Overview Electrical Machines and Drives

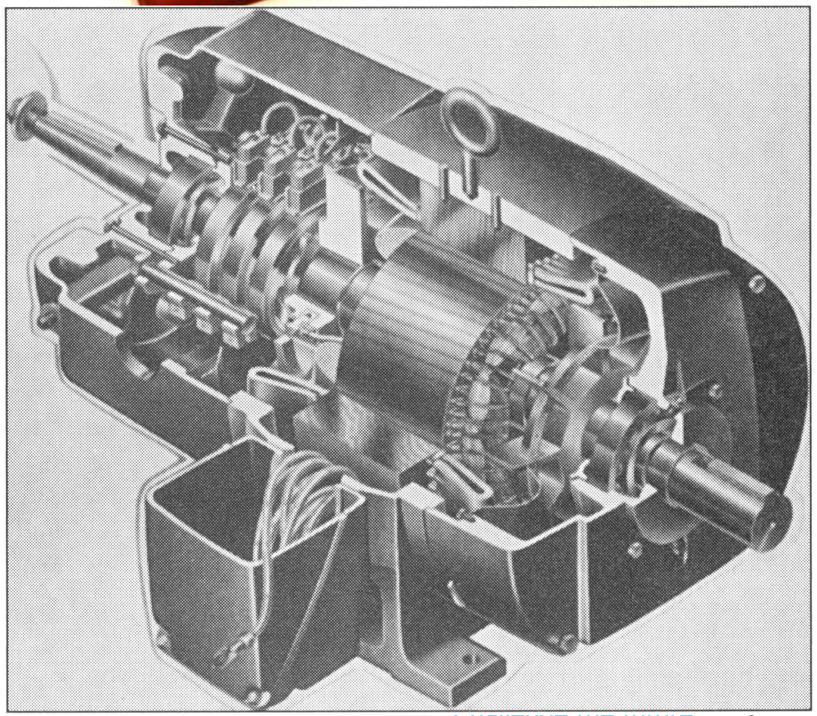
- 7-9 1: Introduction, Maxwell's equations, magnetic circuits
- 11-9 1.2-3: Magnetic circuits, Principles
- 14-9 3-4.2: Principles, DC machines
- 18-9 4.3-4.7: DC machines and drives
- 21-9 5.2-5.6: IM introduction, IM principles
- 25-9 Guest lecture Emile Brink
- 28-9 5.8-5.10: IM equivalent circuits 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?
- Induced voltage (5.3, also for SM)
- Definitions (5.4, 5.5)
- Equivalent circuits and voltage equations (5.7)
- Parameter identification (5.8)
- Performance characteristics (5.9)
- Power flow in three modes of operation (5.10)
- Speed control (5.13)
- Linear induction motors (5.16)

Recapitulation

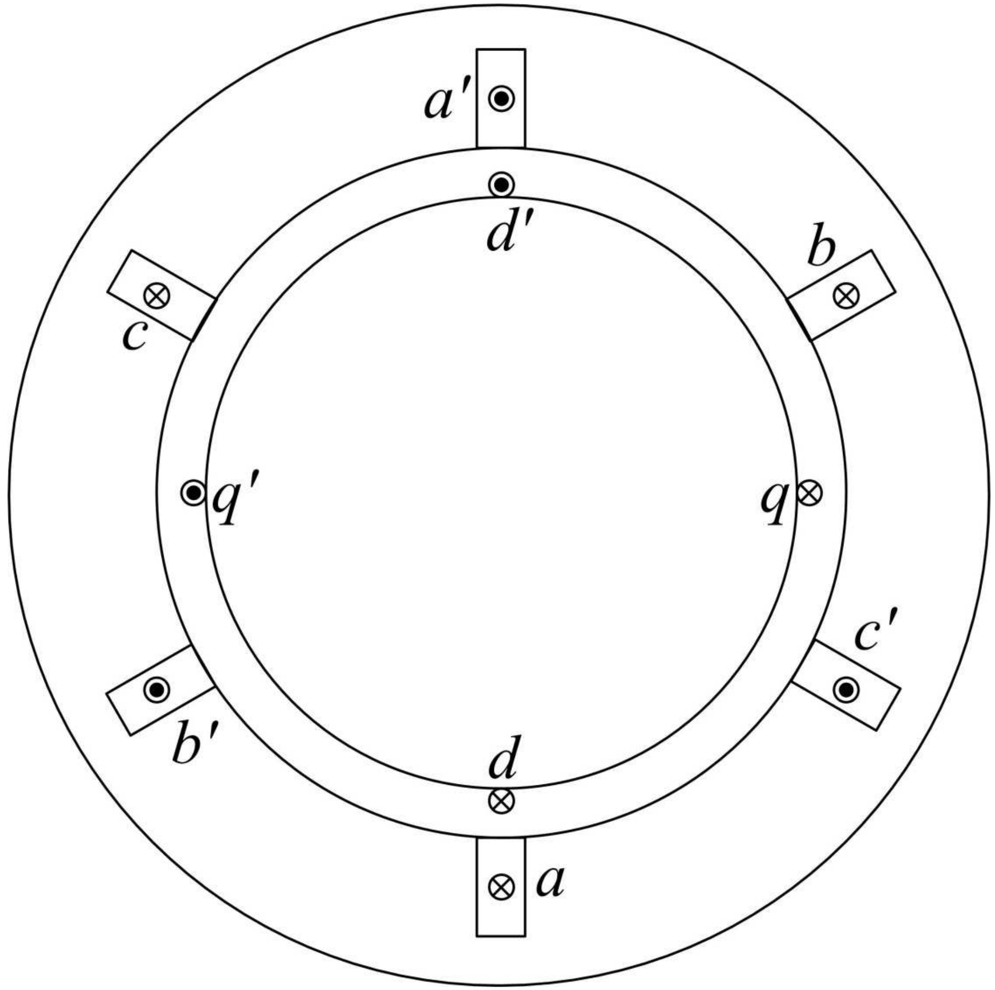
- Why is the induction machine the workhorse of industry?
- How does the stator of an induction machine create a rotating magnetic field?
- Why does the induction machine develop torque?



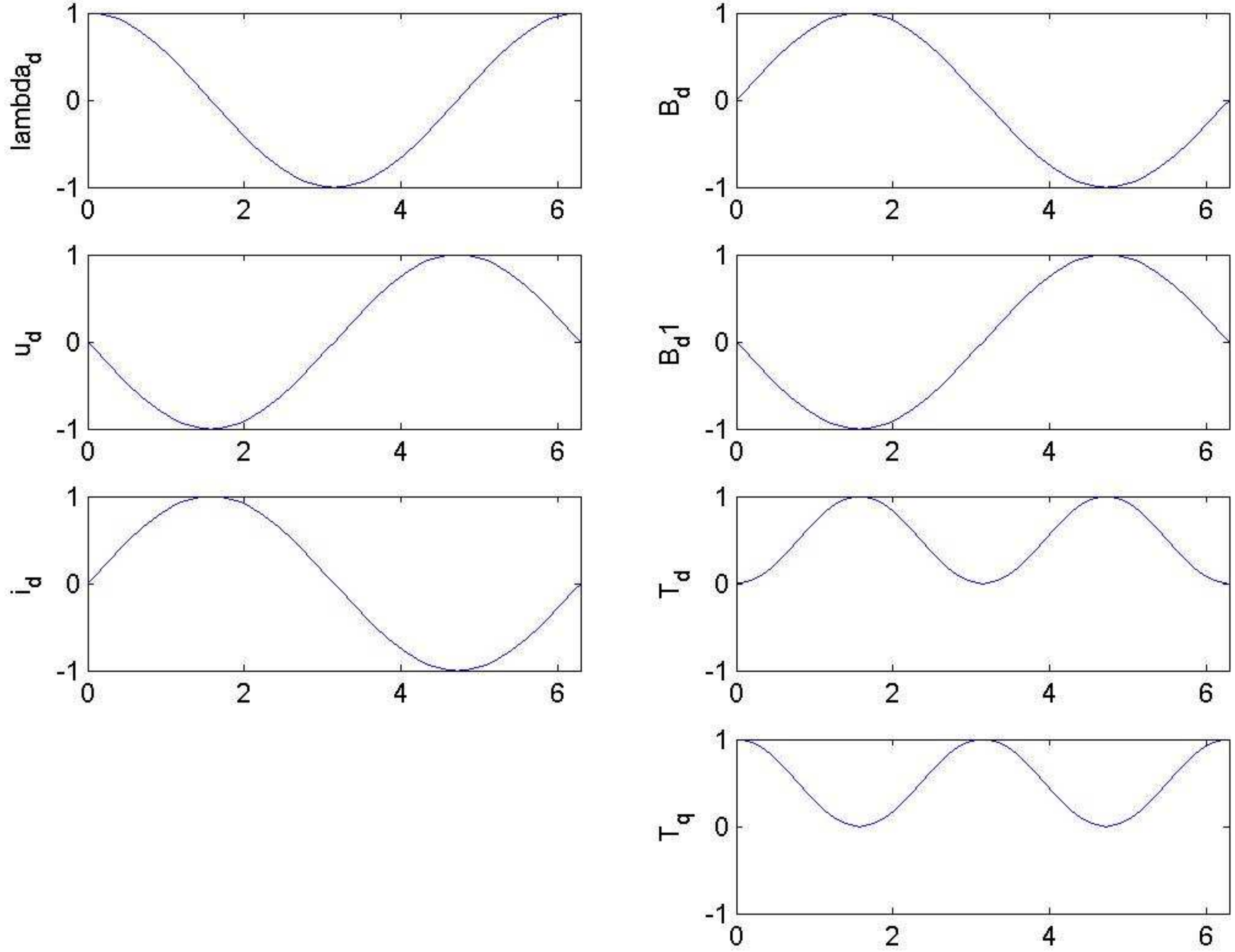
Why does an IM work?

$$B_s(\theta,t) = \hat{B}\cos(\theta - \omega t)$$

1 Sketch the flux linkage of *dd′*.
2 Sketch induced voltage in *dd′*.
The rotor turns *dd′* and *qq′* are short-circuited via a large resistance R_r.
3 Sketch the current through *dd′*.
4 Sketch the flux density at the location of *d′* $B(\pi/2,t)$.
5 Sketch the flux density at the location of *d′* $B(3\pi/2,t)$.
6 Sketch the torque on *dd′*.
7 Sketch the torque on *qq′* in the same way.



Results



Conclusions

- constant torque with two turns
- at synchronous speed: no torque
- torque proportional to rotor frequency (slip frequency) if the effect of the rotor currents on the field is negligible

Induction machines

- Introduction (5.1)
- Rotating magnetic field (5.2, also for SM)
- Why does an induction machine rotate?
- Induced voltage (5.3, also for SM)
- Definitions (5.4, 5.5)
- Equivalent circuits and voltage equations (5.7)
- Parameter identification (5.8)
- Performance characteristics (5.9)
- Power flow in three modes of operation (5.10)
- Speed control (5.13)
- Linear induction motors (5.16)

Induced voltage (also for SM)

- Air gap flux density: $B_s(\theta,t) = \hat{B}\cos(\theta - \omega t)$
- Maximum air gap flux per pole (t =0):

$$\Phi_p = \iint \vec{B}\cdot\vec{n}\,\mathrm{d}A = \int_{-\pi/2}^{\pi/2} \hat{B}\cos(\theta - \omega t) lr\,\mathrm{d}\theta = 2lr\hat{B}$$

- Flux linkage of phase a if phase is a concentrated full-pitch winding with N turns: $\lambda_a = N\Phi_p\cos(\omega t)$
- Induced voltage: $e_a = \dfrac{\mathrm{d}\lambda_a}{\mathrm{d}t} = -\omega N\Phi_p\sin(\omega t)$
- In equation (5.23), a minus is inserted

Induced voltage and winding factor

$$\begin{cases} e_a = -\omega N\Phi_p \sin(\omega t) \\ e_b = -\omega N\Phi_p \sin(\omega t - \tfrac{2}{3}\pi) \\ e_c = -\omega N\Phi_p \sin(\omega t - \tfrac{4}{3}\pi) \end{cases}$$

$$E = \frac{\omega N\Phi_p}{\sqrt{2}} = \sqrt{2}\pi f N\Phi_p = 4.44\, fN\Phi_p$$

A phase winding is generally not a concentrated full-pitch winding, but a distributed winding.
Therefore, the voltages induced in the different turns are not in phase and the resulting induced voltage is lower.
This is taken into account by including the winding factor.

$$E = \sqrt{2}k_w \pi f N\Phi_p$$

Induction machines

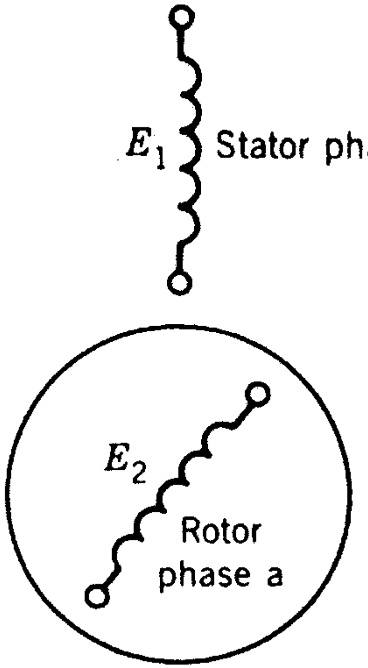
- Introduction (5.1)
- Rotating magnetic field (5.2, also for SM)
- Why does an induction machine rotate?
- Induced voltage (5.3, also for SM)
- Definitions (5.4, 5.5)
- Equivalent circuits and voltage equations (5.7)
- Parameter identification (5.8)
- Performance characteristics (5.9)
- Power flow in three modes of operation (5.10)
- Speed control (5.13)
- Linear induction motors (5.16)

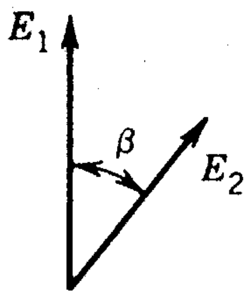
Standstill operation: transformer

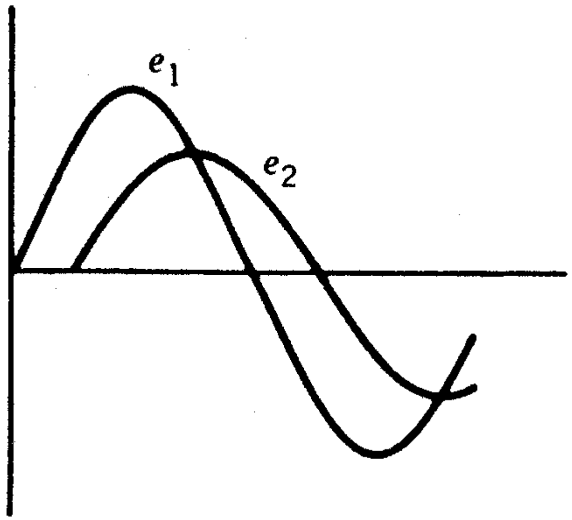
- A wound rotor induction machine with blocked rotor works as a transformer

$$E_1 = \sqrt{2} k_{w1} \pi f N_1 \Phi_p$$

$$E_2 = \sqrt{2} k_{w2} \pi f N_2 \Phi_p$$



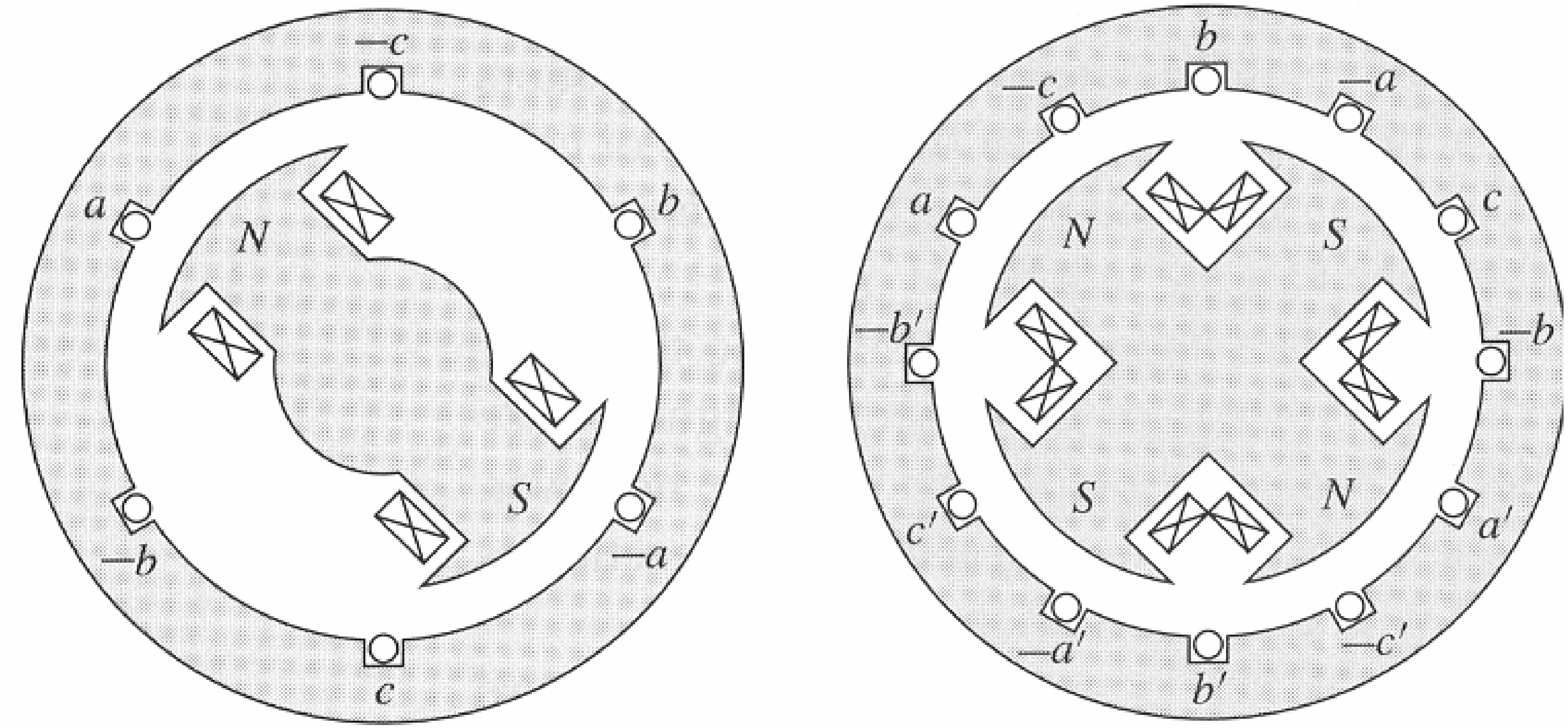




p-pole machines

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

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



Three-phase stator winding

Running operation

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

for f_1=50Hz

p	2	4	6	8	10	20
n_s (rpm)	3000	1500	1000	750	600	300

n is the actual speed of the rotor

s is the slip

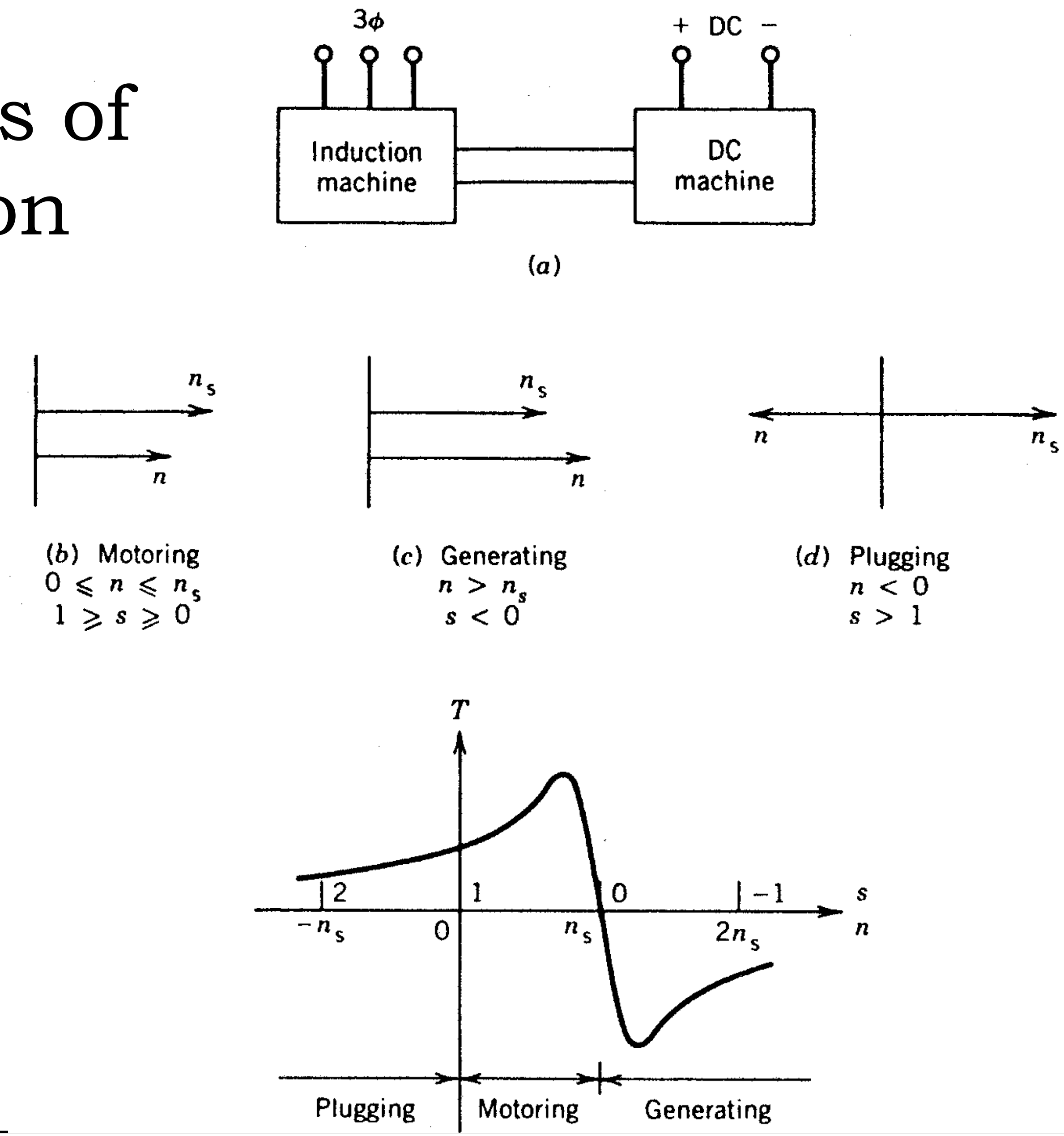
$$s = \frac{n_s - n}{n_s} \qquad n = (1-s)n_s \qquad n_s = n + sn_s$$

f_2 is the rotor frequency $$f_2 = sf_1$$

$$E_{2s} = \frac{2\pi}{\sqrt{2}} f_2 k_{w2} N_2 \Phi_p = \frac{2\pi}{\sqrt{2}} sf_1 k_{w2} N_2 \Phi_p = sE_2$$

What is the speed of the rotor field with respect to the stator field?

Three modes of operation



- demo

Induction machines

- Introduction (5.1)
- Rotating magnetic field (5.2, also for SM)
- Why does an induction machine rotate?
- Induced voltage (5.3, also for SM)
- Definitions (5.4, 5.5)
- Equivalent circuits and voltage equations (5.7)
- Parameter identification (5.8)
- Performance characteristics (5.9)
- Power flow in three modes of operation (5.10)
- Speed control (5.13)
- Linear induction motors (5.16)

Equivalent circuits in Sen

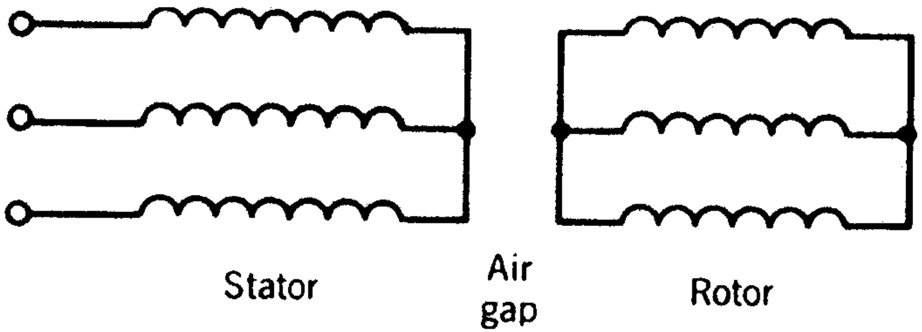


FIGURE 5.12 Three-phase wound rotor induction motor.

- When an induction machine is in standstill, it works as a transformer.
- When the rotor rotates, also a voltage will be induced in the rotor windings.
- Therefore an equivalent circuit is assumed which is comparable to a transformer.

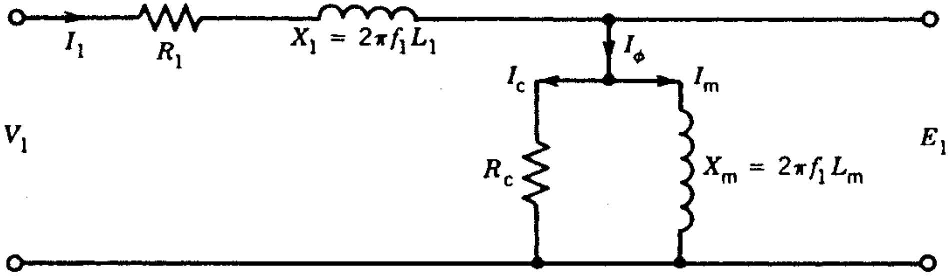
Development

$$\underline{I}_2 = \frac{s\underline{E}_2}{R_2 + \mathrm{j}s\omega L_2}$$

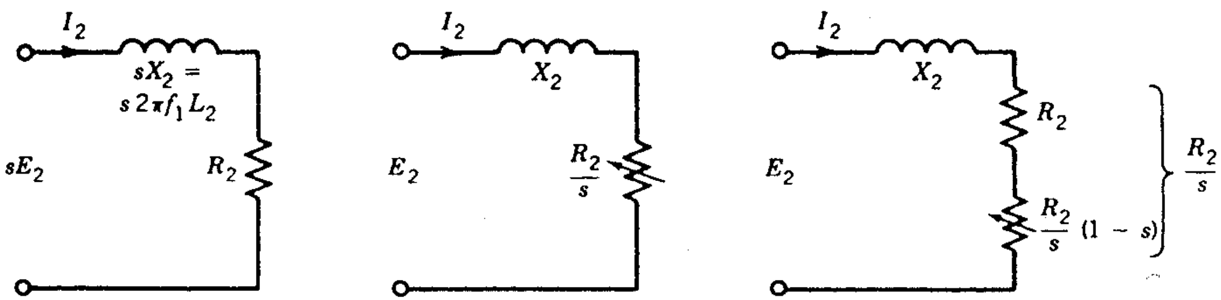
$$\underline{I}_2 = \frac{\underline{E}_2}{\frac{R_2}{s} + \mathrm{j}\omega L_2}$$

$$\underline{I}_2' = \frac{\underline{E}_1}{\frac{R_2'}{s} + \mathrm{j}\omega L_2'}$$

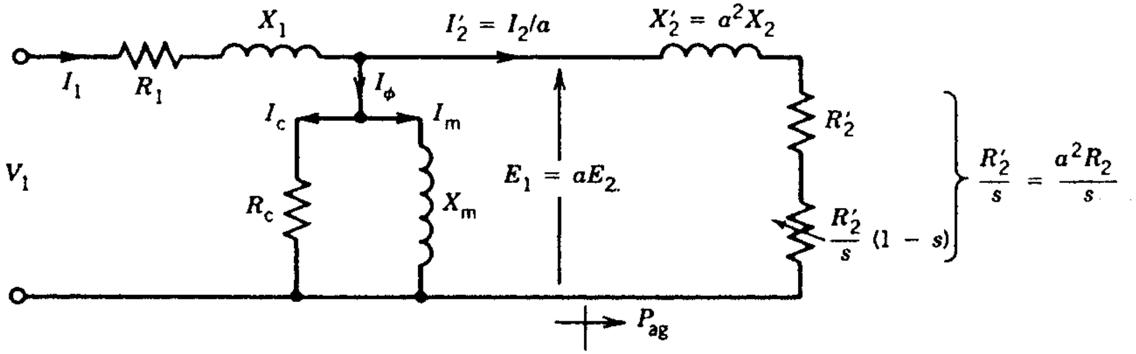
$$\frac{R_2}{s} = R_2 + \frac{1-s}{s}R_2$$



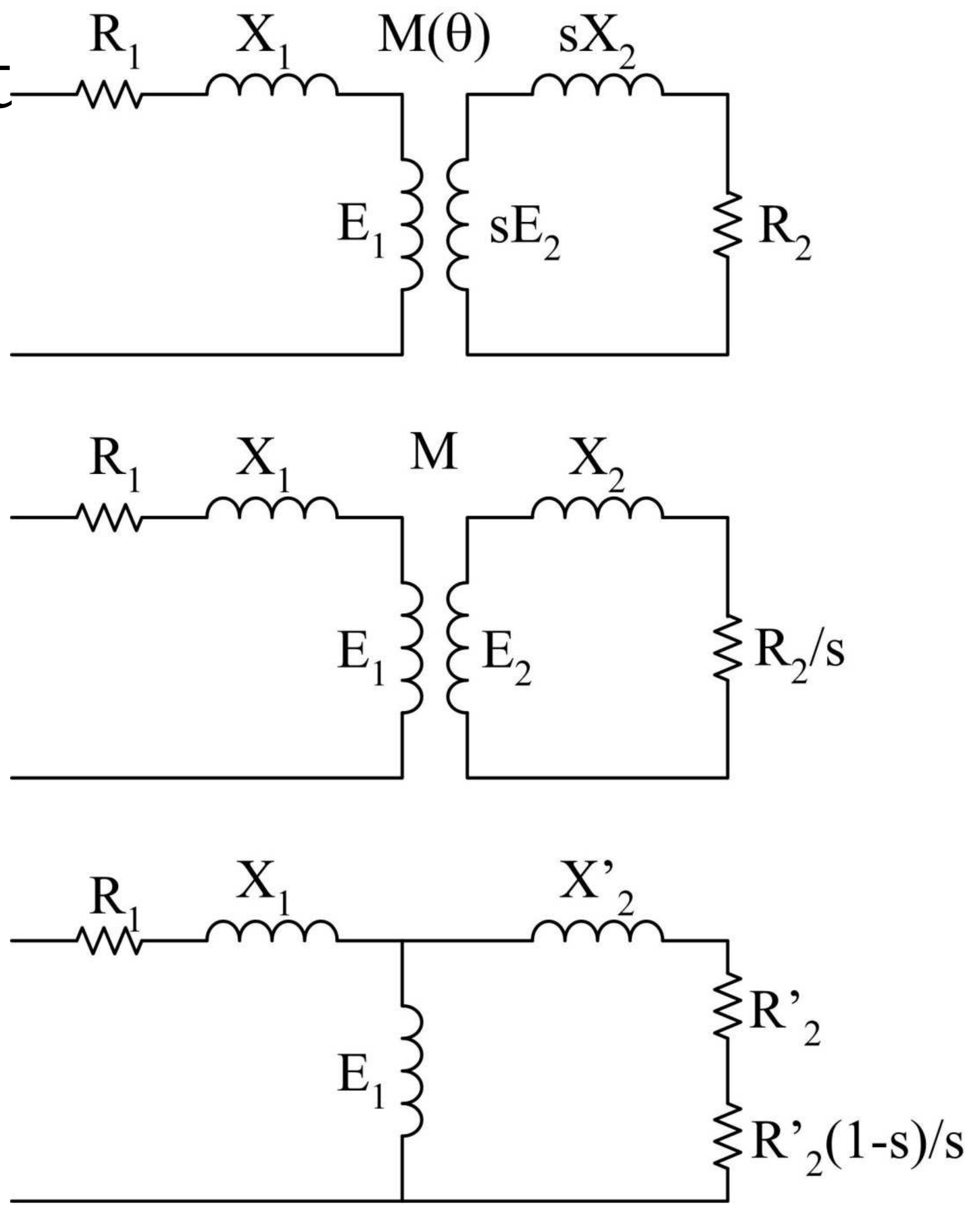
(a)



(b) (c) (d)

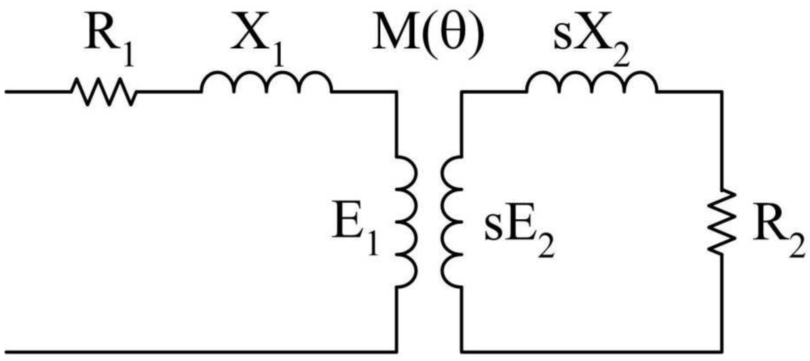


Equivalent circuit development



- L_1 and L_2 are the stator and rotor leakage inductances.
- Where are the leakage fields?

Voltage equations



$$\begin{cases} u_1 = R_1 i_1 + \dfrac{\mathrm{d}\lambda_1}{\mathrm{d}t} \\ 0 = R_2 i_2 + \dfrac{\mathrm{d}\lambda_2}{\mathrm{d}t} \end{cases}$$

or using phasors $u_1 = \mathrm{Re}(\sqrt{2}\underline{U}_1\, \mathrm{e}^{\mathrm{j}\omega t})$

$$\begin{cases} \underline{U}_1 = R_1 \underline{I}_1 + \mathrm{j}\omega\underline{\lambda}_1 \\ 0 = R_2 \underline{I}_2 + \mathrm{j}s\omega\underline{\lambda}_2 \end{cases}$$

where

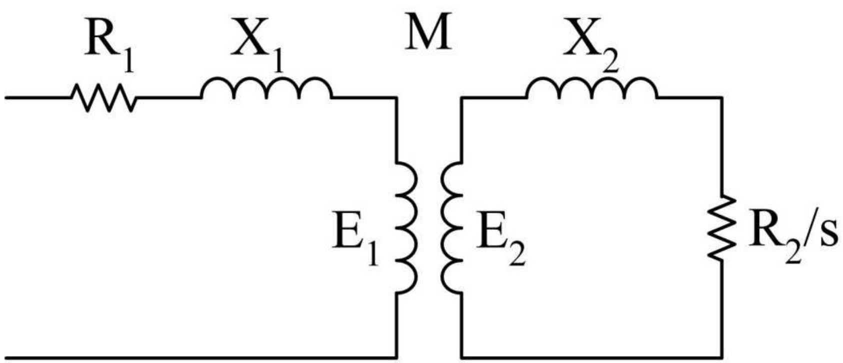
$$\begin{cases} \underline{\lambda}_1 = L_1 \underline{I}_1 + L_{m1}\underline{I}_1 + M\underline{I}_2 \\ \underline{\lambda}_2 = L_2 \underline{I}_2 + L_{m2}\underline{I}_2 + M\underline{I}_1 \end{cases}$$

L_1 and L_2 are the stator and rotor leakage inductances
L_{m1} and L_{m2} and are the stator and rotor main inductances that give the ratio between the phase flux linkage and the phase current assuming three-phase currents
M is the mutual inductance between stator and rotor that gives the ratio between the phase flux linkage and the phase current assuming three-phase currents

Transformations of the voltage equations

The rotor voltage equation is divided by the slip:

$$\begin{cases} \underline{U}_1 = R_1\underline{I}_1 + \mathrm{j}\omega L_1\underline{I}_1 + \mathrm{j}\omega L_{m1}\underline{I}_1 + \mathrm{j}\omega M\underline{I}_2 = R_1\underline{I}_1 + \mathrm{j}\omega L_1\underline{I}_1 + \underline{E}_1 \\ 0 = \dfrac{R_2}{s}\underline{I}_2 + \mathrm{j}\omega L_2\underline{I}_2 + \mathrm{j}\omega L_{m2}\underline{I}_2 + \mathrm{j}\omega M\underline{I}_1 = \dfrac{R_2}{s}\underline{I}_2 + \mathrm{j}\omega L_2\underline{I}_2 + \underline{E}_2 \end{cases}$$



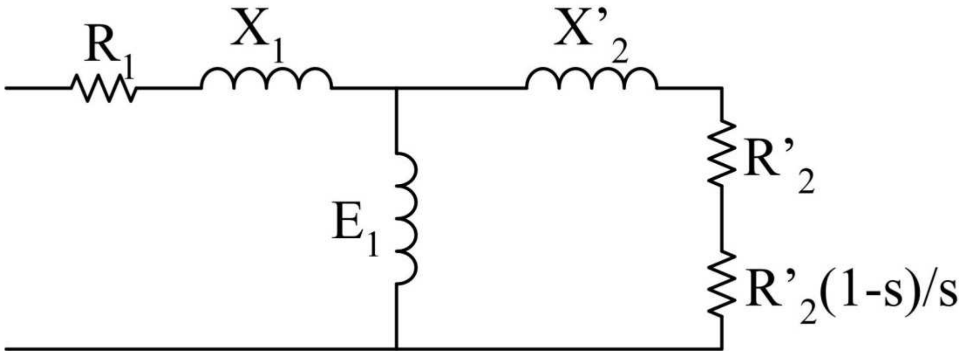
Transformations of voltage equations

Referring the rotor quantities to the stator in a power invariant way

$$\underline{E}_2' = \frac{L_{m1}}{M}\underline{E}_2 \qquad \underline{I}_2' = \frac{M}{L_{m1}}\underline{I}_2 \qquad R_2' = \frac{L_{m1}^2}{M^2}R_2 \qquad L_2' = \frac{L_{m1}^2}{M^2}L_2$$

using $M^2 = L_{m1}L_{m2}$ gives

$$\begin{cases} \underline{U}_1 = R_1\underline{I}_1 + \mathrm{j}\omega L_1\underline{I}_1 + \mathrm{j}\omega L_{m1}(\underline{I}_1 + \underline{I}_2') = R_1\underline{I}_1 + \mathrm{j}\omega L_1\underline{I}_1 + \underline{E}_1 \\ 0 = \frac{R_2'}{s}\underline{I}_2' + \mathrm{j}\omega L_2'\underline{I}_2' + \mathrm{j}\omega L_{m1}(\underline{I}_1 + \underline{I}_2') = \frac{R_2'}{s}\underline{I}_2' + \mathrm{j}\omega L_2'\underline{I}_2' + \underline{E}_1 \end{cases}$$



Γ-equivalent circuit

$$\begin{cases} \underline{U}_1 = R_1\underline{I}_1 + \mathrm{j}\omega L_1\underline{I}_1 + \mathrm{j}\omega L_{m1}(\underline{I}_1 + \underline{I}_2') \\ 0 = \dfrac{R_2'}{s}\underline{I}_2' + \mathrm{j}\omega L_2'\underline{I}_2' + \mathrm{j}\omega L_{m1}(\underline{I}_1 + \underline{I}_2') \end{cases}$$

substituting

$$\underline{I}_2' = \frac{L_s}{L_{m1}}\underline{I}_R'$$

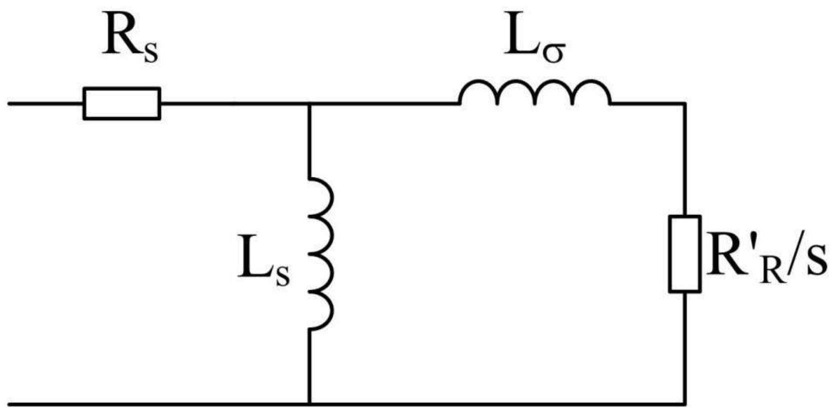
$$L_s = L_{m1} + L_1$$

$$\begin{cases} \underline{U}_1 = R_1\underline{I}_1 + \mathrm{j}\omega L_s(\underline{I}_1 + \underline{I}_R') \\ 0 = \dfrac{R_R'}{s}\underline{I}_2' + \mathrm{j}\omega L_\sigma\underline{I}_R' + \mathrm{j}\omega L_s(\underline{I}_1 + \underline{I}_R') \end{cases}$$

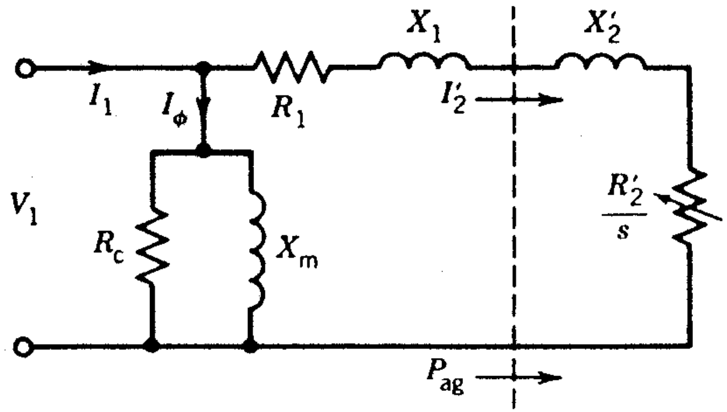
where

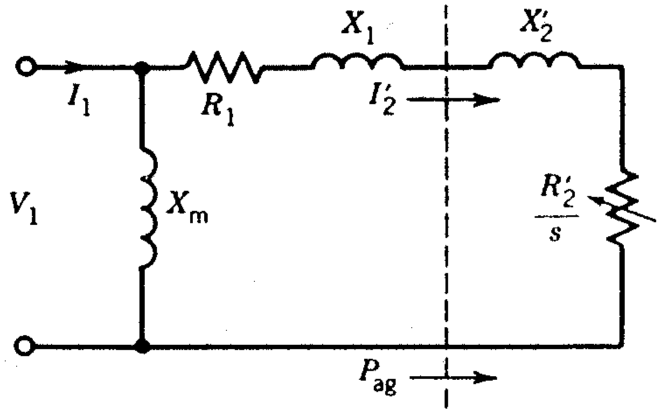
$$L_\sigma = \left(\frac{L_s(L_{m1} + L_2)}{L_{m1}^2} - 1\right)L_s$$

$$R_R' = \frac{L_s^2}{L_{m1}^2}R_2'$$

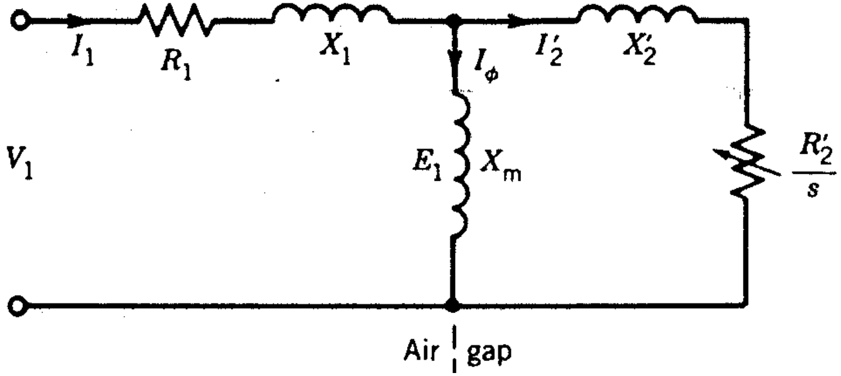


Other equivalent circuits





approximations



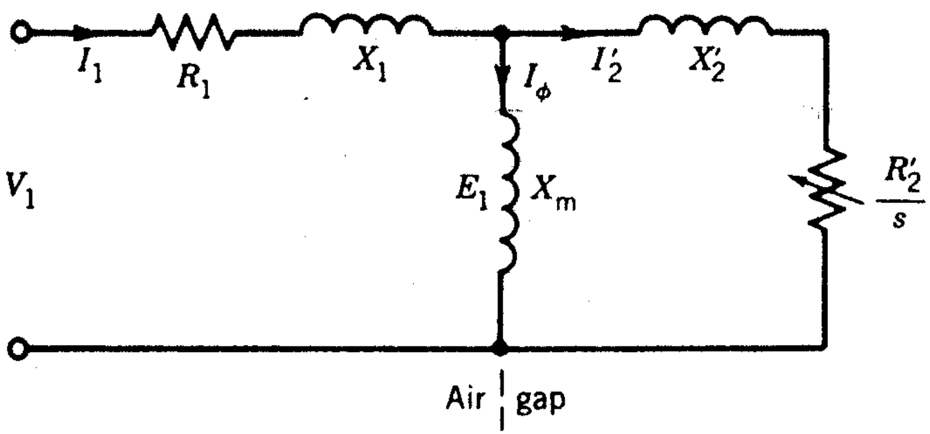
IEEE-recommended

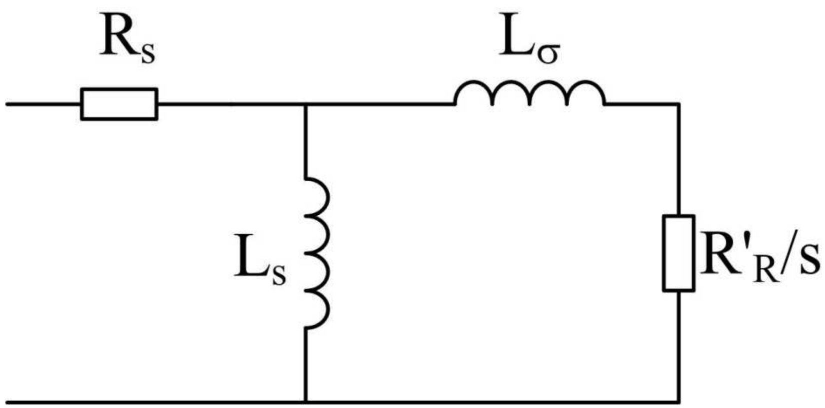
Induction machines

- Introduction (5.1)
- Rotating magnetic field (5.2, also for SM)
- Why does an induction machine rotate?
- Induced voltage (5.3, also for SM)
- Definitions (5.4, 5.5)
- Equivalent circuits and voltage equations (5.7)
- Parameter identification (5.8)
- Performance characteristics (5.9)
- 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?





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
- 18-9 4.3-4.7: DC machines and drives
- 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