Gelijkstroommachines

R. BELMANS

HOOFDSTUK 1

BASISBEGRIPPEN

Overzicht

- Basisbegrippen
- Opbouw van een magnetisch veld
- Geïdealiseerde gelijkstroommachine
- Stationair gedrag
- De gelijkstroommachine als element in een regelketen

Basisbegrippen

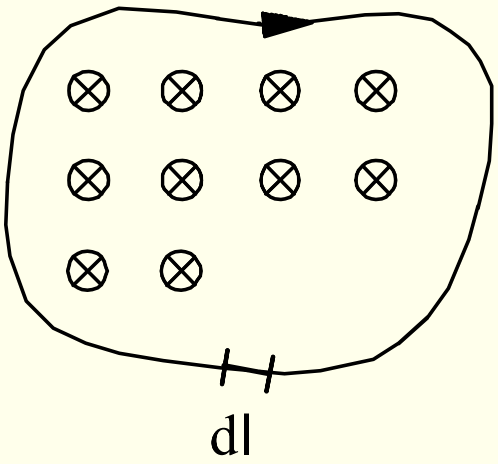
- Motormodel
- Werkingsprincipe
- Commutatie
- Praktische uitvoering

Motormodel

Ferromagnetisch materiaal
Luchtspleet
Fluxopwekking: m.m.k.

$$\Theta = Ni$$

$$\oint \vec{H} \cdot d\vec{\ell} = \Theta = Ni$$



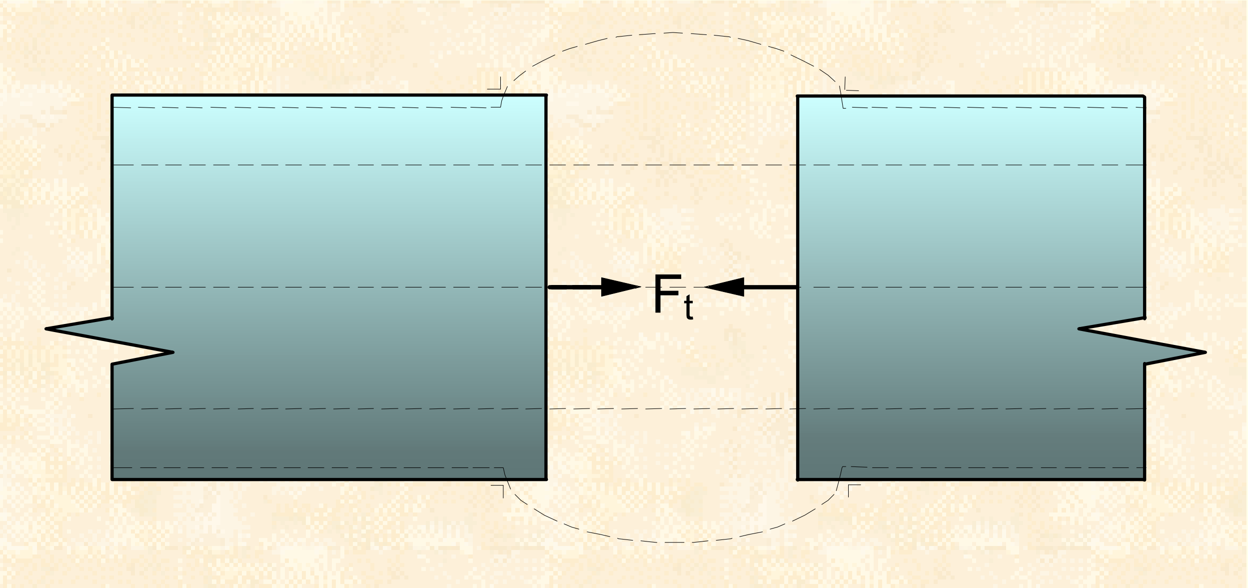
$$\iint \vec{B} \cdot d\vec{A} = \phi$$

$$i \quad \rightarrow \quad \Theta \quad \rightarrow \quad \vec{H} \quad \rightarrow \quad \vec{B} \quad \rightarrow \quad \phi$$

$$\phi = \frac{\Theta}{\Re_m} = \Theta\Lambda = \frac{Ni}{\Re_m} = Ni\Lambda$$

Magnetische weerstand Fe, meestal verwaarloosbaar

Maxwell'se trekspanning

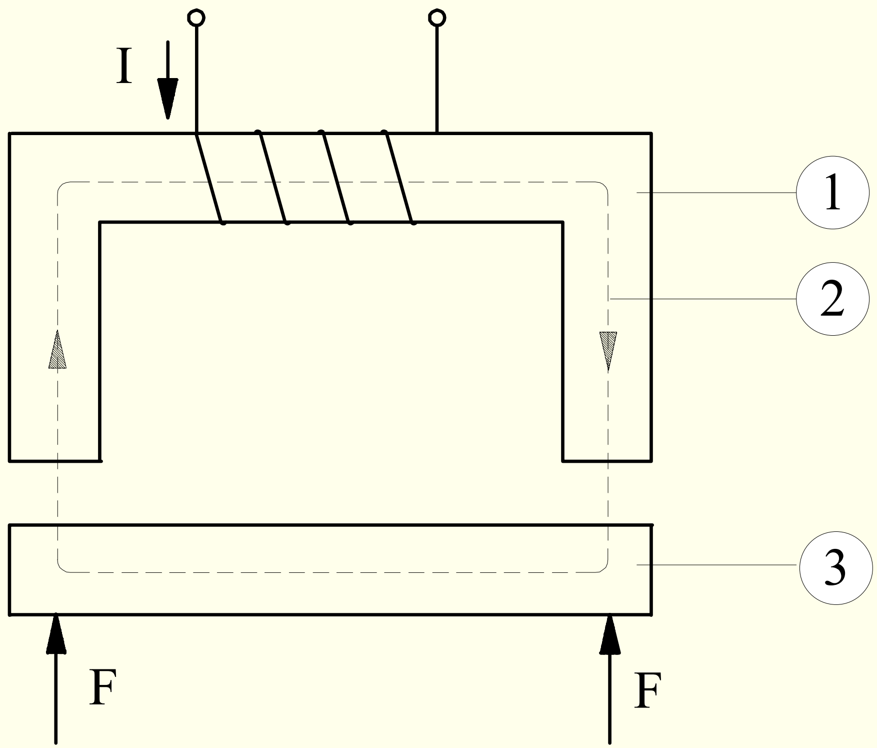


$$\sigma_t = \frac{F_t}{A} = \frac{B^2}{2\mu_0}$$

Werkingsprincipe

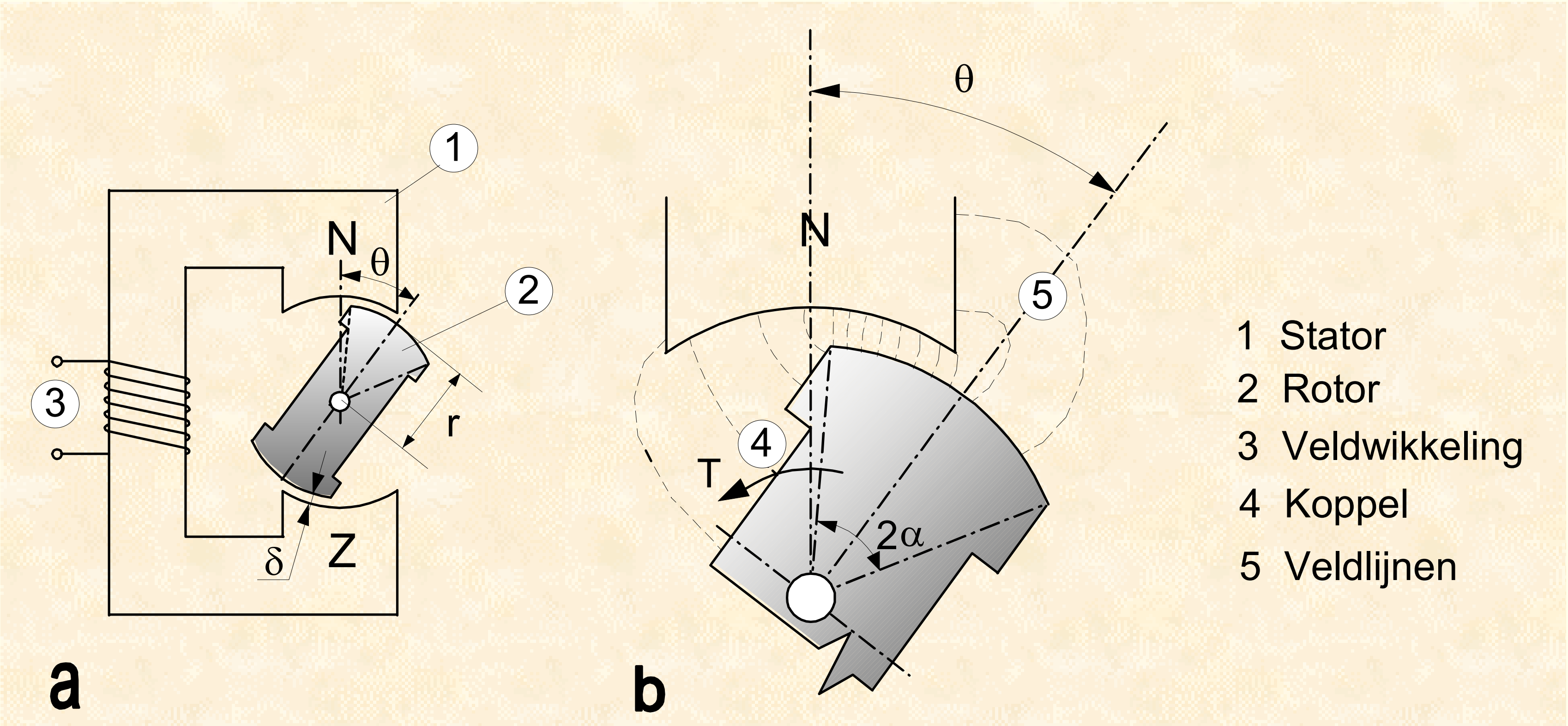
- Reluctantiekracht (aligneerkracht)
- Interactiekracht
- Geïnduceerde spanning (e.m.k.)

Reluctantiekracht



1 ijzer
2 veldlijn B
3 ijzer

Werking van een elementaire elektrische motor - aligneerkracht



$$w_{magn} = \frac{1}{2} B.H = \frac{B^2}{2\mu_0}$$

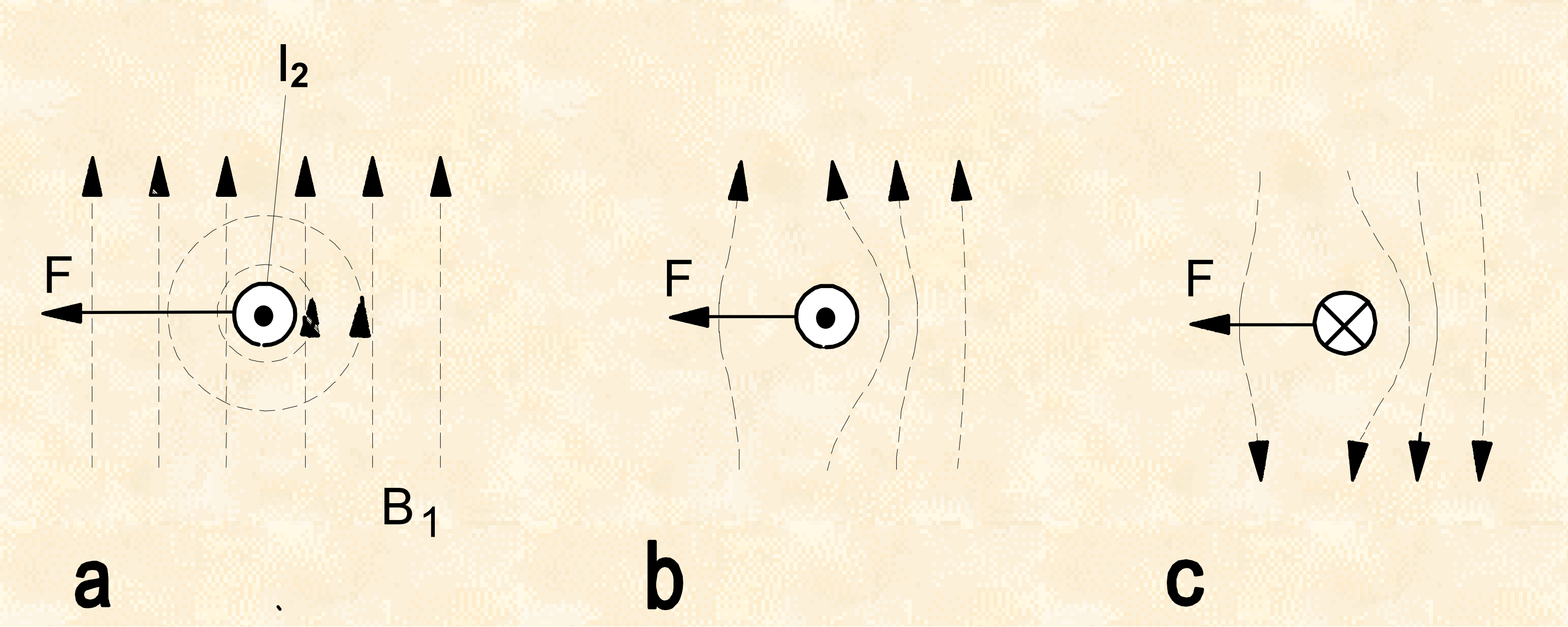
$$V = \ell\, \delta\, r\, (2\alpha - \theta)$$

$$W = \frac{B^2}{\mu_0} \ell\, \delta\, r\, (2\alpha - \theta)$$

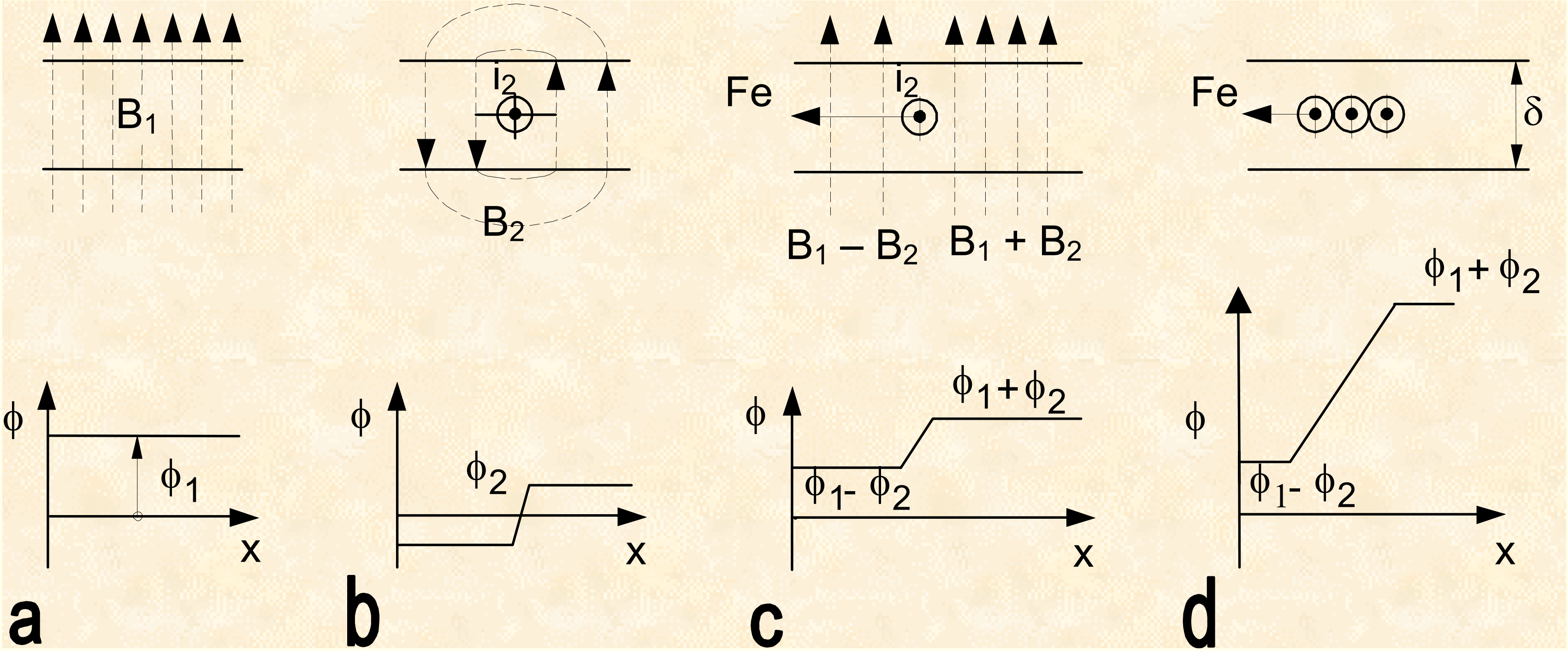
$$T = \left| \frac{dW}{d\theta} \right| = \frac{B^2 \ell\, \delta r}{\mu_0}$$

Interactiekracht

$$F = B_1 \ell\, i_2$$



Veldverdeling in de luchtspleet

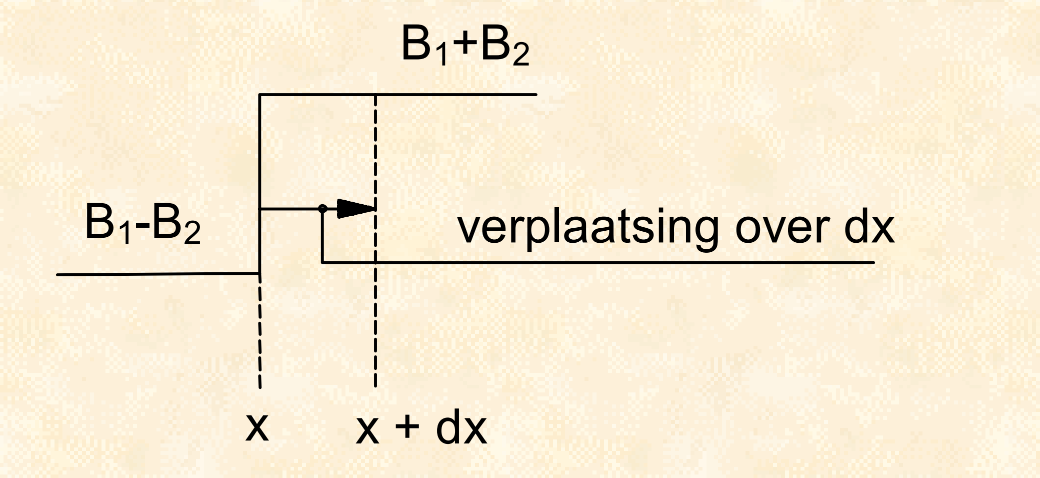


$$B_1 = \mu_0 H = \mu_0 \frac{\Theta_1}{2\delta}$$

$$H_2 2\delta = i_2$$

$$B_2 = \frac{i_2 \mu_0}{2\delta}$$

Wet van de virtuele arbeid voor de krachtberekening



$$dV = \ell\,\delta\,dx$$

$$dW = \frac{1}{2}\left[\left(B_1 + B_2\right)^2 - \left(B_1 - B_2\right)^2\right]\frac{\ell\,\delta\,dx}{\mu_0} = \frac{2}{\mu_0}B_1 B_2\,\ell\,\delta\,dx$$

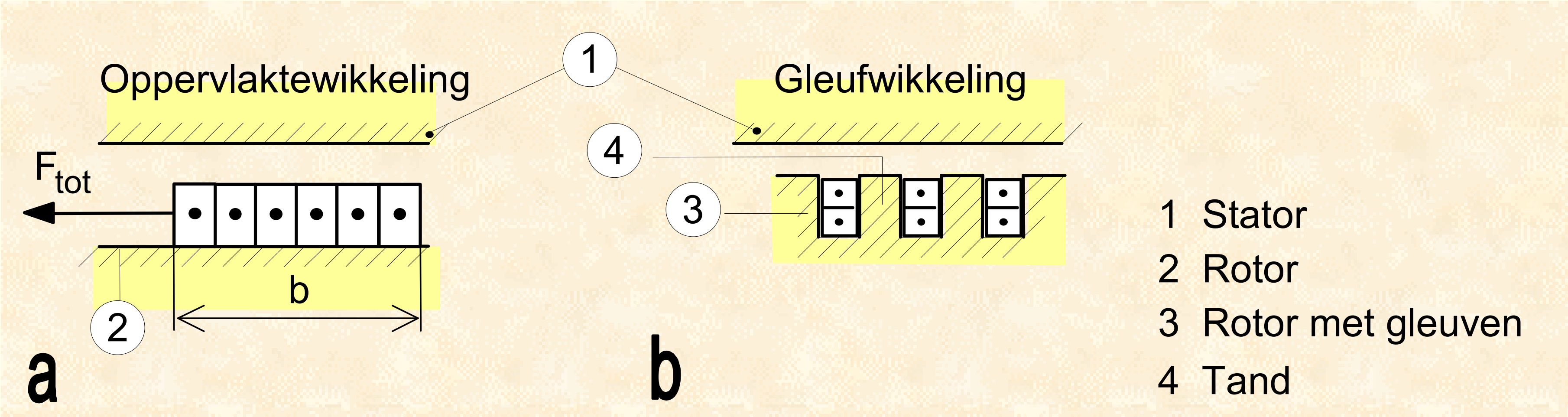
$$dW = B_1 i_2 \ell dx$$

$$F = \frac{dW}{dx} = B_1 i_2 \ell$$

$$\phi_2 = \frac{\mathrm{N}\ \mathrm{i}_2}{\Re_{\mathrm{m}}}$$

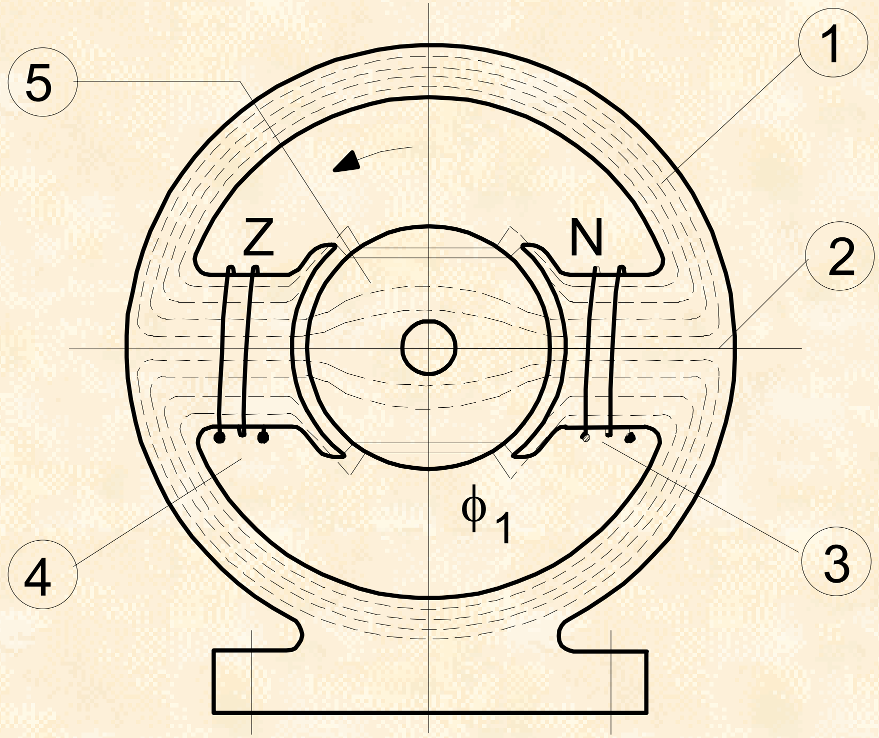
$$F = B_1 \ell N i_2$$

Gleuven



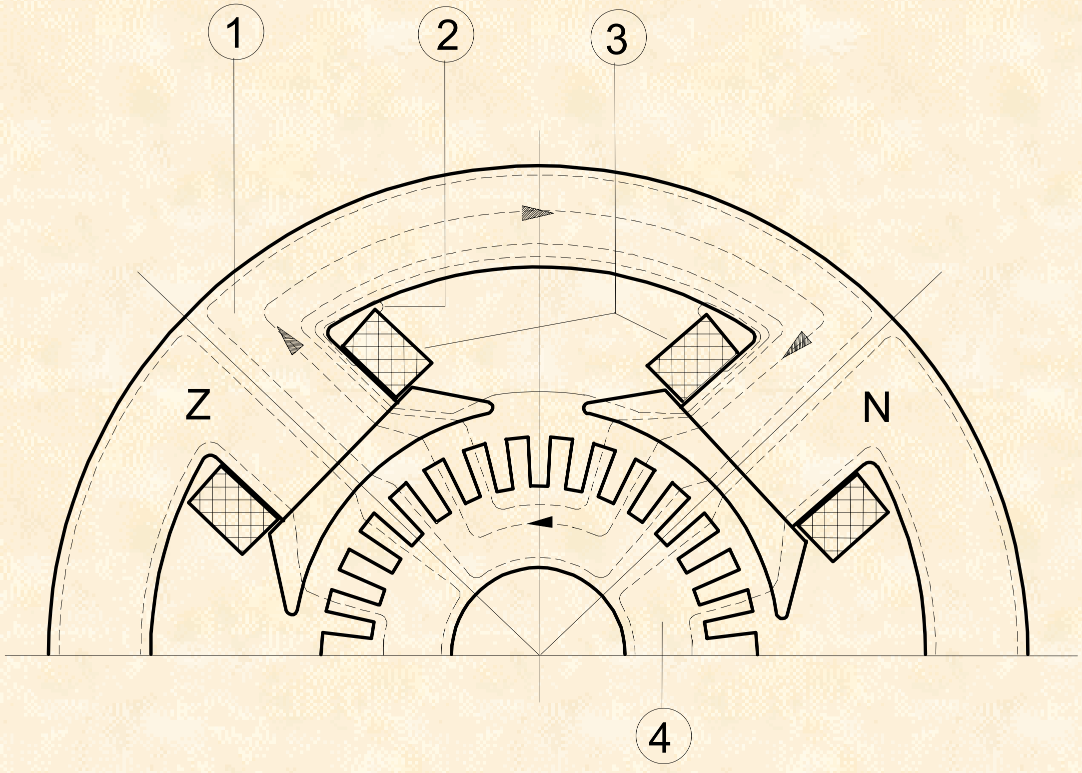
Kracht op tanden
Kortere luchtspleet

Tweepolige machine



1 Juk
2 Pool
3 Bekrachtigingsspoel
4 Bekrachtigingsspoel
5 Rotor (anker)

Vierpolige machine



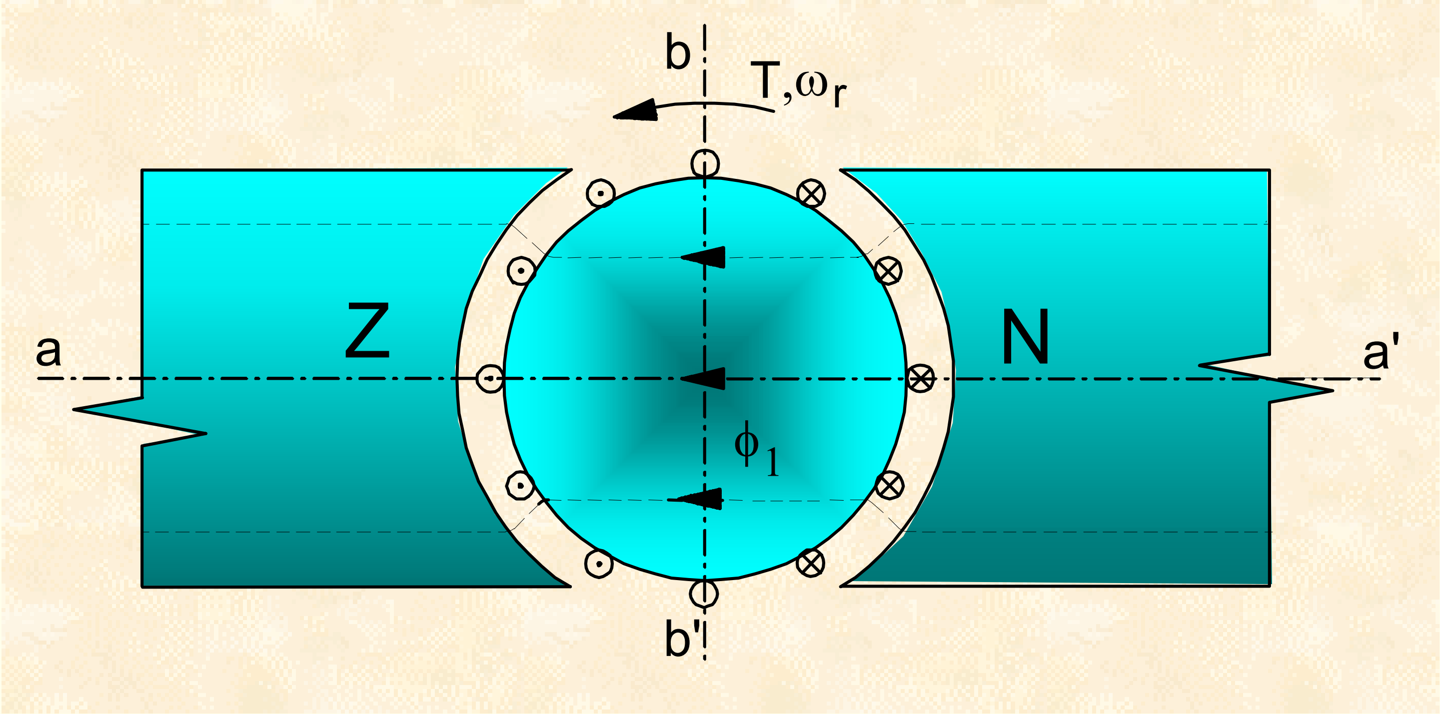
1 Hoofdflux

2 Lekflux

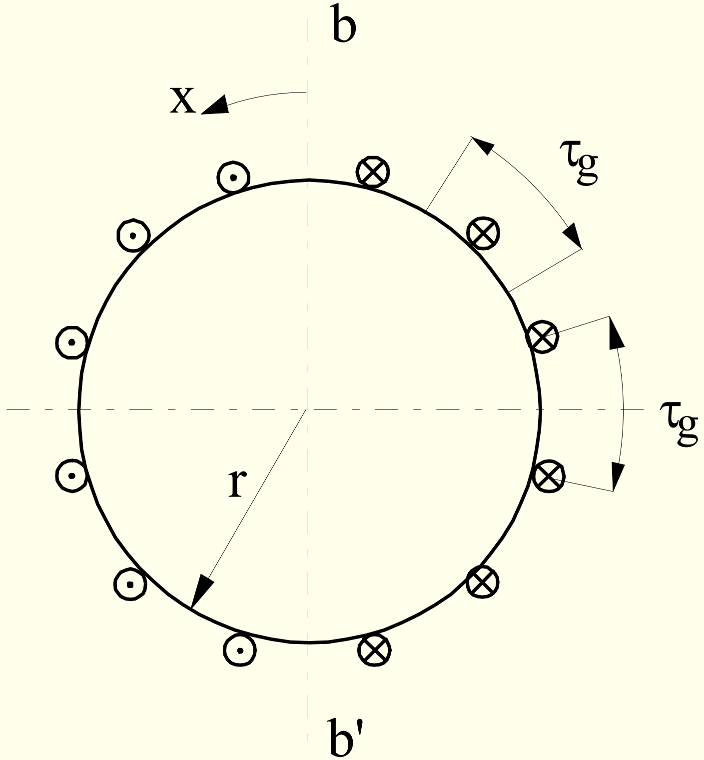
3 Veldwikkeling

4 Rotor

Fundamenele krachtwerking



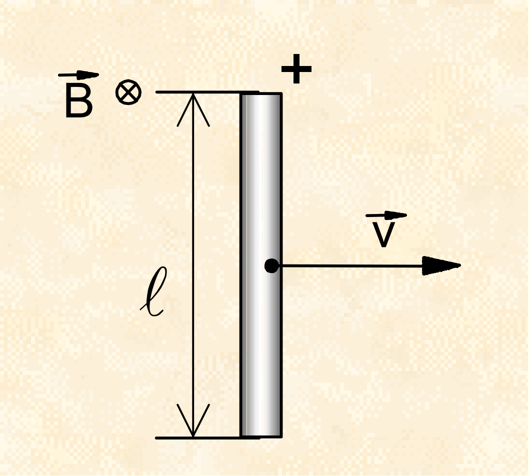
Gleufsteek



x = omtrekscoördinaat

τ_g = gleufsteek

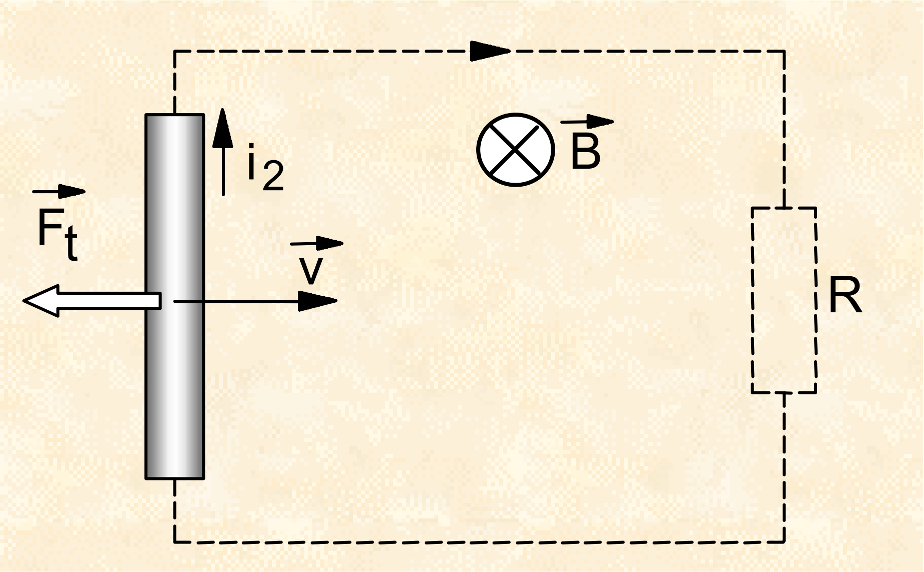
Geïnduceerde spanning



$$\oint \vec{E} \cdot d\vec{\ell} = -\frac{d\phi}{dt}$$

$$\oint \vec{E} \cdot d\vec{\ell} = -B\ell v = e_r$$

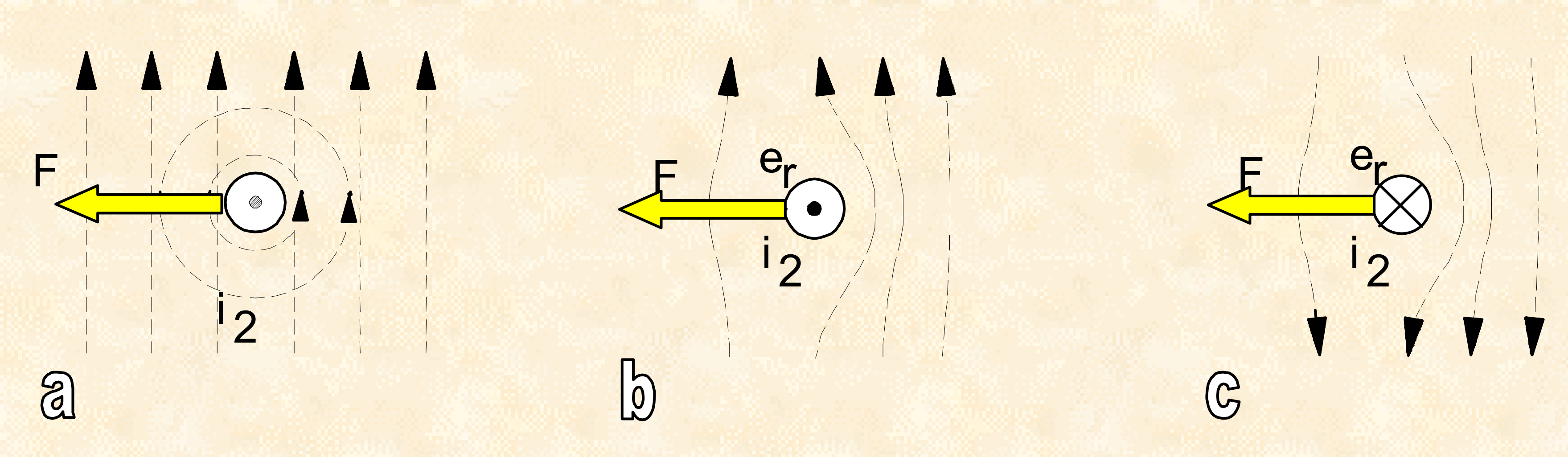
Vermogenoverdracht

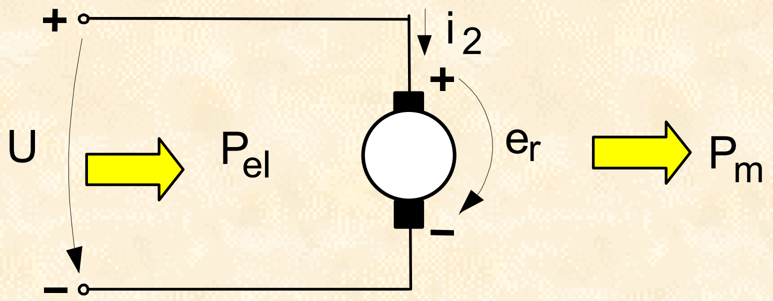


$$P_m = Fv = B_1 \ell\, i_2 v$$

$$P_m = B_1 \ell\, v i_2 = e_r i_2$$

Opgedrukte stroom en resulterende beweging met geïnduceerde spanning



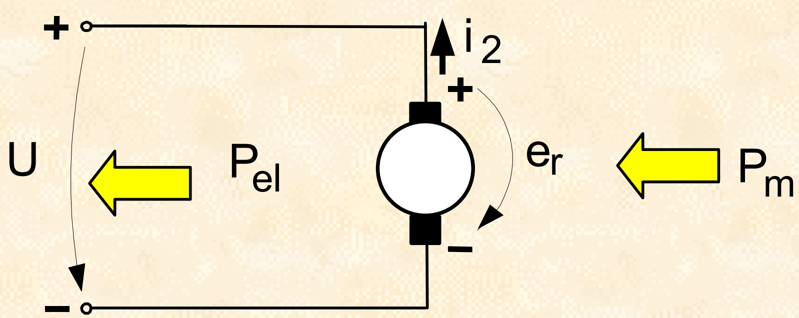


U = bronspanning

e_r = geïnduceerde e.m.k.

i_2 = stroom

Motor



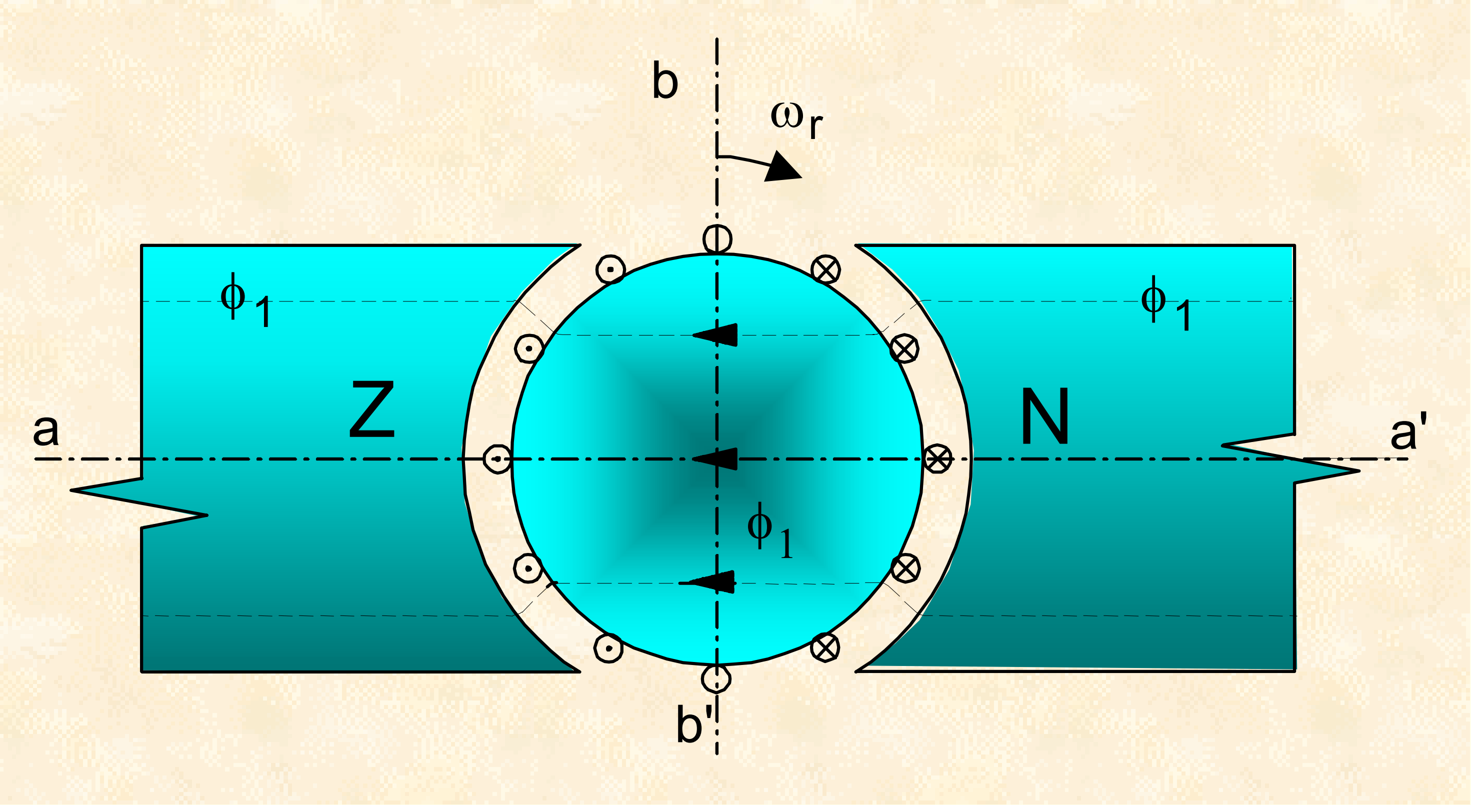
Generator

Vermogens

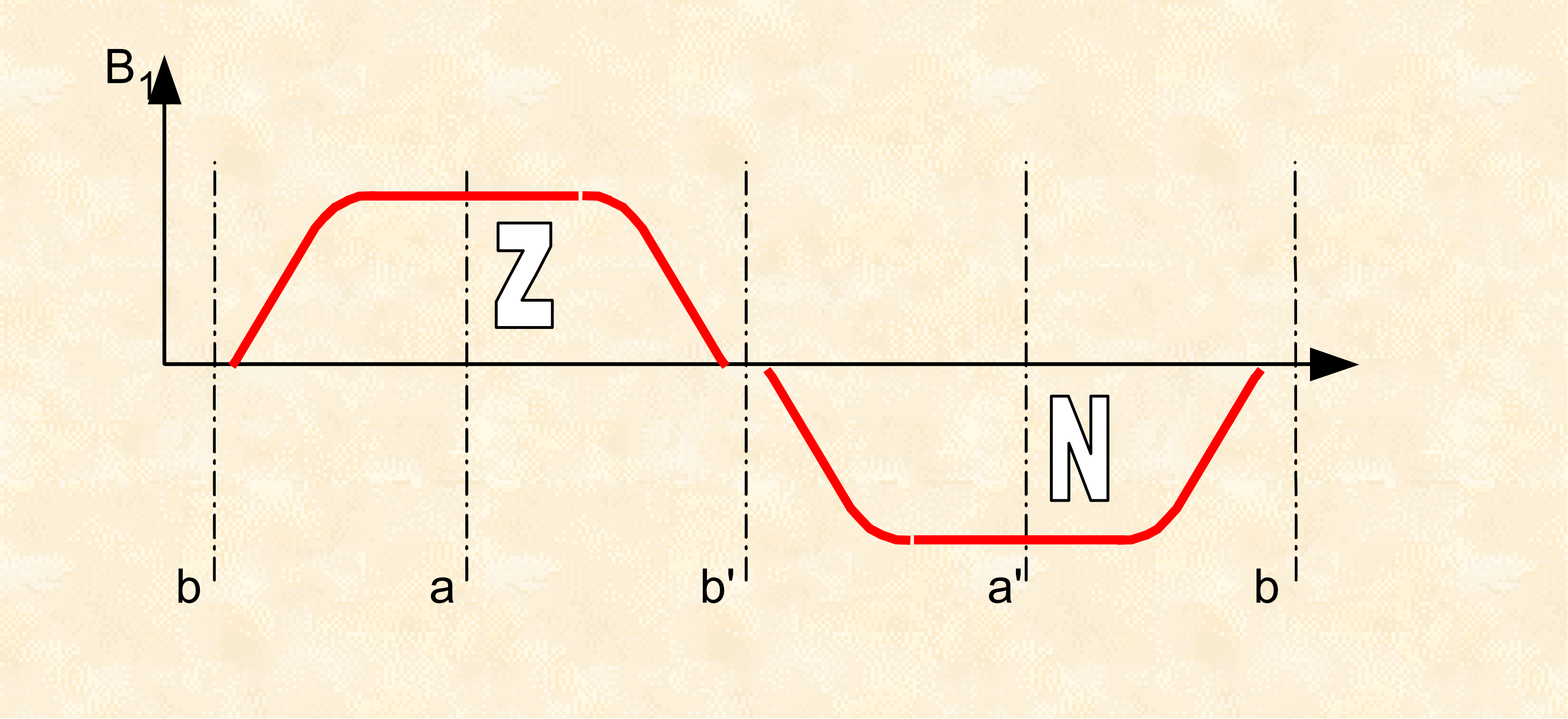
$$P_{el} = e_r i_2$$

$$P_m = P_{el}$$

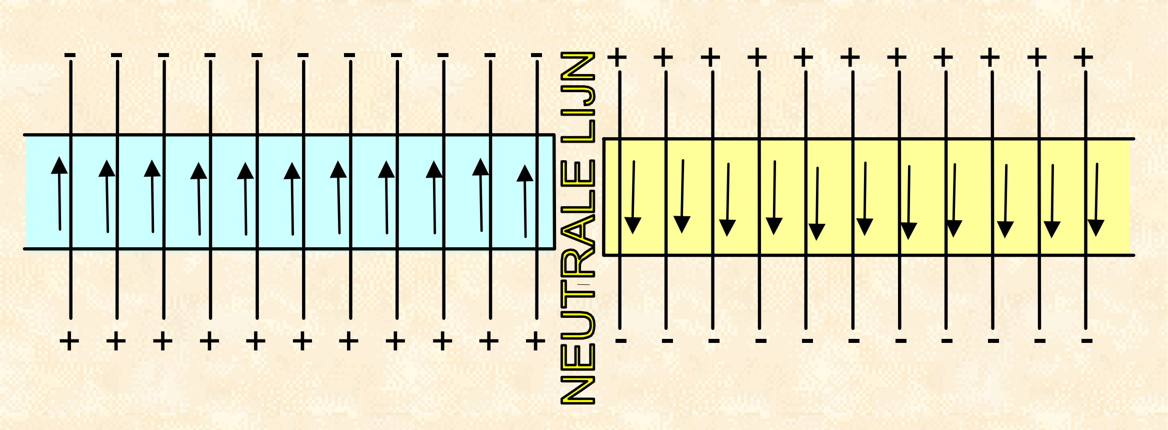
Generator: spanningsontwikkeling

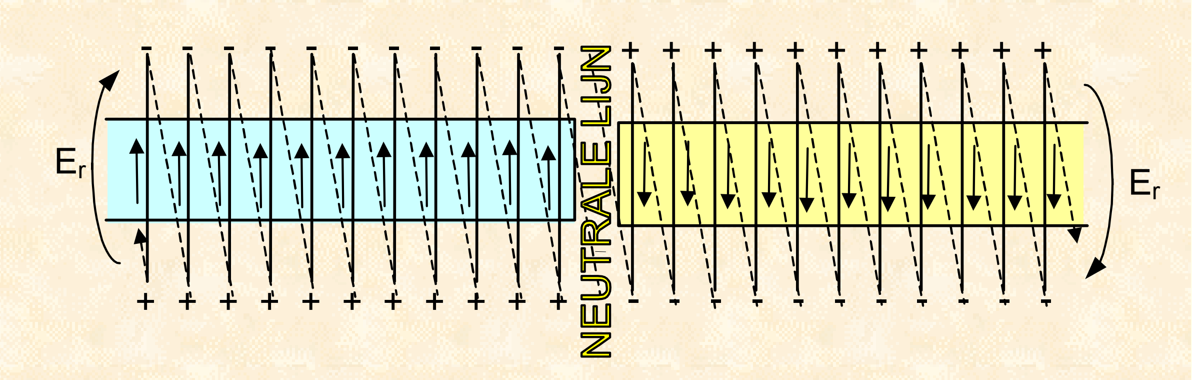


Luchtspleetinductie

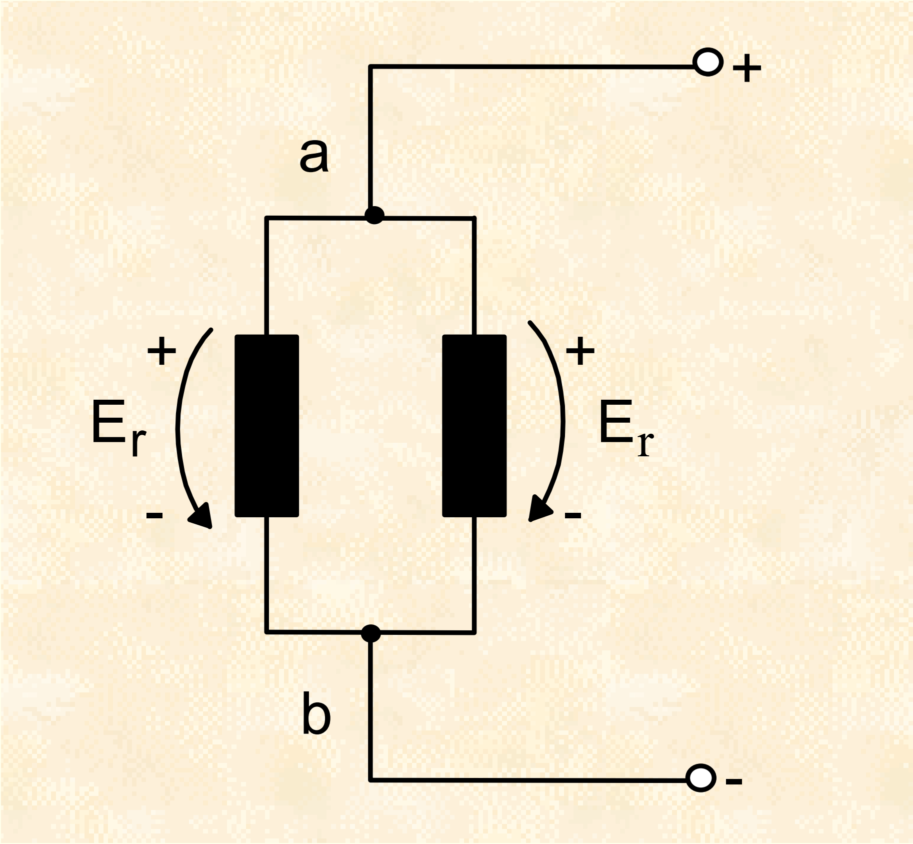


Wikkelingen

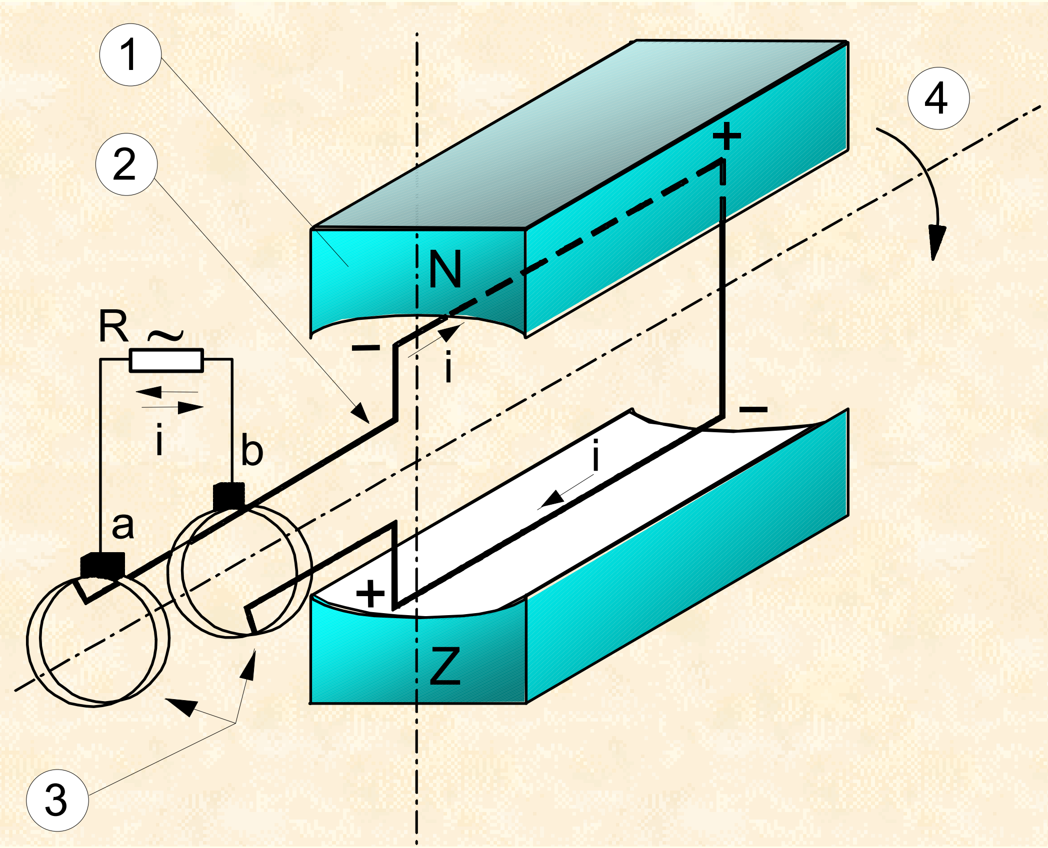




Koppeling van beide machinehelften



Commutatie



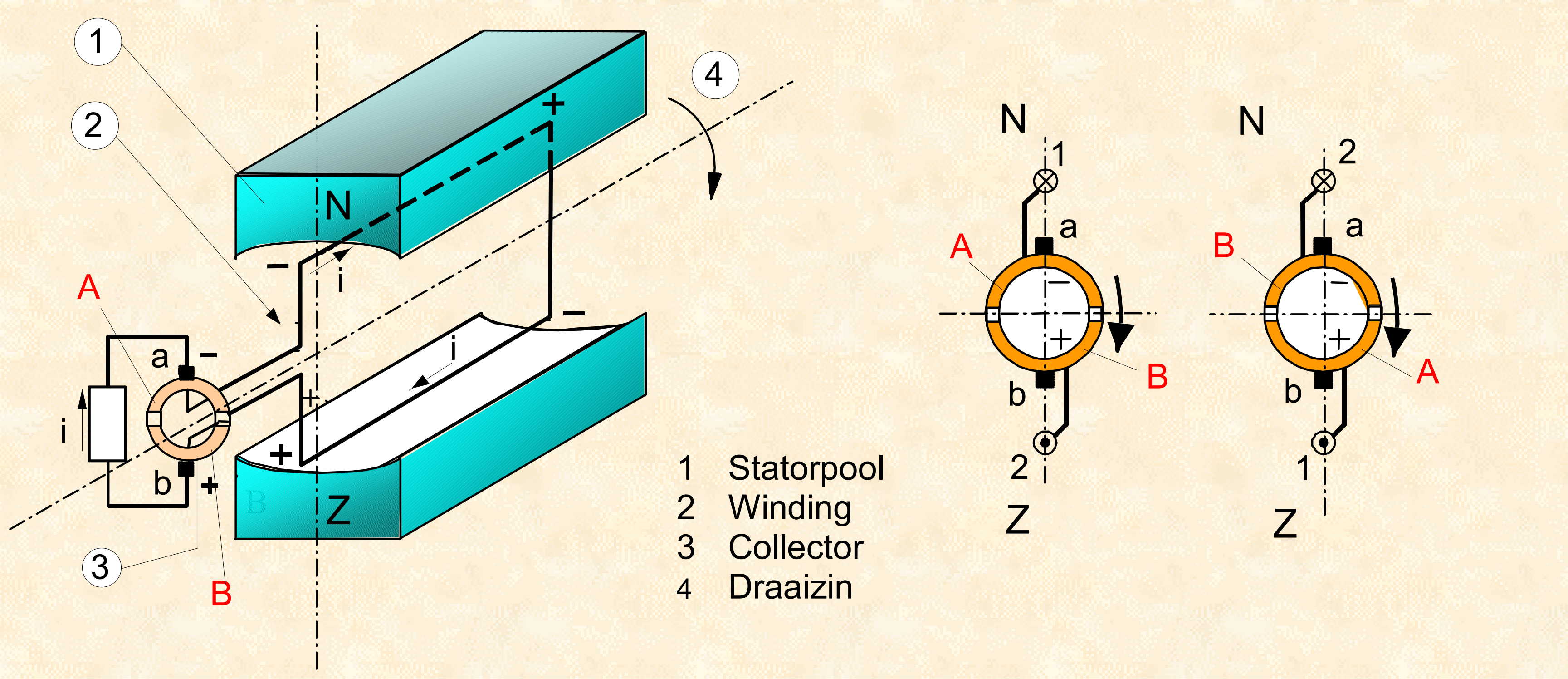
1 Statorpool

2 Rechthoekige winding

3 Sleepring

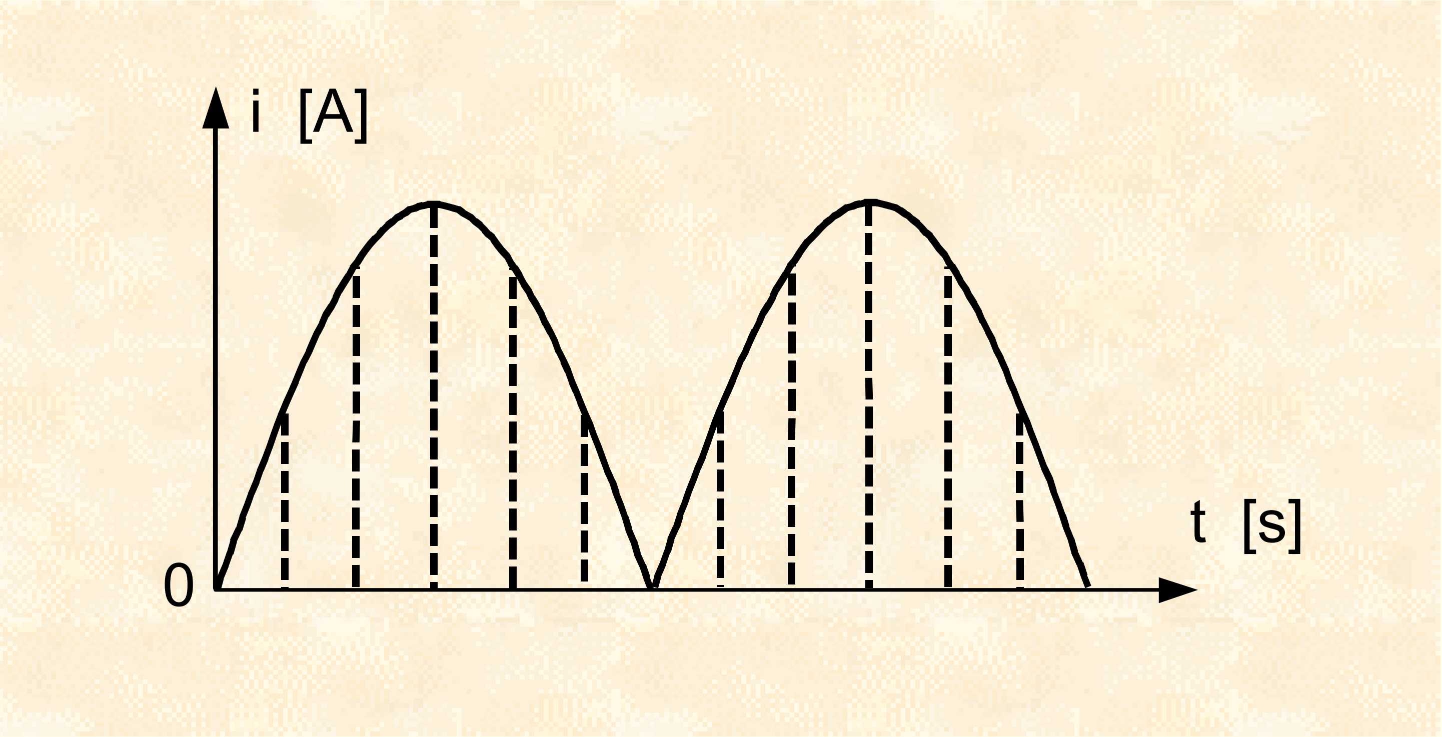
4 Draaizin

Primitieve commutator



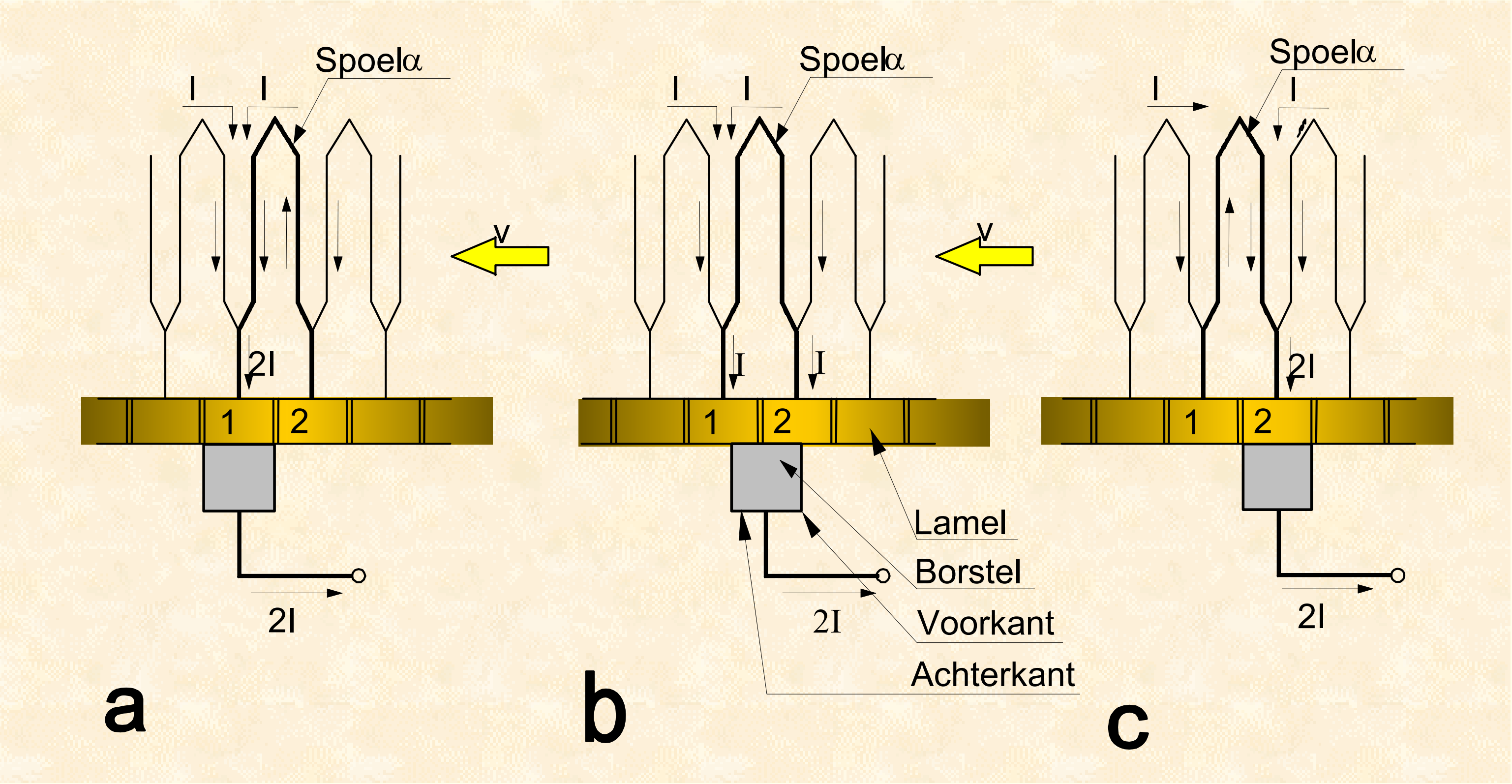
1 Statorpool
2 Winding
3 Collector
4 Draaizin

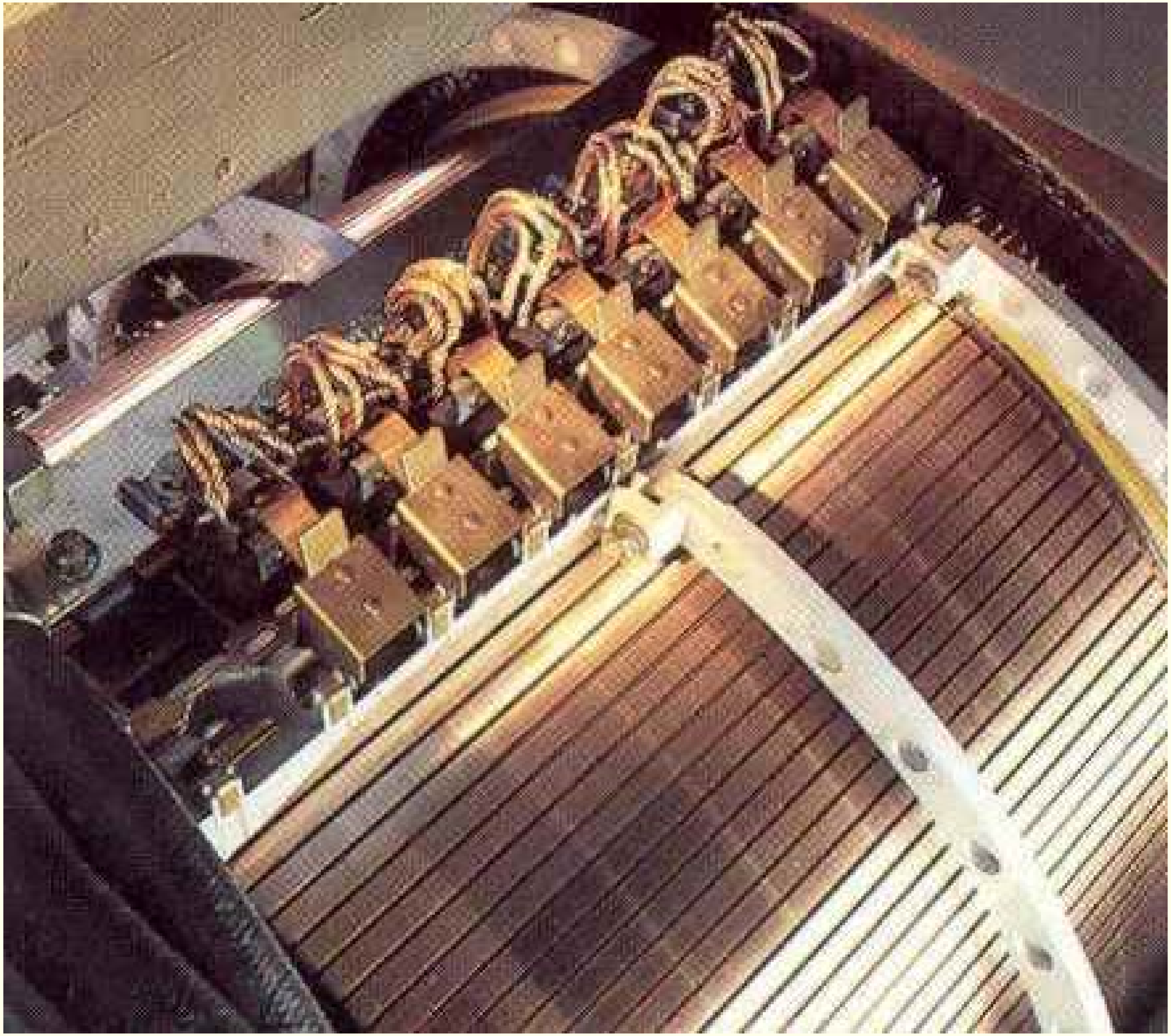
Pulserende gelijkstroom van de elementaire generator



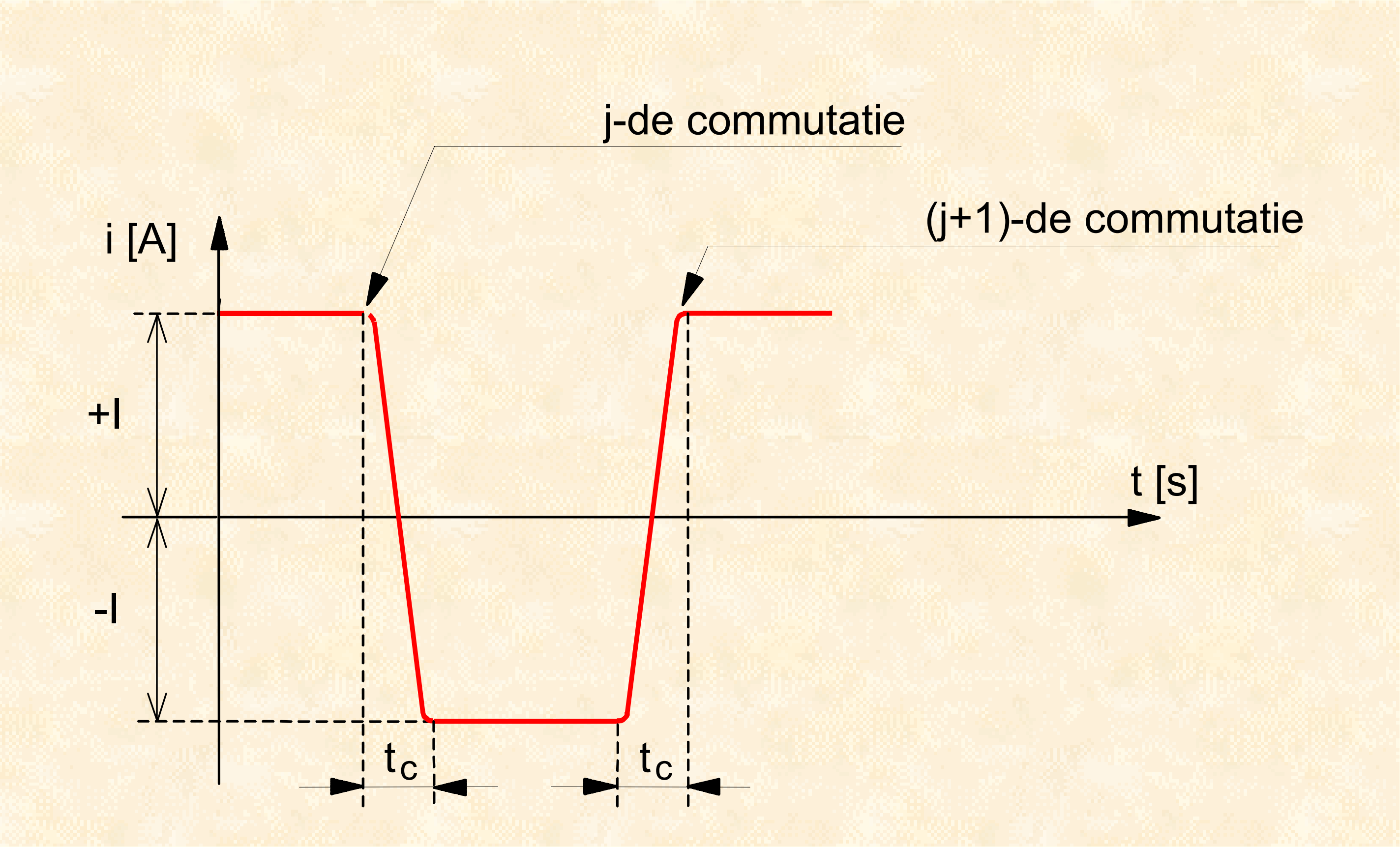
Commutatie-Praktisch

Maken en verbreken

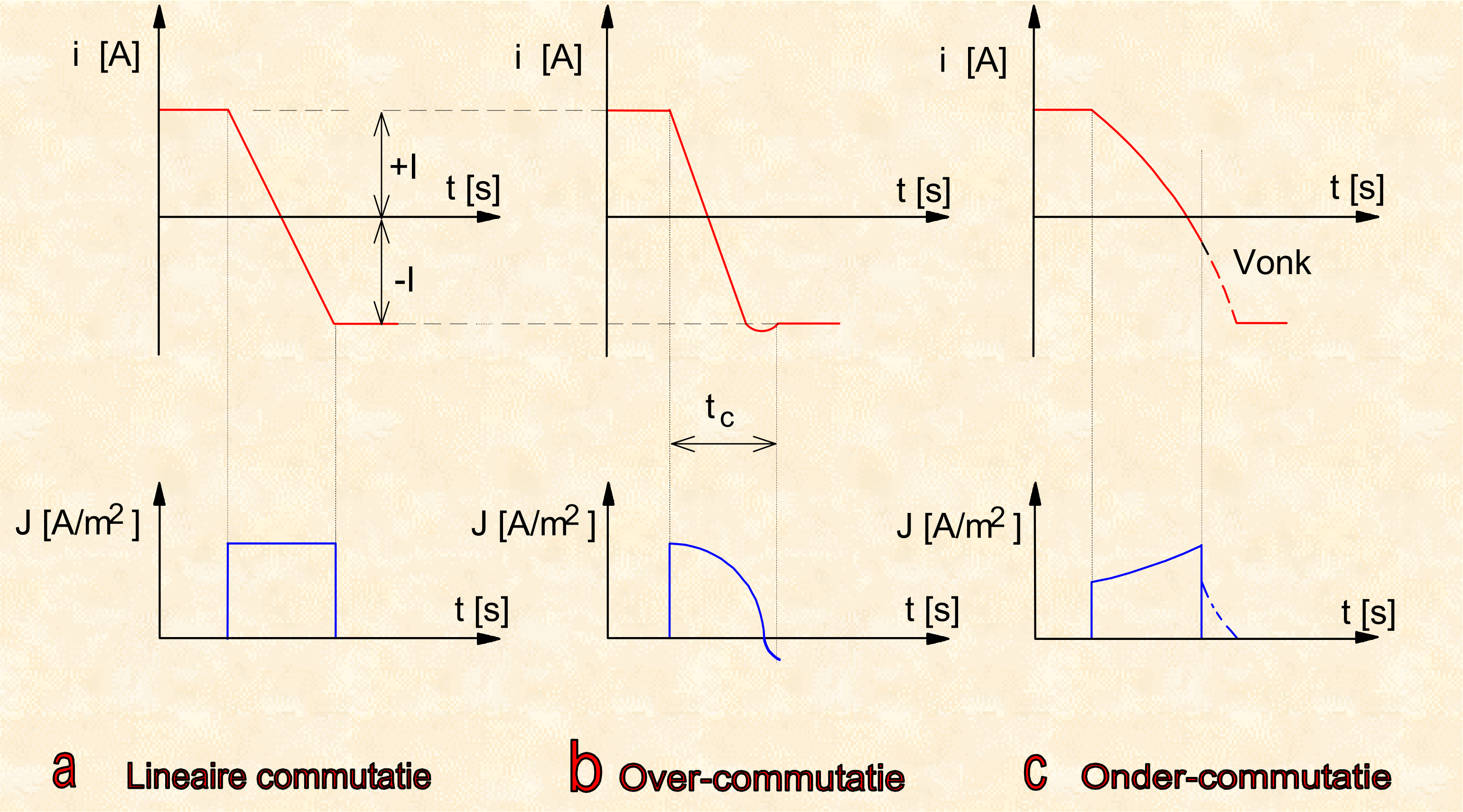




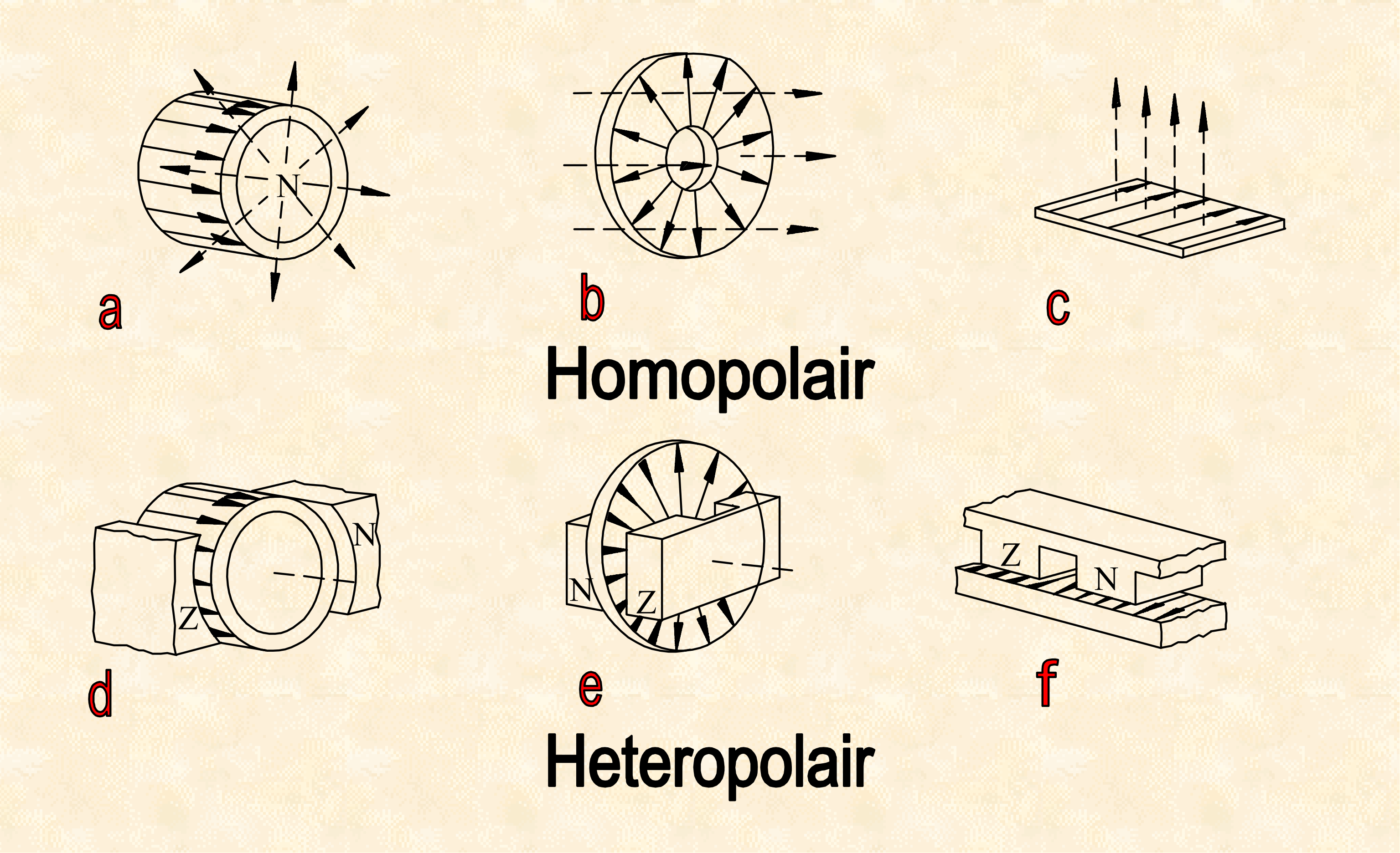
Stroom in een spoelzijde



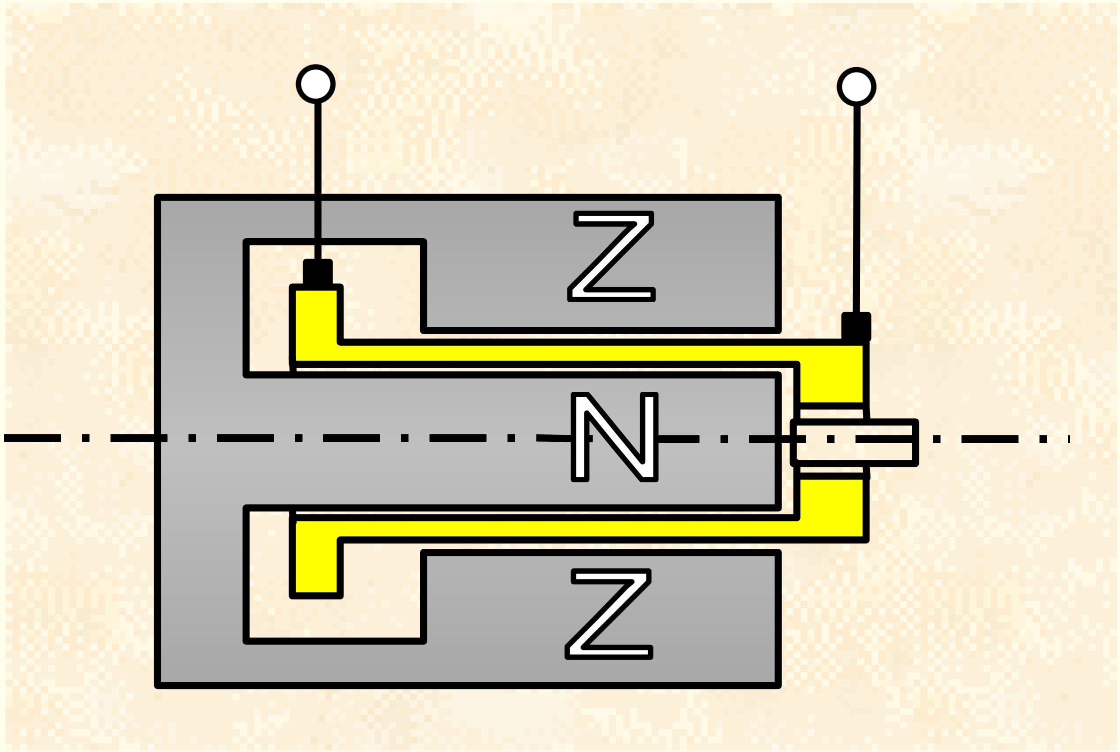
Types voor stroomverloop



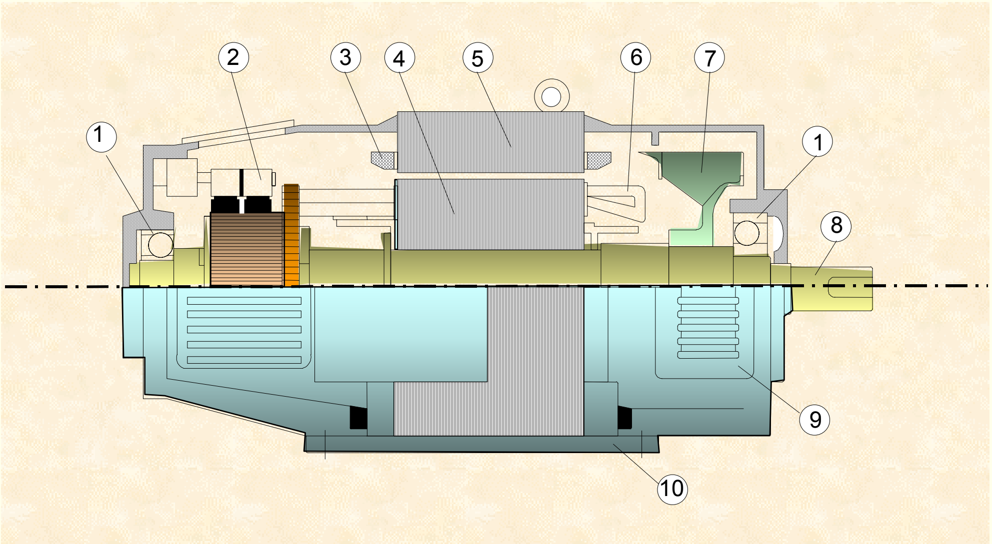
Praktische machines



Homopolaire machines



Heteropolaire machines

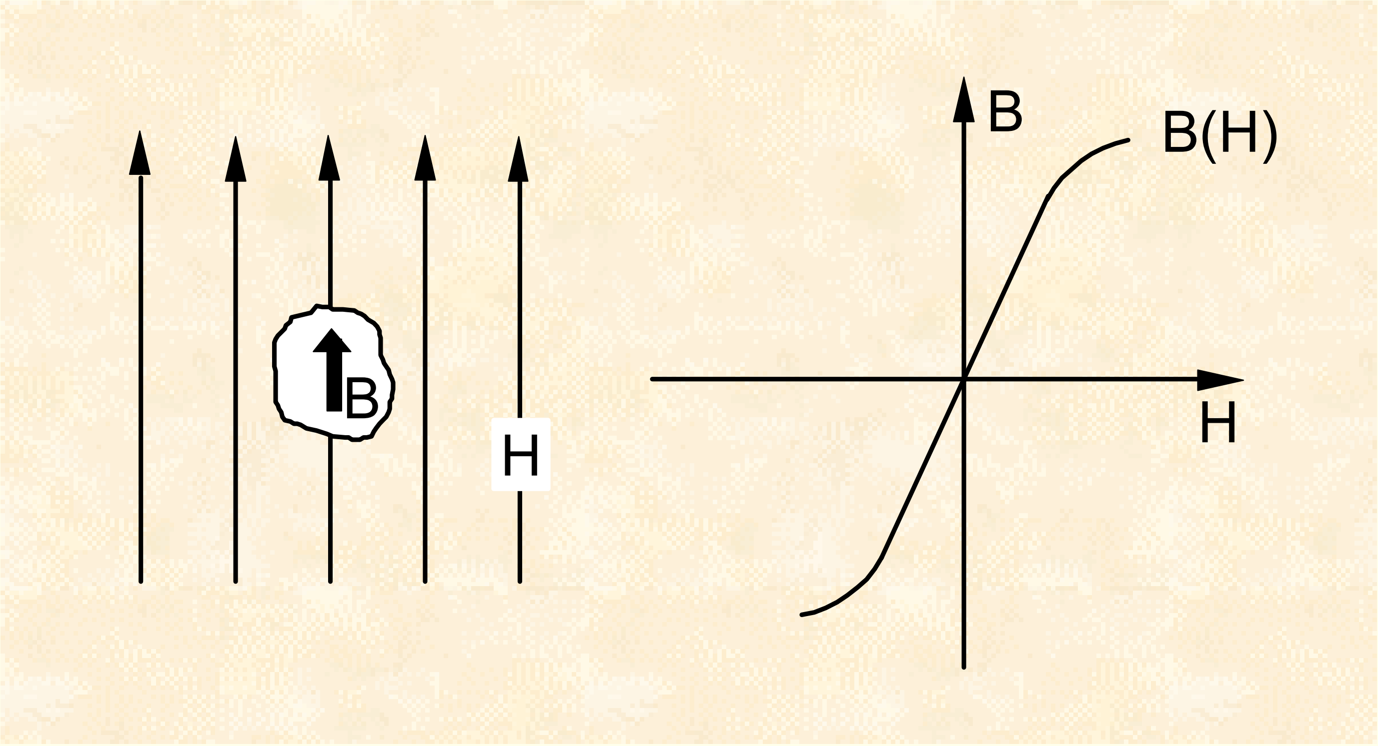


1 lager	4 Ankerblik	7. Ventilator
2 Borstels	5. Statorblik	8. As met spiebaan
3 Veldwikkeling	6. Ankerwikkeling	9. Luchtinlaat
		10. Motorvoet

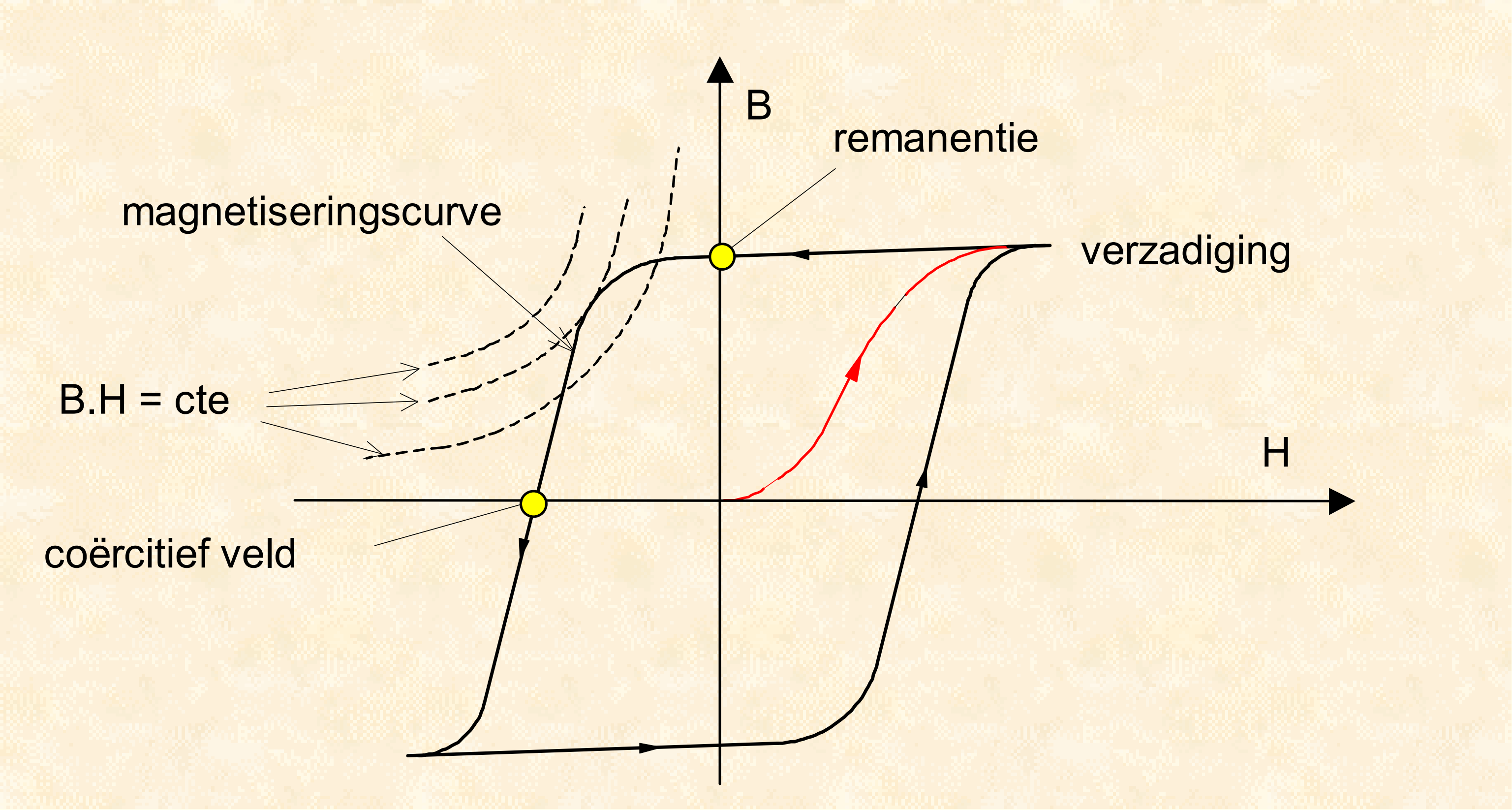
HOOFDSTUK 2

OPBOUW VAN HET MAGNETISCH VELD

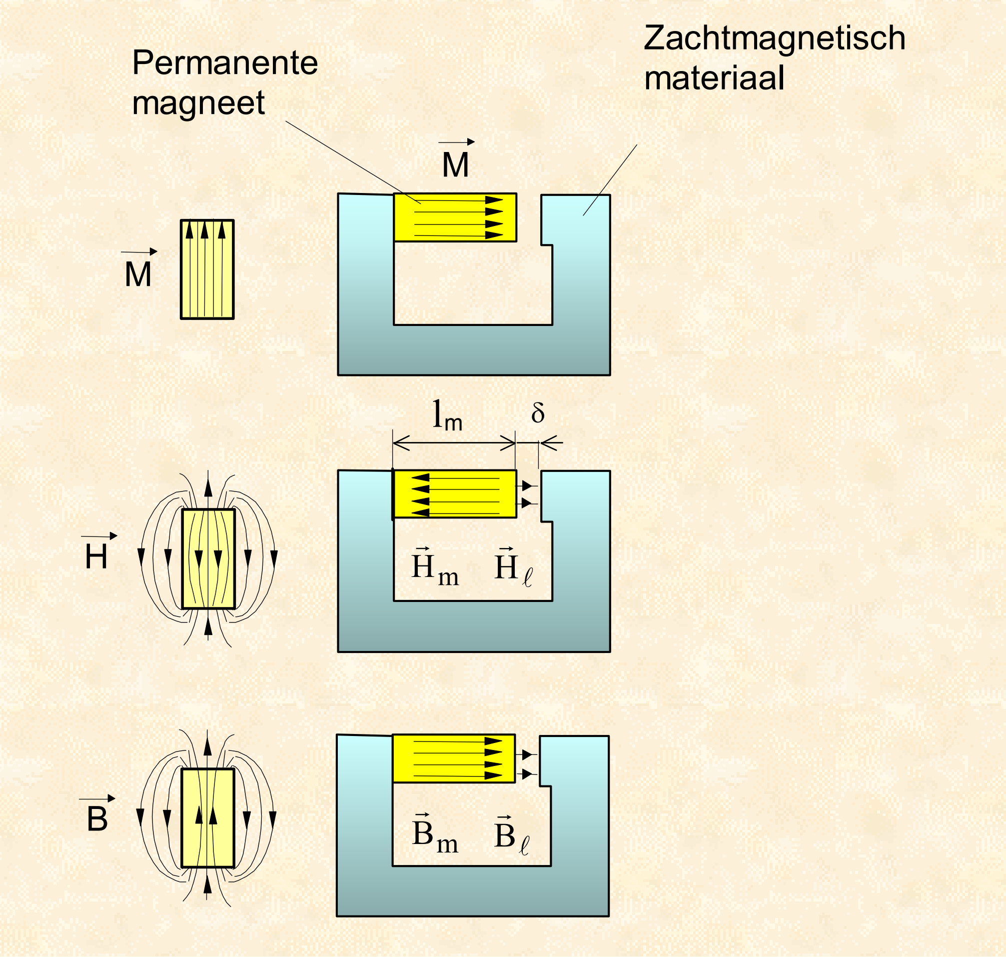
Permanente magneten



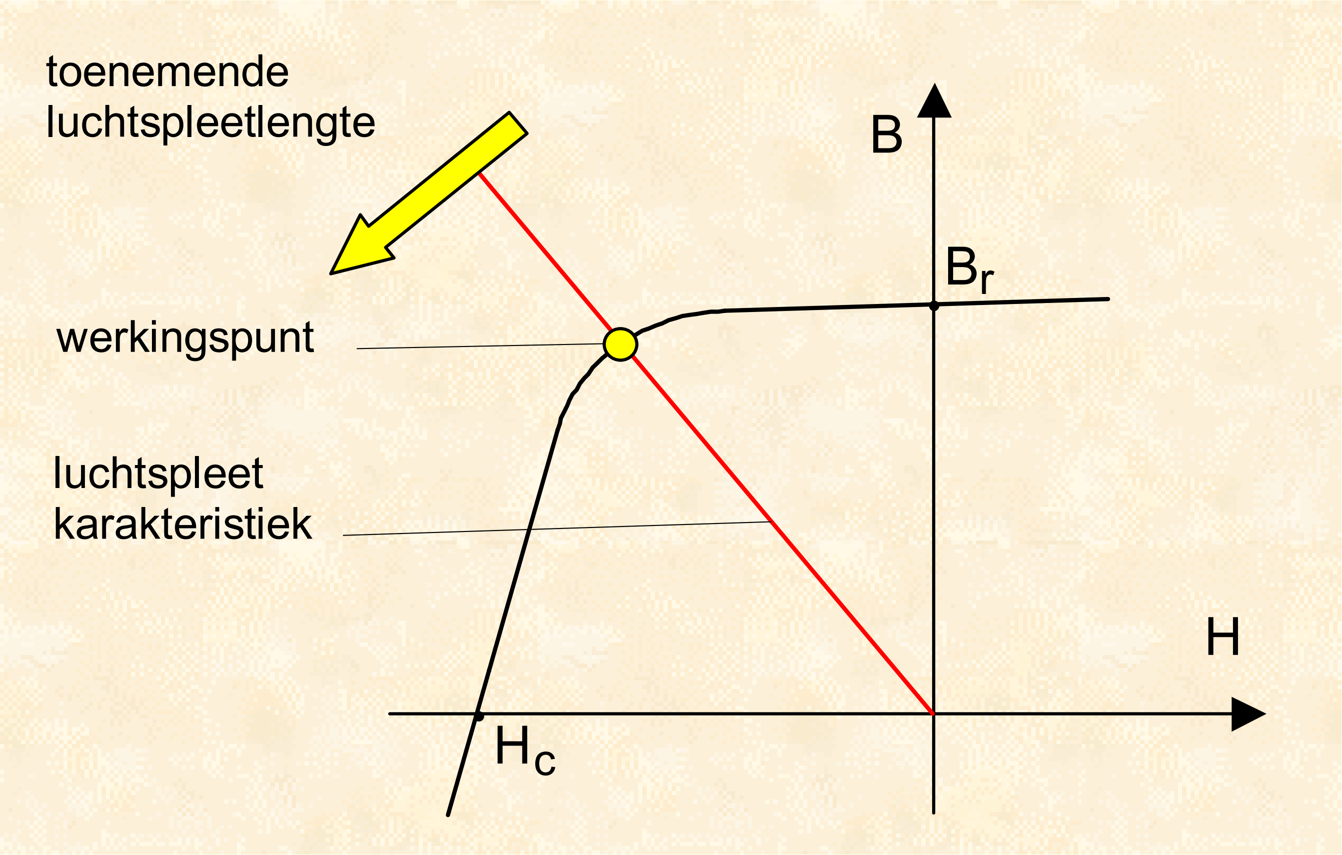
Hysteresiscurve



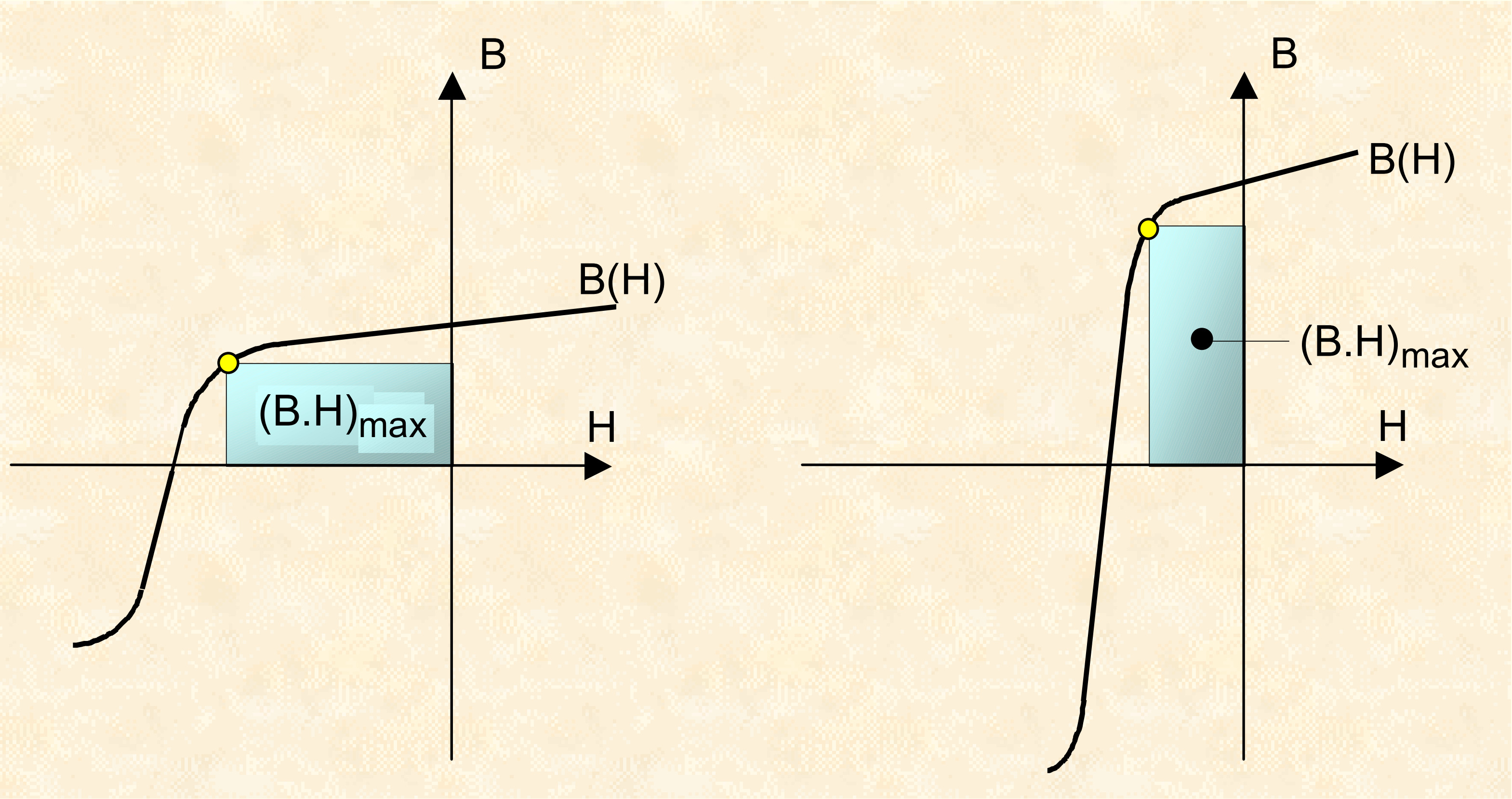
Veldsterkte en inductie van een permanente magneet



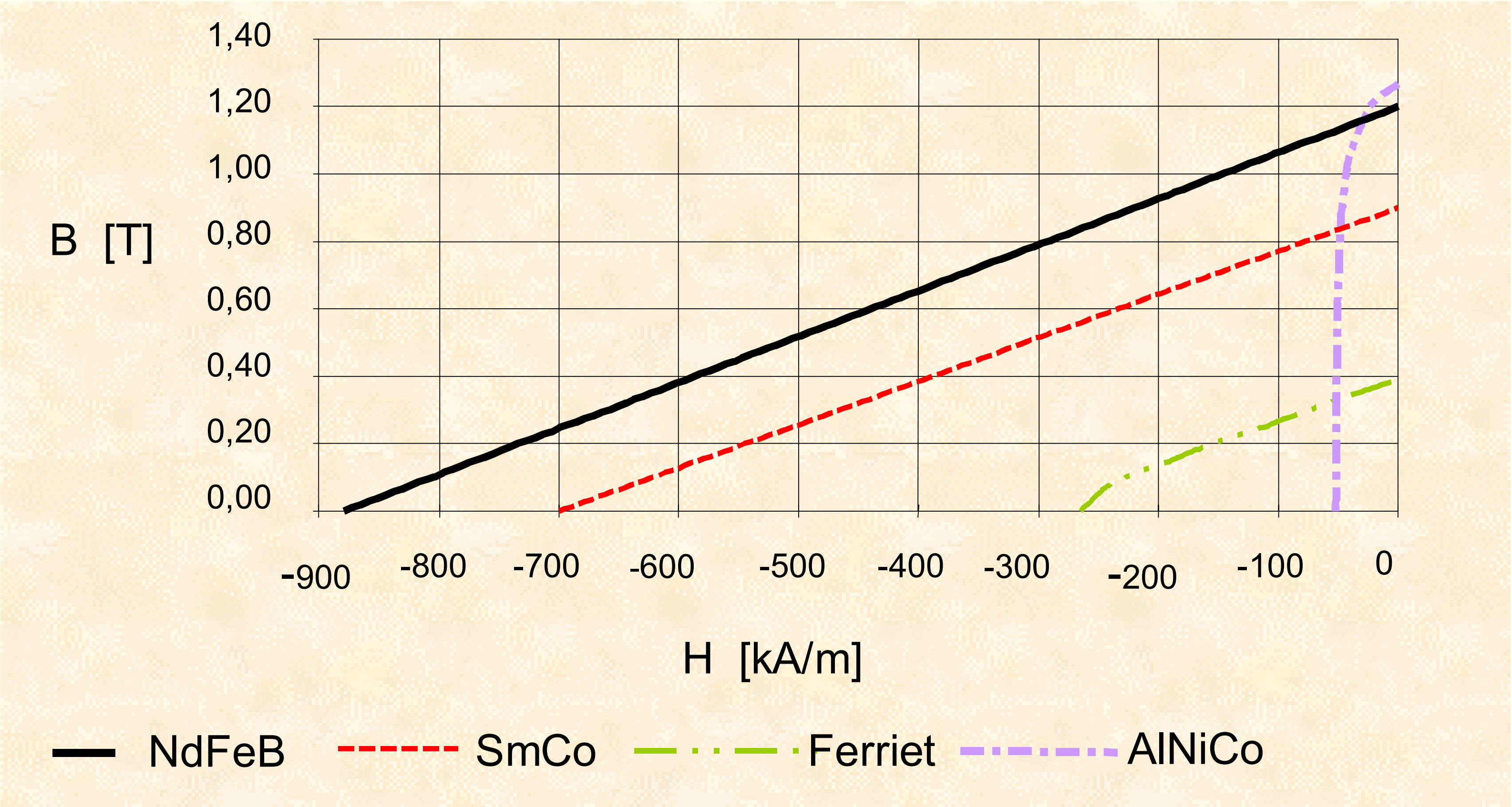
$$H_m = -\frac{\delta}{l_m}\frac{B_m}{\mu_0}$$



Magnetiseringscurven



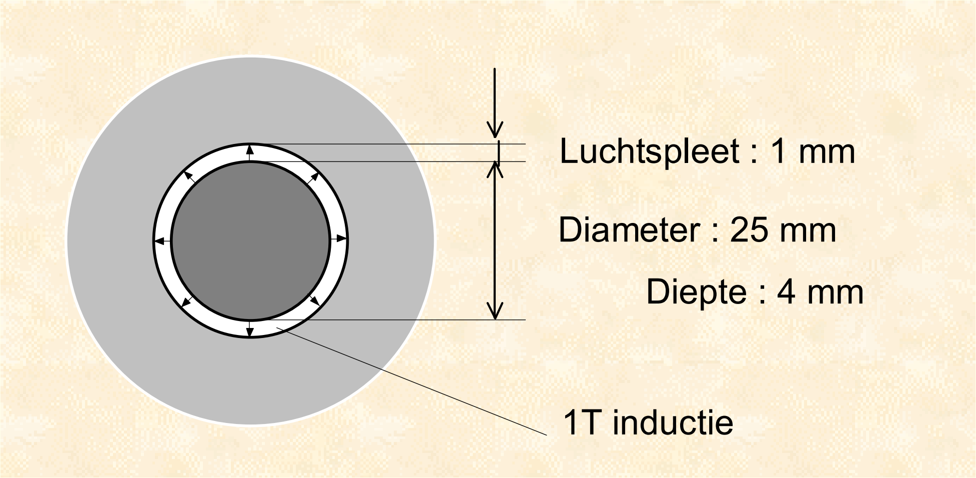
Permanent magneetmaterialen



Soorten

- Al-Ni-Co
- Ferrieten
- Zeldzame aarden
  - Samarium - Cobalt
  - Neodymium - Ijzer - Boor

Dimensionering

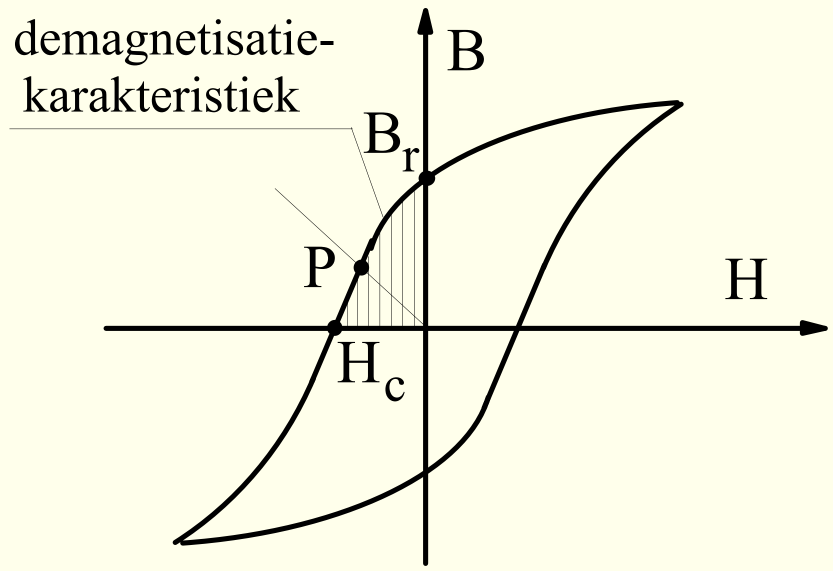


$$S_M = S_L \frac{B_L}{B_M}$$

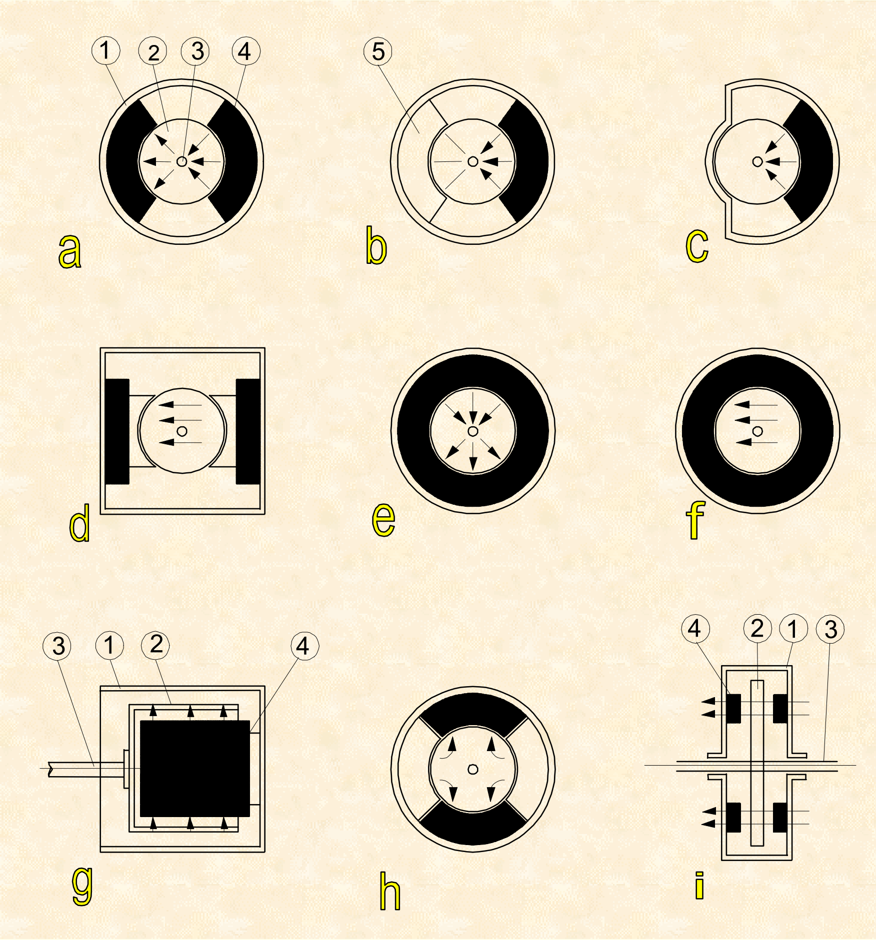
$$l_M = \delta \frac{H_L}{H_M}$$

Magnetische keten

Bekrachtigingswijzen
Permanente magneten

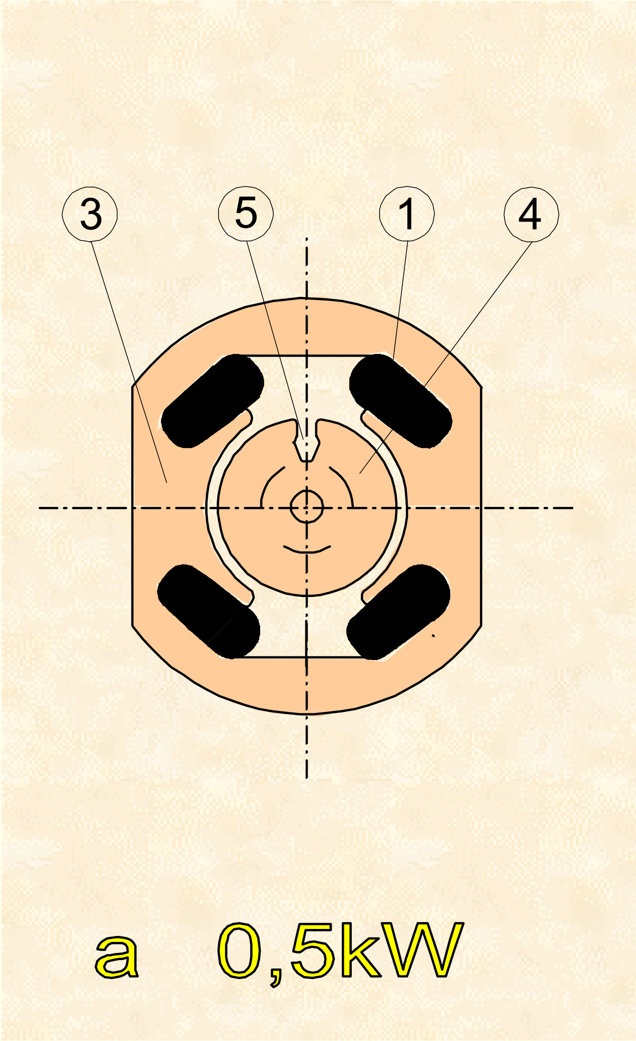


Schikking van de magneten



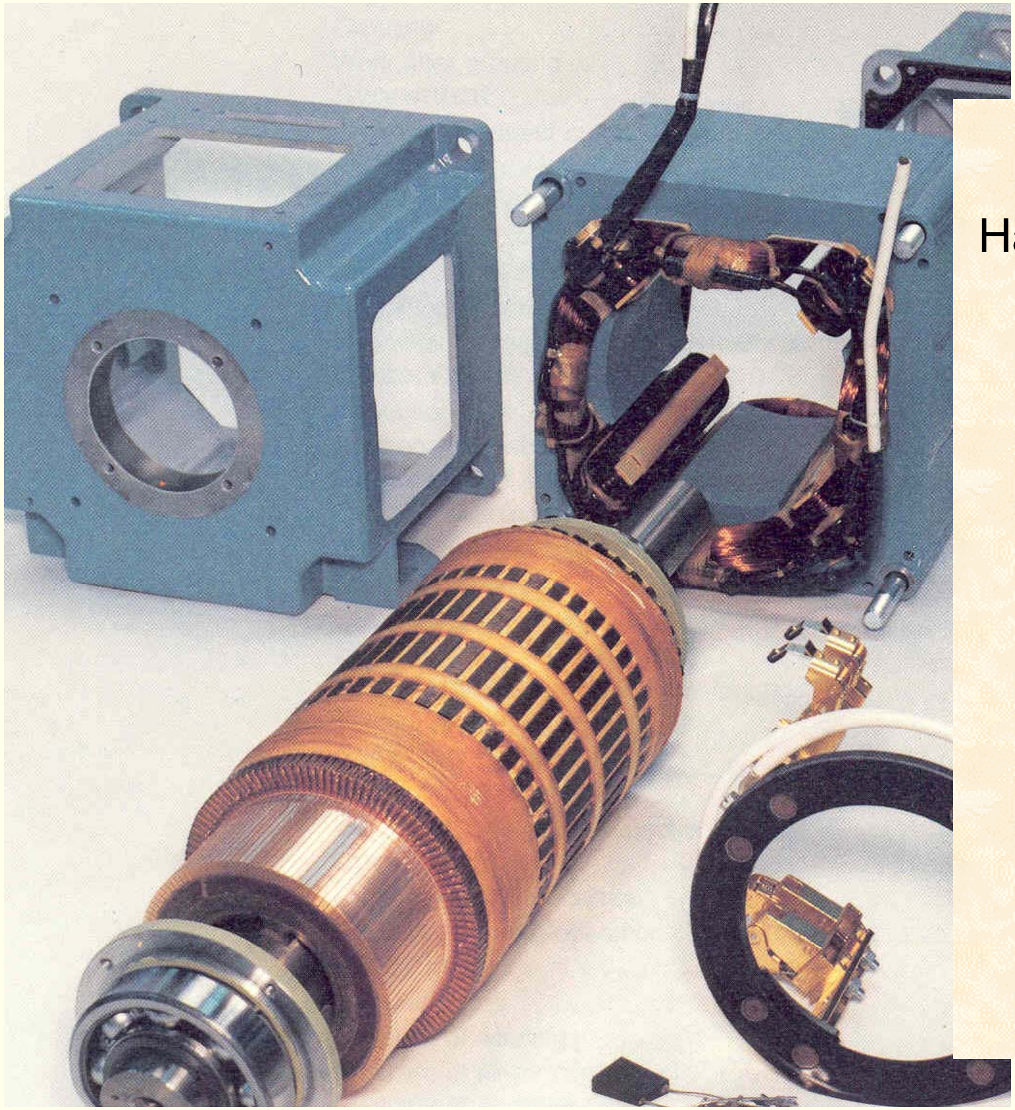
1. Motorhuis
2. Rotor
3. Rotoras
4. Permanente magneet
5. Weekijzer

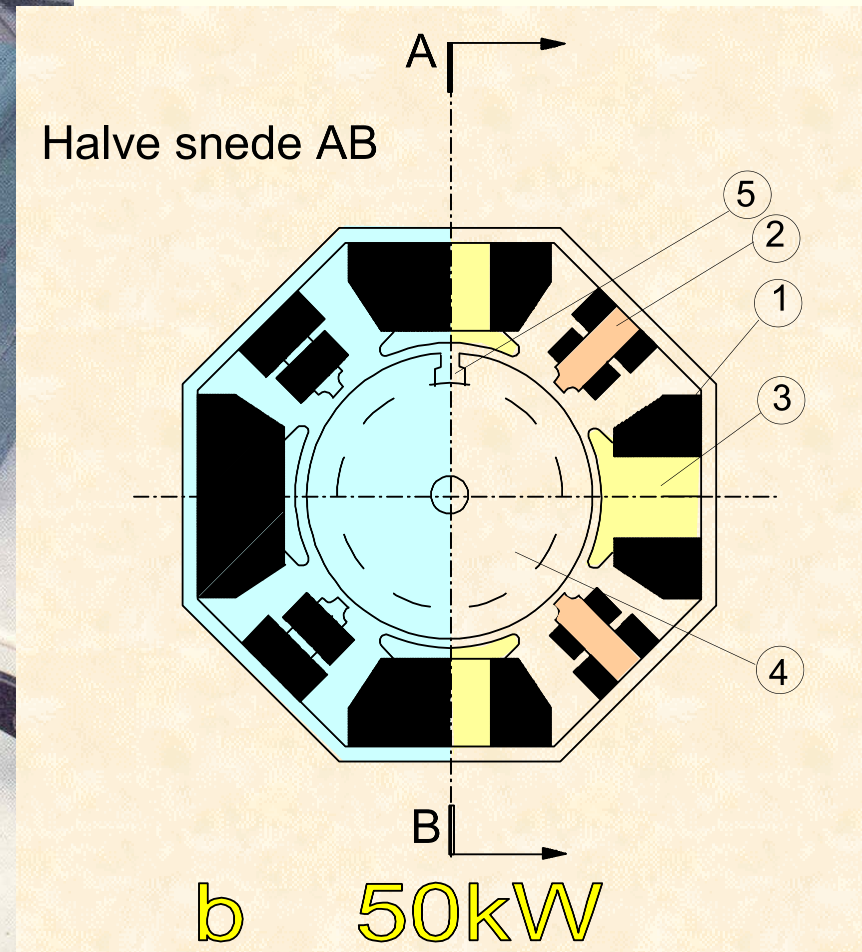
Stroombekrachtiging



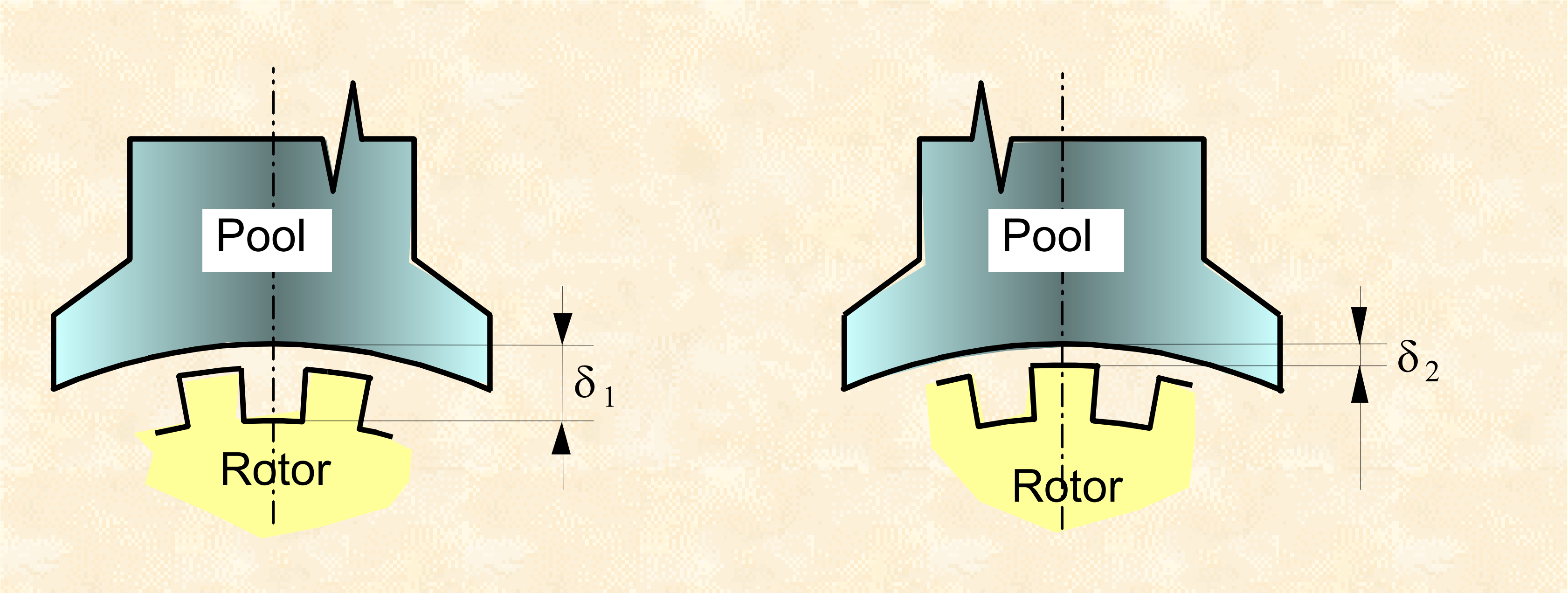
1. Veldwikkeling
2. Commutatiepool
3. Hoofdpool
4. Anker
5. Gleuf

Stroombekrachtiging

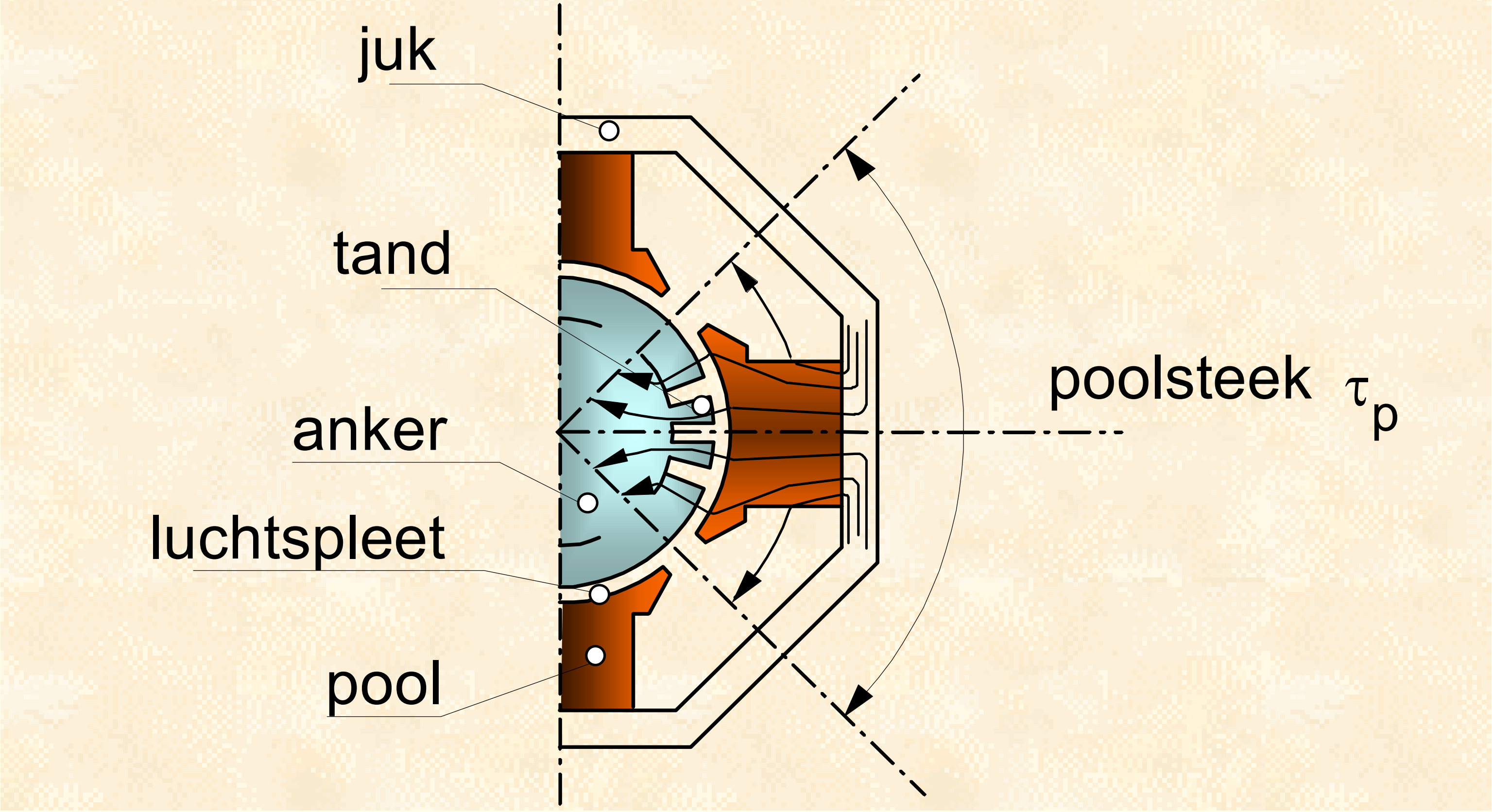




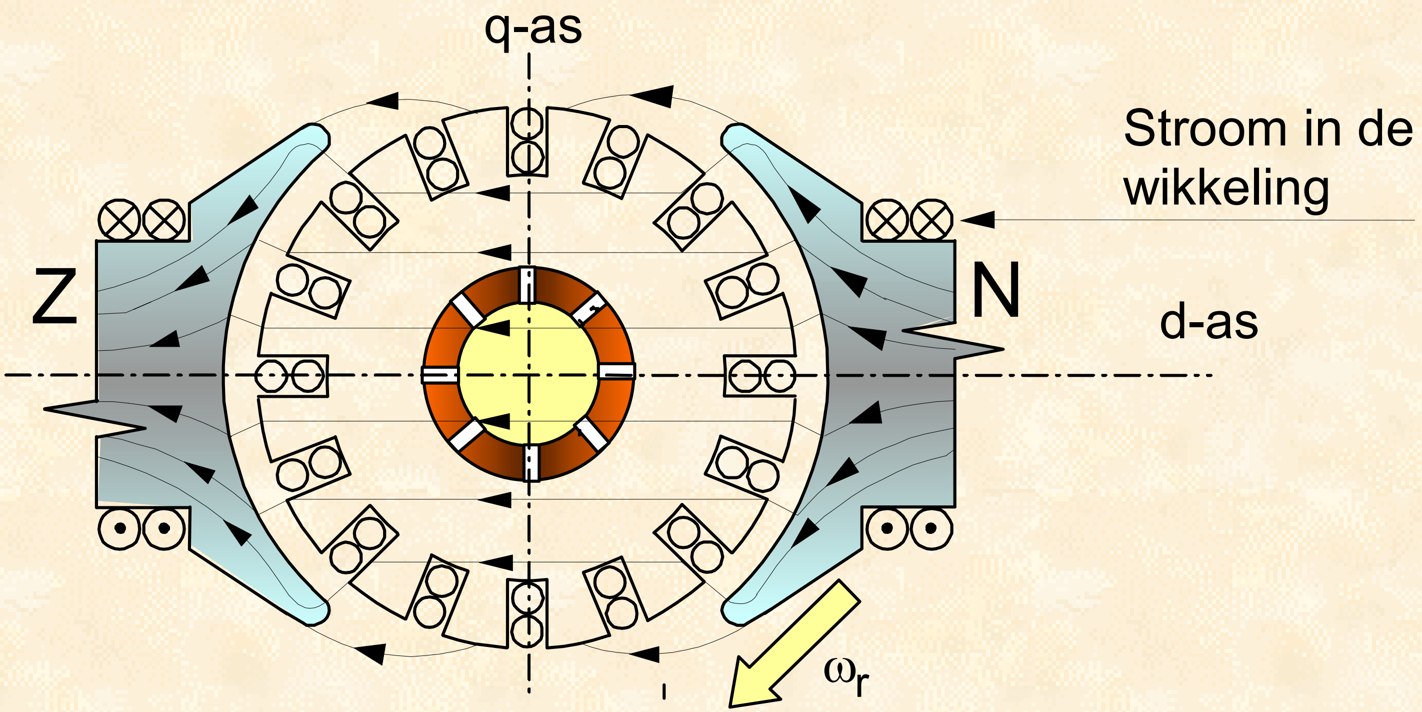
Fluxverloop-Lamellering



Fluxverloop in een vierpolige machine

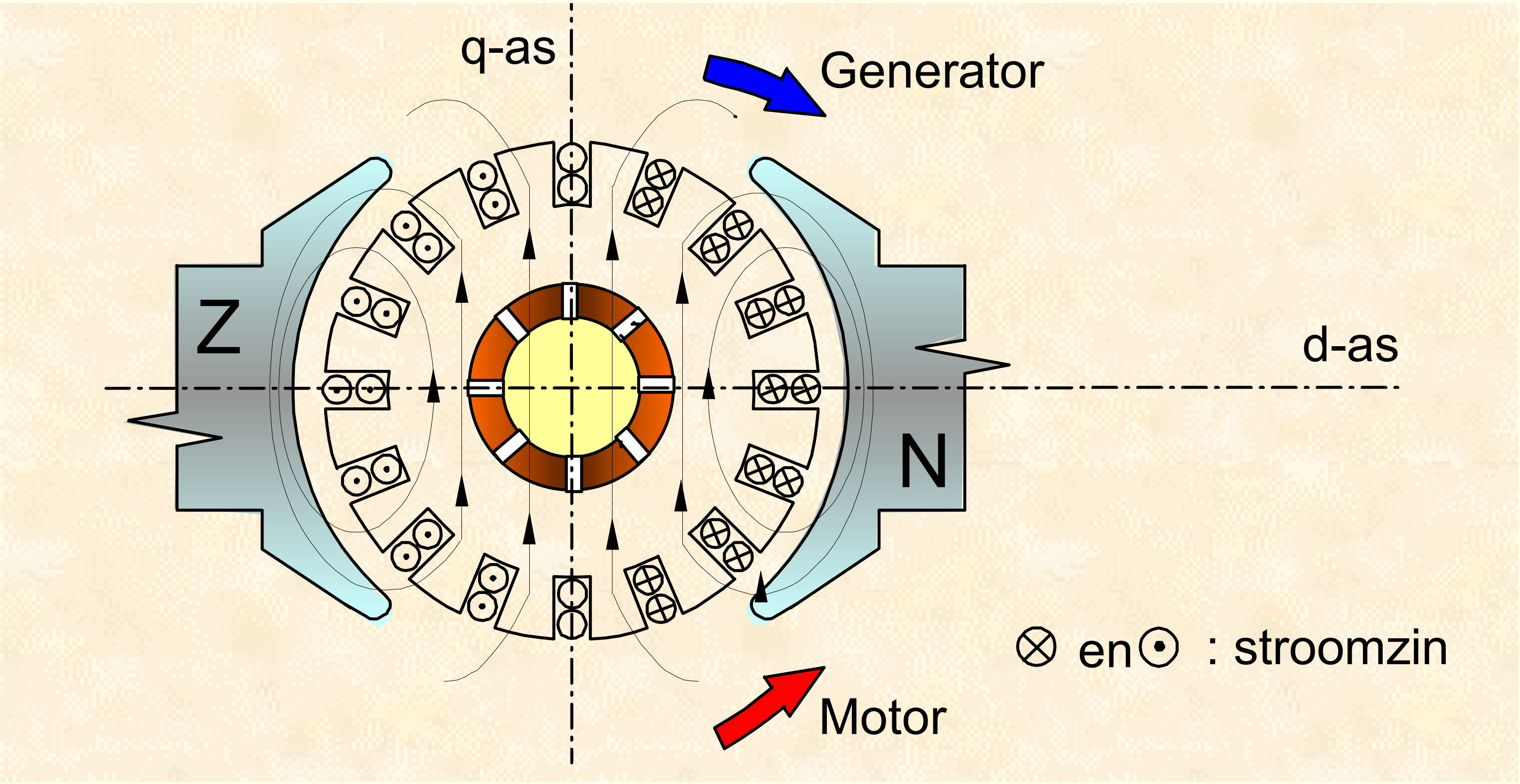


Ankerreactie

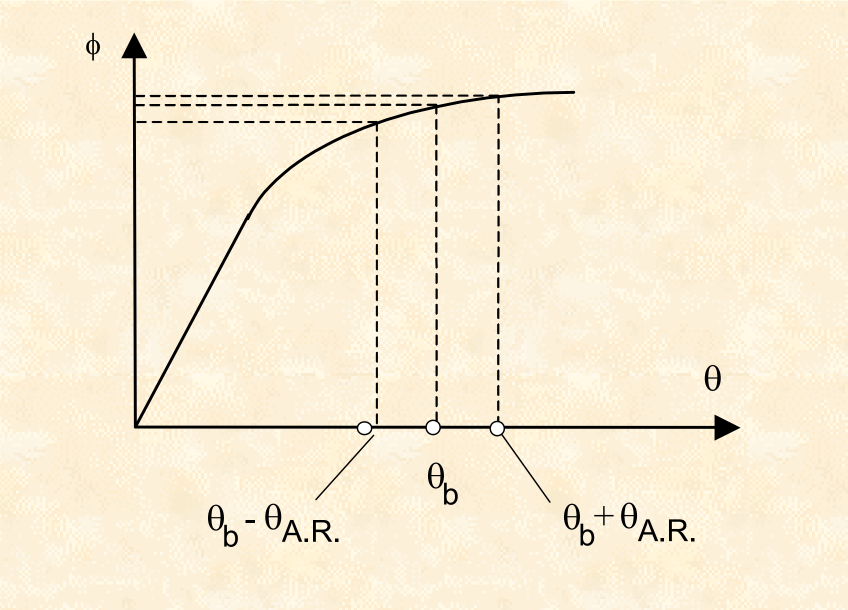


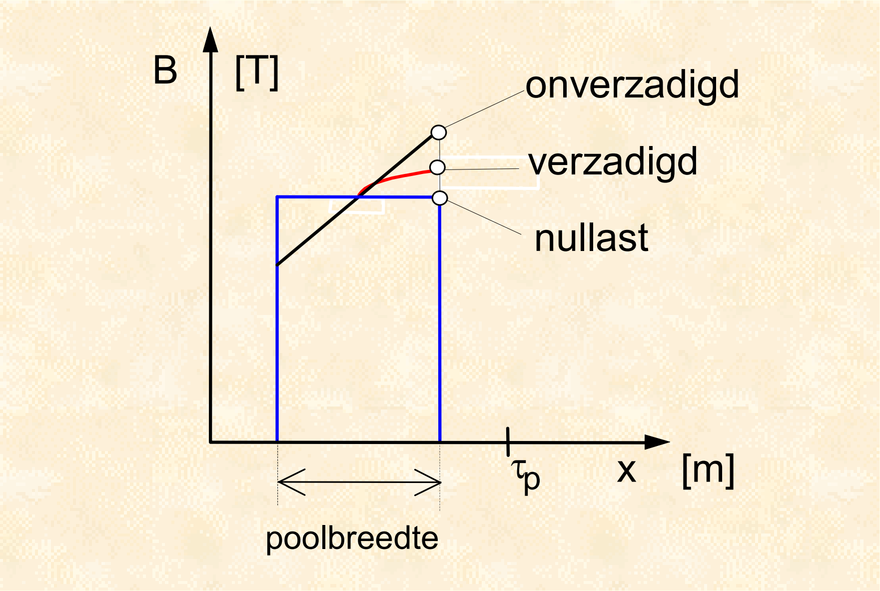
Volle cilindrische rotor (ook magnetische as)

Veld van de ankerstroom

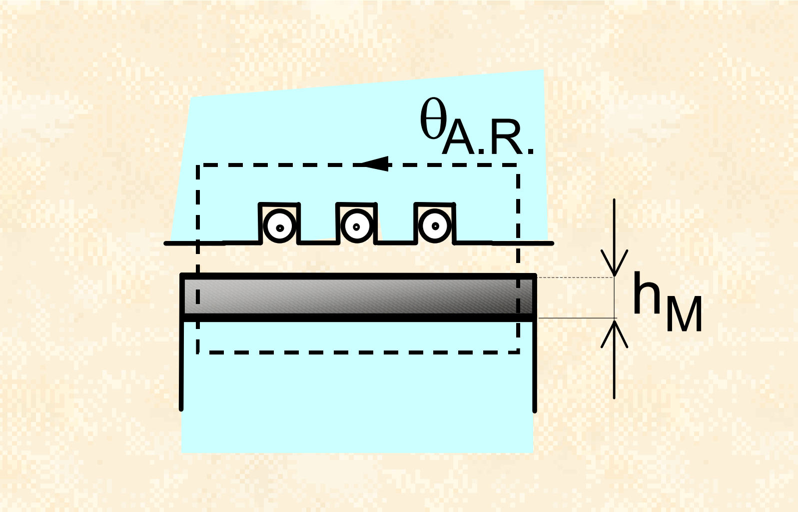


Fluxverandering-Inductiewijziging





Permante magneten



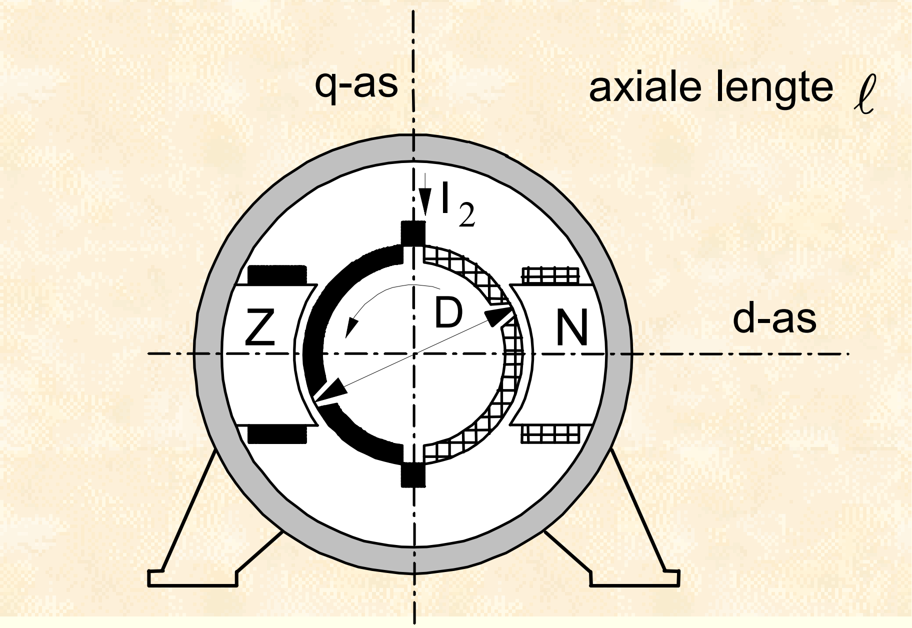
$$B_{A.R,elektro} \sim \frac{\theta_{A.R}}{\delta}$$

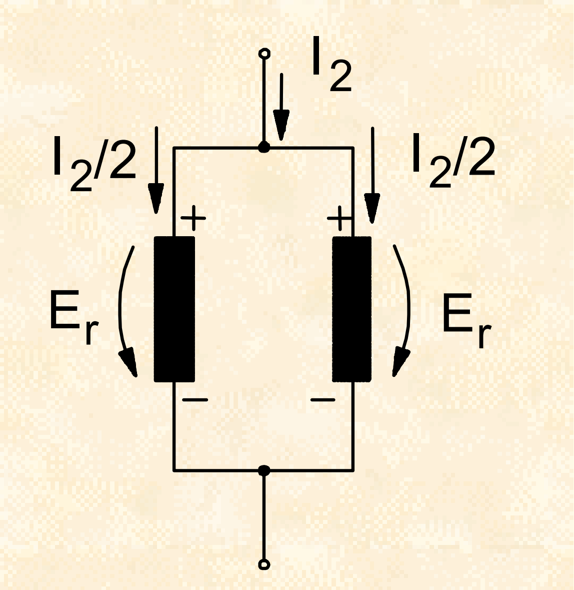
$$B_{A.R,Perm.magn.} \sim \frac{\theta_{A.R}}{\delta + h_M}$$

HOOFDSTUK 3

GEIDEALISEERDE GELIJKSTROOMMACHINE

Geïdealiseerde gelijkstroommachine: e.m.k.





$$\omega_r = \frac{2\pi n}{60}$$

$$t_1 = \frac{\pi}{\omega_r}$$

$$e_{r_{gem}} = \frac{1}{t_1}\int_0^{t_1} e_r \cdot dt = \frac{1}{t_1}\int_0^{t_1} B_1 \ell v \cdot dt$$

$$= \frac{1}{t_1}\int_0^{t_1} B_1 \ell \frac{dx}{dt} \cdot dt = \frac{1}{t_1}\int_0^{\pi D/2} B_1 \ell \cdot dx = \frac{1}{t_1}\phi = \frac{\phi\omega_r}{\pi}$$

$$E_r = \frac{N_2}{\pi} \omega_r \phi$$

$$\tau_p = \frac{\pi D}{2} \qquad [\mathrm{m}]$$

$$t_{p=} \frac{\pi}{\mathrm{p}\omega_{\mathrm{r}}}$$

$$e_{r_{gem}} = \frac{1}{t_p} \int_0^{t_p} e_r dt = \frac{p\phi\omega_r}{\pi}$$

$$E_r = \frac{N_2 p}{\pi a} \omega_r \phi$$

of

$$E_r = C \omega_r \phi$$

$$C = \frac{N_2 p}{\pi a}$$

Geïdealiseerde gelijkstroommachine: koppel

$$F_{gem} = \frac{1}{t_p}\int_0^{t_p} B_1 \ell \frac{I_2}{2a} dt \;= \frac{I_2}{2at_p}\int_0^{t_p} B_1 \ell dt$$

$$F_{gem} = \frac{I_2}{2at_p v}\int_0^{\tau_p} B_1 \ell dx = \frac{I_2}{2at_p v}\phi \;= \frac{I_2 \phi}{2at_p r\omega_r}$$

$$F_{gem} = \frac{I_2 \phi p}{2a\pi r}$$

$$T_{gem} = rF_{gem} = \frac{pI_2\phi}{2\pi a}$$

$$T = \frac{N_2 p}{\pi a}\phi I_2$$

of

$$T = C\phi I_2$$

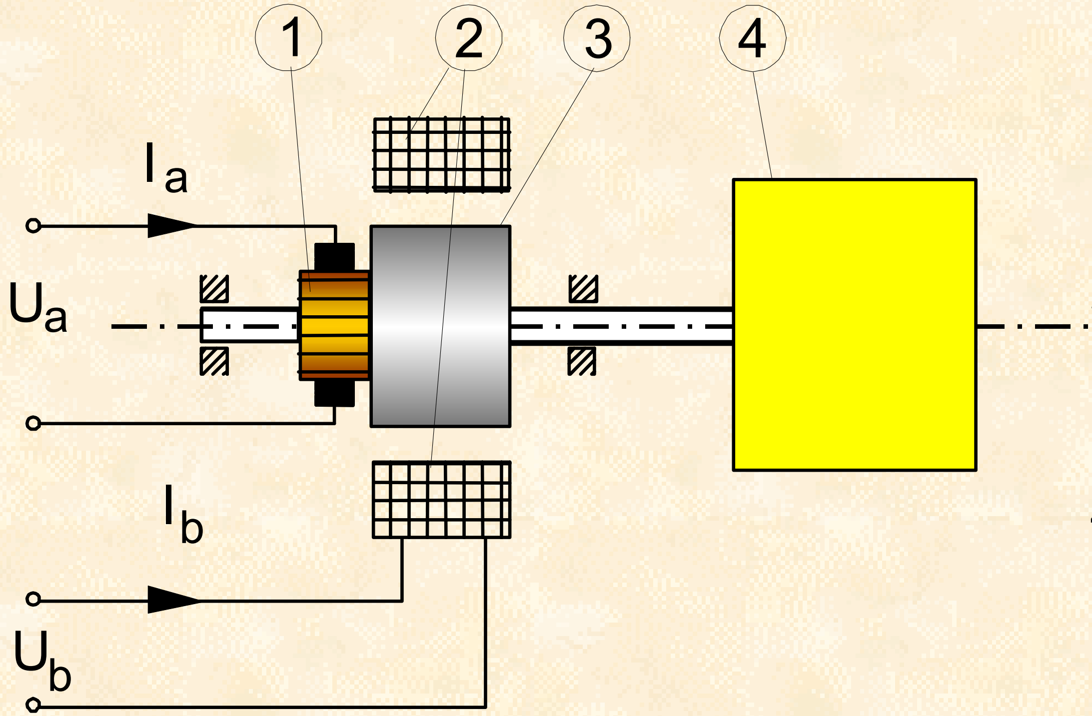
$$C = \frac{N_2 p}{\pi a}$$

$$P_{el} = P_{mech}$$

$$E_r I_2 = T\omega_r$$

$$C\omega_r \phi I_2 = C\phi I_2 \omega_r$$

Stationair gedrag: bekrachtiging



1 Collector

2 Veldwikkeling

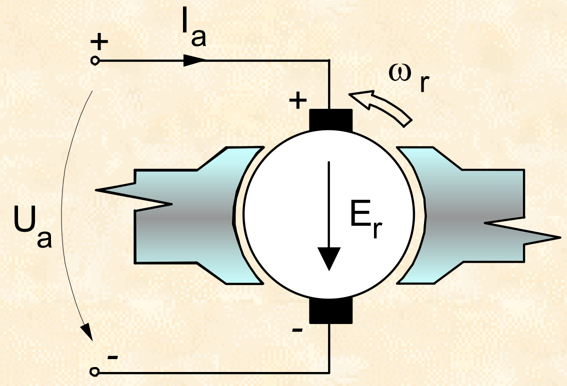
3 Anker

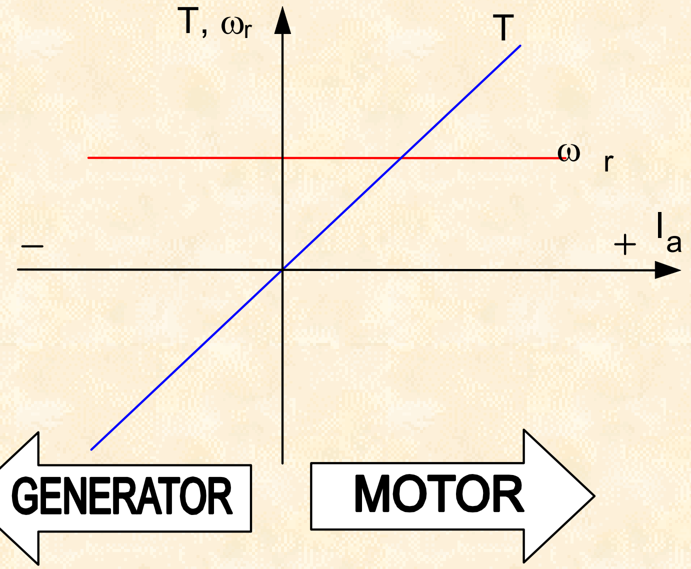
4 Aandrijfaggregaat of belasting

Permanente magneten

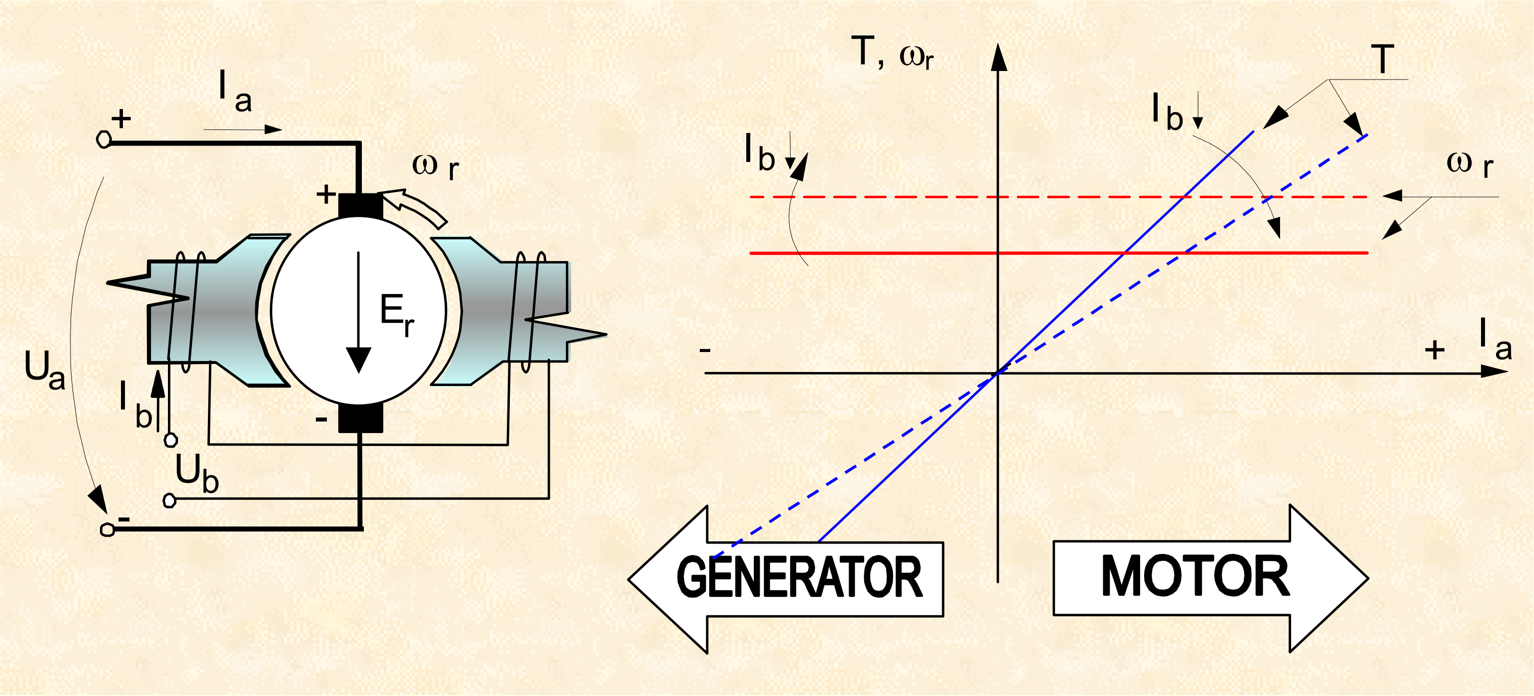
$$E_r = k_e \omega_r \qquad k_e = C\phi_b$$

$$T = k_t I_a \qquad k_t = C\phi_b = k_e$$



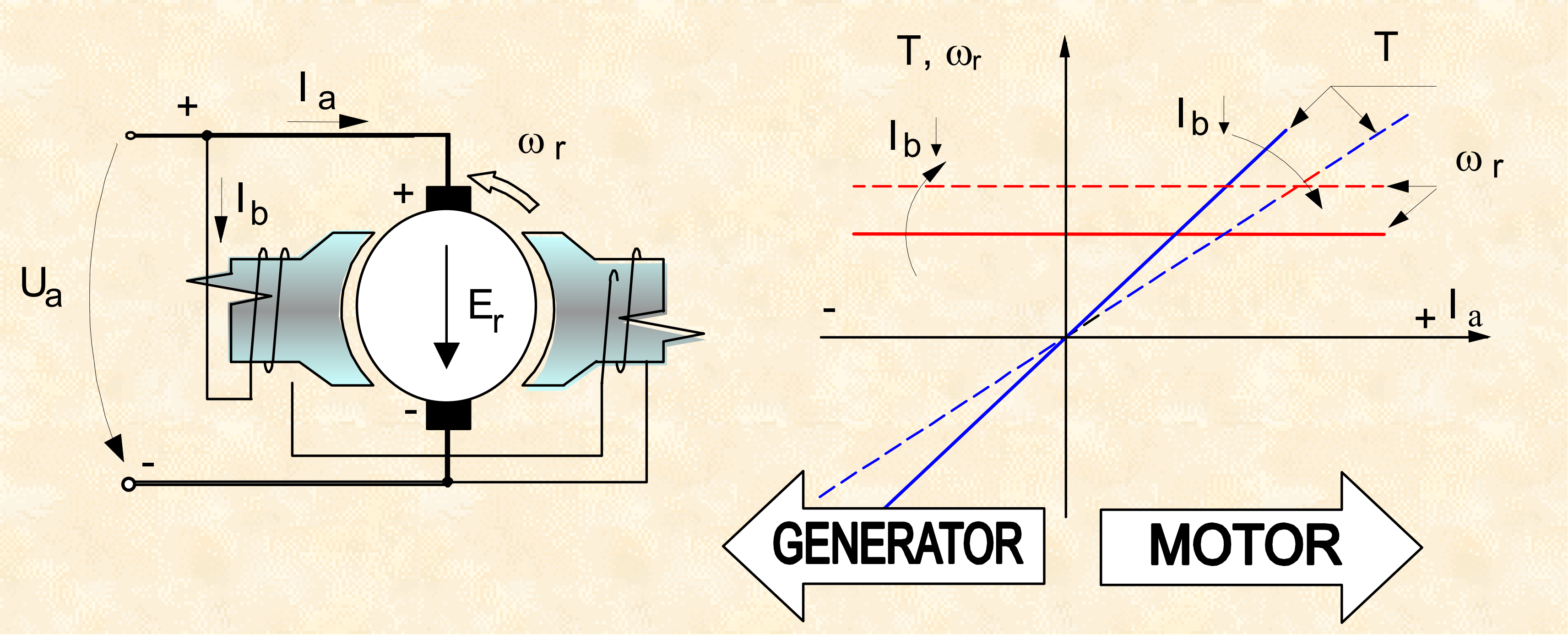


Onafhankelijke bekrachtiging

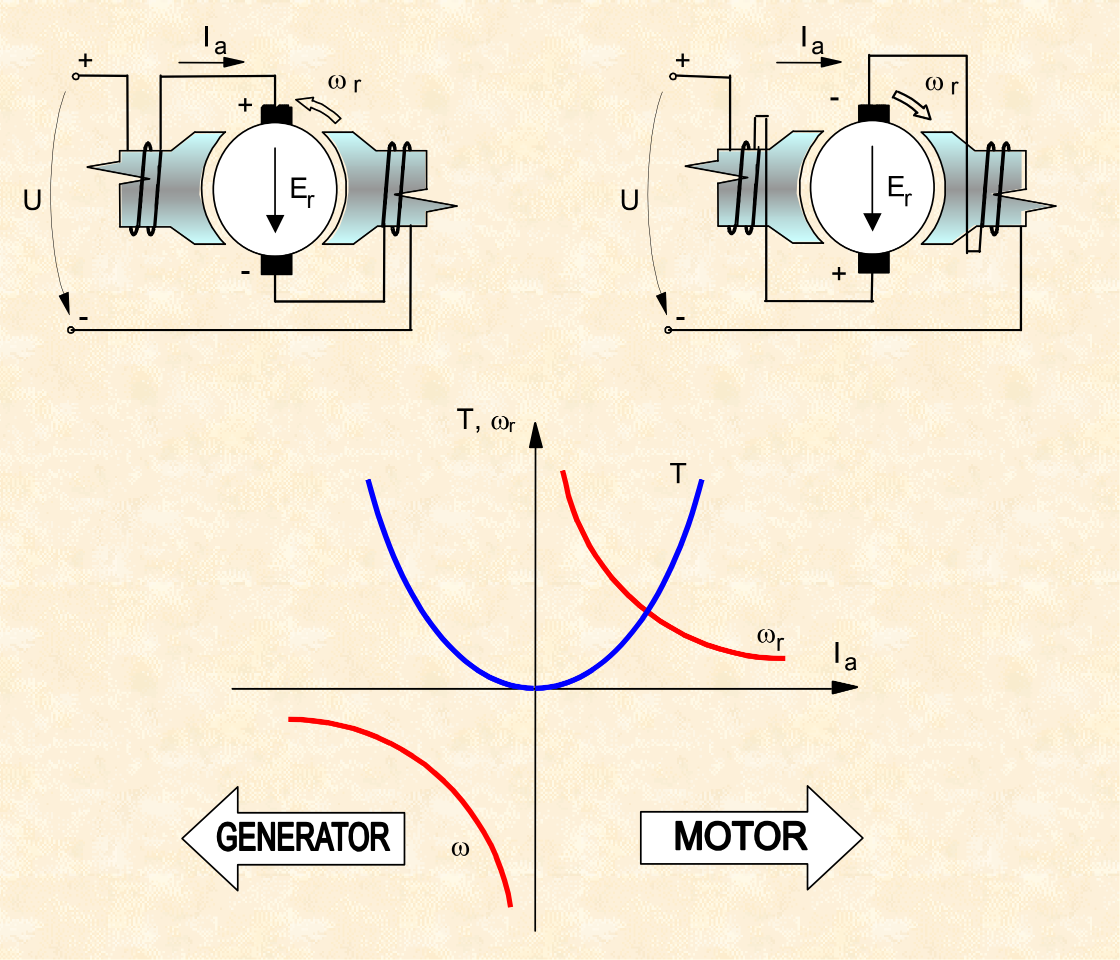


$$U_a = E_r = G I_b \omega_r \qquad T = G I_b I_a$$

Shunt-bekrachtiging



Serie-bekrachtiging

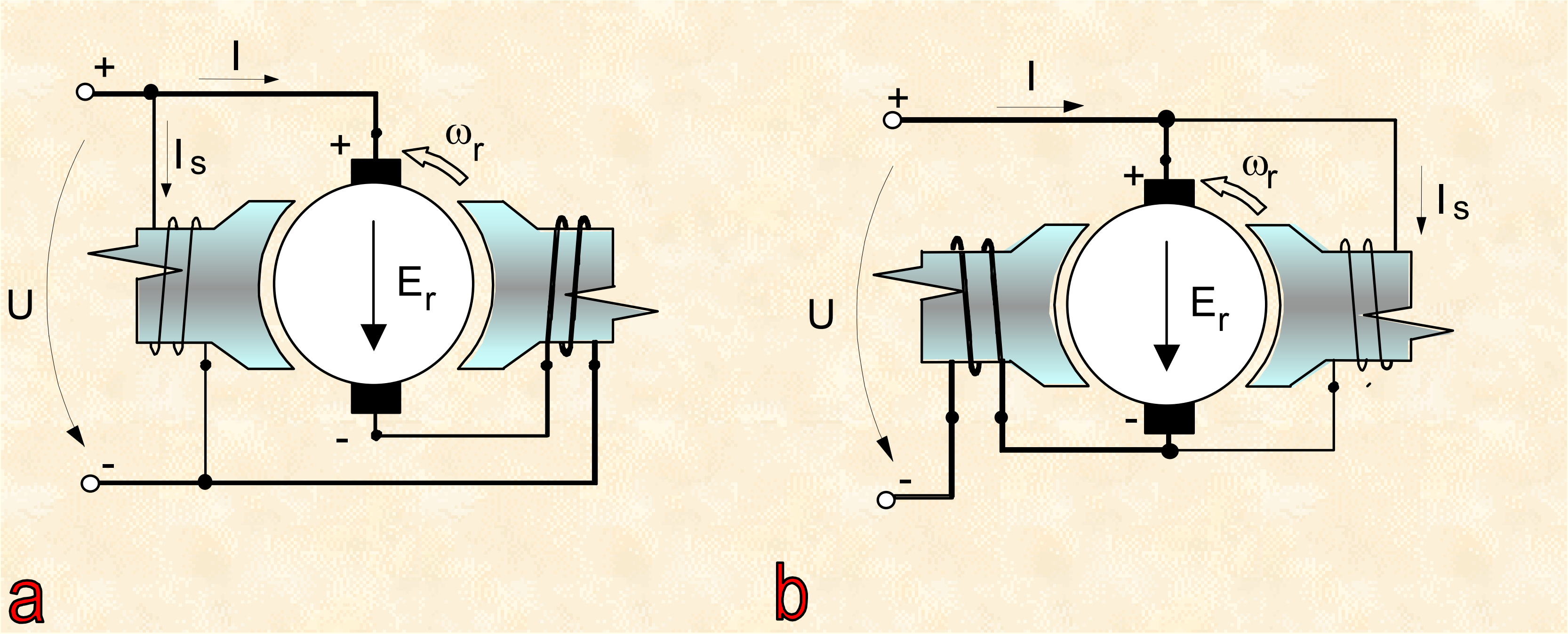


$$I = I_a = I_b$$

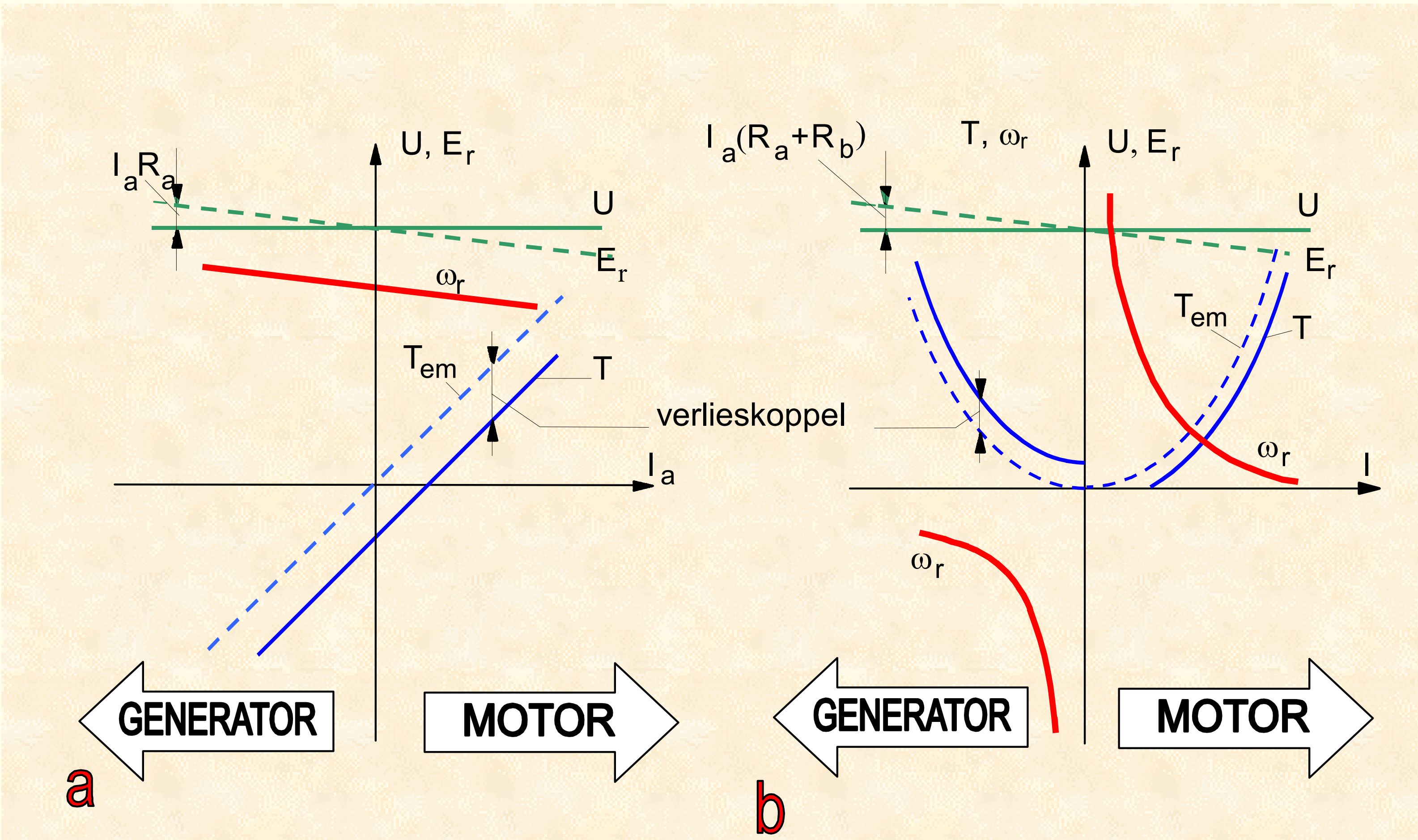
$$U = E_r = GI\omega_r$$

$$T = GI^2$$

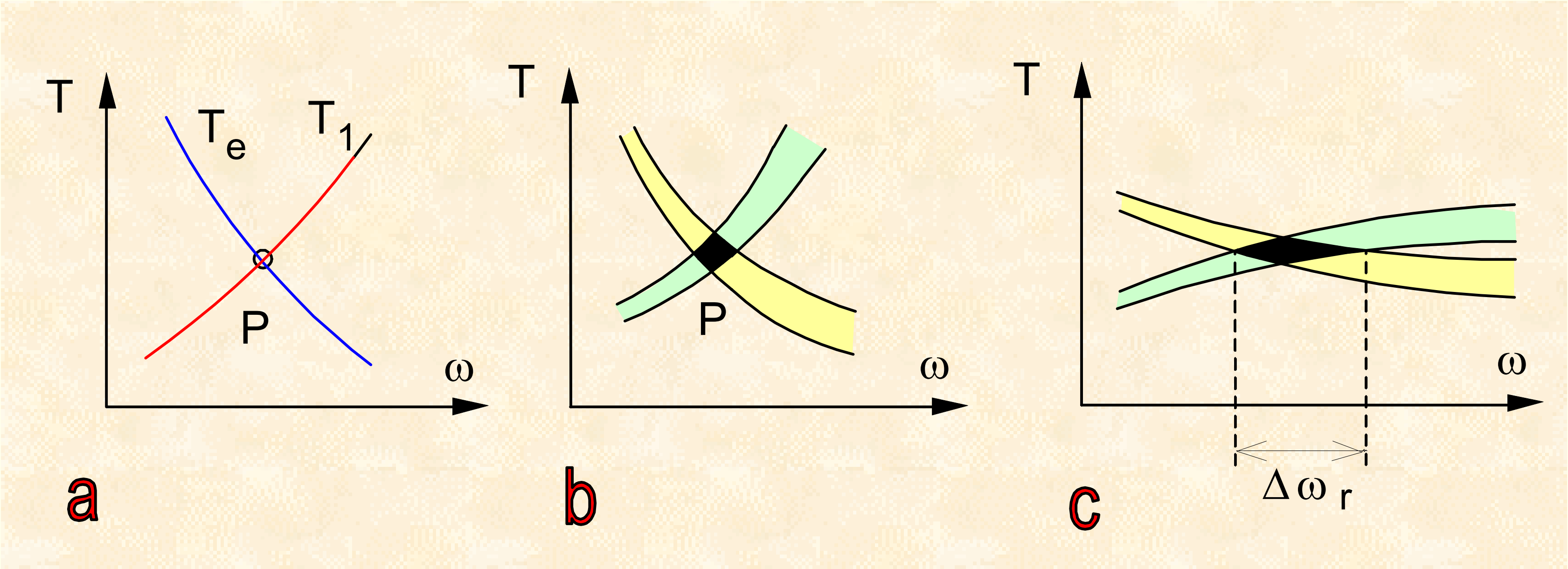
Compound bekrachtiging



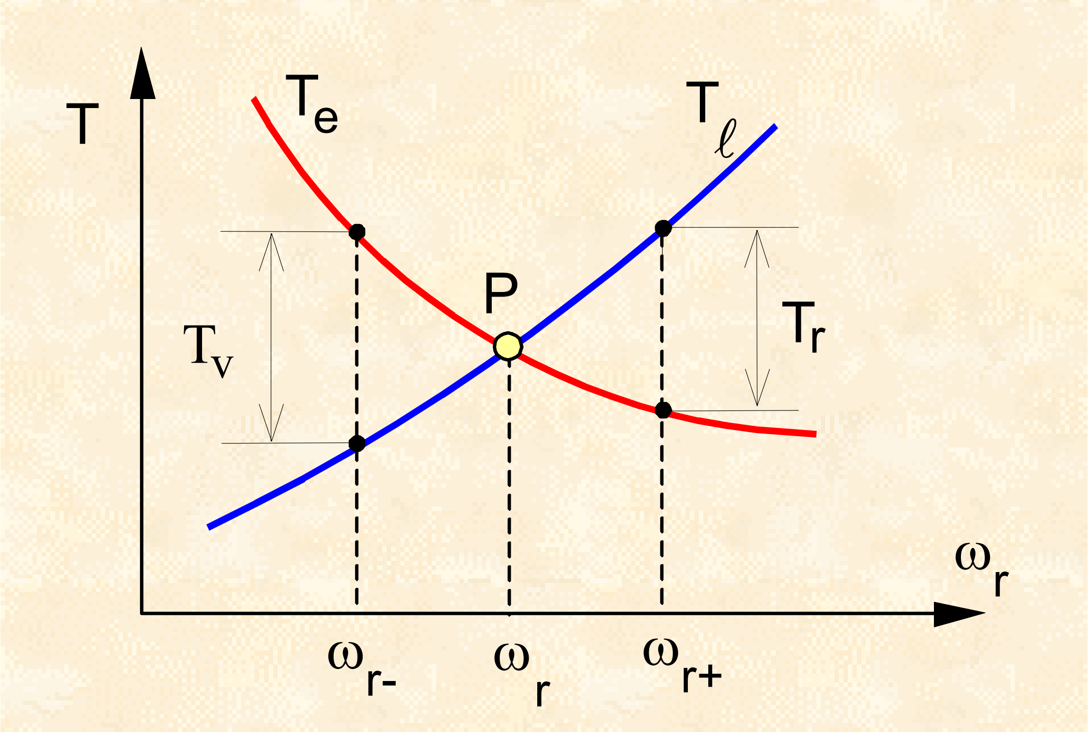
Karakteristieken van werkelijke machines



Werkingspunt en stabiliteit: motor



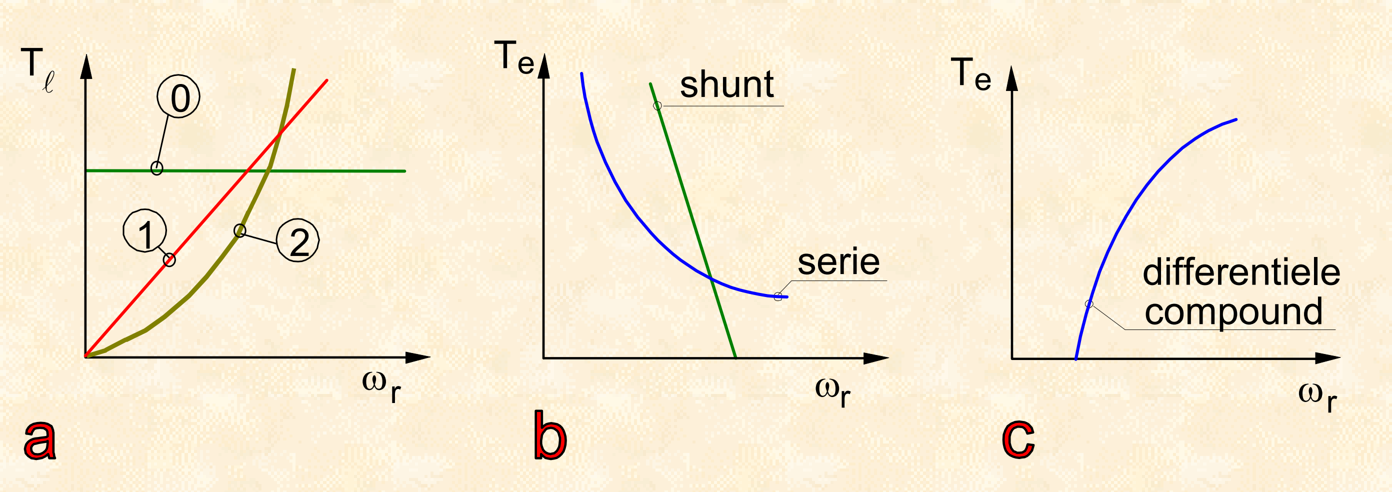
$$\frac{dT_\ell}{d\omega_r} > 0$$



$$\frac{dT_\ell}{d\omega_r} > \frac{dT_e}{d\omega_r}$$

Statisch stabiel werkingspunt

Motor- en lastkarakteristieken

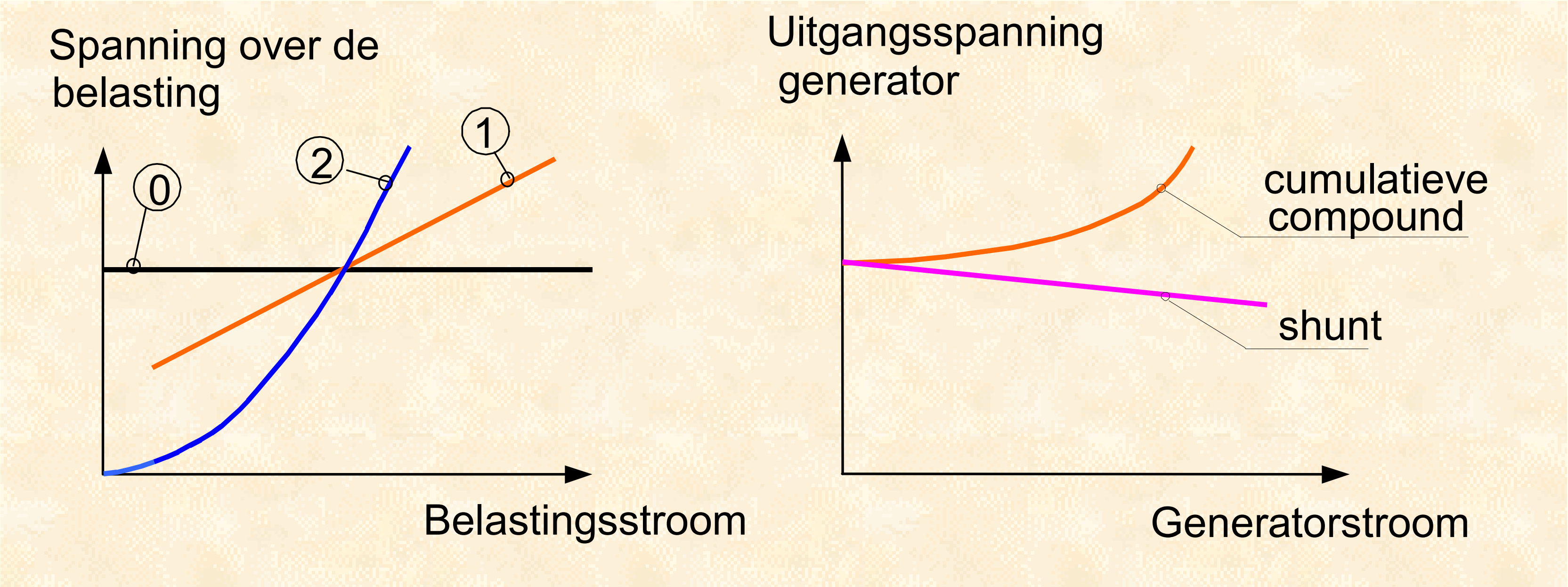


0. $T_l = k$ $\quad P_l = k\omega_r$ (kraan, lift)

1. $T_l = k\omega_r$ $\quad P_l = k\omega_r^2$ (werktuigmachine)

2. $T_l = k\omega_r$ $\quad P_l = k\omega_r^2$ (pomp-ventilator)

Werkingspunt en stabiliteit: generator



$$\frac{dU_\ell}{dI_\ell} > \frac{dU_g}{dI_g}$$

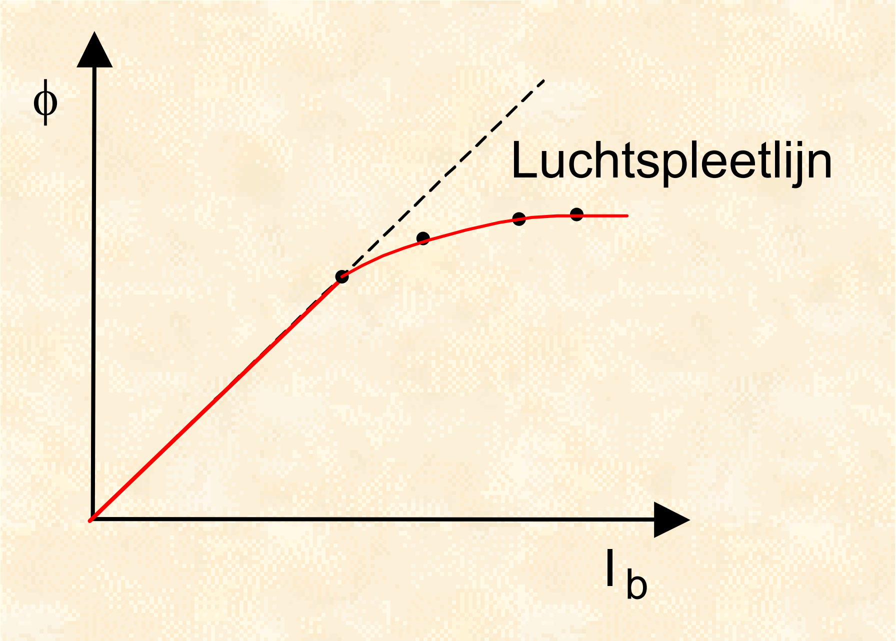
HOOFDSTUK 4

STATIONAIR GEDRAG VAN DE GELIJKSTROOMMOTOR

Stationair gedrag

- Onderzoeksmethode
- Permanent magneet, onafhankelijke en shuntbekrachtiging
- Seriebekrachtiging
- Universeelmotor
- Compoundbekrachtiging
- Snelheidsregeling
- Remmen

Onderzoeksmethode



$$U = E_r + I_a R_a$$

motor

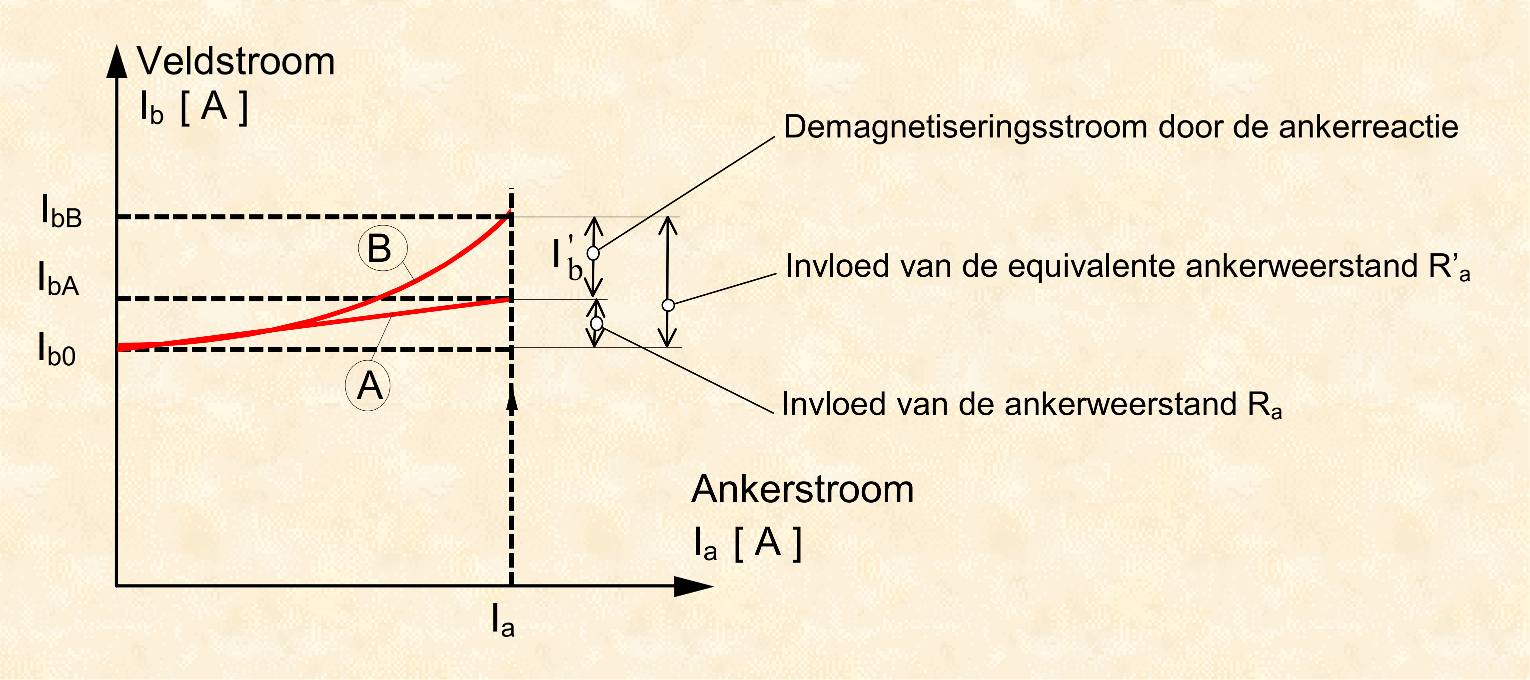
$$U = E_r - I_a R_a$$

generator

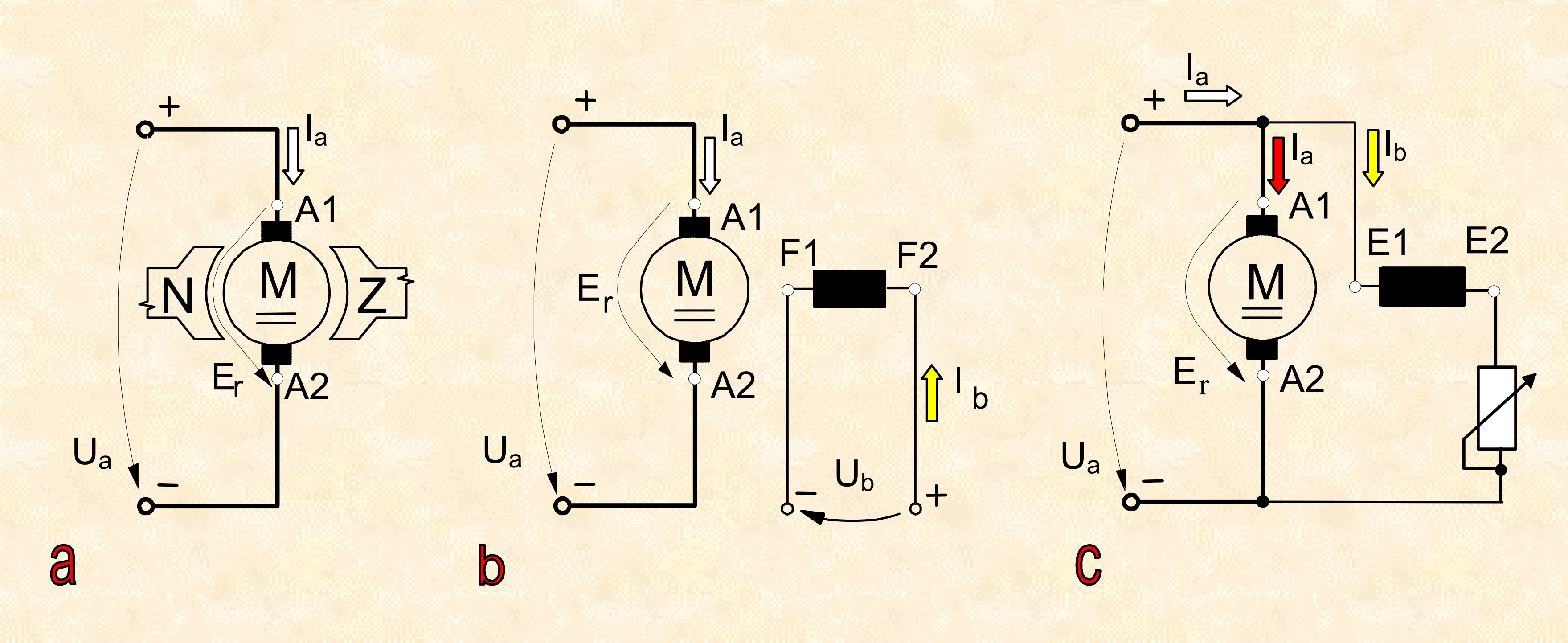
$$E_r = \frac{N_a p}{\pi a}\omega_r \phi = C\omega_r \phi$$ e.m.k.

$$T = \frac{N_a p}{\pi a} I_a \phi = C I_a \phi$$ koppel

$$E_r I_a = T\omega_r$$ vermogen



Permanent magneet, onafhankelijke en shuntbekrachtiging



Karakteristieken

$$T = C\phi I_a$$

$$T = \frac{C\phi(U_a - C\phi\omega_r)}{R_a} \sim \frac{U_a}{I_b}$$

$$P = T\omega_r = \frac{C\phi\omega_r(U_a - C\phi\omega_r)}{R_a}$$

$$C\phi = GI_b$$

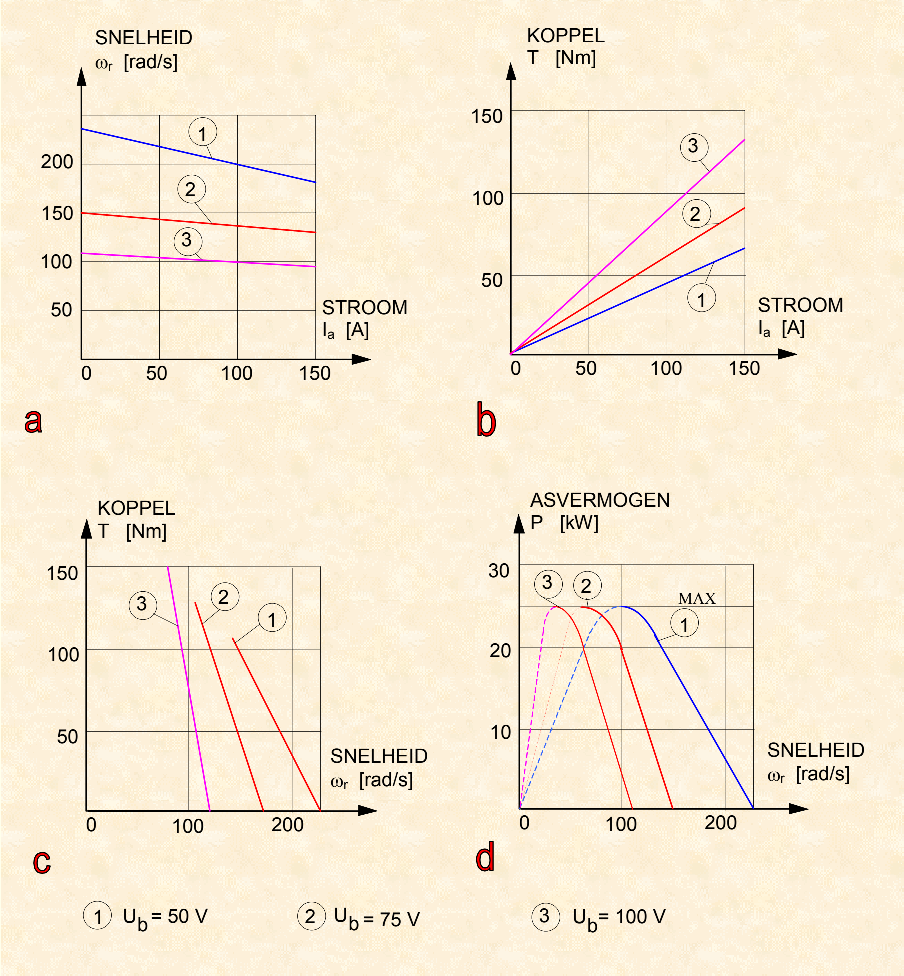
$$N_b I_b = \Re_m \phi$$

$$E_r = G I_b \omega_r = G \frac{U_b}{R_b} \omega_r$$

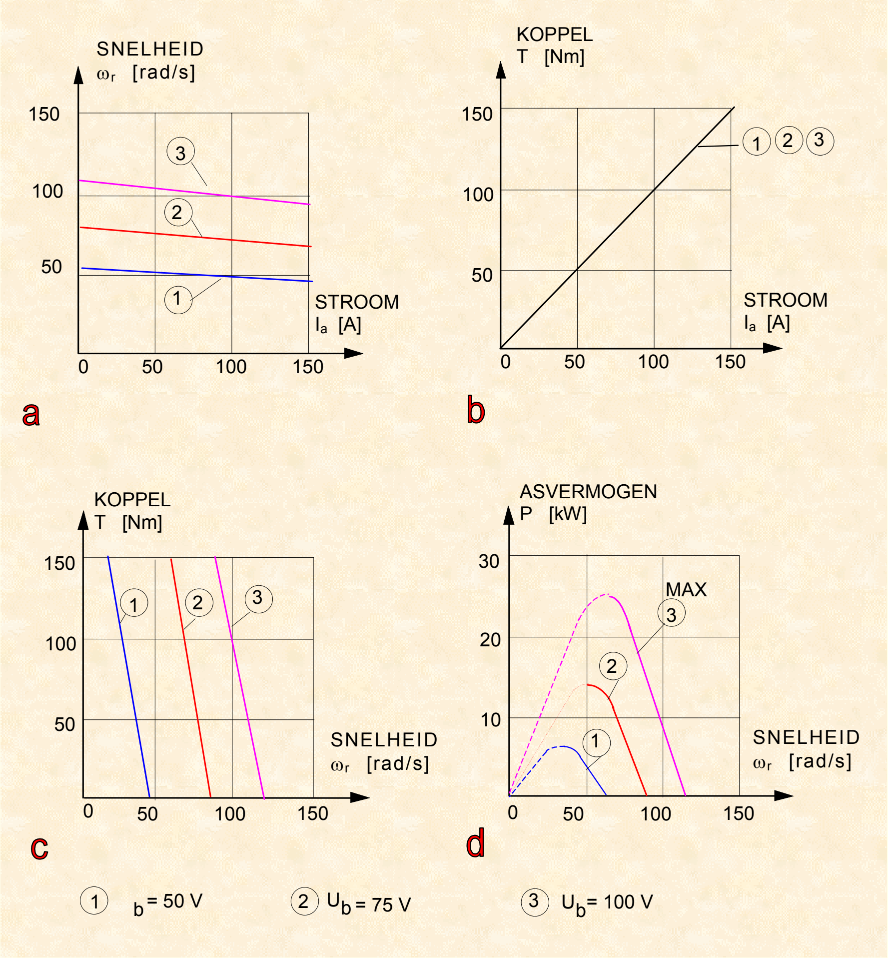
$$\omega_r = \frac{(U_a - I_a R_a) R_b}{G U_b}$$

$$T = G I_b I_a = \frac{G U_b}{R_b R_a} \left[U_a - G\left(\frac{U_b}{R_b}\right) \omega_r \right]$$

Veldregeling

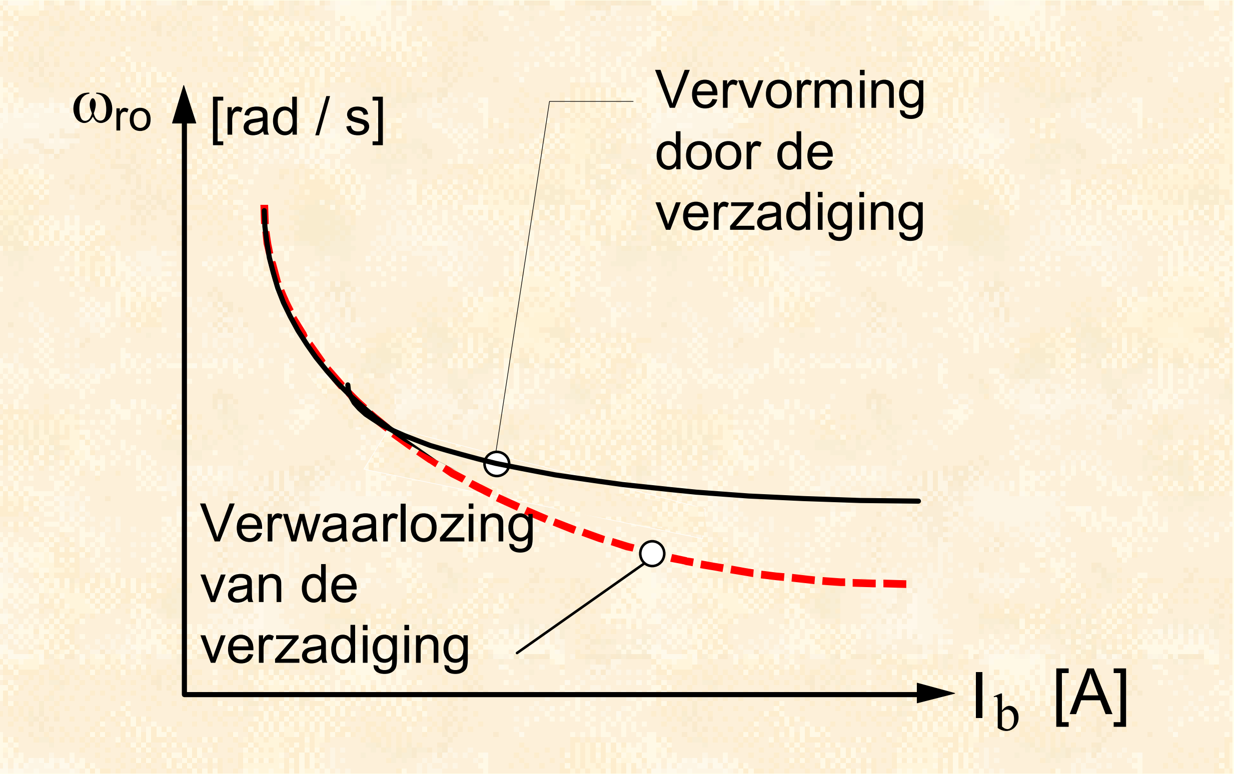


Spanningsregeling



Nullastsnelheid

$$\omega_{r0} = \frac{U_a}{C\phi}$$



Seriebekrachtiging

$$\omega_r = \frac{(U - IR)}{C\phi}$$

$$T = C\phi I$$

$$T = \frac{C\phi}{R}\left(U - C\phi\omega_r\right)$$

$$P = T\omega_r = \frac{C\phi\omega_r}{R}\left(U - C\phi\omega_r\right)$$

$$C\phi = GI$$

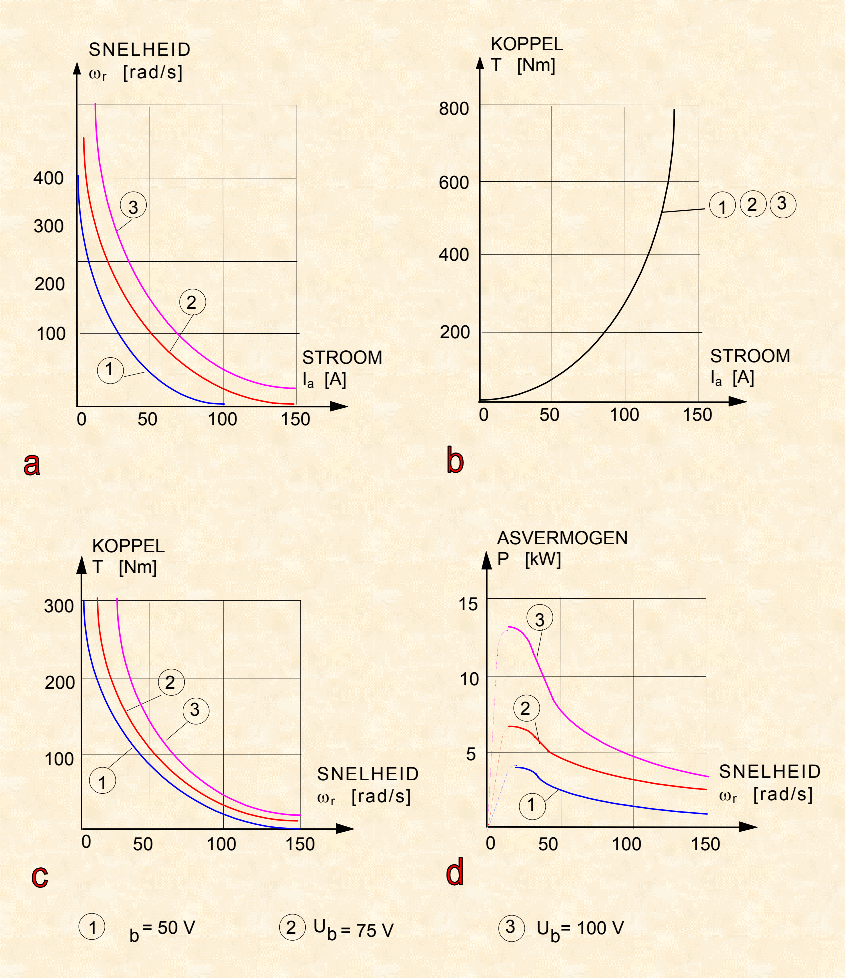
$$E_r = G\omega_r I$$

$$\omega_r = \frac{(U - IR)}{GI}$$

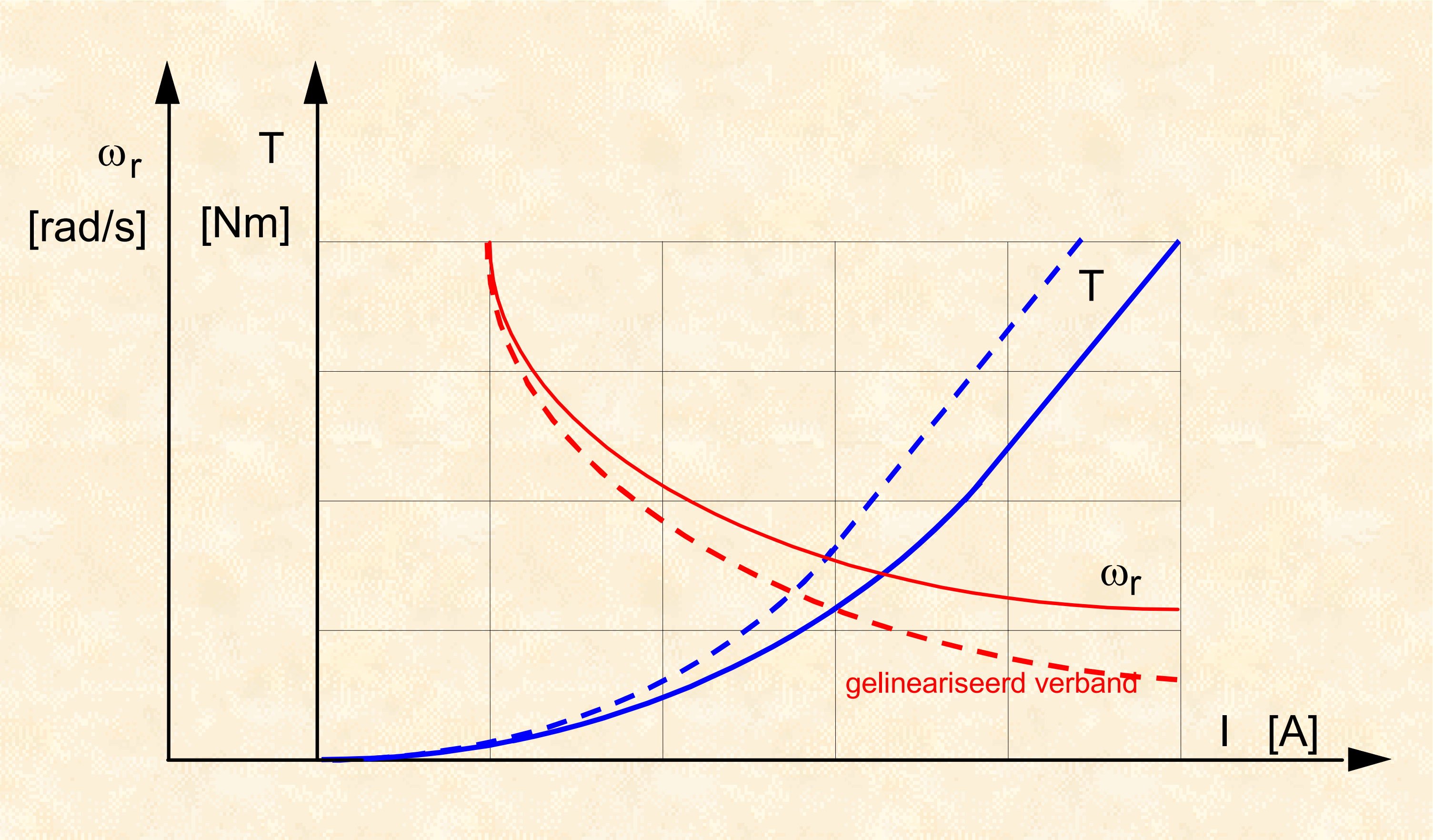
$$T = GI^2$$

$$T = \frac{GU^2}{\left(\omega_r G + R\right)^2}$$

Karakteristieken

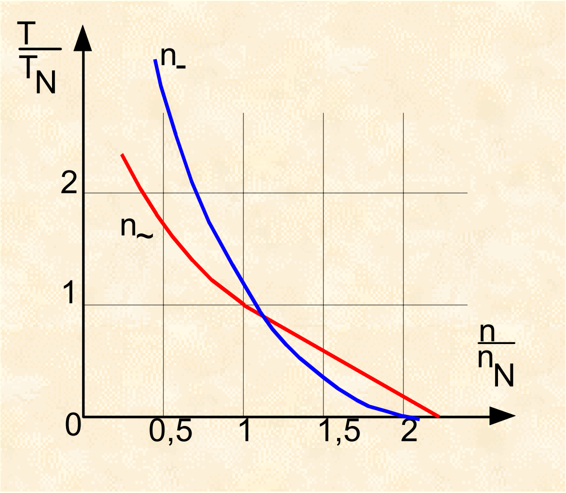


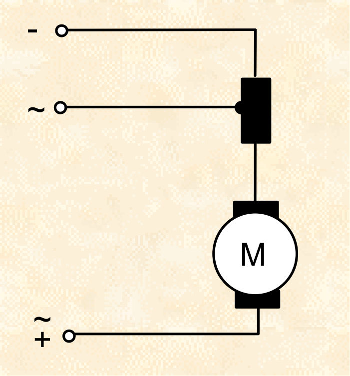
Invloed van verzadiging

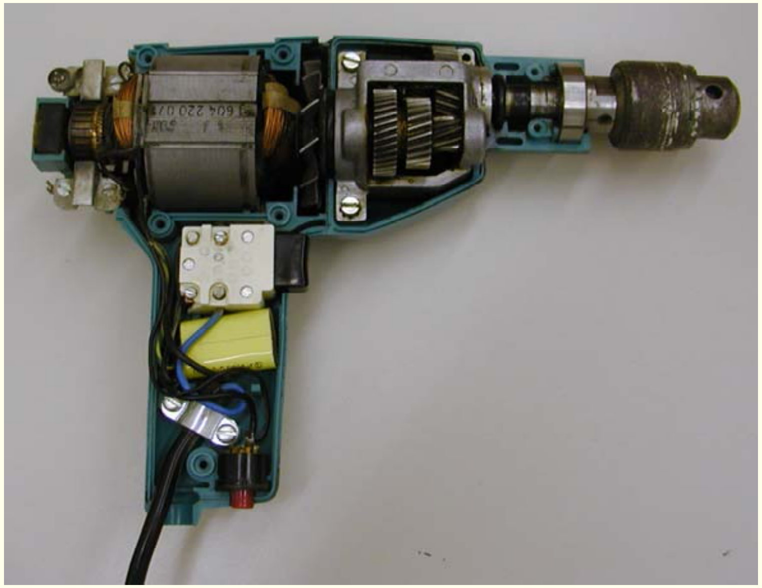


Universeelmotor

- $T = k \Phi I$
- Reactieve spanningsval
- Verzaidiging van stroompieken

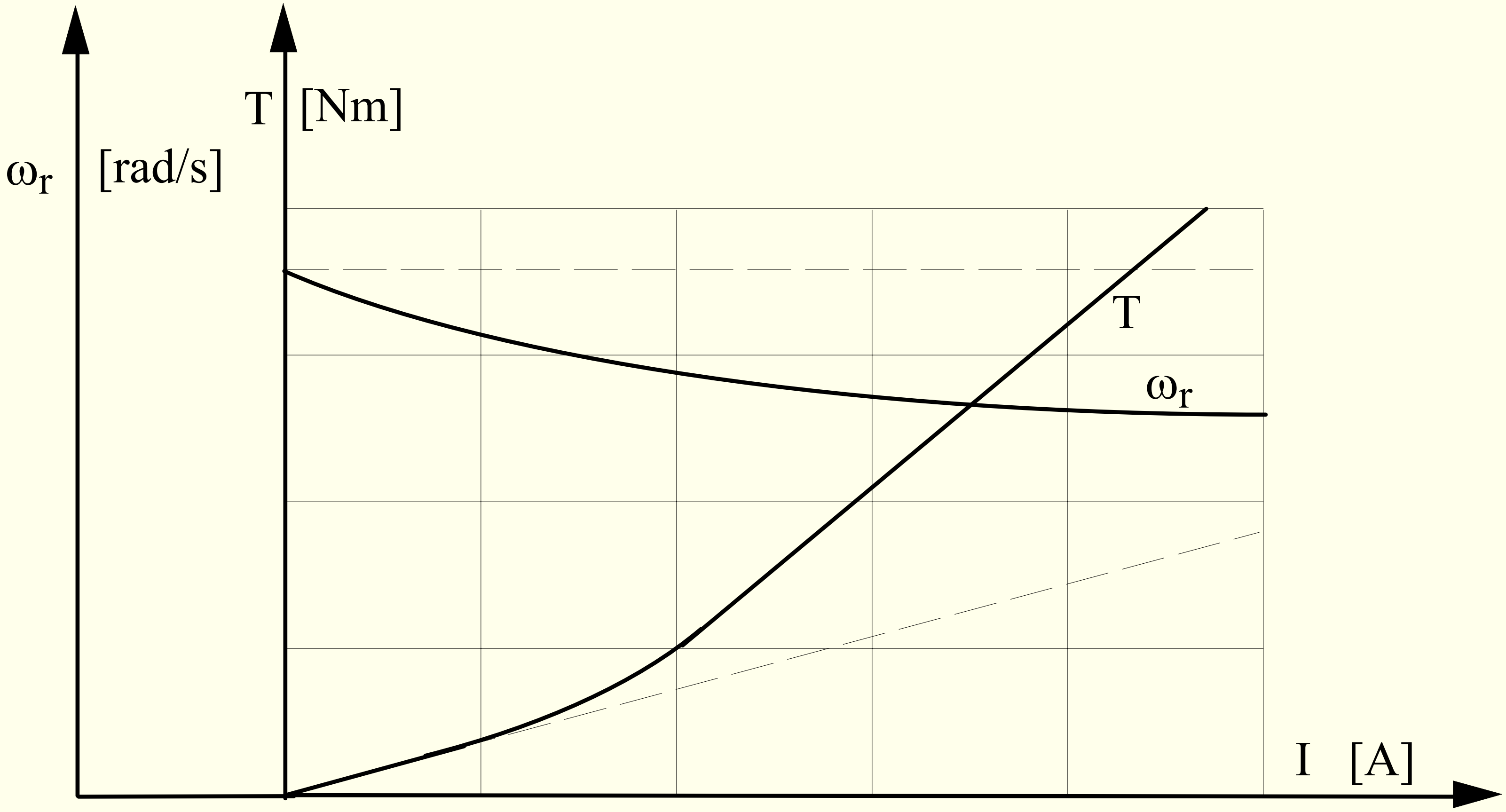






Goedkoop en hoge snelheid
Toerental regelbaar
Vonken op collector

Compoundbekrachtiging



Snelheidsregeling

$$\omega_r = \frac{E_r}{C\phi} = \frac{(U_a - I_a R_a)}{C\phi}$$

$\Delta\Phi$: **Veldsturing**

ΔR_a: **Indirecte ankersturing**

ΔV_a: **Ankersturing**

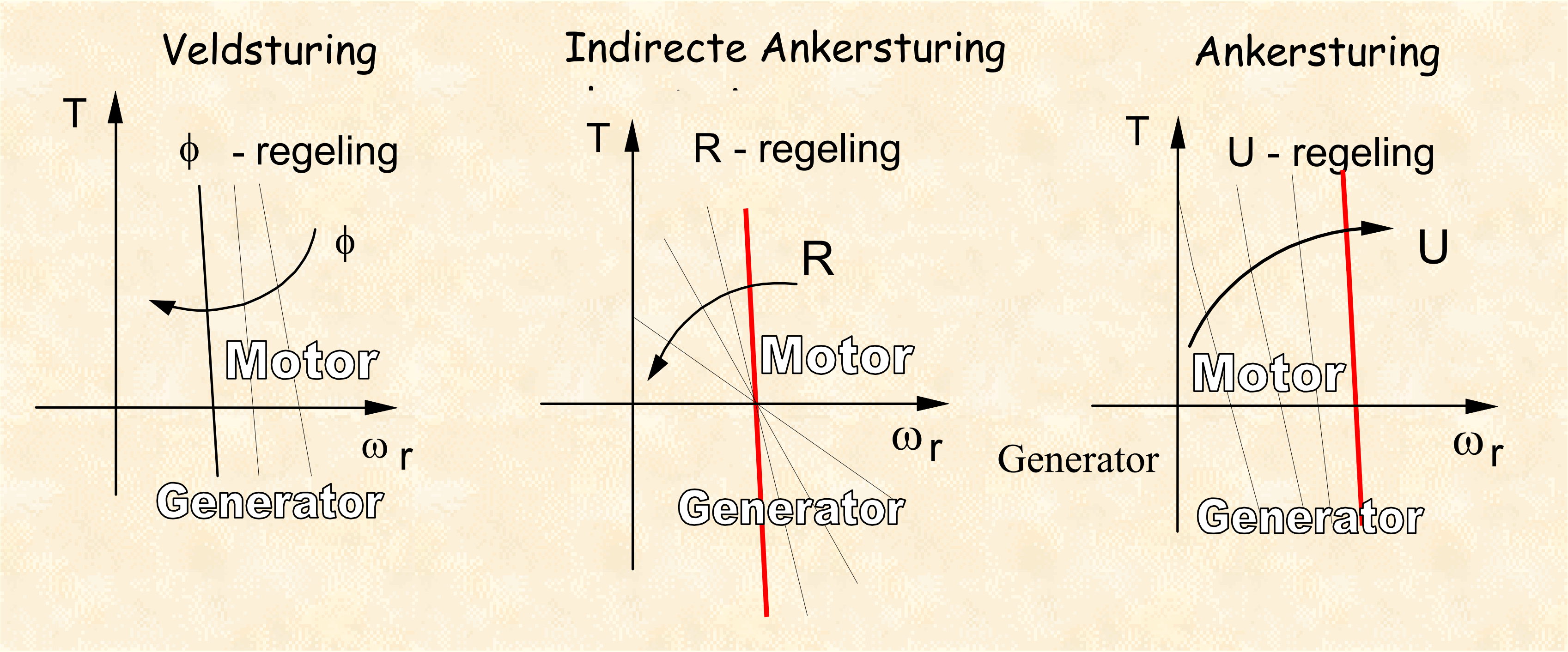
T-ωr karakteristieken-shunt

$$T = \frac{C\phi(U_a - C\omega_r\phi)}{R}$$

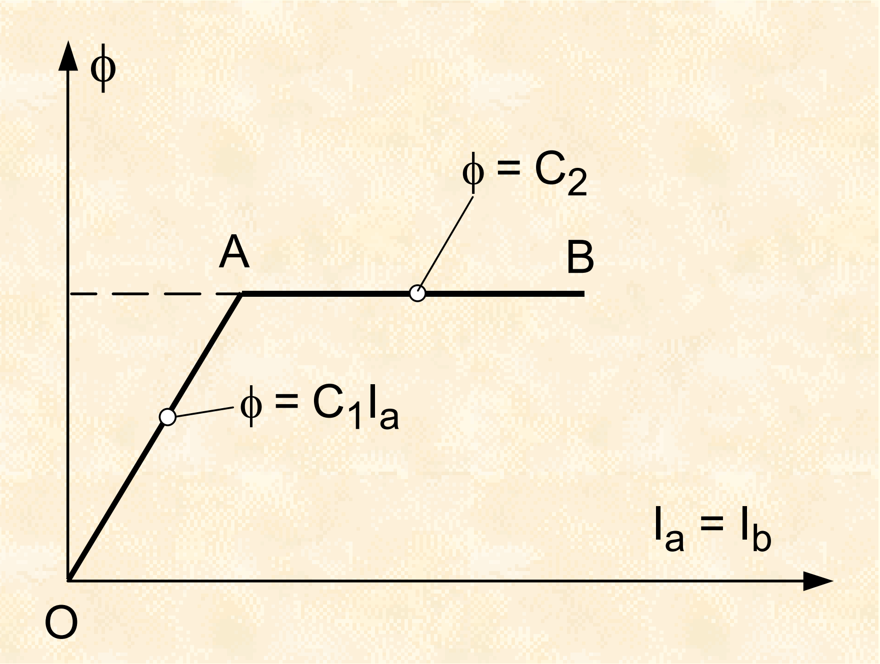
$$\omega_{r0} = \frac{U_a}{C\phi}$$

$$\frac{dT}{d\omega_r} = -\frac{C^2\phi^2}{R}$$

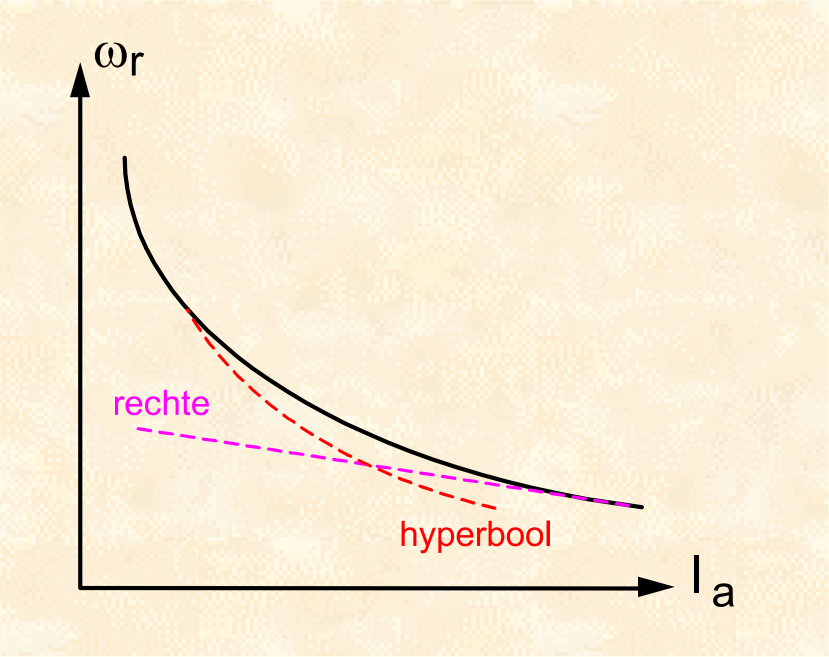
Regelmogelijkheden



T-ωr karakteristieken-serie



$$\omega_r = \frac{U}{C\ C_1 I_a} - \frac{R}{C\ C_1} \qquad \omega_r = \frac{U}{C\ C_2} - I_a \frac{R}{C\ C_2}$$

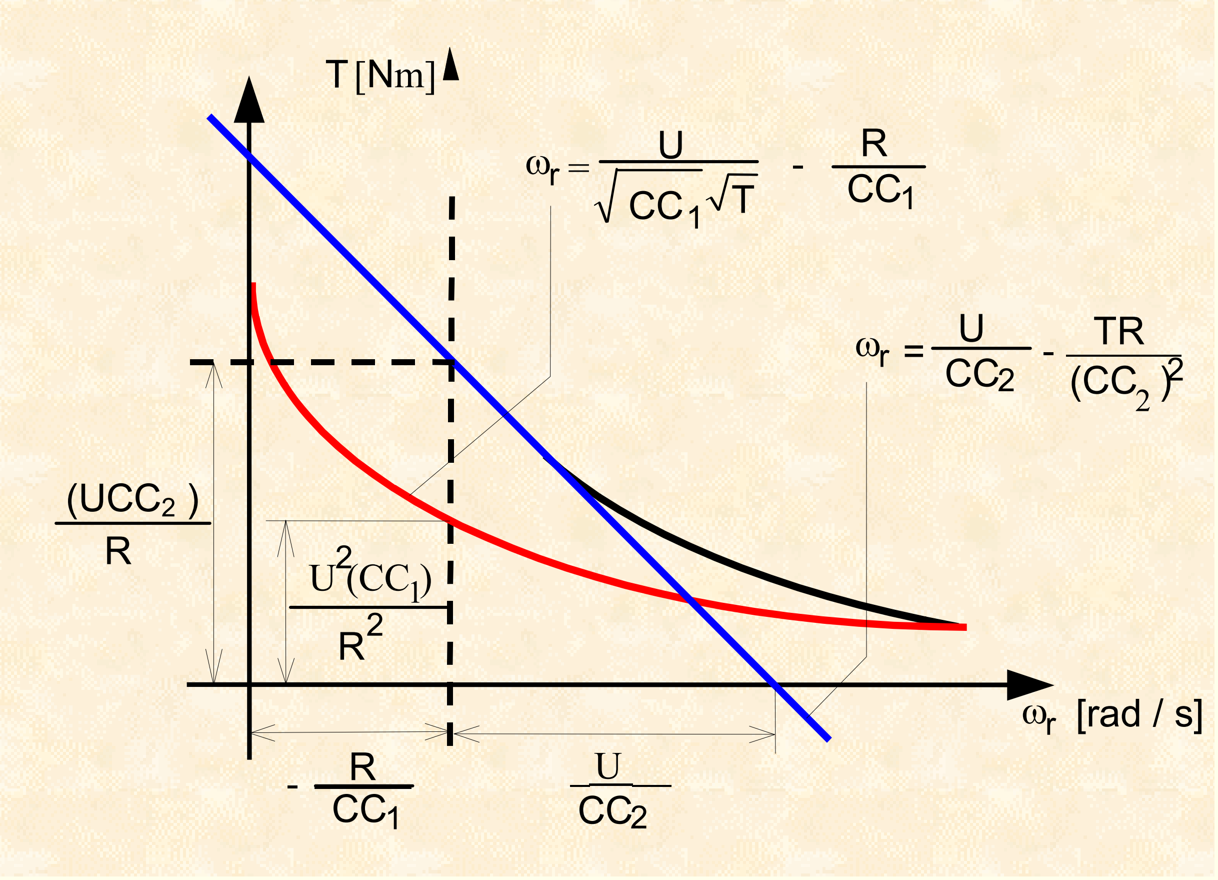


Toerental

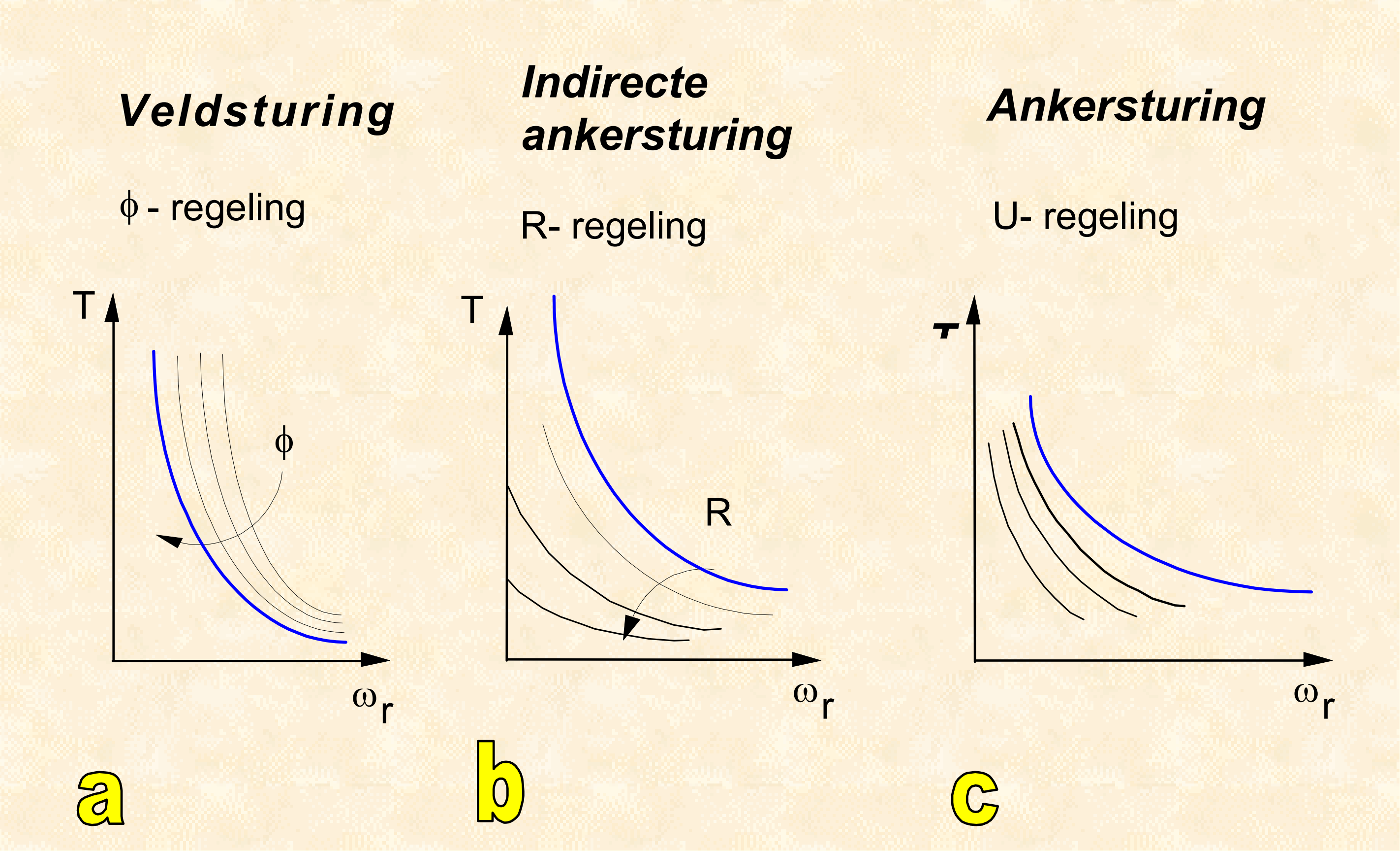
$$I_a = \sqrt{\frac{T}{C\,C_1}} \qquad I_a = \frac{T}{C\,C_2}$$

$$\omega_r = \frac{U}{\sqrt{C\,C_1}\sqrt{T}} - \frac{R}{C\,C_1} \qquad \omega_r = \frac{U}{C\,C_2} - \frac{T\,R}{(C\,C_2)^2}$$

Koppel-toerentalkarakteristiek voor een seriemotor



Toerentalregeling voor een gelijkstroomseriemotor



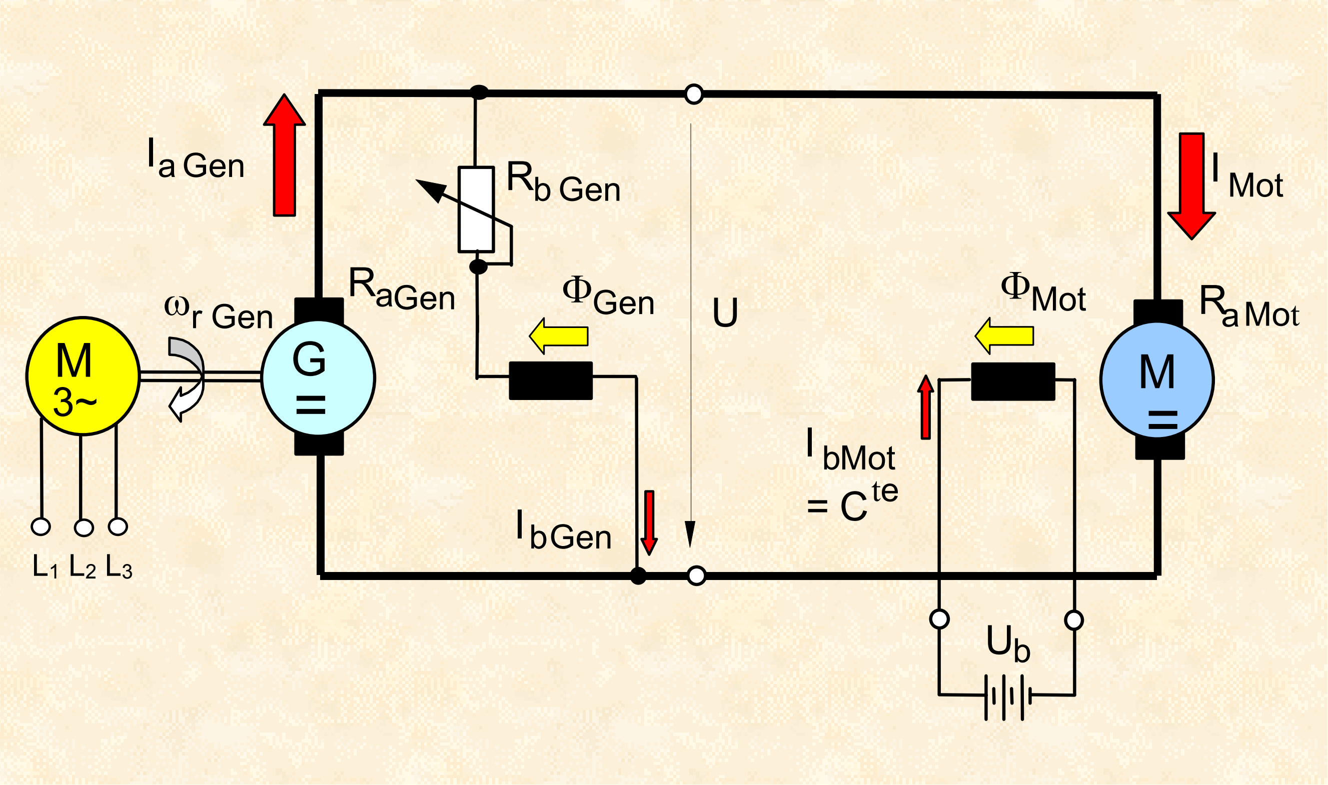
Veldsturing

- $\phi\downarrow$ $\omega\uparrow$ maar $I\uparrow$
- shunt: supplementaire weerstand
- onafhankelijk: U_b of weerstand

Indirecte ankersturing

- Veel verliezen

Ankersturing: gelijkstroomgenerator

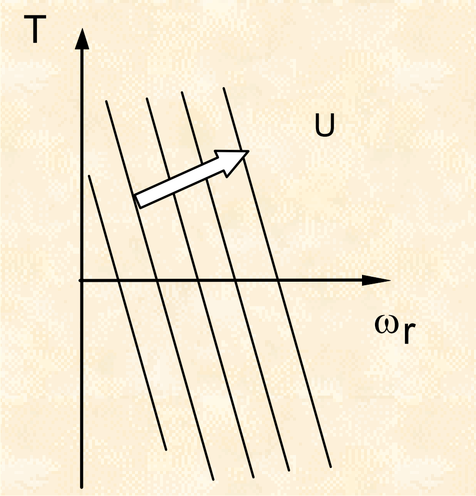


Ward-Leonard

$$\omega_{rGen} \rightarrow E_{rGen} = C\omega_{rGen}\phi_{Gen}$$

$$U = E_{rGen} - R_{aGen}I_{aGen}$$

$$\omega_{rMot} = \frac{U - R_{aMot}I_{aMot}}{C\phi_{Mot}} \quad \frac{U}{C\phi_{Mot}} \sim U$$



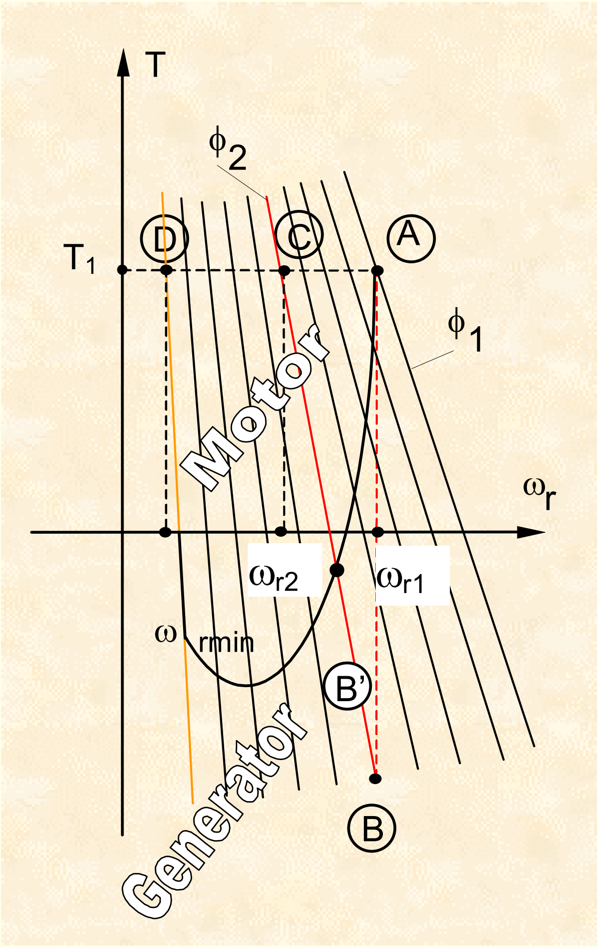
Koppel-snelheidskarakteristieken
van
een Ward-Leonard schakeling

Remmen

- Tegenstroomremming
  - ! Draairichting
  - ! Hoge stromen
- Rheostatisch

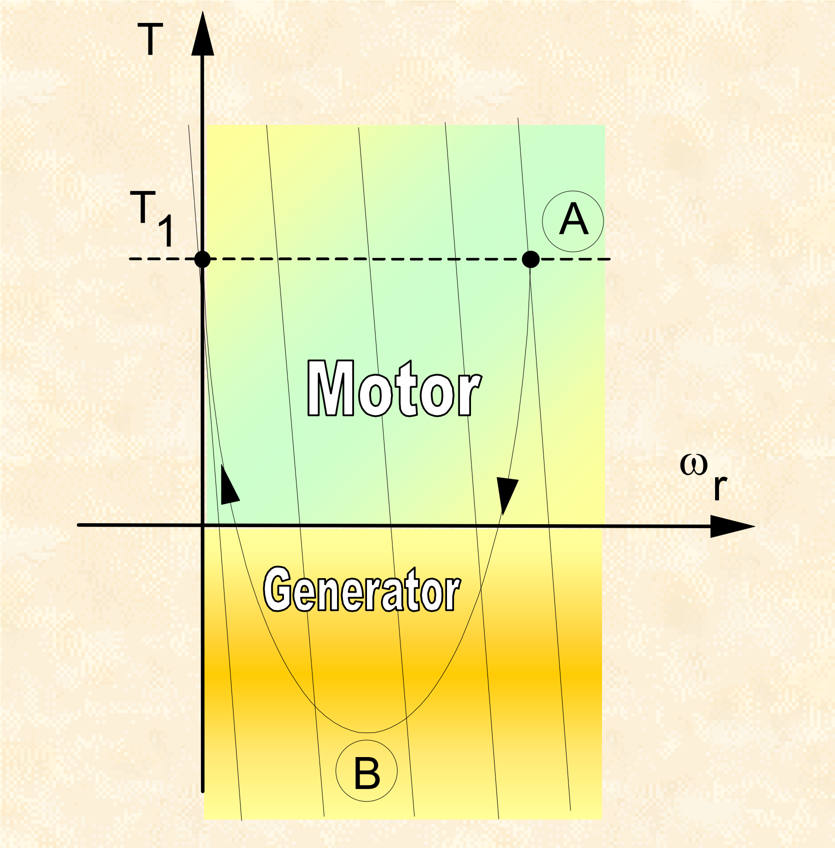
$$I = \frac{U + E_r}{R_{tot}}$$

Recuperatieremming-shuntmotor



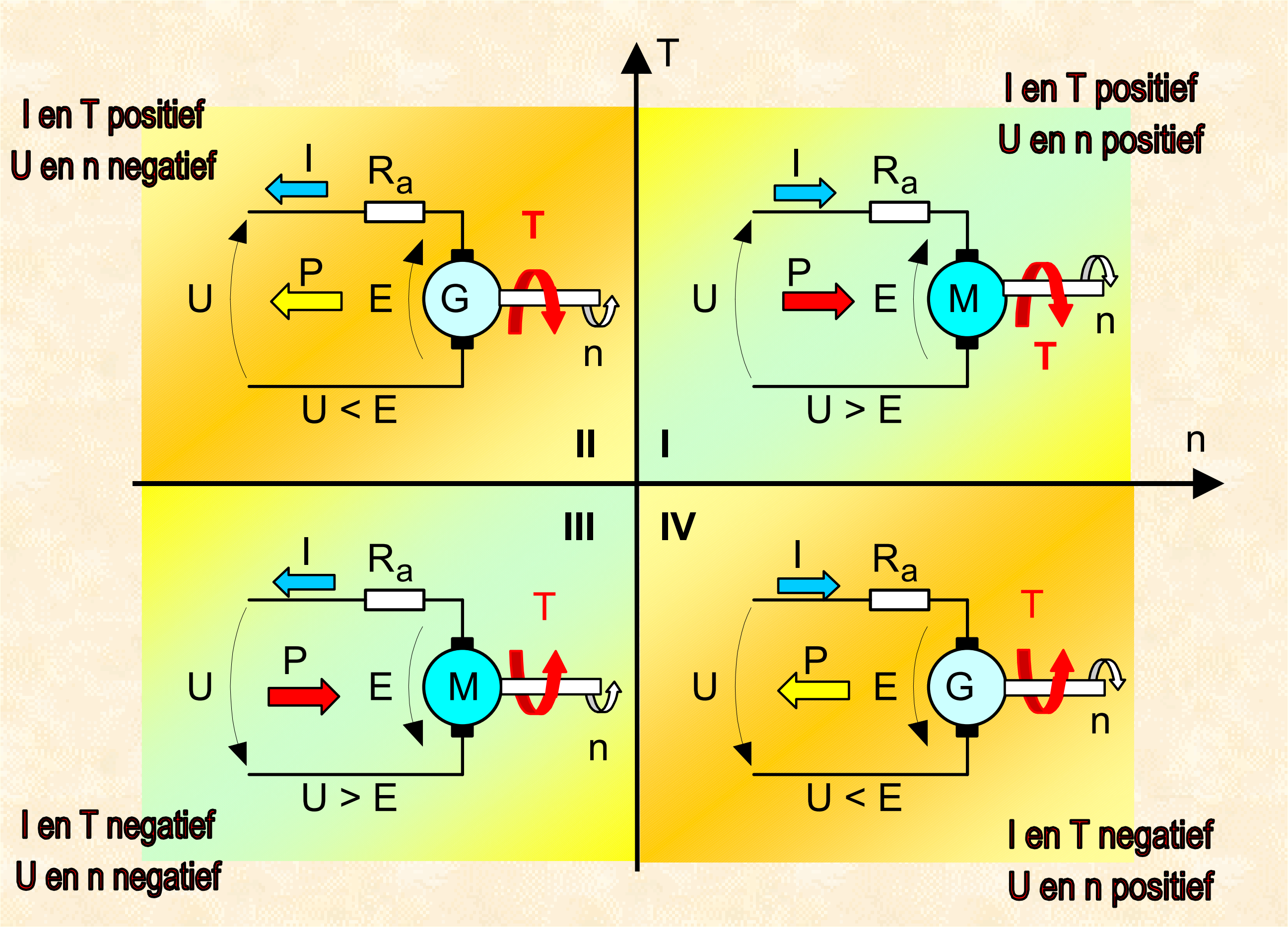
$$I_a = \frac{U - E_r}{R_a}$$

Recuperatieremming-Klassieke Ward-Leonard

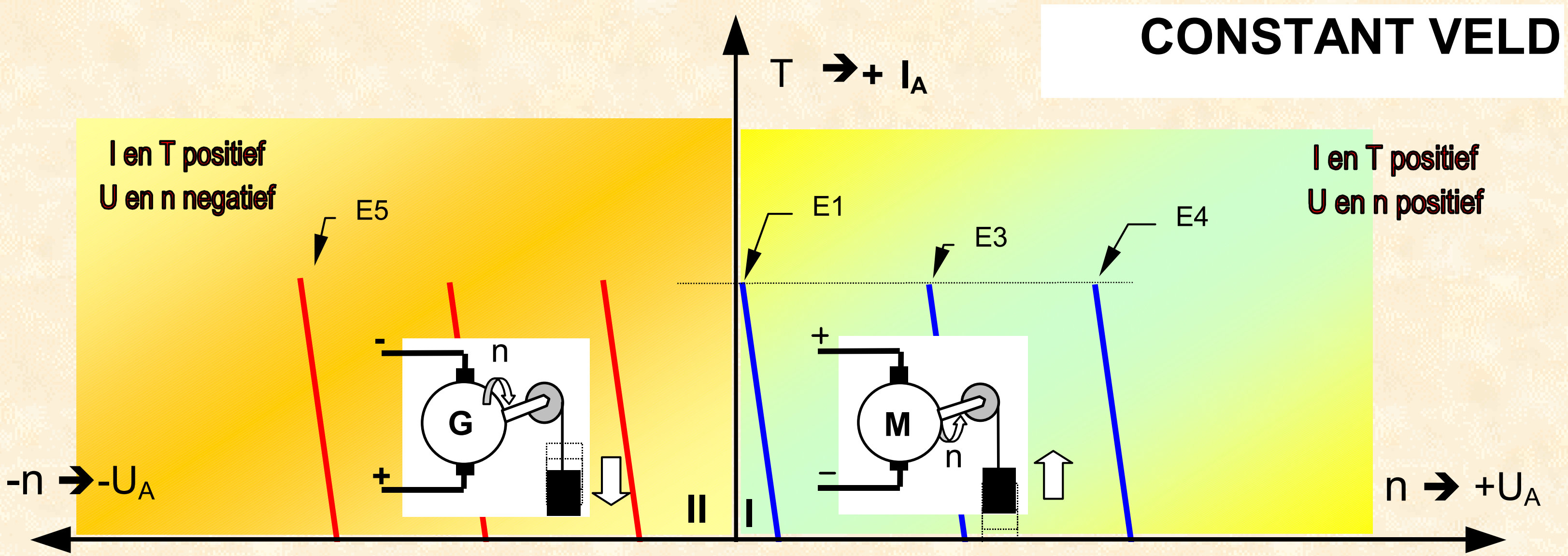


$$I_a = \frac{U - E_r}{R_a}$$

Werking in vier kwadranten



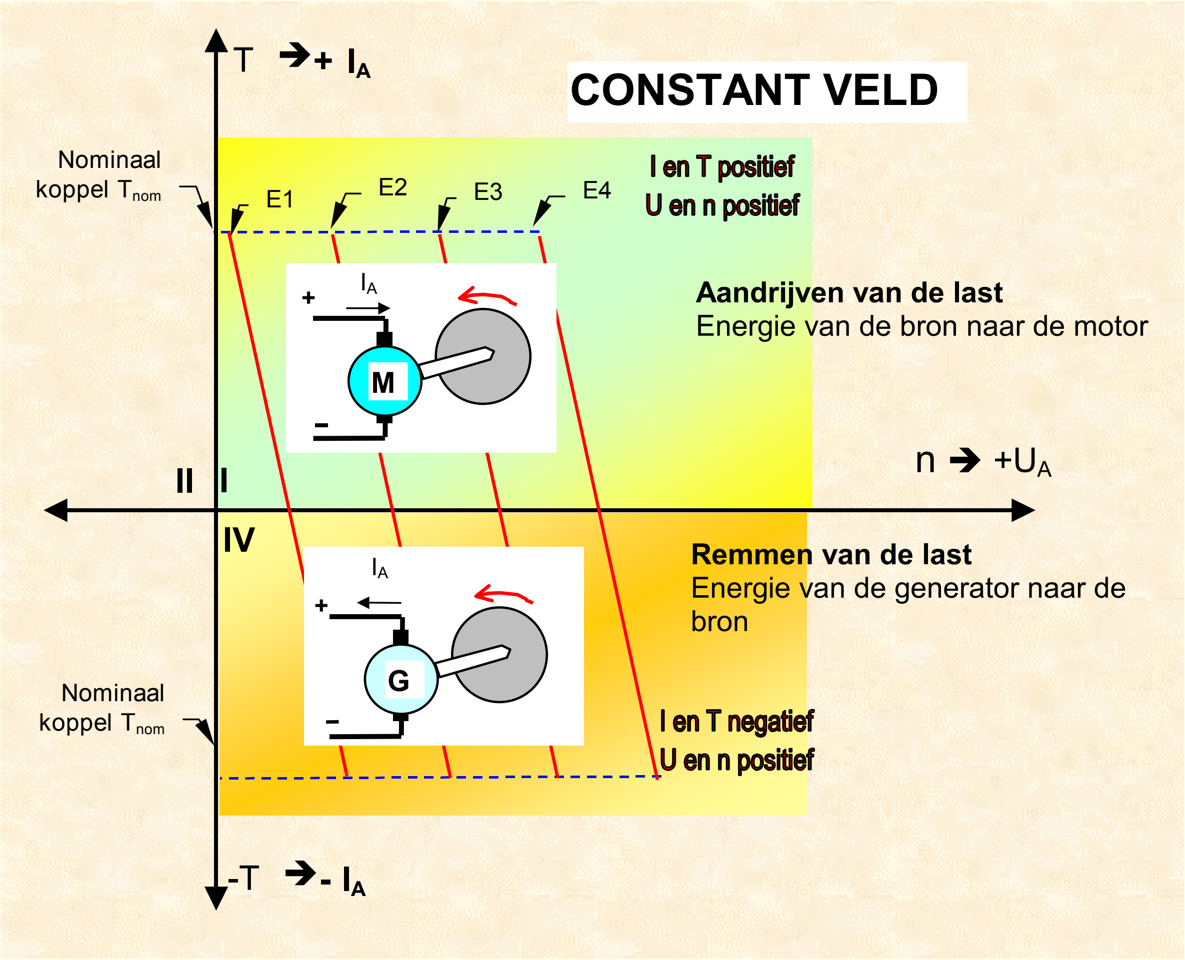
Tweekwadrantenwerking I



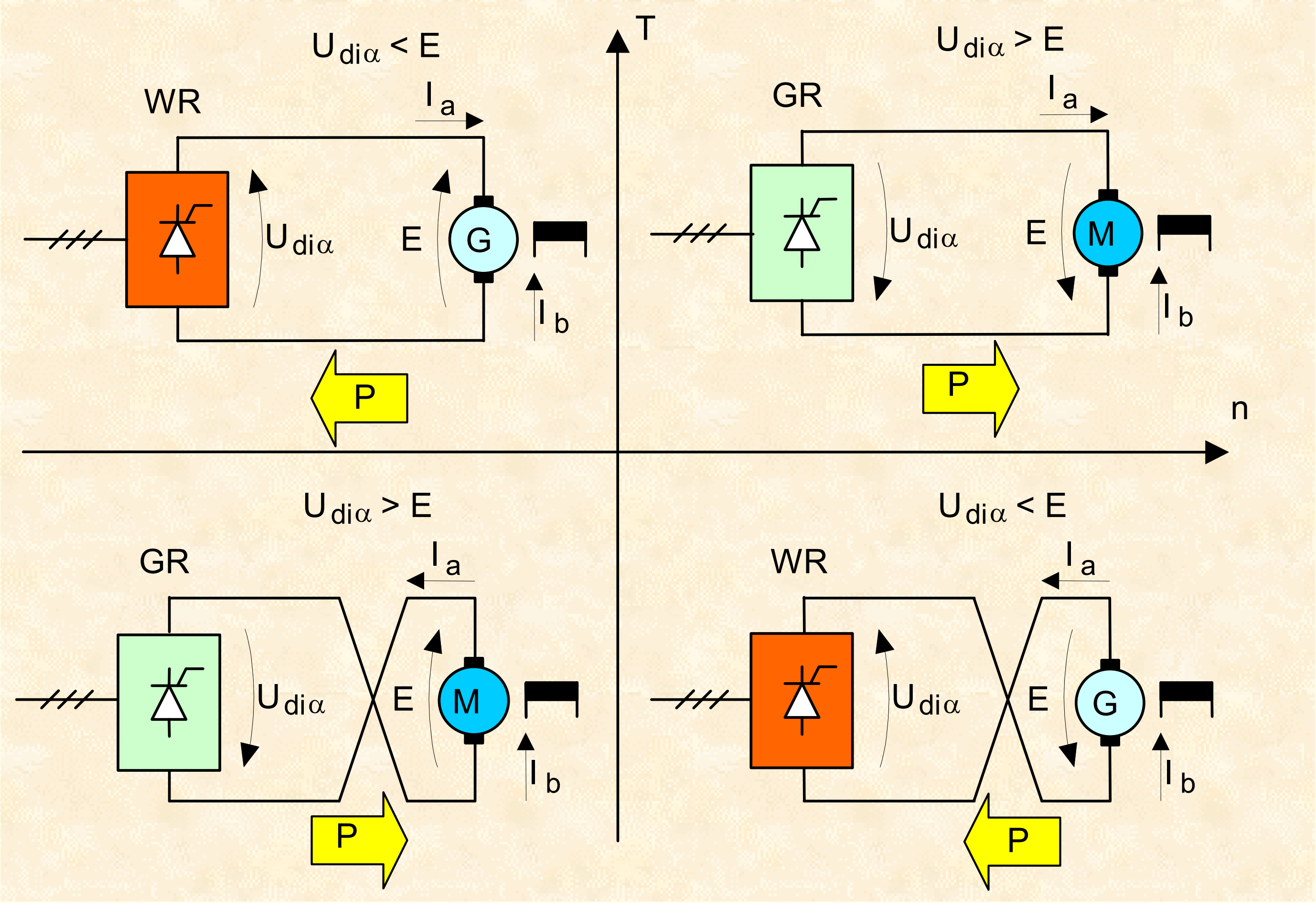
Strijken van de last
Energie van de generator naar de bron

Hijsen van de last
Energie van de bron naar de motor

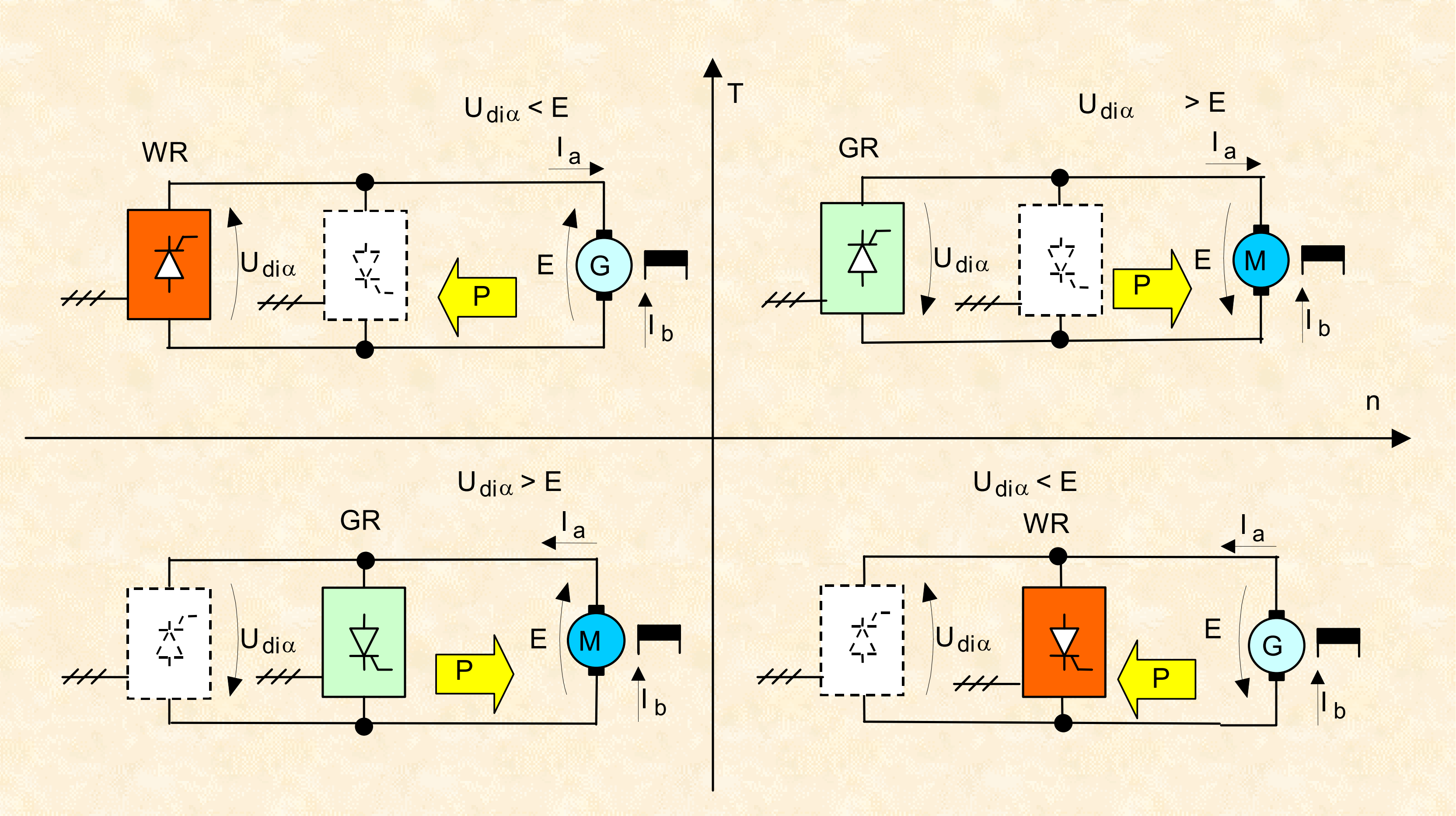
Tweekwadrantenwerking II



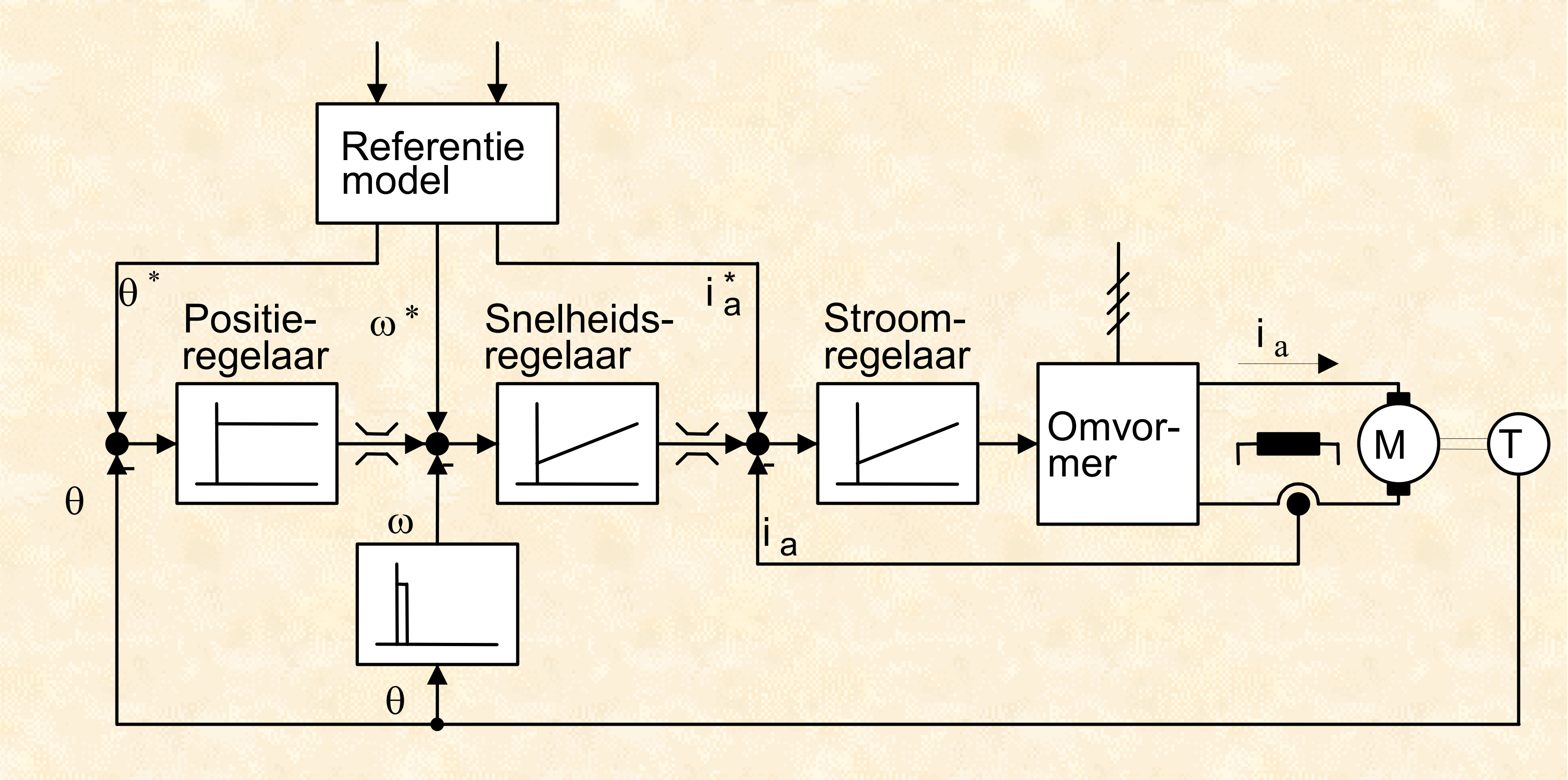
Ankerkringomschakeling



Meerkwadrantenaandrijving



Cascaderegeling



Geregelde eenkwadrantaandrijving