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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- 19-10: rest, questions
- 9-11: exam

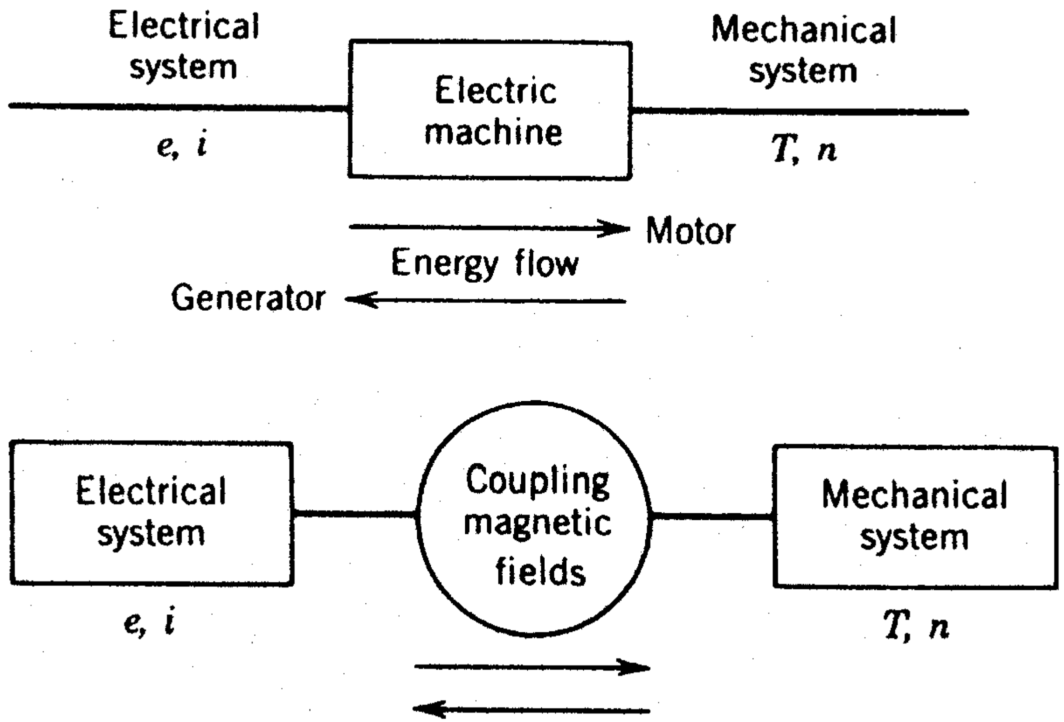
Organisation 3

- Laboratory work:
- 3 half days between 17 September and 3 November
- DC machines, IM and SM
- In groups of up to 8 students
- Register via blackboard
  - 17 (morning), 17 (afternoon), 20 (afternoon) Sept for DCM
  - 24 (morning), 24 (afternoon), 27 (afternoon) Sept for DCM
  - 1 (morning), 1 (afternoon), 4 (afternoon) Oct for IM
  - 8 (morning), 8 (afternoon), 11 (afternoon) Oct for IM
  - 15 (morning), 15 (afternoon), 18 (afternoon) Oct for SM
  - 22 (morning), 22 (afternoon), 25 (afternoon) Oct for SM

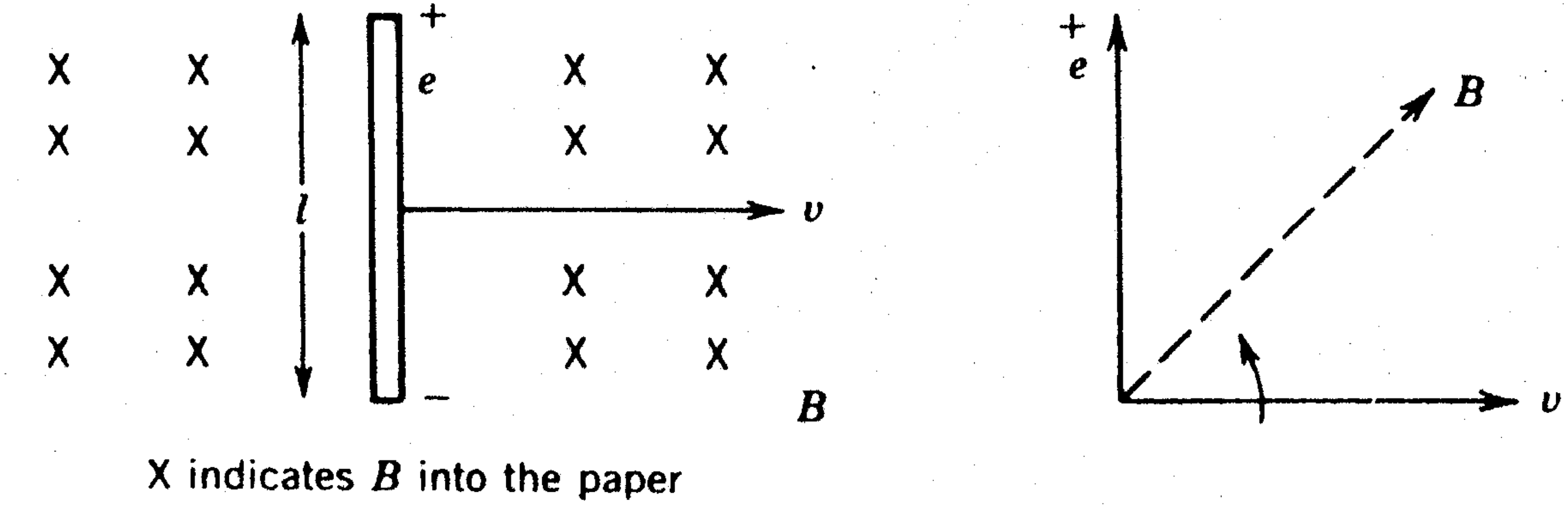
Principles of electromechanics (3)

- Lorentz force, induced voltage (4.1)
- Energy or power balance (3.1)
- Energy and coenergy (3.2)
- Calculation of force from (co)energy (3.3)
- Application to actuators and rotating machines (3.4, 3.5)

Electromagnetic energy conversion (4.1)

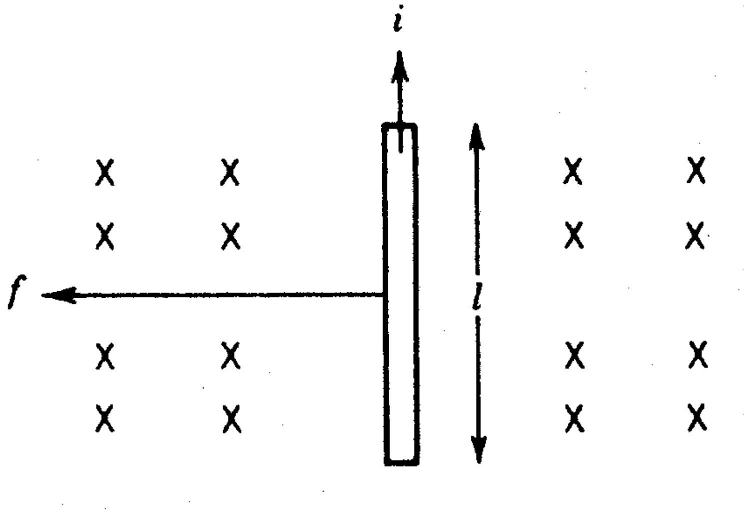


Induced voltage



$$E = Blv$$

Lorentz force



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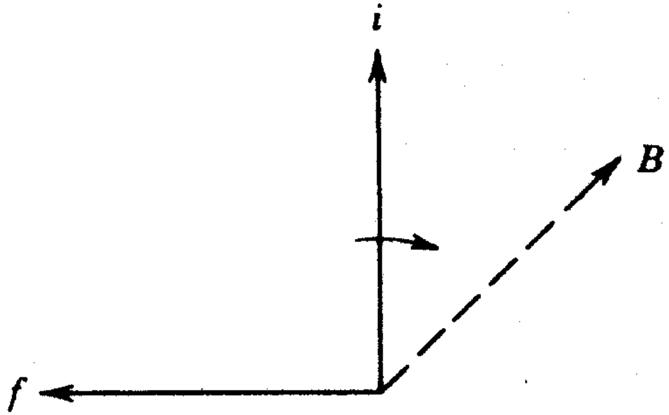
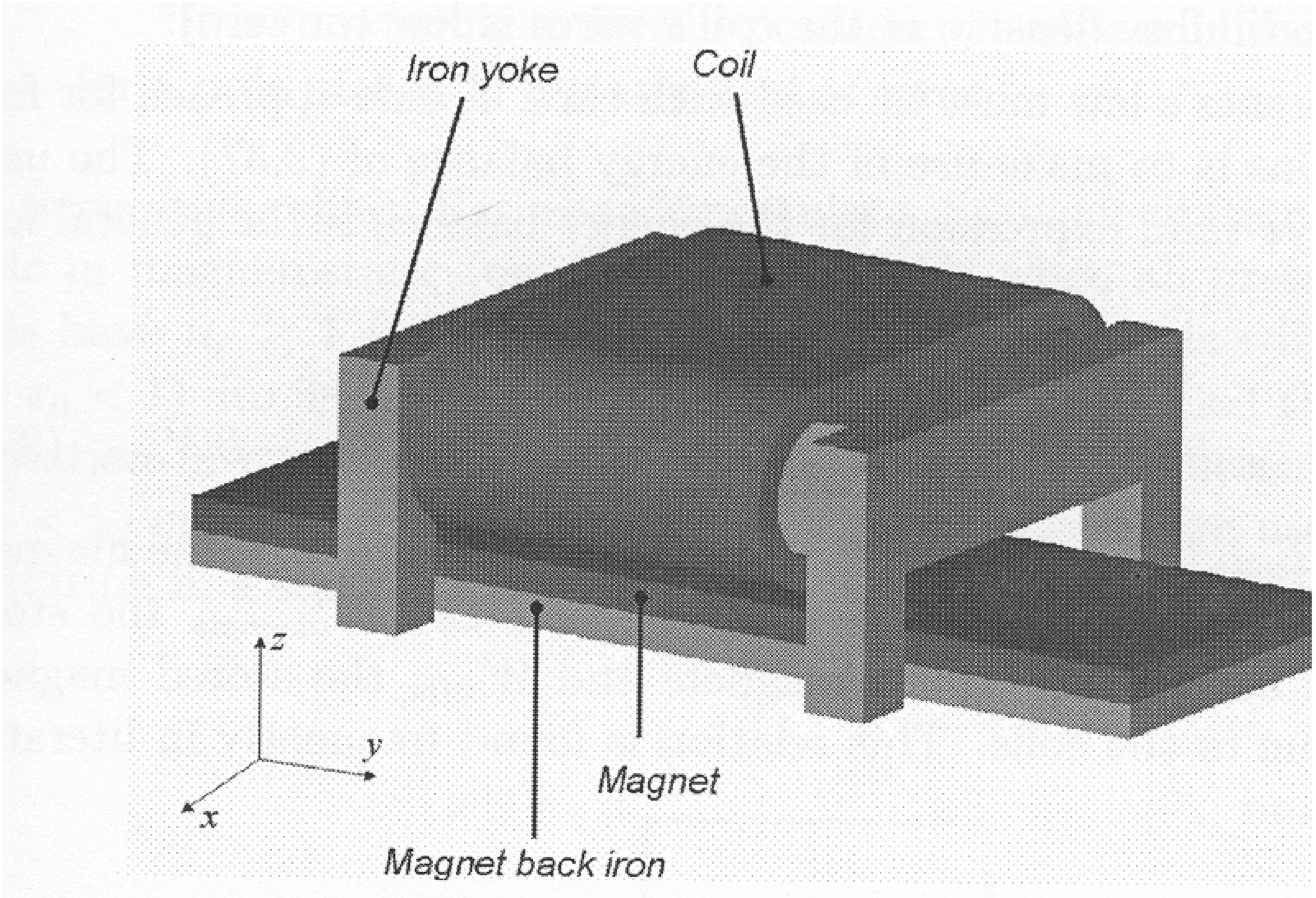


(b)

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \qquad F = Bli$$

Power balance holds: $P = Ei = Blvi = Fv$

Lorentz force



Lorenz force, induced voltage

- Generally not valid when iron is present
- Sometimes dangerous, only valid if flux linkage changes
- Safe way of calculating voltage: from flux linkage

$$u = Ri + \frac{\mathrm{d}\lambda}{\mathrm{d}t} \approx Ri + N\frac{\mathrm{d}\Phi}{\mathrm{d}t}$$

- Safe way of calculating forces: power or energy balance

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Energy or power balance

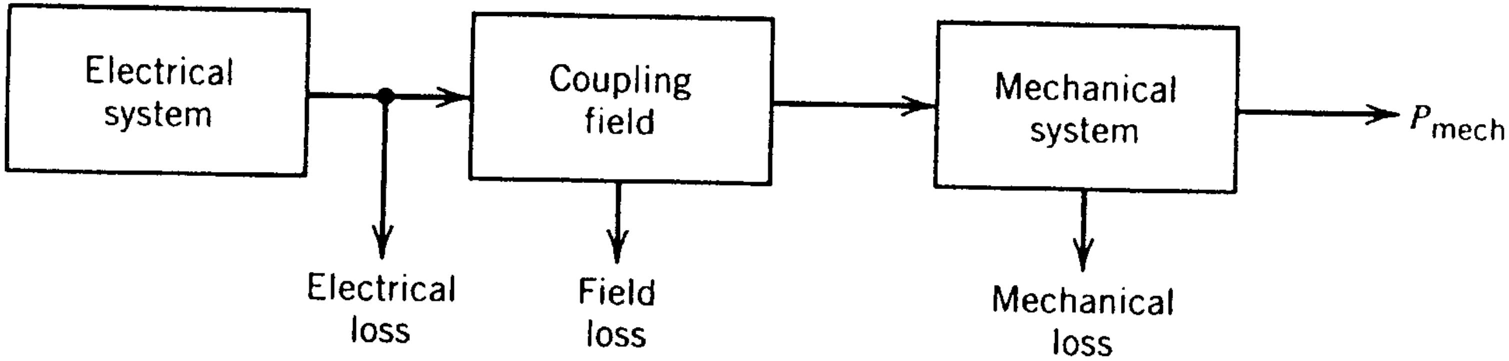

FIGURE 3.1 Electromechanical converter system.

Electrical energy input = Energy losses + Increase stored energy + Mechanical energy output

Energy balance

Electrical energy input - resistance losses	=	Increase stored energy + core losses	+	Mechanical energy output + friction, windage losses

$\mathrm{d}W_e$ is the electrical energy input during dt
$\mathrm{d}W_{mech}$ is the mechanical energy output during dt
$\mathrm{d}W_f$ is the change in stored field energy (core loss neglected)

$$\mathrm{d}W_e = \mathrm{d}W_{mech} + \mathrm{d}W_f$$

$$\mathrm{d}W_e = (ui - Ri^2)\,\mathrm{d}t = ((Ri + \frac{\mathrm{d}\lambda}{\mathrm{d}t})i - Ri^2)\,\mathrm{d}t = i\,\mathrm{d}\lambda$$

$$\mathrm{d}W_{mech} = f_{mech}\,\mathrm{d}x$$

$$i\,\mathrm{d}\lambda = f_{mech}\,\mathrm{d}x + \mathrm{d}W_f$$

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Magnetic field energy

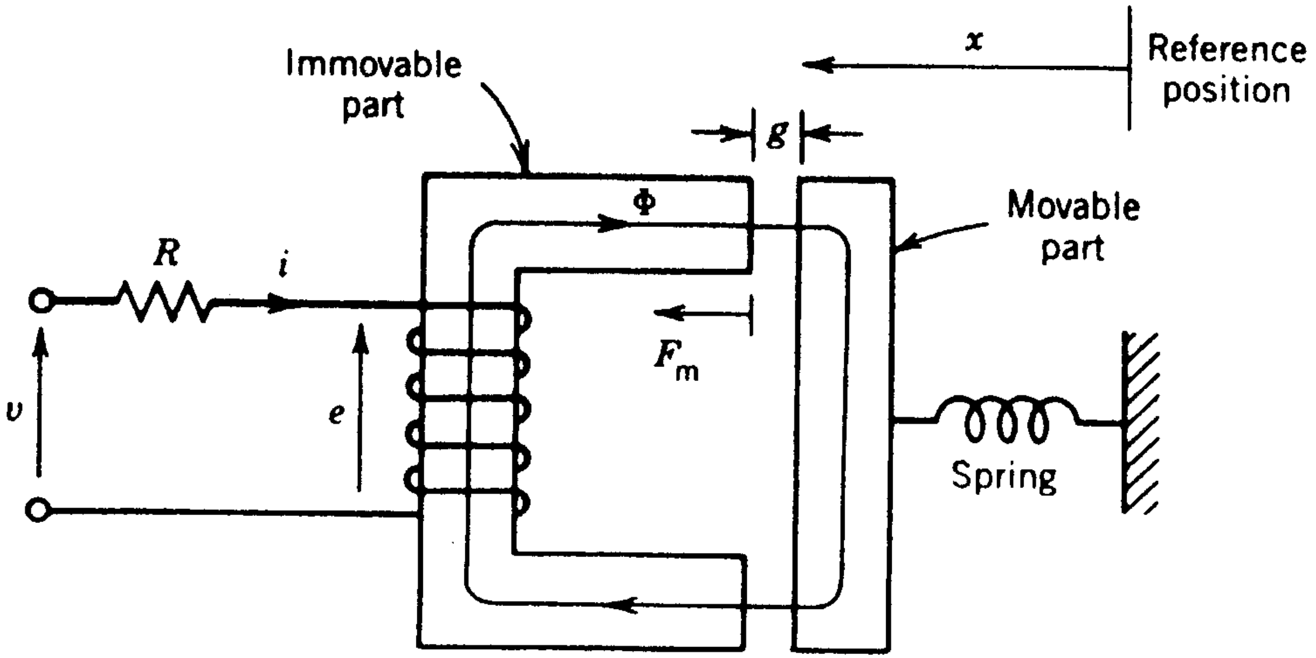
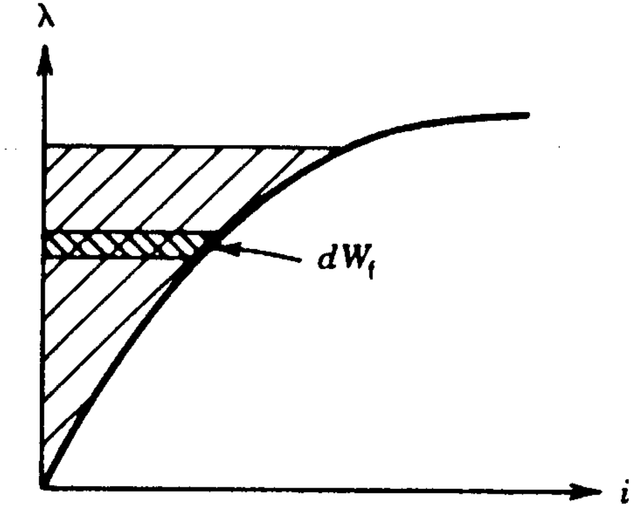
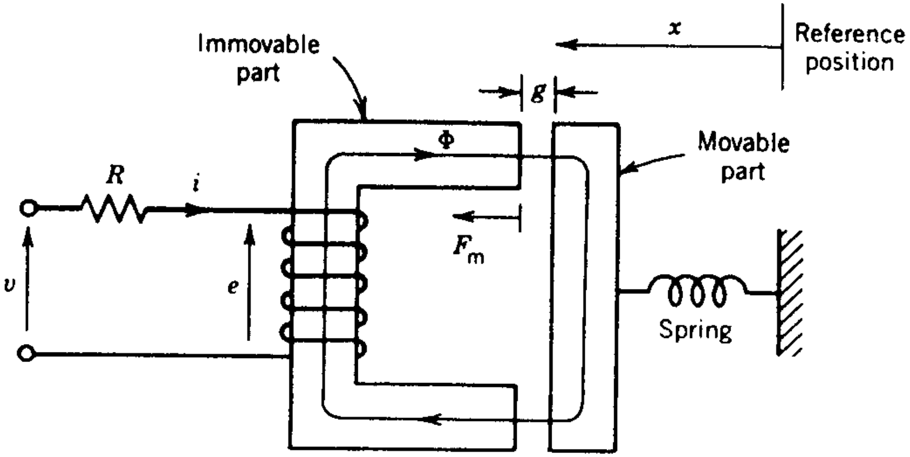


FIGURE 3.2 Example of an electromechanical system.

Calculation of magnetic field energy





Movable part is kept stationary

$$\mathrm{d}W_f = \mathrm{d}W_e = i\,\mathrm{d}\lambda$$

$$W_f = \int^{\lambda} i\,\mathrm{d}\lambda$$

Example calculation of magnetic energy

Using $\oint_{C_m} \vec{H} \cdot \vec{\tau}\, \mathrm{d}s = \iint_{S_m} \vec{J} \cdot \vec{n}\, \mathrm{d}A$

and $\lambda = NBA$

$H_c l_c + H_g l_g = Ni$

l_g is total air gap length
l_c is total core length

$$W_f = \int^{\lambda} i\, \mathrm{d}\lambda = NA \int^{B} \frac{H_g l_g + H_c l_c}{N} \mathrm{d}B = Al_g \int^{B} H_g\, \mathrm{d}B + Al_c \int^{B} H_c\, \mathrm{d}B$$

In case of linear core material $B_c = \mu_0 \mu_r H_c$

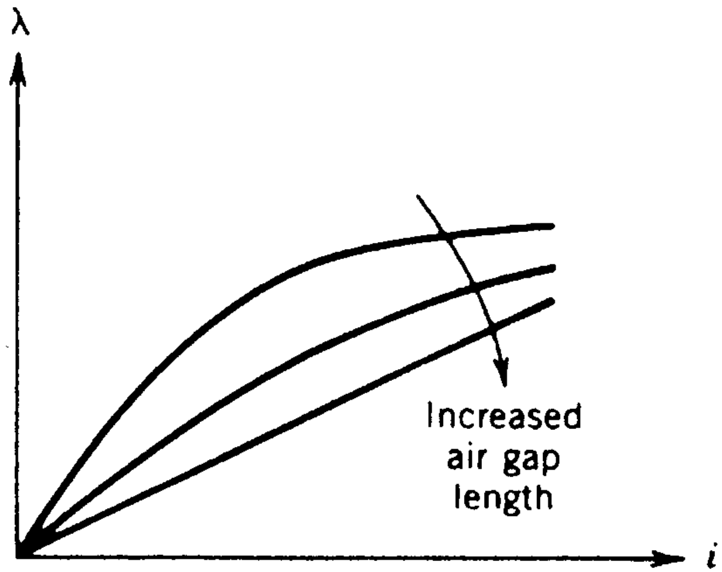
$$W_f = Al_g \frac{B^2}{2\mu_0} + Al_c \frac{B^2}{2\mu_0 \mu_r} = 0.199 + 0.002\,\mathrm{J}$$

Energy mainly in air gap !

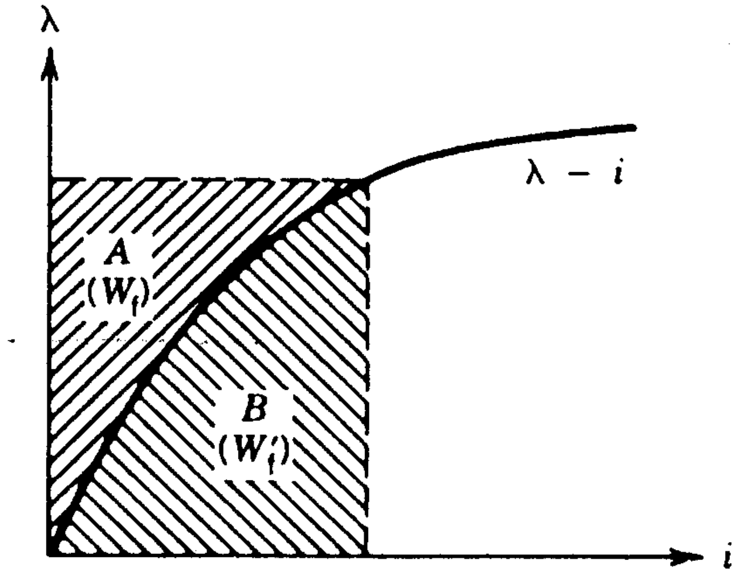
$B = 1$ T
$\mu_r = 5000$
$\mu_0 = 4\pi 10^{-7}$ H/m
$l_c = 0.2$ m
$l_g = 5$ mm
$A_c = 1\ \mathrm{cm}^2$

Coenergy

$$W_f = \int^{\lambda} i \, \mathrm{d}\lambda \qquad W'_f = \int^{i} \lambda \, \mathrm{d}i \qquad W_f + W'_f = \lambda i$$



(a)



(b)

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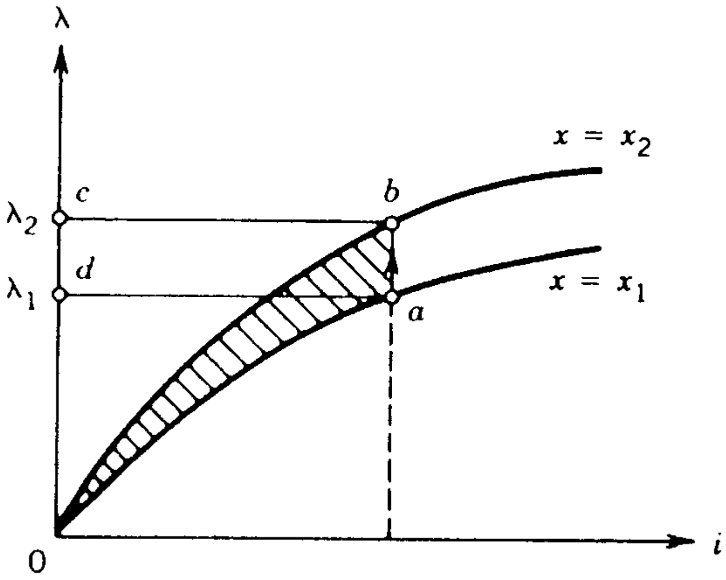
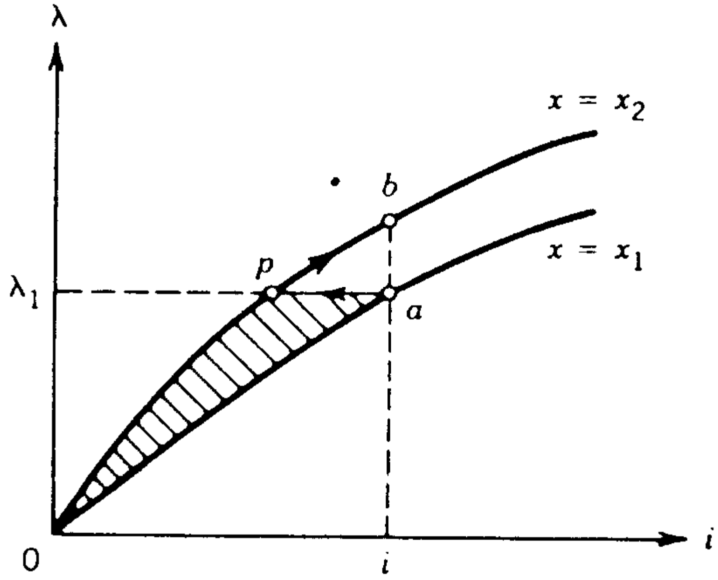
Calculation of force from (co)energy

$$f_{mech}\,\mathrm{d}x = i\,\mathrm{d}\lambda - \mathrm{d}W_f = i\,\mathrm{d}\lambda - \mathrm{d}(\lambda i - W_f') = \mathrm{d}W_f' - \lambda\,\mathrm{d}i$$





$$f_{mech} = \left.\frac{\partial W_f'}{\partial x}\right|_{i=\text{constant}}$$

$$f_{mech} = -\left.\frac{\partial W_f}{\partial x}\right|_{\lambda=\text{constant}}$$

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Calculation of reluctance force

Power balance: $$\frac{\mathrm{d}W_e}{\mathrm{d}t} = \frac{\mathrm{d}W_{mech}}{\mathrm{d}t} + \frac{\mathrm{d}W_f}{\mathrm{d}t}$$ $$\lambda = L(x)i$$

$$\frac{\mathrm{d}W_e}{\mathrm{d}t} = ui - Ri^2 = i(Ri + \frac{\mathrm{d}\lambda}{\mathrm{d}t}) - Ri^2 = i\frac{\mathrm{d}L(x)i}{\mathrm{d}t} = i^2\frac{\mathrm{d}L(x)}{\mathrm{d}x}\frac{\mathrm{d}x}{\mathrm{d}t} + iL(x)\frac{\mathrm{d}i}{\mathrm{d}t}$$

$$\frac{\mathrm{d}W_{mech}}{\mathrm{d}t} = P_{mech} = f_{mech}\frac{\mathrm{d}x}{\mathrm{d}t}$$

$$\frac{\mathrm{d}W_f}{\mathrm{d}t} = \frac{\mathrm{d}\frac{1}{2}L(x)i^2}{\mathrm{d}t} = iL(x)\frac{\mathrm{d}i}{\mathrm{d}t} + \frac{1}{2}i^2\frac{\mathrm{d}L(x)}{\mathrm{d}x}\frac{\mathrm{d}x}{\mathrm{d}t}$$

Conclusion: $$f_{mech} = \frac{1}{2}i^2\frac{\mathrm{d}L(x)}{\mathrm{d}x}$$

Reluctance force from (co)energy

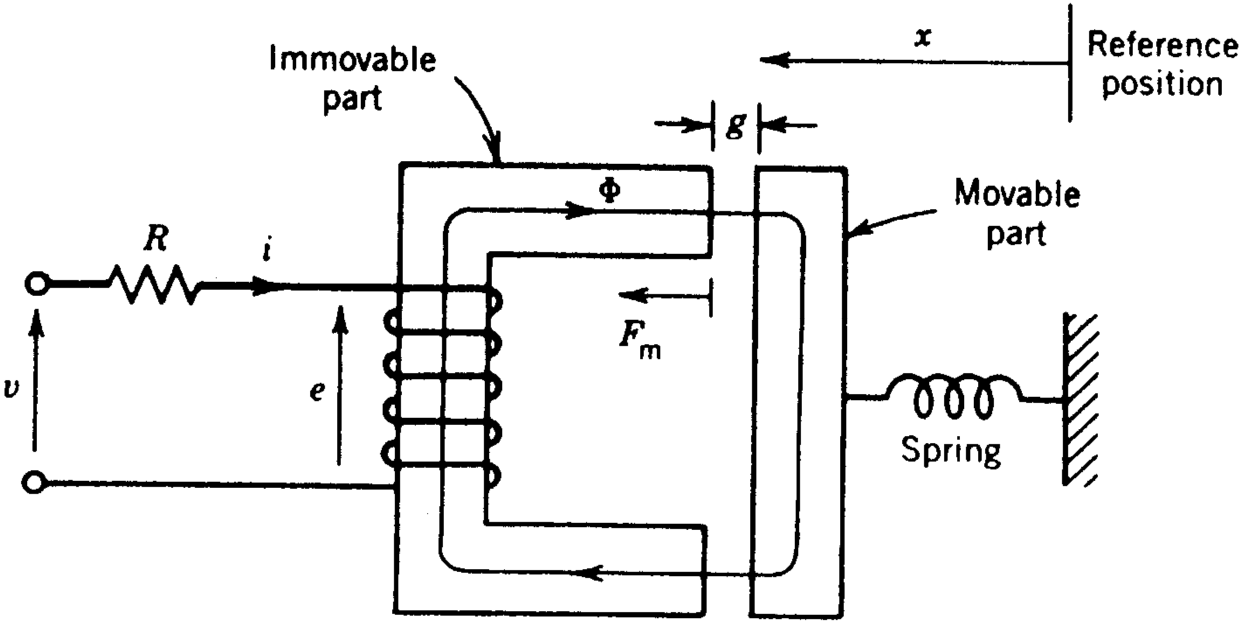
$$f_{mech} = \left.\frac{\partial W_f'}{\partial x}\right|_{i=\text{constant}} = \frac{\partial}{\partial x}\left(\frac{1}{2}L(x)i^2\right) = \frac{1}{2}i^2\frac{\mathrm{d}\,L(x)}{\mathrm{d}\,x}$$

$$f_{mech} = -\left.\frac{\partial W_f}{\partial x}\right|_{\lambda=\text{constant}} = \frac{\partial}{\partial x}\left(\frac{\lambda^2}{2L(x)}\right) = -\frac{\lambda^2}{2L^2(x)}\frac{\mathrm{d}\,L(x)}{\mathrm{d}\,x}$$

Force

- tries to increase inductance
- tries to close the gap

Reluctance force, magnetic pressure



$$L(g) = \frac{\mu_0 A_g N^2}{2g}$$

$$f_{mech} = \frac{1}{2} i^2 \frac{\mathrm{d}\, L(g)}{\mathrm{d}\, g}$$

$$f_{mech} = -\frac{i^2 \mu_0 A_g N^2}{4g^2}$$

Using $Ni = 2gH_g = 2g\frac{B_g}{\mu_0}$ gives $f_{mech} = -\frac{B^2}{2\mu_0} 2A_g$

What is a realistic value of the force density?

Error in form of force

- Do you see the error in the form of the force?

$$i = \frac{120}{6} = 20\ \text{A}$$

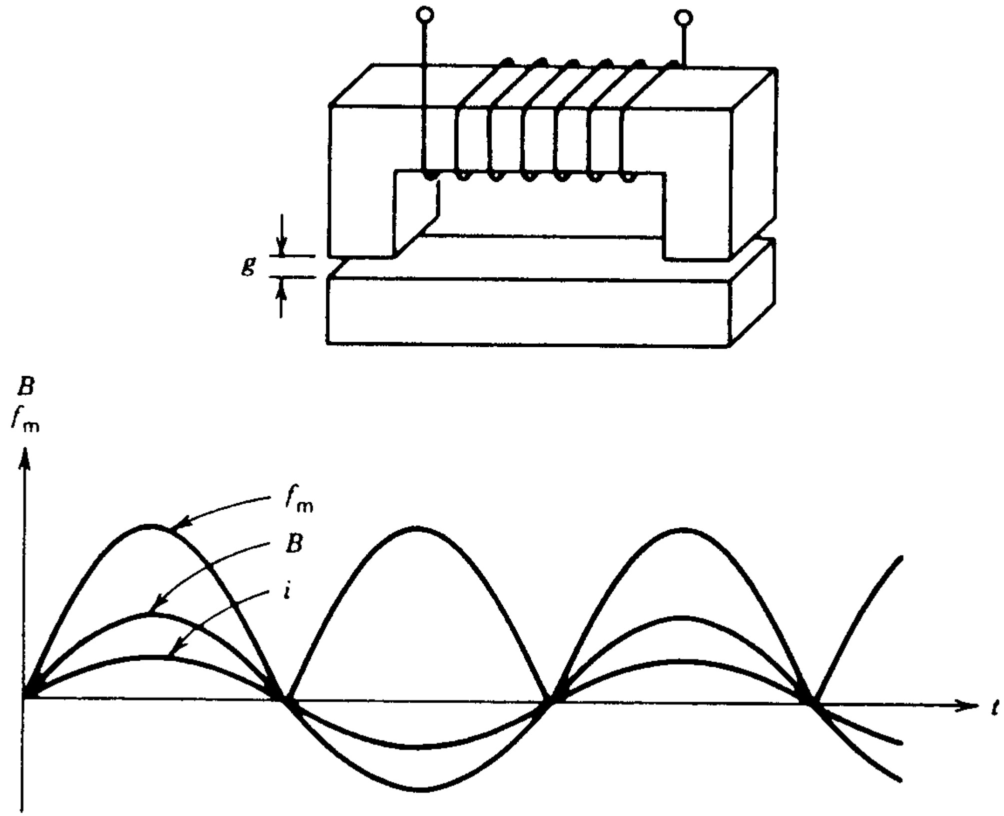
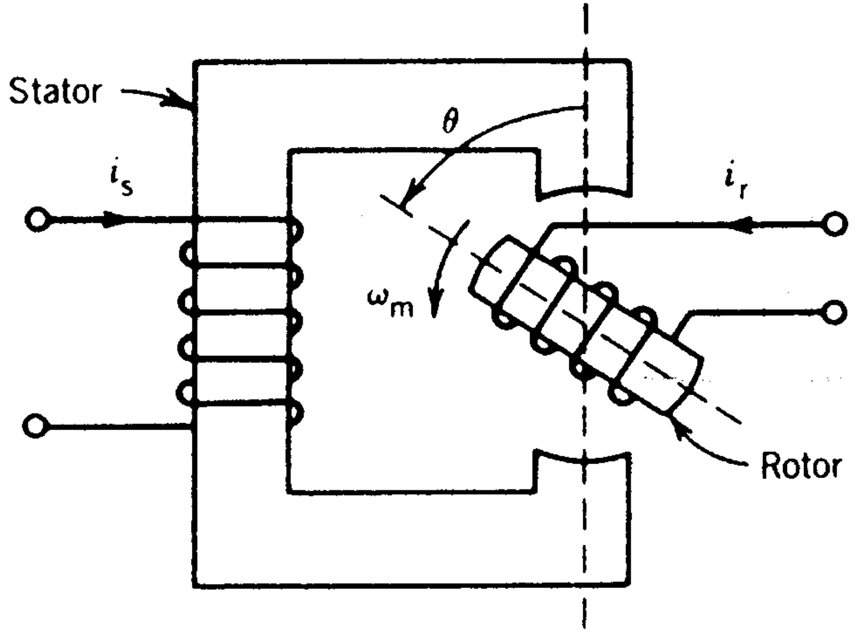


FIGURE E3.4

Rotating machines with saliency (3.4)

$$i_r = 0$$

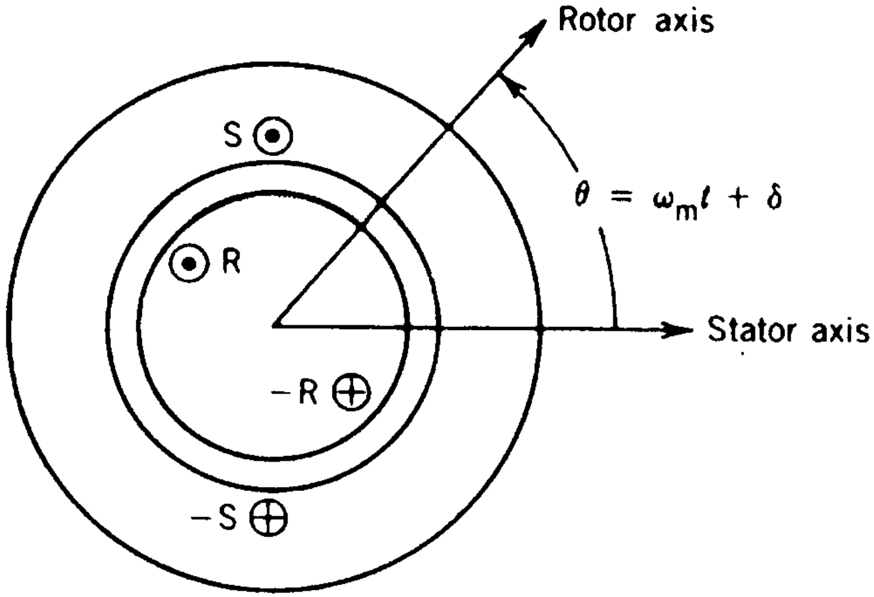
$$T_{mech} = \frac{1}{2} i_s^2 \frac{\mathrm{d}\, L_{ss}}{\mathrm{d}\,\theta}$$



Torque

- tries to increase self-inductance
- tries to close the gap

Cylindrical rotating machines (3.5)



$$T_{mech} = i_s i_r \frac{\mathrm{d}L_{sr}}{\mathrm{d}\theta} = i_s i_r \frac{\mathrm{d}M}{\mathrm{d}\theta}$$

Torque

- tries to increase mutual inductance
- tries to align the fields of stator and rotor

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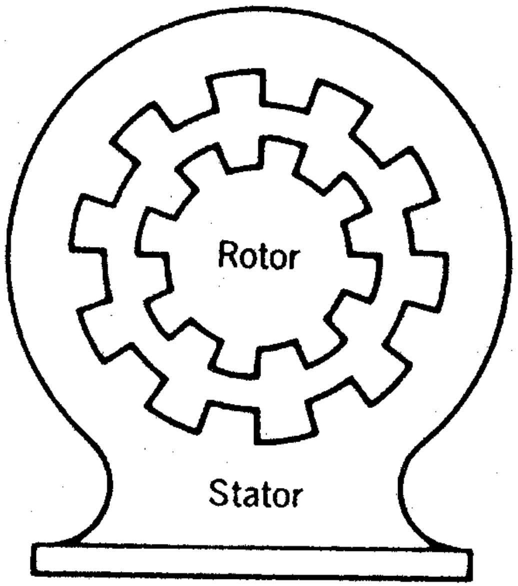
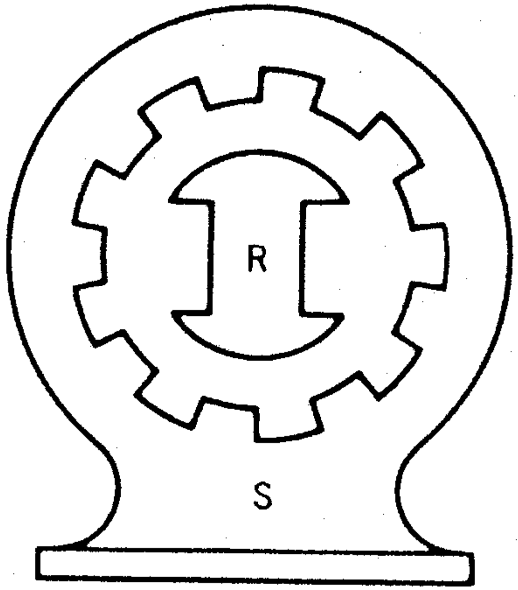
DC machines

- Introduction, construction (4.2)
- Principle of operation and basic calculations (4.2)
- Armature reaction, interpoles, compensating winding (4.3)
- Characteristics, means to control speed (4.4)
- DC machine drives (4.5)
- PMDC machines / PCB machines (4.6, 4.7)

Basic construction elements

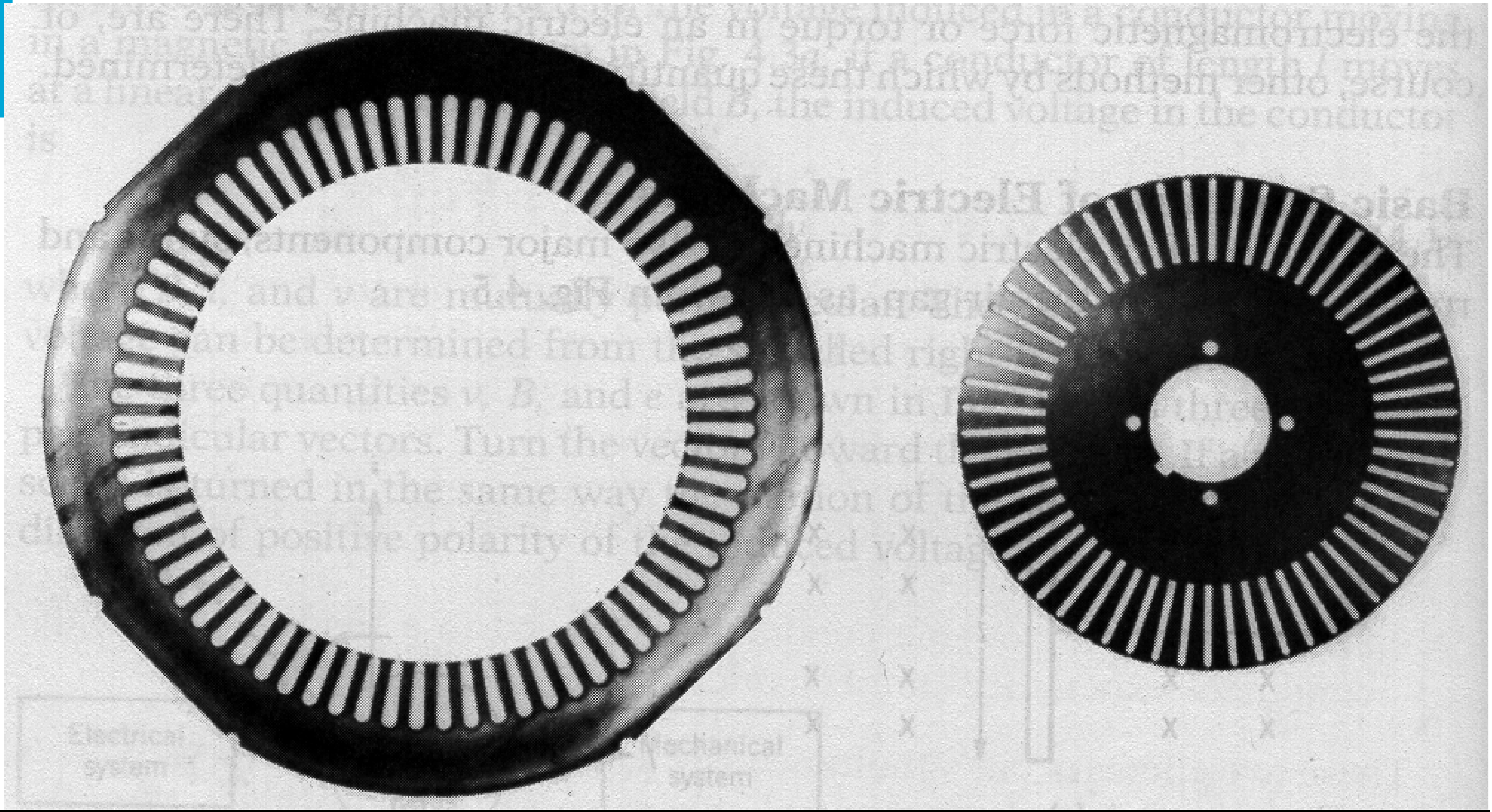




- stator
- rotor
- teeth

- slots
- cylindrical rotor
- salient pole rotor

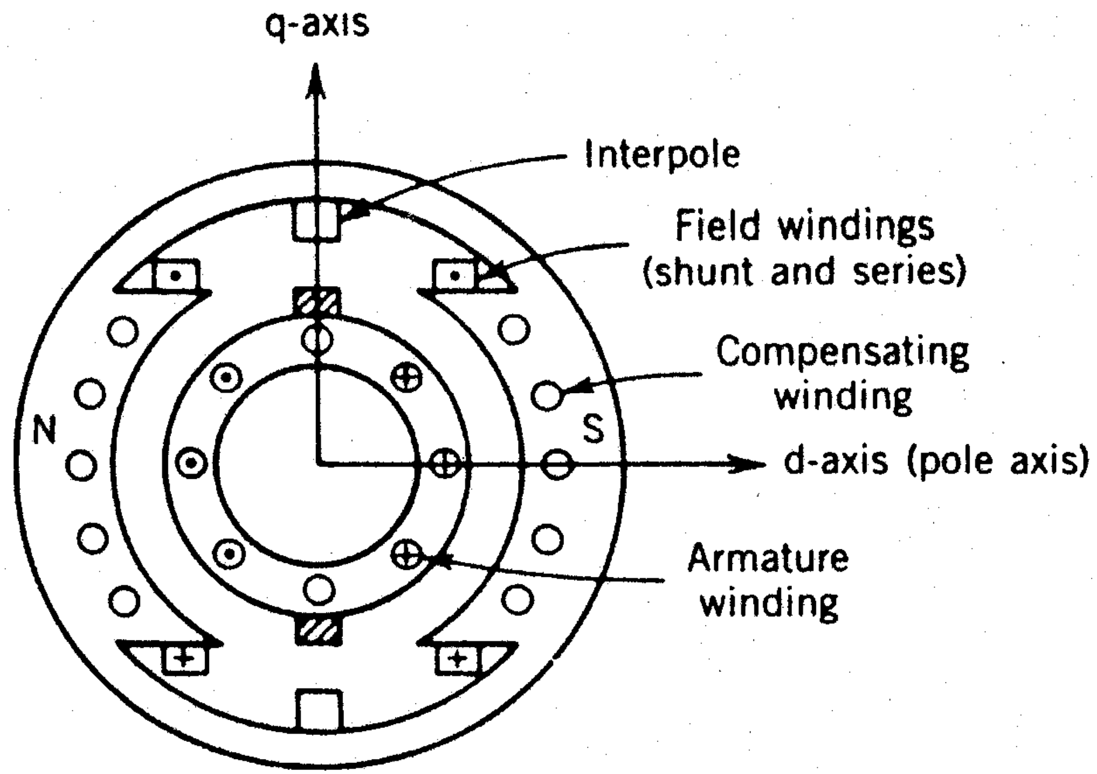
Stator and rotor laminations



DC machine introduction

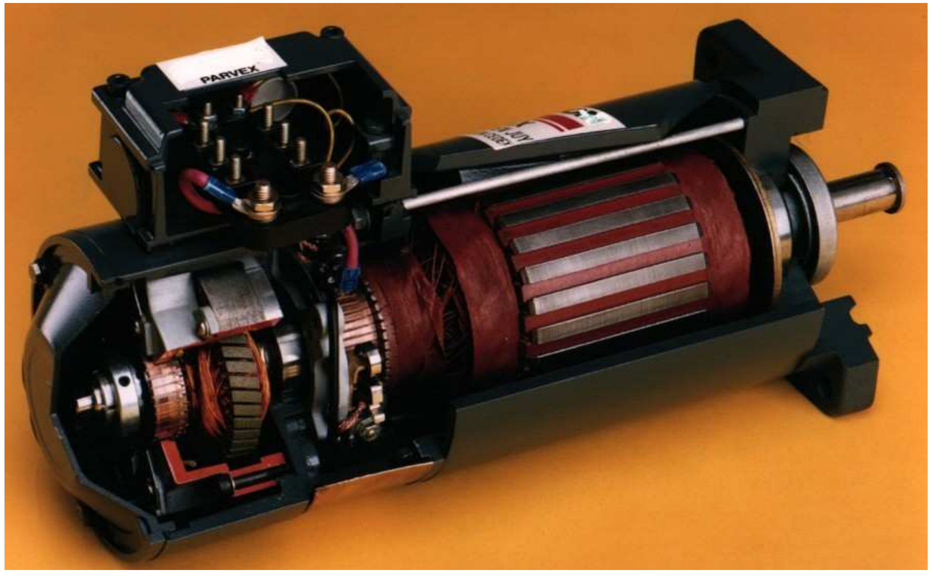
- history: loader for accumulators, moving coil in magnetic field
- generates DC voltage in generating operation
- operates on a DC voltage in motoring operation
- has many applications in controlled drives and traction
- reason: easy to control
- importance decreasing because induction machines with VSI are cheaper and more robust

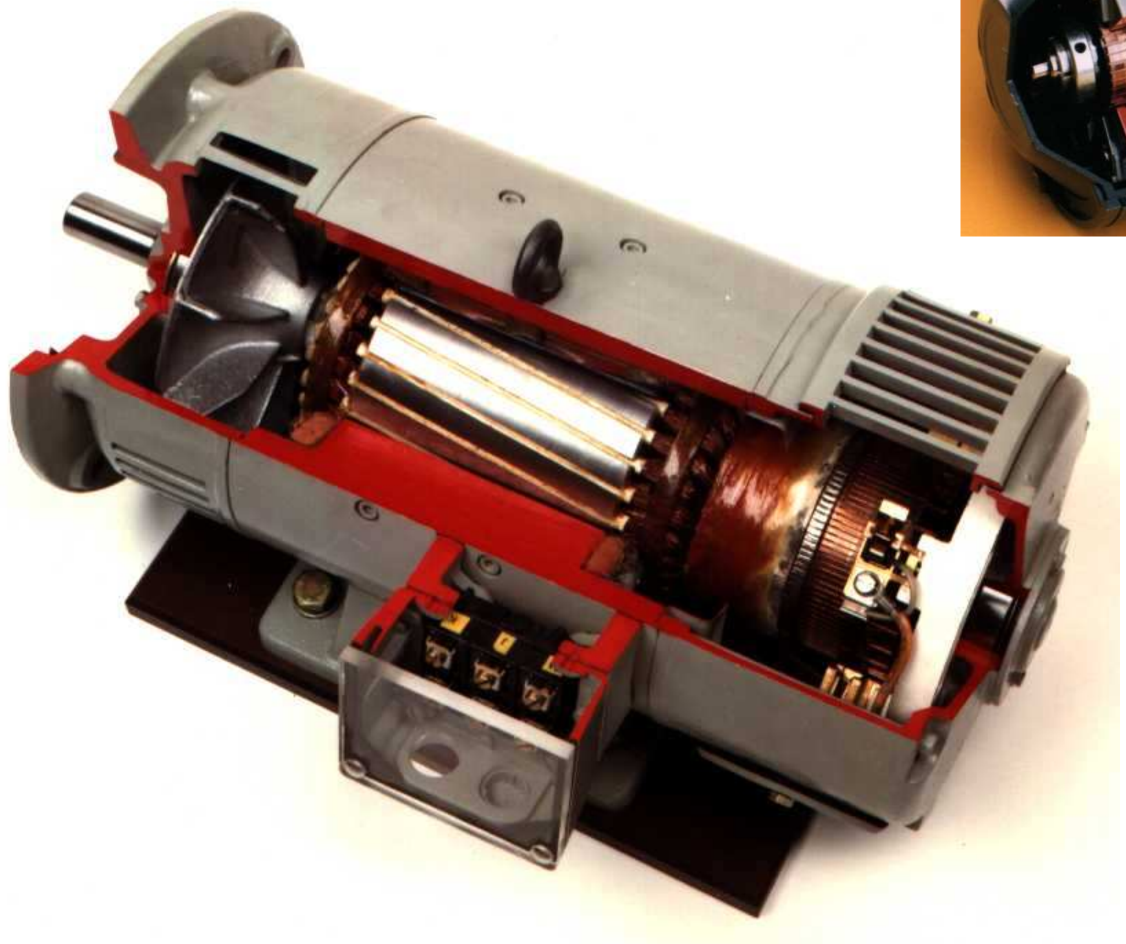
DC machine construction



- stator: yoke, pole, field winding
- rotor / armature: teeth, slots, armature winding
- commutator

Cutaway views of DC machines





DC machine characteristics

- rotor is cylindrical with slots (except at very small power)
- stator has salient poles with field windings or permanent magnets
- the number of poles may be larger than two (but even)
- the rotor is laminated
- the excitation current is a dc current, resulting in a constant excitation field
- the excitation current is provided by
  - a separate source (separately excited dc machine)
  - the armature voltage (shunt dc machine)
  - the armature current (series dc machine)

DC machines

- Introduction, construction (4.2)
- Principle of operation and basic calculations (4.2)
  - air gap flux density (1.1)
  - armature turn voltage and commutation (4.2.2)
  - armature windings (4.2.3)
  - total armature voltage (4.2.4)
  - torque (4.2.5)
  - magnetisation curve (4.2.6)
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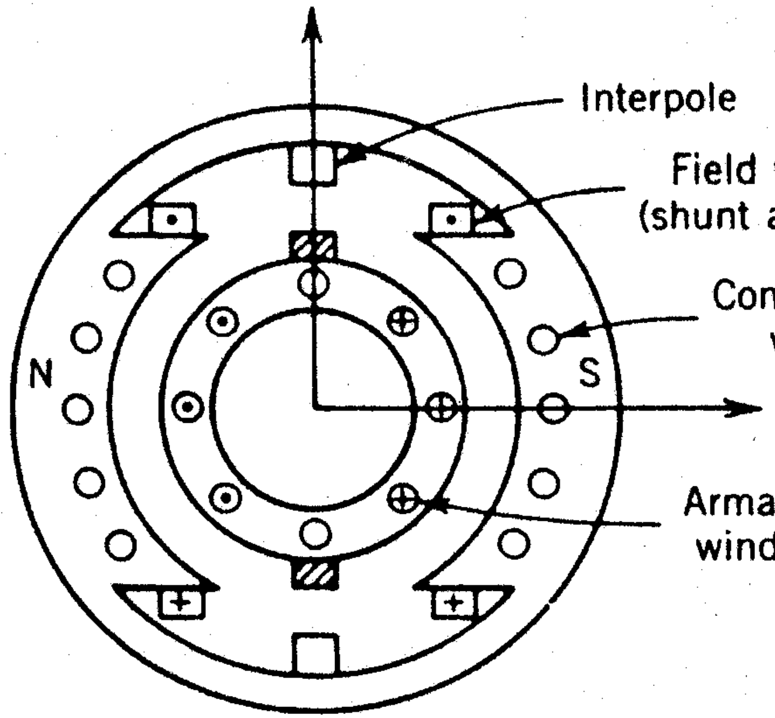
Assumptions for calculations

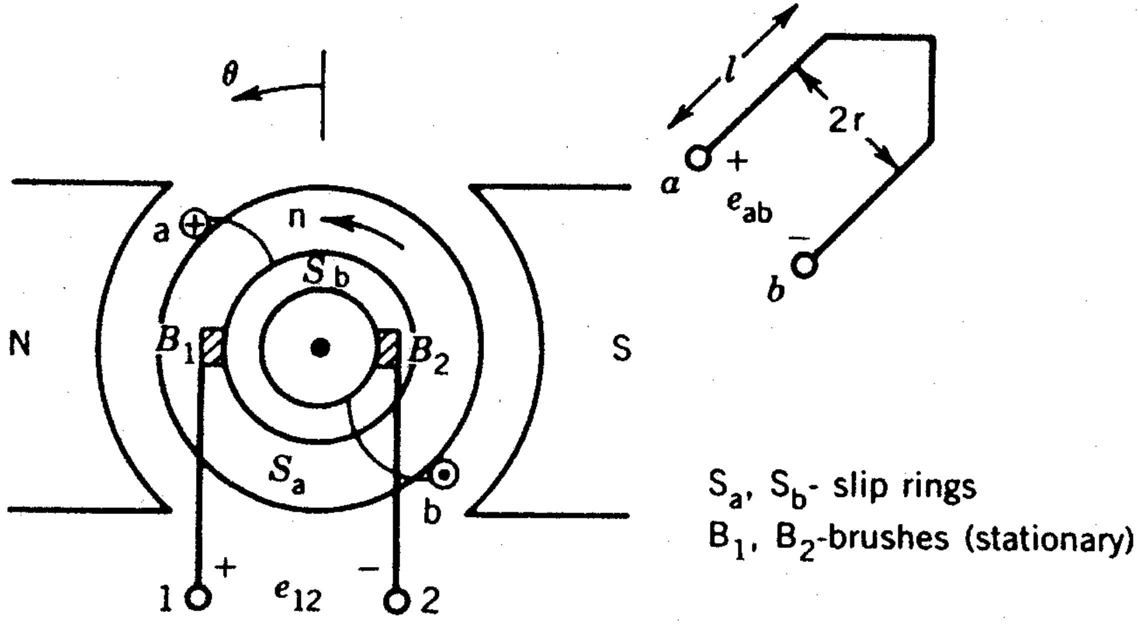
- steady state (mechanical and electrical)
- the air gap is so small that the flux density does not change in radial direction
- the air gap is so small that the flux density crosses the air gap perpendicular
- iron losses are negligible
- the magnetic permeability of iron is infinite

Air gap flux density



- The field winding around one pole has Nf turns and carries a current If
- Calculate the air gap flux density between the poles and the rotor

Flux density

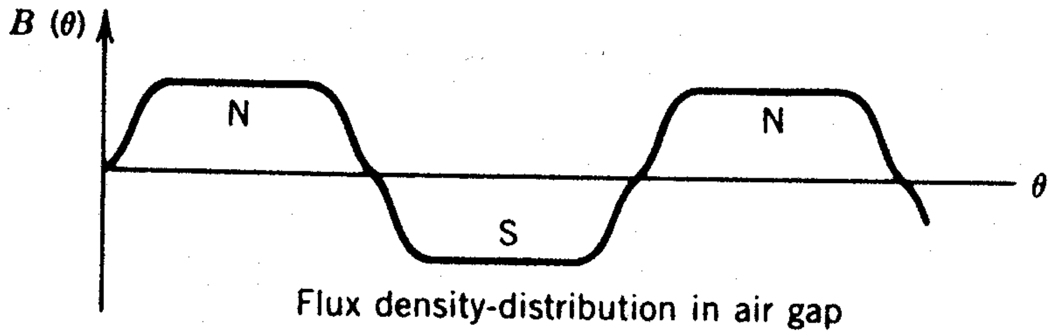


(a)

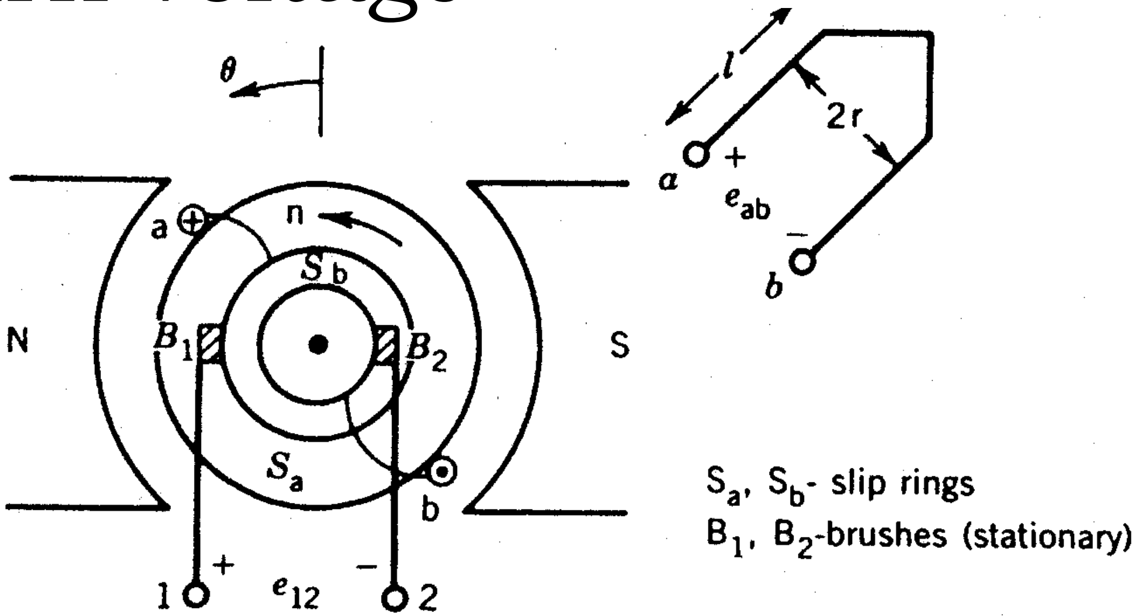
$$\oint_{C_m} \vec{H} \cdot \vec{\tau}\, \mathrm{d}s = \iint_{S_m} \vec{J} \cdot \vec{n}\, \mathrm{d}A$$

$$2H_g l_g = 2N_f I_f$$

$$B_g = \frac{\mu_0 N_f I_f}{l_g}$$



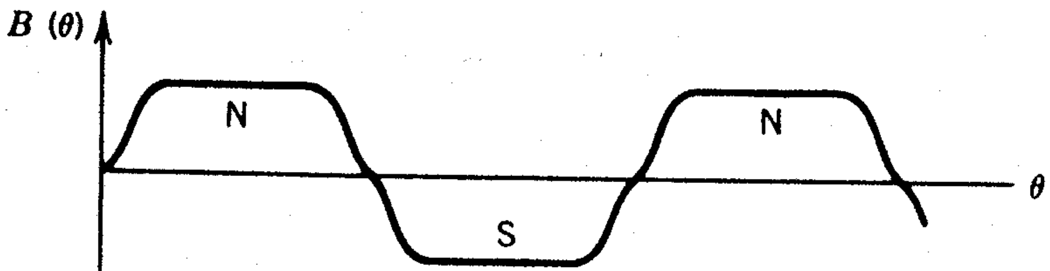
Armature turn voltage



(a)

- Sketch flux linkage of a turn on the rotor

- Calculate the maximum voltage induced in turn from Faraday



Flux density-distribution in air gap

DC Machines

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