Concordia University Department of Electrical and Computer Engineering

ELEC-331

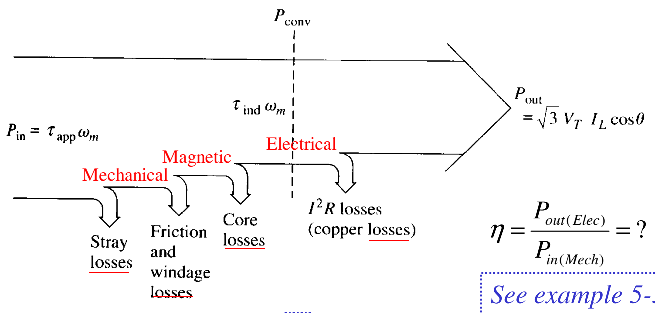
Lecture 9

Synchronous generators (5.6-5.9) and motors (6.1-6.2)

Outline of the lecture

- Power & torque in synchronous generators
- Measuring SG parameters
- Frequency and voltage control of SG
- Effects of load variations (voltage regulation) for *isolated generators*.
- Frequency and active power characteristics
- Voltage and reactive power characteristics
- *Parallel operation with infinite bus* with control of P_{inj} and of Q_{inj}.

Power & torque in sync. generators



$$\eta = \frac{P_{out(Elec)}}{P_{in(Mech)}} = ?$$

See example 5-3c,d

$P = \tau\,\omega$

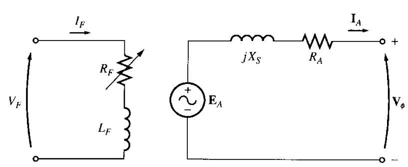
$$P_{conv} = \tau_{ind}\,\omega = 3E_A I_A\cos\gamma,\quad \gamma = \angle E_A - \angle I_A$$

$$P_{out} = P_{conv} - P_{cu} = 3V_\phi I_A\cos\theta,\quad \theta = \angle V_\phi - \angle I_A$$

Electrical side.

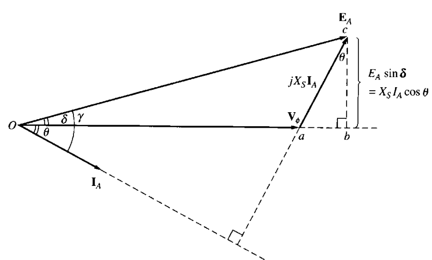
Recall the model…

Power & torque in sync. generators



Neglecting R_A:

$$V_\varphi = E_A - jX_S I_A$$



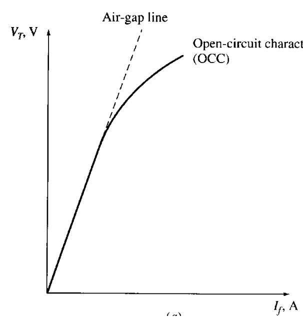
$$P_{out} = 3V_\phi I_A\cos\phi = \frac{3V_\phi E_A\sin\delta}{X_S}$$

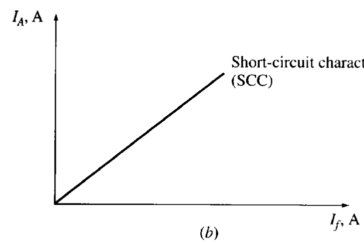
where, $\delta = \angle E_A - \angle V_\phi$ (power angle)

- Speed (and frequency) is assumed to be constant. What happens to δ when P_{out} increases while E_A and V_ϕ remain constant?

Measuring SG parameters

- Main parameters: I_F x E_A relationship, X_S and R_A.
- Open-circuit test → $E_A = V_T$.
- Short-circuit test → $Z_S = \sqrt{R_A^2 + X_S^2} = \dfrac{V_{\phi,oc}}{I_A}$ $\quad X_S \cong \dfrac{V_{\phi,oc}}{I_A}$
- DC voltage test in a Y-connected armature (stator) → $2R_A = \dfrac{V_{DC}}{I_{DC}}$





Example 5-1.

Frequency and voltage control/regulation of synchronous generators

Figure from another book.

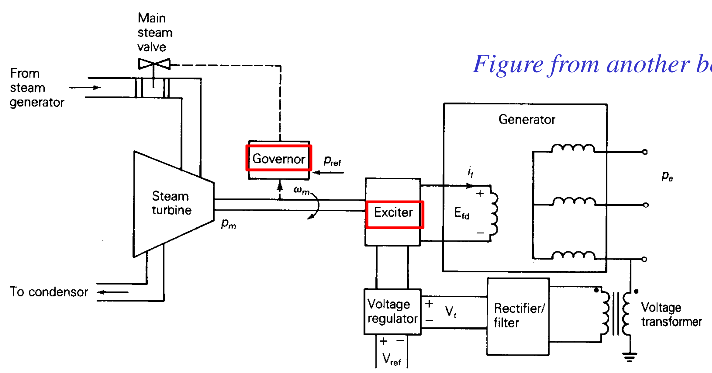
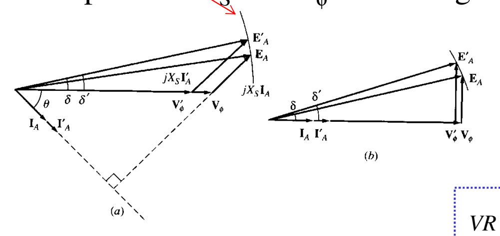


Figure 11.1 Voltage regulator and turbine-governor controls for a steam-turbine generator

The **Governor** increases the flow of steam to increase the shaft speed.
The **Exciter** increases i_f to increase the output voltage of the generator.

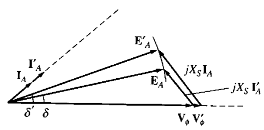
Effects of the load on a synchronous generator operating alone (*islanded*)

- For E_A constant, if the load (current) changes, the voltage drop across X_S and V_ϕ also change → $V_\varphi = E_A - jX_S I_A$



What about the power angle (δ)?

$$VR = \frac{V_{nl} - V_{fl}}{V_{fl}} 100\%$$

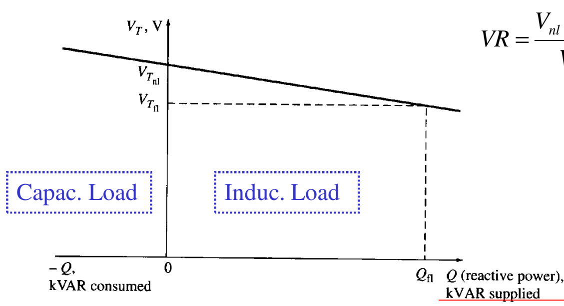


- How can V_ϕ be regulated? By varying I_F. *Ex. 5-2 & tutorial*

Voltage x reactive power characteristics

- Represents the effect of the demanded reactive power on the voltage terminal. Inductive loads have positive while capacitive have negative VR

$$VR = \frac{V_{nl} - V_{fl}}{V_{fl}} x100\%$$

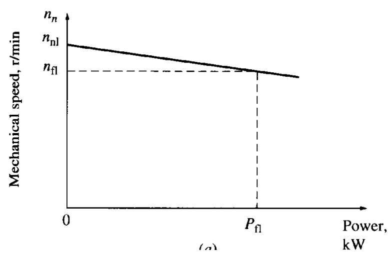


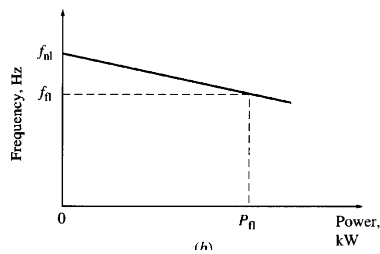
By the SG

Frequency x active power characteristics

- Load (**active power**) variations result in small frequency variations due to a governor's action (droop factor/control)
- "Droop control" facilitates the operation of generators (of similar size) in parallel. (See example 5.6!)

$$SD = \frac{n_{nl} - n_{fl}}{n_{fl}} \approx 3\% \qquad f_e = \frac{n_m P}{120} \qquad P = sp\left(f_{nl} - f_{sys}\right),\ sp(\text{kW/Hz})$$

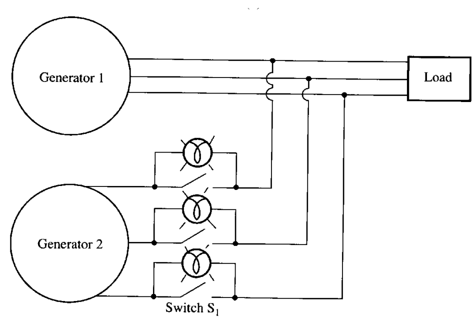




Parallel operation of AC generators

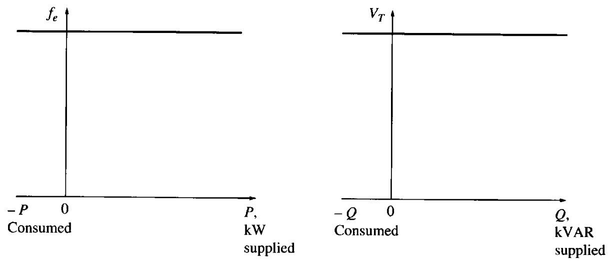
- Conditions: 1) Equal voltage level, 2) phase sequence and 3) phase angle and frequency (after connection).
- Detecting phase sequence and when the voltages of the 2 generators are in-phase...

Oncoming generator



Parallel operation with an infinite bus

- An infinite bus has a flat frequency and voltage profiles.
- It can consume or supply any amount of P and Q.
- The speed of a SG connected to an infinite bus is fixed.



- P_{inj} is controlled by the governor (P_{Mec})

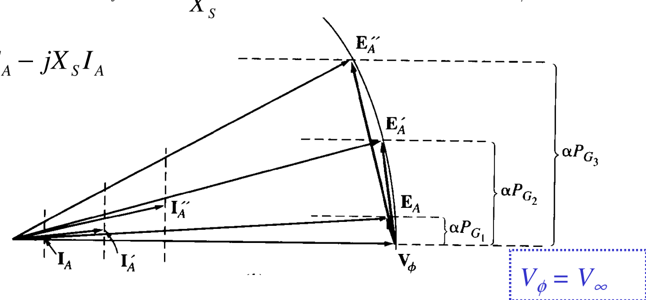
$$P_{inj} = P_{Mec} - P_{losses}, \quad P_{inj} = \frac{3E_A V_\infty \sin\delta}{X_S}, \quad \delta = \angle E_A - \angle V_\infty, (V_\infty = V_\phi)$$

Varying the injected active power (P_{inj})

- P_{inj} is controlled by the governor's set point (P_{Mec})

$$P_{inj} = P_{Mec} - P_{losses} \qquad P_{inj} = \frac{3E_A V_\infty \sin\delta}{X_S}, \quad \delta = \angle E_A - \angle V_\infty, (V_\infty = V_\phi)$$

$$V_\phi = E_A - jX_S I_A$$

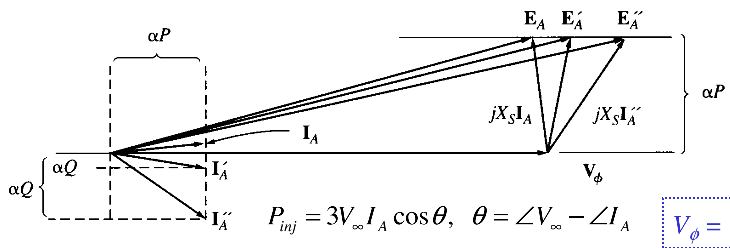


- δ ↑. Since E_A= cnst, Q also ↑ $Q = 3V_\infty I_A \sin\theta, \quad \theta = \angle V_\varphi - \angle I_A$

In this case, the generator now supplies or absorbs Q?

Varying the injected reactive power (Q)

- This is done by varying the exciter's set point (I_F) and E_A.
- It is assumed that the governor's set point (P_{Mec}) remains constant ($P_{inj} = cnst$). When $I_F \uparrow$, $E_A \uparrow$, θ and Q_{inj} change.



$$P_{inj} = 3V_\infty I_A \cos\theta, \quad \theta = \angle V_\infty - \angle I_A$$

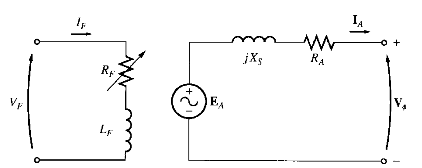
$$Q_{inj} = 3V_\infty I_A \sin\theta$$

$V_\phi = V_\infty$

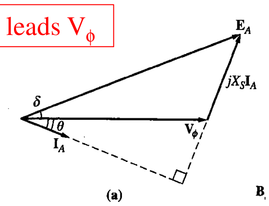
When does the generator supply Q? … absorb Q?

Synchronous generators and motors

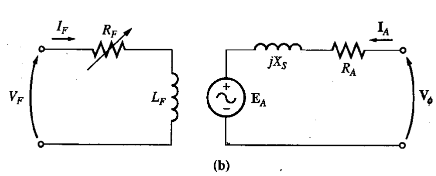
- Equivalent circuit and phasor diagram of SG



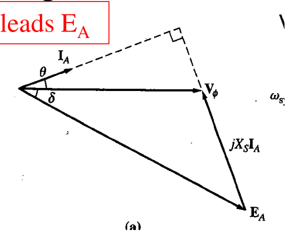
E_A leads V_ϕ



- Equivalent circuit and phasor diagram of SM

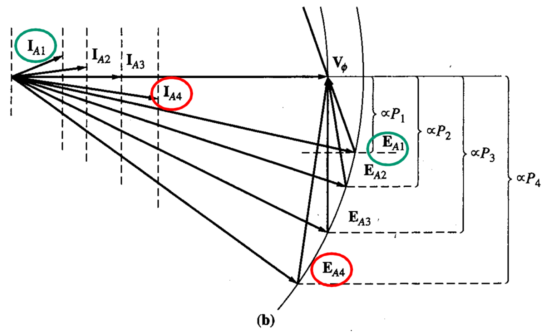


V_ϕ leads E_A



Effect of varying the load power (P_{Mec})

- It is assumed that the grid voltage and frequency remain constant. Besides I_f and E_A are fixed.

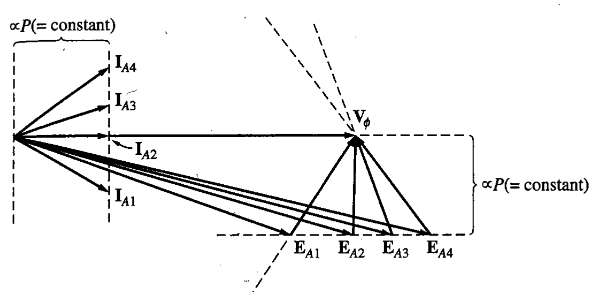


If P↑, the power angle (δ)↑.

- What happens to the reactive power of the motor as the active power it draws is increased?

Effect of varying I_f and E_A

- It is assumed that the grid voltage and frequency remain constant. The load power (P_{Mec}) is fixed.



- What happens to the reactive power of the <u>motor</u>, when for a given P, I_f and E_A increase? Value of E_A for minimum I_A (and unity power factor)?

V curves for synchronous machines

- There is a value of I_f for which the machine operates with UPF (minimum I_A). As I_f increases or decreases, I_A increases. Machine either absorbs or supplies reactive power (Q).

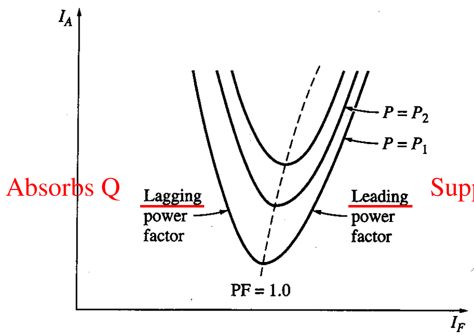


FIGURE 6–9
Synchronous motor V curves.

Recall that E_a varies with I_f…

Phasor diagrams: P and Q control

Projection of phasor E_a on the axis of phasor V_φ.

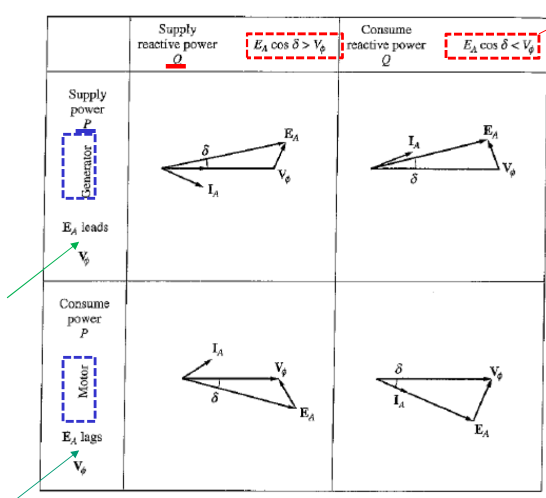
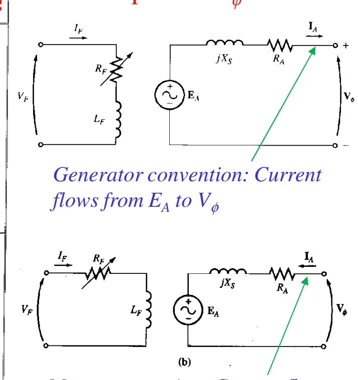


Figure from another book.



Generator convention: Current flows from E_A to V_ϕ

Motor convention: Current flows from V_ϕ to E_A.