Overview Electrical Machines and Drives

- 7-9 1: Introduction, Maxwell's equations, magnetic circuits
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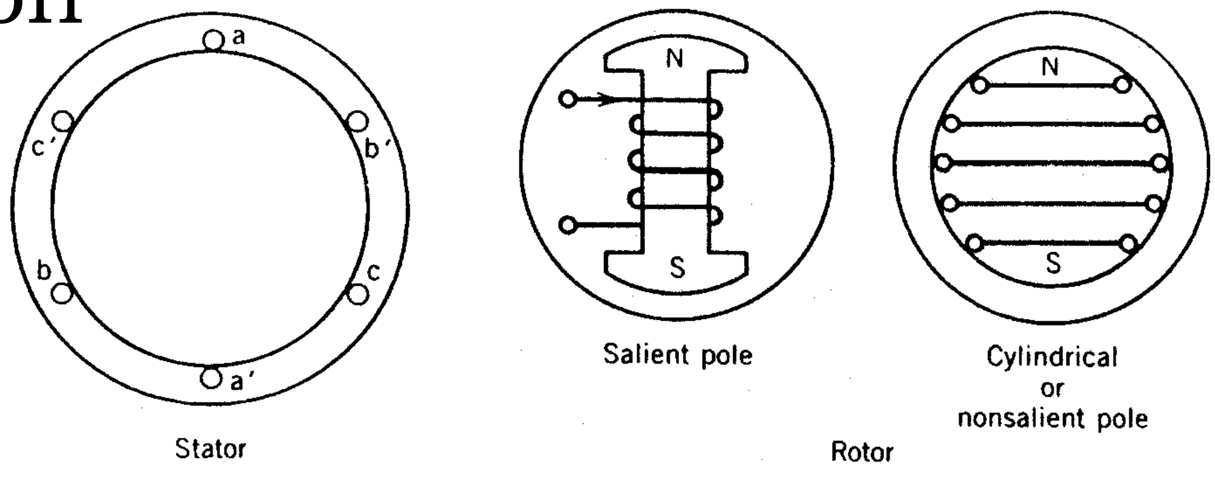
- 9-11: exam

Synchronous machines

- Introduction, construction
- Synchronous generators / motors
- Voltage equations, equivalent circuits and phasor diagrams
- Power and torque characteristics
- Capability curves
- Speed control

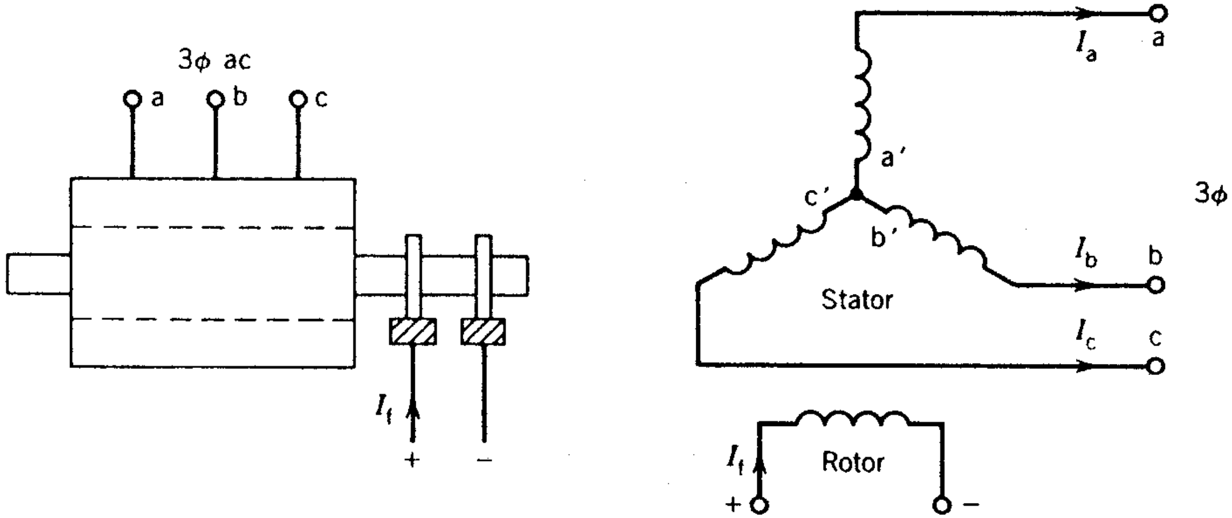
Construction

Stator comparable to IM:
- laminated
- distributed stator windings



(a)

Rotor
- high-speed: cylindrical (p≤4) with distributed winding
- low-speed salient-pole (p≥4) with concentrated winding



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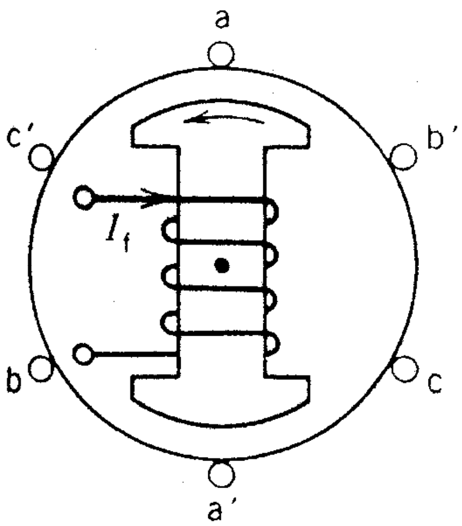
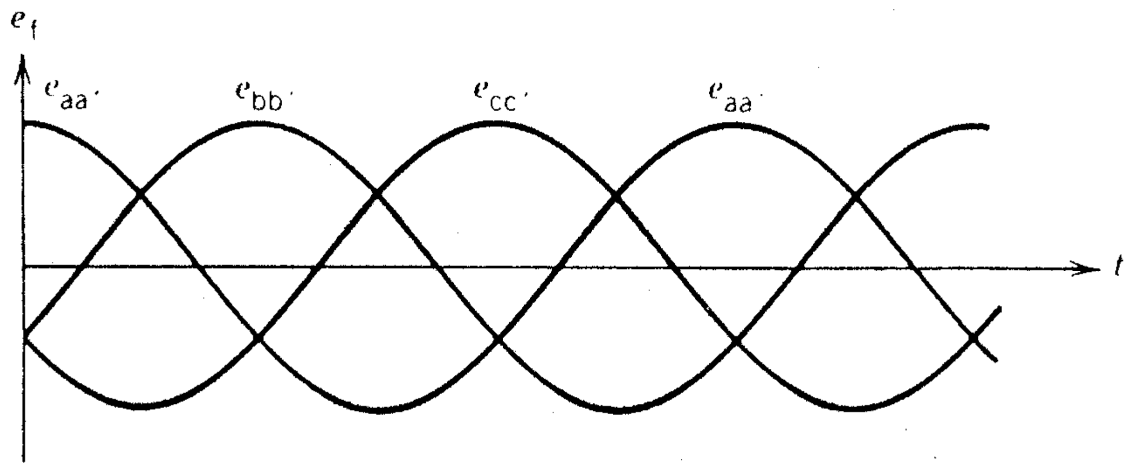
Synchronous generator





$$f_1 = \frac{p}{2}\frac{n}{60}$$ frequency of the stator voltage or excitation voltage

$$n = f_1 60 \frac{2}{p}$$ synchronous speed of the rotor

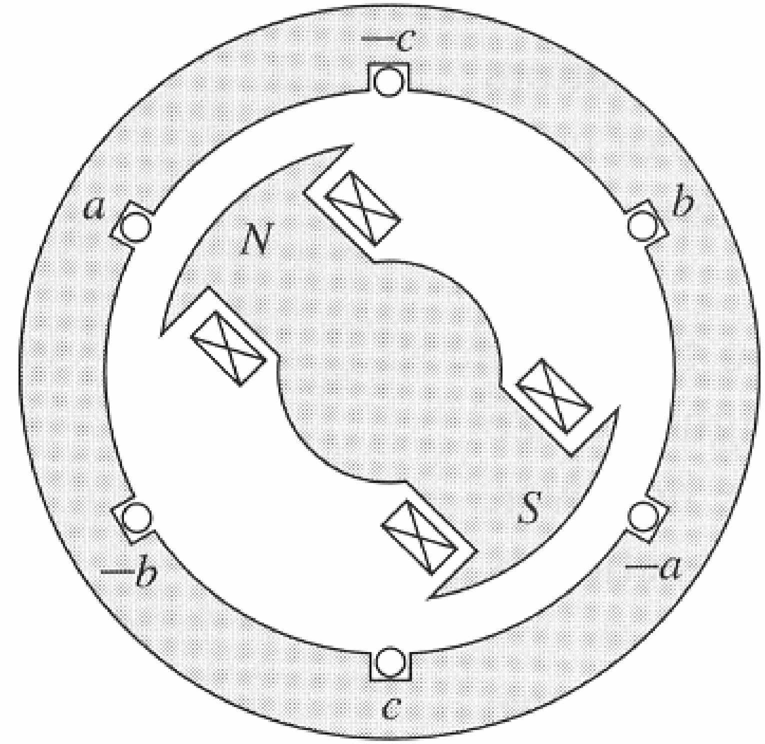
for f_1=50Hz

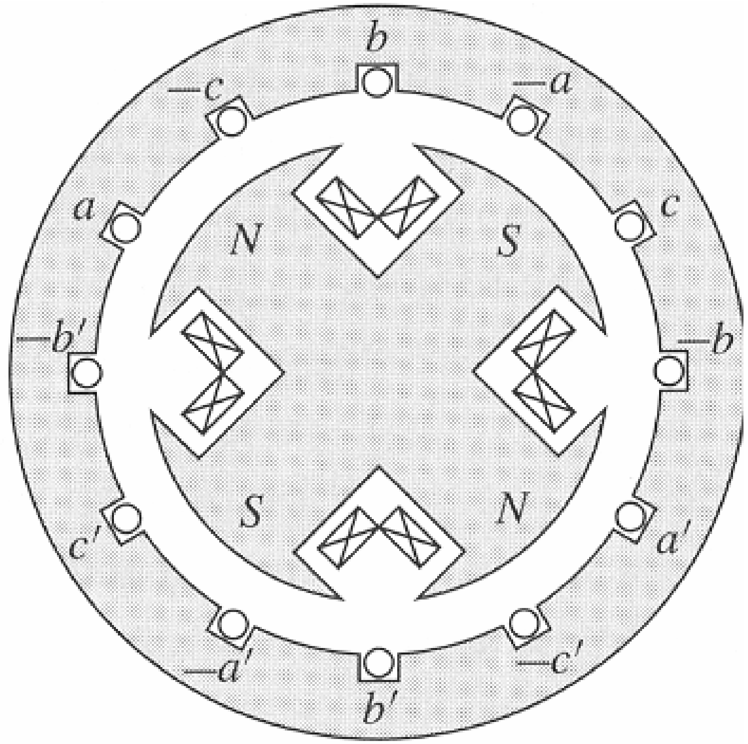
p	2	4	6	8	10	60
n_s (rpm)	3000	1500	1000	750	600	100

P-pole machines

p is the number of poles (in some other books: number of pole-pairs)

$$N_a(\theta) = \frac{N}{2}\sin(\frac{p}{2}\theta) \qquad B_s(\theta,t) = \hat{B}\cos(\frac{p}{2}\theta - \omega t) \qquad \theta_{ed} = \frac{p}{2}\theta_{md}$$





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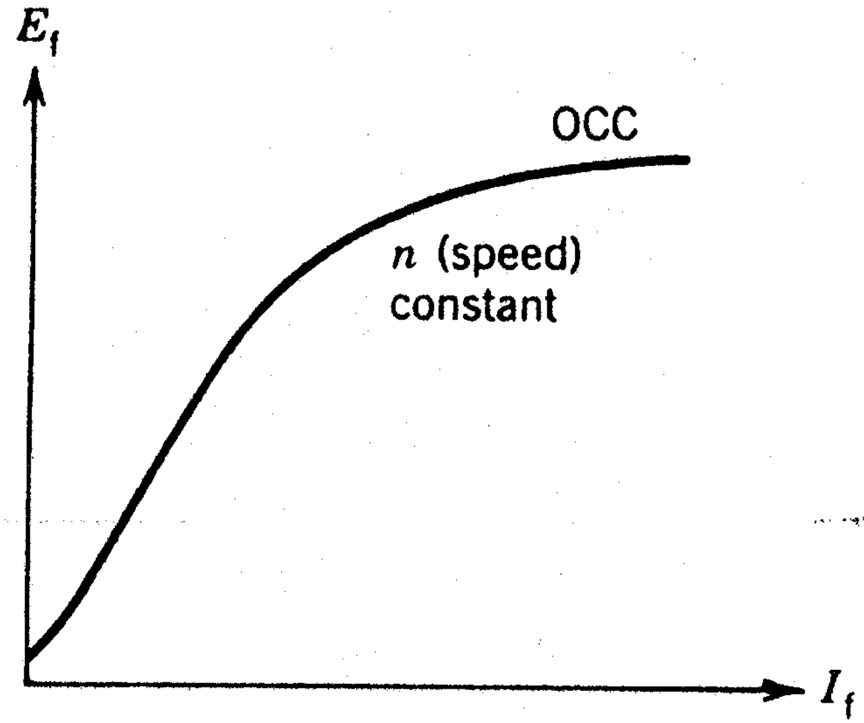
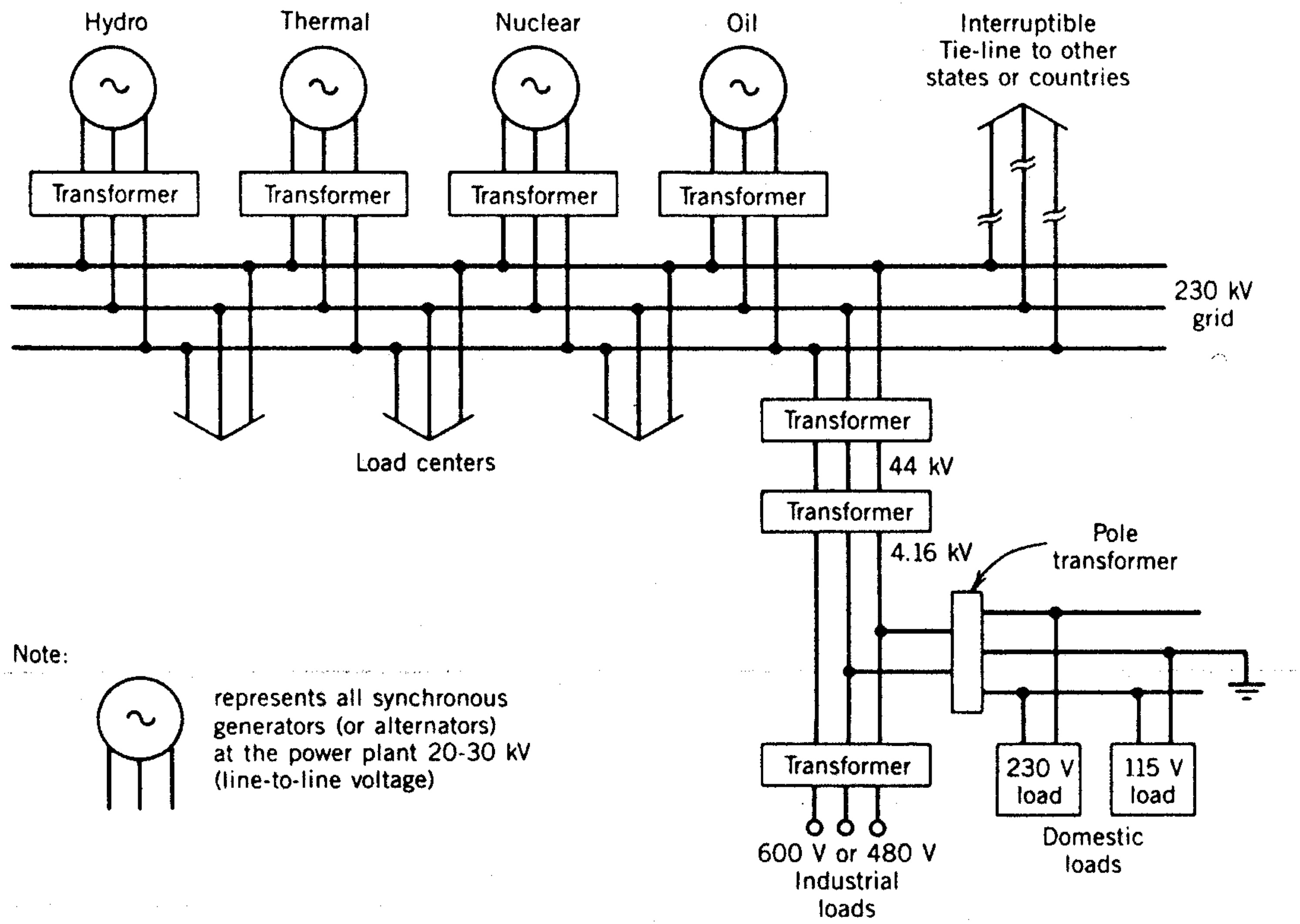
Open circuit characteristic



$$E_f = \frac{2\pi}{\sqrt{2}} f_1 k_{w1} N_1 \Phi_p$$

Position in the grid



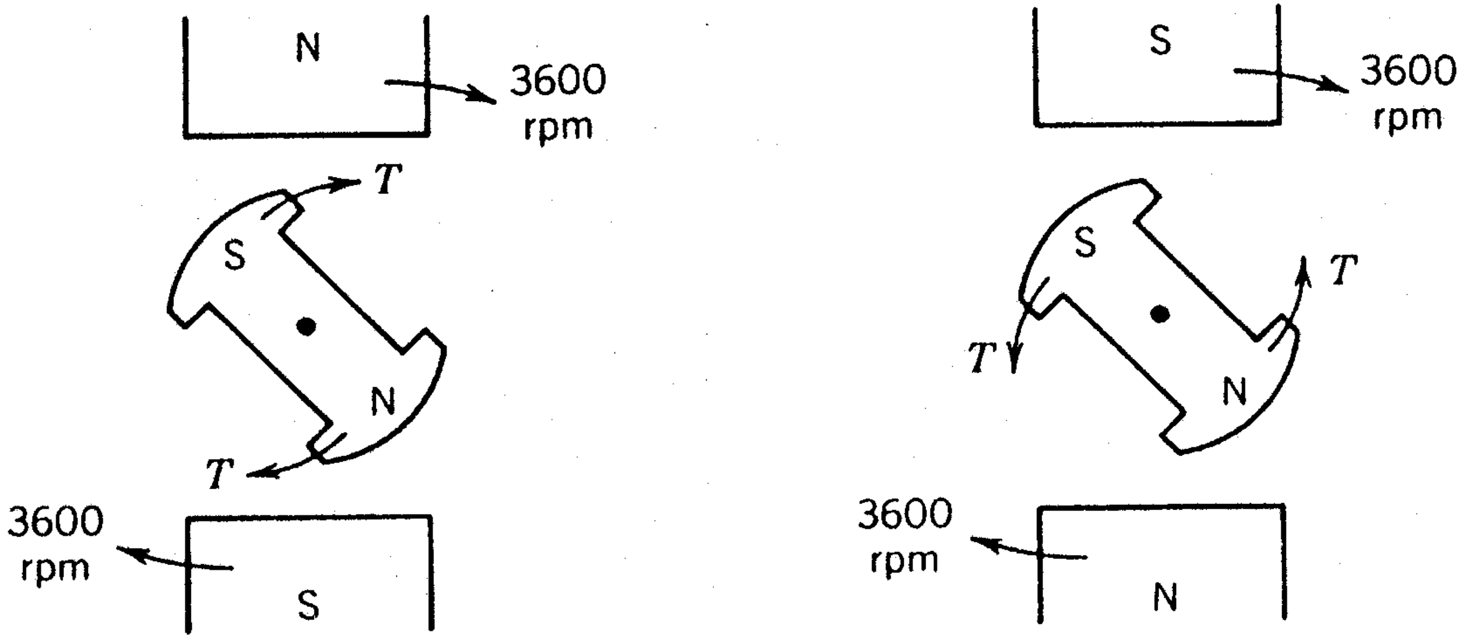
Connecting to the grid (infinite bus)

Before a synchronous machine can be connected to the infinite bus,

1. voltage
2. frequency
3. phase sequence
4. phase

of the synchronous machine and the grid must be the same.

Synchronous motor connected to the grid



- Not self starting, therefore:
- damper cage for asynchronous starting and damping oscillations
- frequency converter

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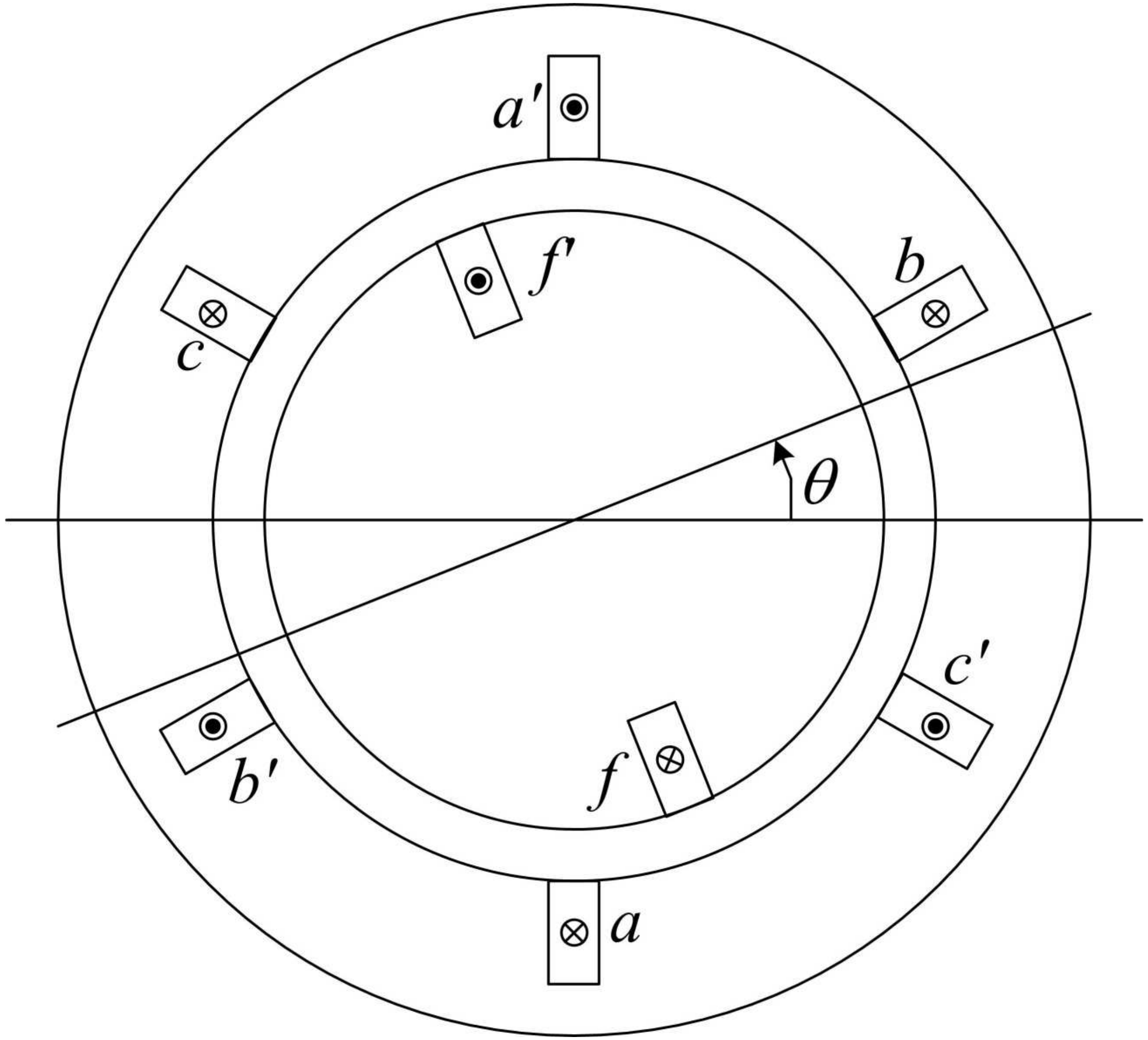
Derivation of voltage equations

- The sketched stator and rotor windings are concentrated, but they represent distributed windings
- How can we derive voltage equations and equivalent circuits?



Voltage equations

Maxwell, Faraday: $u = Ri + \frac{\mathrm{d}\lambda}{\mathrm{d}t}$

$$\begin{cases} \lambda_{sa} = L_{sa} i_{sa} + M_{sab} i_{sb} + M_{sab} i_{sc} + M_{sr}(\theta) i_f \\ \lambda_{sb} = M_{sab} i_{sa} + L_{sa} i_{sb} + M_{sab} i_{sc} + M_{sr}(\theta - \tfrac{2}{3}\pi) i_f \\ \lambda_{sc} = M_{sab} i_{sa} + M_{sab} i_{sb} + L_{sa} i_{sc} + M_{sr}(\theta - \tfrac{4}{3}\pi) i_f \end{cases}$$

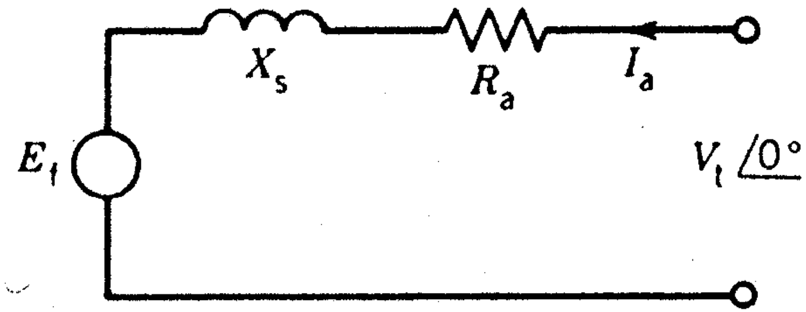
No star-point connection $i_{sa} + i_{sb} + i_{sc} = 0$

$$\begin{cases} \lambda_{sa} = (L_{sa} - M_{sab}) i_{sa} + M_{sr}(\theta) i_f \\ \lambda_{sb} = (L_{sa} - M_{sab}) i_{sb} + M_{sr}(\theta - \tfrac{2}{3}\pi) i_f \\ \lambda_{sc} = (L_{sa} - M_{sab}) i_{sc} + M_{sr}(\theta - \tfrac{4}{3}\pi) i_f \end{cases}$$

Voltage equations, equivalent circuit

Using $L_s = L_{sa} - M_{sab}$

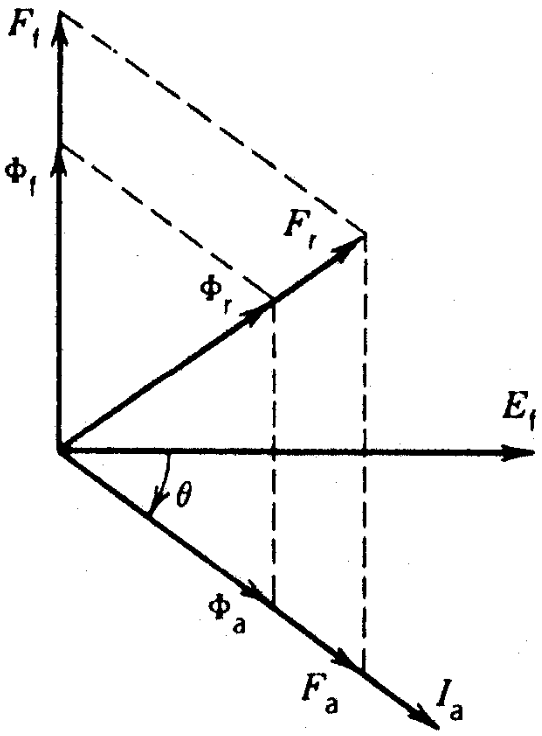
$$
\begin{cases}
u_{sa} = Ri_{sa} + L_s \dfrac{\mathrm{d}i_{sa}}{\mathrm{d}t} + i_f \dfrac{\mathrm{d}M_{sr}(\theta)}{\mathrm{d}t} = Ri_{sa} + L_s \dfrac{\mathrm{d}i_{sa}}{\mathrm{d}t} + e_{fa} \\
u_{sb} = Ri_{sb} + L_s \dfrac{\mathrm{d}i_{sb}}{\mathrm{d}t} + i_f \dfrac{\mathrm{d}M_{sr}(\theta - \frac{2}{3}\pi)}{\mathrm{d}t} = Ri_{sb} + L_s \dfrac{\mathrm{d}i_{sb}}{\mathrm{d}t} + e_{fb} \\
u_{sc} = Ri_{sc} + L_s \dfrac{\mathrm{d}i_{sc}}{\mathrm{d}t} + i_f \dfrac{\mathrm{d}M_{sr}(\theta - \frac{4}{3}\pi)}{\mathrm{d}t} = Ri_{sc} + L_s \dfrac{\mathrm{d}i_{sc}}{\mathrm{d}t} + e_{fc}
\end{cases}
$$



Armature reaction

The rotating magnetic field consists of two parts

1. the field created by the three-phase stator currents
2. the field created by the rotor excitation



$$\Phi_r = \Phi_f + \Phi_a$$

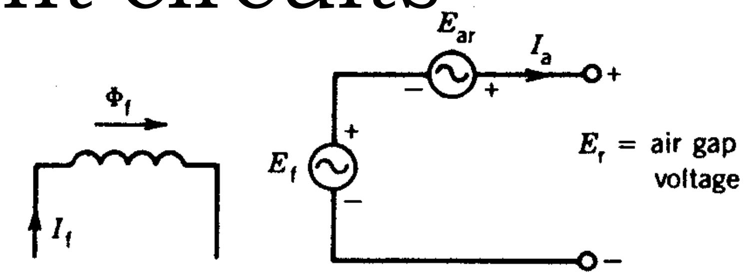
Generator convention:

$$E_f = -\frac{d\lambda}{dt}$$

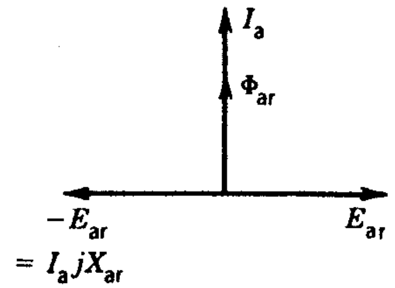
$$\underline{E}_f = -j\omega\underline{\lambda}$$

FIGURE 6.6 Space phasor diagram.

Equivalent circuits



(a)

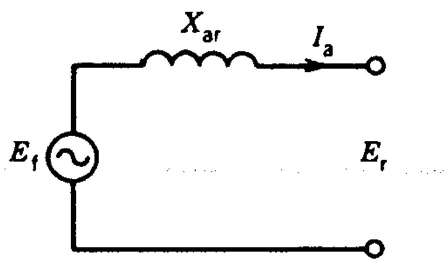


(b)

Generator convention:

$$E_f = -\frac{d\lambda}{dt}$$

$$\underline{E}_f = -j\omega\underline{\lambda}$$



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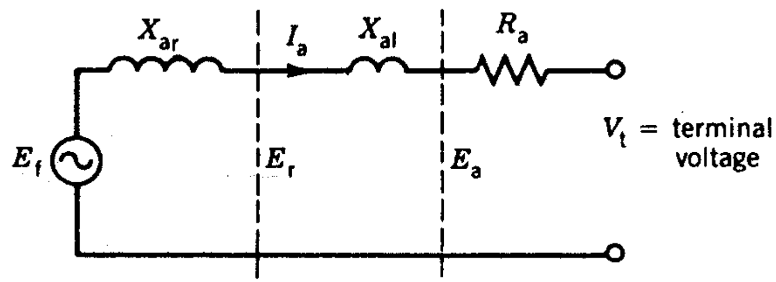

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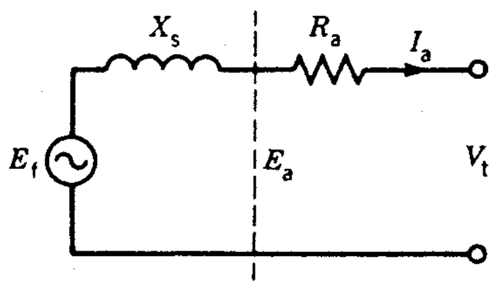
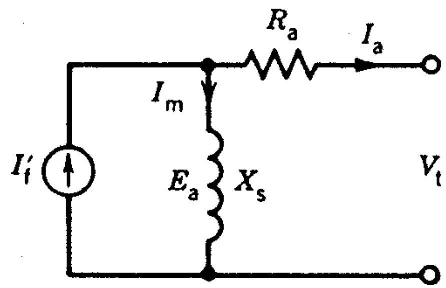
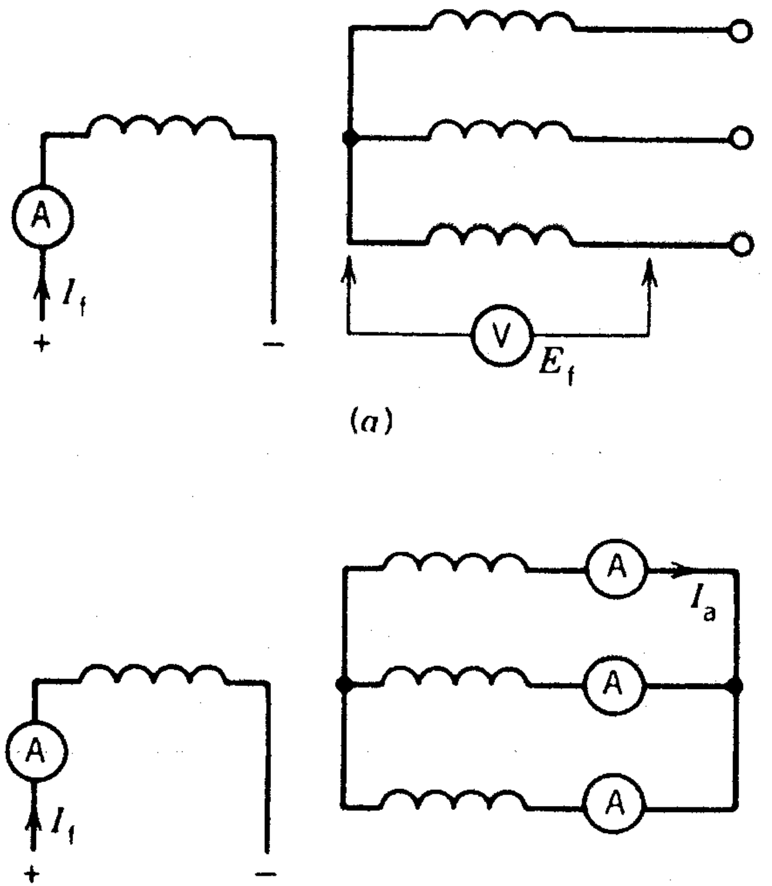
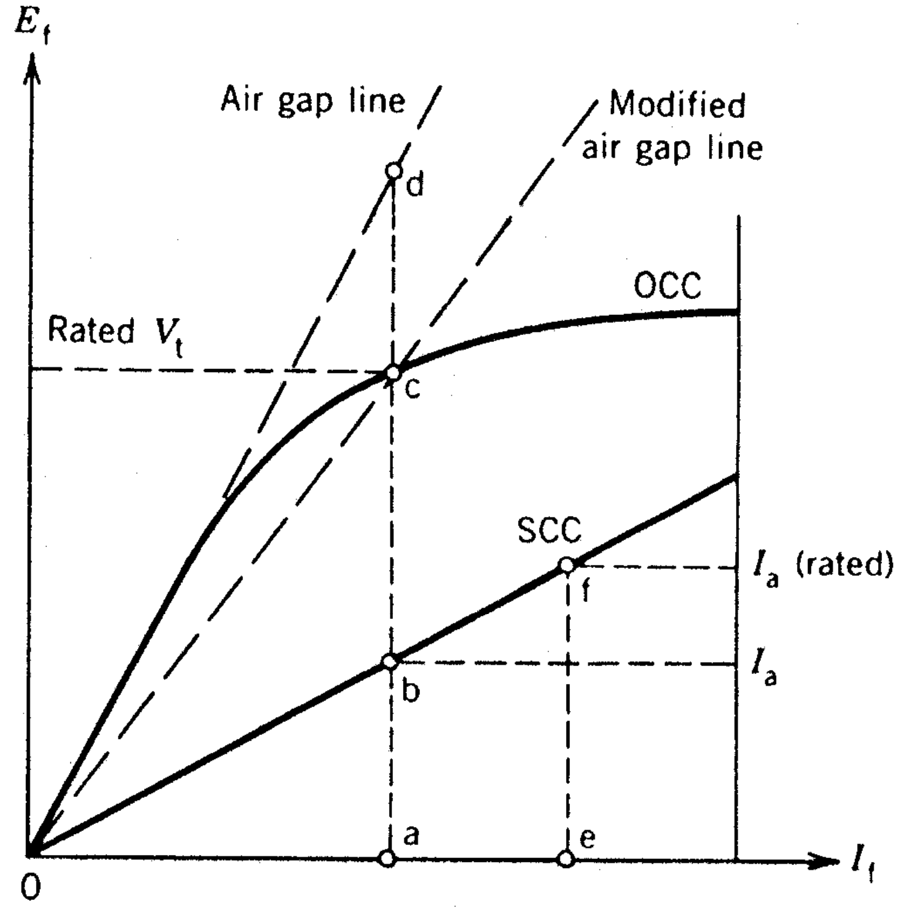




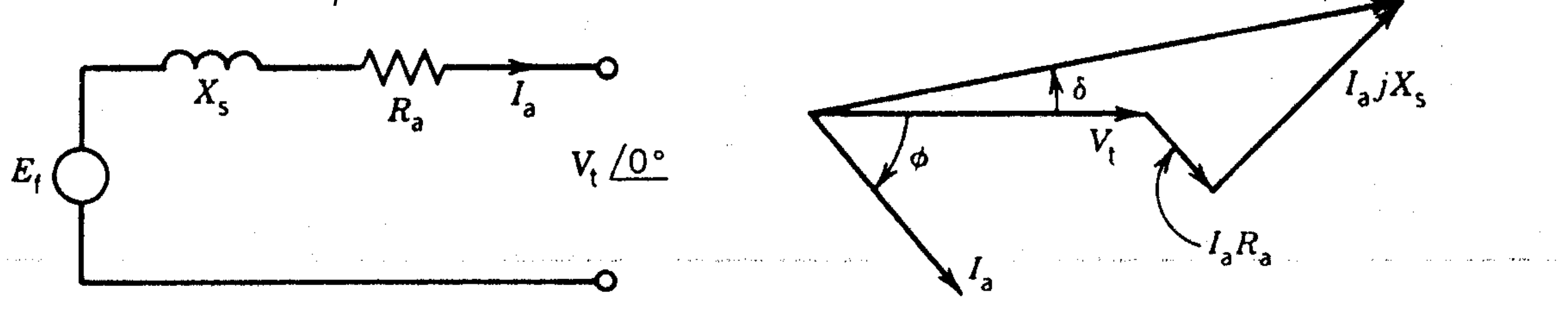
Measuring the synchronous inductance



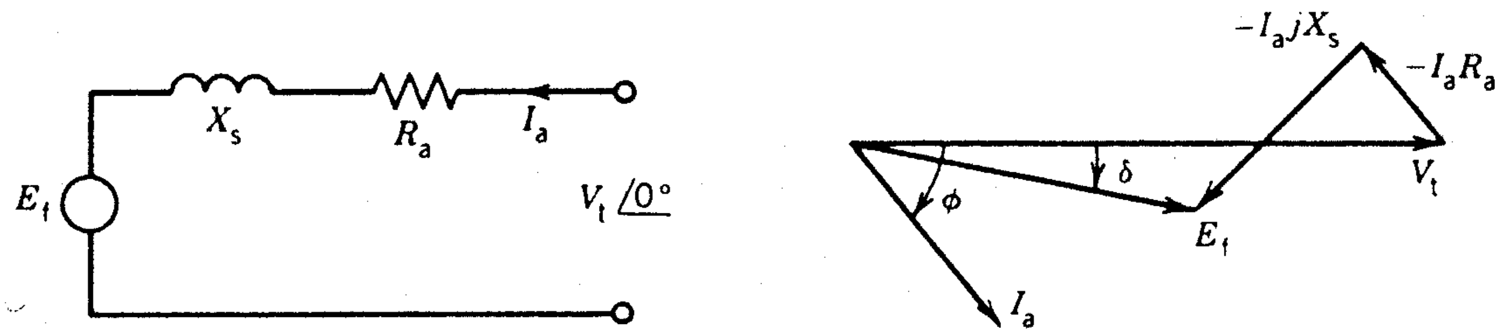


Phasor diagrams

Generator: $\underline{V}_t = \underline{E}_f - R\underline{I}_a - \mathrm{j}\omega L_s \underline{I}_a$



(a)



(b)

Motor: $\underline{V}_t = \underline{E}_f + R\underline{I}_a + \mathrm{j}\omega L_s \underline{I}_a$

Synchronous condenser

- Synchronous machine that
  - behaves like a capacitor or inductor
  - may used for reactive power compensation in power systems
  - has no mechanical load
- Can you sketch the phasor diagrams for capacitive and inductive operation?

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Power characteristics

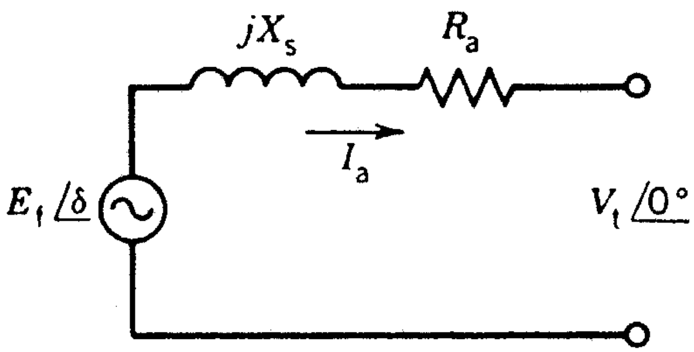

FIGURE 6.18 Per-phase equivalent circuit.

$$R_s = 0 \qquad \underline{V_t} = V_t \qquad \underline{E_f} = E_f(\cos(\delta) + \mathrm{j}\sin(\delta))$$

$$\underline{S} = 3\underline{V_t}\,\underline{I_a}^* = 3V_t\left(\frac{E_f(\cos(\delta) + \mathrm{j}\sin(\delta)) - V_t}{\mathrm{j}X_s}\right)^*$$

$$\underline{S} = 3\frac{V_t E_f \sin(\delta)}{X_s} + 3\mathrm{j}\frac{V_t E_f \cos(\delta) - V_t^2}{X_s} \qquad P = 3\frac{V_t E_f \sin(\delta)}{X_s}$$

Torque characteristics

$$T = \frac{P}{\omega_m} = 3\frac{V_t E_f}{\omega_m X_s}\sin(\delta) = T_{\max}\sin(\delta)$$

- Stability limits
- Also for negative load angle

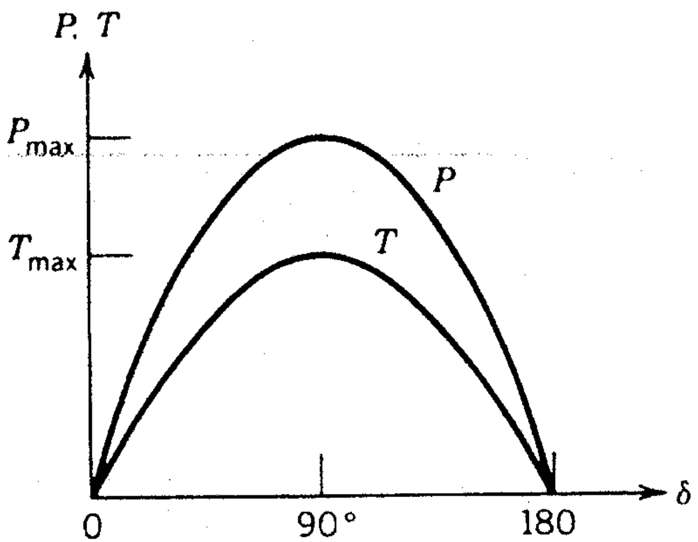

FIGURE 6.20 Power and torque–angle characteristics.

Torque-speed characteristic

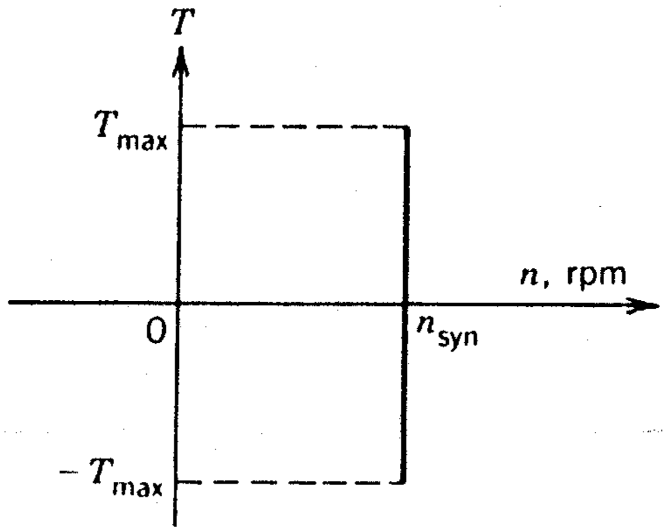

FIGURE 6.21 Torque–speed characteristics.

Synchronous machines

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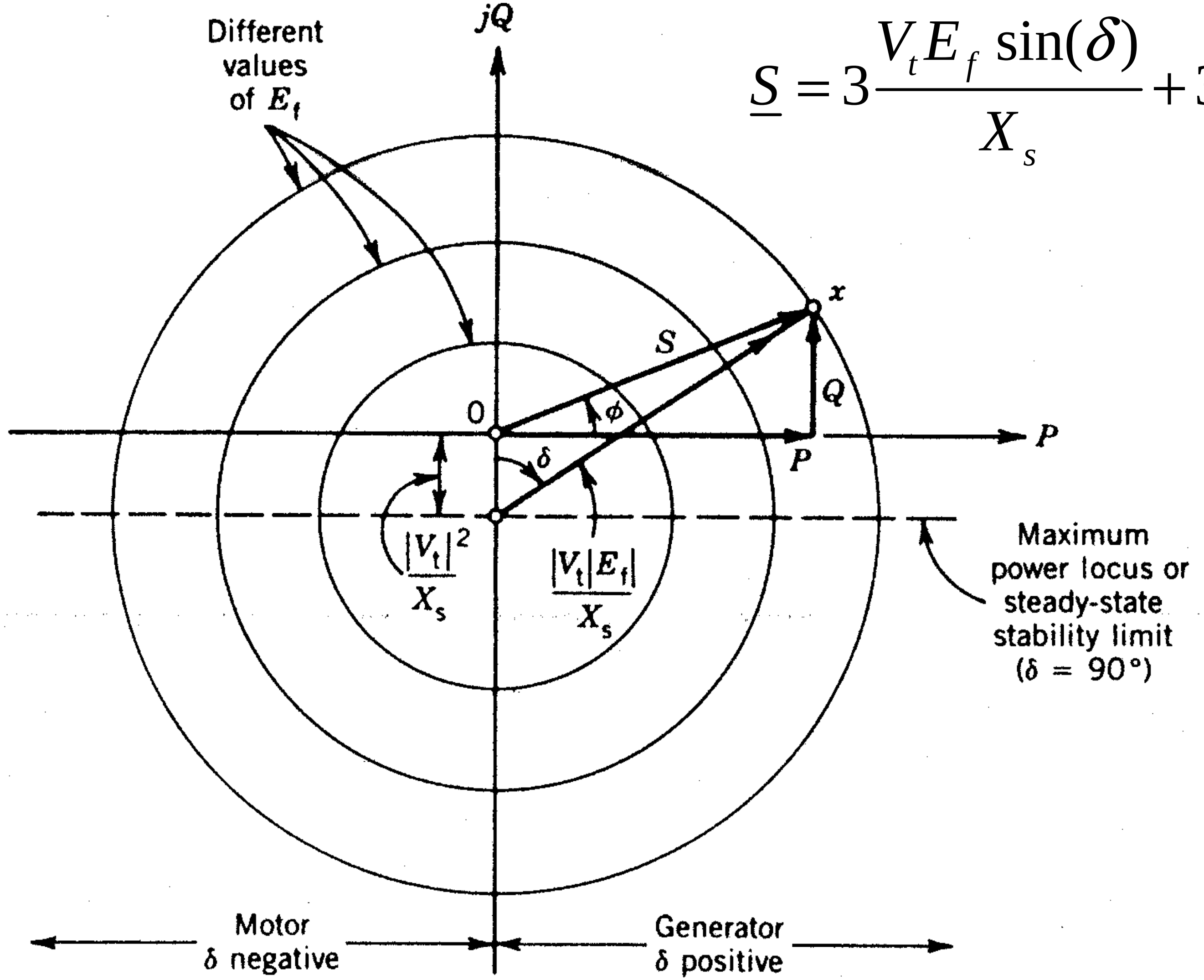
Complex power locus

$$\underline{S} = 3\frac{V_t E_f \sin(\delta)}{X_s} + 3\,j\frac{V_t E_f \cos(\delta) - V_t^2}{X_s}$$

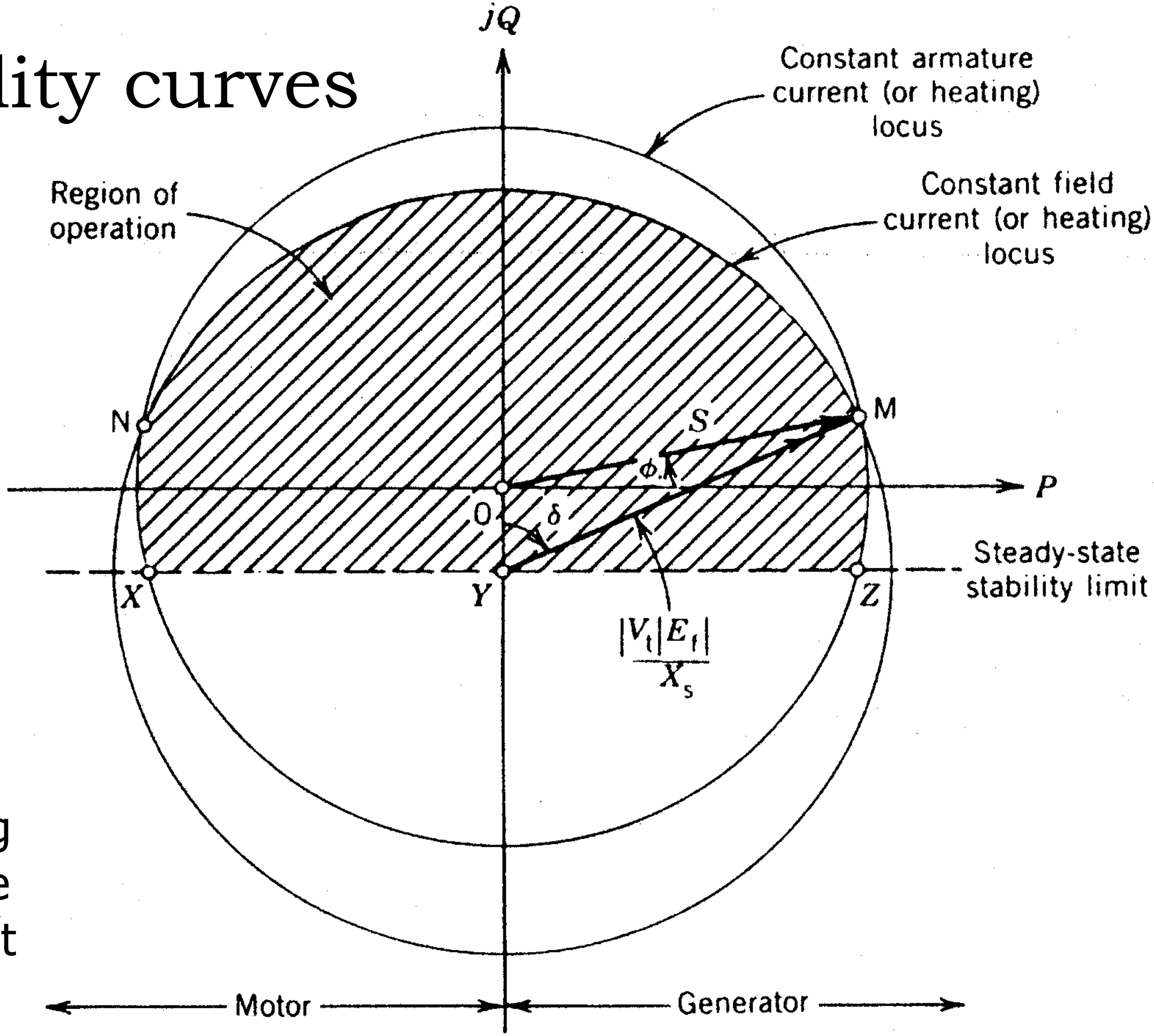


What happens if the power is increased?

What happens if the field current is increased?

Capability curves

Capability is limited by
- armature heating
- field heating
- steady-state stability limit



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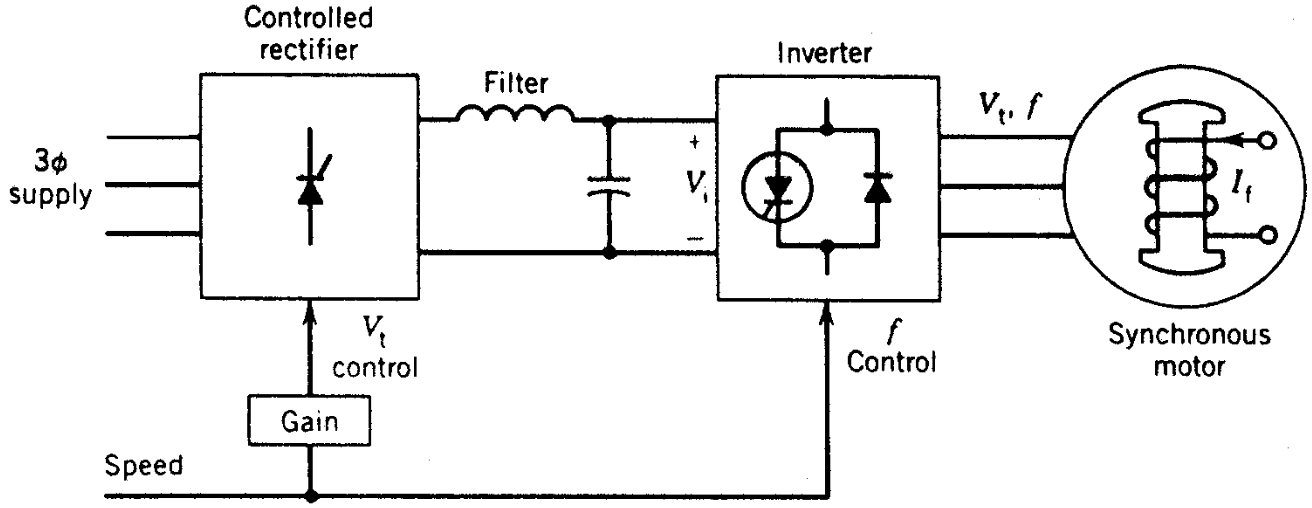
Speed control of synchronous machines

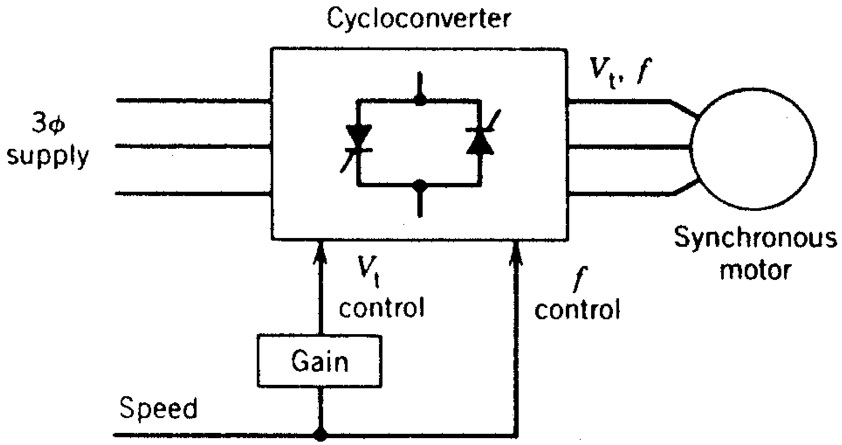
- How can the speed of synchronous machines be controlled?

Frequency control



(a)

VSI is important. The cycloconverter is not discussed in this course.



Flux weakening

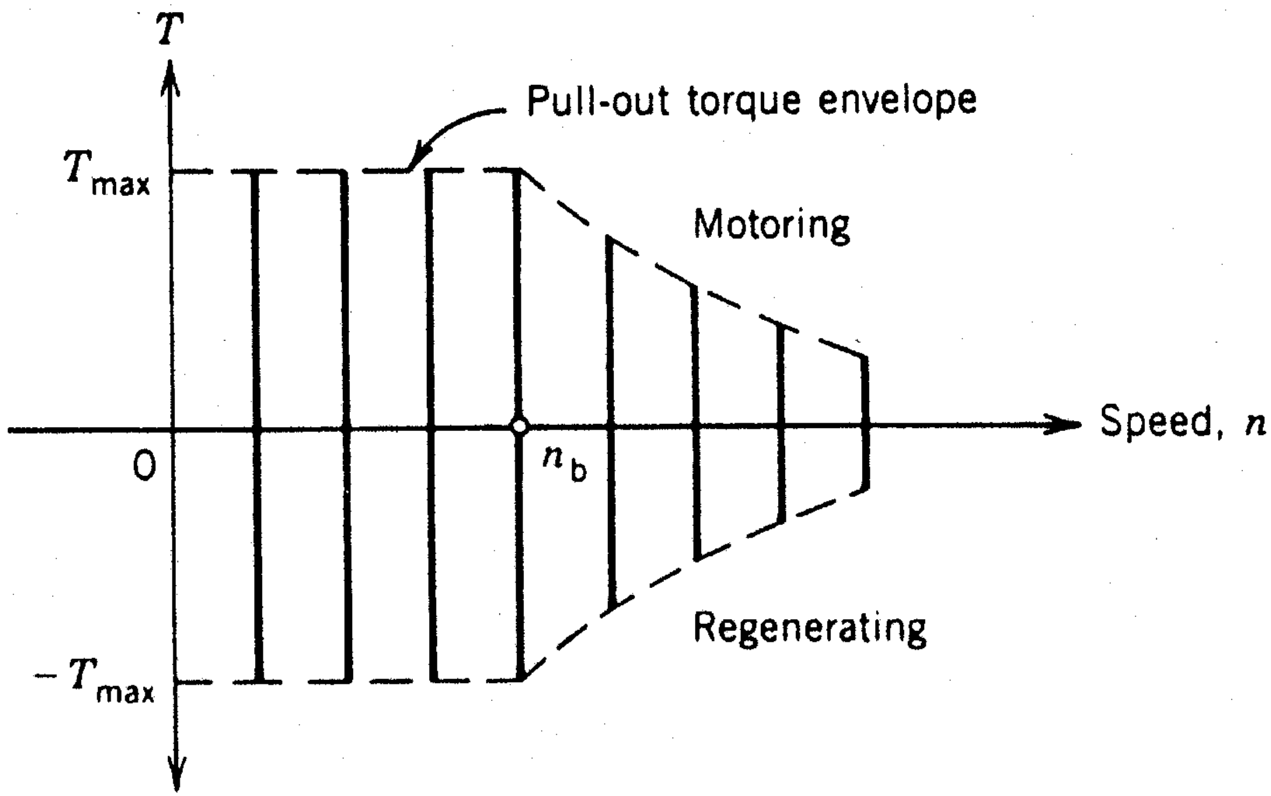


FIGURE 6.32 Torque–speed characteristic of synchronous machines.

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