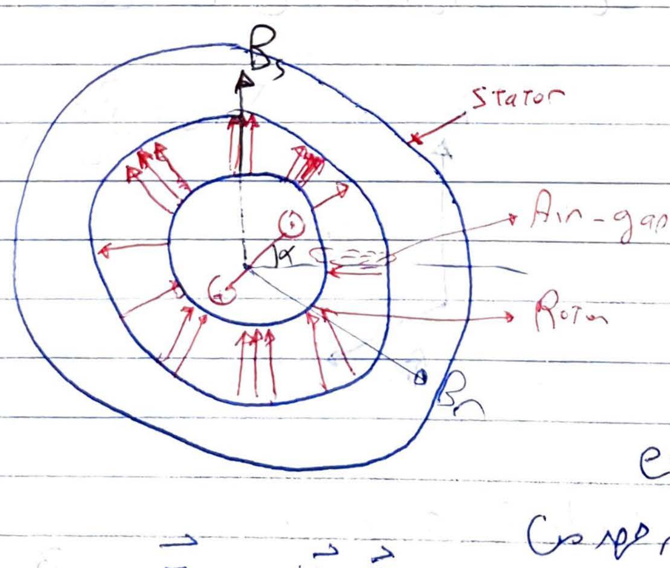
⊗ Induced Torque in Ac machine:

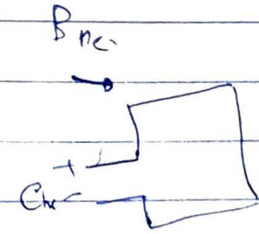
Assume that the magnitude of flux has a sinusoidal distribution

$$B_{stator} = B_s \sin\alpha$$

Assume that there is a coil of wire mounted on the rotor.

① تصور سلك داخل الملف
الموجود على Rotor
② بس B له اتجاه





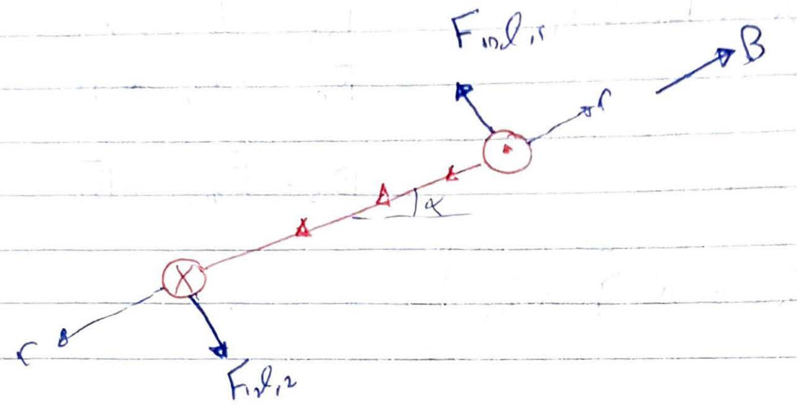
$$e_{ind} = (v \times B) \cdot L$$

المشكلة : الحصول على فرق جهد من
مكان متوقف

induced force $\longrightarrow$ $\vec{F}_{ind} = i \vec{L} \times \vec{B}$

Induced Torque $\longrightarrow$ $\vec{T}_{ind} = \vec{r} \times \vec{F}$

الحل : انه نكون مدار B_s بشكل
sinosoidal



$F_{ind,1} = iLB_s\sin\alpha \Rightarrow \tau_{ind} = riLB_s\sin\alpha$ CCW

$F_{ind,2} = iLB_s\sin\alpha \Rightarrow \tau_{ind} = riLB_s\sin\alpha$ CCW

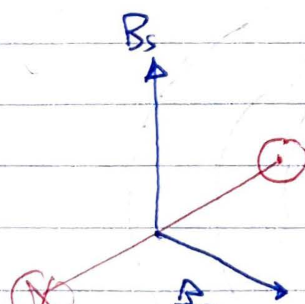
⊗ The net induced torque, τ_{ind} is given by:

$$\tau_{ind} = \tau_{ind,1} + \tau_{ind,2} = 2riLB_s\sin\alpha$$

⊗ According to Ampere's law ($\oint H \cdot dL = I_{enc} = i$), the rotor magnetic flux density, B_r, is given by:

$B_r = ci$, where c is constant.

$$\boxed{i = \frac{B_r}{c}} \quad \text{— (1)}$$

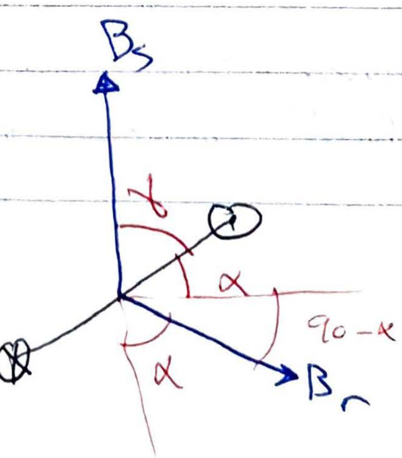


$$\tau_{ind} = \frac{2rL}{c} B_r B_s \sin\alpha$$

γ: is the angle between B_s & B_r

$\gamma + \alpha = 180°$

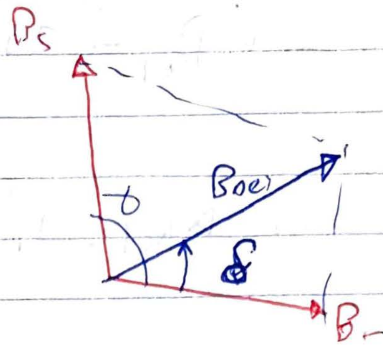
$\alpha = 180 - \gamma$



$T_{ind} = K B_r B_s \sin\alpha$, $K = \frac{2rL}{c}$

$T_{ind} = K B_r B_s \sin(180 - \delta)$

$$\boxed{T_{ind} = K \vec{B_r} \times \vec{B_s}}$$



$\vec{B}_{net} = \vec{B}_r + \vec{B}_s$

$\vec{B}_s = \vec{B}_{net} - \vec{B}_r$

$\vec{T}_{ind} = K \vec{B}_r \times (\vec{B}_{net} - \vec{B}_r) \Rightarrow \boxed{T_{ind} = K B_r \times \vec{B}_{net}}$

$T_{ind} = K B_r B_{net} \sin\delta$

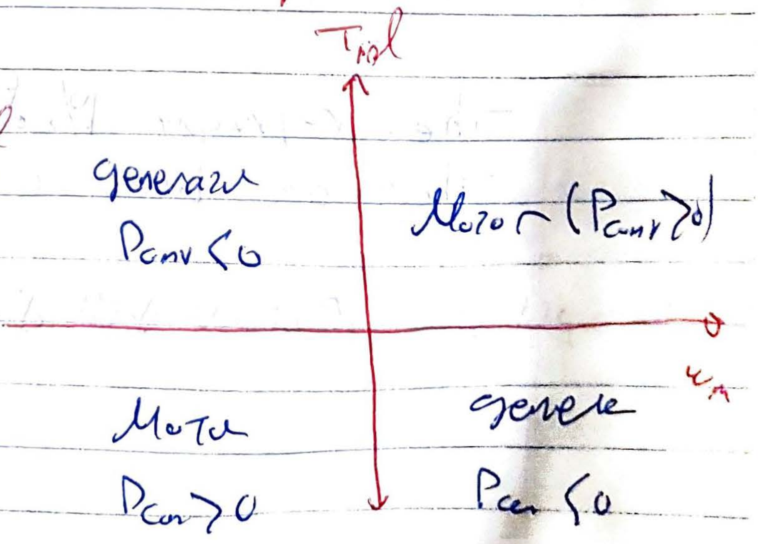
Notes: ⊗ if the direction of induced Torque is oppsite to the direction of rotation, then the machine acts as a generator

⊗ if the direction of Induced Torque is the same as direction of rotation, then the machine acts as a motor

4 quadrants of operation

$P_{conv} = T_{ind}\, \omega_m$

Converted Power ← ; ↓ ; ↳ speed



Power losses in AC Machine

1) Electric or copper losses: due to the winding Resistance

$\boxed{3\text{-}\phi}$

Stator $\longrightarrow$ $P_{sel} = 3 I_s^2 R_s$, R_s: stator Resistance

R_r: Rotor Resistance

Rotor $\longrightarrow$ $P_{Rcl} = I_r^2 R_r$

Rotor copper losses

2) Core losses: eddy current & hysteresis losses.

Core losses $\propto B^2 \omega_m^{3/2}$

3) Mechanical losses

Friction (Bearings)

من الاحتكاك shafts Rotor

Windage losses "تحرك هوا الـ Rotor"
friction between the air and the moving part

Mechanical losses $= a_1 \omega_m + a_2 \omega_m^2 + a_3 \omega_m^3$

4) Stray losses

They represent 1% of full load
They are losses which are not accounted for

* تعويض اجمالي للخسائر من العوامل غير محسوبة على المحركات

Efficency calculations of Ac Machine.

The efficency, η of ac machine is calculated by:

$$\eta = \frac{P_{OUT}}{P_{in}} \times 100\%$$

For generator operation: $P_{in} = T_{app}\,\omega_m$, $P_{OUT} = 3V_\phi I_\phi \underbrace{\cos\theta_\phi}_{\text{power factor}} = \sqrt{3}\,V_L I_L \cos\theta_\phi$

always θ_{phase}

θ_ϕ: angle between V_ϕ & I_ϕ

In motor: $P_{in} = 3 V_\phi I_\phi \cos\theta_\phi = \sqrt{3}\,V_L I_L \cos\theta_\phi$, $P_{OUT} = T_L\,\omega_m$

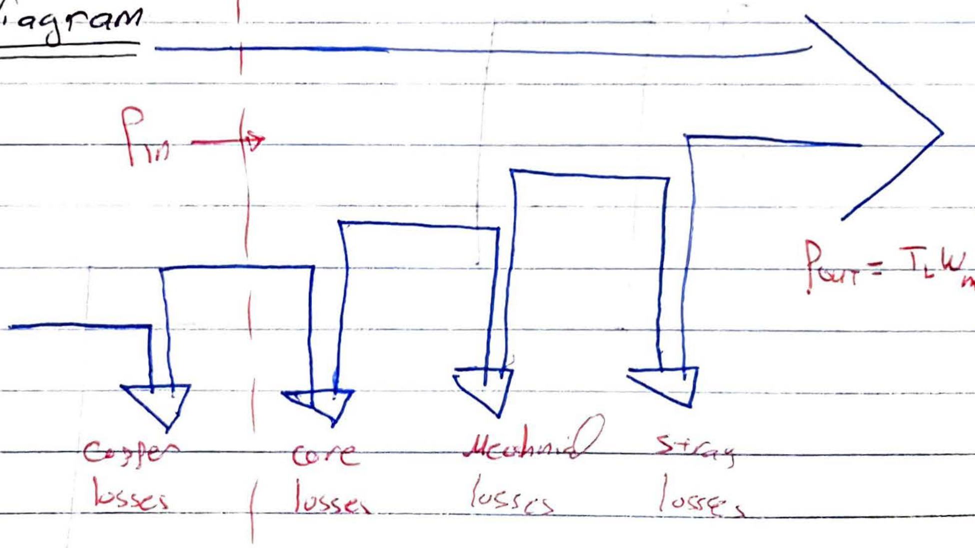
T_L: load Torque applied to the shaft

$P_{conv} = T_{ind}\,\omega_m$

Power flow diagram

Motor:

$P_{in} = 3 V_\phi I_\phi\, PF$



P_{conv}: its the converted power to $\begin{cases}\text{Mechanical} & \text{Motor}\\ \text{Electrical} & \text{Generator}\end{cases}$

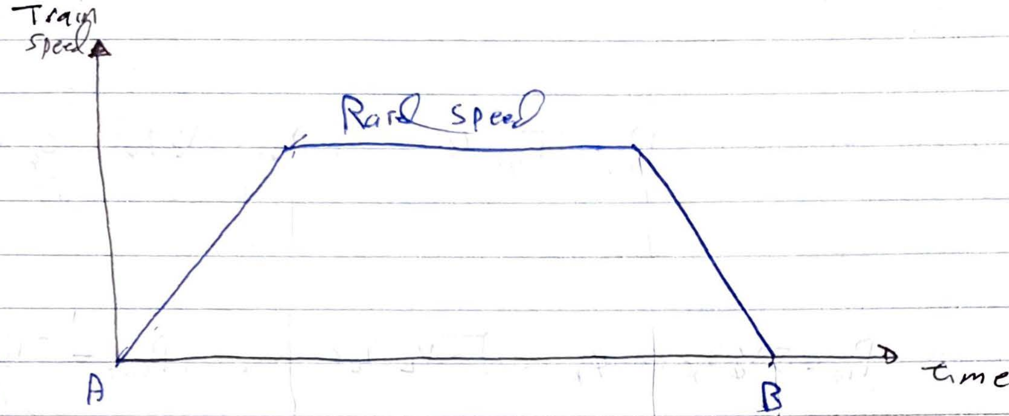
its given by: $P_{conv} = T_{ind}\,\omega_m$

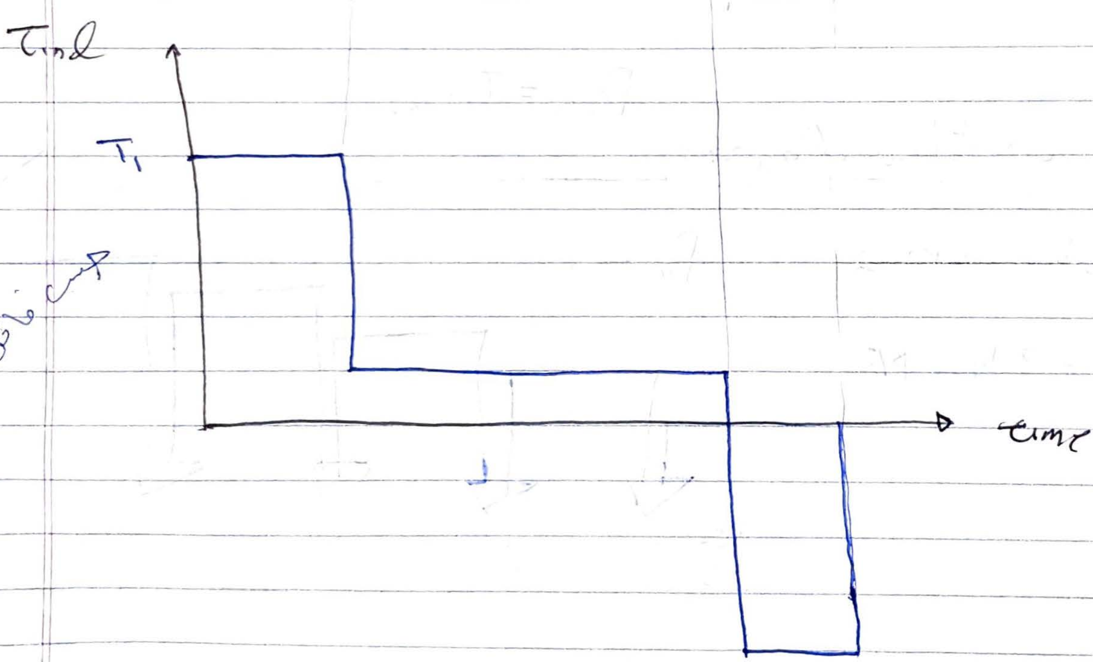
T_{ind}: Induced Torque

Newton, 2^{nd} law

$$\sum T = J \frac{d\omega_m}{dt} \quad : \quad T_{ind} - T_L = J \frac{d\omega}{dt} + T_{friction}$$

Example





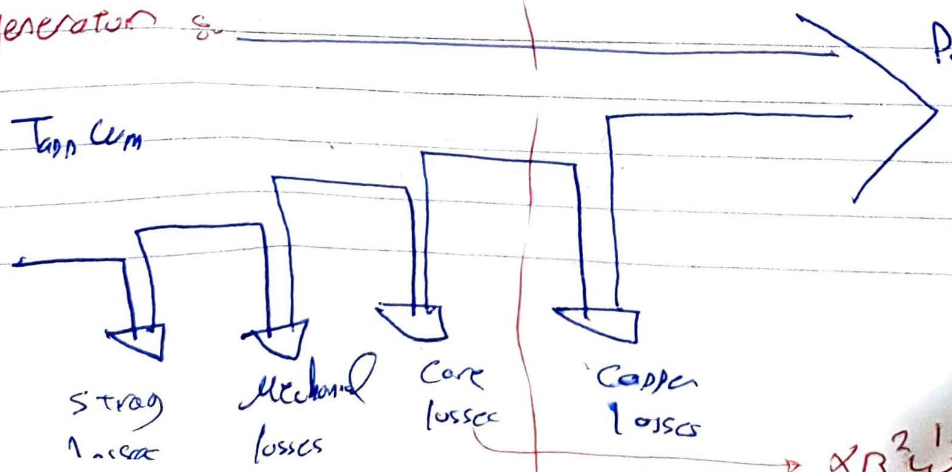
$P_{conv} = T_{ind}\,\omega_m$

generator

$P_{in} = T_{app}\,\omega_m$

$P_{out} = \sqrt{3}\, V_L I_L\, PF$

$= 3 V_\phi I_\phi\, PF$



Voltage Regulation :- its a measure of generator ability to Keep constant Voltage Load condition.

$$VR = \frac{V_{NL} - V_{Fl}}{V_{Fl}} \times 100\%$$

Speed Regulation (SR) :- its ability of motor to Keep constant speed under load conditions

No load

$$SR = \frac{\omega_{NL} - \omega_{Fl}}{\omega_{Fl}} \times 100\%$$

Full load