

Overview Electrical Machines and Drives

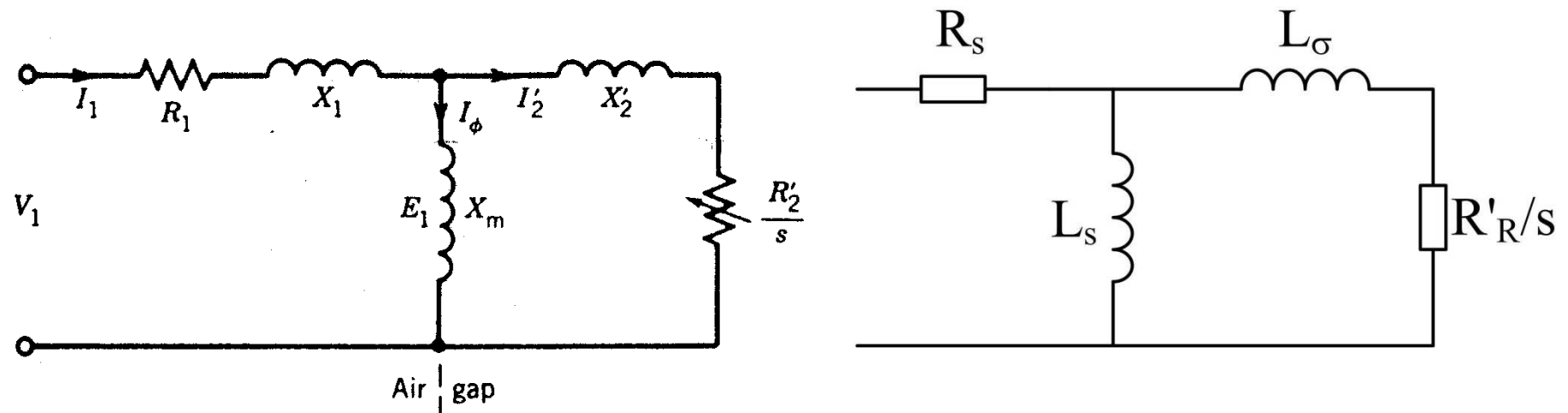
- 7-9 1: Introduction, Maxwell's equations, magnetic circuits
- 11-9 1.2-3: Magnetic circuits, Principles
- 14-9 3-4.2: Principles, DC machines
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- 21-9 5.2-5.6: IM introduction, IM principles
- 25-9 Guest lecture Emile Brink
- 28-9 5.8-5.10: IM equivalent circuits and characteristics
- 2-10 5.13-6.3: IM drives, SM
- 5-10 6.4-6.13: SM, PMACM
- 12-10 6.14-8.3: PMACM, other machines
- 19-10: rest, questions
- 9-11: exam

Induction machines

- Introduction (5.1)
- Rotating magnetic field (5.2, also for SM)
- Why does an induction machine rotate?
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- Equivalent circuits and voltage equations (5.7)
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- Performance characteristics (5.9)
 - Torque-speed characteristic
 - Stator current
- Efficiency / Power flow in three modes of operation (5.10)
- Speed control (5.13)
- Linear induction motors (5.16)

Parameter identification (5.8)

- resistance measurement (dc current) - which resistance?
- no-load test - which parameters?
- blocked-rotor test - which parameters?



Performance characteristics (5.9)

Power balance:

$$P_e = P_{mech} + P_{dis} + \frac{dW_f}{dt}$$

- neglect iron losses
- field energy constant

The power crossing the air gap **per phase** is

$$P_{ag} = \frac{R'_R}{s} I_R'^2 = R'_R I_R'^2 + \frac{1-s}{s} R'_R I_R'^2$$

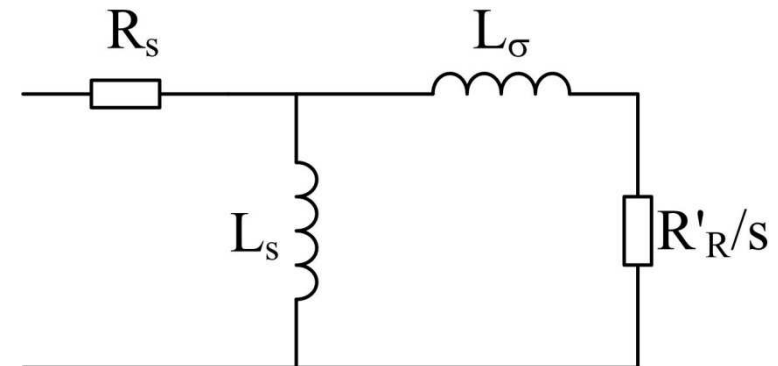
$$P_{ag} = P_2 + P_{mech}$$

From this analysis:

$$P_2 = sP_{ag}$$

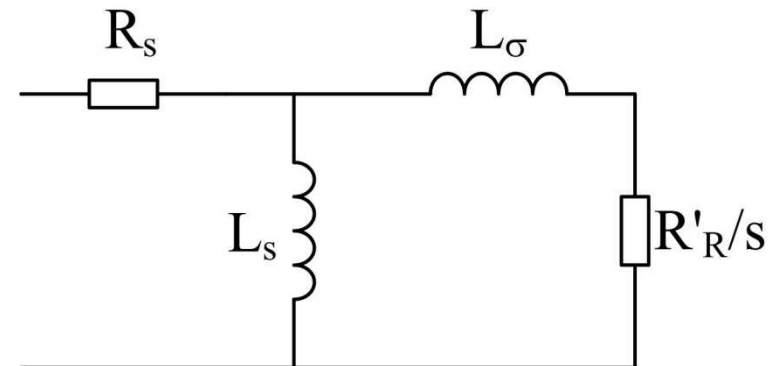
$$P_{mech} = (1-s)P_{ag}$$

$$P_2 : P_{mech} : P_{ag} = s : (1-s) : 1$$



Torque-speed characteristic per phase

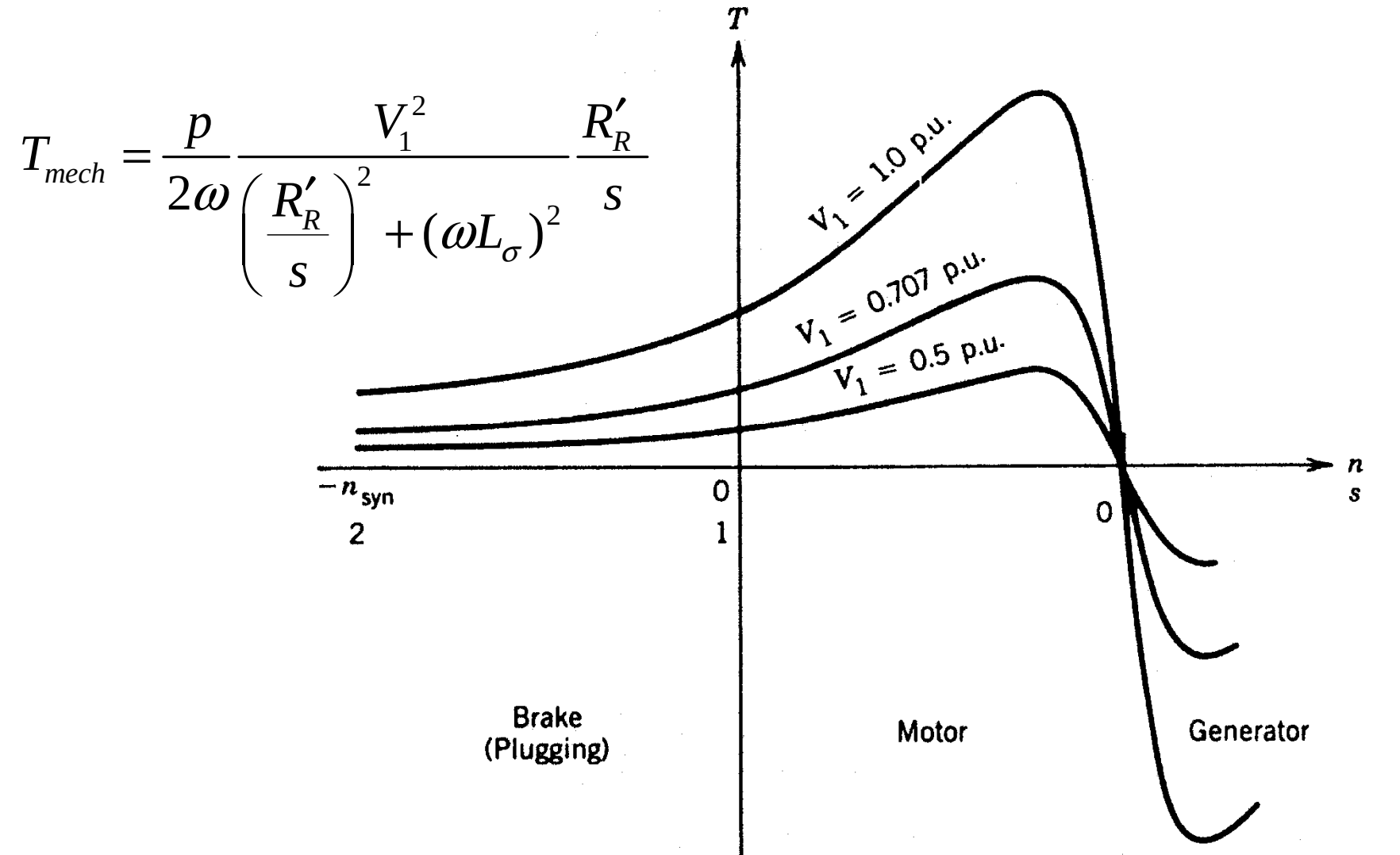
$$\left. \begin{aligned} P_{mech} &= (1-s)P_{ag} = \frac{(1-s)}{s} R'_R I_R'^2 \\ P_{mech} &= \omega_m T_{mech} = \frac{2}{p} (1-s) \omega T_{mech} \end{aligned} \right\} T_{mech} = \frac{p}{2} \frac{R'_R I_R'^2}{s\omega} = \frac{p}{2\omega} P_{ag}$$



assuming $R_1 = 0$

$$T_{mech} = \frac{p}{2} \frac{R'_R I_R'^2}{s\omega} = \frac{p}{2\omega} \frac{V_1^2}{\left(\frac{R'_R}{s}\right)^2 + (\omega L_\sigma)^2} \frac{R'_R}{s}$$

Torque speed characteristic



Torque-speed characteristic per phase

At low values of the slip $\frac{R'_R}{s} \gg \omega L_\sigma$

$$T_{mech} = \frac{p}{2\omega} \frac{V_1^2}{\left(\frac{R'_R}{s}\right)^2 + (\omega L_\sigma)^2} \frac{R'_R}{s} \approx \frac{p}{2\omega} \frac{s}{R'_R} V_1^2$$

> Torque is proportional to the slip

At high values of the slip $\frac{R'_R}{s} \ll \omega L_\sigma$

$$T_{mech} = \frac{p}{2\omega} \frac{V_1^2}{\left(\frac{R'_R}{s}\right)^2 + (\omega L_\sigma)^2} \frac{R'_R}{s} \approx \frac{p}{2\omega} \frac{V_1^2}{(\omega L_\sigma)^2} \frac{R'_R}{s}$$

> Torque is inversely proportional to the slip

Maximum torque

$$\frac{dT}{ds} = 0 \quad s = \pm \frac{R'_R}{\omega L_\sigma}$$

proportional to R_R

$$T_{mech} = \pm \frac{p}{4\omega} \frac{V_1^2}{\omega L_\sigma}$$

independent of R_R

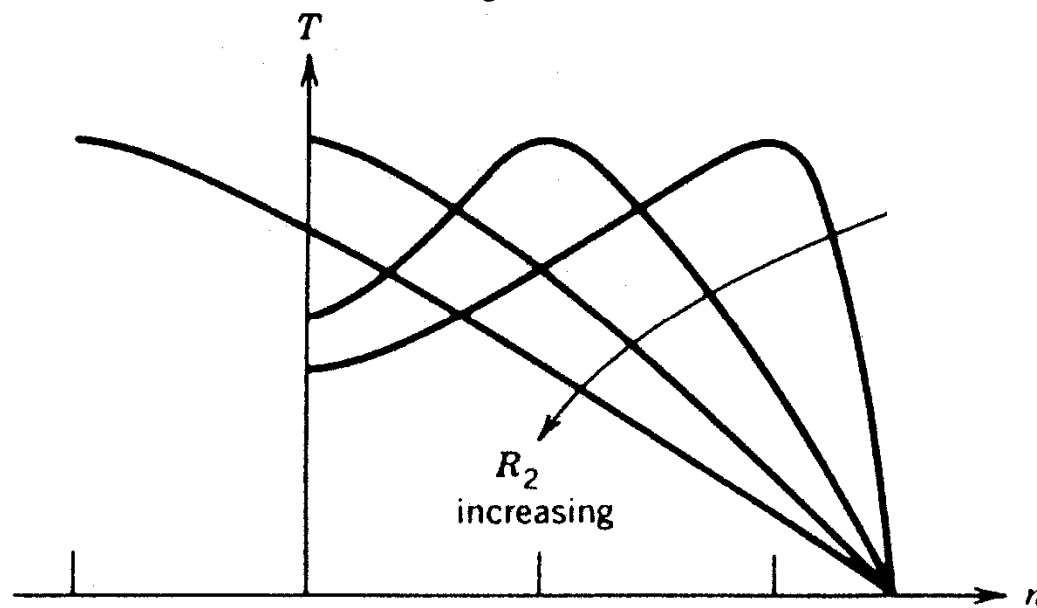


FIGURE 5.18 Torque–speed characteristics for varying R_2 .

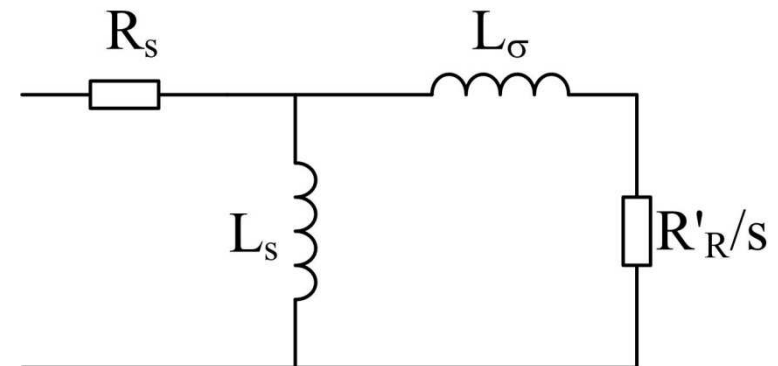
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Stator current

assuming $R_1 = 0$

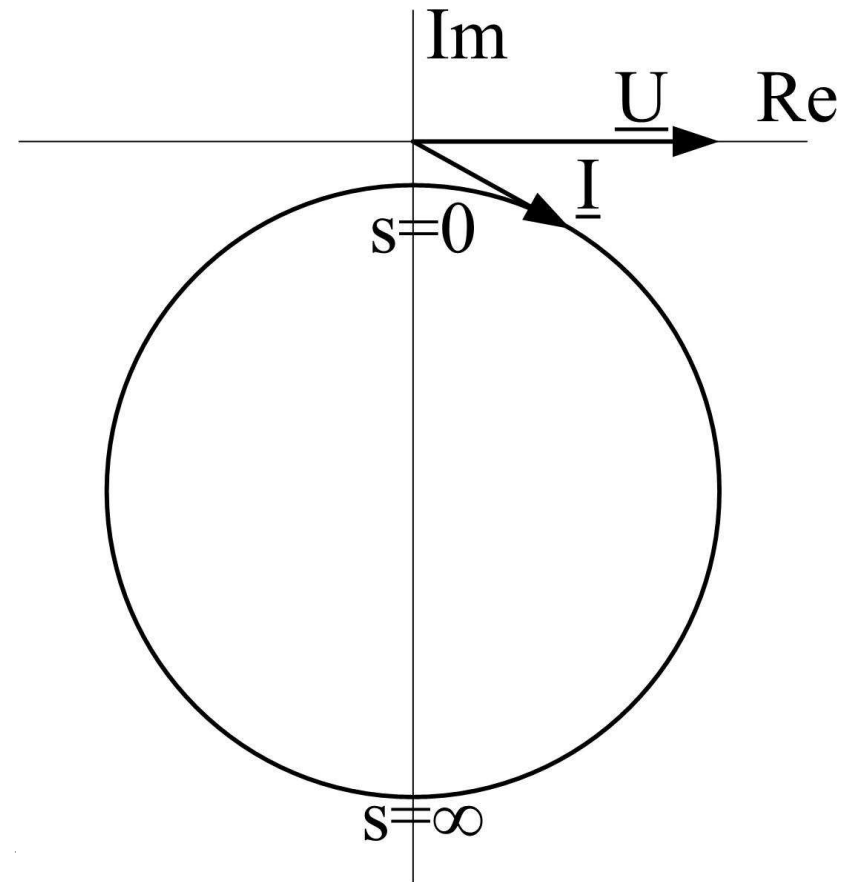
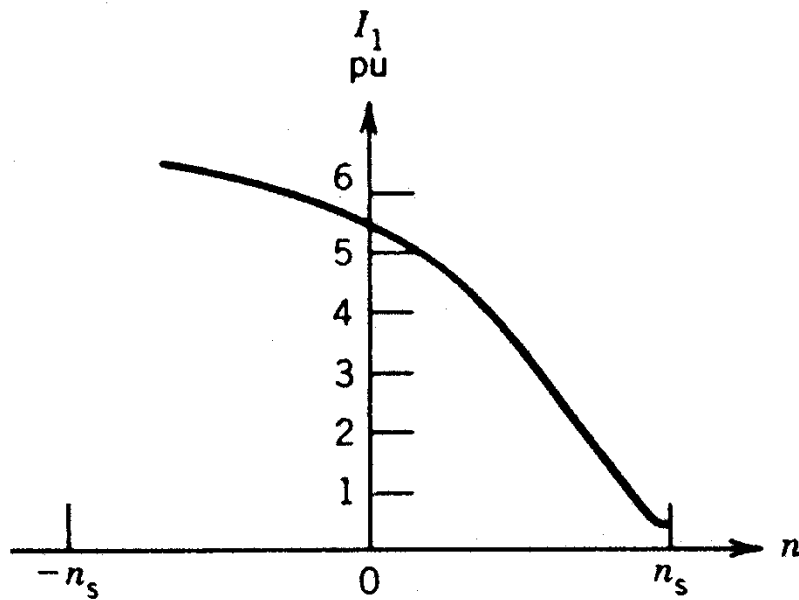
$$\underline{I} = \frac{\underline{U}}{j\omega L_s} + \frac{\underline{U}}{\frac{R'_R}{s} + j\omega L_\sigma}$$



- Calculate the current phasor for $s=0$
- Calculate the current phasor for $s=\infty$
- What is form of the trajectory of the stator current phasor?

Stator current: Heyland circle

$$\underline{I} = \frac{\underline{U}}{j\omega L_s} + \frac{\underline{U}}{\frac{R'_R}{s} + j\omega L_\sigma}$$



Power factor

- What is the power factor?

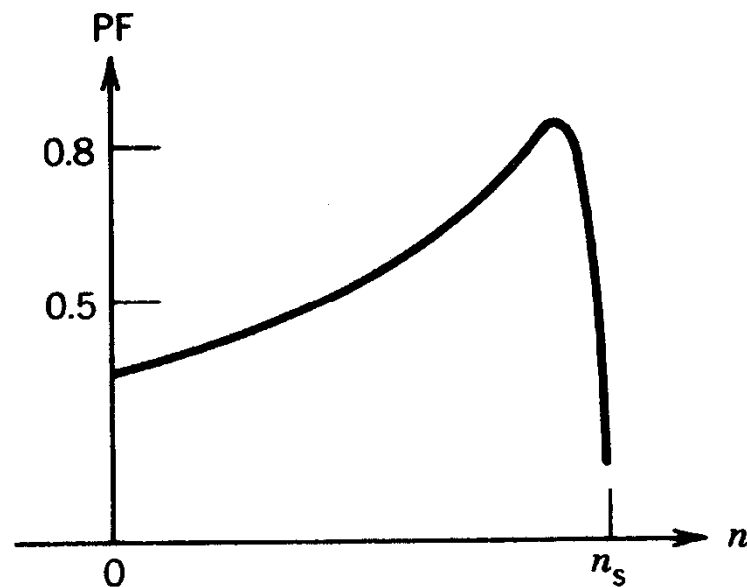


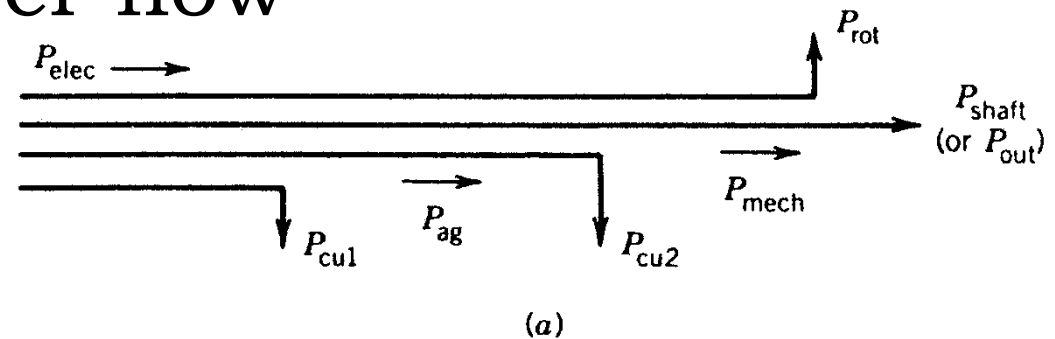
FIGURE 5.20 Power factor as a function of speed.

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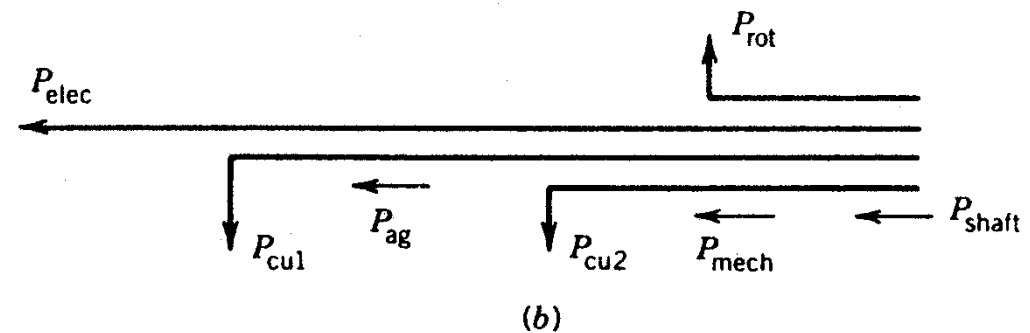
Efficiency: power flow

P_{rot} : core, friction and windage losses

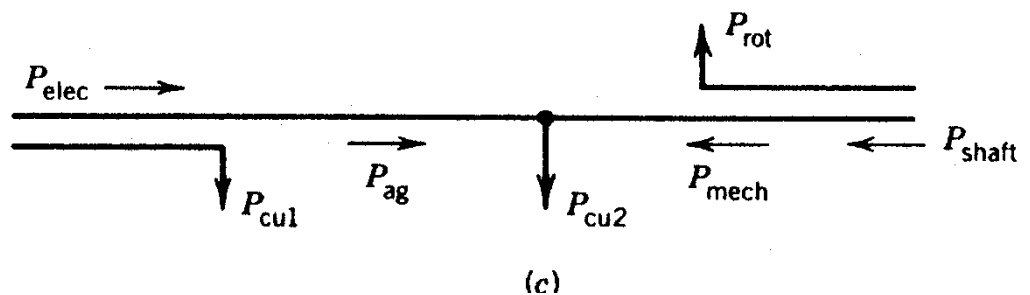


$$P_2 = sP_{ag} \quad P_{ag} = \frac{P_2}{s}$$

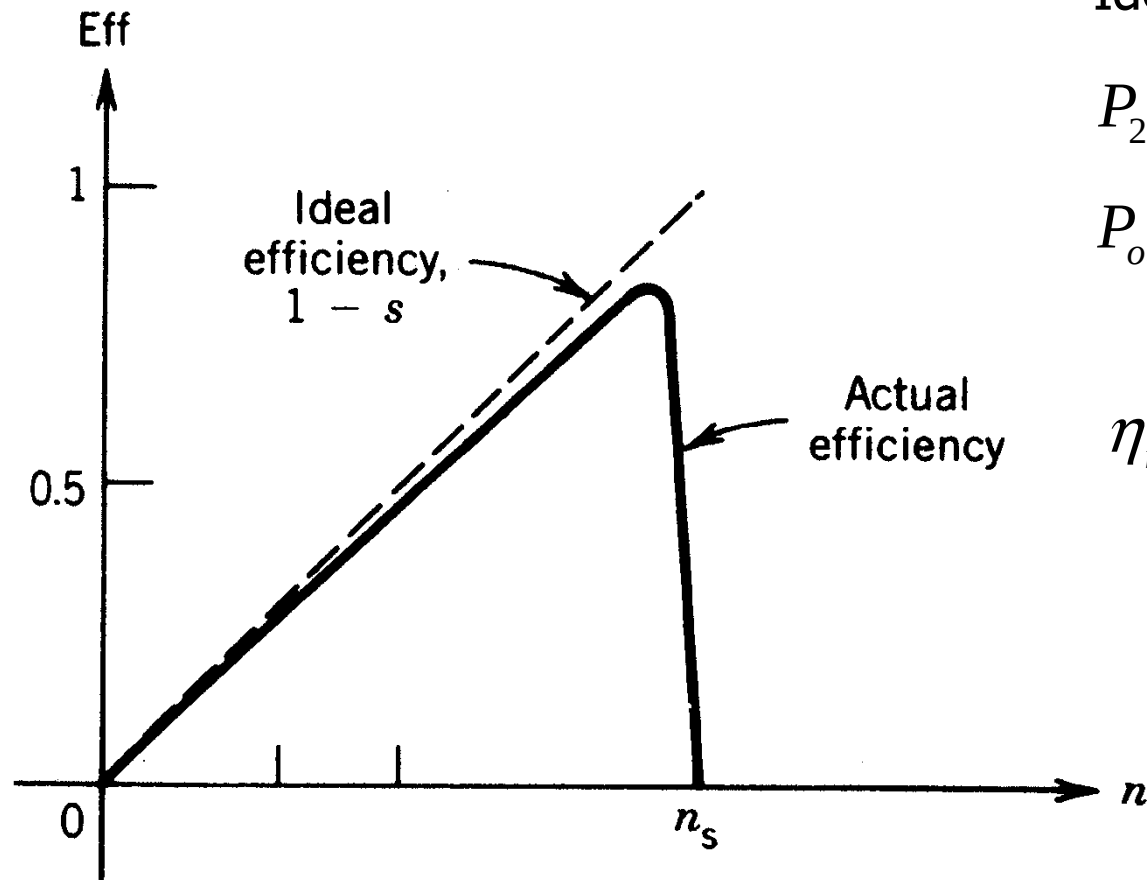
$$P_{mech} = (1-s)P_{ag}$$



	P_{ag}	P_{mech}
motor	+	+
generator	-	-
plugging	+	-



Efficiency



Ideal: $P_{in} = P_{ag}$

$$P_2 = sP_{ag}$$

$$P_{out} = P_{mech} = (1 - s)P_{ag}$$

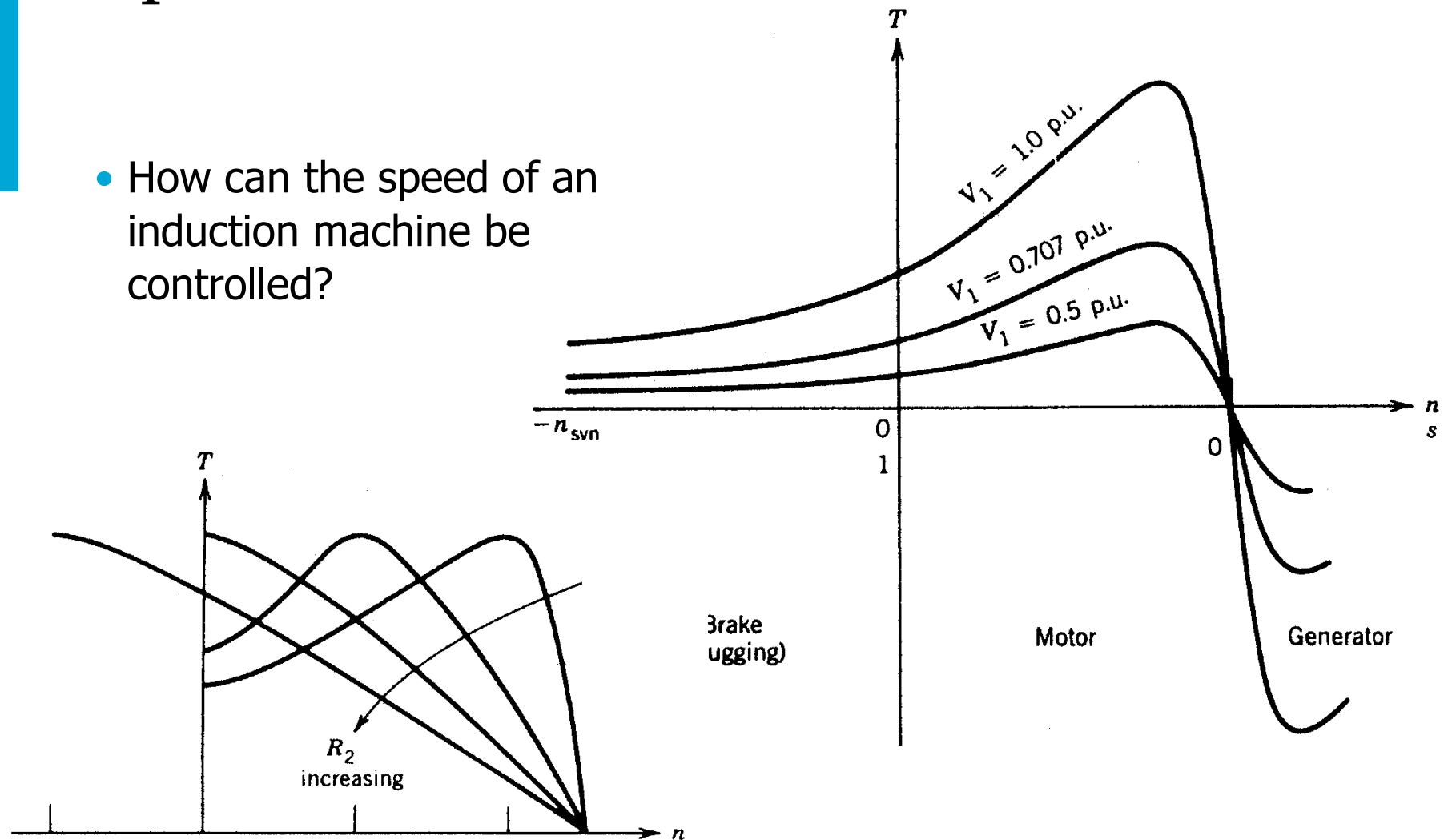
$$\eta_{ideal} = \frac{P_{out}}{P_{in}} = 1 - s$$

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Speed control

- How can the speed of an induction machine be controlled?

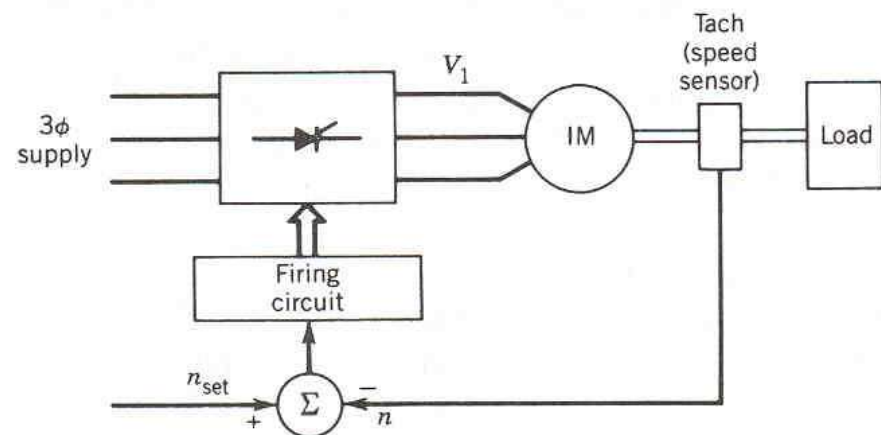
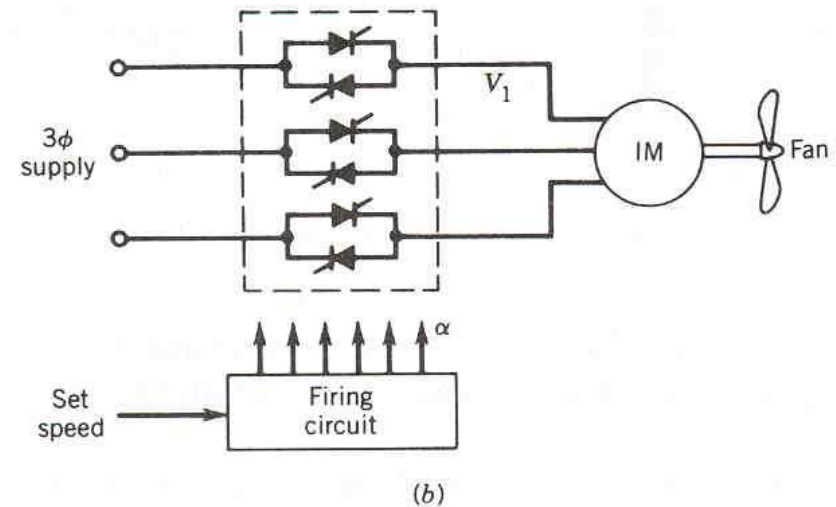
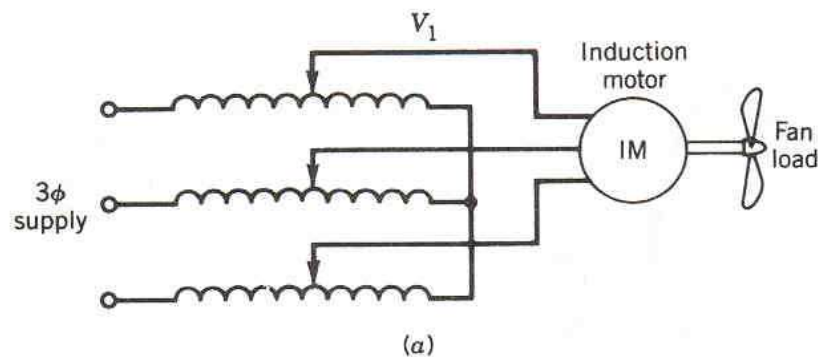


Speed control

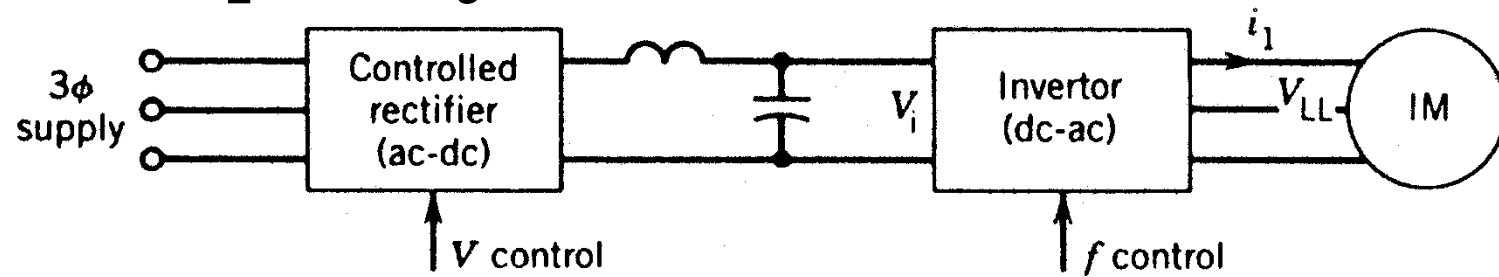
- Old:
 - pole changing
 - line voltage control
 - rotor resistance control
- State-of-the-art:
 - line frequency control
 - rotor slip energy recovery
- Realized by means of
 - Voltage source inverter (VSI)
 - Current source inverter (CSI) not discussed
- Replaces dc motor drives

Line voltage control / soft starter

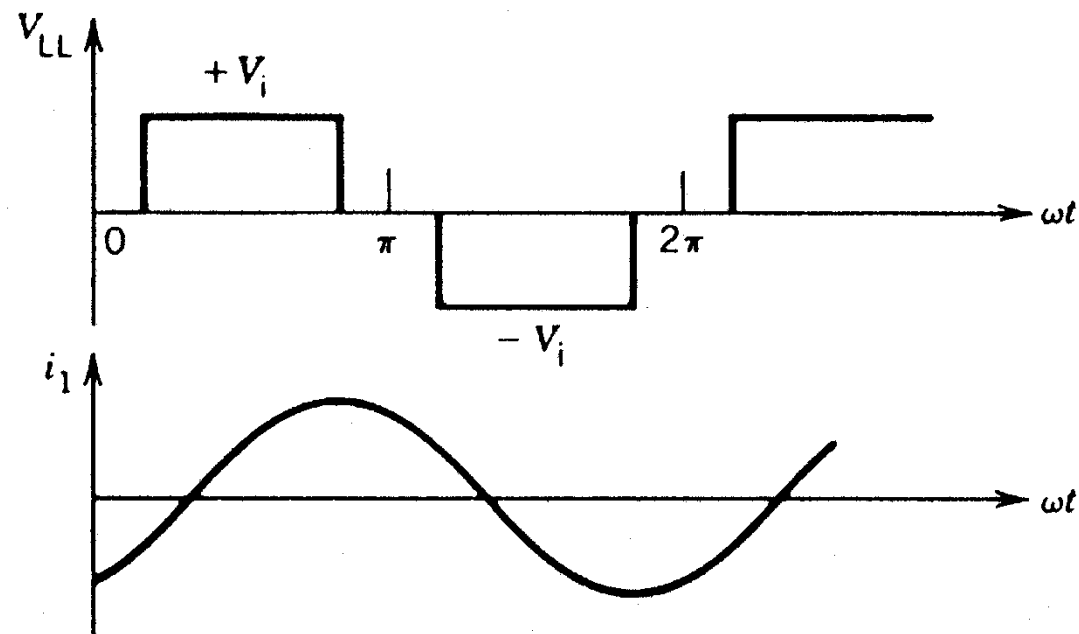
- To limit inrush currents



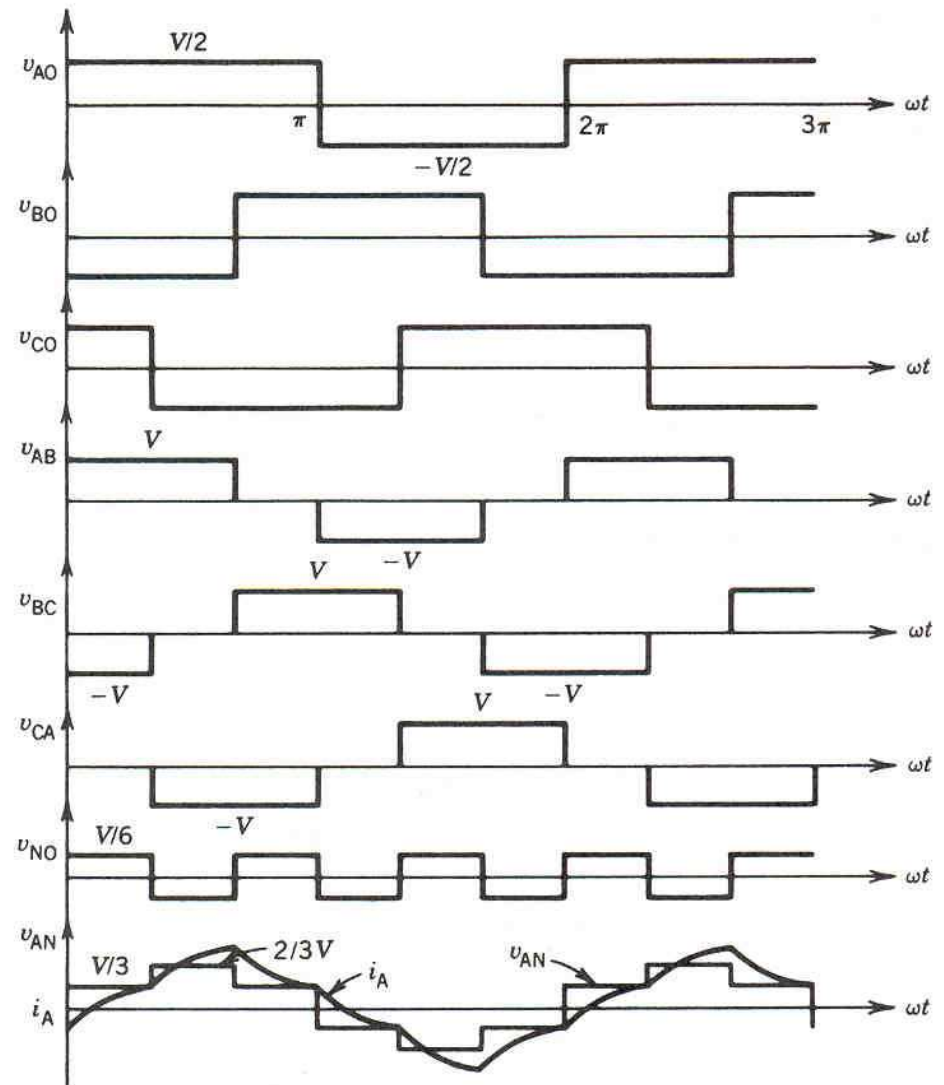
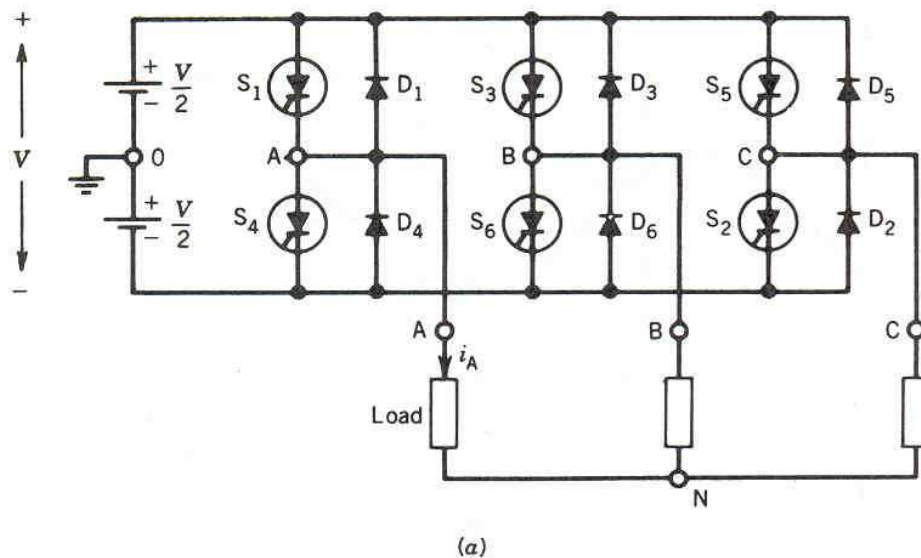
Line frequency control



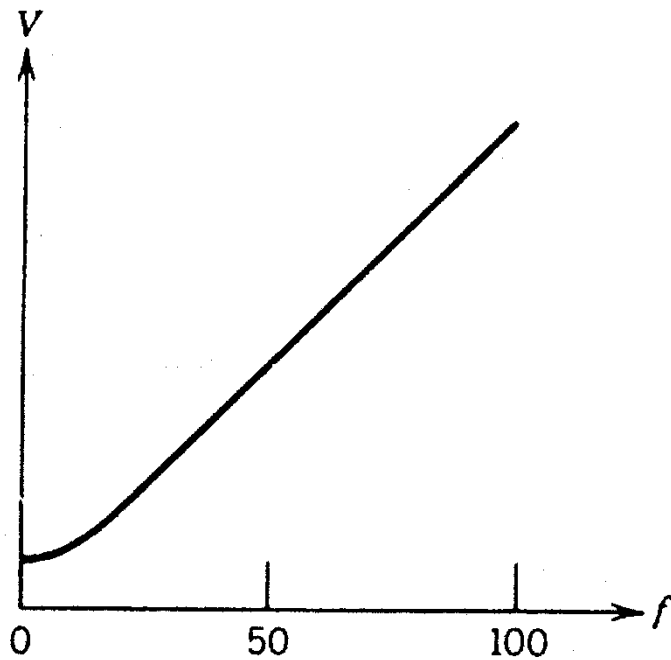
(a)



Line frequency control



Voltage as a function of frequency

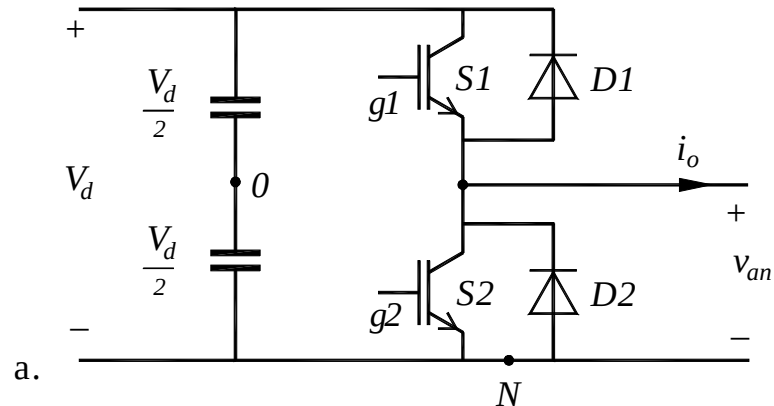


$$E = \sqrt{2}k_w\pi fN\Phi_p$$

Can be realized with

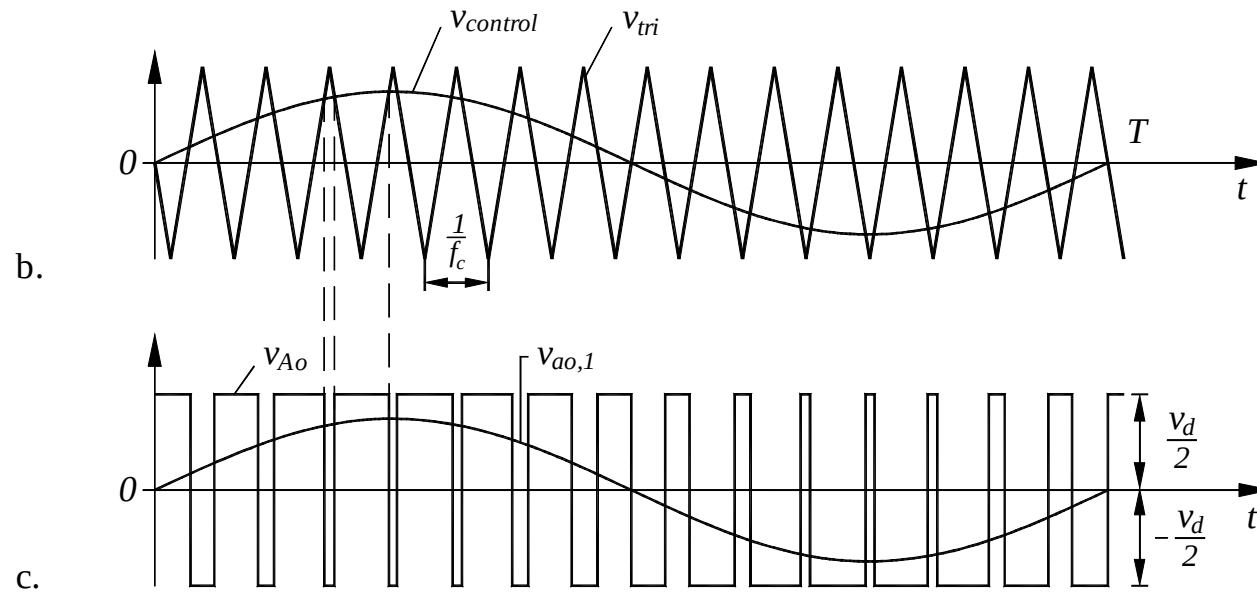
- controlled rectifier
- PWM

Principle of voltage source converter



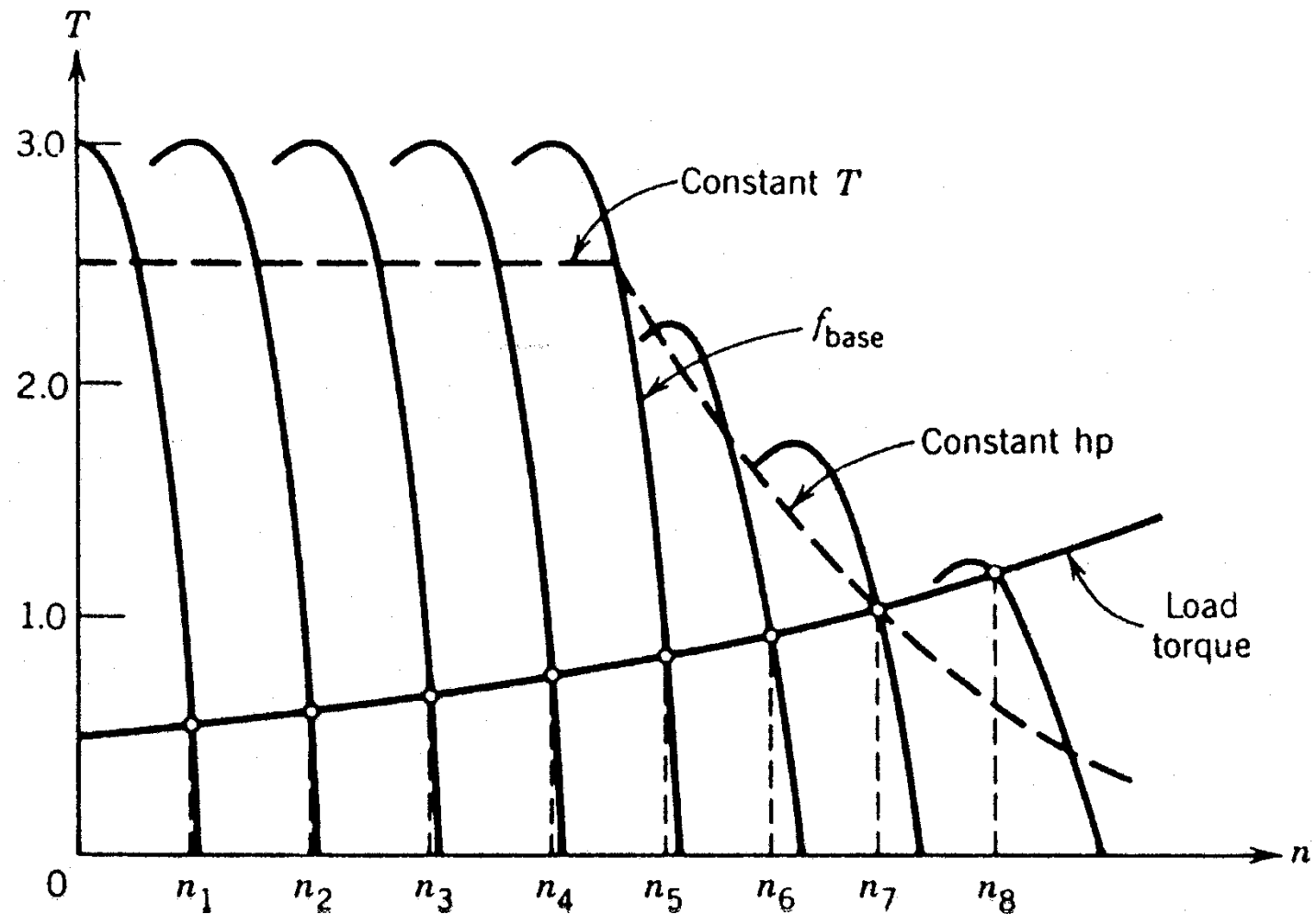
Phase leg of
Voltage Source Converter

=
Basic building block of
modern power electronics

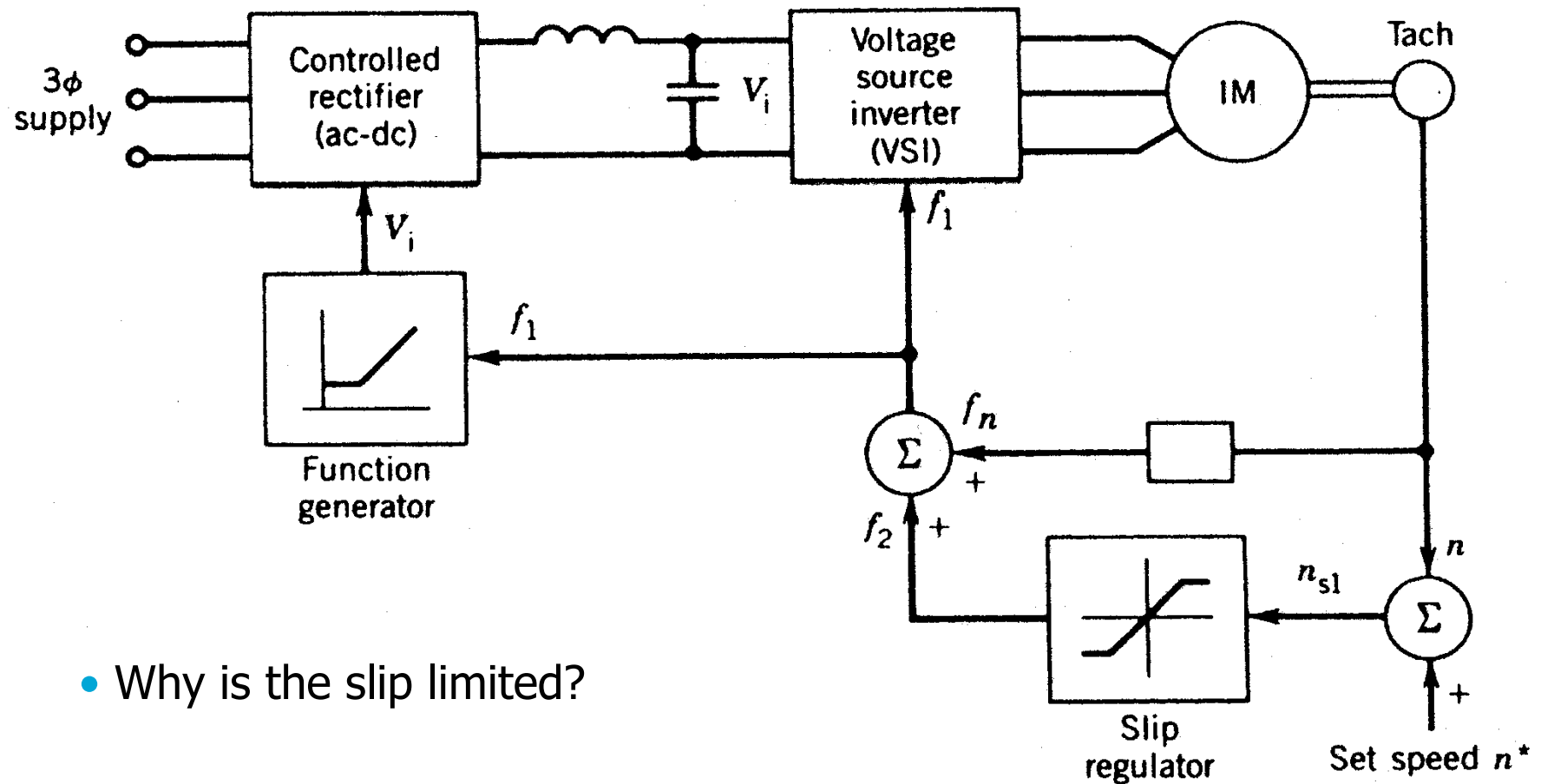


Average output
voltage is a
replica of v_{control}

Field weakening above base speed



Closed loop speed control

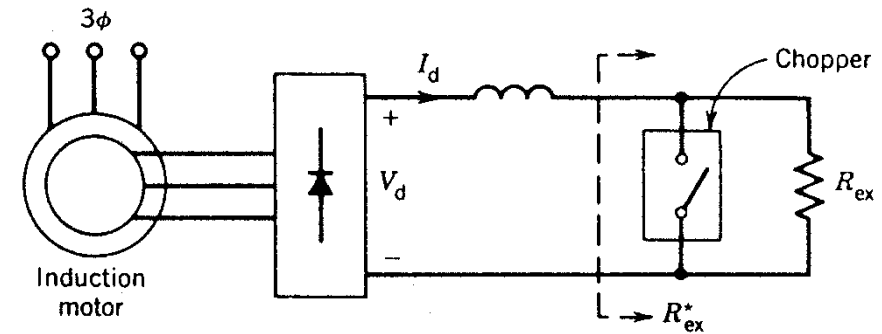
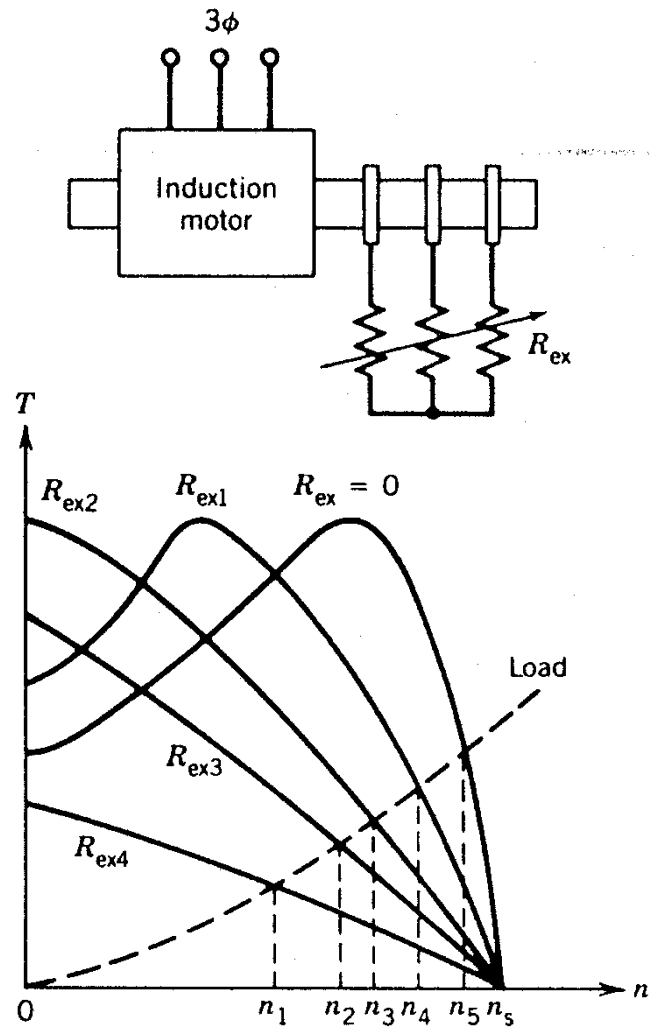


- Why is the slip limited?

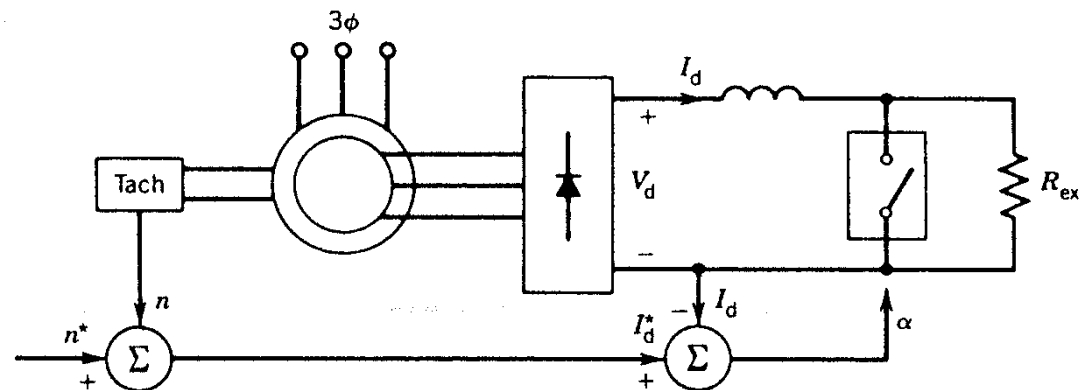
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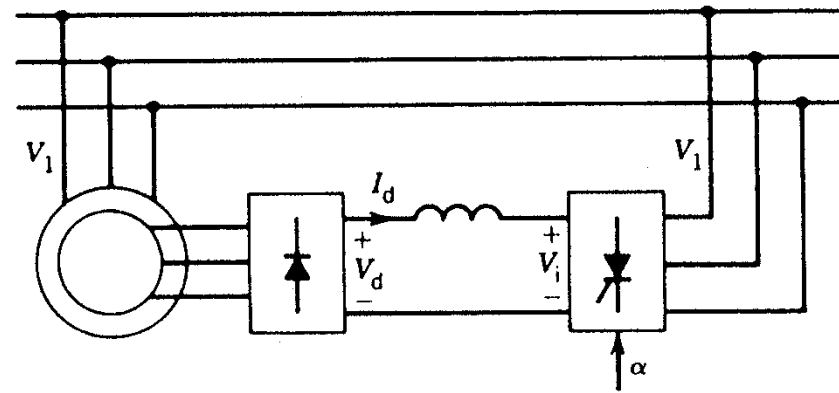
Rotor resistance control



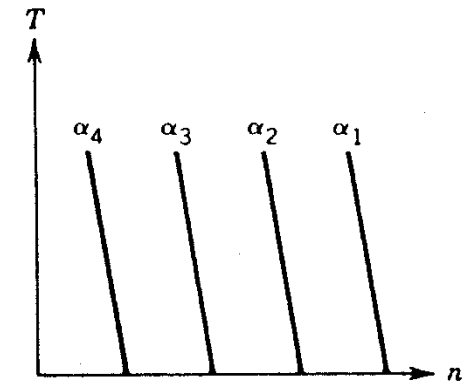
(c)



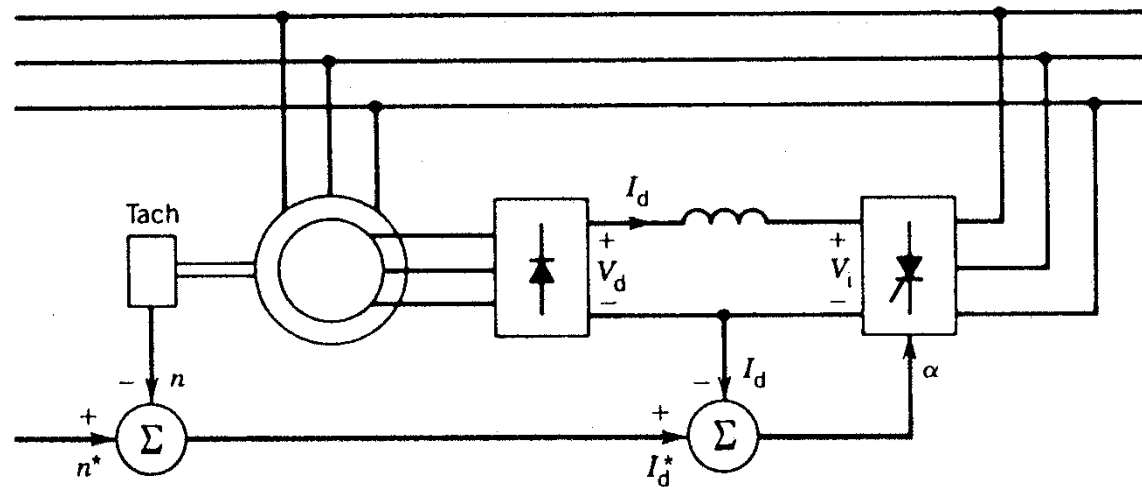
Slip energy recovery



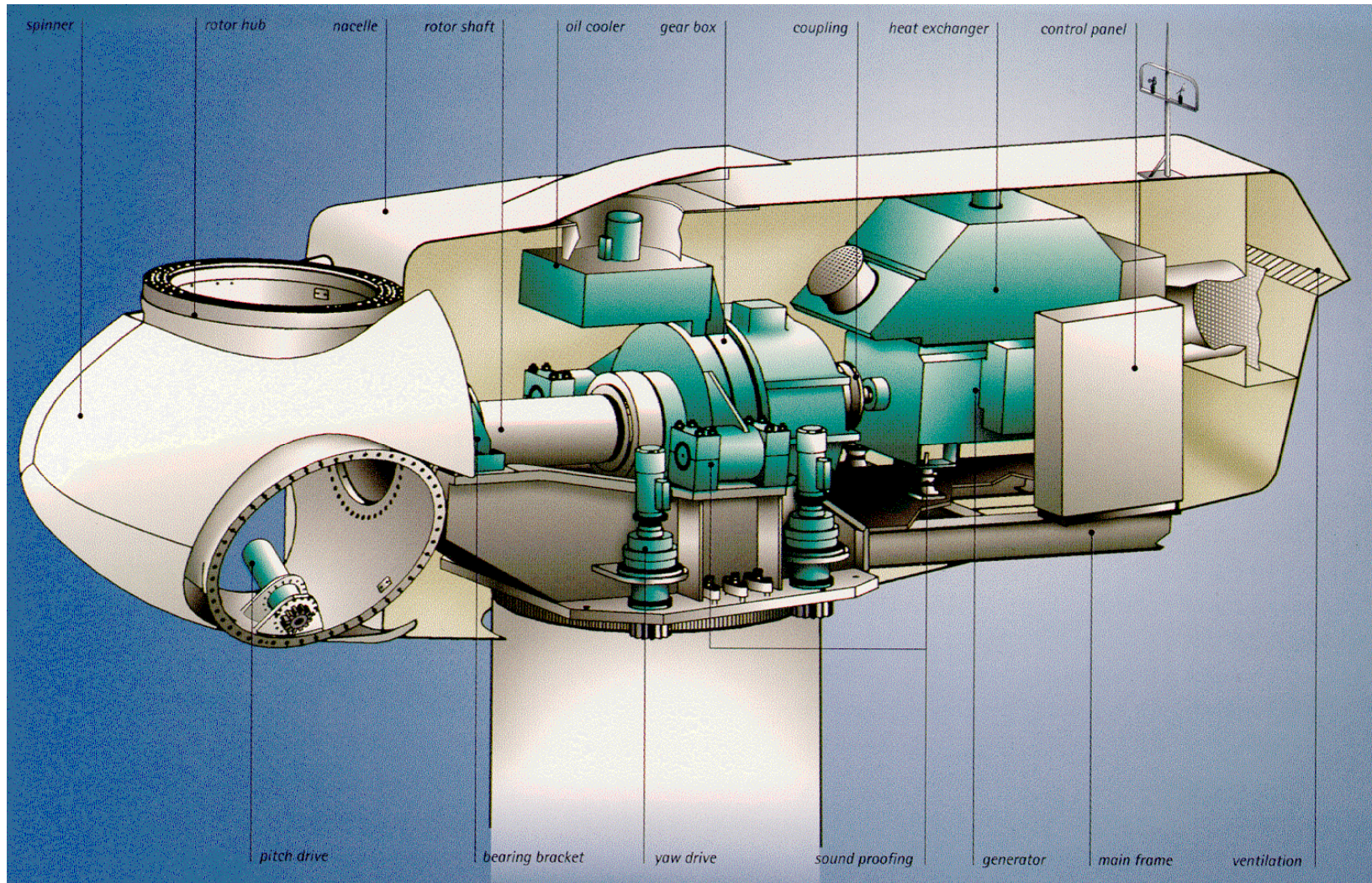
(a)



(b)

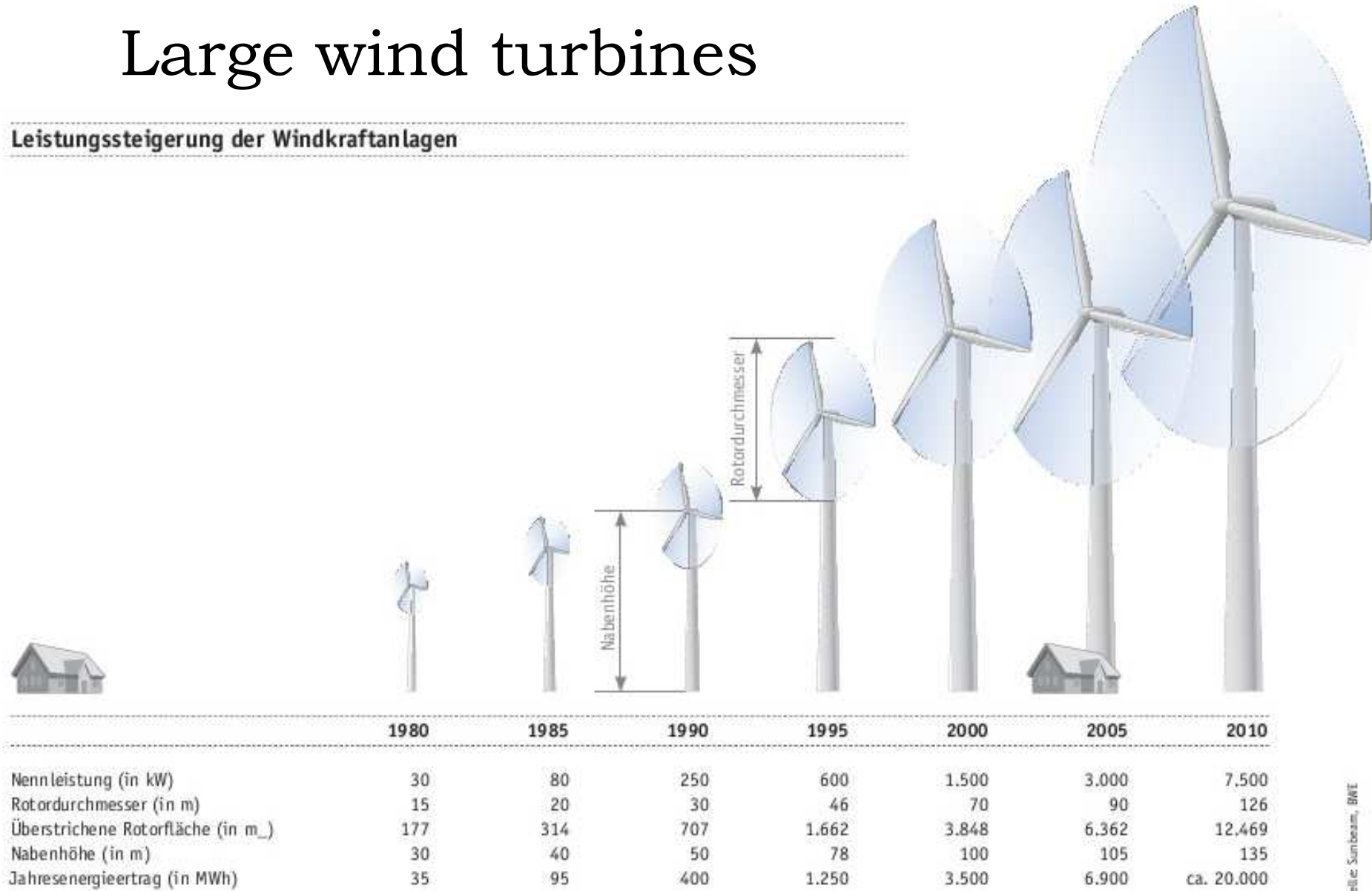


Doubly fed induction generator



Large wind turbines

Leistungssteigerung der Windkraftanlagen



Example large wind turbine

REpower

- 5 MW
- 12 rpm
- 126 m rotor diameter
- 100 m tower

Source: REpower Systems AG, photo: Jan Oelker.



Wind power stations: Horns Rev

80 x 2 MW

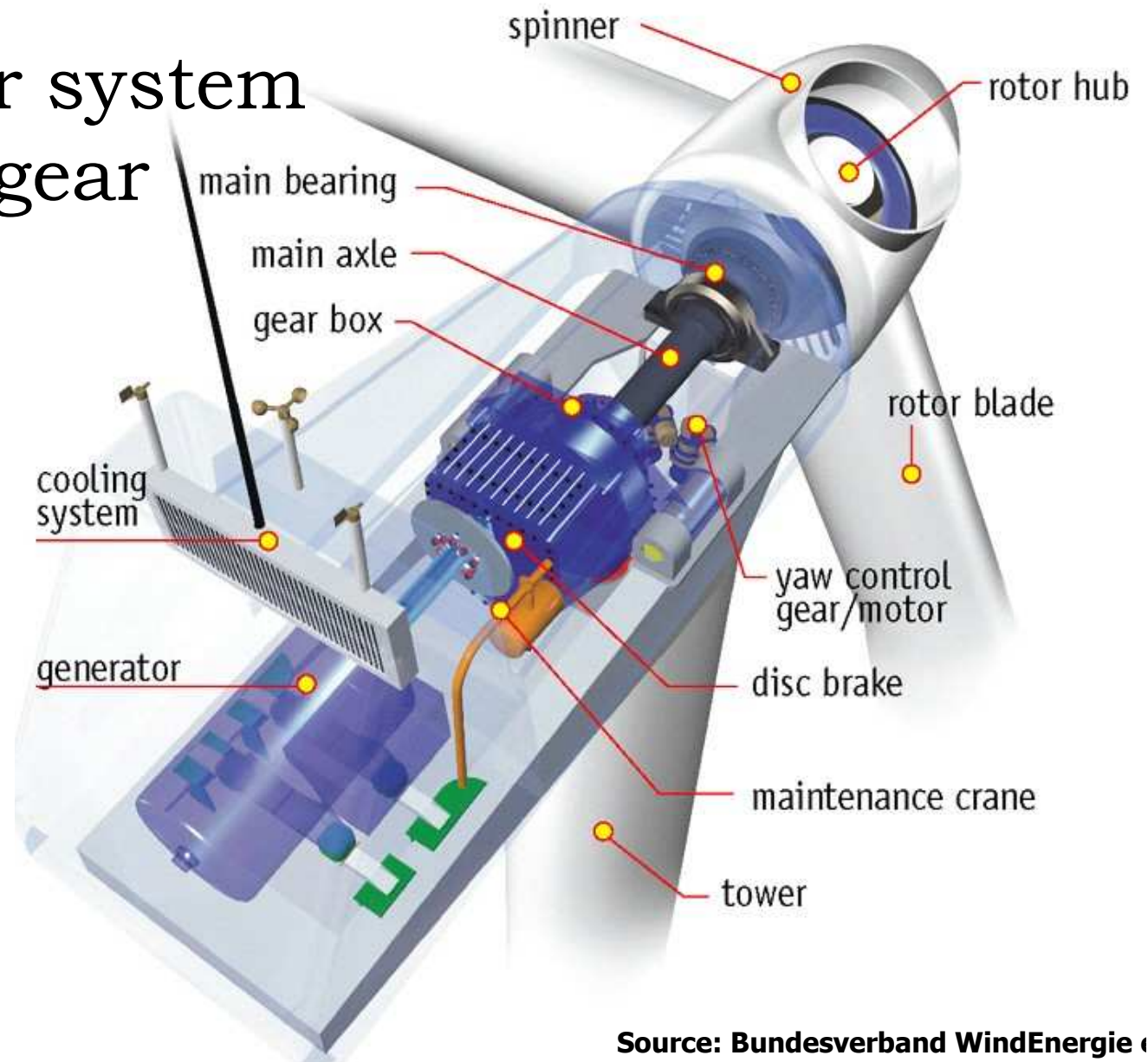


Horns Rev construction



Generator system with gear

NEG Micon



Source: Bundesverband WindEnergie e.V.

DFIG system

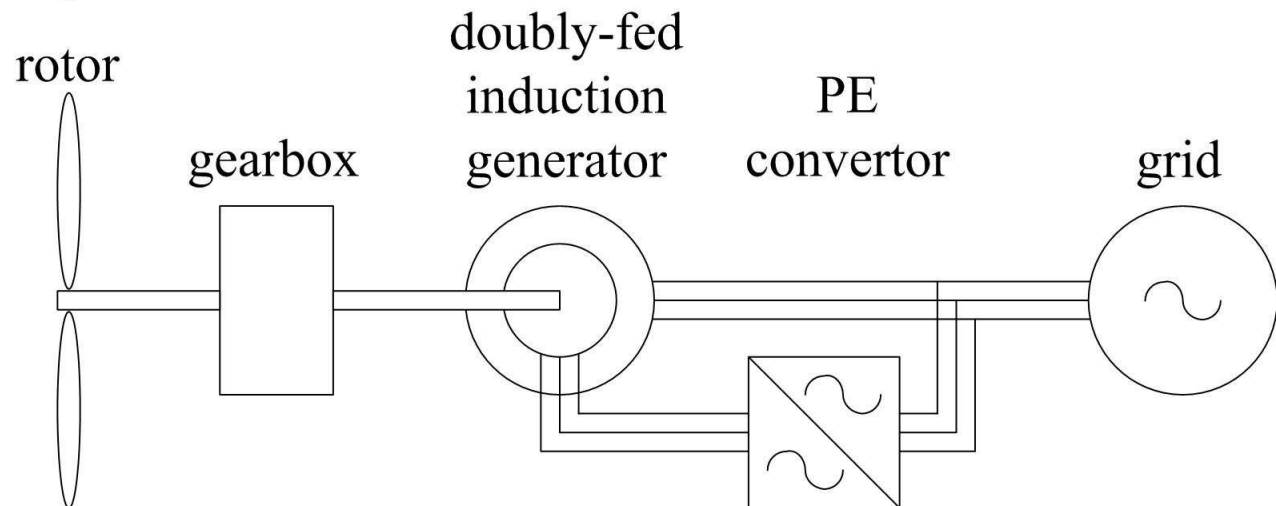
Works as a generator both below and above synchronous speed.

What is the direction of the energy flow in generator operation

- Above synchronous speed?
- Below synchronous speed?

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Linear induction machines

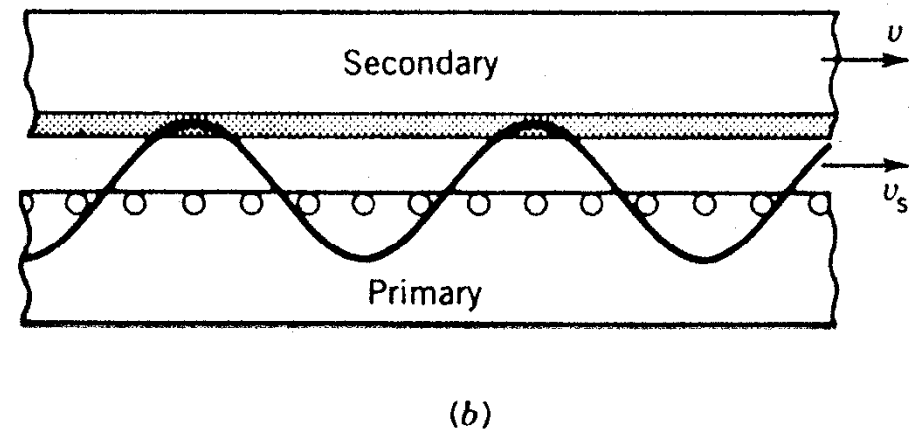
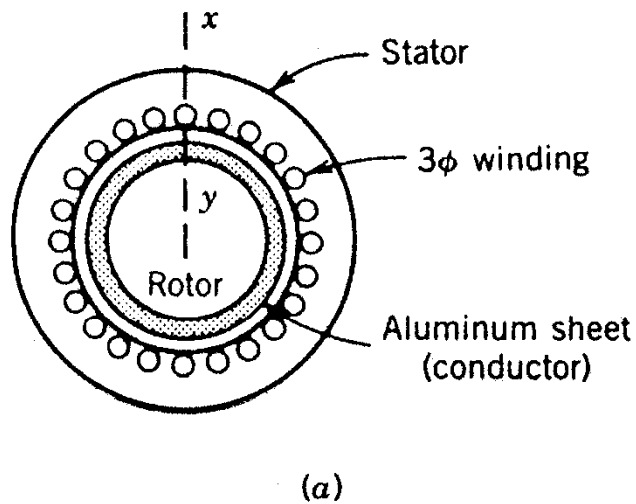


FIGURE 5.45 Induction motors. (a) Rotary induction motor. (b) Linear induction motor (LIM).

Linear induction machines

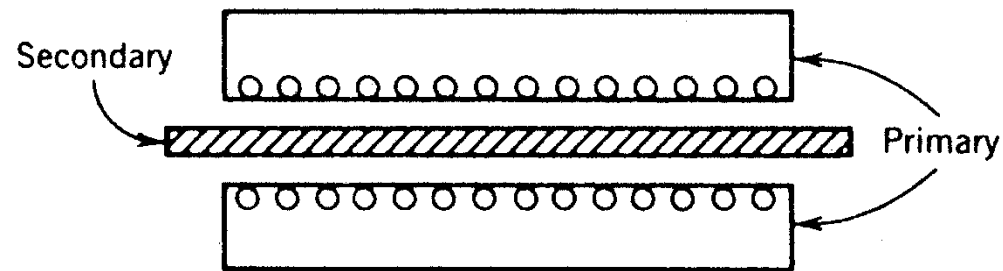


FIGURE 5.47 Double-sided LIM (DLIM).

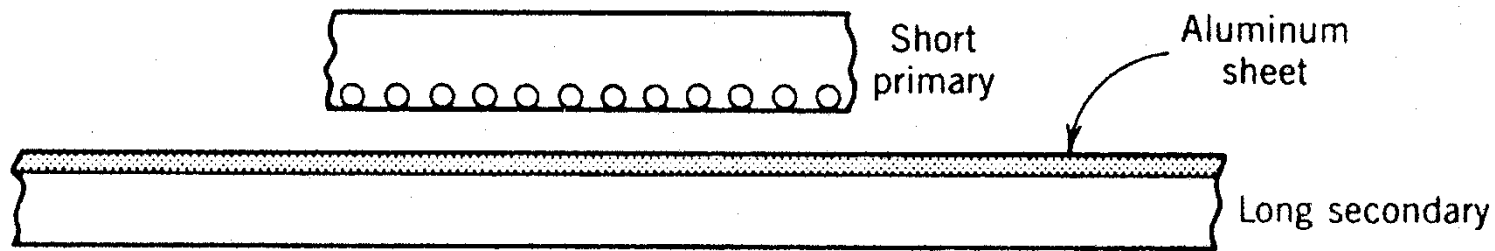
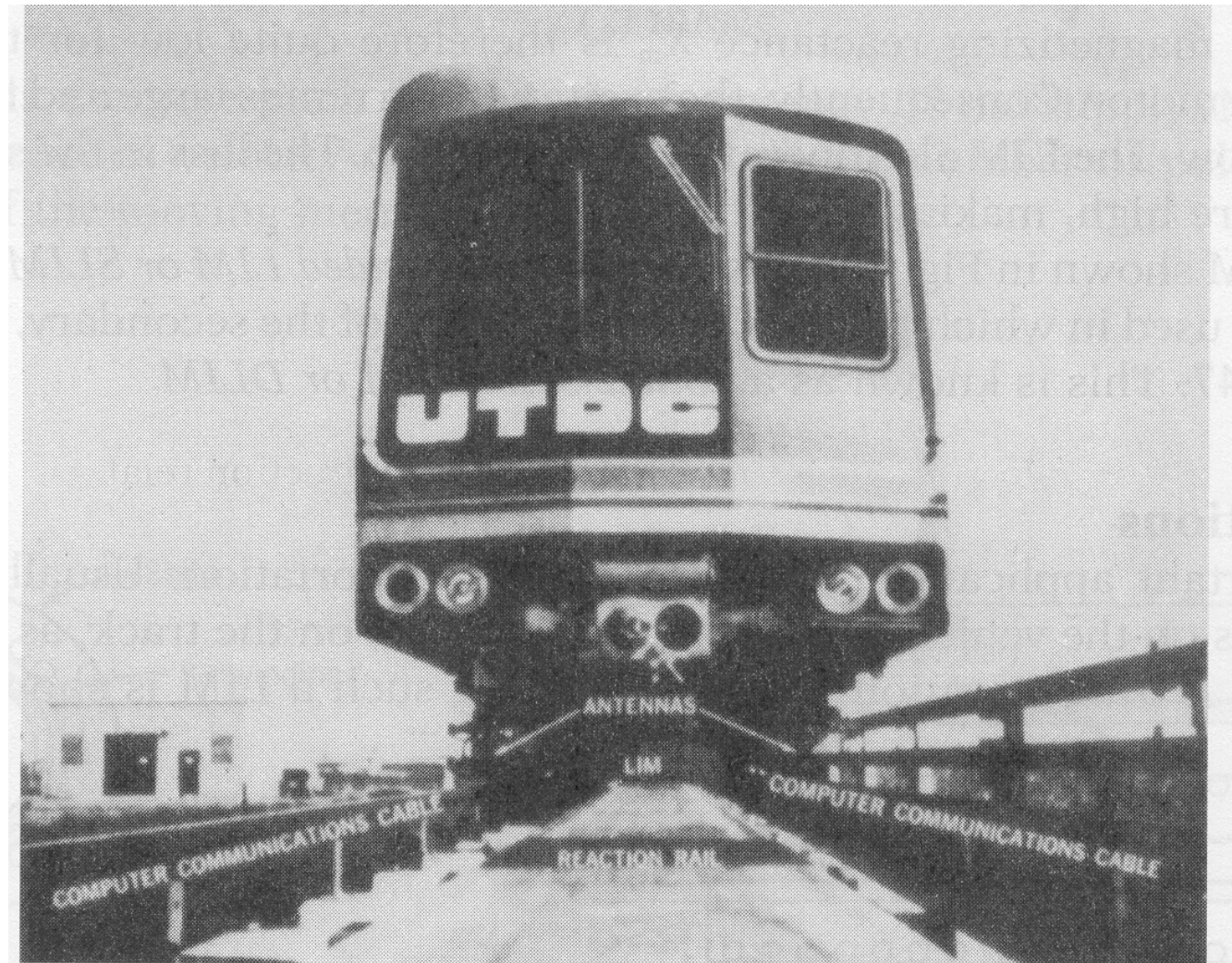


FIGURE 5.48 LIM for a vehicle.

Traction application LIM



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