Overview Electrical Machines and Drives

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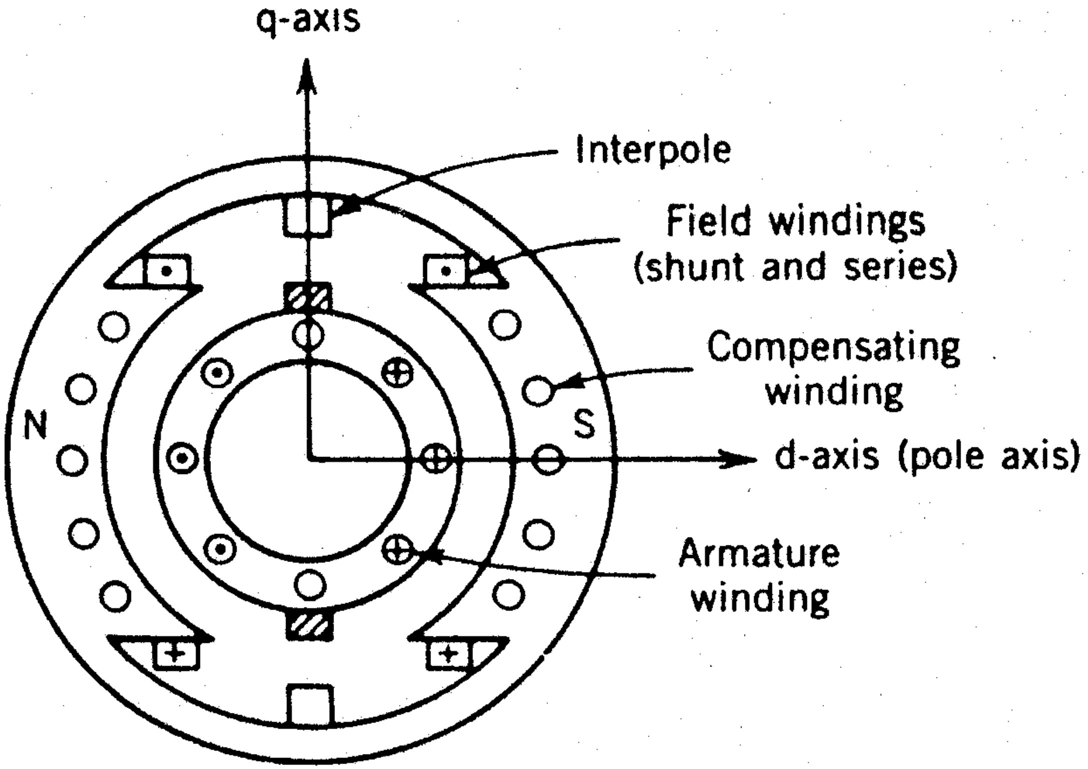
DC Machines

- 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)
- 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)

Assumptions for calculations

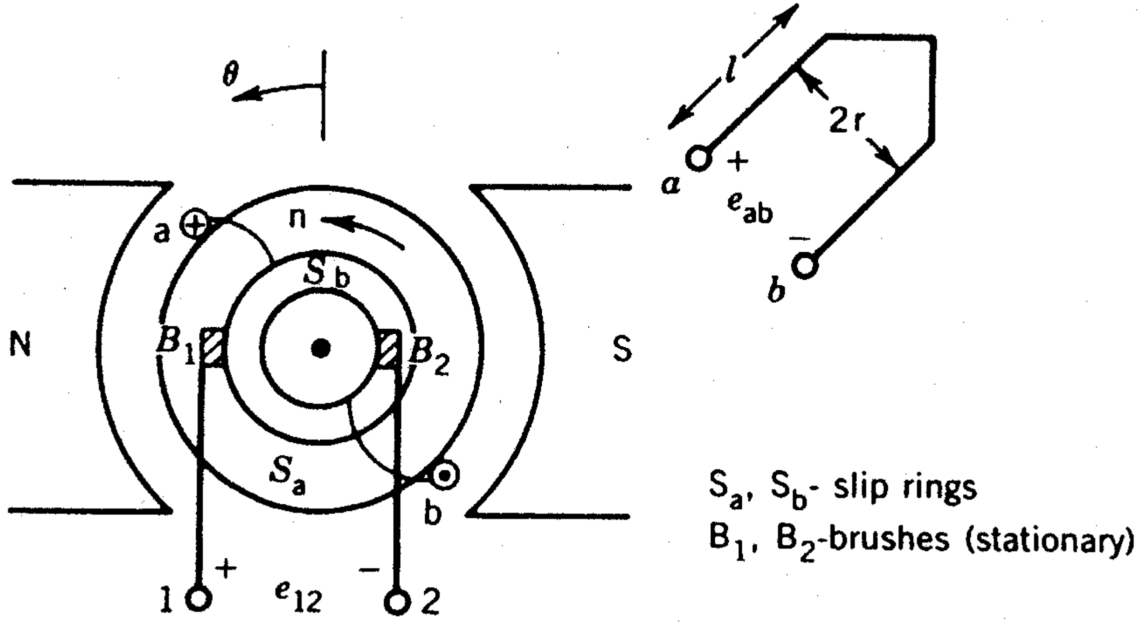
- steady state (mechanical and electrical)
- the air gap is so small that the flux density does not change in radial direction
- the air gap is so small that the flux density crosses the air gap perpendicular
- iron losses are negligible
- the magnetic permeability of iron is infinite

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

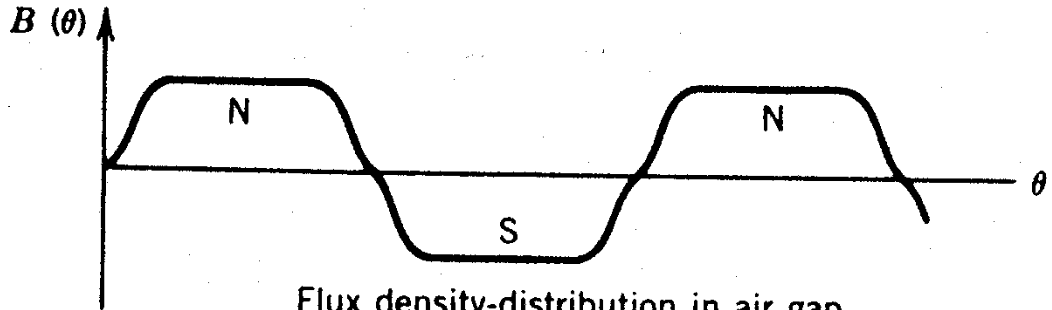


(a)

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

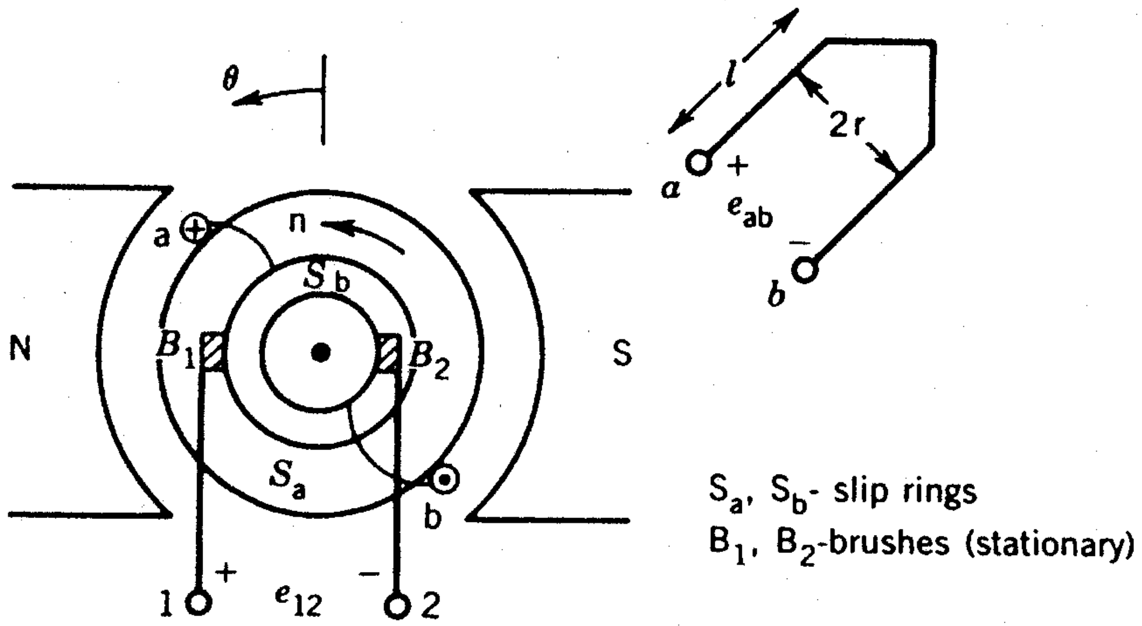
$$2H_g l_g = 2N_f I_f$$

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



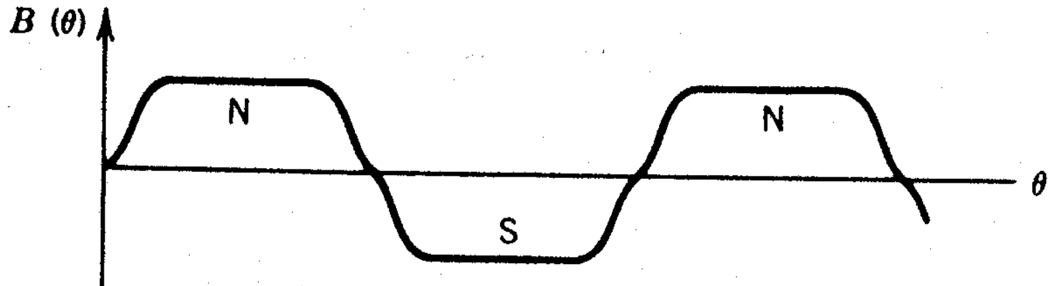
Flux density-distribution in air gap

Flux density



(a)

- Sketch flux linkage of a turn on the rotor
- Calculate the maximum voltage induced in turn from Faraday's law



Flux density-distribution in air gap

Armature turn voltage

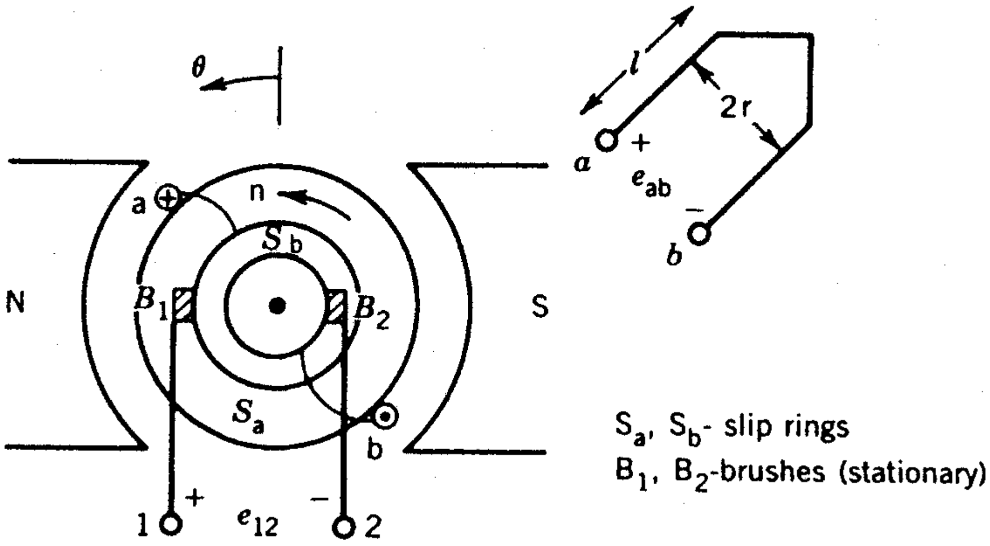
At θ=0, the flux linkage is minimum

$$e_t = \frac{\mathrm{d}\lambda}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\iint_{S_e} \vec{B}\cdot\vec{n}\,\mathrm{d}A$$

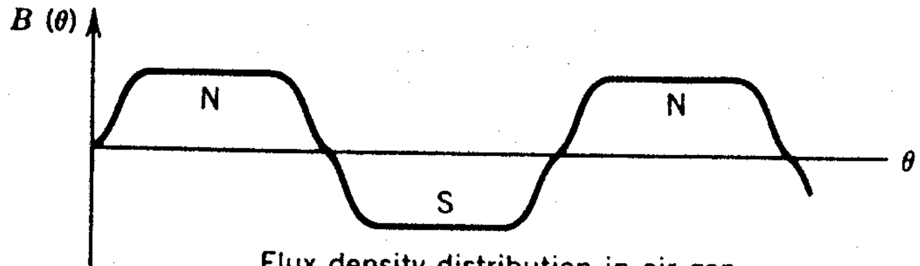
$$= -l\frac{\mathrm{d}}{\mathrm{d}t}\int_{\theta}^{\theta+\pi} B(\theta)r\,\mathrm{d}\theta$$

$$= lrB(\theta)\frac{\mathrm{d}\theta}{\mathrm{d}t} - lrB(\theta+\pi)\frac{\mathrm{d}\theta}{\mathrm{d}t}$$

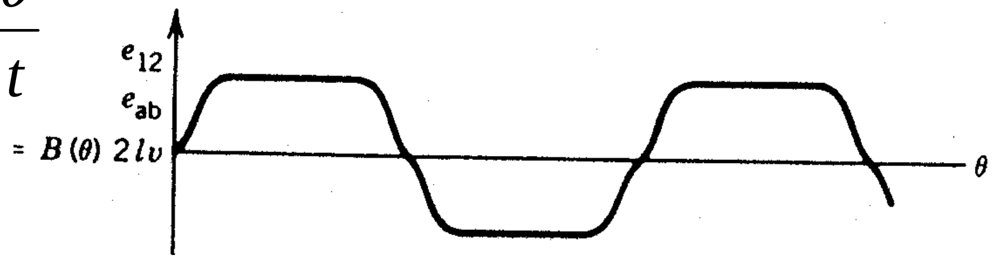
$$= 2lrB(\theta)\omega = 2lB(\theta)v$$



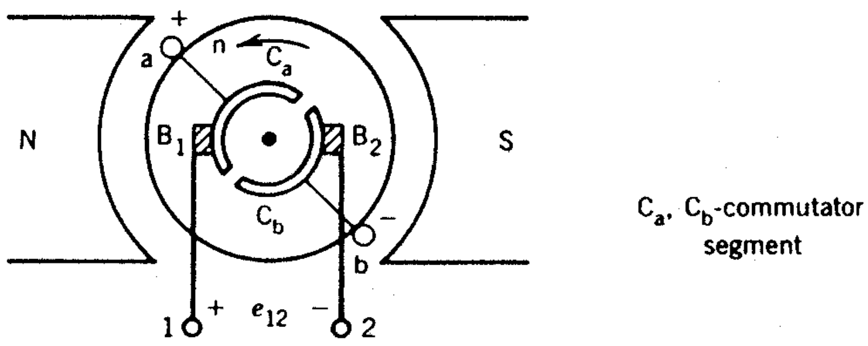
(a)



Flux density-distribution in air gap



Commutator as rectifier



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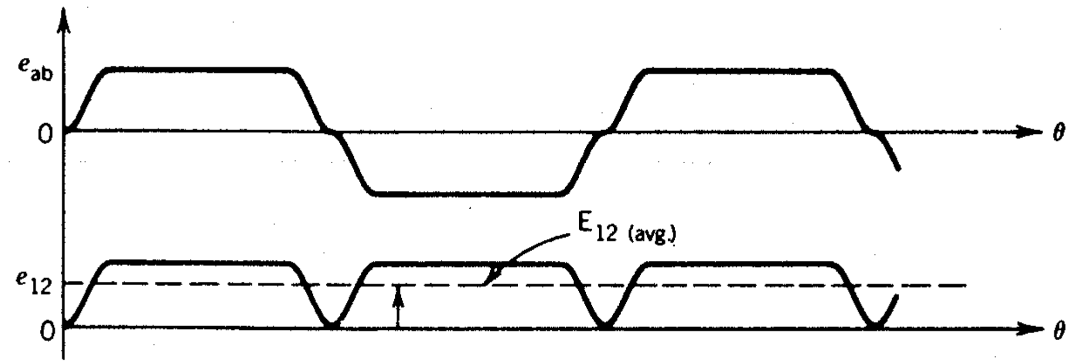
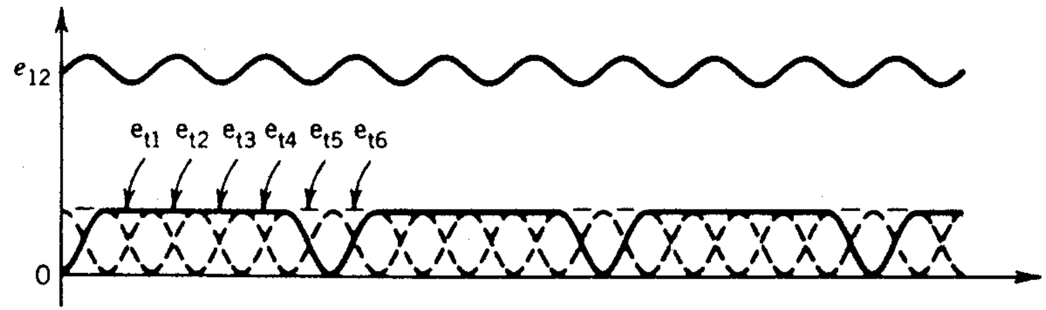
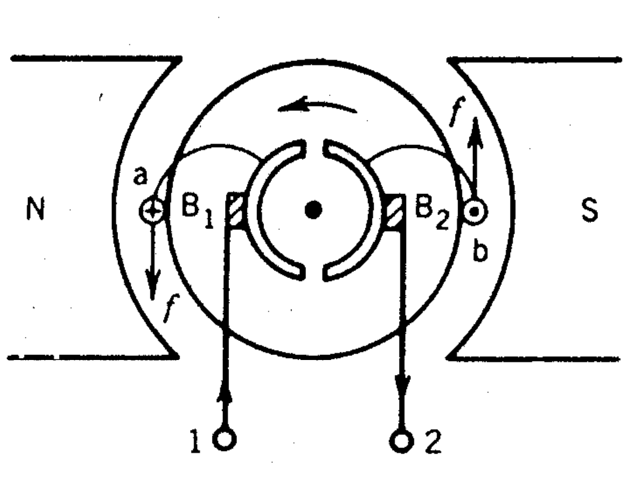


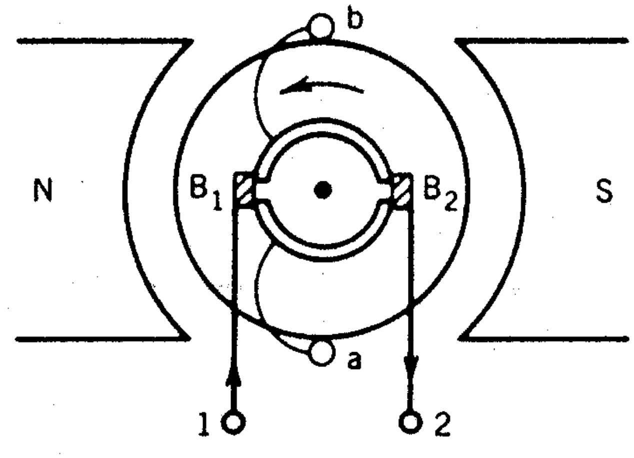
(b)



Commutation

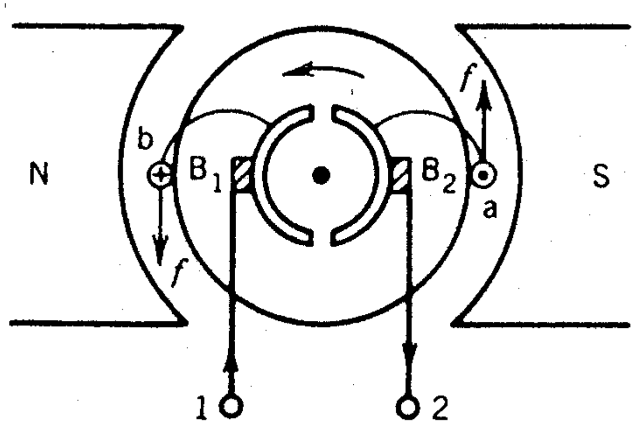


(a)

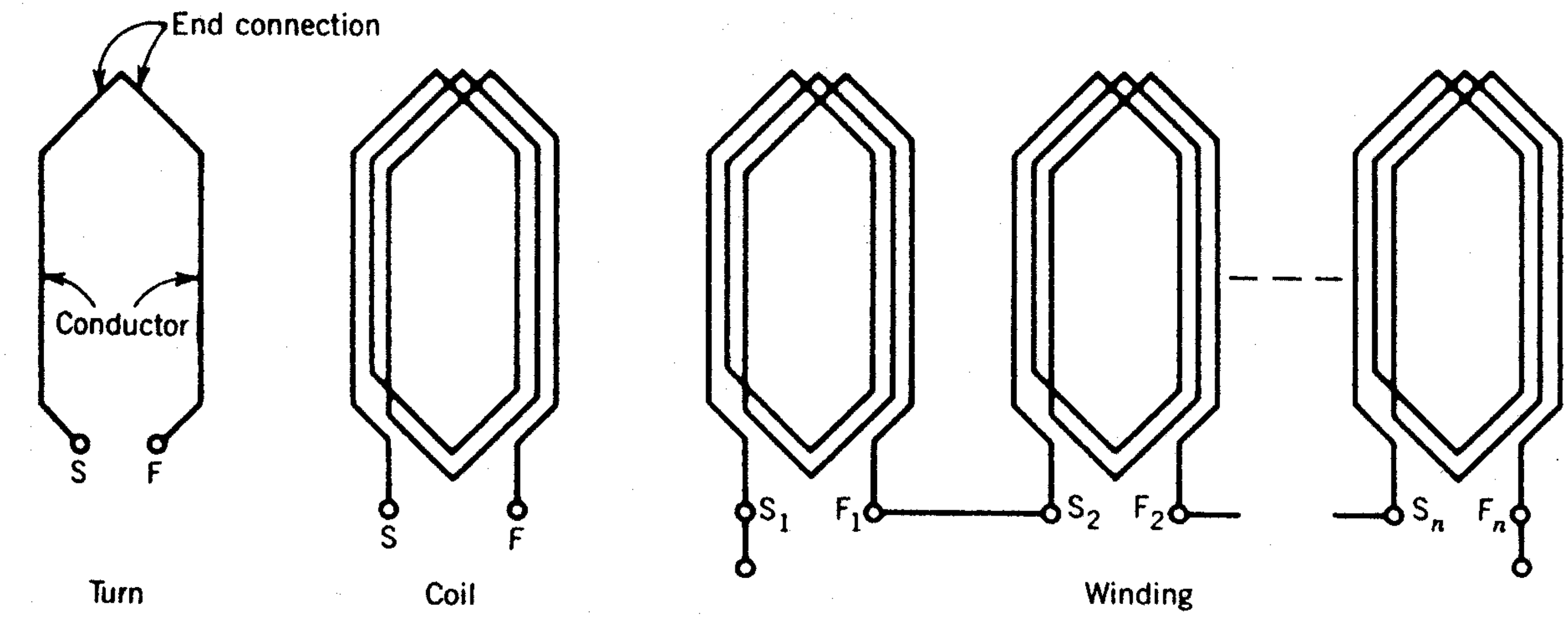


(b)

Commutating coil in interpolar region: no induced voltage



Armature windings



- English: turn, coil, winding
- Dutch: winding, spoel, wikkeling

Mechanical and electrical angles

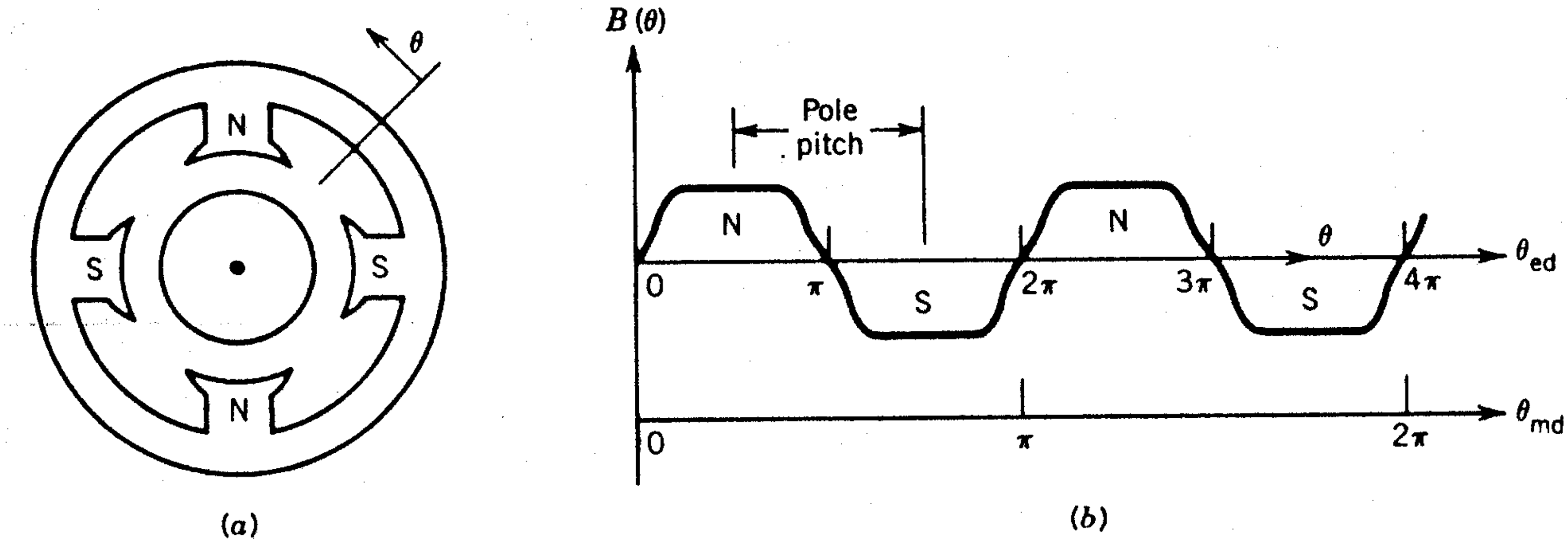


FIGURE 4.16 Mechanical and electrical degrees. (*a*) Four-pole dc machine. (*b*) Flux density distribution.

$$\theta_e = \frac{p}{2}\theta_m \qquad \omega_e = \frac{p}{2}\omega_m$$

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Armature voltage

An armature winding has *N* turns
with *a* parallel paths
and therefore *N/a* series-connected turns

For the turn voltage, we found $$e_t = 2lr\omega_m B(\theta)$$

The average is lower: $$\bar{e}_t = 2lr\omega_m \overline{B}(\theta)$$

Flux per pole $$\Phi = \iint \vec{B} \cdot \vec{n} \, \mathrm{d}A = l \int_0^{2\pi/p} B(\theta) r \, \mathrm{d}\theta = \frac{2\pi}{p} rl\overline{B}(\theta)$$

Using this, the turn voltage is given by $$\bar{e}_t = \frac{p}{\pi} \Phi \omega_m$$

Therefore $$E_a = \frac{N}{a} \bar{e}_t = \frac{Np}{\pi a} \Phi \omega_m = K_a \Phi \omega_m$$

Voltage and torque from power balance

$$U = RI_a + L\frac{\mathrm{d}I_a}{\mathrm{d}t} + K_a\Phi\omega_m$$

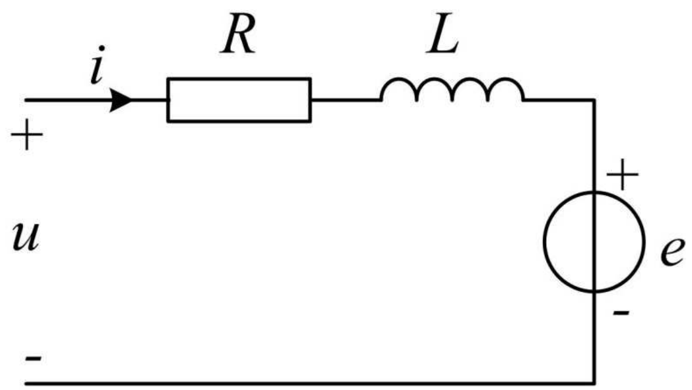
$$P = UI_a = RI_a^2 + I_aL\frac{\mathrm{d}I_a}{\mathrm{d}t} + I_aK_a\Phi\omega_m$$

Power balance:

$$P = P_{Cu} + P_f + P_{mech}$$

Therefore

$$T = \frac{P_{mech}}{\omega_m} = K_a\Phi I_a$$



Electromagnetic torque from Lorenz

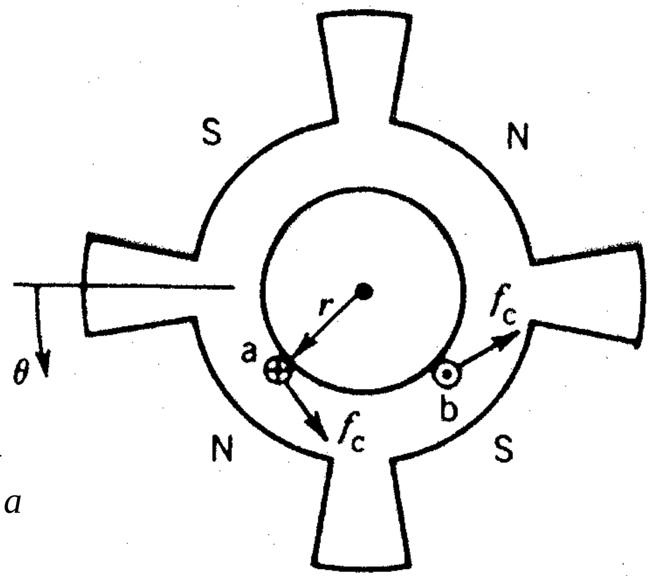
$$F_c = B(\theta) l I_c = B(\theta) l \frac{I_a}{a}$$

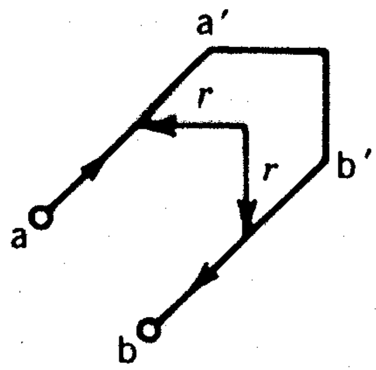
$$T_c = r F_c = B(\theta) r l \frac{I_a}{a}$$

$$\overline{T}_c = \overline{B}(\theta) r l \frac{I_a}{a} = \frac{p}{2\pi a} \Phi I_a$$

$$T = 2N\overline{T}_c = \frac{Np}{\pi a} \Phi I_a = K_a \Phi I_a$$

$$P = \omega_m T = \omega_m K_a \Phi I_a = E_a I_a$$

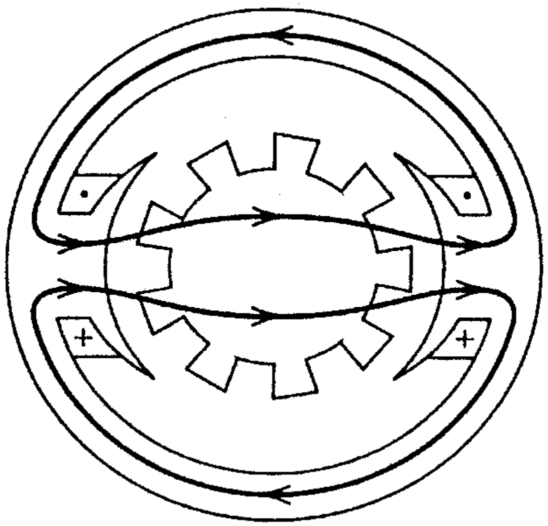




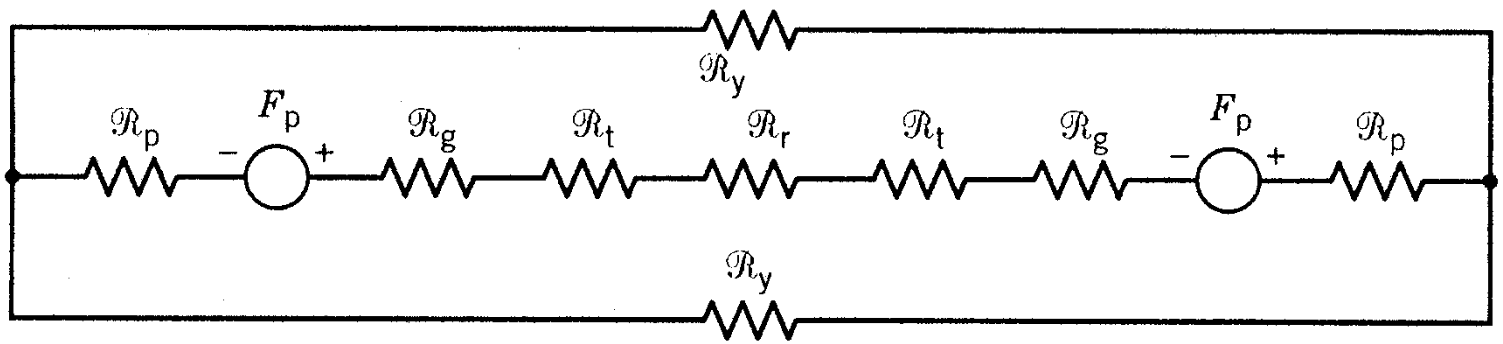
Lorenz force gives the same result as power balance.

Magnetic circuit

Which part saturates first?
Why?



(a)



Magnetization curve

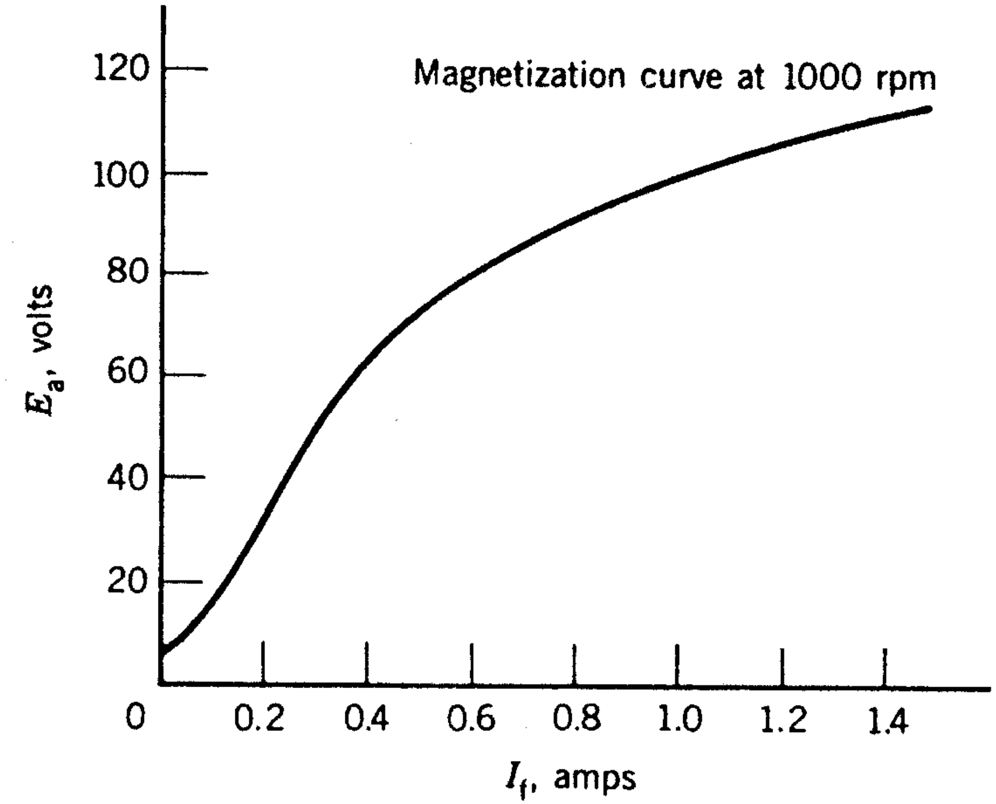


FIGURE 4.24 Test result: magnetization curve.

Why is this not a straight line?
Why does it not start from zero?

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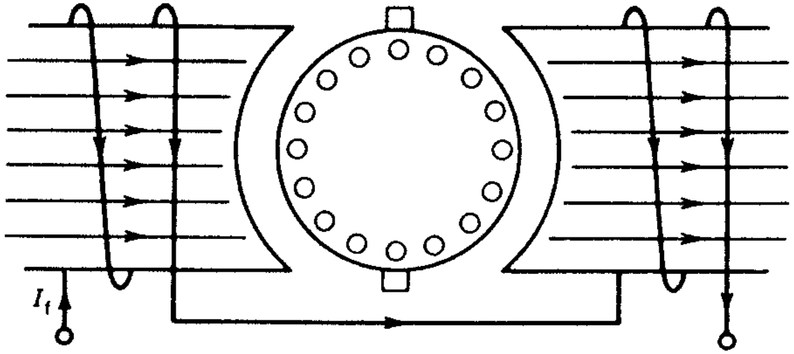
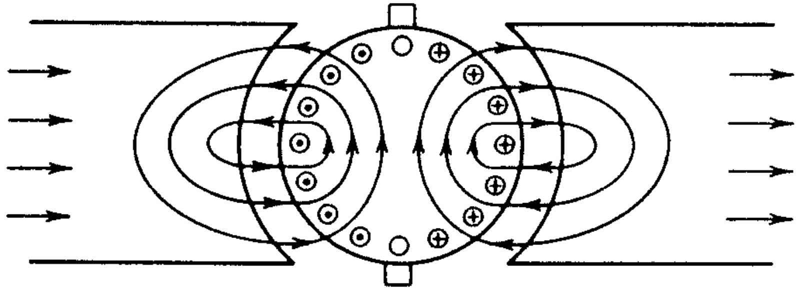
Armature reaction

- Section 4.3 (Sen) has the title “DC generators”
- DC machines are hardly used as generators
- The operating principles are the same in motoring and generating
- Therefore, we only look at constructional aspects of DC machines discussed in 4.3, which are present in DC motors as well as in DC generators:
  - compensating winding (Dutch: compensatiewikkeling)
  - interpoles (Dutch: hulppolen)
- Both are related to armature reaction

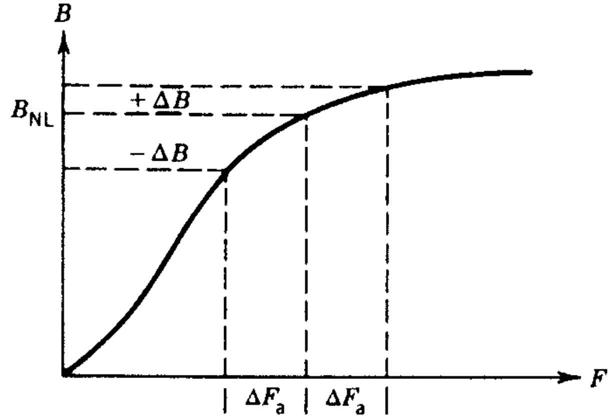
Armature reaction



(a)

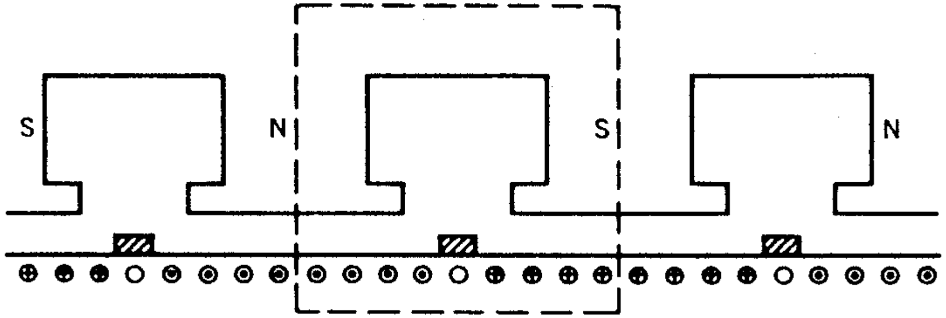


(b)

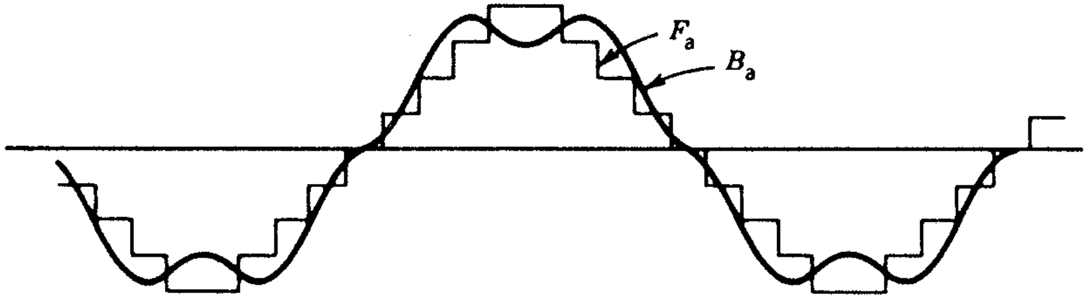


Consequences armature reaction

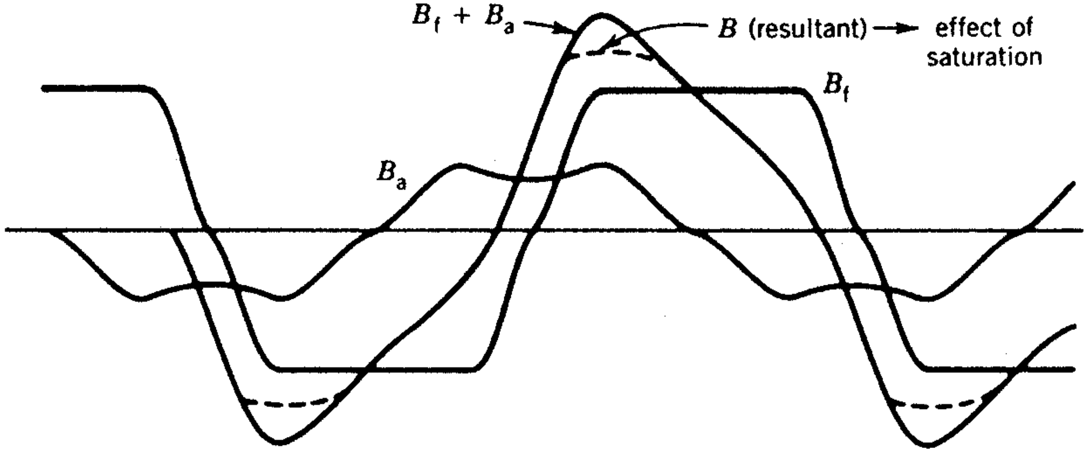
- Saturation
- Commutation problems



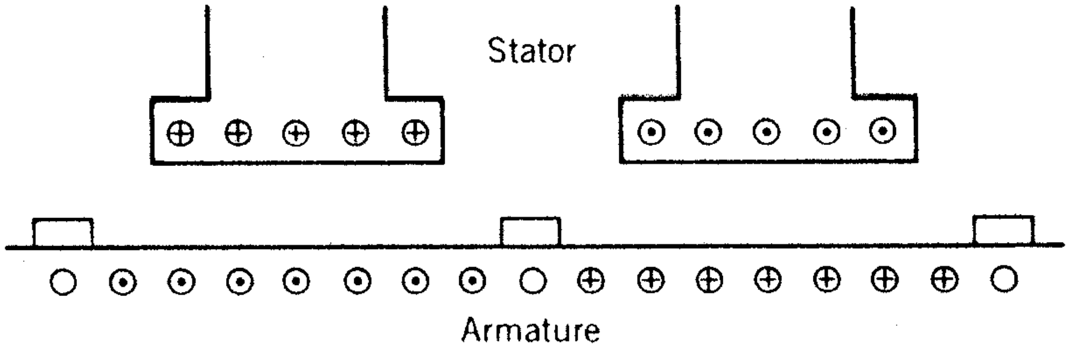
(a)



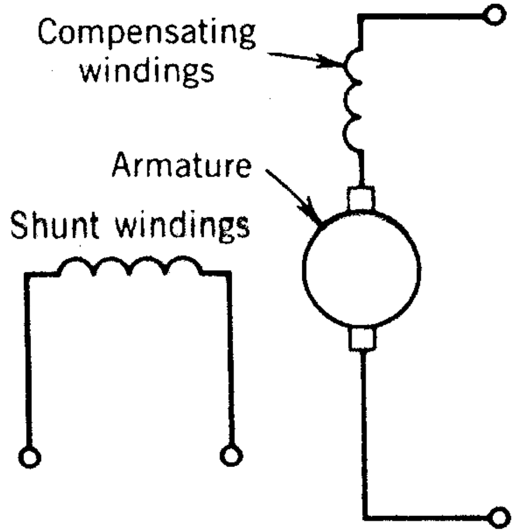
(b)



Compensation winding



(a)

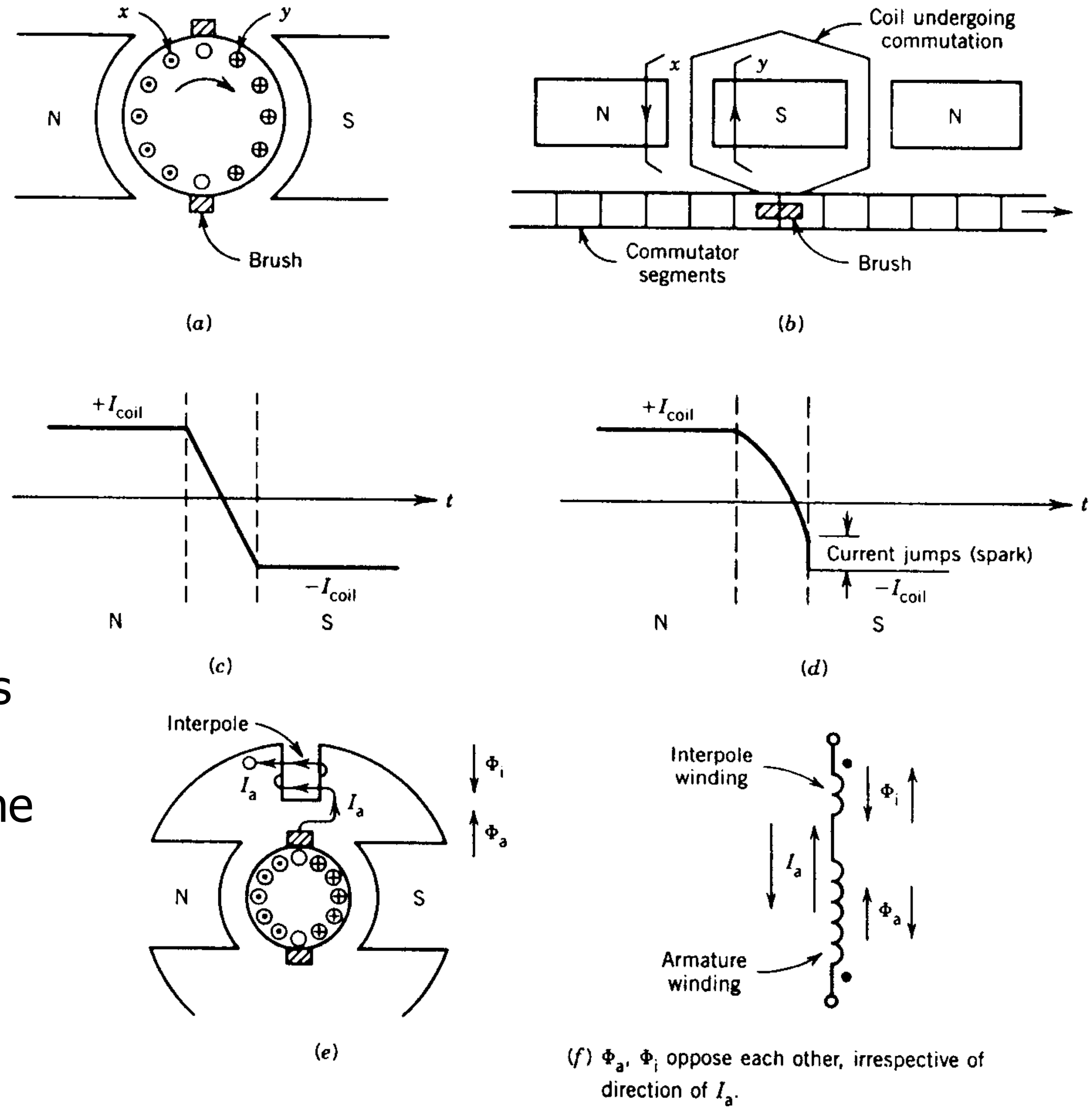


(b)

- Saturation problem reduced
- Expensive; only applied in machines that are often heavily loaded. Why in these machines?

Interpoles

Armature reaction produces a flux density in the interpolar region, so that a voltage is induced in the commutating coil. This voltage opposes commutation. Interpoles reverse the direction of this flux density to induce a voltage that accelerates commutation.



DC Machines

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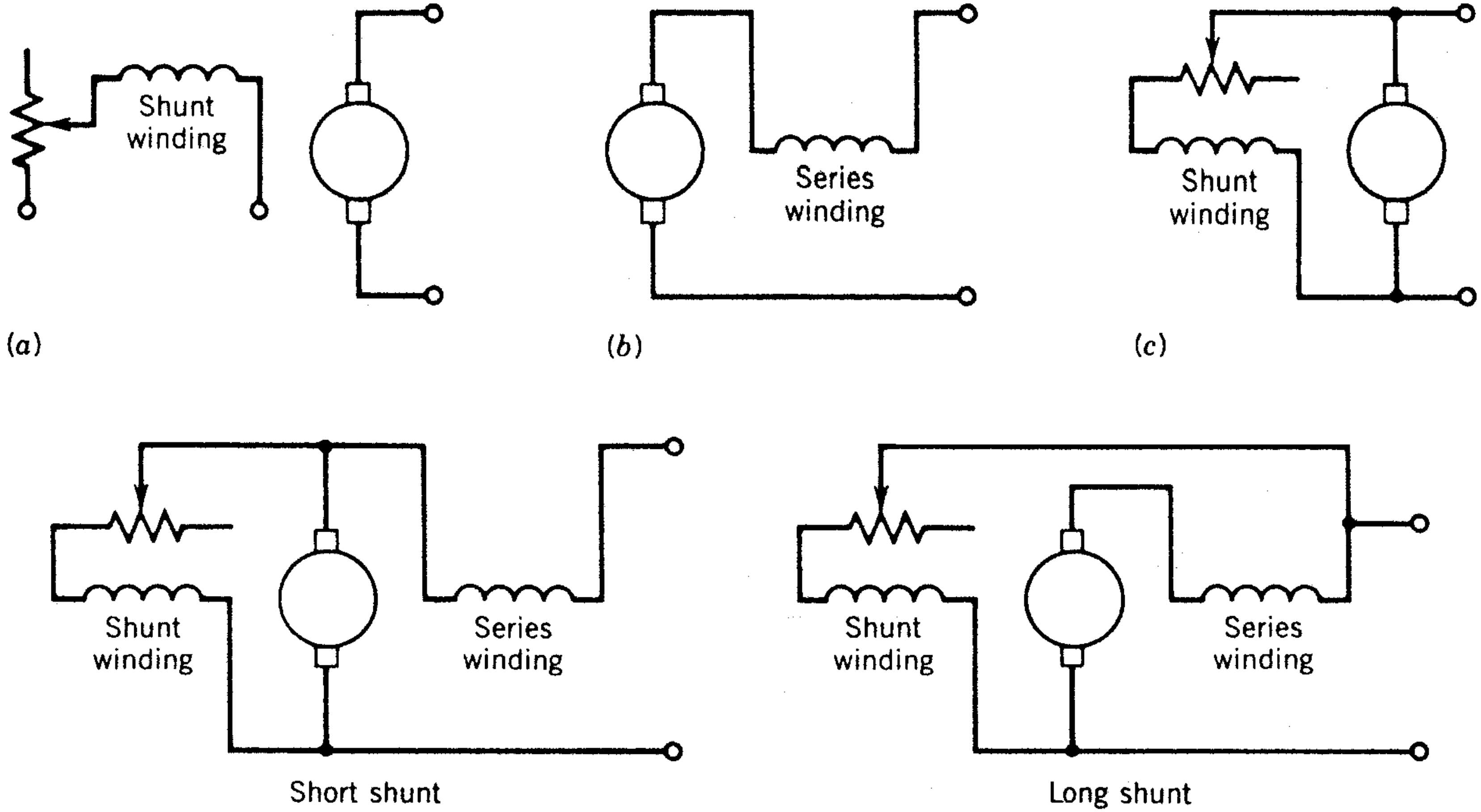
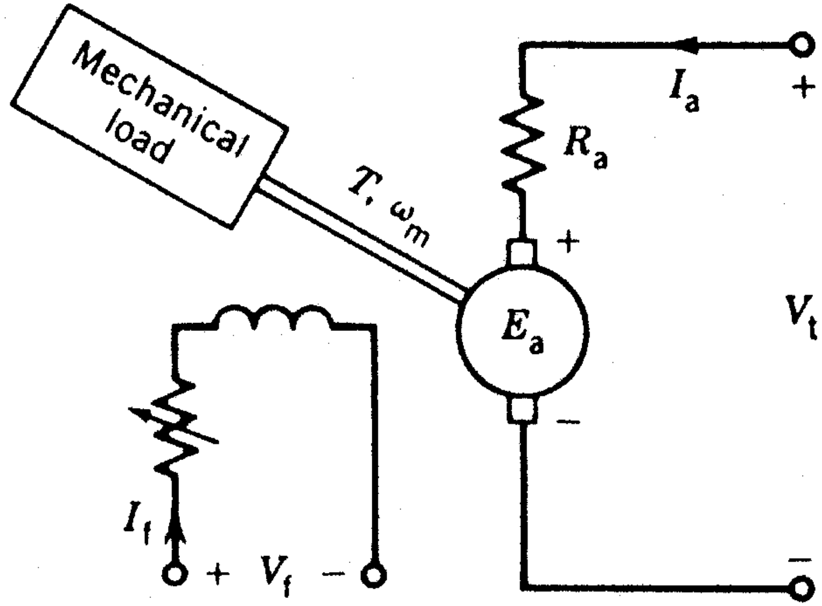
- Characteristics, means to control speed (4.4)
  - Connections of DC machines
  - Separately excited DC machine
  - Series connected DC machine
- DC machine drives (4.5)
- PMDC machines / PCB machines (4.6, 4.7)

Connections of DC machines



Separately excited DC machines



Pole flux does not depend on armature voltage and load

$$T = K_a \Phi I_a$$

$$E_a = \omega_m K_a \Phi$$

$$U_t = R_a I_a + E_a$$

$$\omega_m = \frac{U}{K_a \Phi} - \frac{R_a I_a}{K_a \Phi} = \frac{U}{K_a \Phi} - \frac{R_a T}{(K_a \Phi)^2}$$

How to control speed?

Calculate no-load speed and stall torque.

Torque speed characteristic

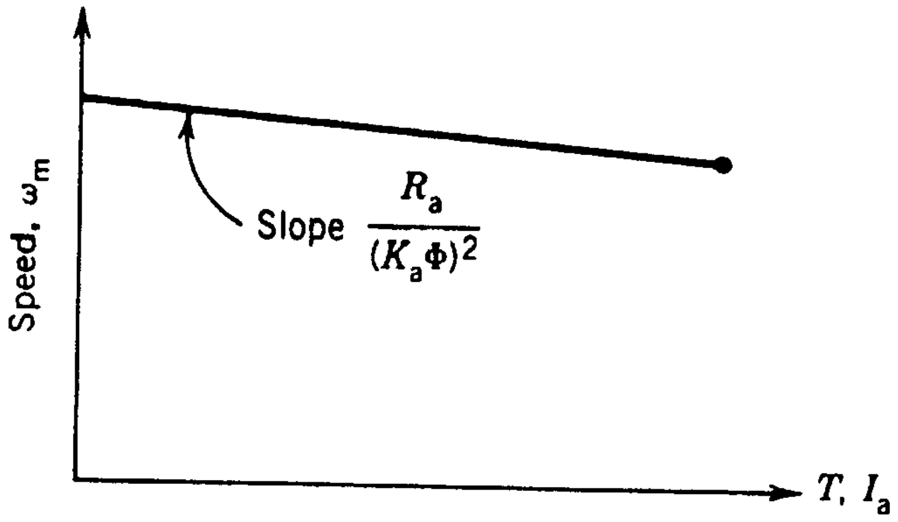
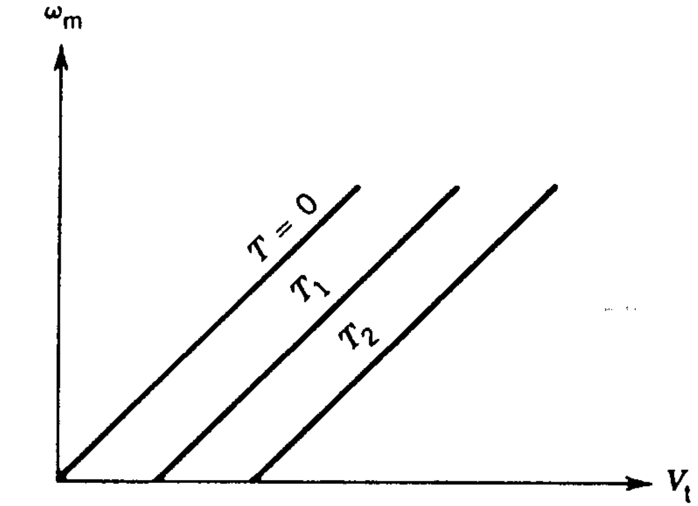


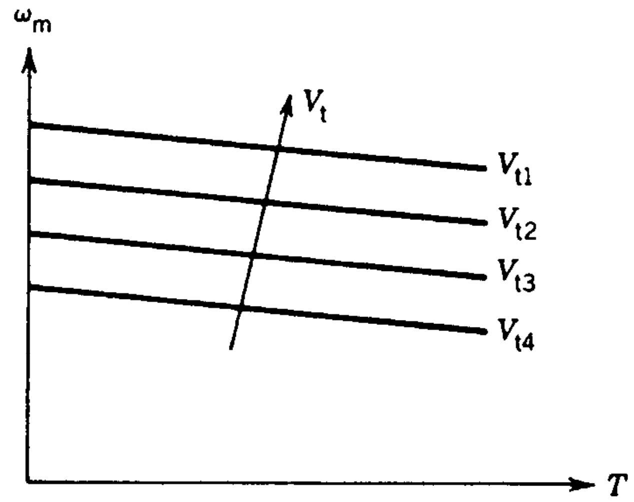
FIGURE 4.51 Torque–speed characteristics of a separately excited dc motor.

- Where are motor, generator and plugging operation?
- Speed control by means of
  - Voltage control: what happens if the voltage is increased?
  - Field control: what happens if the current is increased?
  - Resistance control: old-fashioned

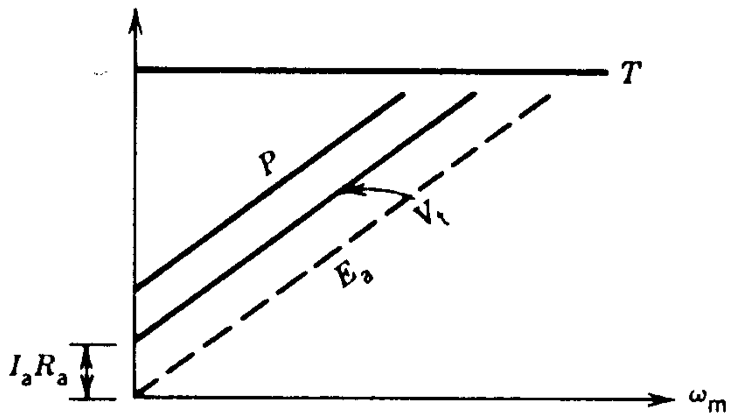
Voltage control

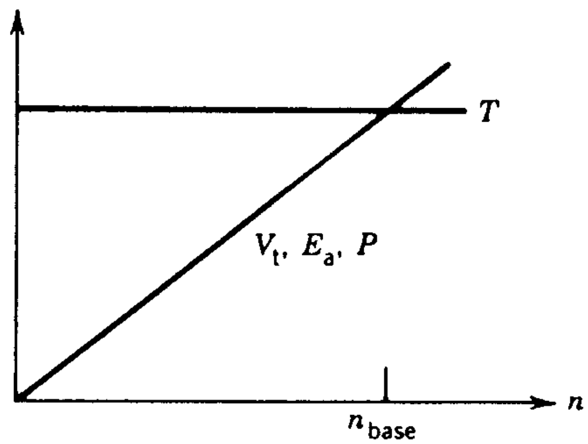


(a)

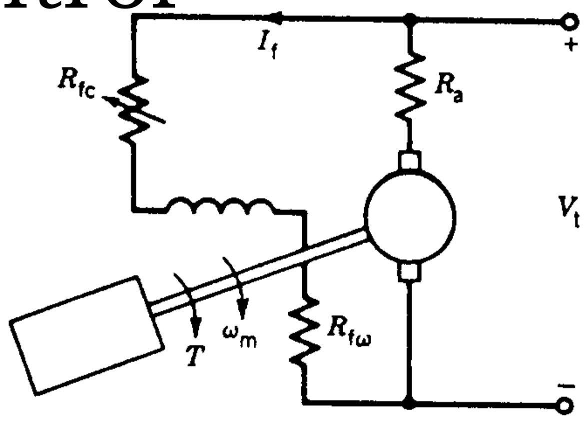


(b)

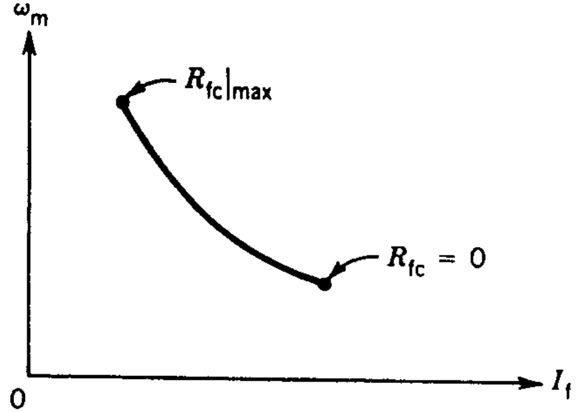




Field control

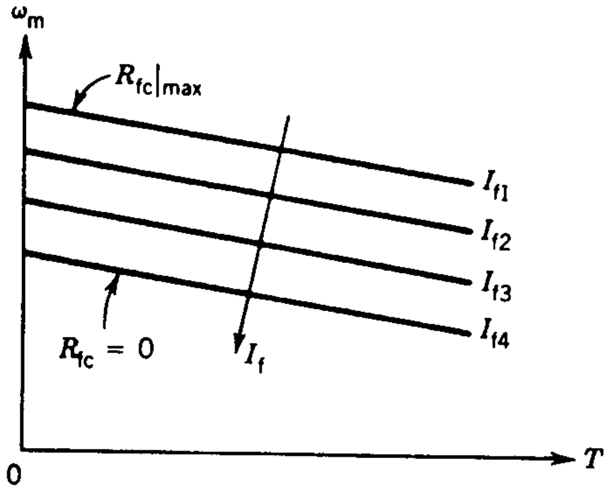


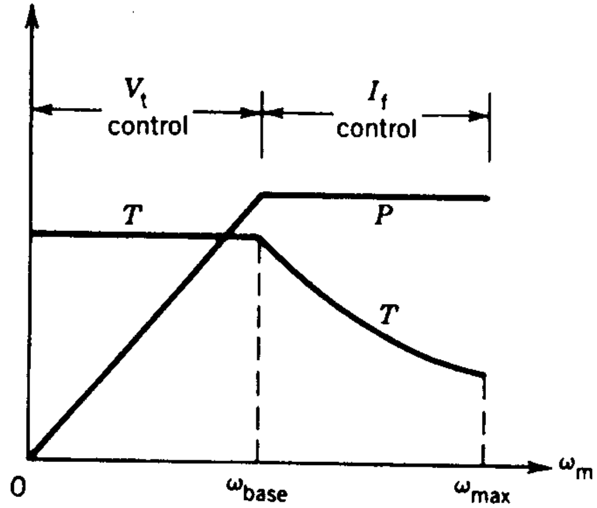
(a)



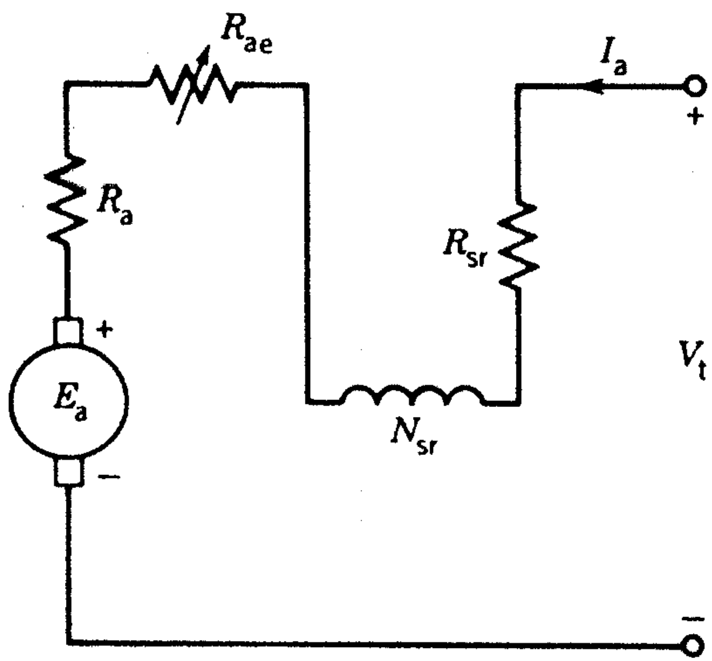
(b)

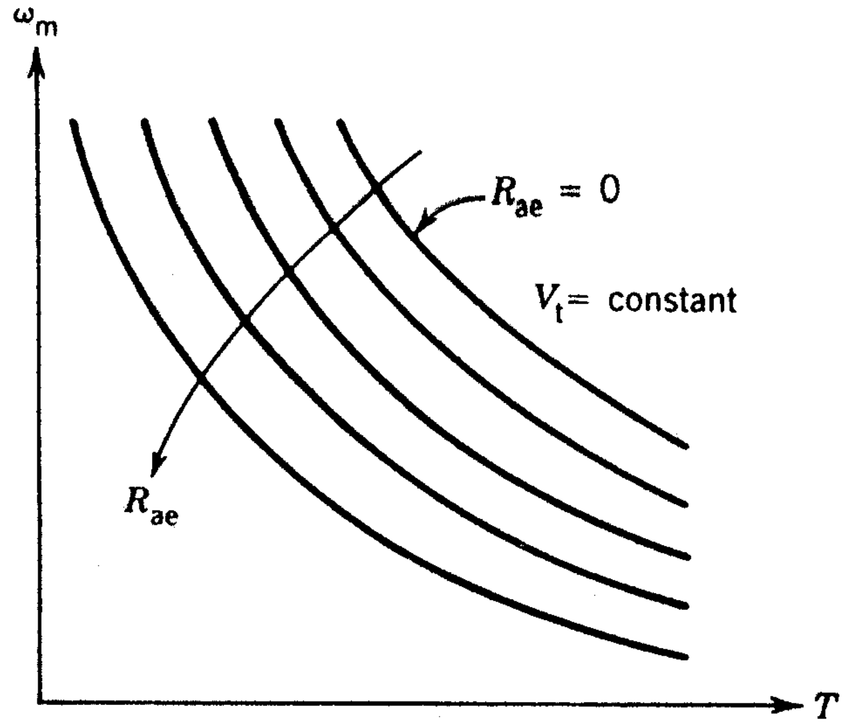
Are the characteristics of (c) parallel?





Series DC machine (universal motor)





$$\Phi = K_1 I_a \qquad T = K_a \Phi I_a = K_a K_1 I_a^2$$

Neglecting saturation!

What happens to the speed when the torque is zero?

Series DC motor

$$\Phi = K_1 I_a$$

$$T = K_a \Phi I_a = K_a K_1 I_a^2$$

$$U_t = R_a I_a + E_a = R_a I_a + K_a \Phi \omega_m = R_a I_a + K_a K_1 I_a \omega_m$$

$$I_a = \frac{U_t}{R_a + K_a K_1 \omega_m}$$

$$T = K_a \Phi I_a = K_a K_1 I_a^2 = K_a K_1 \frac{U_t^2}{(R_a + K_a K_1 \omega_m)^2}$$

$$\omega_m = \pm \frac{U_t}{\sqrt{K_a K_1 T}} - \frac{R_a}{K_a K_1}$$

DC machines

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- DC machine drives (4.5)
  - Ward-Leonard system
  - Power electronics (Rectifier, Chopper)
  - Closed loop control
- PMDC machines / PCB machines (4.6, 4.7)

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