Outcome of this lecture

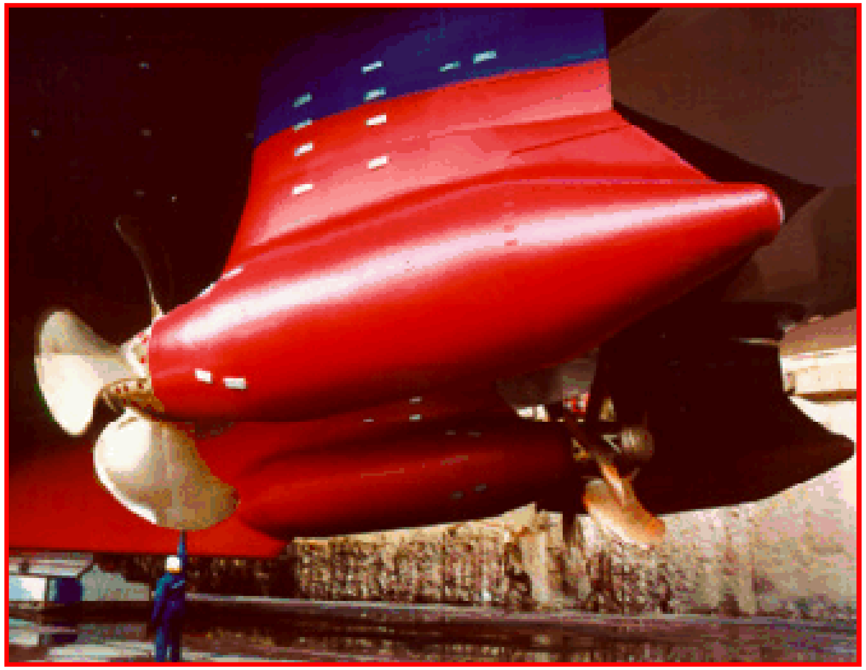
At the end of this lecture you will be able to:

- List the different parts of a synchronous machine
- Explain the operation principles of the machine
- Use the equivalent circuit model of the machine
- Analyze the steady-state operation of the machine
- Calculate the power transfer of the machine
  - (Torque, power, power factor, etc…)

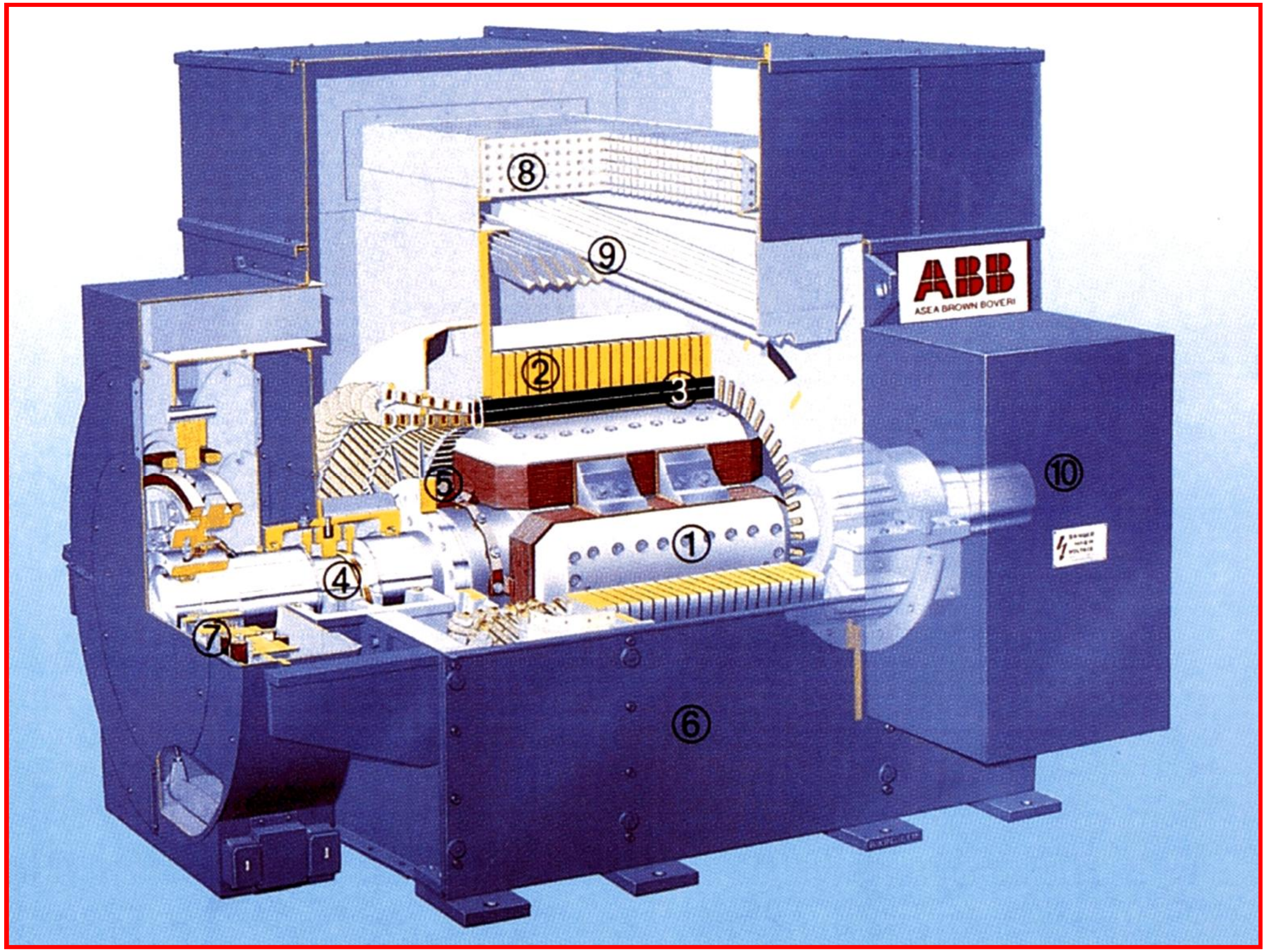
Your will understand the difference between salient pole and non-salient pole machines

Contents of this lecture

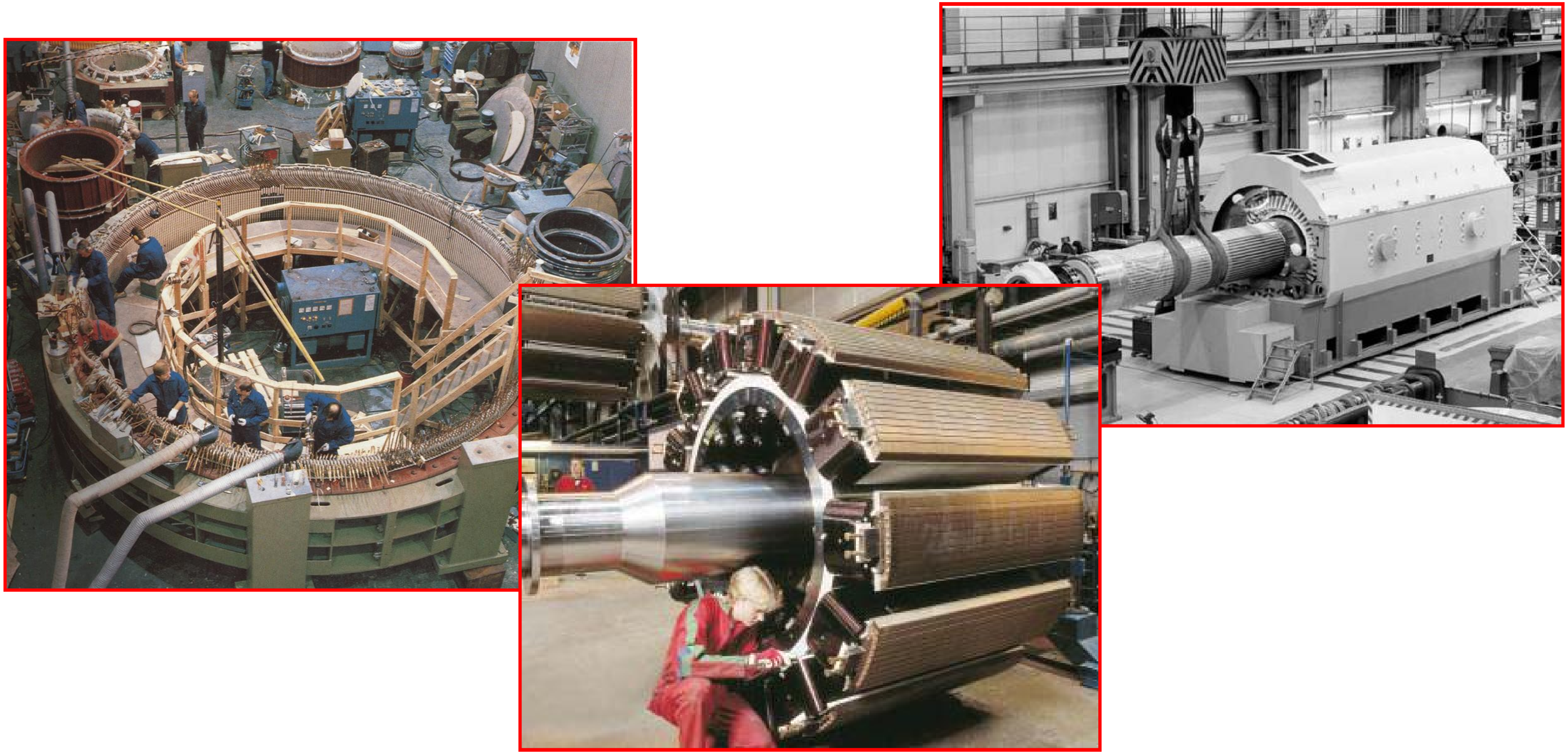
- Structure, construction and use of synchronous machines
- Infinite bus and synchronization
- Equivalent circuit of synchronous machine
- Performance characteristics
    - (torque, power, power factor, etc…)
- Experimental determination of reactances
- Salient pole machine
    - phasor diagrams and power transfer



Structure of synchronous machines

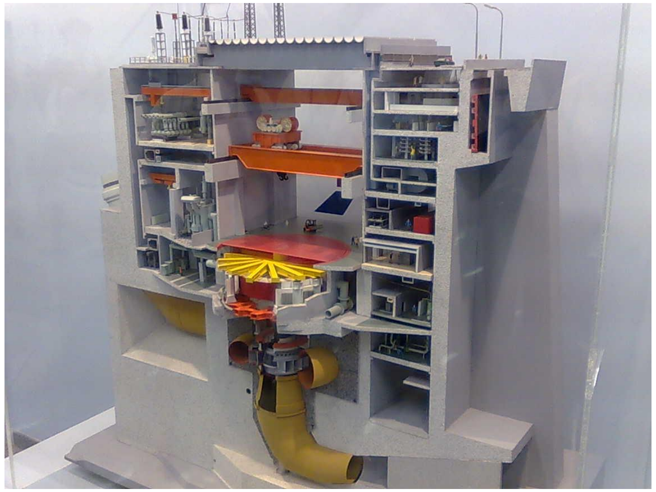


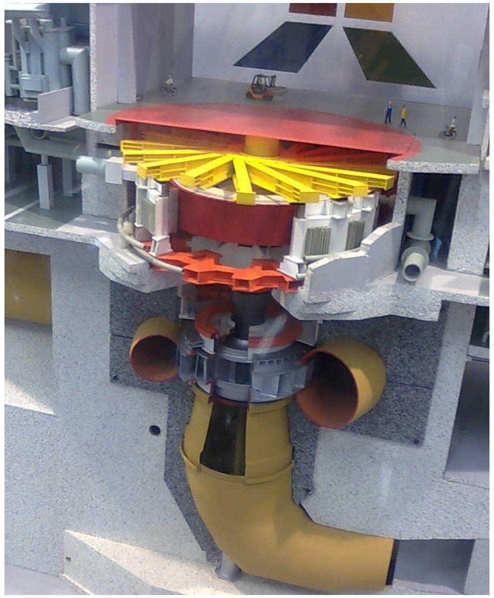
Structure of synchronous machines



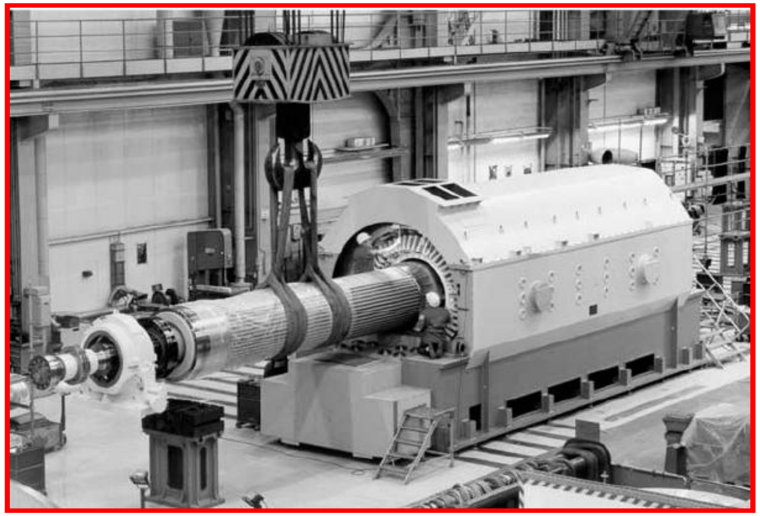
Main characteristics

- Rotates at constant speed.
- Primary energy conversion devices of the word’s electric power system.
- Both generator and motor operations
- Can draw either a lagging or a leading reactive current from the supply.





Usage of different types of synch. machines



Non-salient pole generator

- High speed (2 - 4 poles)
- Large power (100 – 1 600 MVA)
- Steam power plants

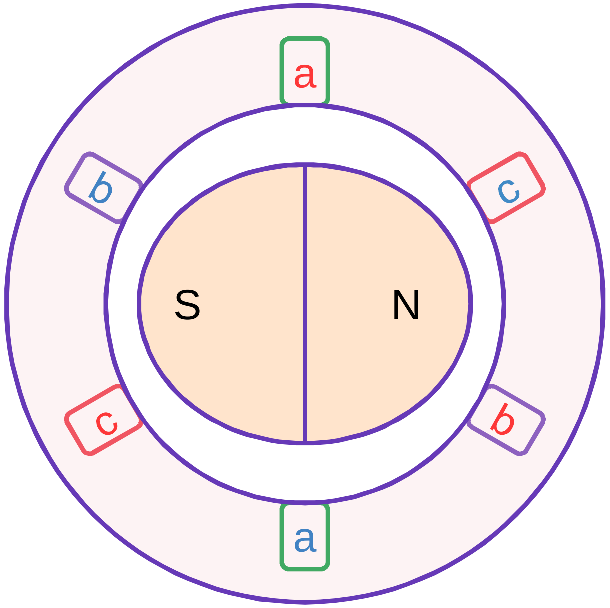
Salient pole generator

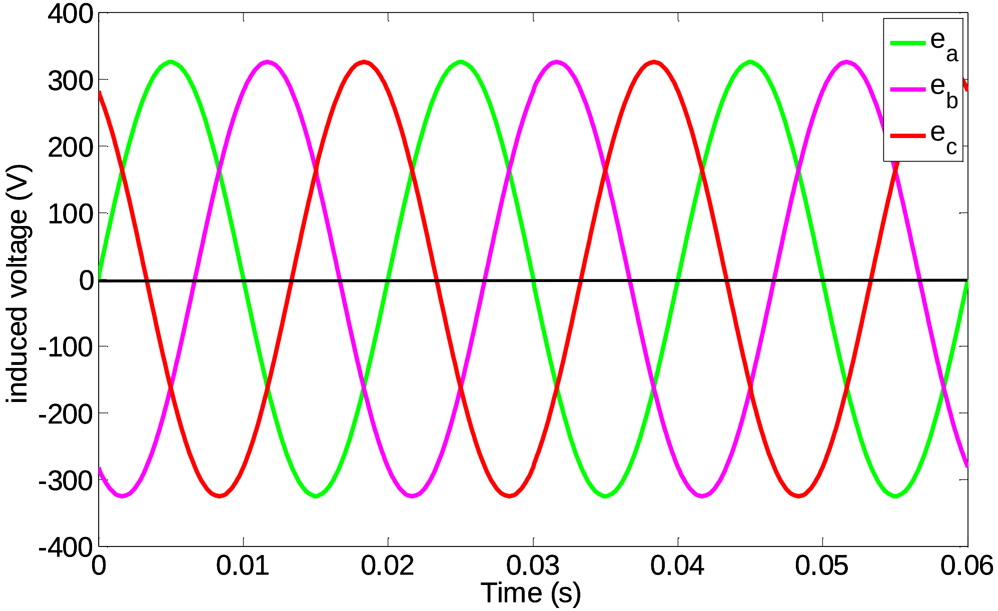
- Low speed
- Small and mid-size power (0 – 800 MVA)
- Motors for electrical domestic devices
- Mid size generators for emergency power supply
- Motors for pumps and ship propulsion
- Large size generators in hydro-electric power plants

3-phase voltage generation

$$e = N\frac{dF}{dt}$$

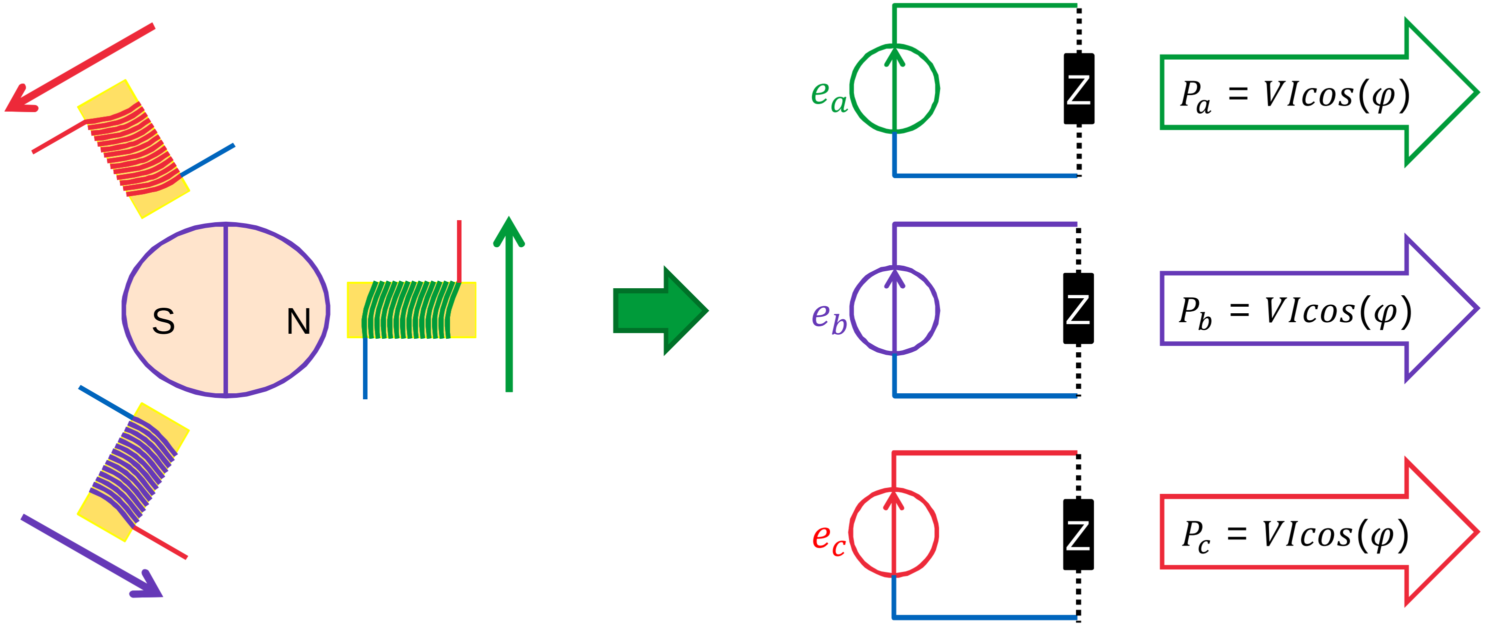
- Simple generator





Connecting the 3-phase voltages

- 3 single-phase circuits at different phase angle!



$P_a = VIcos(\varphi)$

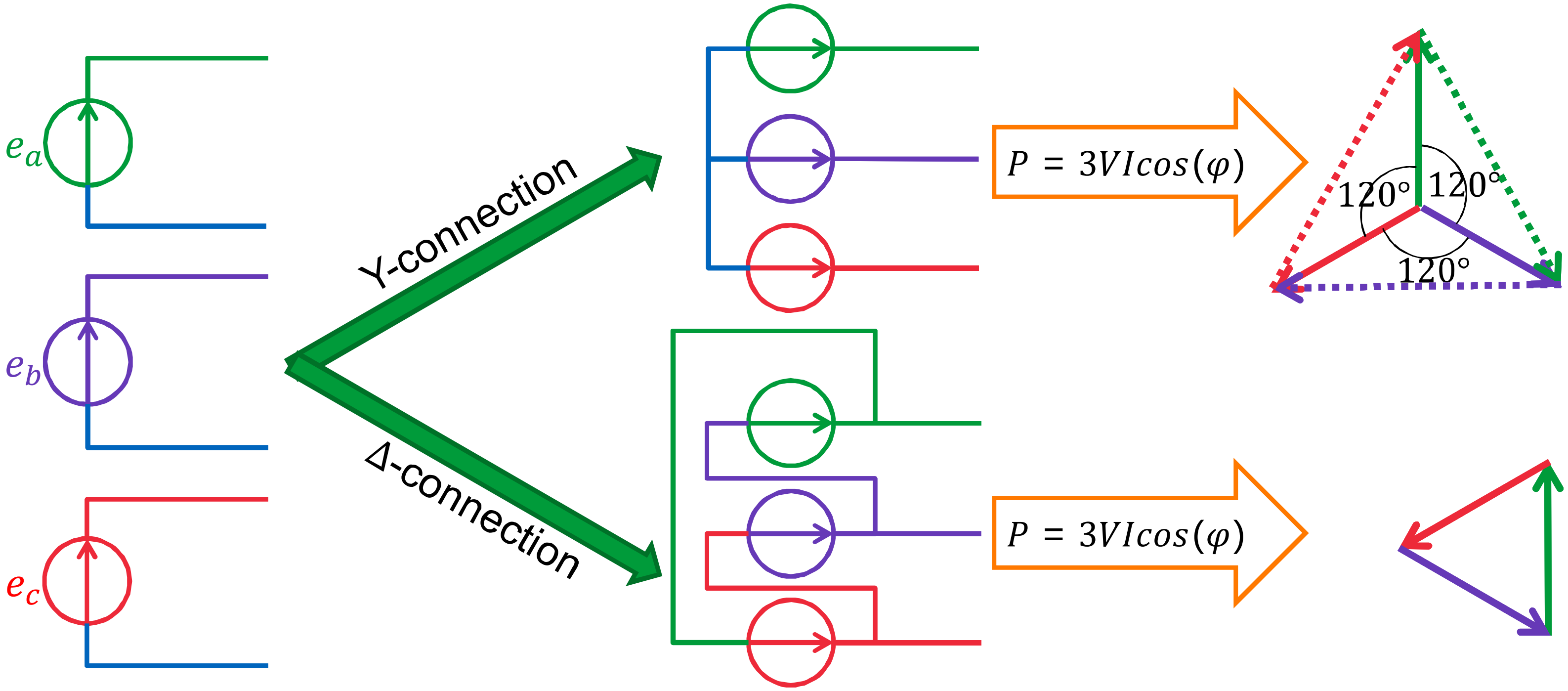
$P_b = VIcos(\varphi)$

$P_c = VIcos(\varphi)$

$$\boxed{p_a = u_a i_a = P_a - VIcos(2\omega t + \varphi)}$$

Connecting the 3-phase voltages

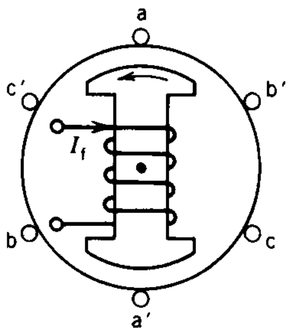
- The potential difference is known but not the potentials !

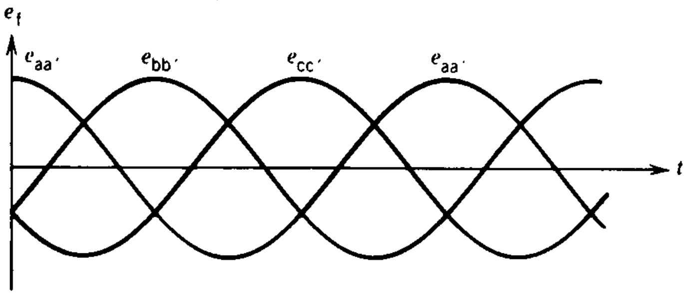


$$p = u_a i_a + u_b i_b + u_c i_c = 3P_a$$

Synchronous Generators – No-load

- Excitation voltages

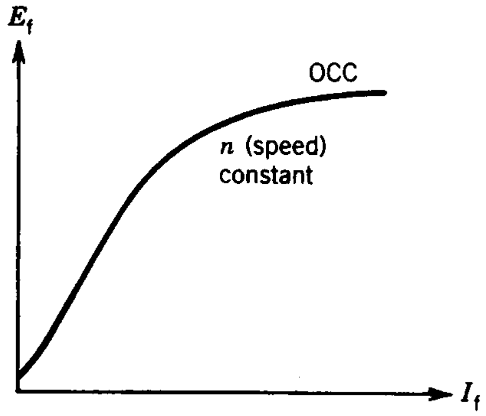




- Frequency depends on the speed

$$f = \frac{np}{120} \qquad n = \frac{120\, f}{p}$$

$$E_f = \frac{2p}{\sqrt{2}} f F_f N K_w \qquad E_f \mu \, nF_f$$

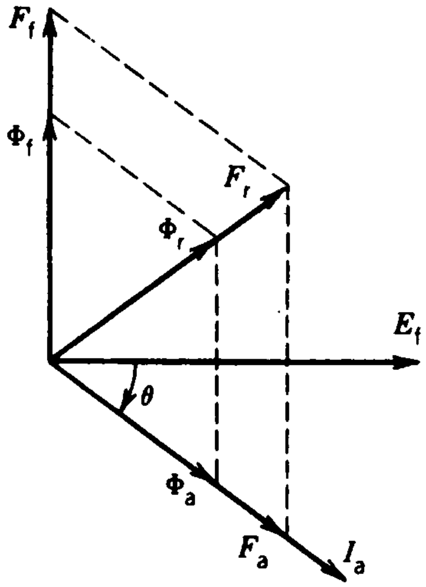


- Open circuit characteristics
- Magnetization characteristics

Synchronous Generators - loaded

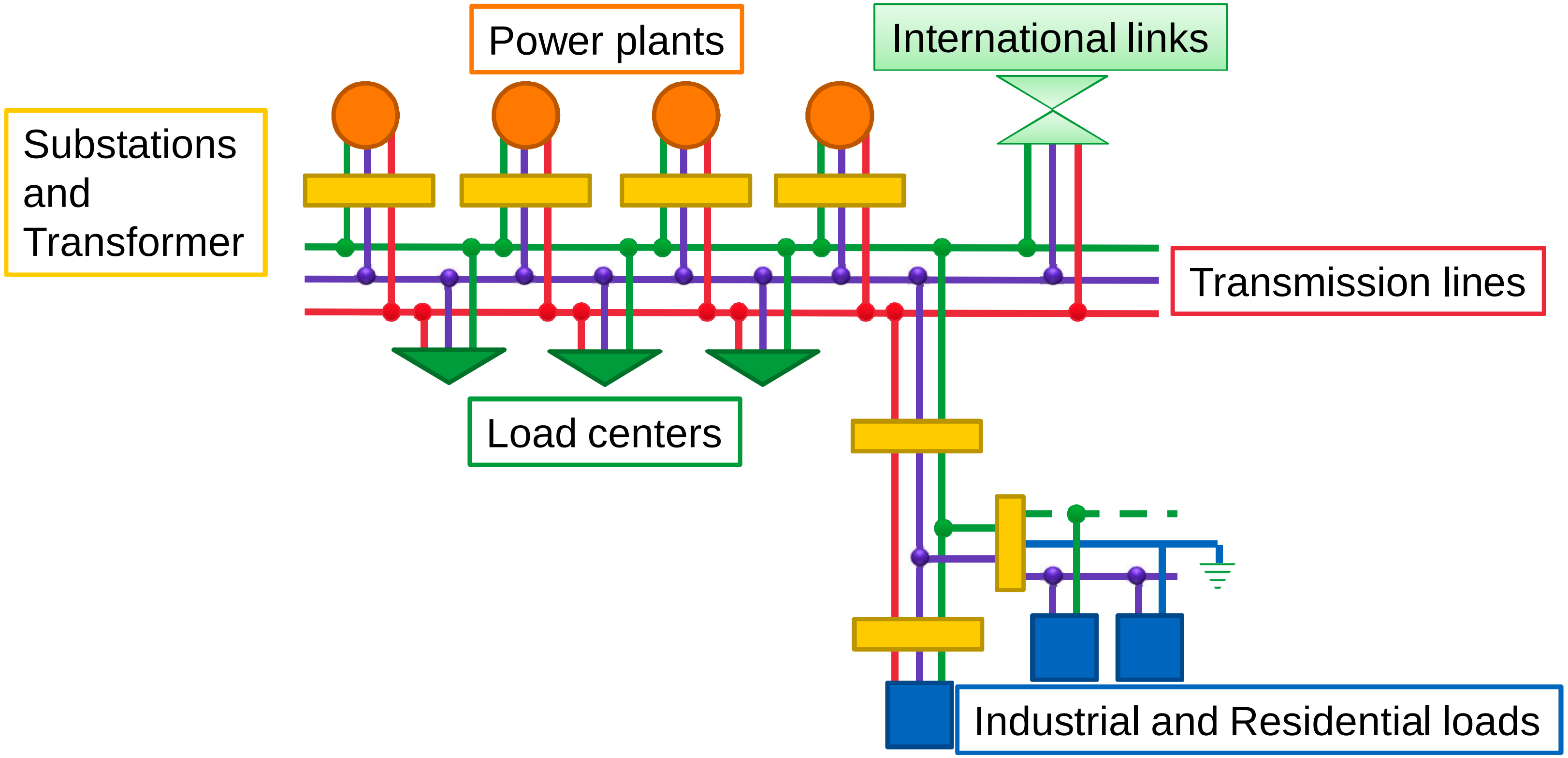
- Stator currents establish a rotating field in the air-gap
- Armature reaction flux ϕ_a
- Resultant air-gap flux

$$F_r = F_f + F_a$$



The infinite bus

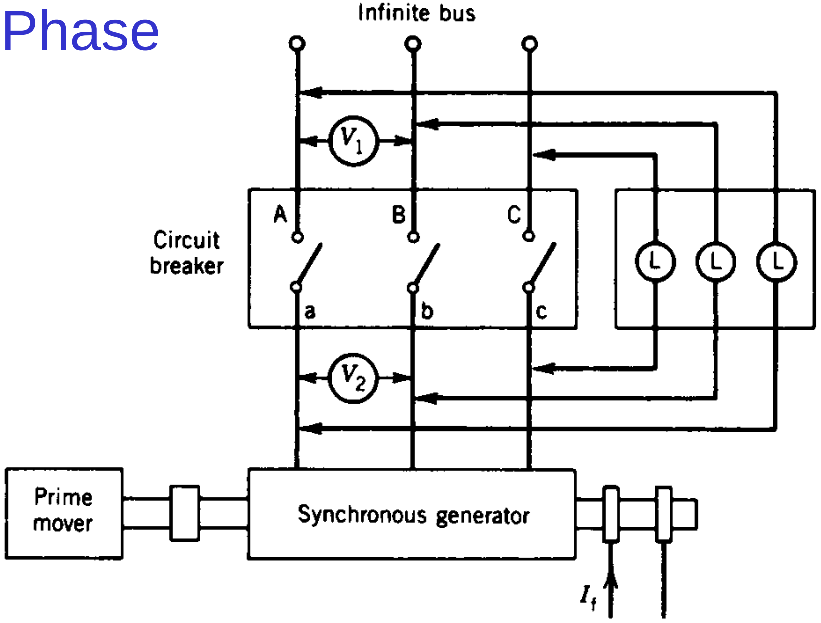
- The quasi totality of the electric power generated worldwide is three-phase.



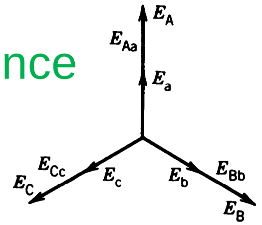
Paralleling with the infinite bus

Same

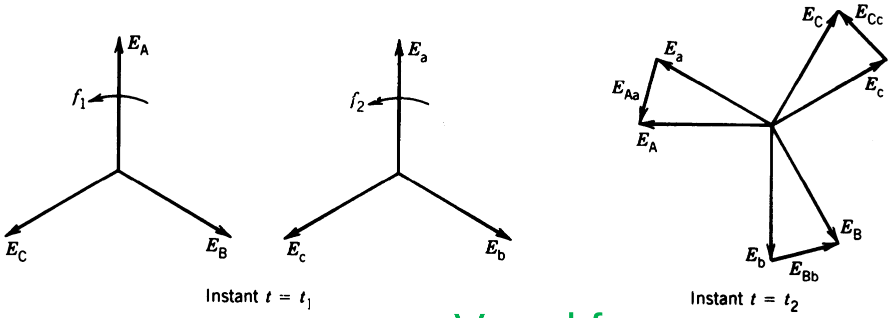
- Voltage
- Frequency
- Phase sequence
- Phase



same f and phase sequence



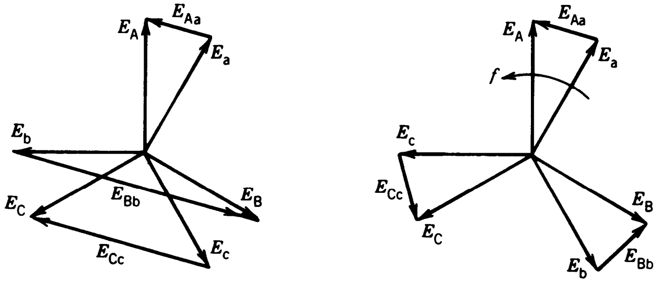
same V and phase sequence



Instant $t = t_1$

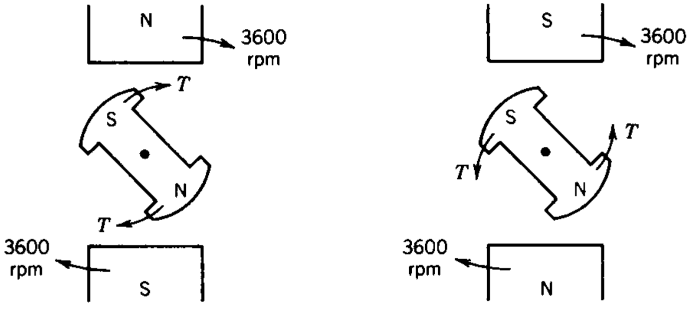
Instant $t = t_2$

same V and f



Starting the synchronous motor

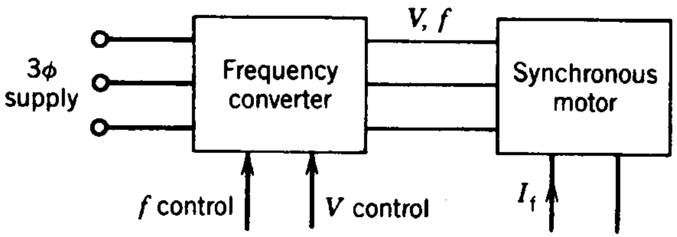
- High inertia of the rotor prohibits direct connection into supply net



(a) $t = 0$ (b) $t = t_1$

Start as an induction motor

Variable-frequency supply



Per phase equivalent circuit model

- Armature flux, armature reaction flux, armature leakage flux

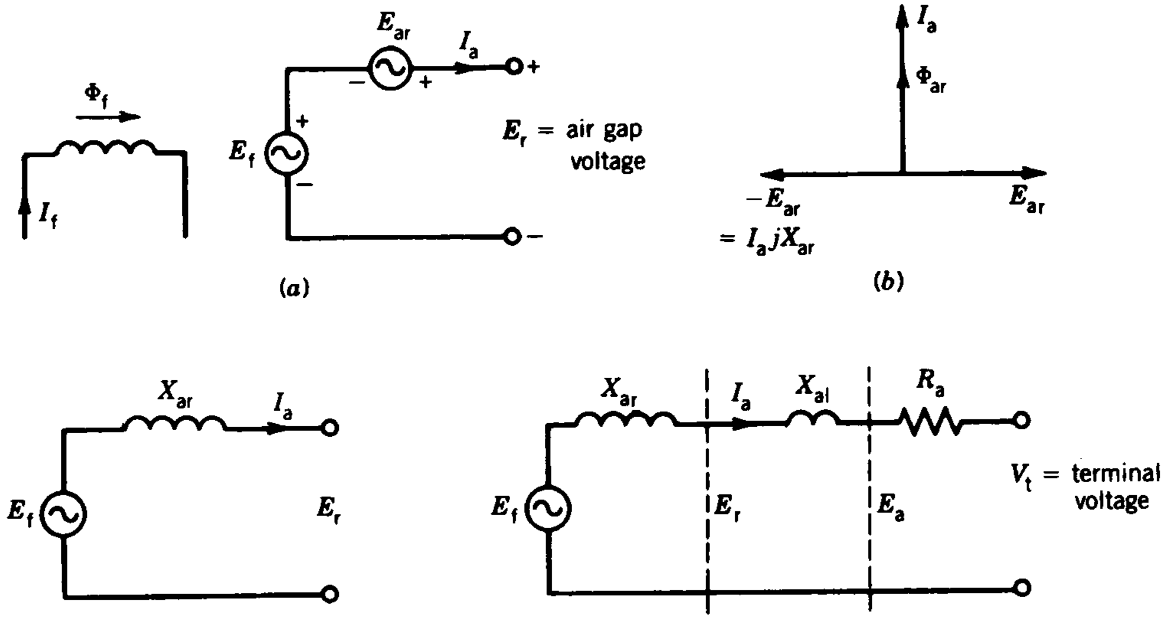
$$F_a = F_{ar} + F_{al}$$

$$F_r = F_f(I_f) + F_{ar}(I_a)$$

$$E_r = E_{ar} + E_f$$

$$-E_{ar} = jX_{ar} I_a$$

$$E_f = I_a jX_{ar} + E_r$$

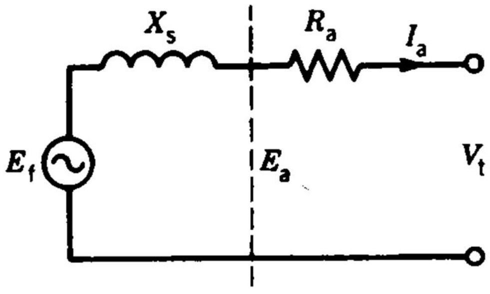


- Magnetizing reactance X_{ar} , (reactance of armature)
- Synchronous reactance $X_s = X_{ar} + X_{al}$
- Synchronous impedance $Z_s = R_a + jX_s$

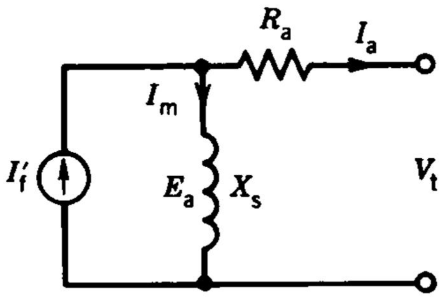
Equivalent circuit model

- Norton equivalent circuit

$$I'_f = \frac{E_f}{X_s} \qquad \left|I'_f\right| = \frac{X_{ar}}{X_s} n I_f \qquad n = \frac{\sqrt{2}}{3}\frac{N_{re}}{N_{se}}$$



(e)

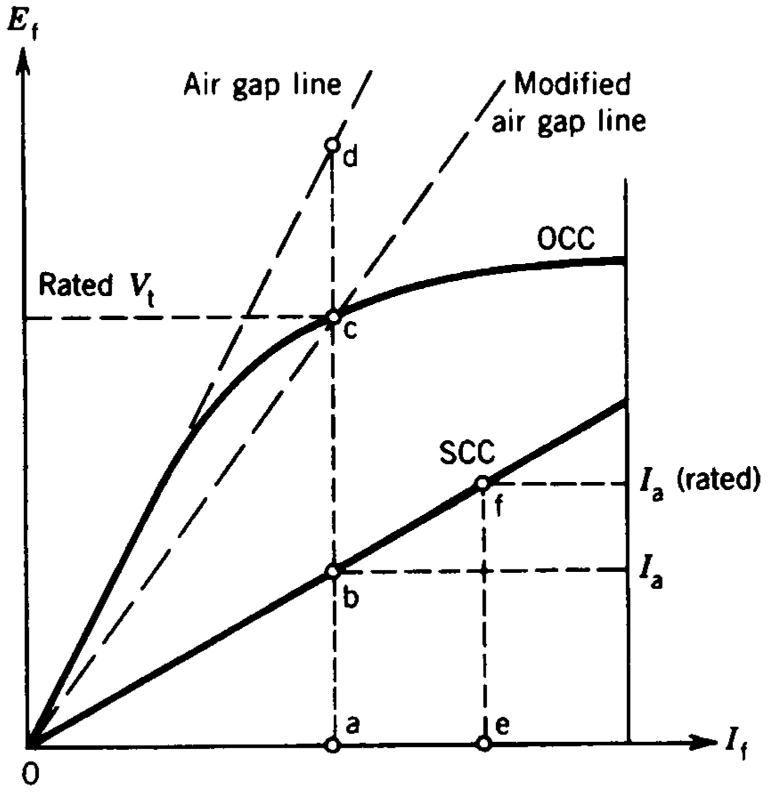


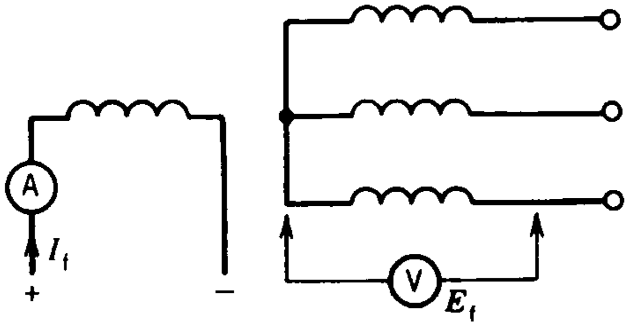
(f)

Determination of synchronous reactance

Open circuit test

- Synchronous speed
- Stator open-circuited
- Measure $V_t(I_f)$
  - Open-circuit characteristic
  - Air gap line

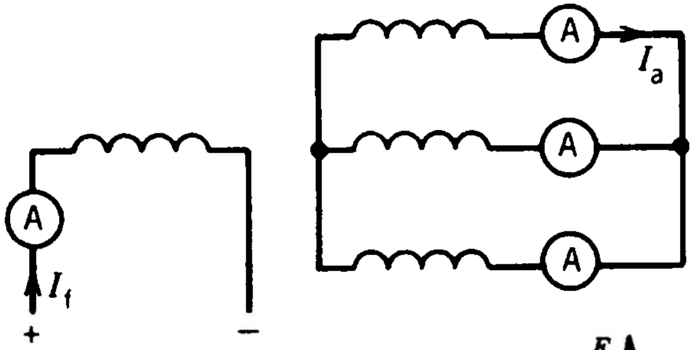


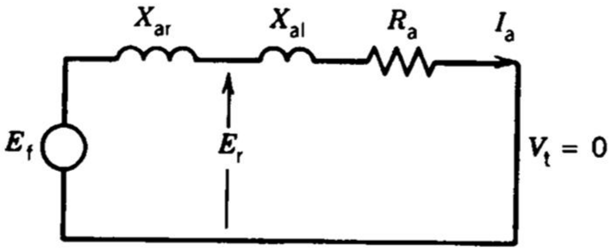


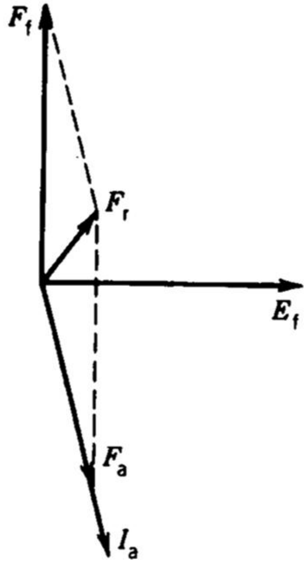
Determination of synchronous reactance

Short circuit test

- Synchronous speed
- Stator short-circuited
- Measure $I_a(I_f)$
  - Short-circuit characteristic
  - Straight line
  - Flux remains at low level







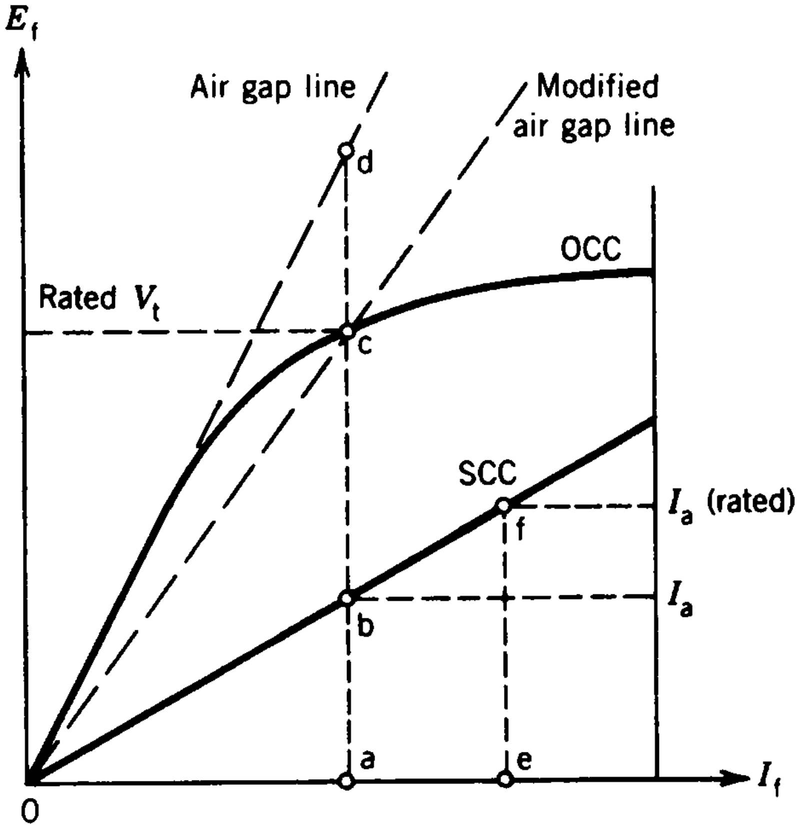
- I_a lags E_f by almost 90 because $R_a \ll X_s$

Unsaturated synchronous reactance

Unsaturated value from the air-gap line

$$Z_{\mathrm{s(unsat)}} = \frac{E_{\mathrm{da}}}{I_{\mathrm{ba}}} = R_{\mathrm{a}} + jX_{\mathrm{s(unsat)}}$$

$$X_{s(unsat)} \cong \frac{E_{da}}{I_{ba}}$$



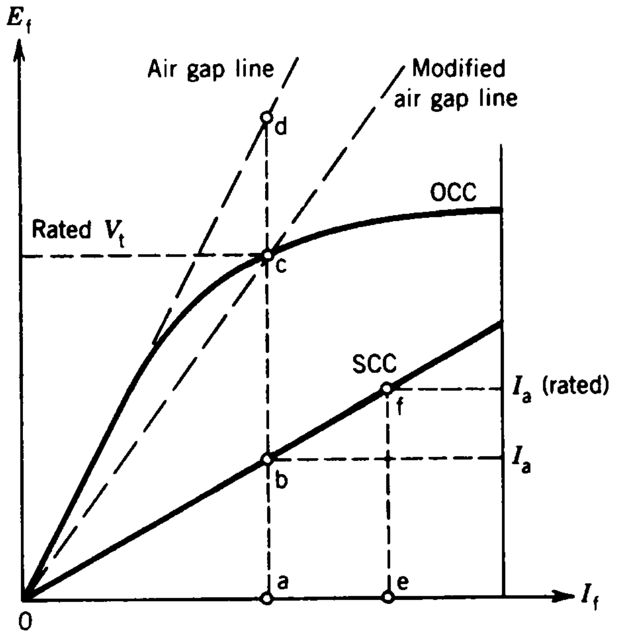
Saturated synchronous reactance

- At infinite bus operation the saturation level is defined by terminal voltage operation point c
- If the field current is changed the excitation voltage will change along modified air-gap line OC

$$E_r = V_t + I_a(R_a + jX_{al}) \approx V_t$$

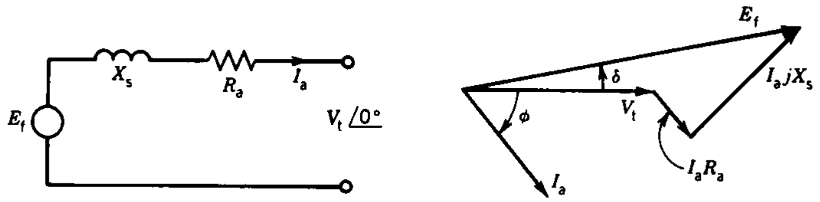
$$Z_{s(sat)} = \frac{E_{ca}}{I_{ba}} = R_a + jX_{s(sat)}$$

$$X_{s(sat)} \cong \frac{E_{ca}}{I_{ba}}$$



Phasor diagram

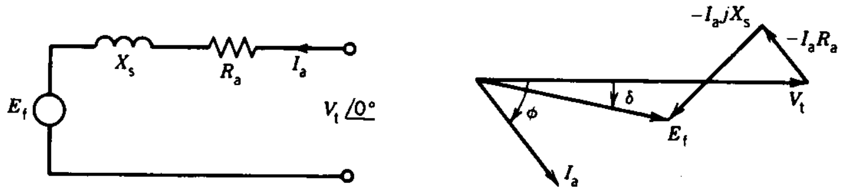
- Terminal voltage taken as the reference vector
- Generator load angle positive
- Motor load angle negative



$$E_f = V_t + I_a R_a + I_a jX_s = |E_f| \angle d$$

$$V_t = E_f + I_a R_a + I_a jX_s$$

$$E_f = V_t \angle 0° - I_a R_a - I_a jX_s$$
$$= |E_f| \angle -d$$



Convention: generating current flows out of the machine

Main operation quantities

$$V_t = |V_t| \angle 0^\circ$$

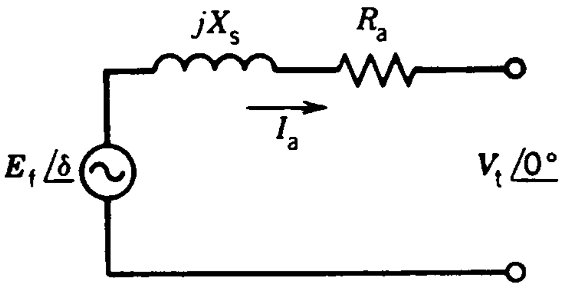
$$E_f = |E_f| \angle \delta$$

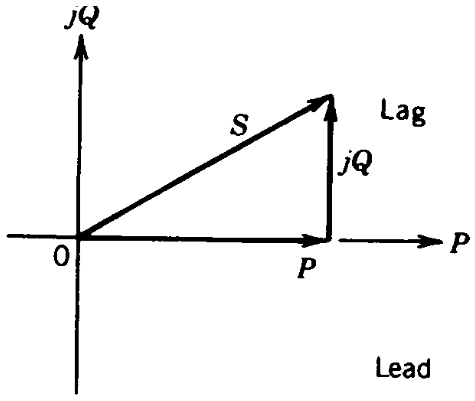
$$Z_s = R_a + jX_s = |Z_s| \angle \theta_s$$

$$S = V_t I_a^*$$

$$I_a^* = \left(\frac{E_f - V_t}{Z_s} \right)^* = \frac{E_f^*}{Z_s^*} - \frac{V_t^*}{Z_s^*}$$

$$= \frac{|E_f|}{|Z_s|} \angle \theta_s - \delta - \frac{|V_t|}{|Z_s|} \angle \theta_s$$





convention: lagging reactive power positive

Per phase power

- Complex power

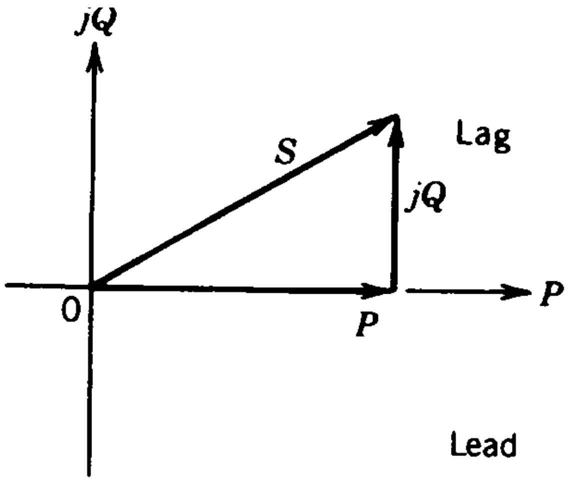
$$S = \frac{|V_t||E_f|}{|Z_s|} \angle q_s - d - \frac{|V_t|^2}{|Z_s|} \angle q_s$$

- Real power

$$P = \frac{|V_t||E_f|}{|Z_s|} \cos(q_s - d) - \frac{|V_t|^2}{|Z_s|} \cos q_s$$

- Reactive power

$$Q = \frac{|V_t||E_f|}{|Z_s|} \sin(q_s - d) - \frac{|V_t|^2}{|Z_s|} \sin q_s$$



Power and torque

R$_a$ neglected

- Real power

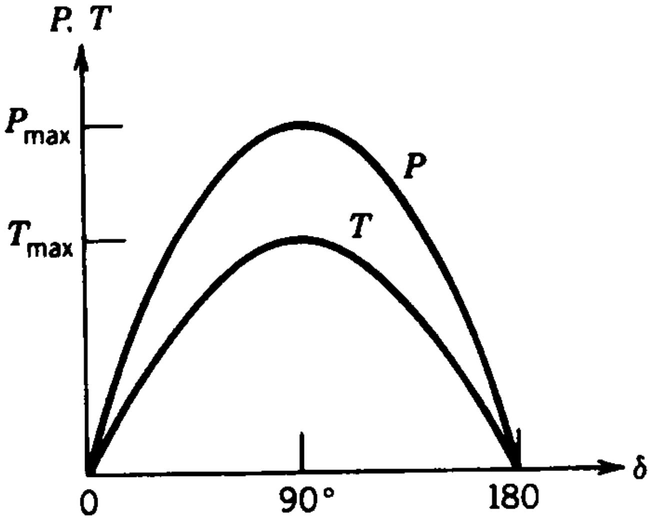
$$P_{3f} = \frac{3|V_t||E_f|}{|X_s|}\sin d = P_{\max}\sin d$$

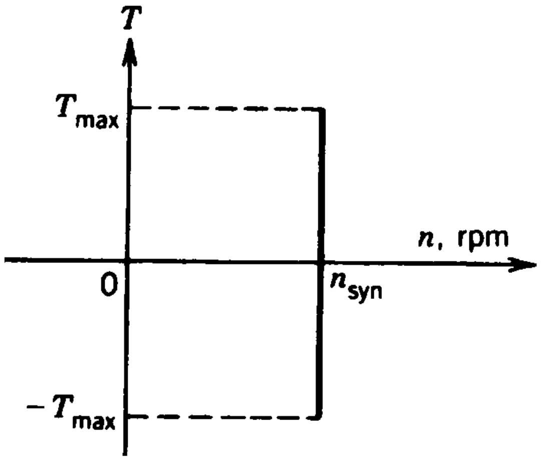
- Reactive power

$$Q_{3f} = \frac{3|V_t||E_f|}{|X_s|}\cos d - \frac{3|V_t|^2}{|X_s|}$$

- Torque

$$T = \frac{P_{3f}}{w_{syn}} = \frac{3}{w_{syn}}\frac{|V_t||E_f|}{X_s}\sin d = T_{\max}\sin d$$

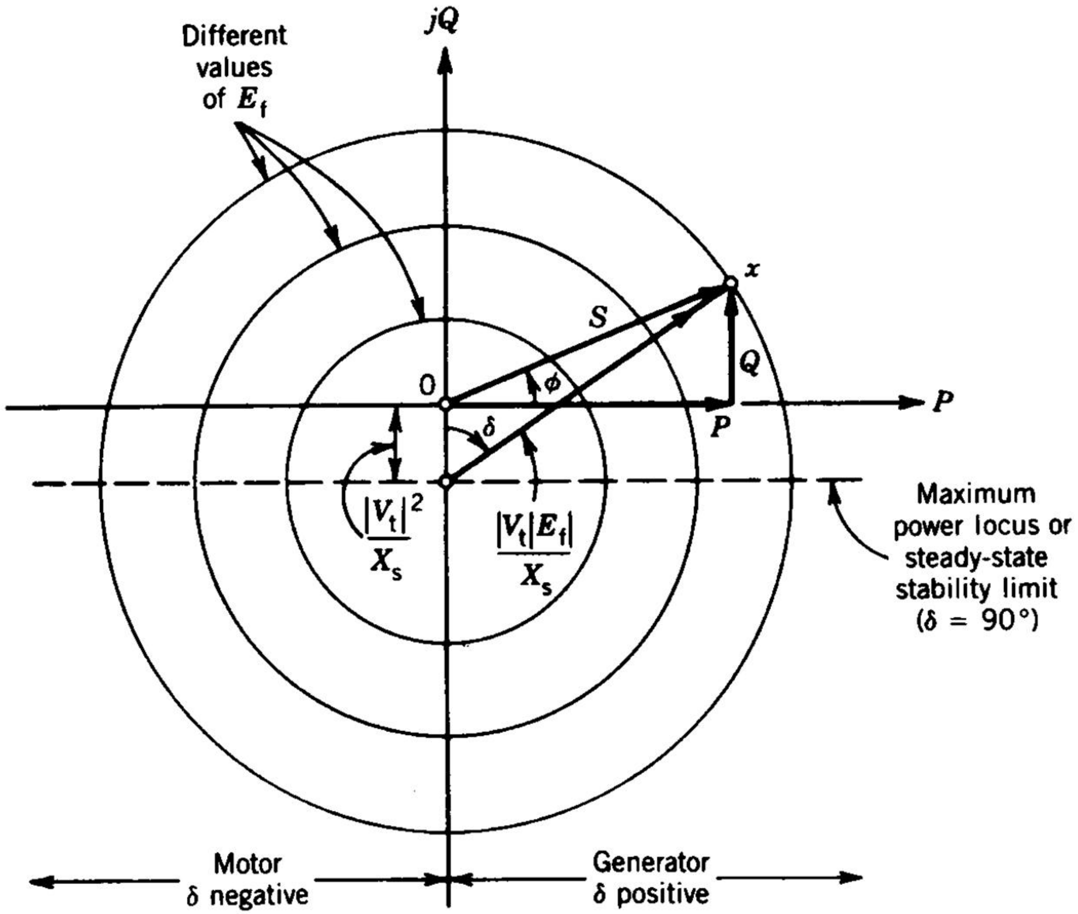




Complex power locus

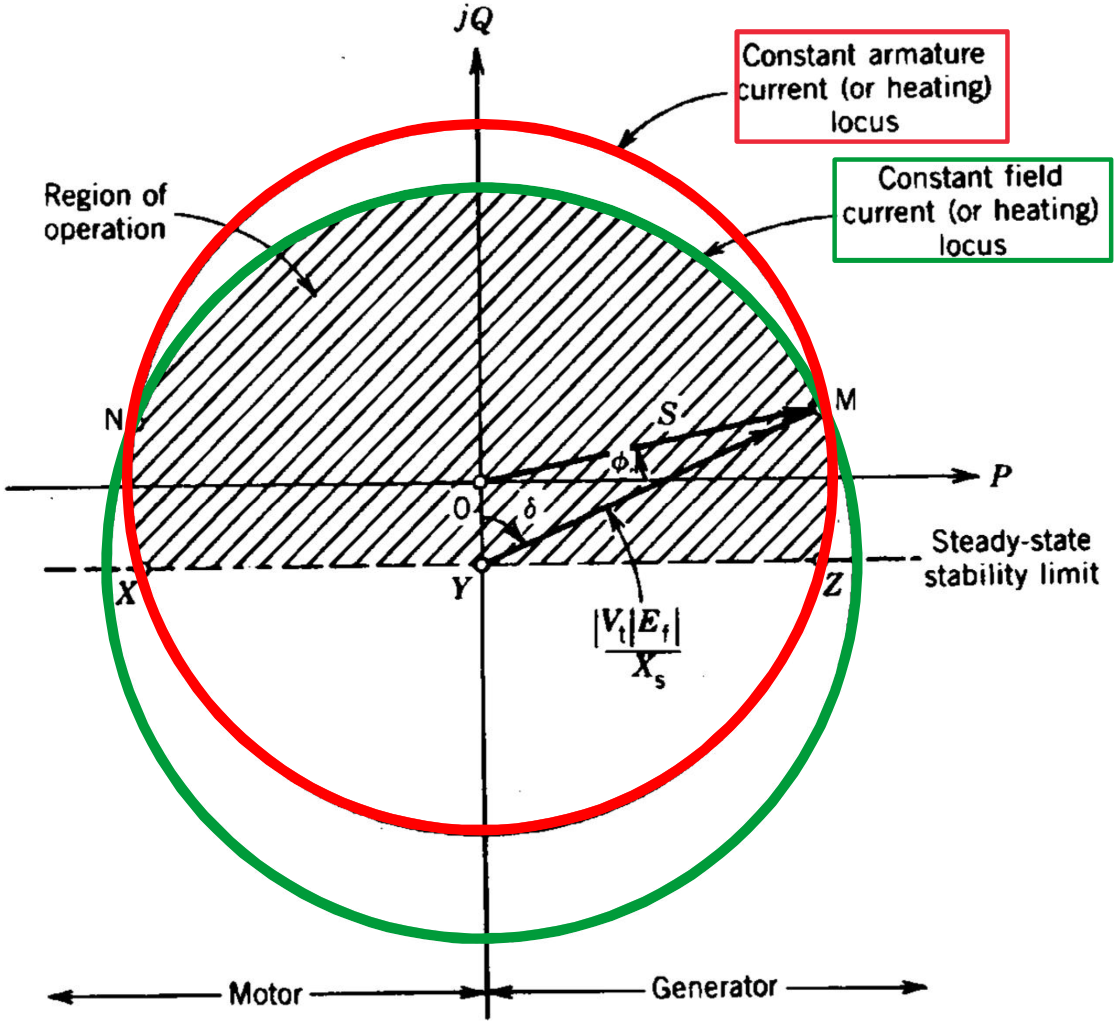
$$P_{3f} = \frac{3|V_t||E_f|}{|X_s|} \sin d = P_{\max} \sin d$$

$$Q_{3f} = \frac{3|V_t||E_f|}{|X_s|} \cos d - \frac{3|V_t|^2}{|X_s|}$$

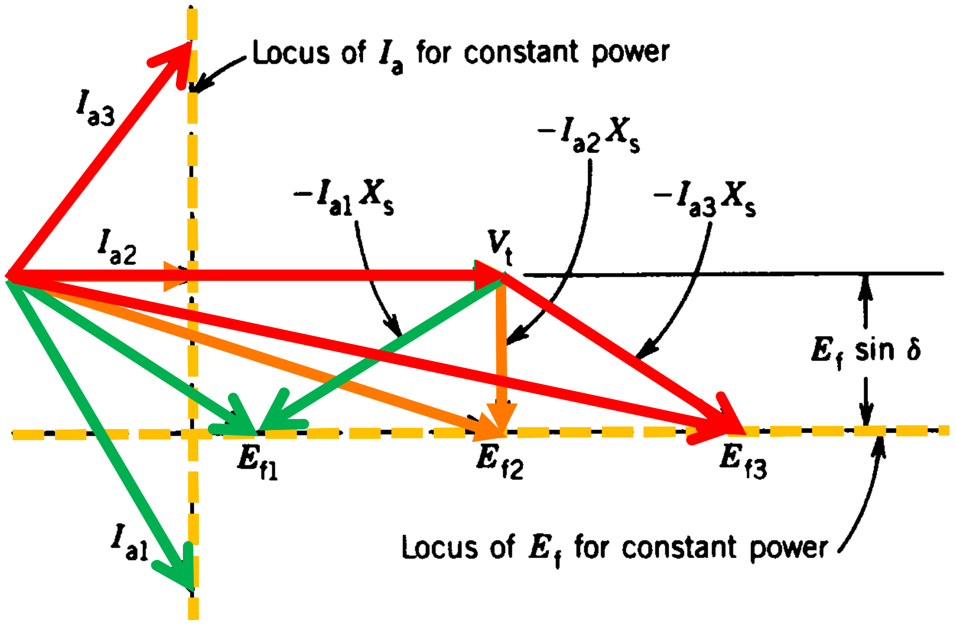


Capability curves

- Armature heating, length of OM
- Field heating, length of YM
- Steady-state stability d



Power factor control



- Connected to an infinite bus

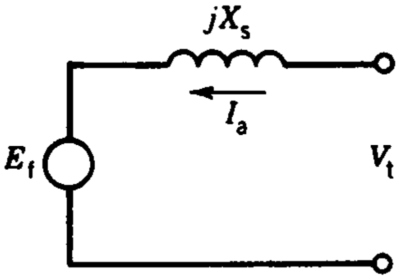
$$P = 3V_t I_a \cos f$$

- Constant power operation

$$\left| I_a \cos f \right| = \text{const.}$$

$$jX_s I_a = V_t - E_f$$

- Reactive current can be controlled by field current



- Also $$P = 3\frac{V_t E_f}{X_s} \sin d \qquad E_f \sin d = \text{const}$$

Independent generators

- Purely inductive load (I_{sc} is short-circuit current)

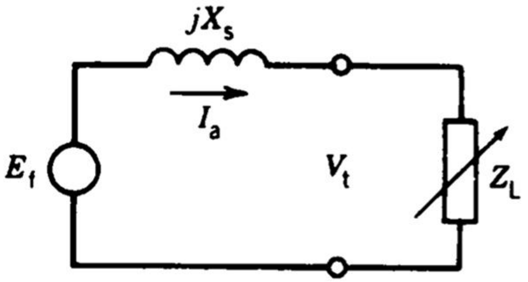
$$\begin{aligned} V_t &= E_f - I_a X_s \\ &= X_s(I_{sc} - I_a) \end{aligned}$$

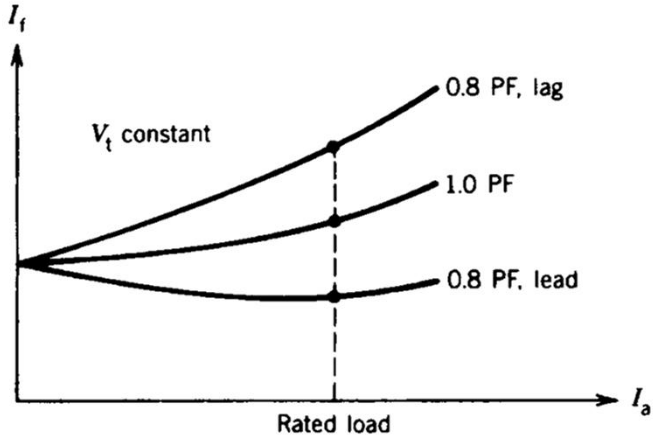
- Purely resistive load

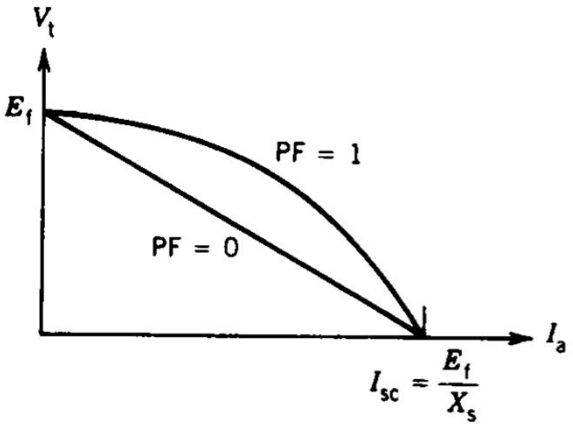
$$\underbrace{V_t = I_a R_L \qquad I_a = \frac{X_s I_{sc}}{\sqrt{R_L^2 + X_s^2}}}$$

$$\frac{V_t^2}{(X_s I_{sc})^2} + \frac{I_a^2}{I_{sc}^2} = 1$$

quarter ellipse



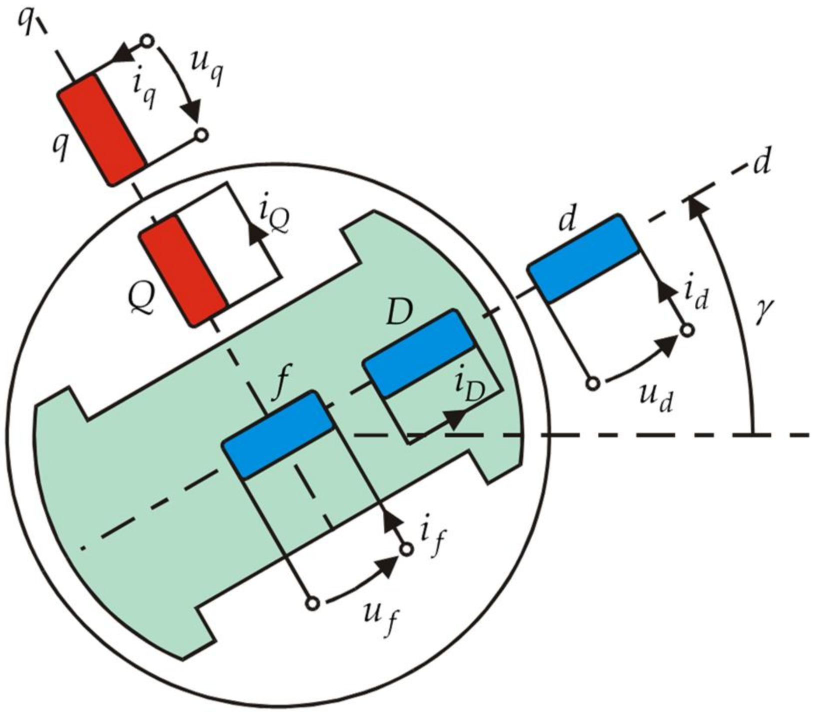


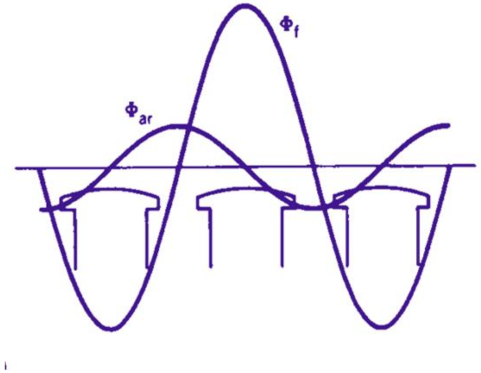


Salient pole machines

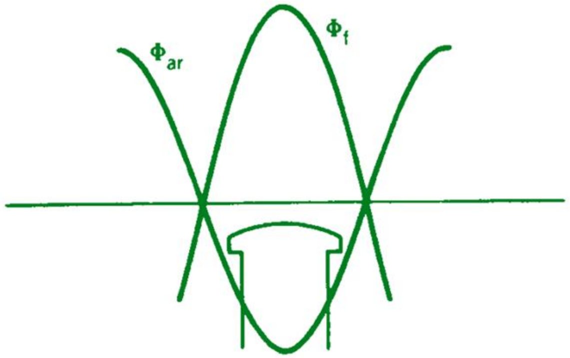
How reactance is related to inductance ? What was the definition of inductance ?

- Field mmf and flux along the d-axis
- Same magnitude of armature mmf produces more flux in d- than in q-direction è magnetizing reactance not unique in salient pole machine





I_a in phase with voltage



I_a lagging voltage by 90°

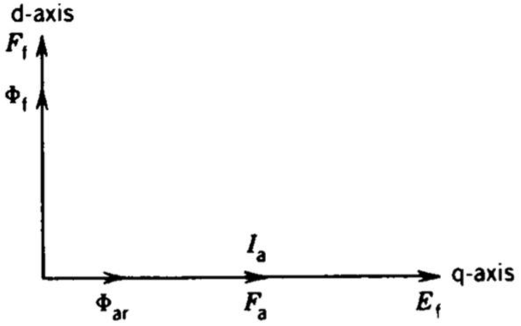
Two axis decomposition

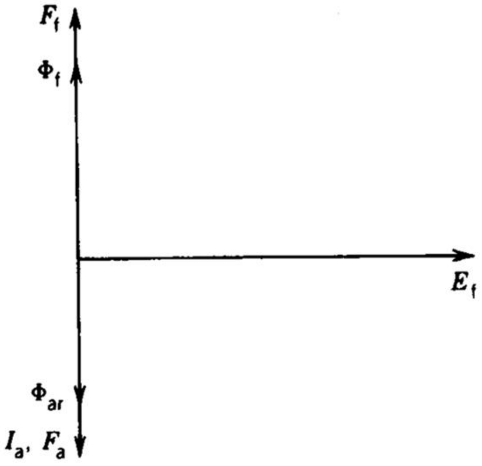
- Armature quantities can be resolved into two components (ϕ_d, I_d) (ϕ_q, I_q)
- Components produce fluxes along respective axes (ϕ_{ad}, ϕ_{aq})
- d-axis armature reactance X_d
- q-axis armature reactance X_q
- Leakage reactance X_{al}

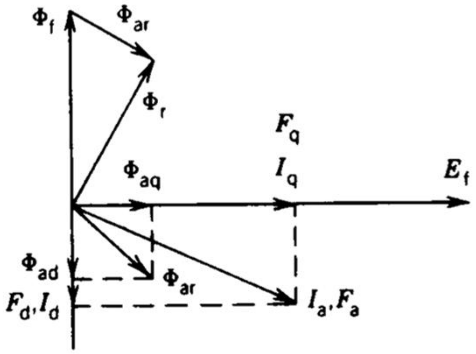
- Synchronous reactances

$$X_d = X_{ad} + X_{al}$$

$$X_q = X_{aq} + X_{al}$$





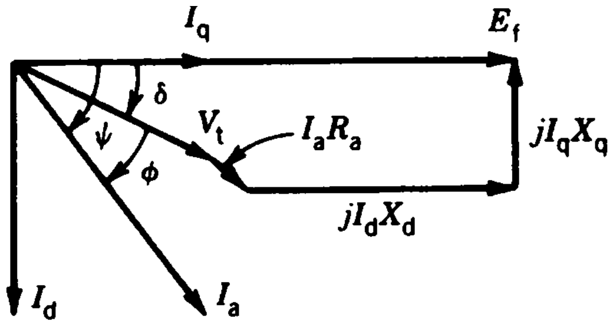


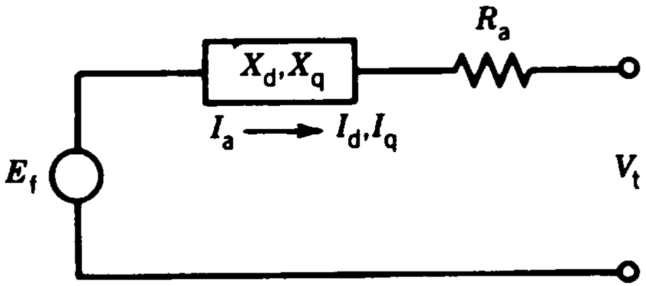
Phasor Diagrams

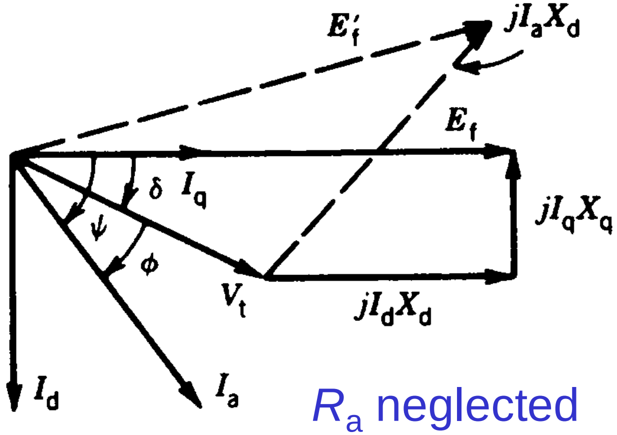
- Component currents (I_d, I_q) produce voltage drops (jI_dX_d, jI_qX_q)

$$E_f = V_t + I_a R_a + I_d jX_d + I_q jX_q \qquad I_a = I_d + I_q$$

- Generator phasor diagram (I_a lagging)
- *y* internal power factor angle
- *f* terminal power factor angle
- *d* load angle

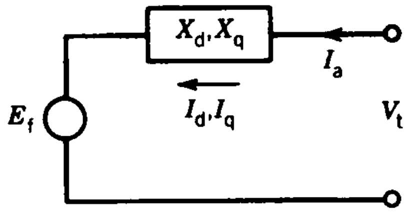






R_a neglected

Currents from phasor Diagrams



- Motoring phasor diagram (I_a lagging)
  - y internal power factor angle
  - f terminal power factor angle
  - d torque angle

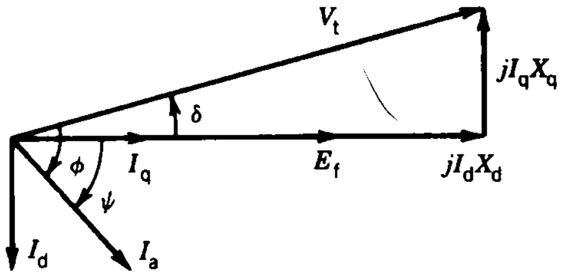
$$V_t = E_f + I_d jX_d + I_q jX_q$$

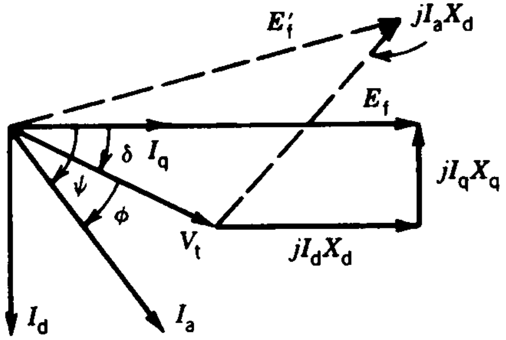
$$y = f \pm d$$

$$I_d = I_a \sin y = I_a \sin(f \pm d)$$

$$I_q = I_a \cos y = I_a \cos(f \pm d)$$

$$\tan d = \frac{I_a X_q \cos f}{V_t \pm I_a X_q \sin f} \qquad E_f = V_t \cos d \pm I_d X_d$$





Power Transfer

$$\begin{aligned} S &= V_t I_a^* \\ &= |V_t| \angle -\delta \left(|I_q| - j|I_d| \right)^* \\ &= |V_t| \angle -\delta \left(|I_q| + j|I_d| \right) \end{aligned}$$

$$|I_d| = \frac{|E_f| - |V_t| \cos\delta}{X_d}$$

$$|I_q| = \frac{|V_t| \sin\delta}{X_q}$$

⇓

$$S = \frac{|V_t|^2}{X_q} \sin\delta \angle -\delta + \frac{|V_t||E_f|}{X_d} \angle 90^\circ - \delta - \frac{|V_t|^2}{X_d} \cos\delta \angle 90^\circ - \delta$$

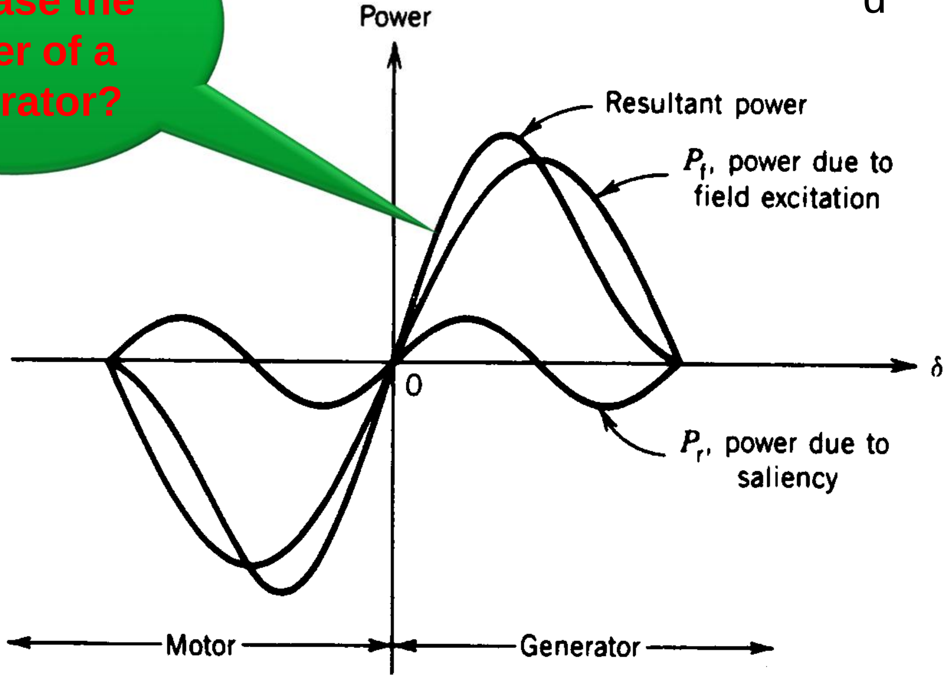
Power transfer

$$S = P + jQ$$

$$P = \frac{|V_t||E_f|}{X_d}\sin d + \frac{|V_t|^2 (X_d - X_q)}{2X_d X_q}\sin 2d$$

$$Q = \frac{|V_t||E_f|}{X_d}\cos d - |V_t|^2 \left| \frac{\sin^2 d}{X_q} + \frac{\cos^2 d}{X_d} \right|$$

How do you increase the power of a generator?



if $X_d = X_q$, then:

$$P = \frac{|V_t||E_f|}{X_d}\sin d$$

$$Q = \frac{|V_t||E_f|}{X_d}\cos d - \frac{|V_t|^2}{X_d}$$

Determination of X_d and X_q

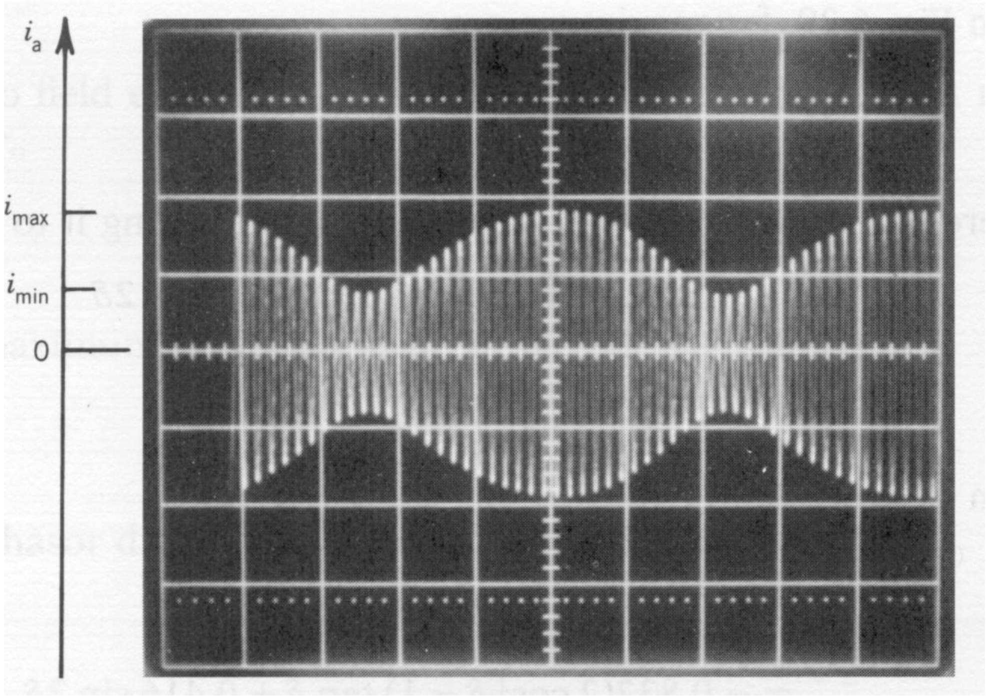
What if the rotor is at synch. speed

Slip test

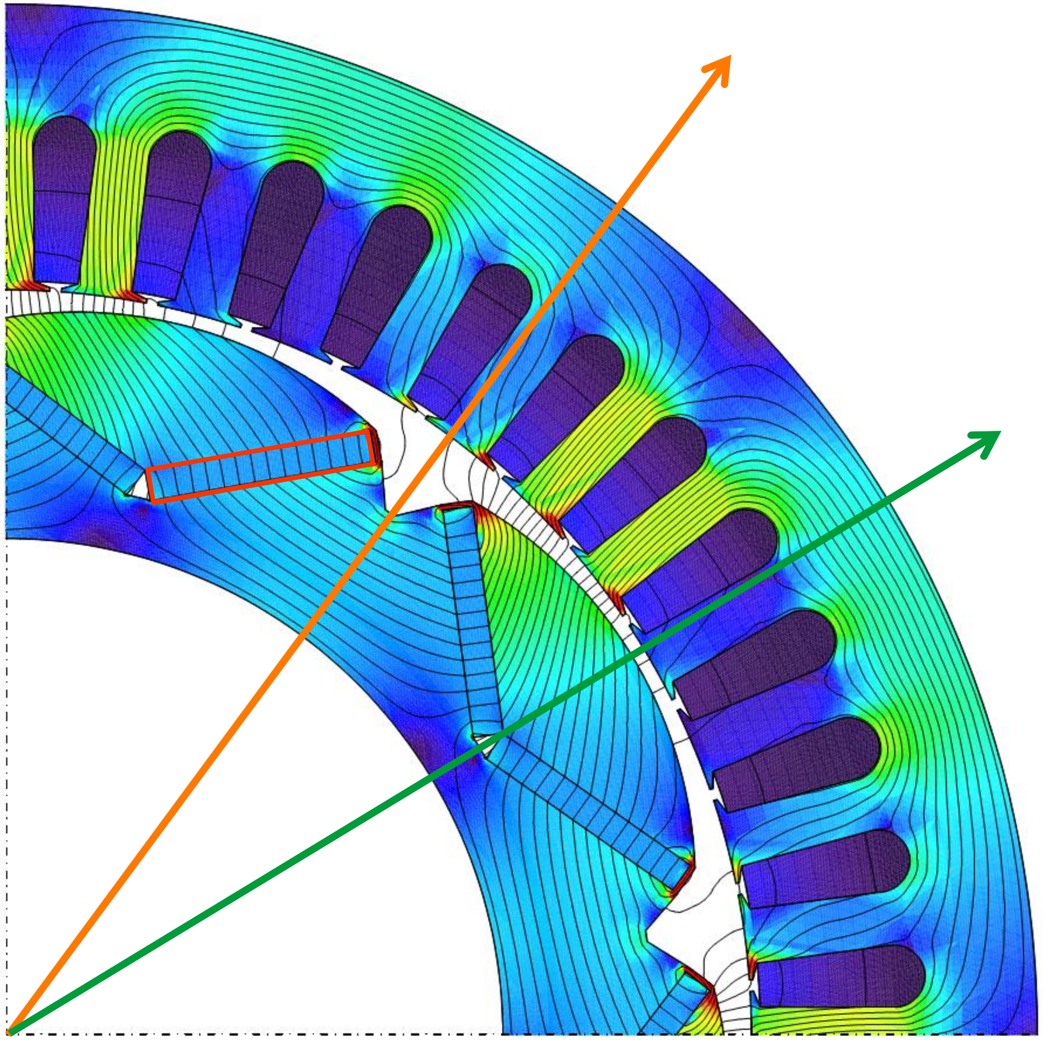
- Rotor driven at small slip
- Field winding open-circuited
- Stator connected to balanced three phase supply
- Stator encounters varying reluctance path
- Amplitude of the stator current varies

$$X_d = \frac{V_t}{i_{min}/\sqrt{2}}$$

$$X_q = \frac{V_t}{i_{max}/\sqrt{2}}$$

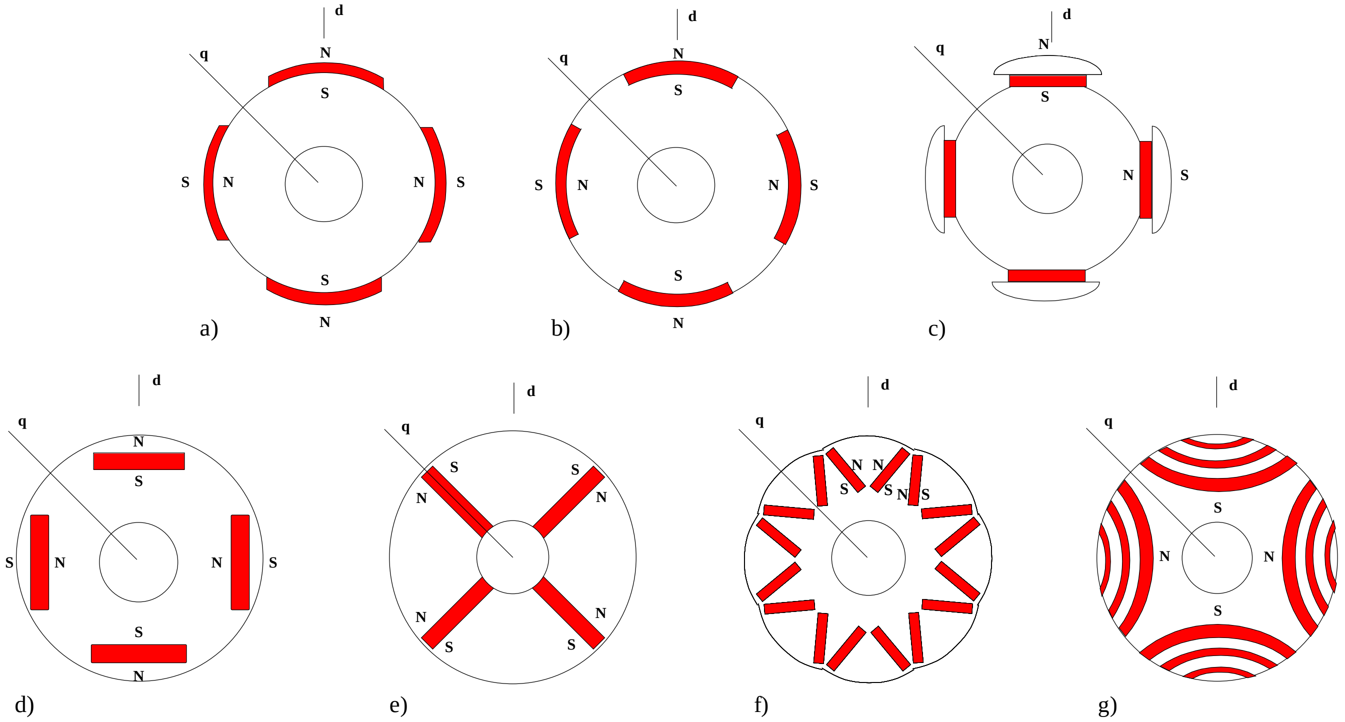


Permanent Magnet Machine



- No filed control
- No Field current
- Cost of PM
- Power factor ?

PM rotor configurations



a) surface mounted magnets
b) inset rotor with surface magnets
c) surface magnets with pole shoes
d) embedded circumferential magnets

e) embedded radial magnets
f) embedded V-magnets with shaped air-gap
g) permanent magnet assisted synchronous reluctance