EE-362 ELECTROMECHANICAL ENERGY CONVERSION-II

Introduction to Synchronous Machines

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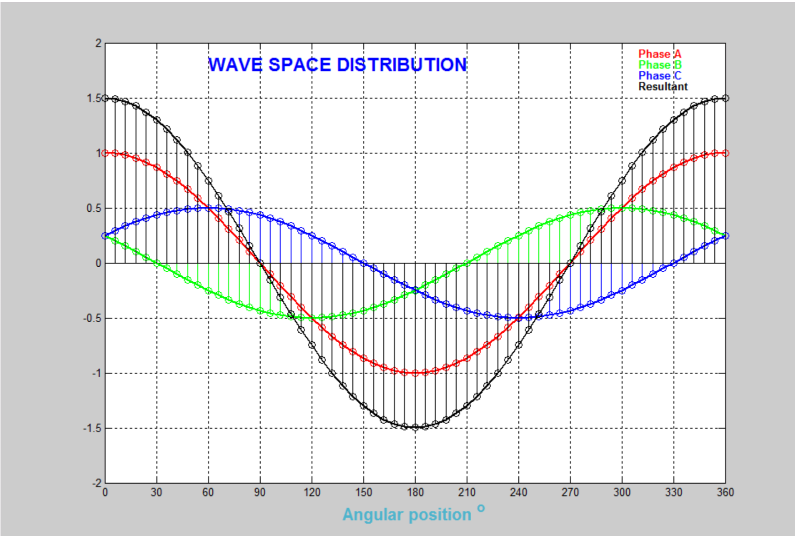
Review

Rotating MMF generated by 3-phase winding



Fundamental Idea of all AC Machines

Rotor tries to catch the rotating MMF

(in order to reach minimum magnetic energy point).

Synchronous Machines

Generates 90% of the world's electricity

PMSM are used by many electric car brands

Suggested Video: **Matrix Reloaded**

Synchronous Machines

Armature:

- 3-phase cylindrical stator.
- Generates rotating MMF (ie moves the carrot)

Rotor (Field Windings):

- Either Salient Pole or Cylindrical Rotor
- Excited with DC!
- or can also have permanent magnets for excitation

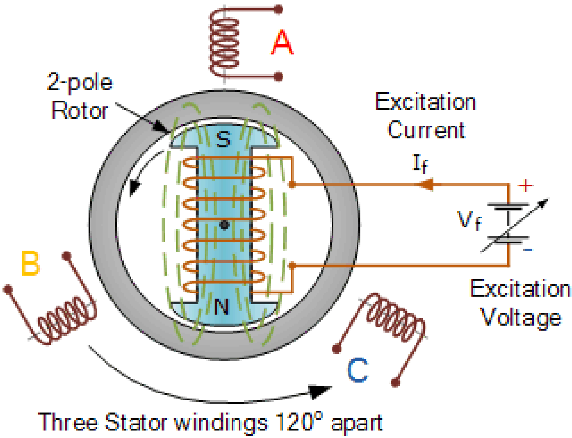
Synchronous Machines: Rotor

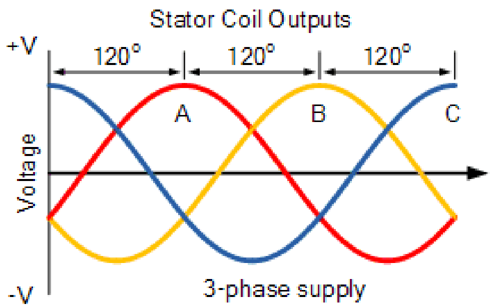
Rotor is excited with DC, becomes an electromagnet

Needs two slip rings to carry to current to rotor

Theory of Operation:

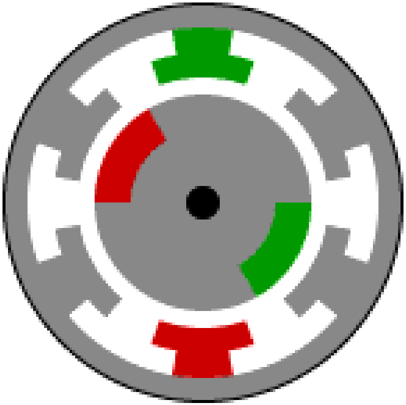
Stator winding create rotating MMF





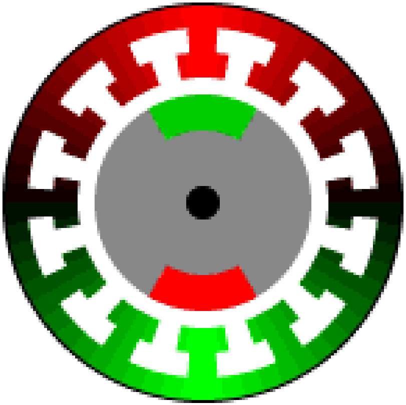
Theory of Operation

Rotor MMF (DC) locks with stator MMF, and rotates at the synchronous speed



A BLDC motor with concentrated stator windings

Theory of Operation

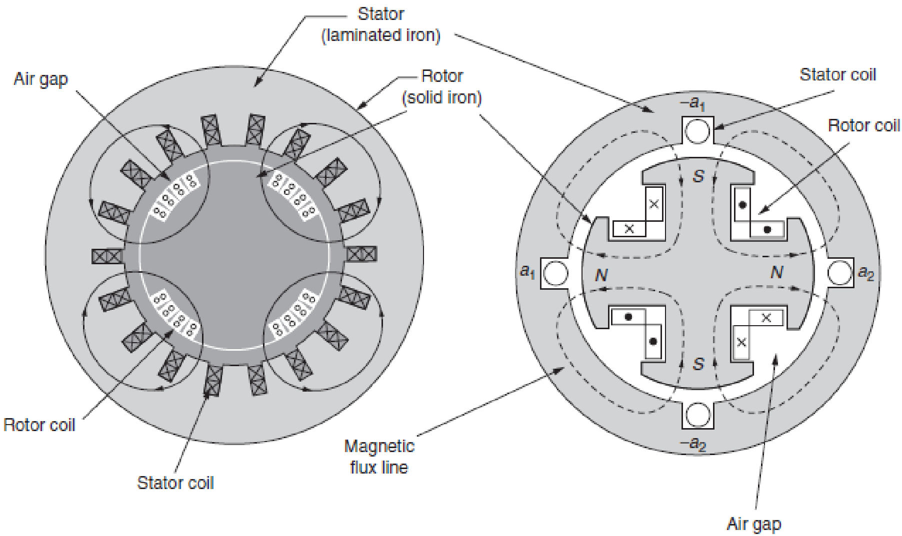


A smoother MMF distribution with distributed winding and AC excitation

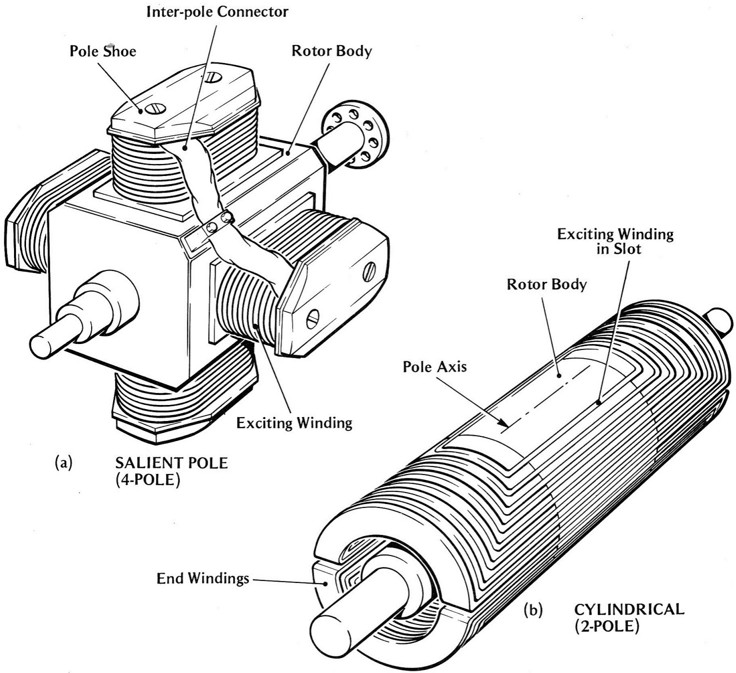
[Operation animation]

Synchronous Machines: Rotor

Cylindrical vs Salient Pole



Cylindrical vs Salient Pole



Cylindrical Rotor Synchronous Machines

Fig: Cylindrical rotor with slotted rotor surface along axial length to house field windings

Airgap (and hence inductance) is more or less constant

No reluctance torque ($\frac{dL(\theta)}{d\theta} = 0$) but there is still synchronous torque ($\frac{dM(\theta)}{d\theta}$)

Cylindrical Rotor Synchronous Machines

Used in high speed turbo-generators (2 or 4 poles)

[How a Gas Turbine Works]

Salient Pole Rotor Synchronous Machines

Airgap is not uniform.

There are both reluctance and synchronous torque components

Salient Pole Rotor Synchronous Machines

Used in large-pole low-speed generators (e.g. hydroelectric plants)

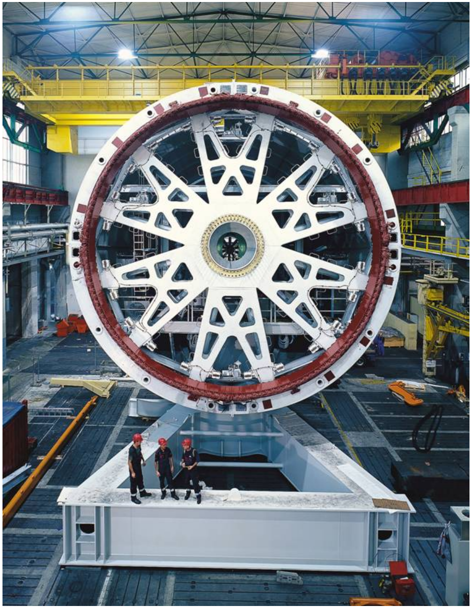
Synchronous Machines are usually big machines

Direct-Drive Permanent-Magnet Synchronous Generator for Wind Turbines (Siemens)

Synchronous Machines are usually big machines

2-pole 3000rpm Synchronous Generator (For Steam Turbines)

Very Big



Wind Turbine Synchronous Generator (12 rpm)

Very Very Big

Itaipu Hydro Plant, Brazil

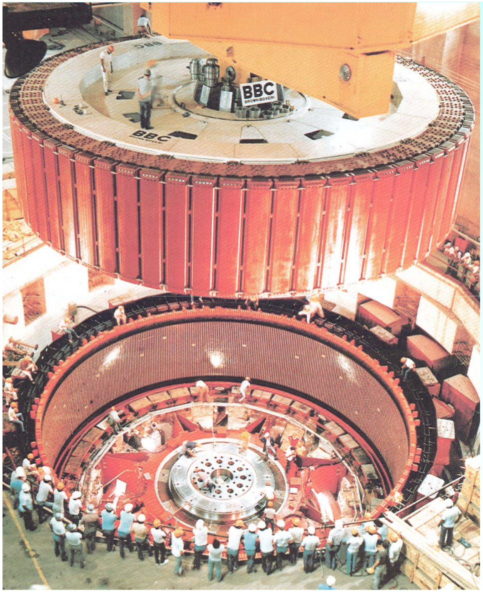
20 Turbines, 700 MW each

Very Very Big

Itaipu Hydro Plant, Brazil

Shaft of The Generator

Very Very Big: [700 MW Synchronous Generator]



16 m diameter, 91 rpm, Rotor Mass: 2650 t

Even Bigger: Three Gorges Dam, China

Total Power Capacity: 22.5 GW (1/3 of Turkey's Consumption)

Slowed down the rotation of earth by 0.06 microseconds

Video1, Video2, Richard Feynman on Generators and Our Civilization

Assume the stator is not excited, only the rotor is excited with DC.

What is the shape of the induced voltage in the stator windings?

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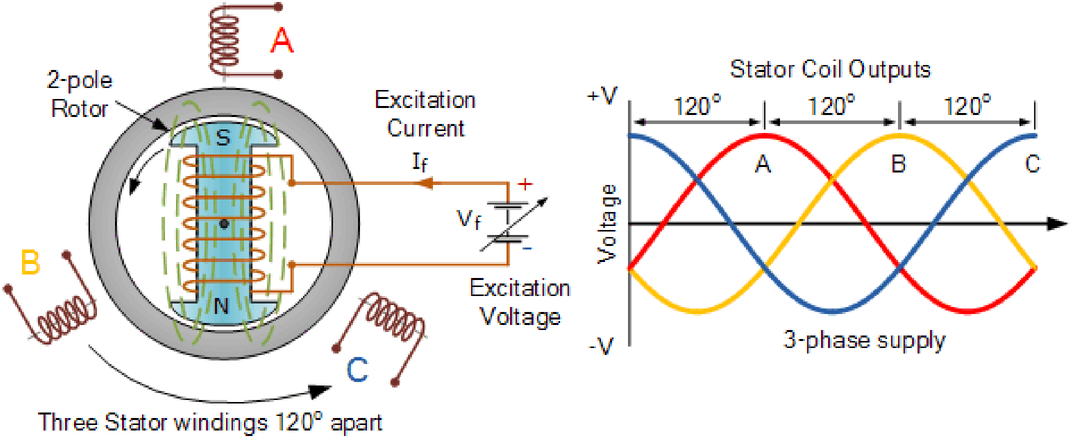
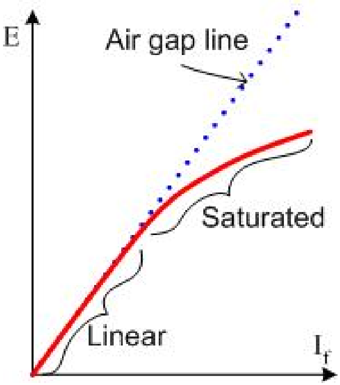


Induced Voltage Proportional to?

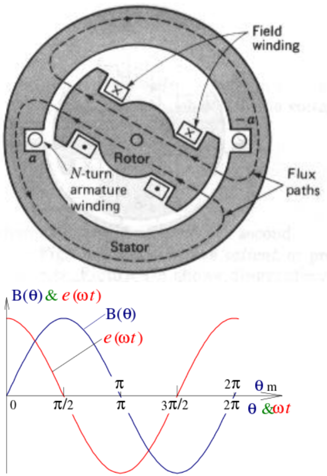
Induced voltage $\propto$ Field Current $\times$ Frequency

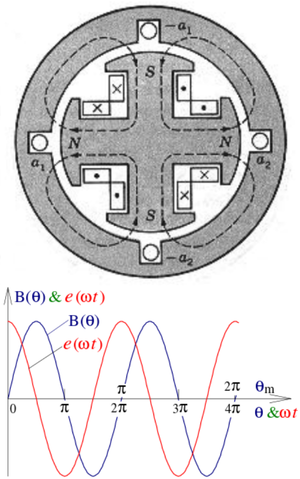


We would like to operate in the linear region, but beware of saturation & residual magnetism)

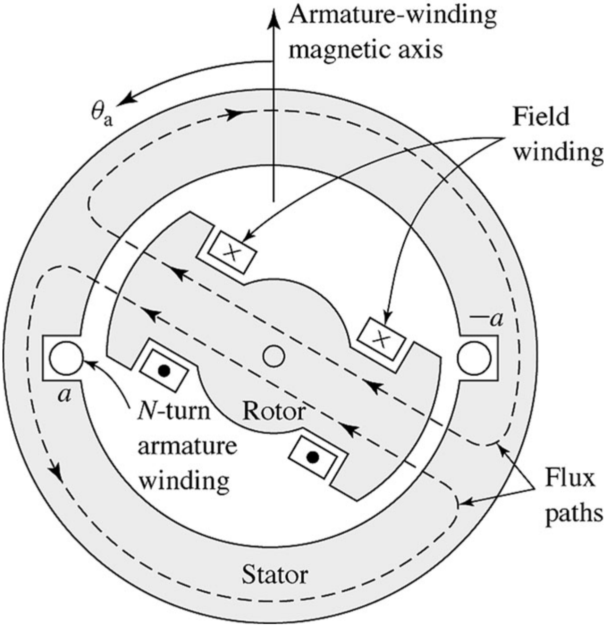
Mechanical Rotation Frequency vs. Electrical Frequency

The machine on the right induces a voltage twice the frequency of mechanical rotation frequency.

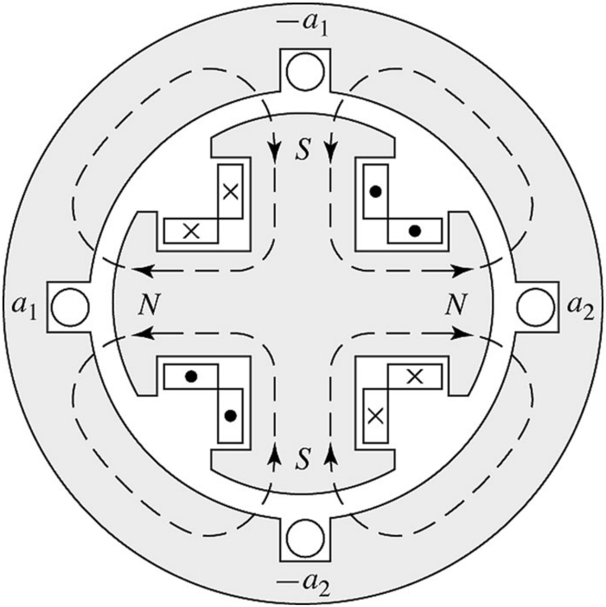




Number of Poles: 2-pole machine



Number of Poles: 4-pole machine



How many poles does this machine has?

What should be the rotational speed in RPM to induce 50 Hz voltage?

Electrical Speed is not equal to Mechanical Speed!

$$\omega_{elec} = (\frac{p}{2})\omega_{mech}$$

p : Number of poles (always an even number)

$\frac{p}{2}$: Number of pole pairs

$$\theta_{elec} = (\frac{p}{2})\theta_{mech}$$

Synchronous Machines

Rotate only at synchronous speed!

Synchronous Speed in RPM (revolutions per minute):

$$n_s = \frac{60 f_{elec}}{(p/2)} = \frac{120 f_{elec}}{p}$$

They are constant speed machines (under constant stator voltage frequency)

A few videos to watch

Renault Zoe Synchronous Motor Manufacturing

Audi e-tron motor

Enercon Wind Turbine Generator

ABB Azipod Ship Propulsion Motor

Siemens Turbo Generator

Hydro Generator Manufacturing

Induced Voltage

Cause $\longrightarrow$ Effect

$$I_{field(DC)} \rightarrow MMF_{field} \rightarrow \Phi_f \rightarrow$$

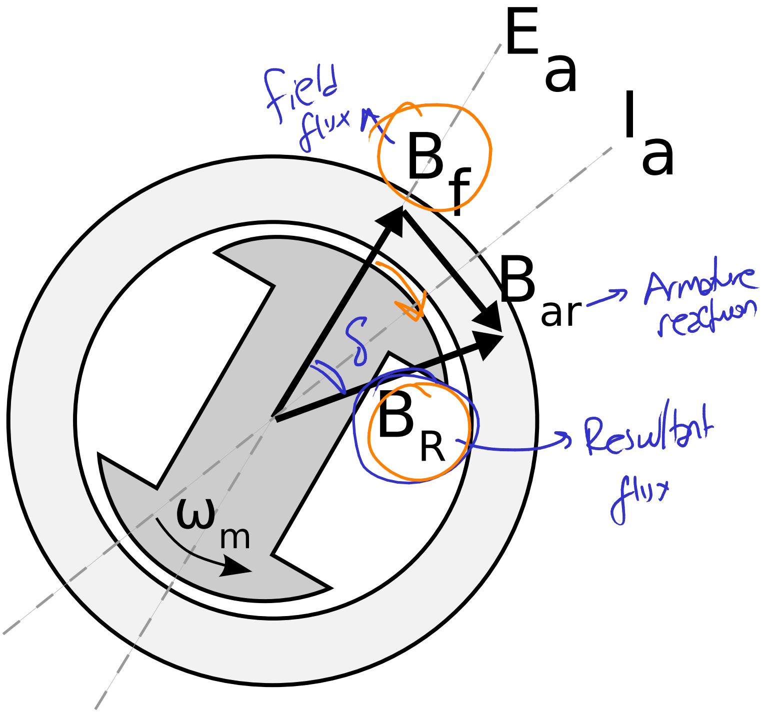
$$e_a, e_b, e_c \rightarrow I_a, I_b, I_c \rightarrow MMF_{armature}$$

$$\rightarrow \Phi_{ar}$$

Resultant MMF:

$$\Phi_R = \Phi_f + \Phi_{ar}$$

B_R: Resultant flux density



Torque in Synchronous Machines

$$T = K\Phi_f \Phi_R sin(\delta)$$

K: Constant (we'll see what it is in the following lectures)

Φ_f : Field generated flux (rotor-side)

Φ_R: Resultant (or Air-gap) flux ($\Phi_R = \Phi_f + \Phi_{ar}$)

δ: Load-angle (very important!)

Torque vs Load Angle

$\delta > 0$: Generating Action

$\delta < 0$: Motoring Action

$\delta = \pm\frac{\pi}{2}$: Maximum torque point

Torque vs Load Angle

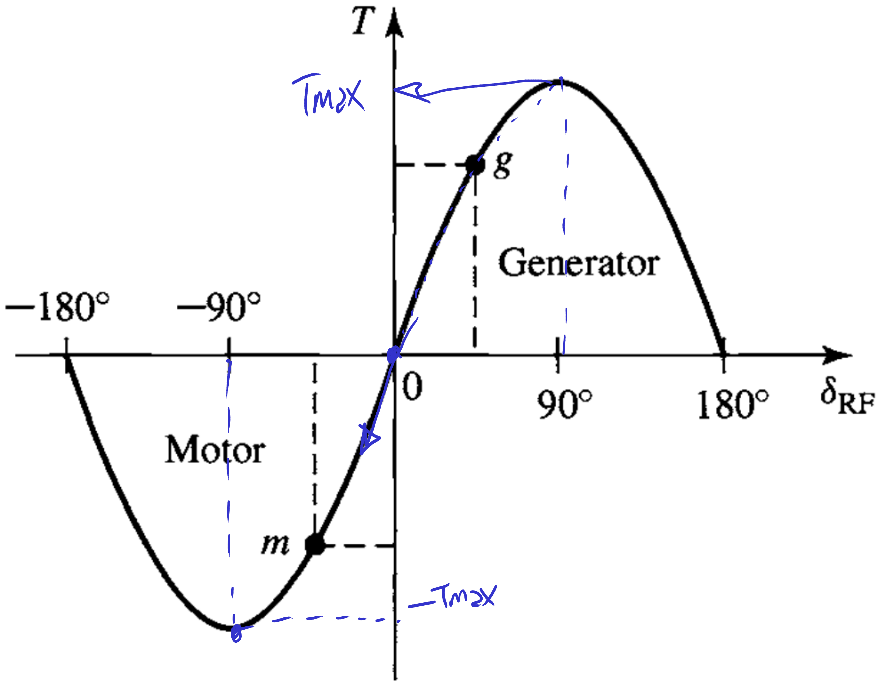
$\delta > 0$: Generating Action

$\delta < 0$: Motoring Action

$\delta = \pm\frac{\pi}{2}$: Maximum torque point

$\delta = 0$: Zero Torque (Donkey eats the carrot)

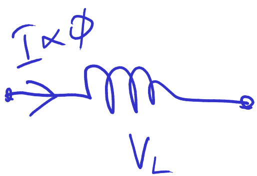
Torque vs Load Angle



Phasor Diagram

$\overrightarrow{E_{ar}}$ lags $\overrightarrow{\Phi_{ar}}$ 90 degrees

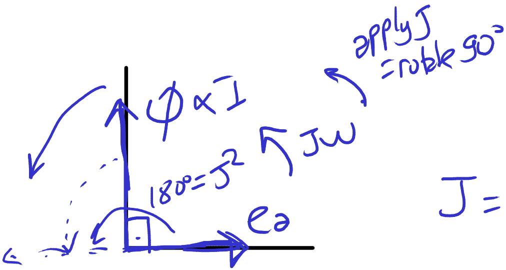
$\propto I_{ar}$



$e_a(t) = -N \cdot \frac{d\Phi}{dt}$ → taking derivative ↳ multiplying by Jω

Φ is in the form of sin ...

e_a ⇒ in the form of −cos ...



$J = \sqrt{-1}$

$J \times J = -1$

Phasor Diagram

$\overrightarrow{E_{ar}}$ lags $\overrightarrow{\Phi_{ar}}$ 90 degrees

Armature reaction can be represented as a voltage drop in an inductance

$$\overrightarrow{E_{ar}} = -jX_Q\overrightarrow{I_a}$$

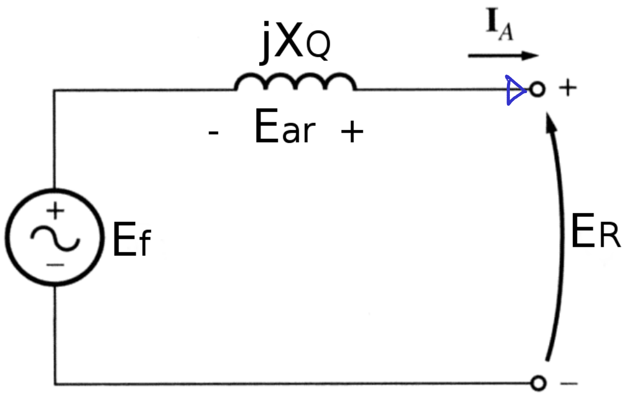
$$\overrightarrow{E_R} = \overrightarrow{E_f} - jX_Q\overrightarrow{I_a}$$

Simple Equivalent Circuit

Assumption: Cylindrical rotor (constant air-gap) (No reluctance torque for now)

Simple Equivalent Circuit

Assumption: Cylindrical rotor (constant air-gap)



$$\overrightarrow{E_R} = \overrightarrow{E_f} - jX_Q\overrightarrow{I_a}$$

Simple Equivalent Circuit

However, there is also the leakage flux: jX_l

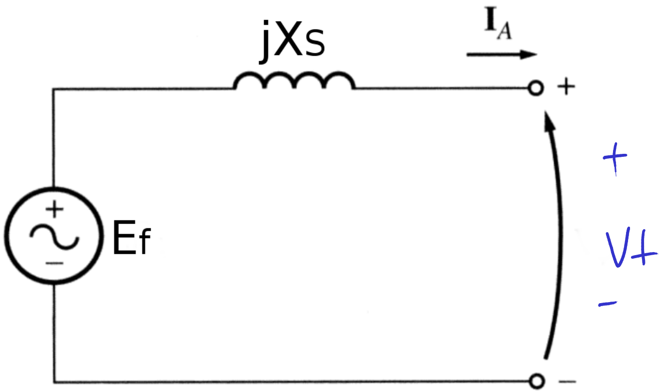
Define stator total reactance as:

$$jX_S = jX_Q + jX_l$$

stator total reactance

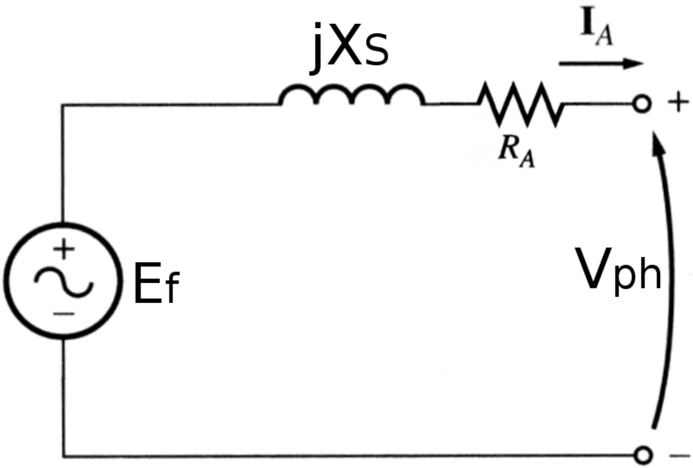
Thus, the equivalent circuit becomes:

Simple Equivalent Circuit



$$\vec{E} = \overrightarrow{E_f} - jX_s\overrightarrow{I_a}$$

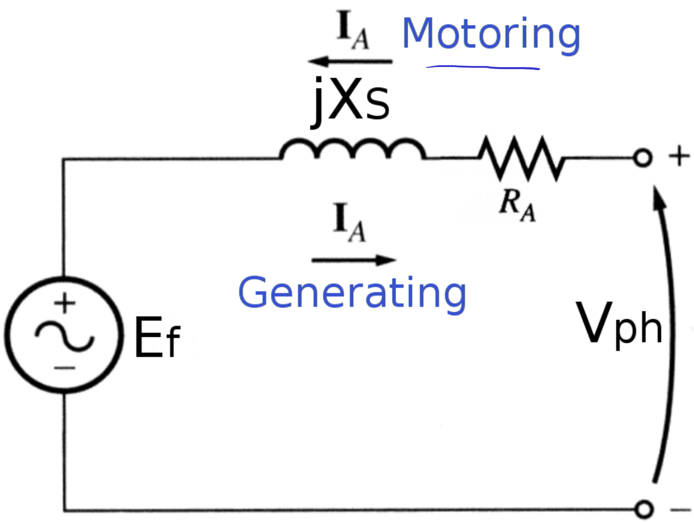
What about the resistance of the phase windings?



$$\overrightarrow{V_{ph}} = \overrightarrow{E_f} - (jX_s + R_a)\overrightarrow{I_a}$$

Motoring and Generating Convention

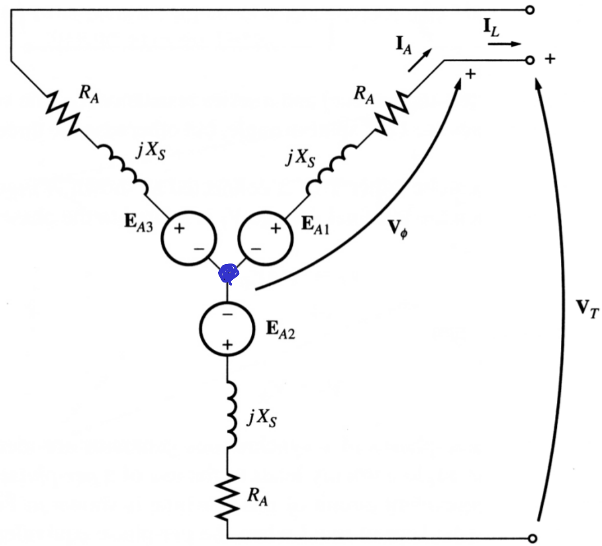
Remember synchronous machines are mostly used as generators.



per-phase equivalent circuit

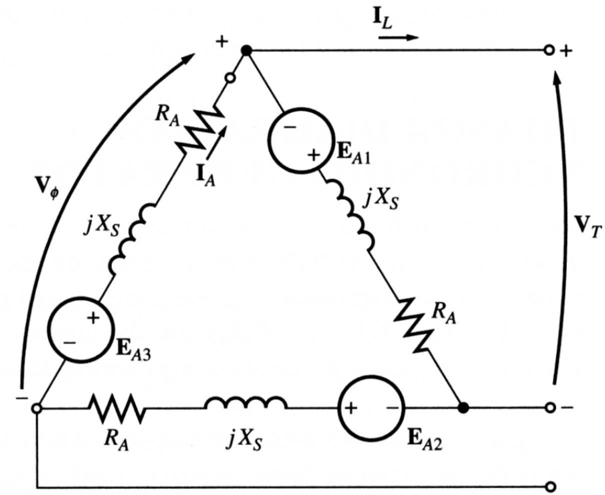
Remember the Equivalent Circuit is per Phase

Synchronous machines can be Wye or Delta connected



Remember the Equivalent Circuit is per Phase

Synchronous machines can be Wye or Delta connected

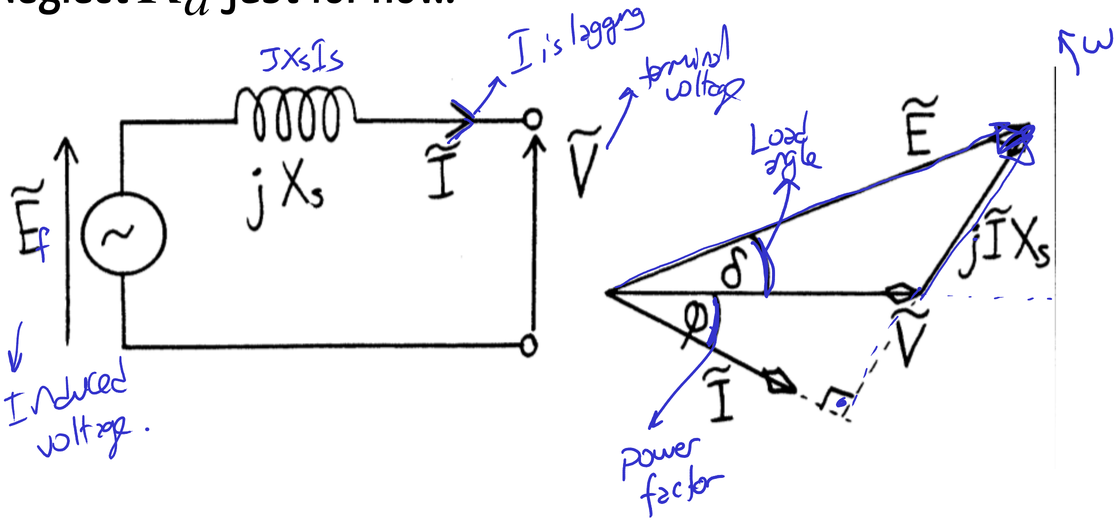


Most important definitions

- Load Angle (δ): Angle between phase voltage and field voltage
- Power Factor Angle (θ): Angle between phase voltage and current.

Load Angle and Power Factor

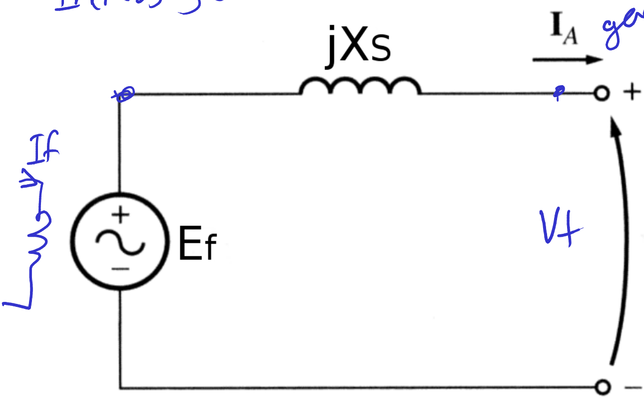
Neglect R_a just for now.

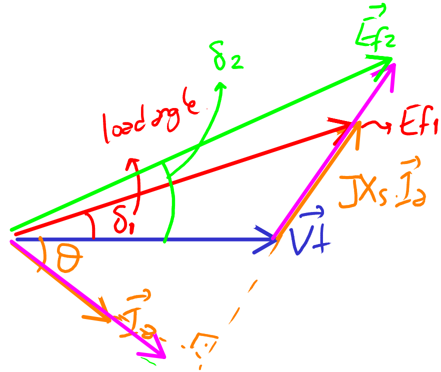


A few exercises with the simple equivalent circuit

Neglect R_a for now.

Increasing current with same pf.





$\cos(\theta) \Rightarrow$ power factor

$\vec{E}_f = \vec{V}_t + jX_s.\vec{I}_a$

$P_{out} = 3.V_t.I_a.\cos(\theta)$

What happens if current is increased with the same pf.

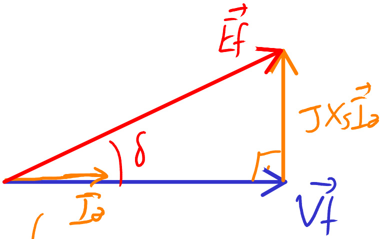
$\delta_2 > \delta_1 \Rightarrow$ Load angle is increased

↳ Torque is increased

$|\vec{E}_{f2}| > |\vec{E}_{f1}|$ ↳ field current should be increased

A few exercises with the simple equivalent circuit (Generator mode)

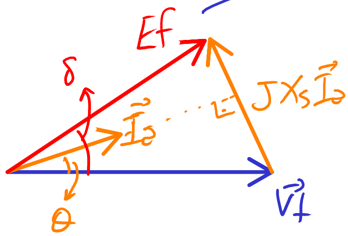
Unity pf. (generating mode)



θ=0 ⇒ unity pf.

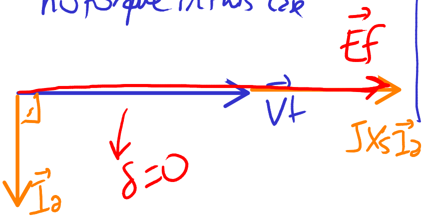
leading pf.

|Ef| can be controlled by the field current



90° lagging pf

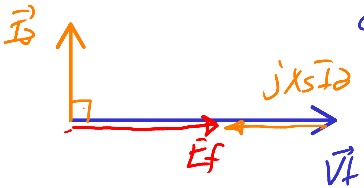
no torque in this case



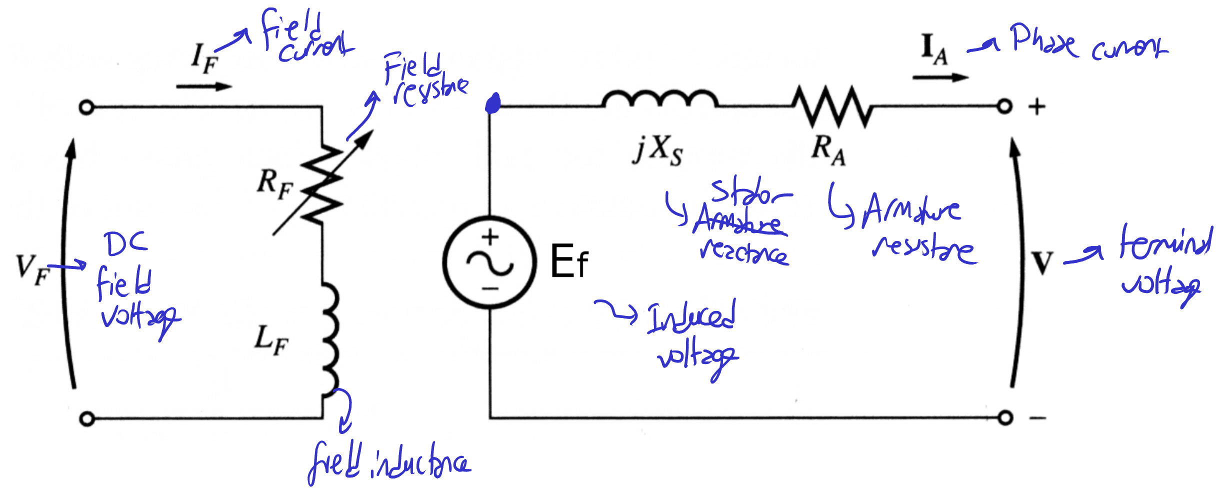
90° leading pf.

If θ = 90° leading

δ ⇒ 0 ⇒ Torque = 0



Full Equivalent Circuit with Field Circuit



L_f can be neglected at steady state (DC) conditions $I_f \propto |E_f|$

Remember I_f can be controlled to adjust E_f