Energy conversion I

Lecture 15:

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 Machines Capability Curve**
- **Start-up of synchronous motors**

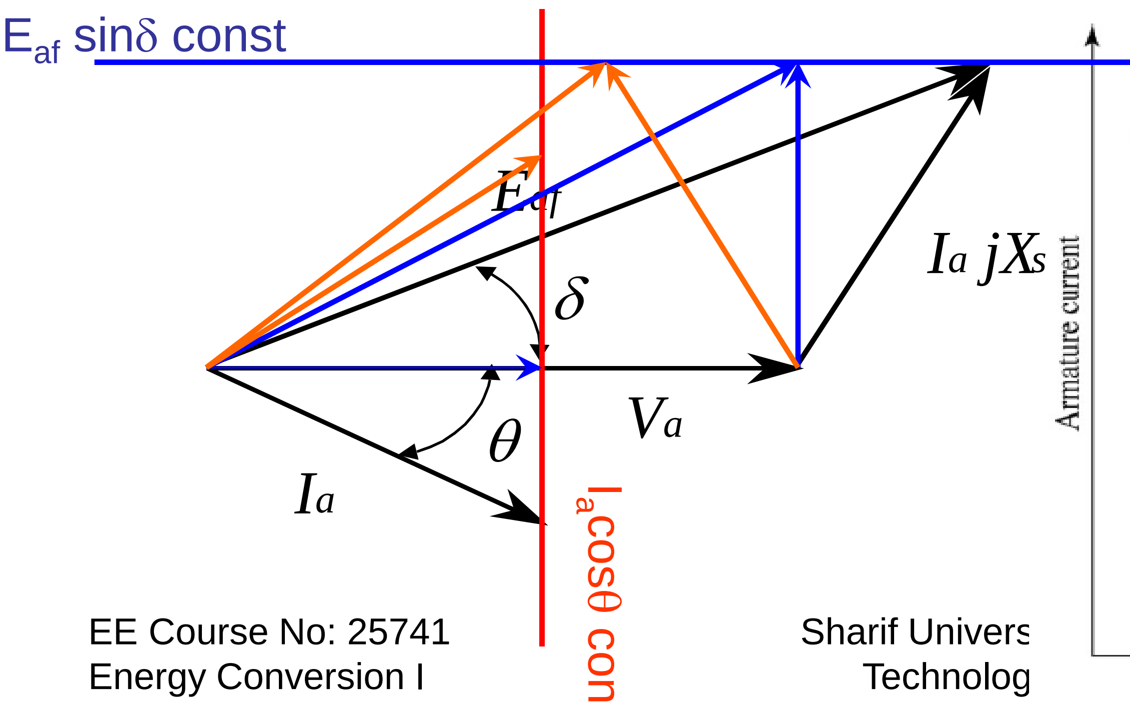
Grid connected Synchronous machines

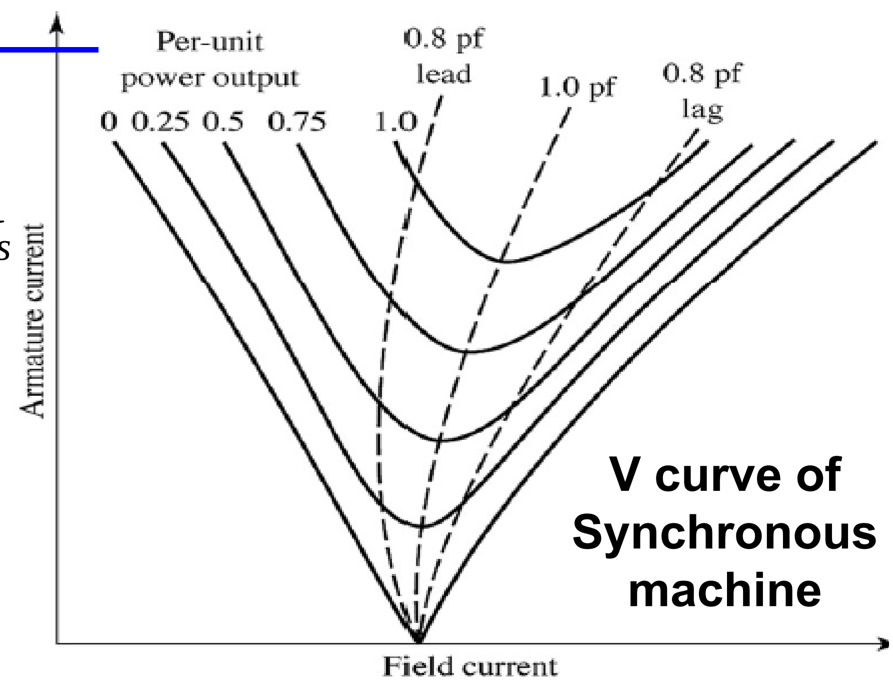
Synchronous machine should rotate at **synchronous speed** to generate **torque.**

Power rating of each **generator** is usually much **smaller** than the sum of **generators connected to grid.**

Grid can be considered as an **ideal AC voltage** source**. (constant frequency/ constant amplitude, some times with an output Impedance)**

Constant power operation: $I_a\cos\theta$ const, $E_{af}\sin\delta$ const





V curve of Synchronous machine

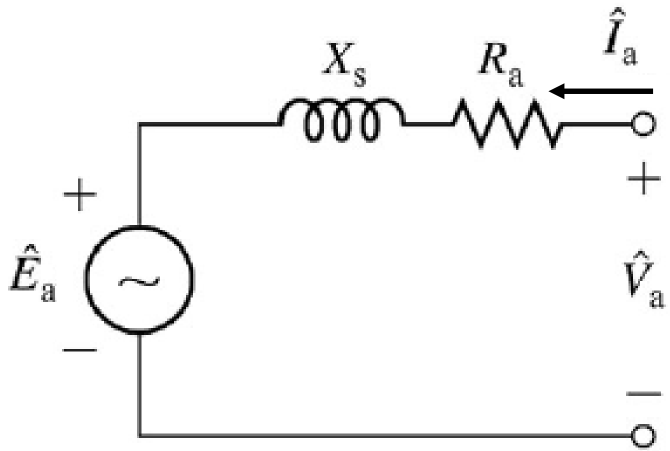
Synchronous Condenser

No-load grid connected synchronous machine:

motor $V_a = E_a + (R_a + jX_s)I_a$

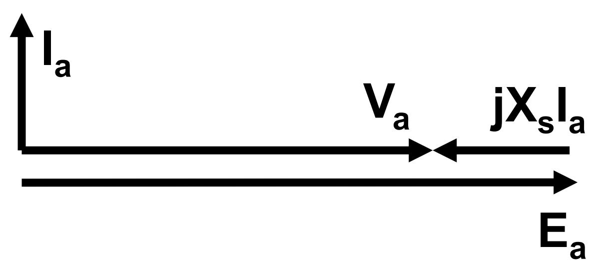
$$P = -3\frac{E_a V_a}{X_s}\sin\delta$$

Electrical Power converted to mechanical power

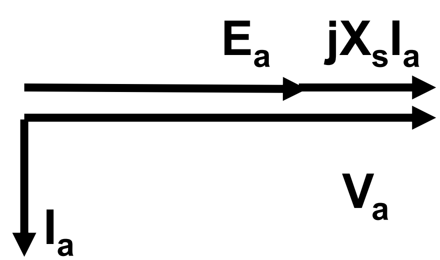


$\mathrm{Re}(V_a I_a^*)$: active power absorbed from grid

$\mathrm{Imag}(V_a I_a^*)$: reactive power absorbed from grid



Over-excited
Similar to a capacitor



Under-excited
Similar to an inductor

Example:

Three following motors are connected to an infinite bus of 480V, 60 Hz.

Induction motor, 480 v, 100kW, PF=0.78 lag

Induction motor, 480 v, 200kW, PF=0. 8 lag

Synchronous motor, 480 V, 150kW

A: what is the transmission line current and power factor if synchronous motor power factor is 0.85 lag

B: what if the power factor of synchronous motor is 0.85 lead (How ?)

Solution:

A: $Q_1=P_1\tan\theta_1=100\times\tan(\cos^{-1}0.78)=80.2$ kVAR

$Q_2=P_2\tan\theta_2=200\times\tan(\cos^{-1}0.\,8)=150$ kVAR

$Q_3=P_3\tan\theta_3=150\times\tan(\cos^{-1}0.85)=93$ kVAR

$PF_{total} = \cos(\tan^{-1}(Q_1+Q_2+Q_3)/(P_1+P_2+P_3)) = 0.812$ lag

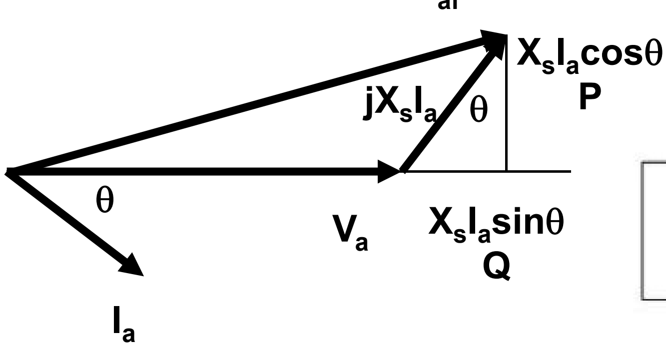
$I_{total} = P_{total}/\sqrt{}\,3V_L\cos\theta = 450\times10^3 / (\sqrt{3}\times 480\times 0.812) = 667$ A

B: $Q_3=P_3\tan\theta_3=150\times\tan(-\cos^{-1}0.85) = -93$ kVAR

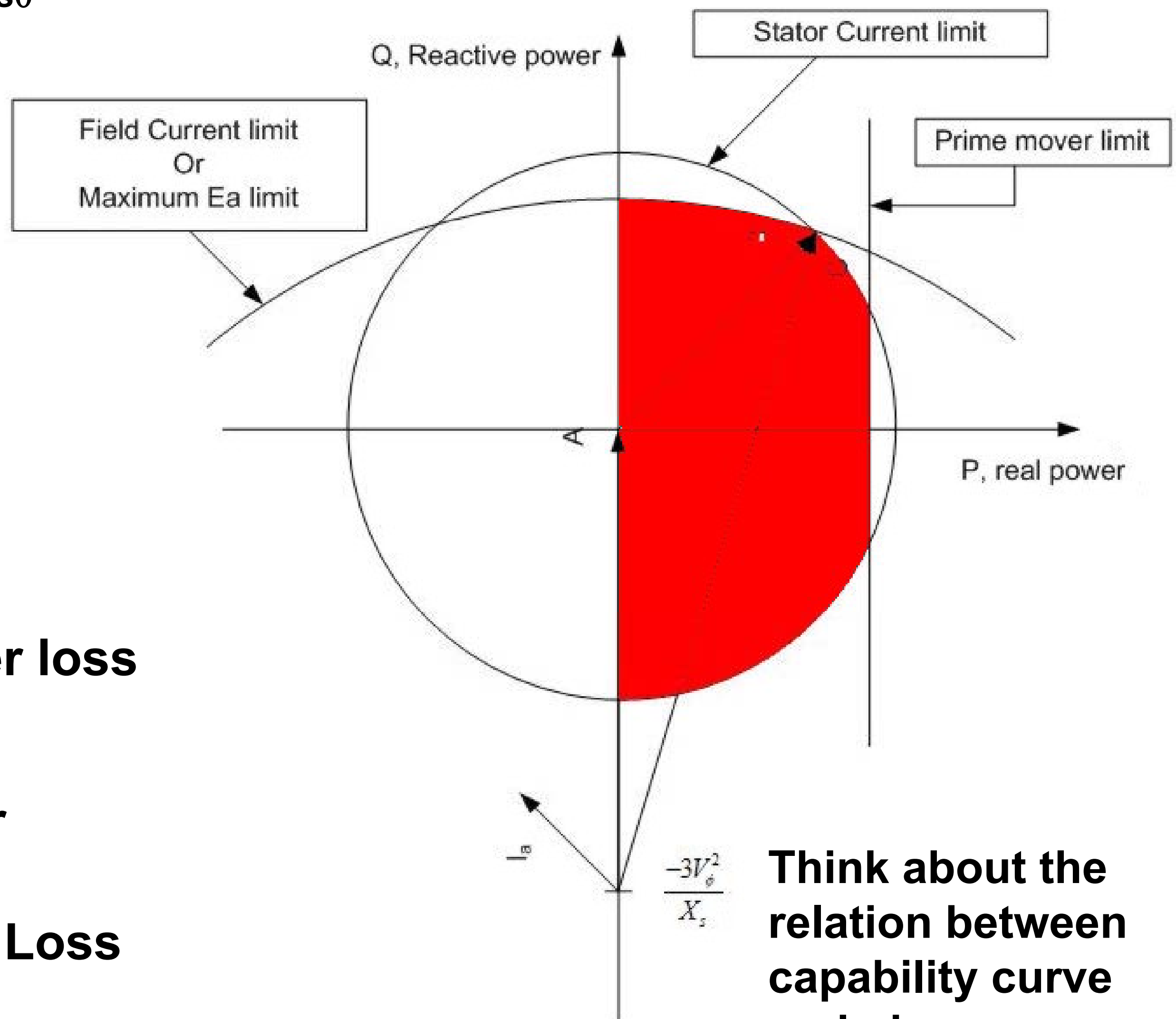
$PF_{total} = \cos(\tan^{-1}(80.2+150-93)/(100+200+150)) = 0.957$ lag

$I_{total} = P_{total}/\sqrt{}\,3V_L\cos\theta = 450\times10^3 / (\sqrt{3}\times 480\times 0.957) = 566$ A

Synchronous Machine Capability Curve



$I_a = I_a\, e^{-j\theta}$
$S = 3\, V_a\, I_a e^{j\theta}$
$P = 3\, V_a I_a \cos\theta$
$Q = 3\, V_a I_a \sin\theta$



Limiting parameters:

- **Maximum stator power loss**
  I_{amax}
- **Maximum input power**

•Maximum Rotor power Loss
I_{fmax} (E_{afmax})

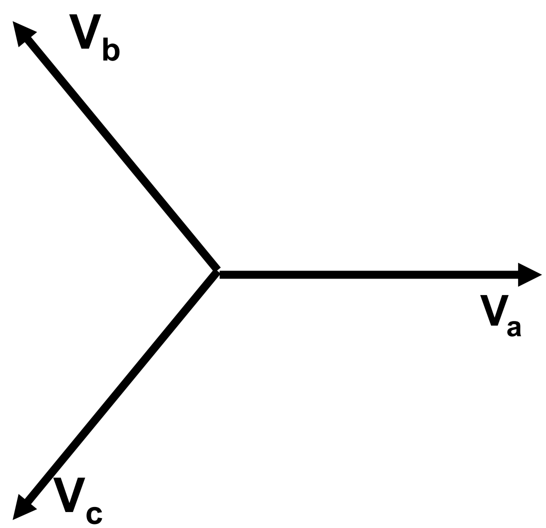
Think about the relation between capability curve and phasor diagram

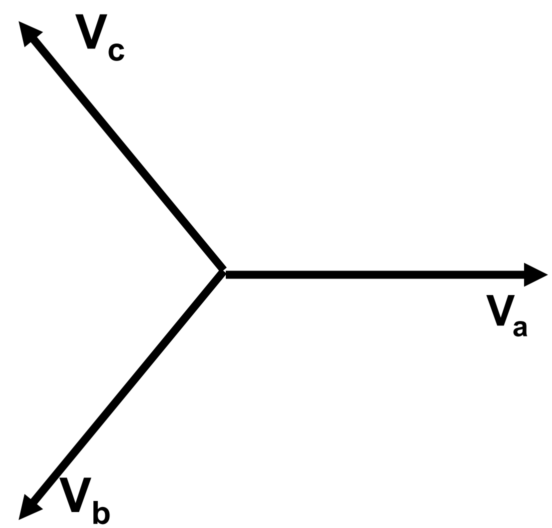
Paralleling Synchronous machines

To connect a rotating synchronous machine (motor/Generator) to a live line (three phase system)

1- Voltage of machine terminal while rotating at synchronous speed should be equal to AC line voltage (can be adjusted by field current)

2- Phase sequence of this two voltages should be the same (can be checked by three light bulb method)

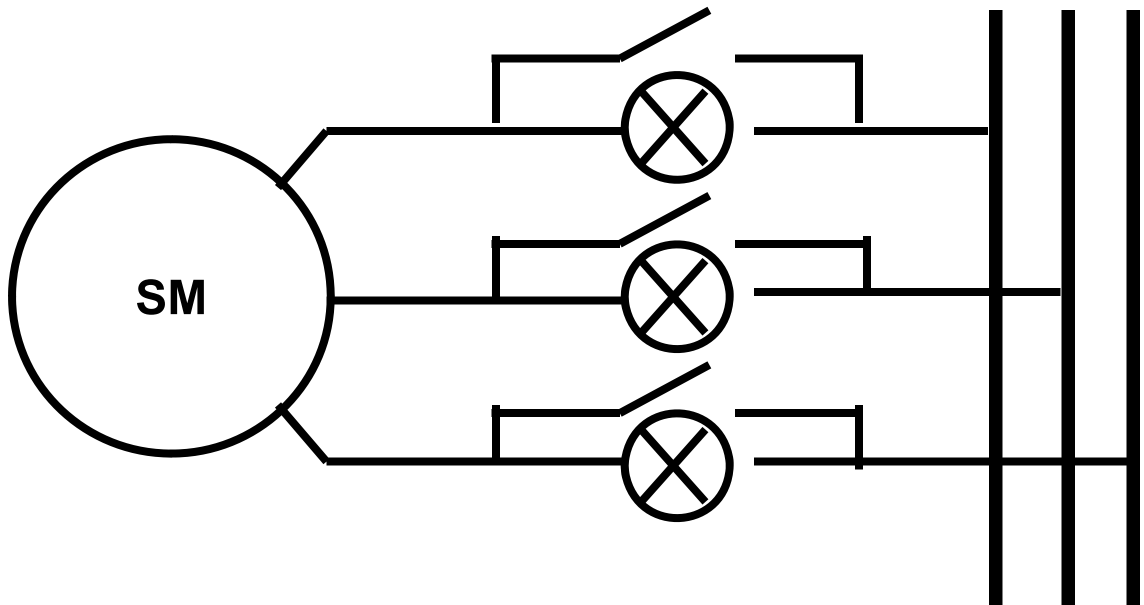




3- The frequency of the generator voltage should be equal to the frequency of the AC line voltage (can be controlled by controlling the prime mover speed and can be verified by three light bulb method)

4- the phase of the generator voltage should be the same as voltages of the AC system

three light bulb method



When all three lamps are off, all four conditions are satisfied

What happens if the voltages are different?

What happens if the frequencies are different?

What happens if there is a phase shift?

What happens if the sequence of the voltages are different?

Start-up of synchronous motors

Synchronous motor: No start-up torque if connected to AC source

1- Motor Starting using Variable frequency AC source (frequency converter).

2- Motor starting external prime mover.

3- Motor starting using amortisseur (damper) windings (like induction motors).

Dampers are short circuited copper bars placed in the pole faces.

Voltage, current and torque are induced if rotor is not synchronized.