02.07.2021

AC Machines

Rotating Magnetic Field: The basis of ac-machines.

AC Machines: Generators / Motors

Synchronous Machines

Rotor normally rotates at the same speed as the rotating magnetic field in the machine.

Induction Machines (Asynchronous machines)

Electrical machine operating by the phenonomenon called electromagnetic induction

Synchronous Generator (Ref. Chapter 5)
(Alternators)

- Electrical machine producing alternating emf of constant frequency.
- In India, 50Hz, USA → 60Hz
- The generated alternating emf could be single-phase or 3-phase.

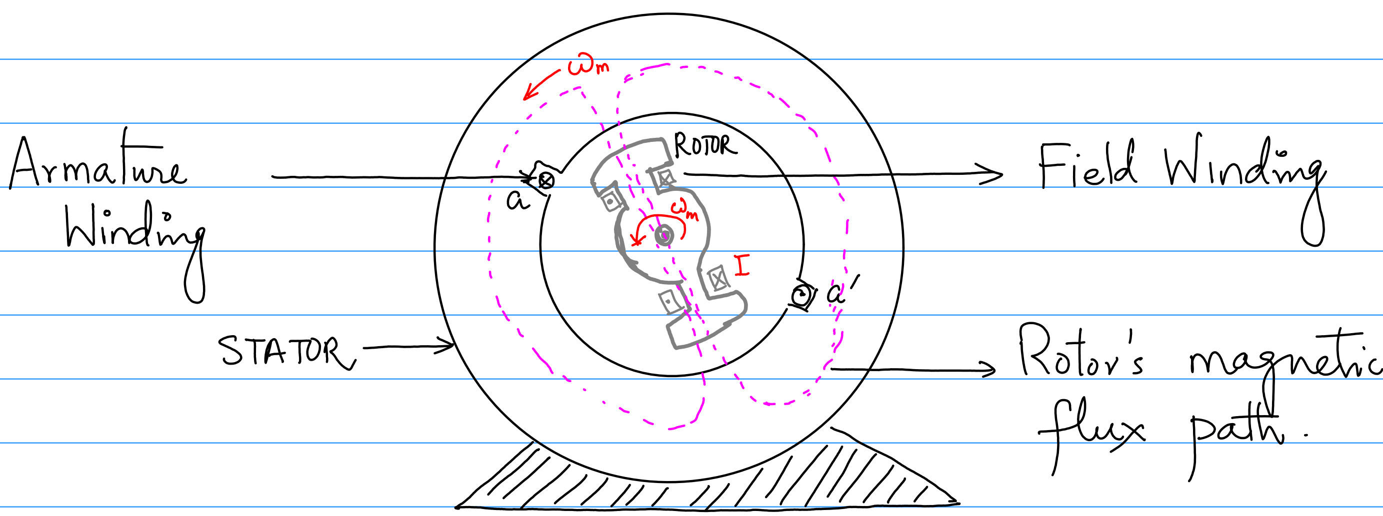
Low power generation — Single-phase

High power generation — 3-phase

Generation of EMF :

Faraday discovered that an emf can be induced (or generated) due to relative motion b/w a magnetic field and a conductor.

Elementary Synchronous Generator



- In syn. generator, a dc current is applied to the rotor winding (field winding), which produces a rotor magnetic field.

- The rotor is rotated by a prime mover producing a rotating magnetic field within the machine.

- The rotating magnetic field induces emf

in the stator's winding (Armature winding)
as there is relative motion b/w the conductor & the magnetic field.

Field Winding — Producing the main magnetic field.

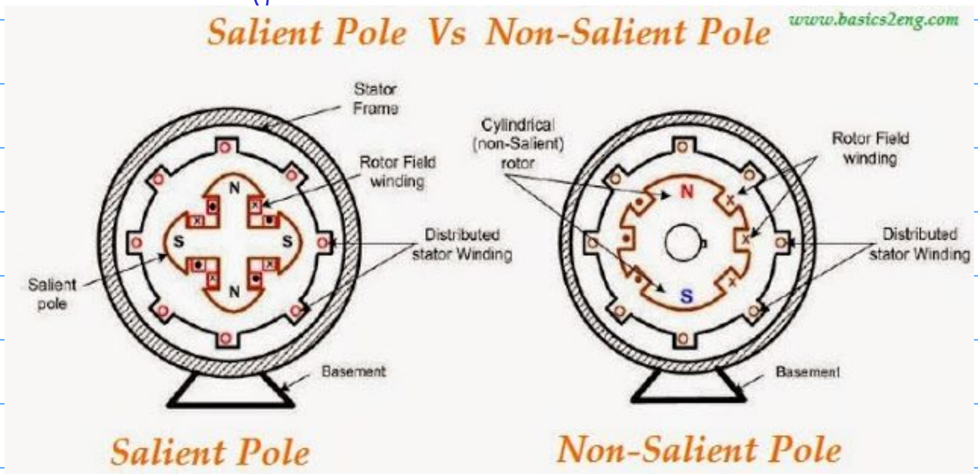
Armature Winding — Voltage is being induced.

Rotor winding ⟷ Field winding
Stator winding ⟷ Armature Winding.

Rotor :

- Essentially it is a large electromagnet.

Design of Rotor



- Since the rotor is subjected to changing magnetic field, it is constructed with thin lamination to reduce Eddy-current.
- To supply dc current to the rotating rotor, special arrangement needs to be done.

(i) Supply dc power from some external dc source to the rotor by means of "SLIP RINGS" and "BRUSHES"

(ii) Supply the dc power from a special dc power mounted directly on the shaft of the sync. generator.

– Self Excited Generators

07.07.2021

① Relationship b/w Electrical frequency produced and Mechanical Rotation of Field.

$$f_e \text{ (in Hz)} = \frac{n_m P}{120}$$

n_m = Mechanical rotation in rpm

P = No. of poles

Therefore, the rate of mechanical rotation required to generate a particular electrical frequency is calculated provided the number of poles is given.

Example: We would like generate electrical power at freq. 50 Hz. The syn. generator having $P = 4$. What would be the mechanical rate of rotation required.

$$n_m = \frac{120 f_e}{P} = \frac{\overset{30}{\cancel{120}} \times 50}{\cancel{4}} = 1500 \text{ rpm}$$

② The internal generated voltage of a sync. generator.

The magnitude of the induced voltage (internal voltage) in a given stator phase. is given as.

$$E_A = \sqrt{2}\,\pi N_c \phi f$$

Using $\omega = 2\pi f$, we can rewrite the above eqn as,

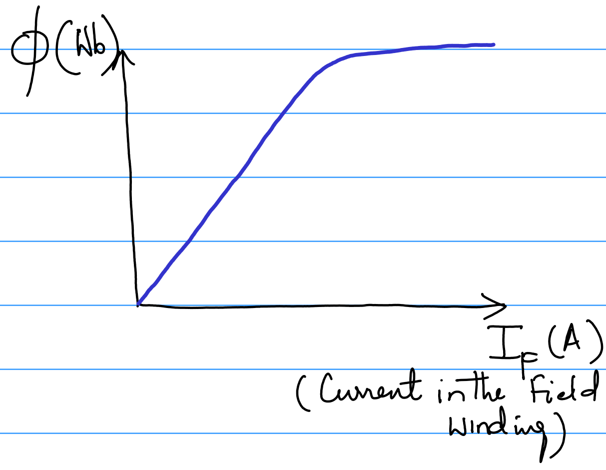
$$E_A = K\phi\omega \quad \text{where,}$$

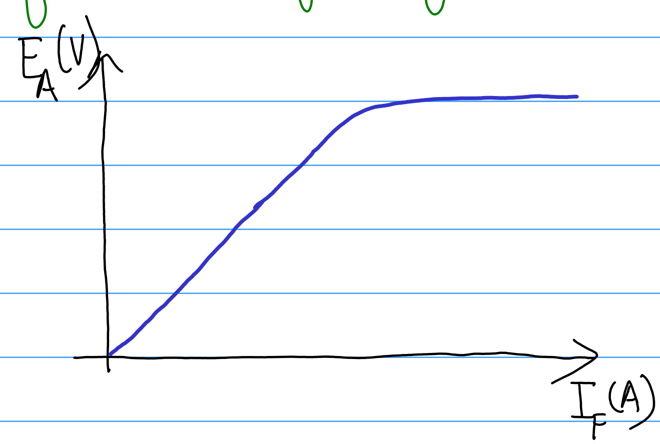
where K = constant representing construction of the machine

$$K = \frac{N_c}{\sqrt{2}} \quad ; \text{ when '}\omega\text{' is electrical radian/sec}$$

$$= \frac{N_c \cdot P}{\sqrt{2}} \quad ; \text{ when '}\omega\text{' is mechanical radians/sec.}$$

Open-ckt. characterstics of the sync. generator.





The Equivalent ckt. Model of a Sync. Generator

Points to keep in mind :

(i) Internal generated voltage E_A in one phase of the sync. generator

(ii) Only when the armature (stator) current is zero (open ckt.) then

$$E_A = V_\phi$$

where V_ϕ = Output voltage of the phase.

otherwise, (ie, $I_A \neq 0$) then,

$$\boxed{E_A \neq V_\phi} \qquad (I_A \neq 0)$$

Ques: Why? What would be the relationship b/w the two?

Factors that cause the difference b/w E_A & V_ϕ.

(i) Armature Reaction : This is basically distortion of the air-gap magnetic field by the current flowing in the stator.

(ii) The self-induction of the armature coil

(iii) The resistance of the armature coil.

(iv) The effect of the shape of the rotor's pole.

Overall conclusion:

There are two voltages present in the stator windings.

V_ϕ (total voltage in one phase of the stator)

$$= \underbrace{E_A}_{\text{Internal generated voltage}} + \underbrace{E_{Stator}}_{\text{Voltage generated due to Armature reaction}}$$

$$\boxed{V_\phi = E_A + E_{Stator}}$$

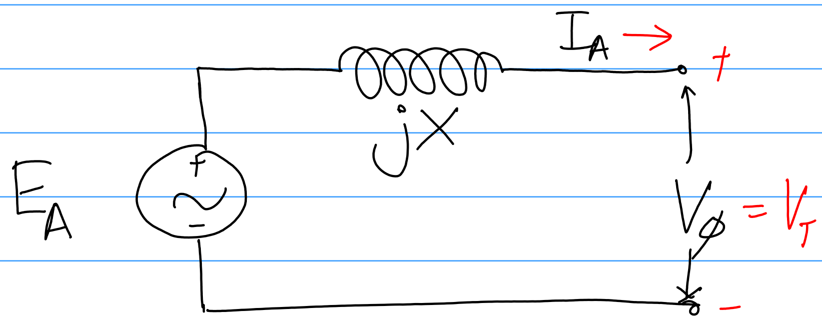
Ques: How can the effects of armature reaction on the phase voltage be modeled as ckt. element?

- E_{Stator} lags by 90° w.r.t I_A
- $E_{Stator} \propto I_A$

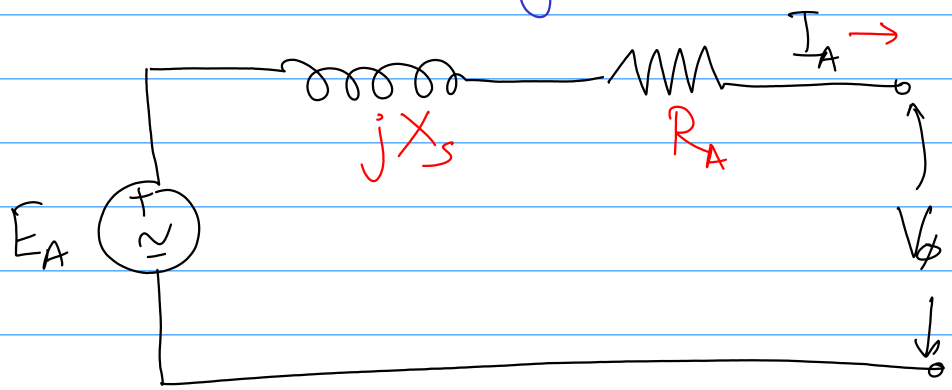
$$E_{stator} = -jX I_A$$

where X = const. of proportionality (Reactance)

$$\boxed{V_\phi = E_A - jX I_A}$$



Considering the self-inductance & resistance of the armature winding we have:



X_s = Sync. Reactance of the machine

9th July 2021

Equivalent ckt. of a 3-phase Sync. Generator

(Ref. Sect 5.4 / 5.5)

We have,

$$V_\phi = E_A - jX_s I_A - R_A I_A$$

where, $X_s = X + X_A$

Synchronous Reactance (X_s)

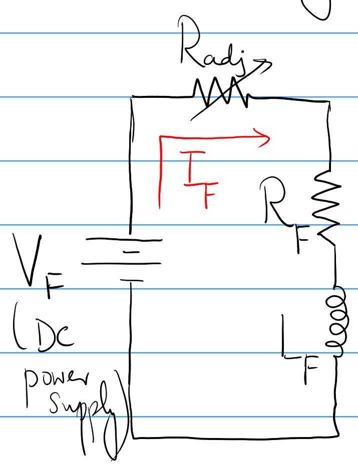
Armature Reaction (X)

Armature self-inductance (L_A) (X_A)

R_A = Armature resistance

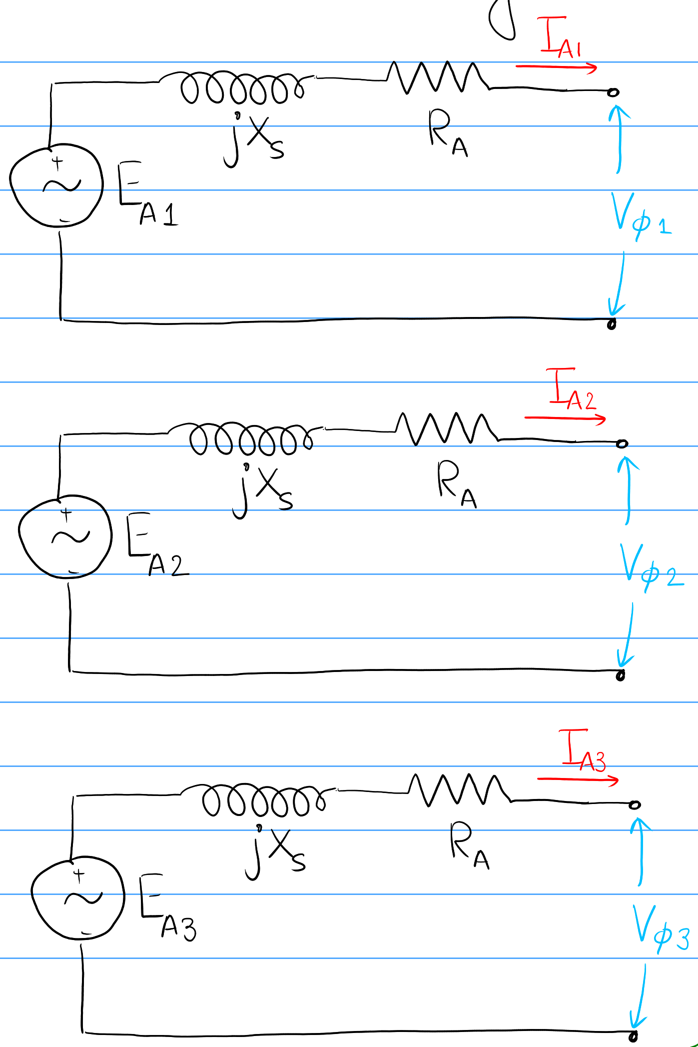
Full Equivalent ckt. Model of the Sync. Generator :

Field Winding :



Rotor of the Sync. Generator

Armature Winding



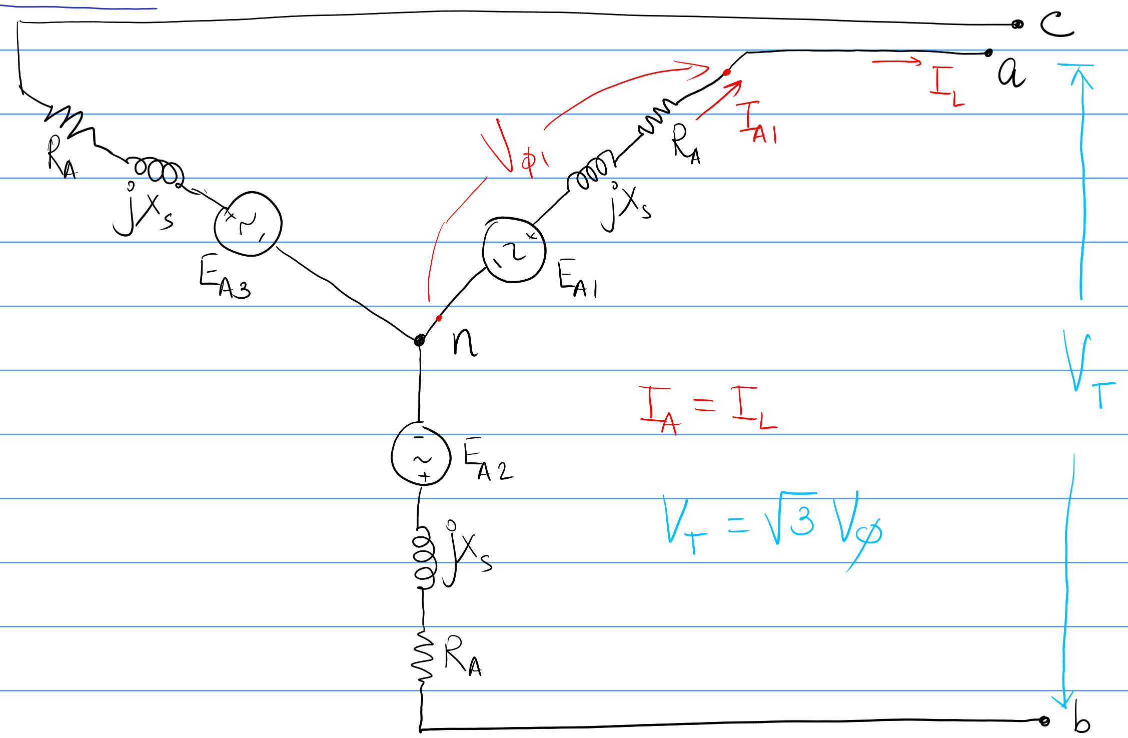
Stator of the Sync. Generator

Note : Each voltage and currents of the 3-phase are 120° apart in phase angle, but otherwise the 3-phase are identical.

Connection of 3-ϕ Sync. Generator :

- Y- connection
- Δ- connection

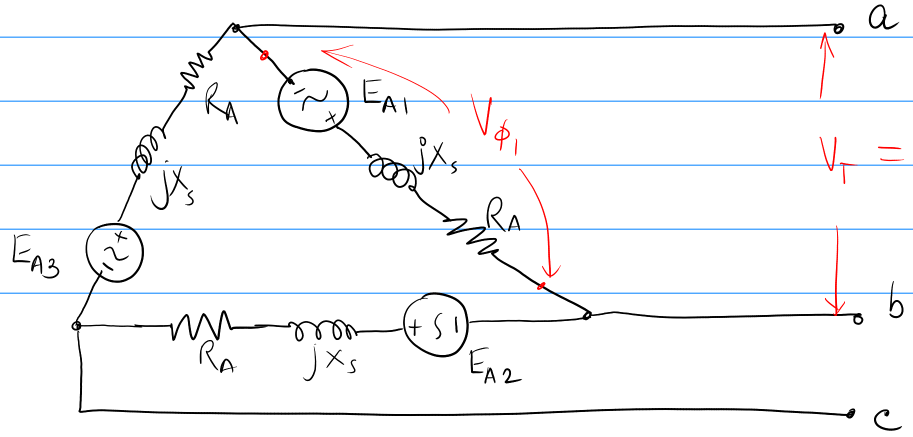
Y- connection :



$$I_A = I_L$$

$$V_T = \sqrt{3}\, V_\phi$$

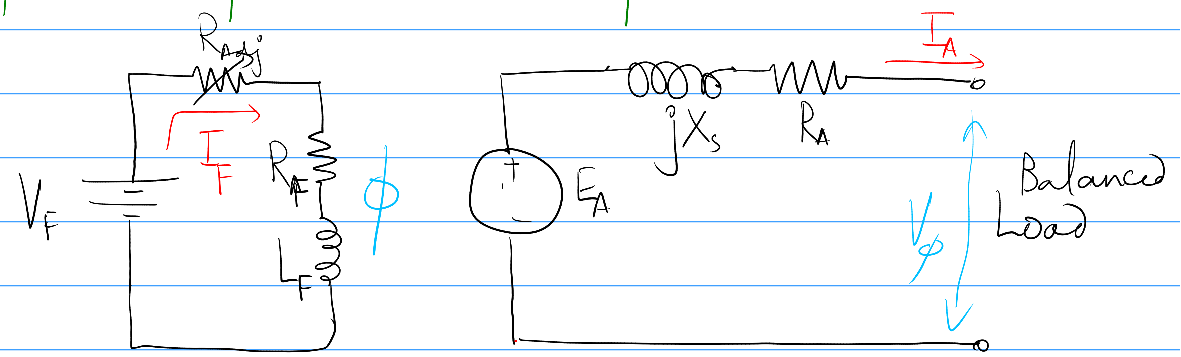
Δ- Connection :



$$V_T = V_\phi$$

Balanced load :

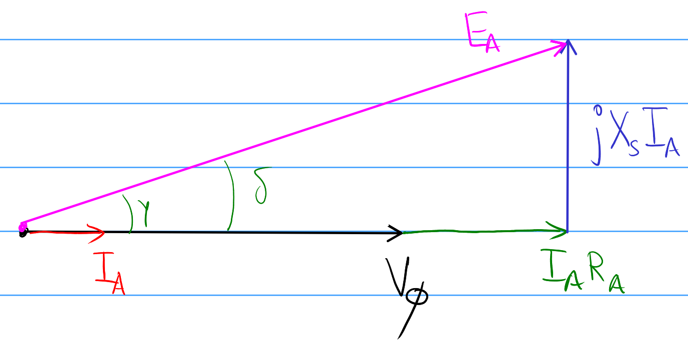
Per-phase equivalent ckt. for a Balanced Load.



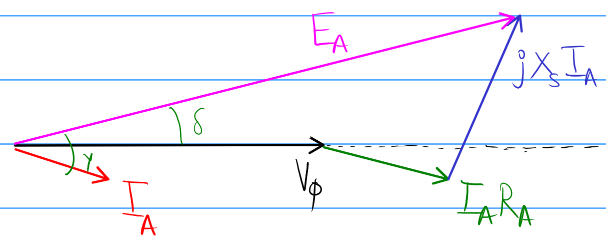
Phasor-Diagram : (With Reference to V_ϕ)

(i) Let the generator is connected to Resistive Load

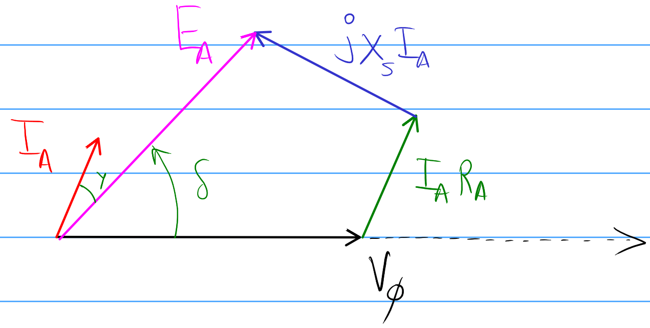
power factor $= \cos\theta = 1$ (Unity)



(ii) Lagging Load (Inductive Load) :



(iii) Leading Load (Capacitive load)



For a given V_ϕ and I_A ;

$$E_A(\text{lagging Load}) > E_A(\text{Leading Load})$$

Since $E_A = K\phi\omega$

ie, $E_A \propto \phi \propto I_F$ ('ω' is constant)

$$I_F(\text{lagging Load}) > I_F(\text{Leading load})$$

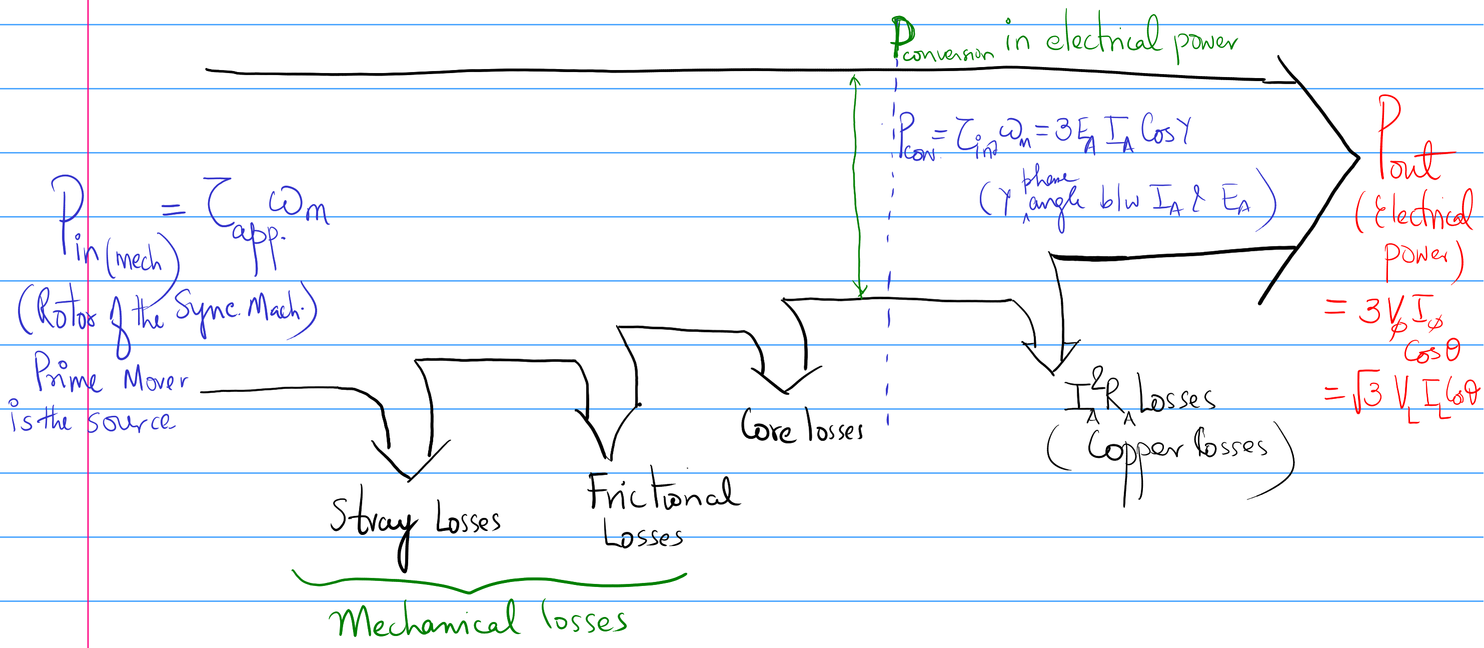
Alternatively :

For a given I_F and the magnitude of load current, the terminal voltage is lower for the lagging load and it is higher for the leading load.

14.07.2021

Power and Torque in Sync. Generator

- Here, the source of mechanical power is a prime mover:
  - Diesel Engine; Steam turbine, water turbine etc.
- Basic requirement: Speed of the prime-mover must remain constant regardless of the electrical power demand, otherwise, the frequency of the electrical power fluctuates.



- Real Electrical Output Power :

$$P_{out} = 3 V_\phi I_A \underbrace{\cos\theta}_{\text{p.f.}} = \sqrt{3}\, V_T I_L \cos\theta$$

p.f. (depends upon the nature of load)

- Reactive Electrical Output Power :

$$Q_{out} = 3 V_\phi I_A \sin\theta = \sqrt{3}\, V_T I_L \sin\theta$$

Assuming $R_A \approx 0$ ie, $X_A >> R_A$

$$P_{conversion} = P_{out} = \frac{3 V_\phi E_A \sin\delta}{X_s}$$

where the angle 'δ' = phase angle b/w V_ϕ & E_A

'δ' is termed as "Torque angle" of the machine

Case where $\delta = 90°$

$$P_{out} = P_{max} = \frac{3 V_\phi E_A}{X_s}$$

this is called "STATIC STABILITY LIMIT" of the sync. gen.

However, in real/practical sync. gen.

the typical torque angle 'δ' lies b/w $15^\circ - 20^\circ$.

Alternate Equation :

$$\vec{\tau}_{ind} = K \left(\vec{B}_R \times \vec{B}_{net} \right)$$

$$\left| \vec{\tau}_{ind} \right| = K \, B_R \cdot B_{net} \, \sin\delta$$

$\vec{B}_R \longrightarrow$ Produce E_A

$\vec{B}_{net} \longrightarrow$ Produce V_ϕ

$$\boxed{\tau_{ind} = \frac{3 V_\phi E_A \sin\delta}{\omega_m X_s}}$$

$\omega_m \rightarrow \omega_e$

Mechanical quantity.

Electrical quantities

Ref. Upto Section 5.6.