Energy conversion I

Lecture 14:

Topic 4: Synchronous Machines (S. Chapman ch. 5&6)

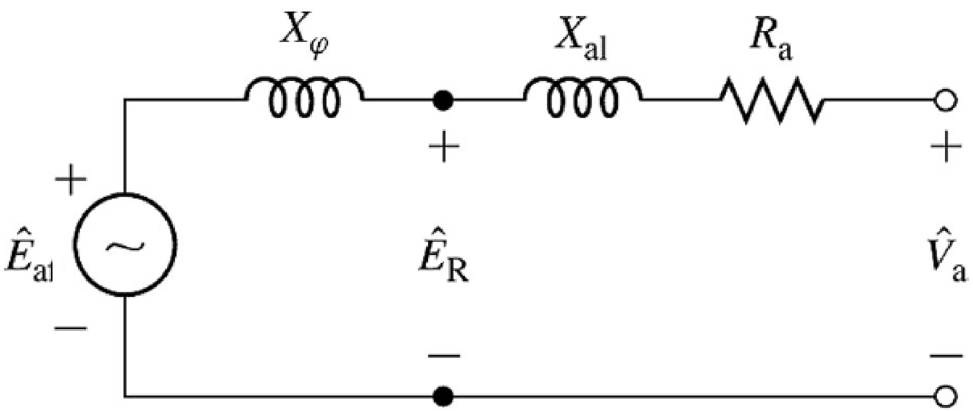
- Introduction
- Synchronous Generators Construction
- **Steady state equivalent circuit**
- **Power and Torque**
- Grid connected Synchronous machines
- Synchronous motors
- Power factor correction
- Start-up of synchronous motors

Steady state equivalent circuit

Rotating stator flux induces three phase voltages in stator three phase winding too (armature reaction).

This induced voltage is similar to the induced voltage in inductances.

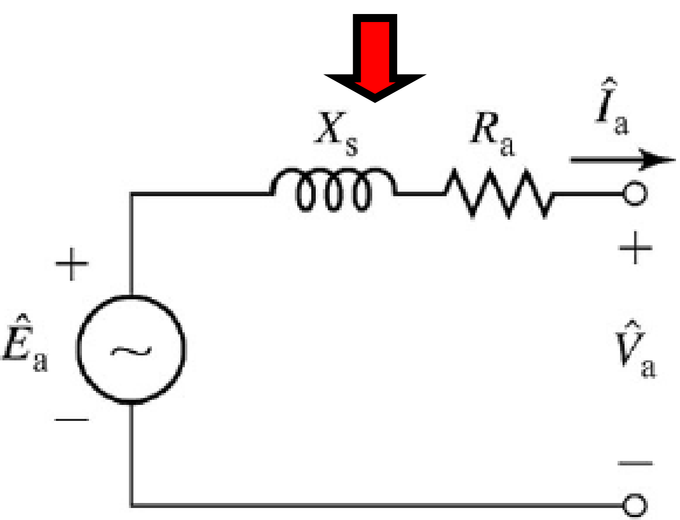
Using Single phase equivalent circuit:



$B_r \rightarrow E_a$, $B_g = B_r + B_s \rightarrow E_R = E_a + E_{stat}$

Flux leakage can be modeled by L_{al}

Winding resistance by R_a



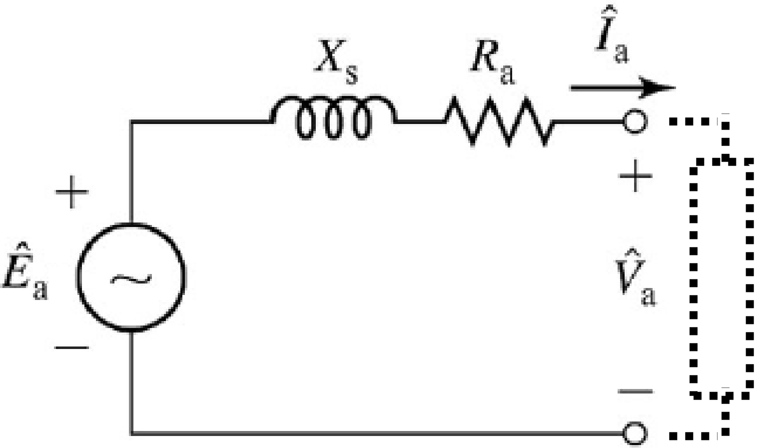
Using generator form for equivalent circuit:

$V_a = E_a - jX_sI_a - R_a I_a$

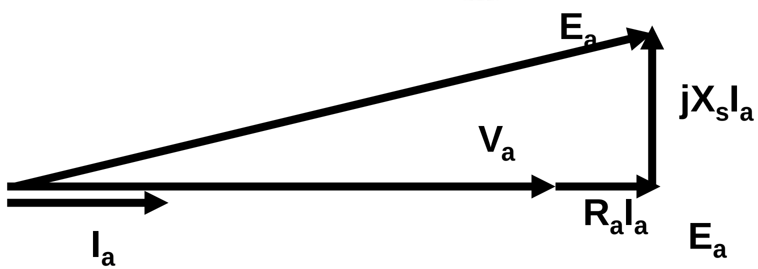
Think about equivalent circuit of Rotor in steady state!!

What about salient pole machines

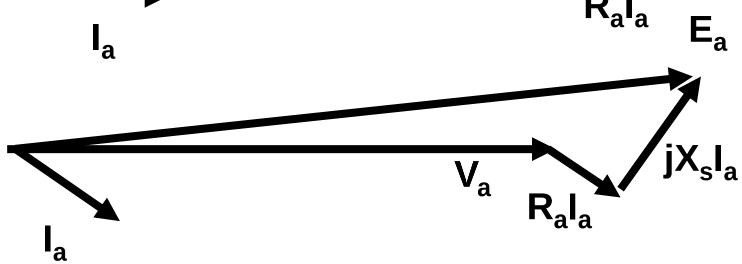
Phasor diagram of a synchronous generator



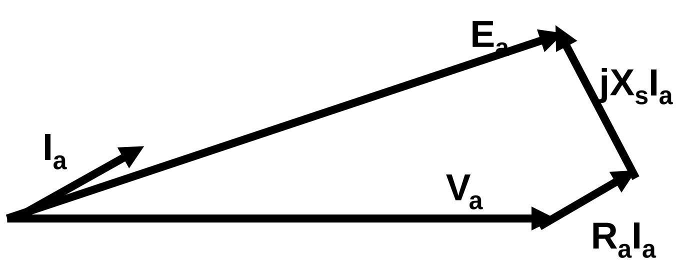
$$V_a = E_a - jX_sI_a - R_a I_a$$



Unity Power factor (Resistive load)



Lagging current (Inductive load)
Generator supplies reactive power

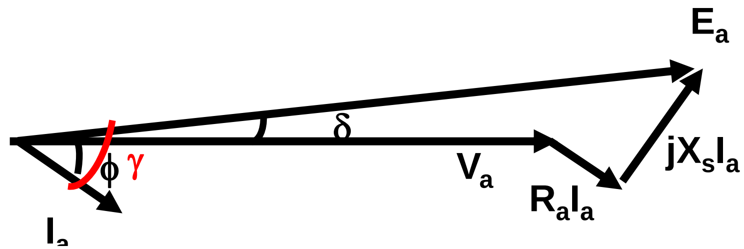


Leading current (Capacitive load)
Generator absorbs reactive power

Compare E_a (/I_f) in these three cases!

Power and Torque of a synchronous generator

$V_a = E_a - jX_sI_a - R_aI_a$



Output power: Electrical delivered to the load (/ Grid) connected to the stator terminals:

$P_{out} = V_a\ I_a \cos\phi$ (per phase)

$Q_{out} = V_a\ I_a \sin\phi$ (per phase) (positive if current is lagging)

Power loss:

Copper loss = $R_aI_a^2$ (per phase)

Iron Loss : (not included in the equivalent circuit)

Where and why iron loss?

Converted Power: Mechanical power converted to electrical power (Generator)

$P_{conv} = E_a\ I_a \cos\gamma$ (per phase) (Electrical)

$P_{conv} = T_{ind}\ \Omega_s$ (three phase) (Mechanical) $\quad \Omega_s = \omega_s * 2/p$

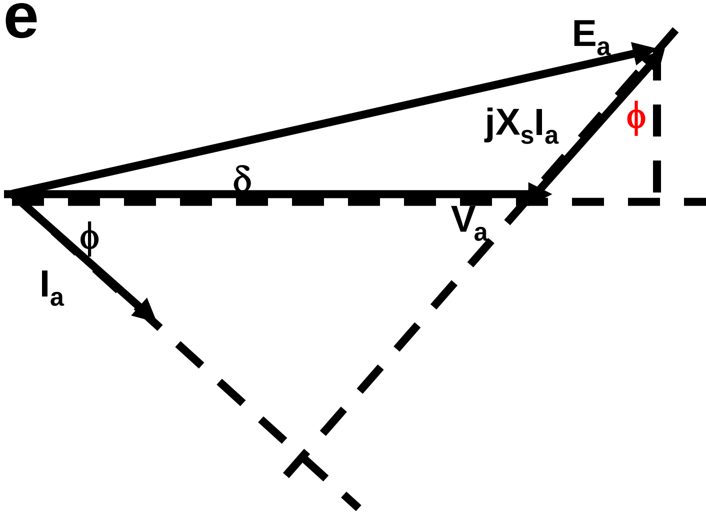
Mechanical power loss:

Friction and windage losses

Input Power: Mechanical

Don't forget field power!

Load / Torque angle



Usually: $R_a << X_s$ and therefore: $V_a = E_a - jX_sI_a$

$X_s\, I_a \cos\phi = E_a \sin\delta$

$$p = \frac{V_a E_a}{X_s} \sin\delta$$ **(per phase)**

$$p_{3ph} = 3\frac{V_a E_a}{X_s} \sin\delta = T\Omega_s$$

$$T_{ind} = \frac{3}{2}\frac{p}{\omega_s}\frac{V_a E_a}{X_s} \sin\delta$$

δ : Torque(/ Load) angle

$\delta > 0$ $T_{ind} > 0$: Generator

$\delta < 0$ $T_{ind} < 0$: Motor

E_a is induced by B_r
V_a is induced by B_g(total flux density)

δ is the angle between B_r and B_g

B_g follows B_r in generating mode
B_r follows B_g in motoring mode

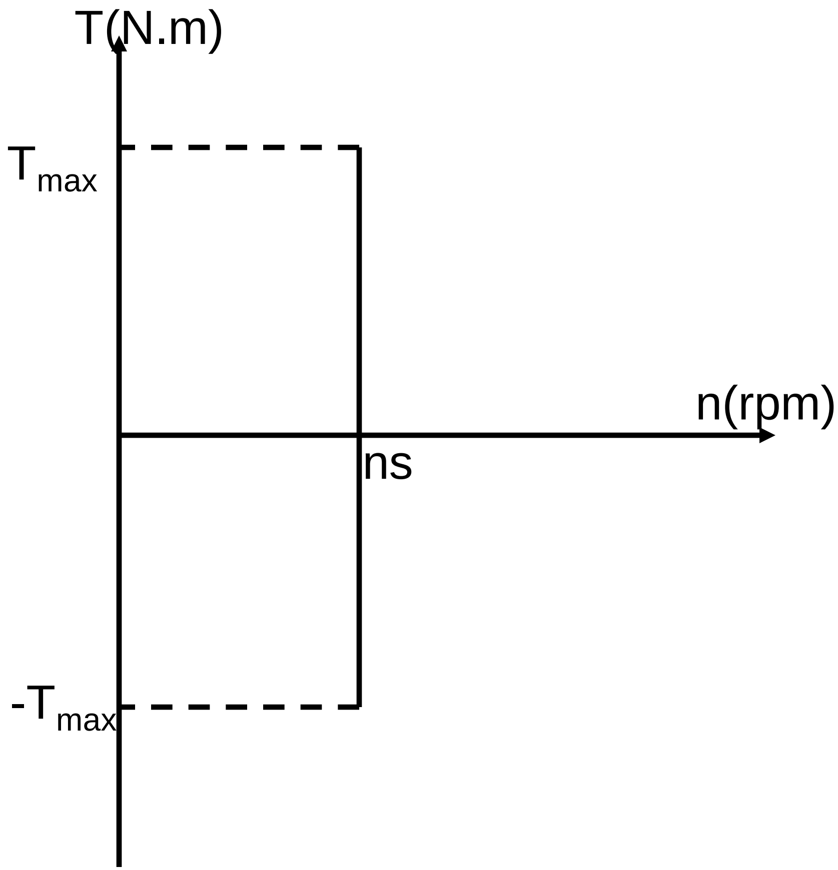
Power and Torque Characteristics

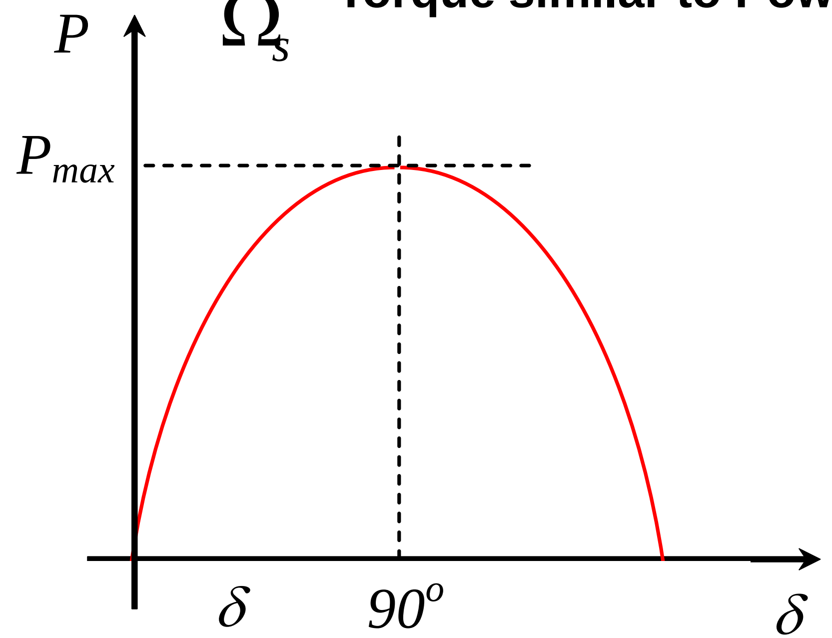
Synchronous Machine: Torque at Synchronous Speed (Torque-speed characteristics)

$$P = 3\frac{E_a V_a}{X_s}\sin\delta$$

$$T = \frac{P}{\Omega_s}$$

Torque similar to Power





Can machine work with δ > 90º Or δ < -90º?

Example:

A three phase, 5kW, 208 V, four-pole, 60 Hz, synchronous machine has negligible stator winding resistance and a synchronous reactance of 8Ω. The machine is connected to a 3phase 208V, 60Hz power supply.
a- Determine the excitation voltage and torque angle when the machine is delivering rated kVA at 0.8 PF lagging.

$$V_a = \frac{208}{\sqrt{3}} = 120V$$

$$I_a = \frac{5000}{\sqrt{3}\times 208}\angle -\cos^{-1}(0.8) = 13.9\angle -36.9$$

$$E_a = V_a + jX_s I_a = 120 + j8\times 13.9\angle -36.9 = 206.9\angle 25.5$$

Excitation voltage: 206.9 V/phase
Power Angle: 25.5°

b- What is the maximum power can be delivered?

$$P_{\max} = 3\frac{V_a \times E_a}{X_s} = 3\frac{120\times 206.9}{8} = 9.3kW$$

c: If the field excitation is now increased by 20%(without changing the prime mover power), find the stator current, power factor and reactive kVA supplied by the machine.

Power is the same as before, therefore:

$$\frac{V_a E_{a1}}{X_s}\sin\delta_1 = \frac{V_a E_{a2}}{X_s}\sin\delta_2$$

$$E_{a1}\sin\delta_1 = E_{a2}\sin\delta_2$$

$$\sin\delta_2 = \frac{E_{a1}}{E_{a2}}\sin\delta_1$$

$$\delta_2 = 21^o$$

Having E_{a2} and δ_2 current can be calculated:

$$I_a = \frac{E_a - V_a}{jX_s} = \frac{248.2\angle 21 - 120}{j8}$$

$$= 17.86\angle -51.5^o$$

$$\text{Power factor} = \cos 51.5 = 0.62\,lag$$

$$\text{Reactive kVA} = 3V_a I_a \sin 51.5$$

$$= 5.03\,kVAR$$

Increasing field current has increased Reactive power delivered