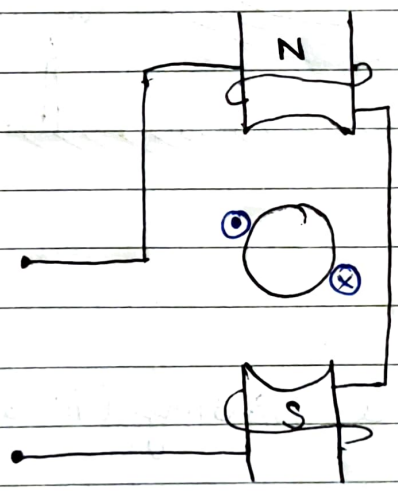
11/1/2023

Electrical Machines

(Fundamentals of AC machine windings)

- Low speed generators / alternators have more no. of poles and are found in hydropower plant.
- High speed generator / alternator have Less no. of poles and are found in thermopower plant.

AC machines → Synchronous (Field winding) Rotor
→ Induction (Armature winding) Stator



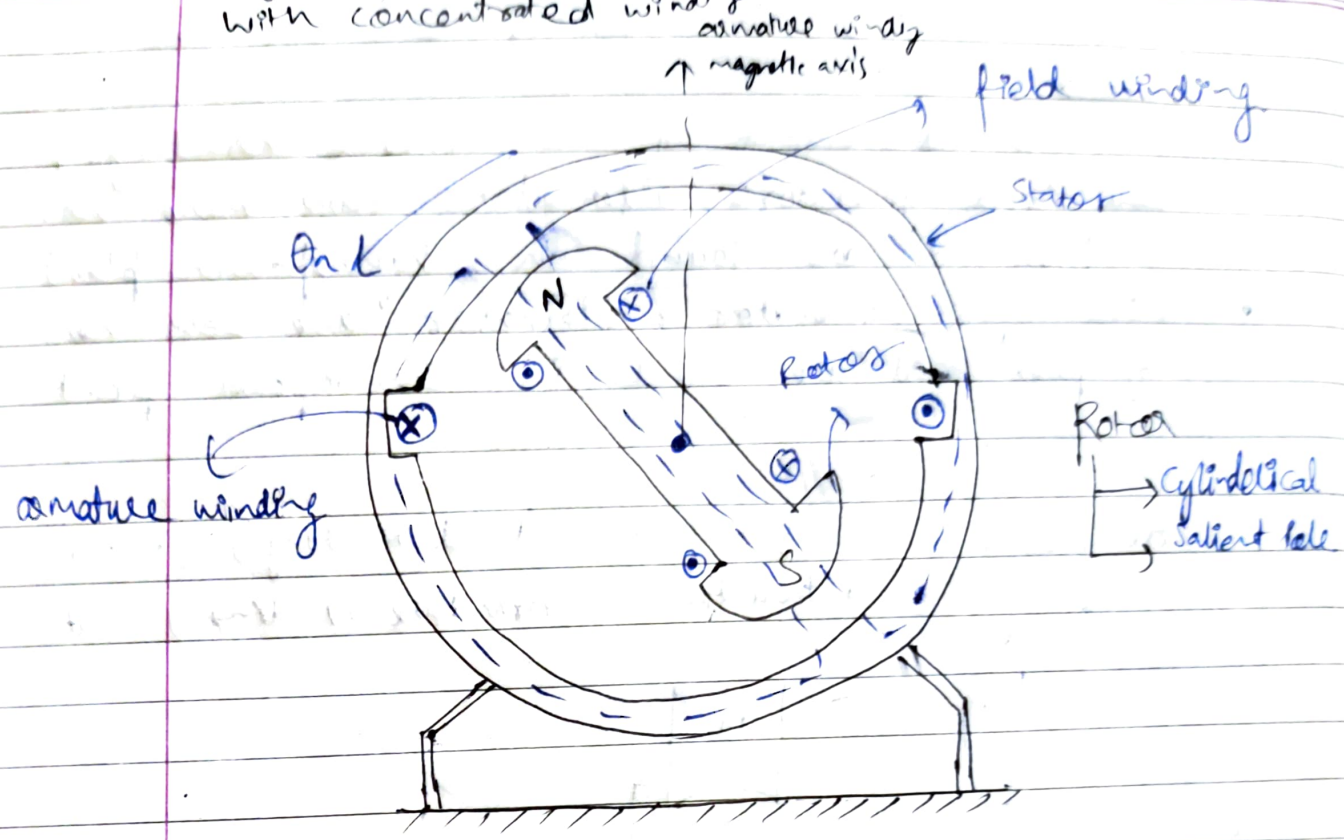
Pole ↑
Flux Linkage ↑

Electromechanical Energy Conversion:-

Lorentz Force $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$

(i) Voltage in a winding can be generated by rotating armature winding mechanically through a magnetic field, ~~or vice~~
(ii) Rotating magnetic field mechanically past the winding.
(iii) Designing a magnetic circuit so that the reluctance varies with the rotor's reluctance.

- Projecting / Salient Pole Construction with concentrated winding



Synchronous :-

- Rotor
  - Field Winding (Always given DC supply)
- Stator
  - Armature Winding
    - Single phase (Single winding)
    - Multi phase (winding)

(1) In synchronous machines the rotor winding currents are supplied directly from the stationary frame (stator) through a rotating contact.

(2) In an induction machine, rotor currents are induced in the rotor winding by a combination of the time variation of stator currents and of the relative motion b/w the

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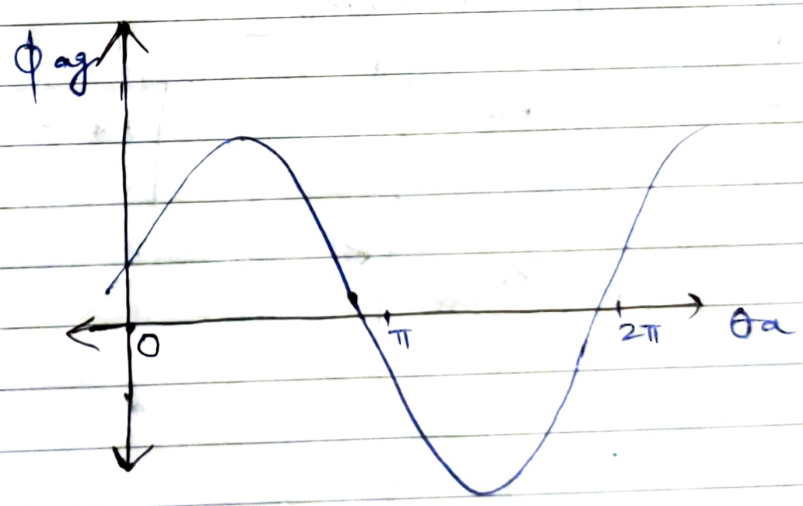
stator & rotor.

(3) Rotors of synchronous Machine:
(a) Cylinderical Rotor
(b) Salient Pole Rotor.

(4) θ_a is the spacial angle (mechanical angle) measured wrt armature winding magnetic axis. The air gap flux is not purely sinusoidal in practice but is close to sinusoidal variation by properly shaping the pole faces.

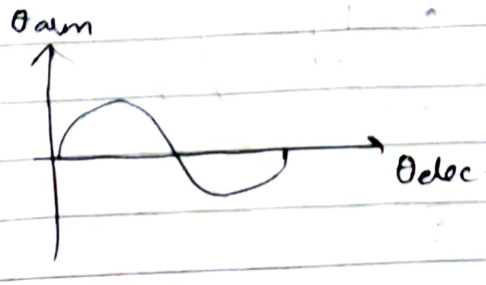
Rotor power < Stator power.



$e_{ag} \propto \frac{d\phi_{ag}}{dt}$

poles, speed

$$\boxed{f = \left(\frac{P}{2}\right)\left(\frac{N}{60}\right)}$$



$\theta_e = \left(\frac{P}{2}\right)\theta_a$

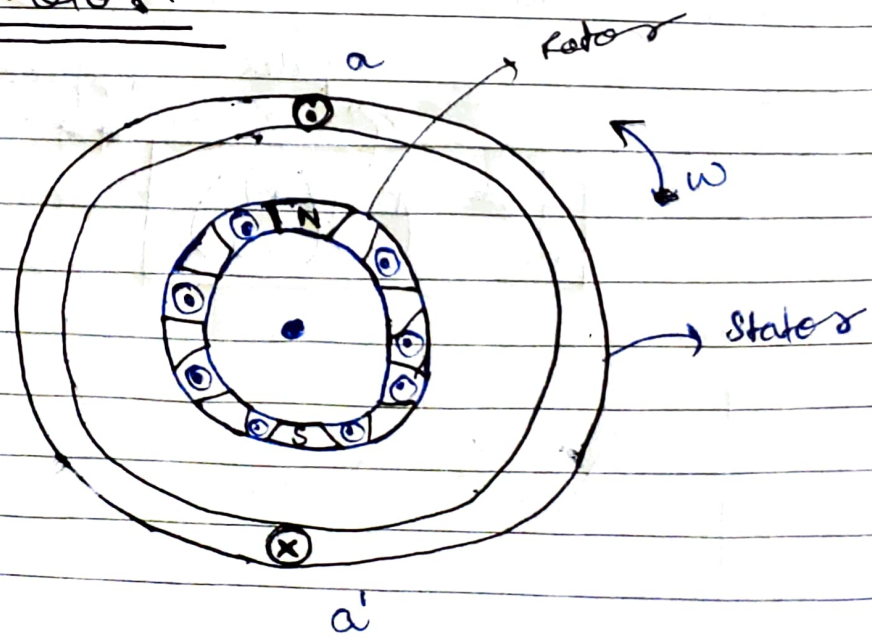
- As the rotor rotates and flux linkages of the armature windings vary wrt time a sinusoidal emf is generated in the armature winding, assuming constant rotor speed and sinusoidal flux distribution.
- The coil voltage passes through 1 complete cycle for 1 complete revolution of a 2 pole machine rotor. Thus the number of cycles per second directly relate to the mechanical speed of the rotor in revolution per second. Hence the electrical freq. of the generated voltage is SYNCHRONISED with the mechanical speed of the machine; hence the name <u>Synchronous Machine</u>.

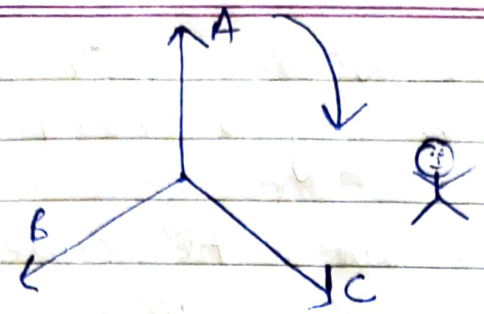
$$\boxed{f_e = \left(\frac{p}{2}\right)\left(\frac{N_s}{60}\right)} \quad * \qquad \boxed{N_s = \frac{120 f}{p}} \quad *$$

$$\boxed{\theta_e = \left(\frac{p}{2}\right) \theta_{mech}} \quad *$$

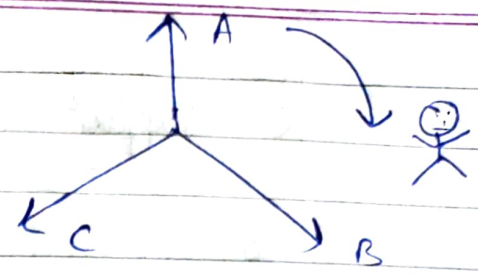
Cylindrical Rotor:-

Stator → Sinusoidal



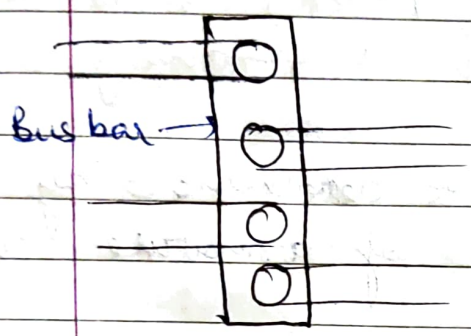


ABC



ACB

Rotation:- by default ↑ Anticlockwise



In synchronous generator the electromagnetic torque opposes rotation and a mechanical torque must be applied from the prime mover to sustain the rotor's rotation. This electromagnetic torque is underlined mechanism through which synchronous generator converts mechanical energy to electrical energy.

syn. motor the electromagnetic is in dirn of rotation (DC current supplied to field winding & AC current supplied to armature winding) and balances the opposing torque required to drive the load.

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SYNCHRONOUS MOTOR :-

AC Supply :- Armature Winding (STATOR)
DC Supply :- Field Winding (ROTOR)

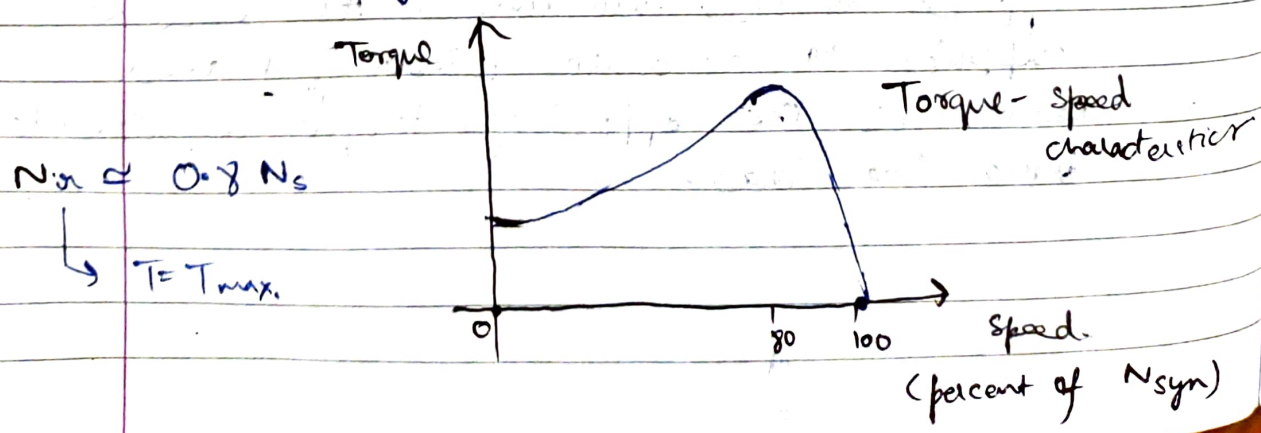
The air flux created due to AC currents in the armature stator windings ~~will create torque~~ rotate at synchronous speed.
To produce a steady electromechanical torque the stator & rotors magnetic flux densities (B_{stator}, B_{rotor}) must be constant in amplitude & stationary wrt each other.
This steady state speed is determined by number of poles & freq. of armature current.

$$\boxed{N_s = \frac{120f}{P}}$$ **

INDUCTION MACHINE :-

AC Currents :- Armature Winding (STATOR)
AC Currents :- Field Windings (ROTOR)

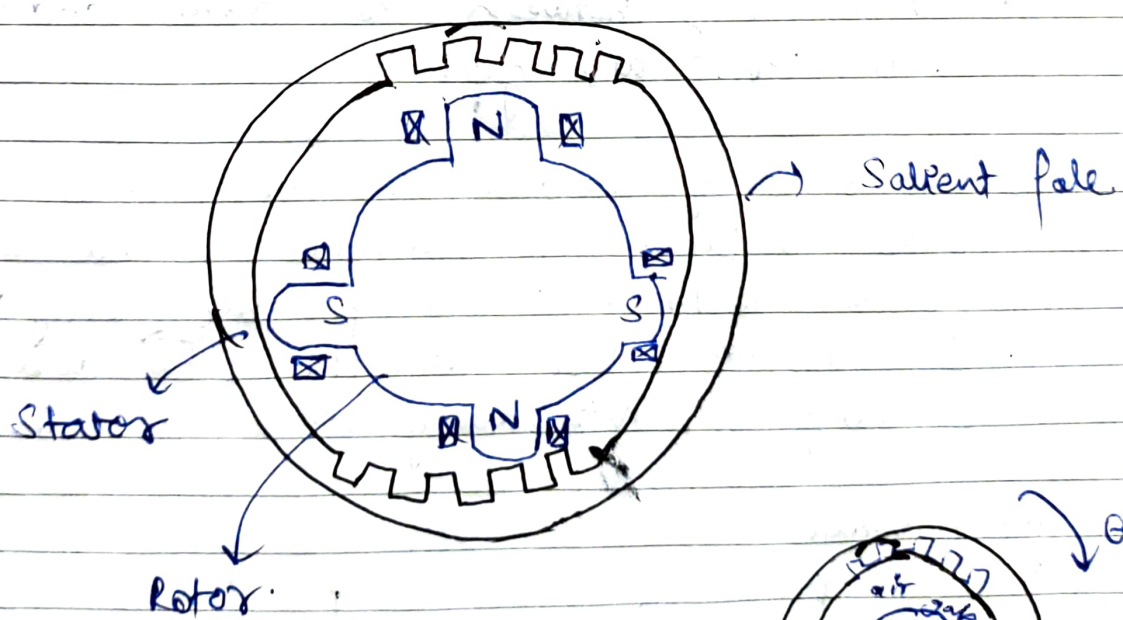
Rotor winding short circuit → Squirrel Cage

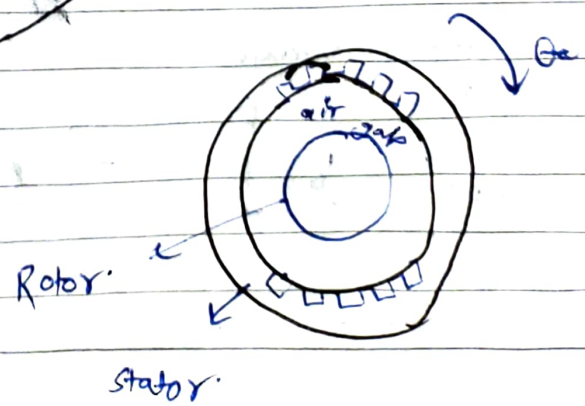


- Used as <u>Frequency Changer</u>

- Induction Machine may be recognised as generalised transformer, in which the electrical power is transformed b/w stator & rotor together with a change of freq. and a flow of mechanical power.

Rotor & stator fluxes rotate at syn. speed and the torque is related to the relative displacement b/w them.
The rotor itself, however, doesn't rotate at syn. speed but slips wrt syn. rotating armature flux.
Electromagnetic <u>induction</u> causes the current's to be induced in the rotor windings. Hence the name induction machine.





$\vec{B}$: vector

$\tilde{B}$: Matrix

Windings:-

- **Distributed:-** $F_{ag} = F_0 \sin\theta_a$

$F_0 \cos\theta_a$

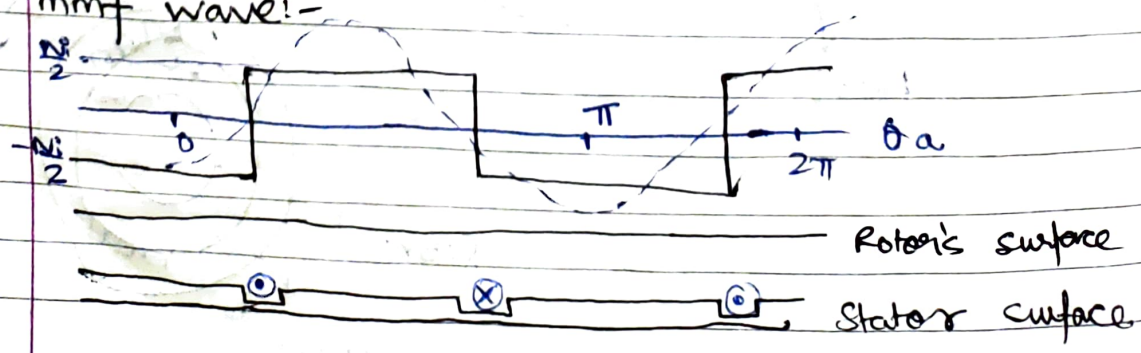
ag: air gap

$$\boxed{n_c = N_0 \sin\theta_a}$$ **

⇒ MMF distribution in distributed winding:-
The rotor AC machines is made up ferromagnetic material and a small air gap exist between stator and rotor frame. The ~~air~~ reluctance of air gap is greater than reluctance of stator & rotor magnetic circuits. The magnetic flux density vector, B, chooses the shortest possible path to traverse ⊥ly between the stator and rotor, through the air gap.

B should be of ~~sinusoidal~~ sinusoidal magnitude in order to produce sinusoidal varing emf in the stator. This is possible only if the magnetic field intensity, $\vec{H}$ and MMF are varying sinusoidally across the air gap.

mmf wave:-



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- Distributed Windings are those which are spread over a number of slots around the airgap periphery. The individual coils (having a number of turns) are interconnected in such a way so that the resultant magnetic field is same as that of created by that of field winding. Hence the distributed armature winding have same no. of poles as that of field winding.

$$\boxed{F_{ag_1} = \frac{4}{\pi}\left(\frac{N i_a}{2}\right)\cos\theta_a}$$

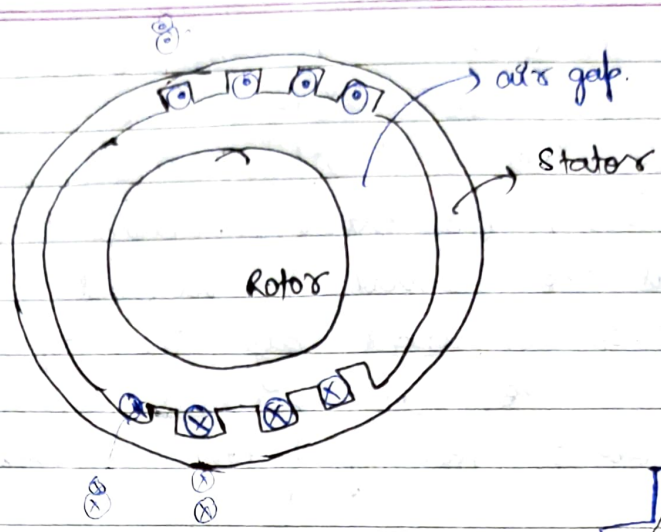
$$F_{ag_{1\,peak}} = \frac{2 N i_a}{\pi}$$

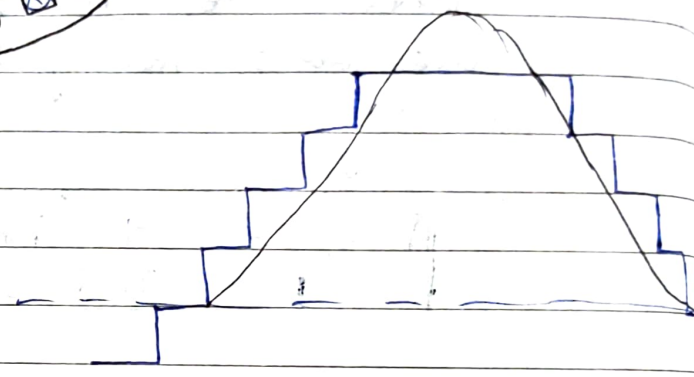
The angle θ_a is measured from the resultant magnetic axis of coil 'a'.

At phase 'b': $F_{ag_1}^{b} = F_{ag_{1\,peak}}^{b} \cos\theta_b$

At phase 'c': $F_{ag_1}^{c} = F_{ag_{1\,peak}}^{c} \cos\theta_c$

$$F_{ag_1}^{abc} = F_{ag_1}^{a} + F_{ag_1}^{b} + F_{ag_1}^{c}$$





If ⊙ ⊗

Ampere turn: $2N_{ca}$.

$$F^{a}_{ag_1} = \frac{4}{\pi}\left(\frac{2N_c i_a}{2}\right)\cos\left(\theta_a - \frac{\theta_{slot}}{2}\right)$$

no. of poles. no. of poles

θ_{slot} = (Slot angle at the top coil side) + (Slot angle at the bottom coil side)

Question: The phase 'a' of a 2 pole armature winding is consisting of "$8N_c$" - turn full pitch coils connected in series, with each slot consisting of 2 coils. There are a total of 24 armature slots. Assume that angle θ_a is measured from the magnetic axis of phase 'a' such that the 4 slots containing the coil sides are at an angle of 67.5°, 82.5°, 97.5°, 112.5°.

Write the expression for the space fundamental MMF wave produced by the 2 coils whose

all

sides are in the slots.

Answer → $67.5 - 180 = -112.5$
→ $82.5 - 180 = -97.5$
→ $97.5 - 180 = -82.5$
→ $112.5 - 180 = -67.5$

} slot angle of bottom coil.

$\theta_{slot} = 67.5 - 112.5 = -45$
$\theta_{slot} = 82.5 - 97.5 = -15$
$\theta_{slot} = 97.5 - 82.5 = 15$
$\theta_{slot} = 112.5 - 67.5 = 45$

- **Distributed winding:-**

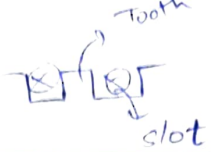
$$F_{ag,1}^{s} = \frac{4}{\pi}\left(\frac{K_w N_{ph}}{P}\right) I_a \cos\left(\theta_a \frac{P}{2}\right)$$

K_w: 0.85 ~ 0.95
N_{ph}: $8N_c$
θ_a: Spatial angle wrt ~~magnitude~~ magnetic axis of the stator winding.

- **Distributed Field Winding:-**

$$F_{ag,1}^{r} = \frac{4}{\pi}\left(\frac{K_f N_r}{P}\right) I_r \cos\left(\theta_r \frac{P}{2}\right)$$

K_f: 0.85 ~ 0.95
N_r
θ_r: Spatial angle wrt magnetic axis of the field winding



The no. of turns in series for each slot may not be equal in case distributed field winding

POLE PITCH :-

$$P_p = \frac{360^\circ}{P}, \text{ mechanical degrees}$$

$$= \frac{2\pi}{P}, \text{ mechanical radians.}$$

Fractional Pitch:- $\rho = \frac{\theta_m}{P_p} \times 180^\circ$

$$= \frac{\theta_m}{P_p} \times \pi$$

- θ_m: Mechanical angle covered by the fractional pitch
- Windings which have fractional pitch in the machine are called as **Chorded Windings.**

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- Rotating m/c → Stator → armature → 3ϕ
  → Rotor → field → dc

- Sync m/c → doubly excited machine

Ques- Why armature is preffered over stator.

Answer: → More economical
→ More efficiency
(2 slip rings instead of 3, less losses)
→ High insulation.
(HV should be stationary)
→ Efficient cooling
→ More output

coils.

Concept of synchronous speed:-

$$\theta_e = \frac{P}{2}\theta_m$$

$$\frac{d\theta_e}{dt} = \frac{P}{2}\frac{d\theta_m}{dt}$$

$$\omega_e = \frac{P}{2}\omega_m$$

ω_e → angular freq

ω_m → angular speed

$$2\pi f = \frac{P}{2}\left(\frac{2\pi N}{60}\right)$$

$$\boxed{N = \frac{120f}{P}}$$ ** synchronous speed

is basically conversion of electrical freq 'f' in in mech. speed in terms of rpm.

Rotor rotates at synchronous speed.

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Alternator
↳ generates alternating voltage
Synchronous Generator

Synchronous generator	Asynchronous generator / Induction generator
(1) Rotor → synchronous speed	(1) Higher than syn speed
(2) Thermal, Nuclear power plant (CONVENTIONAL)	(2) wind, tidal power plant (NON-CONVENTIONAL)
(3) Most power generated. Steam power plant → $\frac{2}{3}$rd S.G.	
(4) Real / Reactive power supplied.	

- **Pole Pitch:-**

Number of conductors per pole is called pole pitch.

- **Winding Diagram:-**

A pattern showcasing placement of conductors or coils in group so that the particular set coil can carry electric current and deliver suitable power.

AC Windings

- Three Phase
  - Single Layer
    - Mush type
    - Concentric type
      - Bifurcated
      - Unbifurcated
  - Multi layer
    - Lap
    - Wave winding
      - Integral slot
        - short chorded
        - full chorded.
      - Fractional Slot

- Integral Slot :- if the slots per pole / per phase is an integer then winding is called integral slot winding.

- Fractional Slot :- if the slots per pole / per phase is a fraction

- Full Pitch = 180
- Pitch < 180

- Mush winding :- if all the coils have same coil span

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- Concentric Winding:-
In which all coils exist in one side of the coil is called as concentric winding. This means all the coils contains contain 1 coil group is placed in 1 slot.

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2 Revolving Magnetic Fields

$$\theta_e = \frac{P}{2}\theta_m$$

$$\omega_e = \frac{P}{2}\omega_m$$

$$f = \frac{\omega_e}{2\pi}$$

$$F_{ag_1} = \frac{4}{\pi}\left(\frac{K_w N \phi}{P}\right) i_a \cos\theta_{ae}$$

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

$$F_{ag_1} = \frac{4}{\pi}\left(\frac{K_w N \phi}{P}\right) I_m \cos\omega_e t \cos\theta_{ae}$$

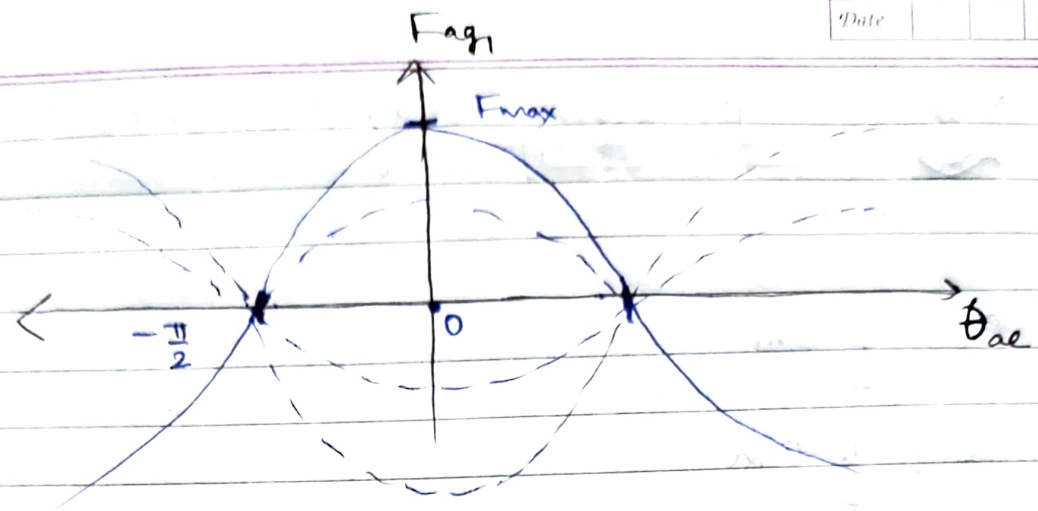
$$\equiv$$

$$F_{ag_1} = F_{ag_1}^{Max} \cos\omega_e t \cos\theta_{ae}$$

M: Max

$$= \frac{1}{2} F_{ag_1}^{M} \cos(\theta_{ae} + \omega_e t) + \frac{1}{2} F_{ag_1}^{M} \cos(\theta_{ae} - \omega_e t)$$

$$= F_{ag_1}^{-} + F_{ag_1}^{+}$$



$K_w = K_d K_p$

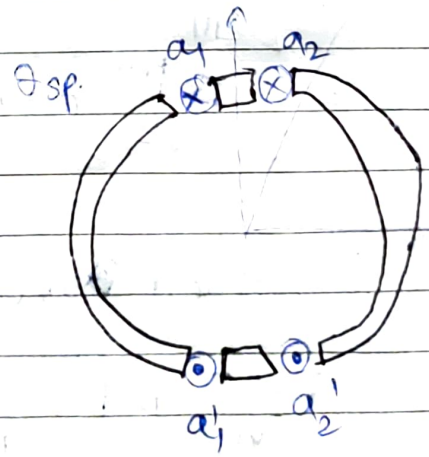
$$\boxed{E_{cw} = N_{series} \times E_{coil}}$$

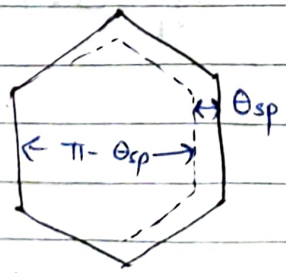
Concentrated winding

$$\vec{E}_{DW} = \vec{E}_{11'} + \vec{E}_{21'} + E$$

$$\boxed{K_w = K_b K_p}$$

SHORT PITCH.





$$\overline{a_1 a_1'} = \frac{\pi}{180^\circ}$$

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Ques. A 3 phase 16 pole synchronous generator has a star connected winding with 144 slots and 10 conductors per slot. The flux per pole is 0.04 weber sinusidally distributed and the speed of machine is 375 rpm. Calculate the freq of machine, slots per pole per phase of machine, slots angle of machine & breadth factor.

Ans. Slots = 144

Conductors/slot = 10

~~Conductors = 144×10 = 1440~~

Slots ~~per pole~~ per phase = ~~1440~~ ~~slots / 2×3~~

$\frac{144}{2} = 72 \times 10$

$= 720$ (3 phase) ~~= 240~~

$= 240$ per phase.

- Slots per pole per phase = 3. $= \frac{144}{16 \times 3}$
- B.F = 0.96
- $f = \frac{N \times P}{120} = \frac{16 \times 375}{120} = 50\,Hz$
- Slot angle :- $\frac{180 \times \text{Poles}}{\text{No. of slots}} = \frac{180 \times 16}{144}$

$= 20^\circ$

Q 3 phase, 50 Hz star connected alternator with 2 layer winding is operating at 600 rpm. It has 12 turns per coil, 4 slots per pole per phase, and a coil pitch of 10 slots. Find the

no. of poles, totals slots, slot angle, B.F, pole pitch, coil pitch, short picking angle pitch factor.

Pole pitch = $\frac{\text{slot}}{\text{Plots}}$

$\theta_{sp} = (P_p - C_p) \times \gamma$

$K_p = \cos\left(\frac{\theta_{sp}}{2}\right)$

Note:- Distribution Factor/ Breadth Factor (K_d):-

$$\boxed{K_d = \frac{\sin(n\alpha/2)}{n \sin(\alpha/2)}}$$

slot angle

slots per pole per phase

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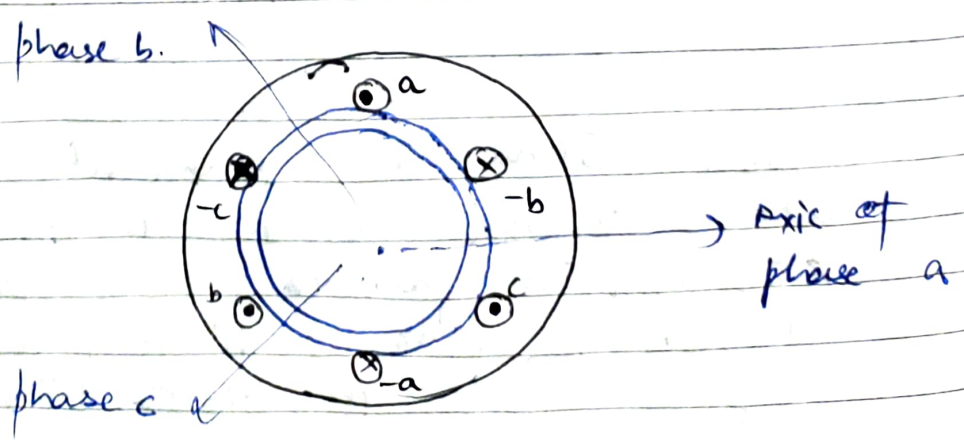
MMF Wave of polyphase windings:-



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MMF Wave of a polyphase winding:-

Under balanced 3-ph conditions, instantaneous currents are:-

$$i_a = I_m \cos \omega_e t$$
$$i_b = I_m \cos(\omega_e t - 120^\circ)$$
$$i_c = I_m \cos(\omega_e t + 120^\circ)$$

I_m → Max^m value of the current.

The mmf of phase 'a' :-

$$F_{a1} = F_{a_1}^{+} + F_{a_1}^{-}$$

where

$$F_{a1}^{+} = \frac{1}{2} F_{max} \cos(\theta_{ae} - \omega_e t)$$

$$F_{a_1}^{-} = \frac{1}{2} F_{max} \cos(\theta_{ae} + \omega_e t)$$

$$\left(F_{max} = \frac{4}{\pi} \left(\frac{K_w N_{ph}}{poles} \right) I_m \right)$$

Similarly :-

$$F_{b1} = F_{b1}^{+} + F_{b1}^{-}$$

$$F_{b1}^{+} = \frac{1}{2} F_{max} \cos(\theta_{ae} - \omega_e t)$$

$$F_{b1}^{-} = \frac{1}{2} F_{max} \cos(\theta_{ae} + \omega_e t + 120^\circ).$$

And $F_{c_1} = F_{c_1}^{+} + F_{c_1}^{-}$

$$F_{c_1}^{+} = \frac{1}{2} F_{max} \cos(\theta_{ae} - \omega_e t)$$

$$F_{c_1}^{-} = \frac{1}{2} F_{max} \cos(\theta_{ae} + \omega_e t - 120^\circ)$$

Total MMF $= F_{a_1} + F_{b_1} + F_{c_1}$

Taking summation in terms of +ve & -ve travelling waves.

$$\Rightarrow \quad F^{-}(\theta_{ae}, t) = F_{a_1}^{-} + F_{b_1}^{-} + F_{c_1}^{-}$$

$$= \frac{1}{2} F_{max} \left[\cos(\theta_{ae} + \omega_e t) + \cos(\theta_{ae} + \omega_e t - \right.$$

$$\left. + \cos(\theta_{ae} + \omega_e t + 120^\circ) \right]$$

$$= 0$$

$$\Rightarrow \quad F^{+}(\theta_{ae}, t) = F_{a_1}^{+} + F_{b_1}^{+} + F_{c_1}^{+}$$

$$= \frac{3}{2} F_{max} \cos(\theta_{ae} - \omega_e t)$$

Result of displacing the 3 windings by 120° in space and displacing the winding currents by 120° in time phase is a single +ve travelling MMF wave.

$$F(\theta_{ae}, t) = \frac{3}{2} F_{max} \cos(\theta_{ae} - \omega_e t)$$

$$= \frac{3}{2} F_{max} \cos\left(\left(\frac{poles}{2}\right)\theta_a - \omega_e t\right)$$

$$\left(\theta_{ae} = \left(\frac{poles}{2}\right)\theta_a\right)$$

$= \frac{3}{2}$ times the individual phase

$$\theta_a = \left(\frac{2}{poles}\right)\omega_e t$$

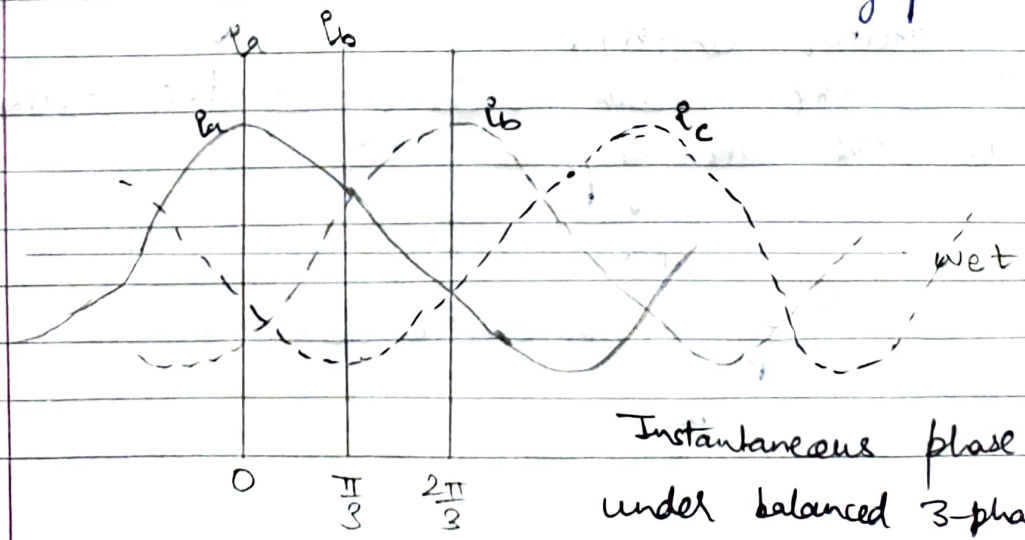
120°

Under balanced 3ph conditions, the 3-ph winding produces an air gap mmf which rotates a synchronous angular velocity ω_s

$$\omega_s = \left(\frac{2}{poles}\right)\omega_e$$

angular freq. of applied electrical excitation

spacial ~~ep~~ angular velocity of the air gap



Instantaneous phase currents under balanced 3-phase conditions.

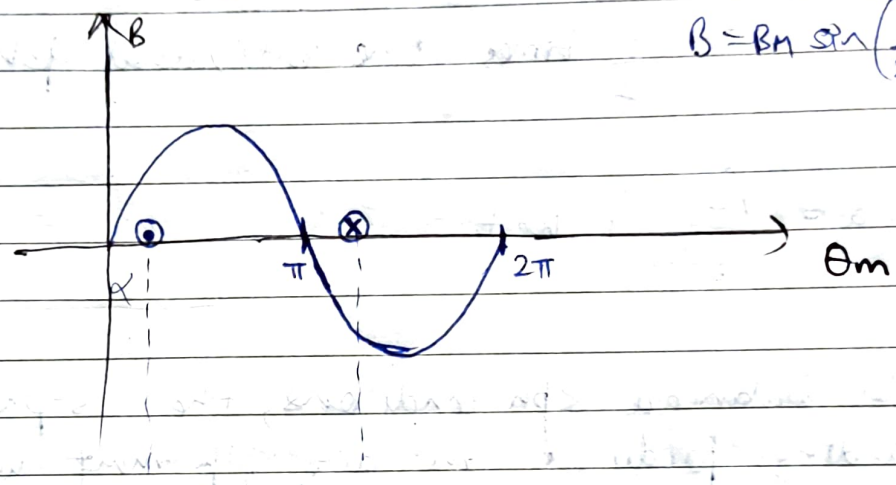
EMF-EQUATION:-

Assumptions:-

(1) Coil pitch = 180° or π-rad
Full pitch

(2) Air gap flux:- field windings

(3) Flux density wave is purely sinusoidal.



$$B = B_M \sin\left(\frac{P}{2}\theta_m\right)$$

$$\phi = \int_{\alpha/P/2}^{(\pi+\alpha)/P/2} B_M \cdot \sin\left(\frac{P\theta_m}{2}\right) l \cdot r \cdot d\theta_m$$

→ "l" is the active coil side length (axial stator length).

→ "r" is the mean radius of the stator at the air gap.

$$= \frac{2}{P}\int_{\alpha}^{\pi+\alpha} B_M \sin\theta_e \, lr \, d\theta_e$$

$$\left(-\left[\cos\theta_e\right]_{\alpha}^{\pi+\alpha}\right)\frac{2}{P}B_M l r$$

$$-\left[\cos(\pi+\alpha)-\cos(\alpha)\right]\frac{2}{P}B_M l r$$

$$(2\cos\alpha)\left(\frac{2}{P}B_m l r\right)$$

$$= \frac{4}{P}B_m(\cos\alpha)\, l r$$

$$\alpha = \omega t$$

$$\phi = \frac{4 B_m l r}{P}\cos\omega t$$

$$\boxed{\phi = \phi_m \cos\omega t} \quad **$$

$$B = B_M \sin\left(\frac{P}{2}\theta\right)$$

Flux Linkage:-

$$\psi = N\phi$$
$$= N\phi_m \cos\omega t$$

$$e = -\frac{d\psi}{dt} = -\frac{d}{dt}(N\phi_m\cos\omega t)$$

emf $e = N\phi_m\omega\sin\omega t$

$$\boxed{e = E_M \sin\omega t}$$

$$E_{rms} = \frac{1}{\sqrt{2}} E_M = \frac{1}{\sqrt{2}} N \phi_m (2\pi f)$$

$$\boxed{E_{rms} = 4.44 N \phi_m f} \; ** \text{ VOLTS}$$

⇒ **Distributed:-**

$$K_b = \frac{\sin m\gamma/2}{m \sin(\gamma/2)}, \quad \gamma = \frac{\pi P}{S}$$

$$\boxed{m = \frac{S}{Pq}} \; *, \quad \sigma = m\gamma, \quad \text{phase spread}$$

S → slots

P → angle b/w slot

q → per pole per phase

$$\boxed{E_{rms} = 4.44 K_b \phi_m f N_p} \; * \text{ VOLTS.}$$

F_{ag} ① → imp. → has meanic component

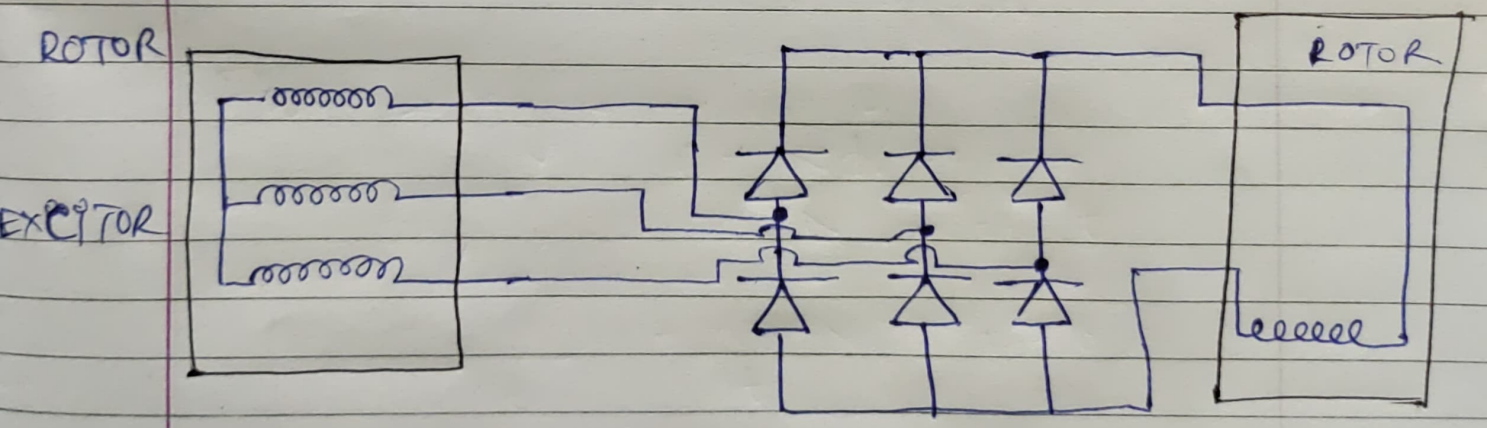
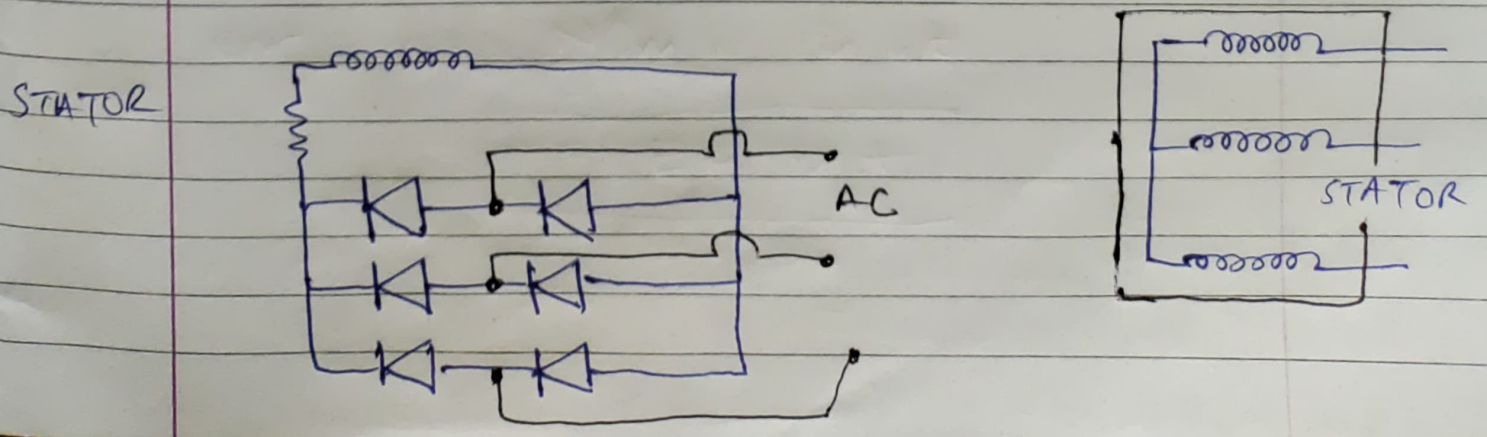
F_{ag} :- is not sinusoidal

20/2/23

Unit 5 — Synchronous Machines

Rotor:-

- Salient (Protruding out) Pole
  $P \geq 4$
  Low speed

- Non Salient
  High speed
  $P \leq 4$

(1) Slip-rings & brushes
(2) Brushless Exitation