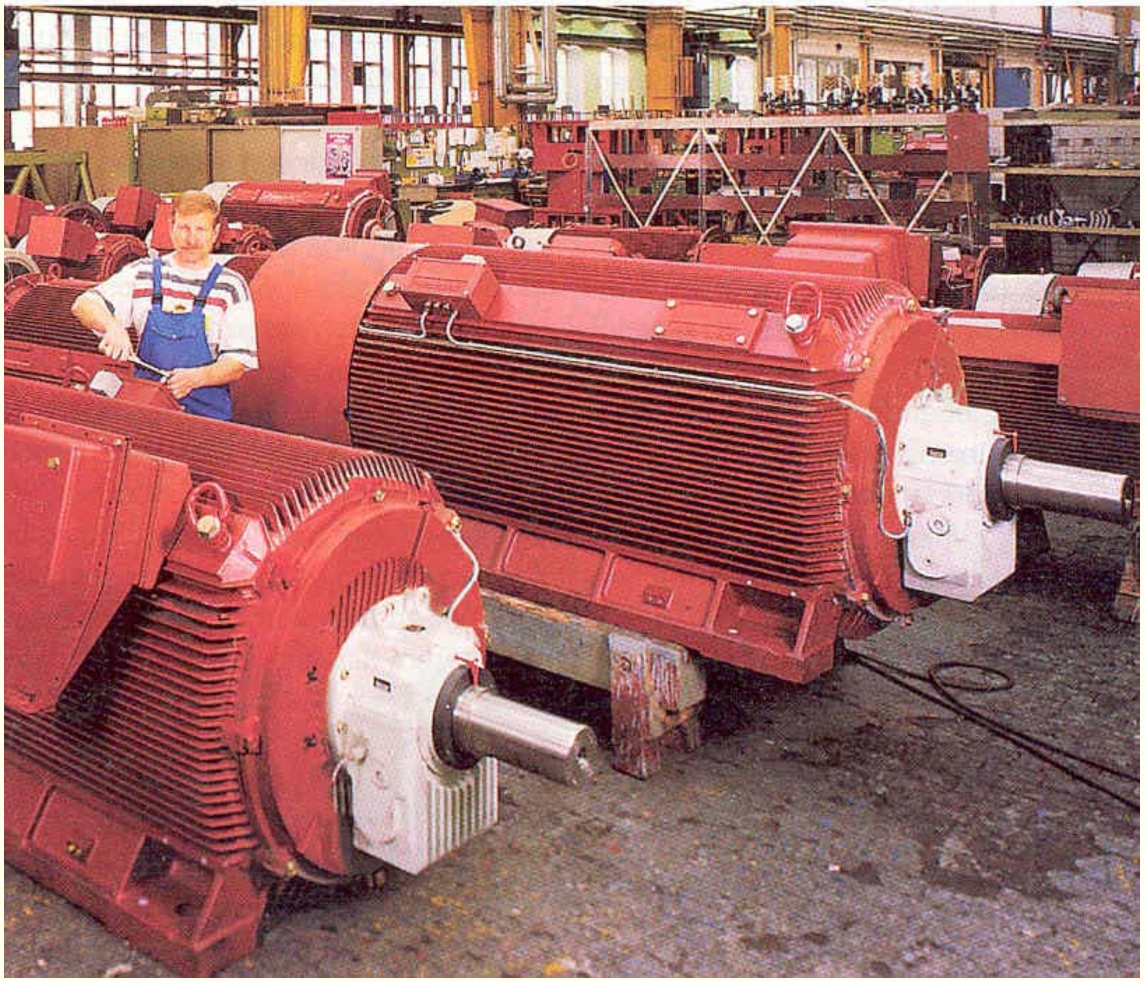
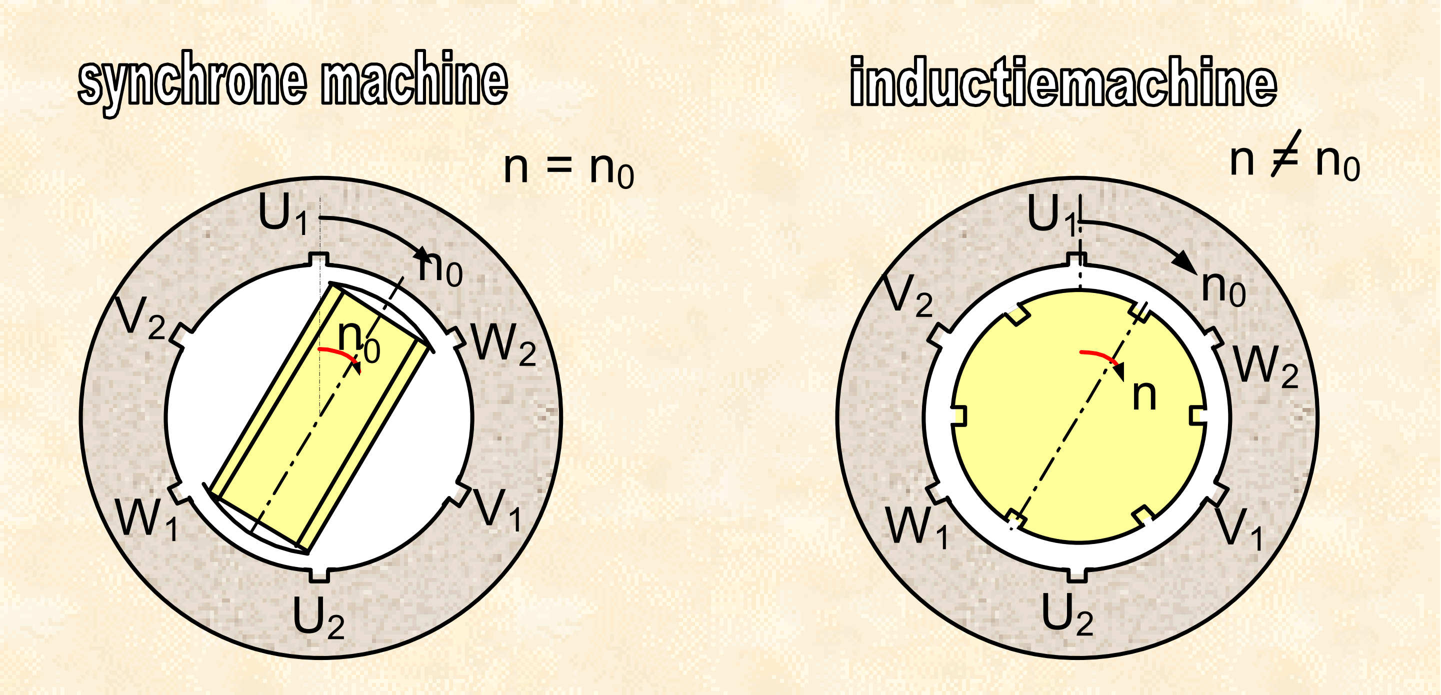
Inductiemachines



Draaiveldtheorie

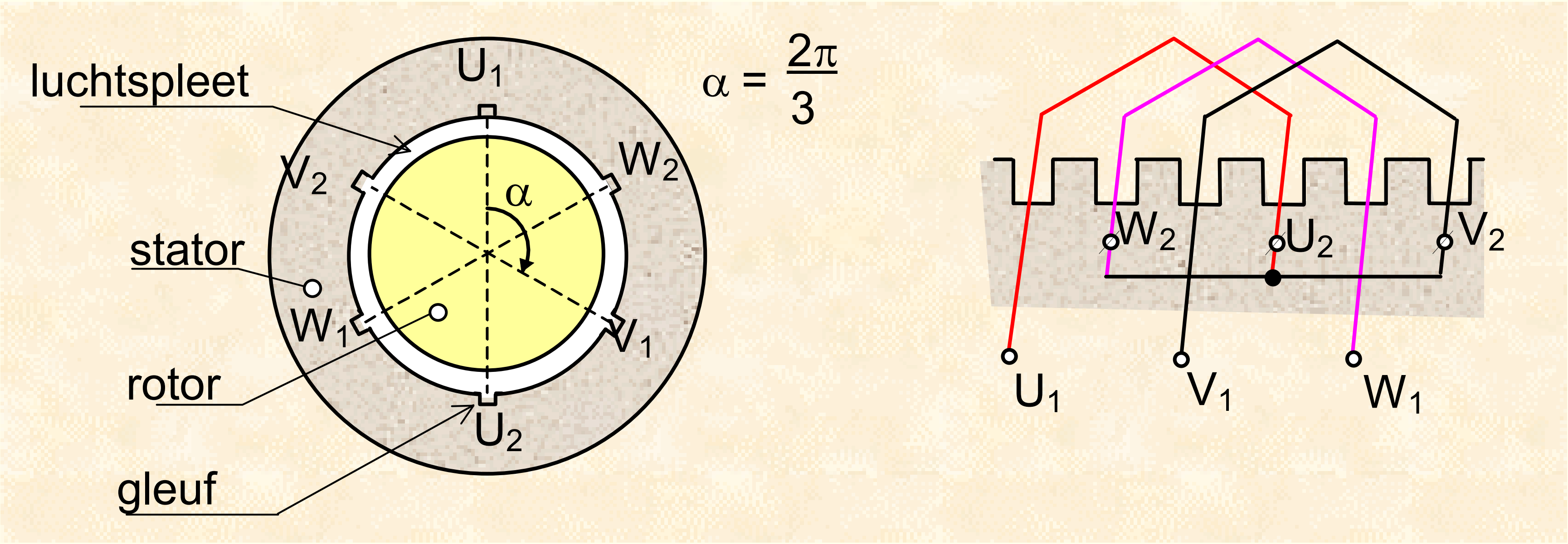
- Principe
- Opbouw van de stator
- Wisselveld
- Draaiveld
- Driefasige wikkeling
- Wikkelfactor
- Spanningsinductie door een draaiveld
- Koppelgeneratie
- Vermogenstroom, frequentievoorwaarde

Principe



Synchrone motor-Inductiemotor

Opbouw van de stator



$$\alpha = \frac{2\pi}{3} \qquad \gamma = -\frac{2\pi}{3}$$

Meerpolig

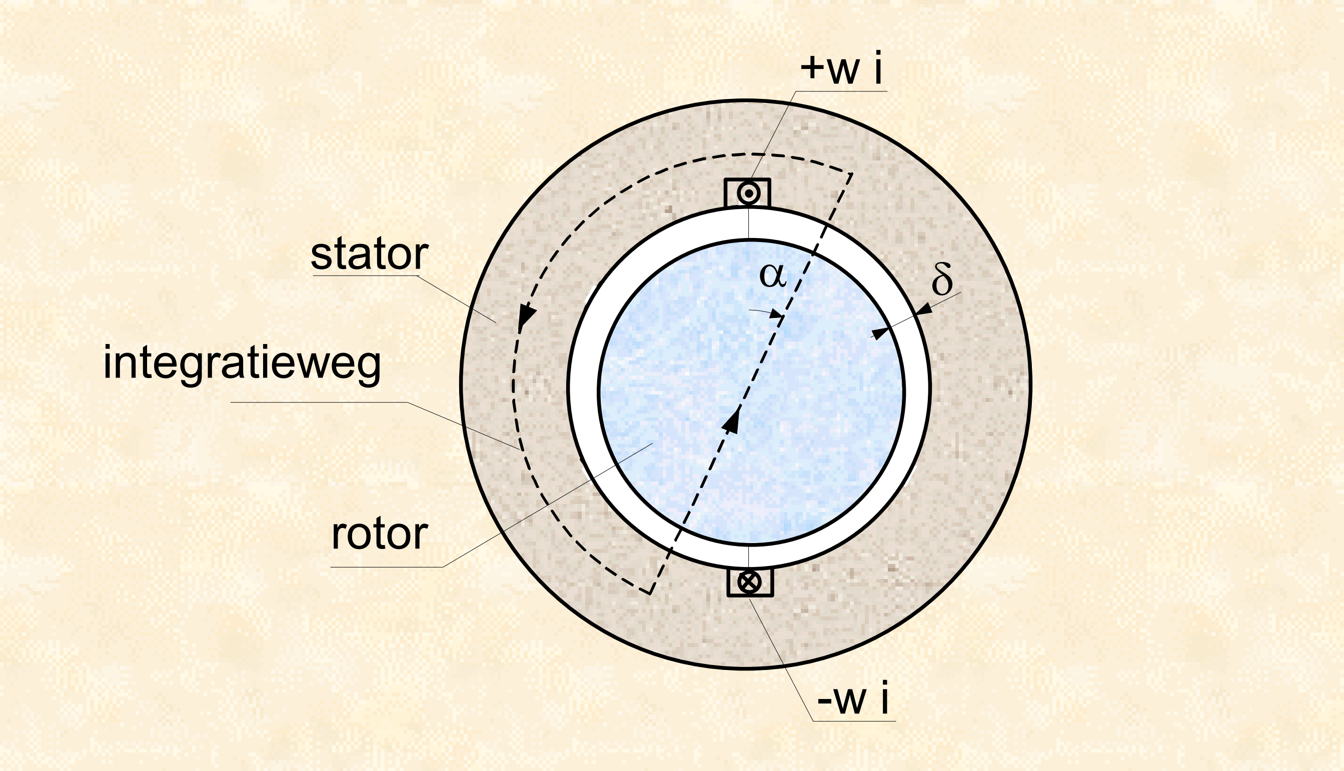
$$\alpha = \frac{2\pi}{3p}$$

p poolpaartal

$$\tau_p = \frac{\pi D}{2p}$$

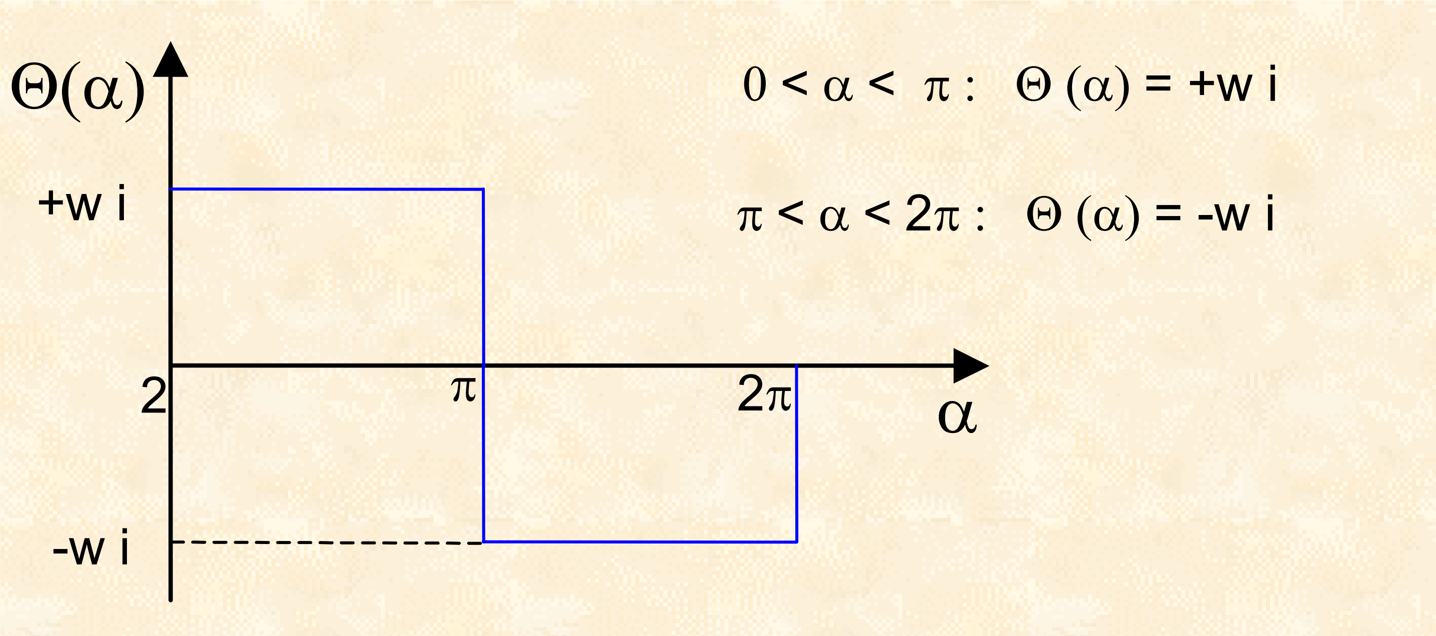
$$N = (2p)\,m\,q$$

Wisselveld



$$\oint \vec{H}\cdot d\vec{\ell} = H(\alpha)\delta + H(\alpha+\pi)(-\delta) = H(\alpha)2\delta = \Theta(\alpha)$$

Doorstroming

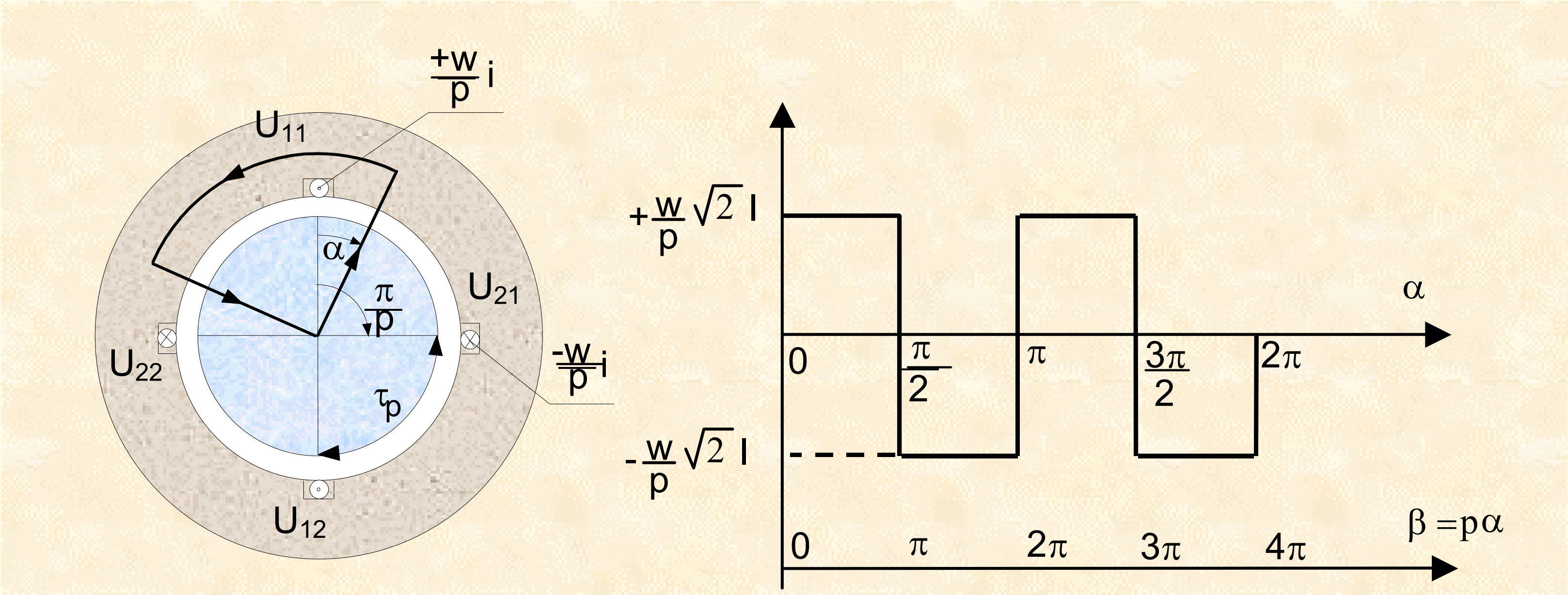


$0 < \alpha < \pi : \quad \Theta(\alpha) = +w\,i$

$\pi < \alpha < 2\pi : \quad \Theta(\alpha) = -w\,i$

$$B(\alpha) = \mu_0 H(\alpha) = \mu_0 \frac{\Theta(\alpha)}{2\delta}$$

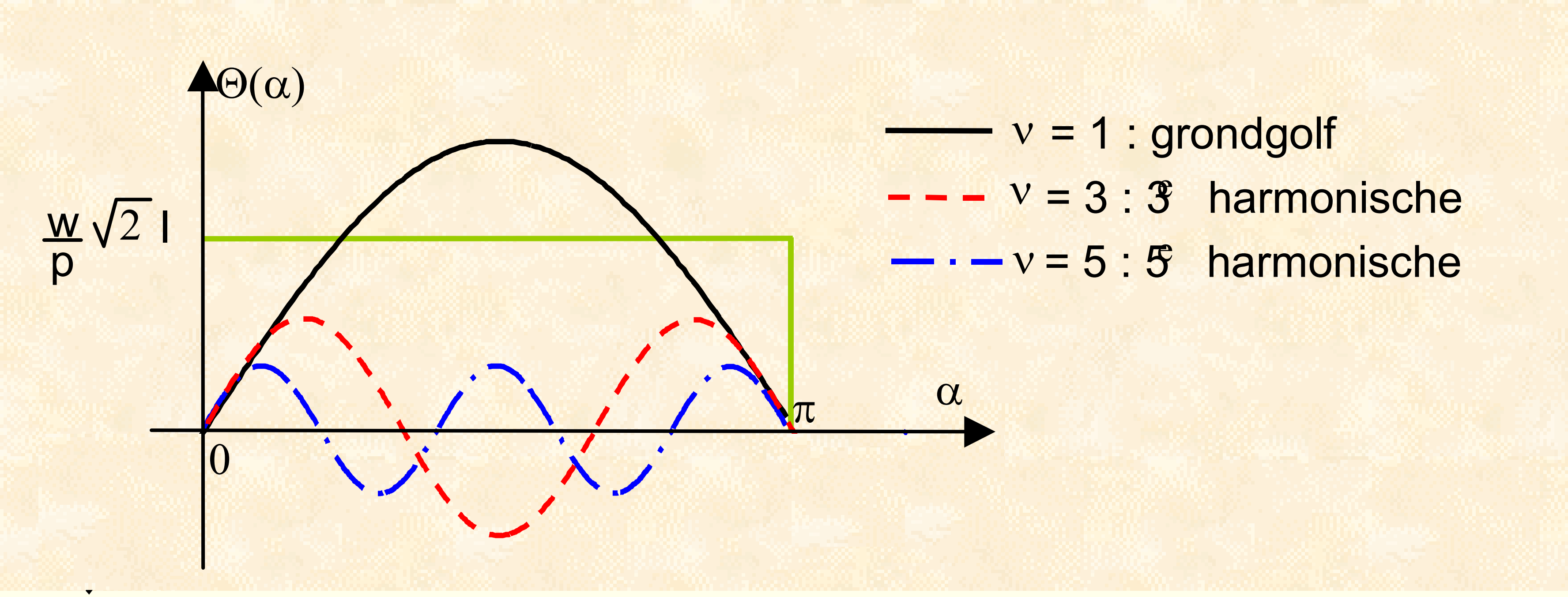
Meerpolige doorstroming



$$0 < \alpha < \frac{\pi}{p}$$

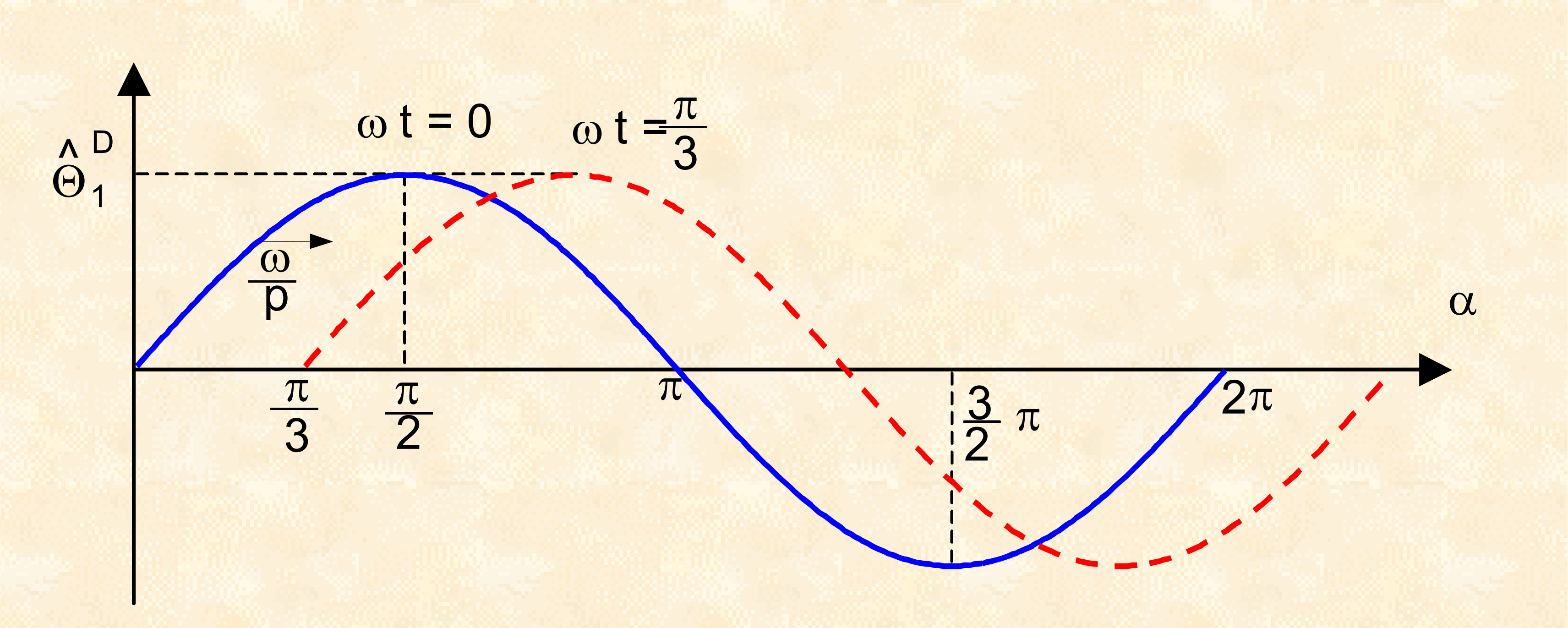
$$\Theta^{w}\left(\alpha, t\right) = \frac{N}{p}\sqrt{2}\, I \cos \omega t$$

Harmonischen



Draaiveld

$$\Theta_1^D(\alpha,t) = \hat{\Theta}_1^D \sin(\alpha p - \omega t)$$



$$\alpha p - \omega t = \text{constante}$$

$$\frac{d\alpha}{dt} = \frac{\omega}{p} = \Omega$$

$$\Theta_1^D(\alpha, t) = \hat{\Theta}_1^D \sin(\alpha p + \omega t)$$

$$\frac{d\alpha}{dt} = -\frac{\omega}{p} = -\Omega$$

Wisselveld-Draaiveld

$$\Theta_1^w(\alpha,t)=\hat{\Theta}_1^w\cos\omega t\sin\alpha p$$

$$=\frac{\hat{\Theta}_1^w}{2}\sin(\alpha p-\omega t)+\frac{\hat{\Theta}_1^w}{2}\sin(\alpha p+\omega t)$$

Ordegetallen

p	50 Hz	60 Hz
1	3000	3600
2	1500	1800
3	1000	1200
4	750	900
5	600	720
6	500	600

$$n_0 = \frac{\Omega_1}{2\pi} = \frac{f}{p}$$

$$s = \frac{\frac{\omega}{p} - \Omega}{\frac{\omega}{p}} = \frac{n_0 - n}{n_0}$$

$$\frac{U_{i2\nu}}{U_{i1\nu}} = \frac{w_2 \xi_{2\nu}}{w_1 \xi_{2\nu}} s_\nu$$

$$U_{i11} = w_1 \xi_{11} \omega \frac{\hat{\phi}_1}{\sqrt{2}} = 2\pi f_1 \xi_{11} w_1 \frac{\hat{\phi}_1}{\sqrt{2}} = 4,44 w_1 \xi_{11} f_1 \hat{\phi}_1$$

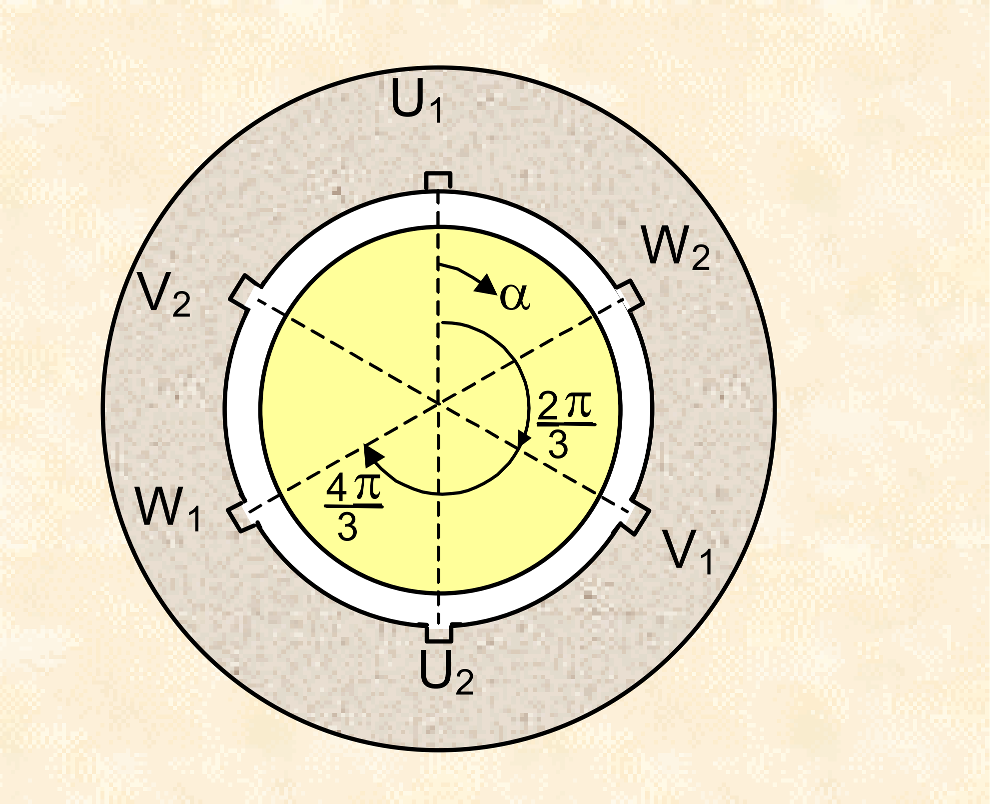
$$U_{i21} = w_2 \xi_{21} s_1 \omega \frac{\hat{\phi}_1}{\sqrt{2}}$$

Koppelgeneratie

$$\Theta_1^D\left(\alpha_1,t\right)=\frac{3}{2}\frac{4}{\pi}\frac{N_1\xi_1}{p_1}\sqrt{2}\,I_1\sin\left(p_1\alpha_1-\omega_1 t\right)$$

$$=\hat{\Theta}_1^D\sin\left(p_1\alpha_1-\omega_1 t\right)$$

Driefasige wikkeling



$$\Theta_2^D(\alpha_2,t)=\frac{3}{2}\frac{4}{\pi}\frac{N_2\xi_2}{p_2}\sqrt{2}\,I_2\sin\left(p_2\alpha_2-\omega_2 t\right)$$

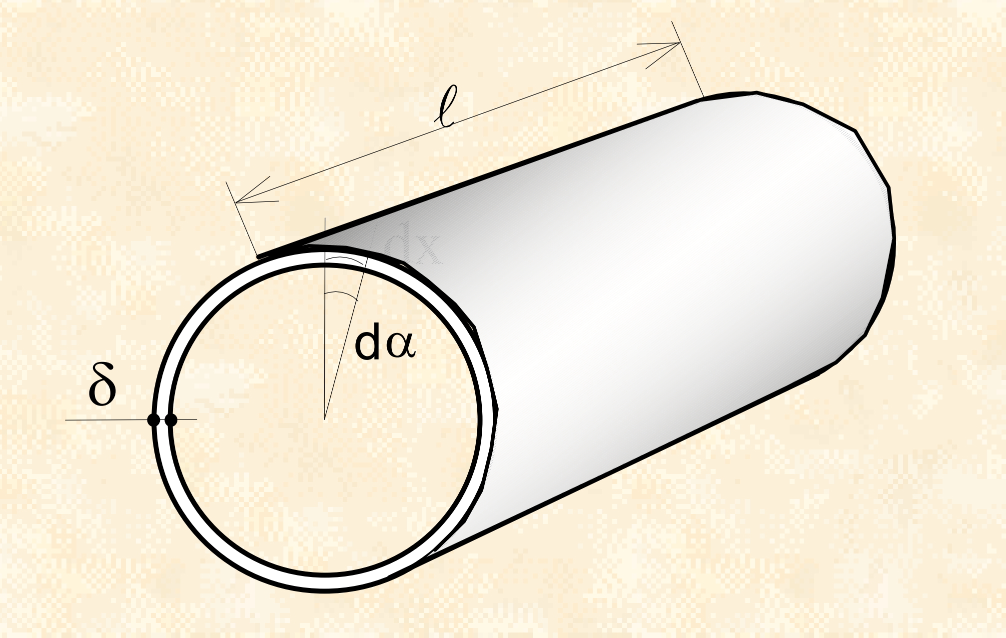
$$\alpha_2=\alpha_1-\varepsilon$$

$$\varepsilon=\Omega t+\varepsilon_0$$

$$\Theta_2^D(\alpha_1,t)=\hat{\Theta}_2^D\sin\left(p_2\alpha_1-\omega_2 t-p_2\varepsilon\right)$$

$$\Theta_1^D(\alpha,t)+\Theta_2^D(\alpha,t)=H(\alpha,t)2\delta$$

$$B(\alpha,t)=\frac{\mu_0}{2\delta}\left[\Theta_1^D(\alpha,t)+\Theta_2^D(\alpha,t)\right]$$



Berekening van de opgeslagen magnetische energie

$$W_m = \iiint_V \frac{B^2(\alpha,t)}{2\mu_0} dV = \int_0^{2\pi} \frac{B^2(\alpha,t)}{2\mu_0} \ell \, \delta \frac{D}{2} d\alpha$$

$$T = \frac{\partial W_m}{\partial \varepsilon} = \frac{\partial}{\partial \varepsilon} \int_0^{2\pi} \frac{B^2(\alpha,t)}{2\mu_0} \ell\, \delta \frac{D}{2} d\alpha$$

$$\frac{\partial}{\partial \varepsilon}\left[B^2(\alpha,t)\right] = 2\,B(\alpha,t)\frac{\partial B(\alpha,t)}{\partial \varepsilon}$$

$$= 2\left(\frac{\mu_0}{2\delta}\right)^2 \left[\Theta_1^D(\alpha,t) + \Theta_2^D(\alpha,t)\right] \frac{\partial \Theta_2^D(\alpha,t)}{\partial \varepsilon}$$

$$T = \frac{\ell\,\delta\,D}{4\,\mu_0} 2 \left(\frac{\mu_0}{2\delta} \right)^2 \int_0^{2\pi} \left[\hat{\Theta}_1^D \sin\left(p_1\alpha - \omega_1 t \right) + \hat{\Theta}_2^D \sin\left(p_2\alpha - \omega_2 t - p_2\varepsilon \right) \right]$$

$$\hat{\Theta}_2^D \left[\left(-p_2 \right) \cos\left(p_2\alpha - \omega_2 t - p_2\varepsilon \right) \right] d\alpha$$

$$\int_0^{2\pi} \sin x \cos x dx = 0$$

$$T = -\frac{p_2 \ell D \mu_0}{4.2\delta} \hat{\Theta}_1^D \hat{\Theta}_2^D \int_0^{2\pi} \sin\left(p_1\alpha - \omega_1 t\right) \cos\left(p_2\alpha - \omega_2 t - p_2\varepsilon\right) d\alpha$$

$$\sin x \cos y = \frac{1}{2}\sin(x+y) + \frac{1}{2}\sin(x-y)$$

$$T = -\frac{p_2 \ell D \mu_0}{4.2\delta} \frac{\hat{\Theta}_1^D \hat{\Theta}_2^D}{2} \int_0^{2\pi} \Big\{ \sin\left[\left(p_1 + p_2\right)\alpha - \left(\omega_1 + \omega_2\right)t - p_2\varepsilon\right]$$
$$+ \sin\left[\left(p_1 - p_2\right)\alpha - \left(\omega_1 - \omega_2\right)t + p_2\varepsilon\right]\Big\} d\alpha$$

$$T = -\frac{p\,\ell\,D\,\mu_0}{4.2\delta}\,\frac{\hat{\Theta}_1^D\hat{\Theta}_2^D}{2}\,2\pi\sin\left[-\left(\omega_1-\omega_2\right)t+\varepsilon p\right]$$

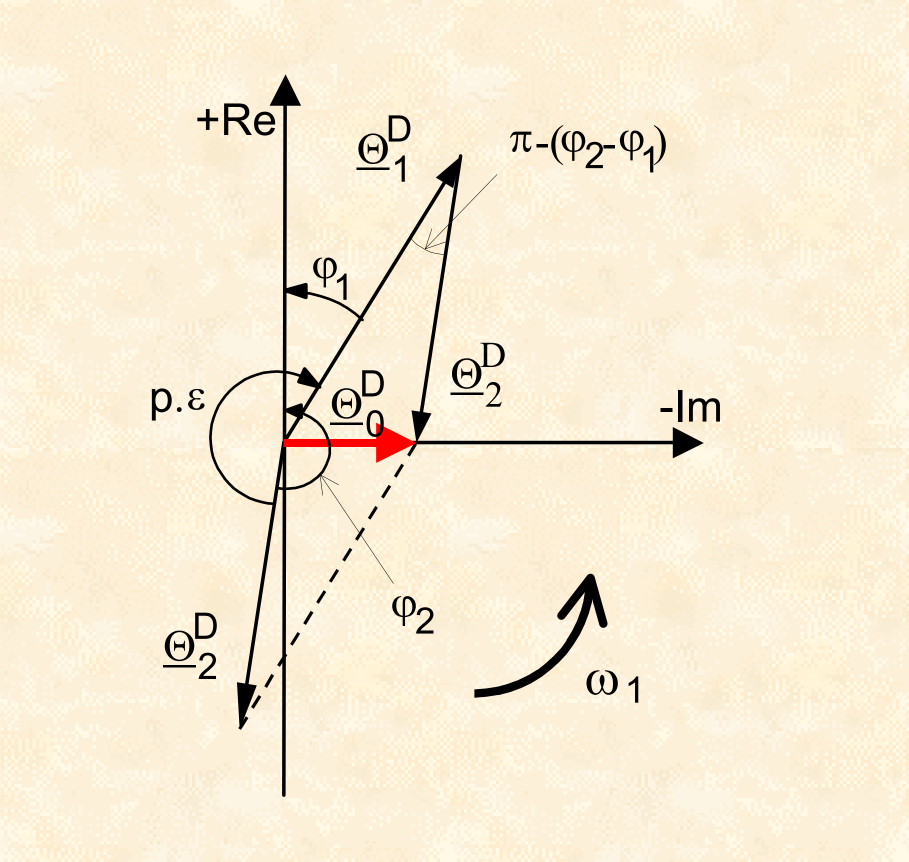
$$T = -\frac{p\,\ell\,D\,\mu_o}{4.2\,\delta}\,\frac{\hat{\Theta}_1^D\hat{\Theta}_2^D}{2}\,2\pi\sin\left[-\left(\omega_1-\left(\omega_2+p\Omega\right)\right)t+p\varepsilon_0\right]$$

$$T = -\frac{p\,\ell\,D\,\mu_0}{4.2\delta}\,\frac{\hat{\Theta}_1^D\hat{\Theta}_2^D}{2}\,2\pi\sin p\varepsilon_0$$

$$\underline{\Theta}_0^D = \underline{\Theta}_1^D + \underline{\Theta}_2^D = \underline{B}\,\frac{2\delta}{\mu_0}$$

$$\hat{\Theta}_0^D = \sqrt{\left(\hat{\Theta}_1^D\right)^2+\left(\hat{\Theta}_2^D\right)^2+2\hat{\Theta}_1^D\hat{\Theta}_2^D\cos\left(\varphi_2-\varphi_1\right)}$$

Verband tussen de fasoren van de doorstromingen



$$T = \frac{p\,\ell\,D\,\mu_0}{4\,2\delta}\,\pi\,\theta_1^D\,\hat{B}\,\frac{2\delta}{\mu_0}\cos\varphi_1$$

$$= \frac{p\,\ell\,D\,\pi}{4}\,\frac{3}{2}\,\frac{4}{\pi}\,\frac{N_1\xi_1}{p}\sqrt{2}\,I_1\hat{B}\cos\varphi_1$$

$$U_i = \omega_1 N_1 \xi_1\,\frac{D\,\ell}{p}\,\frac{\hat{B}}{\sqrt{2}}$$

$$T = \frac{3\,p}{\omega_1}U_i I_1\cos\varphi_1 = \frac{3U_i I_1\cos\varphi_1}{\Omega_1} = \frac{P_\delta 60}{2\,\pi\,n_0}$$

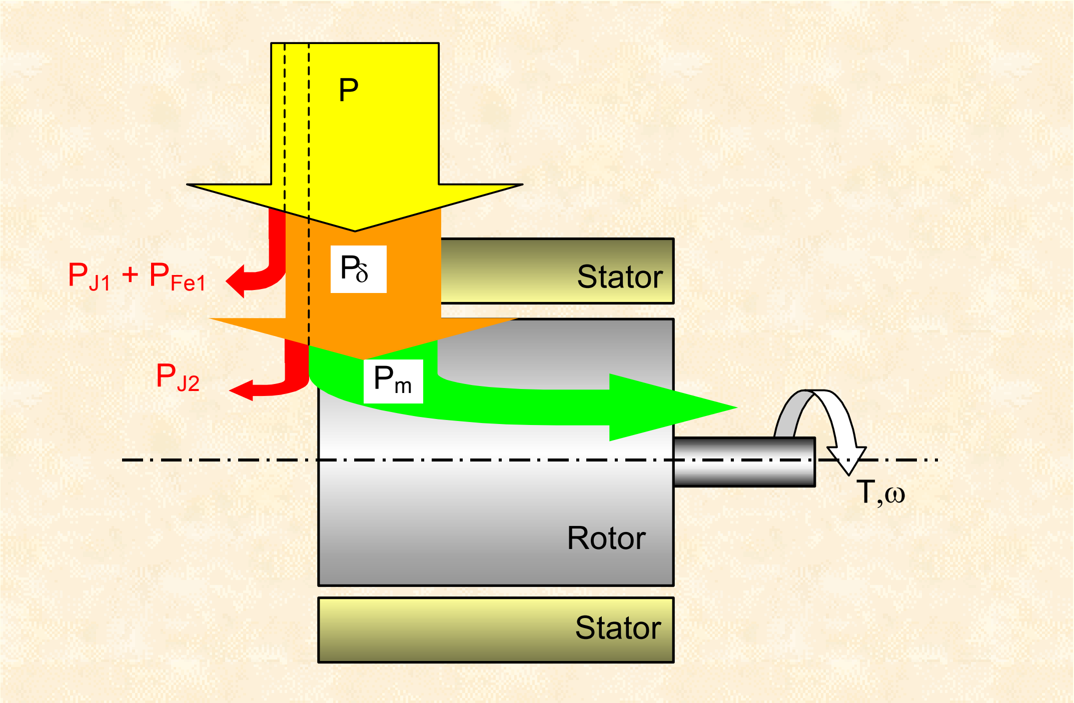
Vermogenstroom, frequentievoorwaarde

$$P_\delta = P_1 - P_{J1} - P_{Fe1} = P_1 - 3R_1 I_1^2 - P_{Fe1}$$

$$P_\delta = 3U_i I_1 \cos\varphi_1 = T\frac{2\pi n_0}{60}$$

$$P_m = T\frac{2\pi}{60}n = T\frac{2\pi}{60}n_0\left(1-s\right) = \left(1-s\right)P_\delta$$

$$P_{J2} = P_\delta - P_m = P_\delta - \left(1-s\right)P_\delta = s\,P_\delta$$



Vermogenstroom in een wisselstroommachine

$$\omega_1 = \omega_2 + p\Omega$$

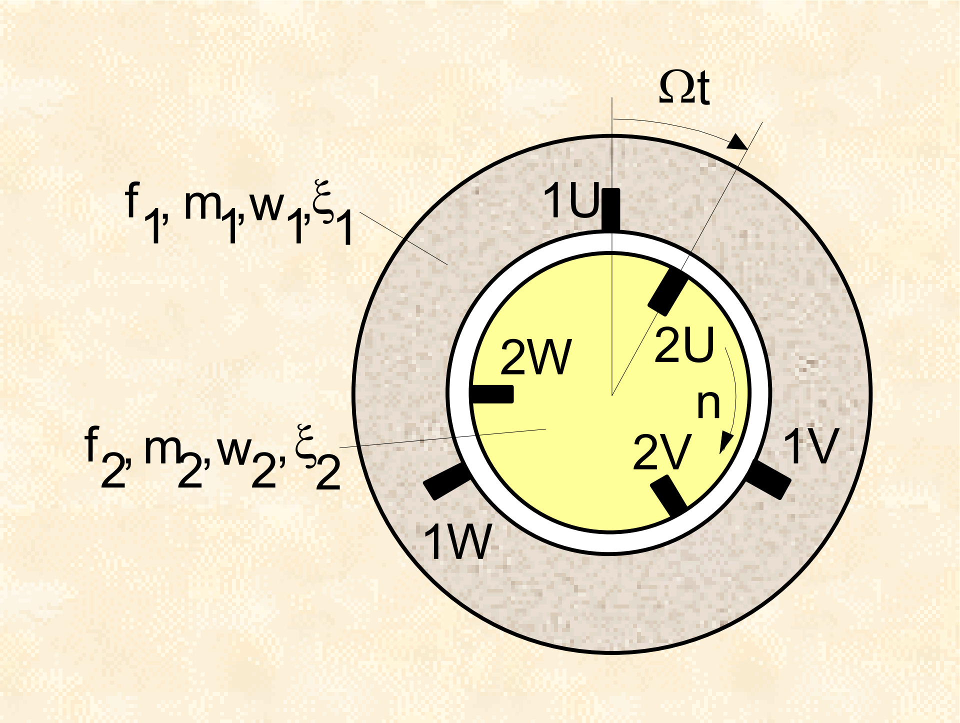
$$\omega_1 = \omega_2 + (1 - s)\,\omega_1$$

$$\omega_2 = s\omega_1 \qquad\qquad \omega_1 = 2\pi f_1$$

Inductiemachine

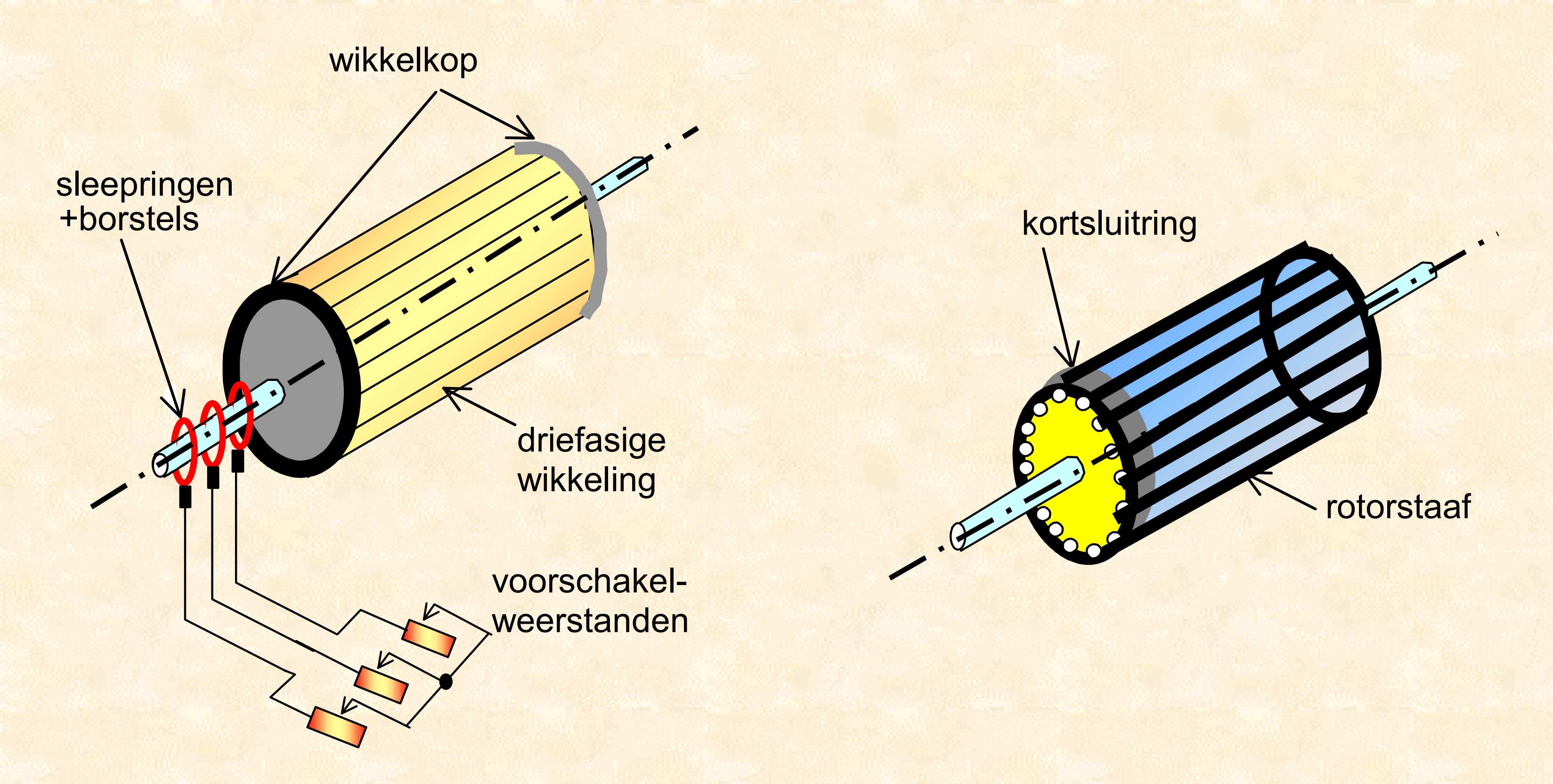
- Equivalent schema
- Inductanties en weerstanden
- Gedrag van de machine
- Kooirotor
- Dubbelkooirotor en stroomverdringingsrotor
- Eenfasige inductiemotor

Equivalent schema

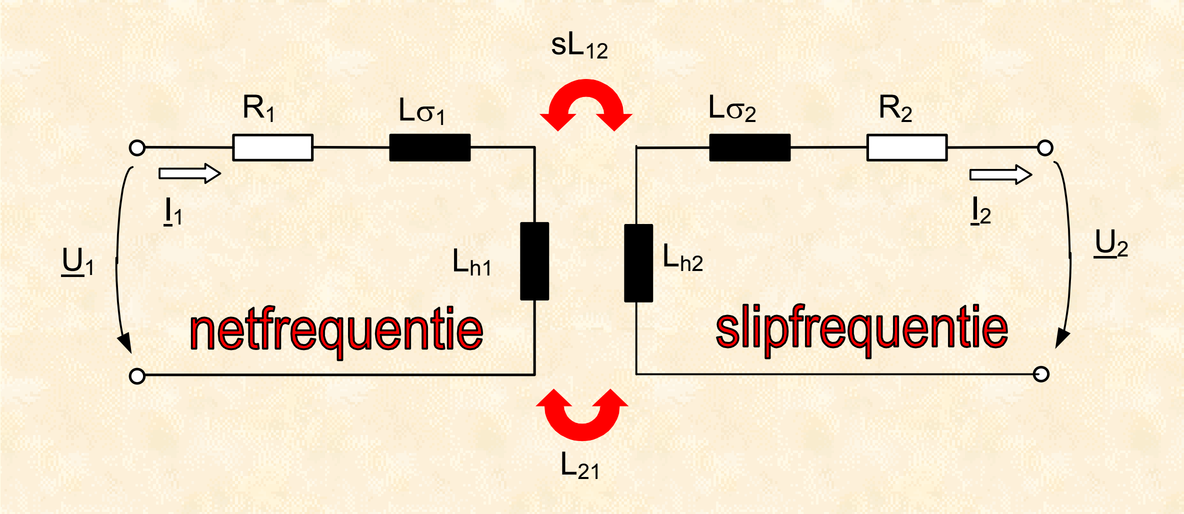


$$n_0 = \frac{f_1}{p} \qquad n = (1 - s)\, n_0 \qquad f_2 = s f_1$$

Soorten


wikkelkop
sleepringen
+borstels
driefasige
wikkeling
voorschakel-
weerstanden
kortsluitring
rotorstaaf

Magnetische koppeling



$$\underline{U}_1 = R_1\underline{I}_1 + j\omega_1 L_1\underline{I}_1 - j\omega_1 L_{21}\underline{I}_2$$

$$\underline{U}_2 = -R_2\underline{I}_2 - j\omega_2 L_2\underline{I}_2 + j\omega_2 L_{12}\underline{I}_1$$

$$L_1 = L_{\sigma 1} + L_{h1} \qquad L_2 = L_{\sigma 2} + L_{h2}$$

Eisen

- Dezelfde doorstroming

$$I_2' = I_2 \frac{m_2 w_2 \xi_2}{m_1 w_1 \xi_1}$$

- Dezelfde hoofdflux

$$U_{i2}' = U_{i2} \frac{w_1 \xi_1}{w_2 \xi_2}$$

- Dezelfde jouleverliezen

$$R_2^{'} = R_2 \frac{m_1 \left(w_1 \xi_1 \right)^2}{m_2 \left(w_2 \xi_2 \right)^2}$$

- Dezelfde magnetische energie

$$L_2^{'} = L_2 \frac{m_1 \left(w_1 \xi_1 \right)^2}{m_2 \left(w_2 \xi_2 \right)^2} \qquad m_2 L_{12} = m_1 L_{21}$$

$$L_{21} = L_{h1} \frac{m_2 w_2 \xi_2}{m_1 w_1 \xi_1} \qquad L_{12} = L_{h1} \frac{w_2 \xi_2}{w_1 \xi_1}$$

Spanningsvergelijkingen

$$\underline{U}_1 = R_1 \underline{I}_1 + j\omega_1 L_1 \underline{I}_1 - j\omega_1 L_{h1} \underline{I}_2^{'}$$

$$\frac{\underline{U}_2^{'}}{s} = -\frac{R_2^{'}}{s} \underline{I}_2^{'} - j\omega_1 L_2^{'} \underline{I}_2^{'} + j\omega_1 L_{h1} \underline{I}_1$$

Met

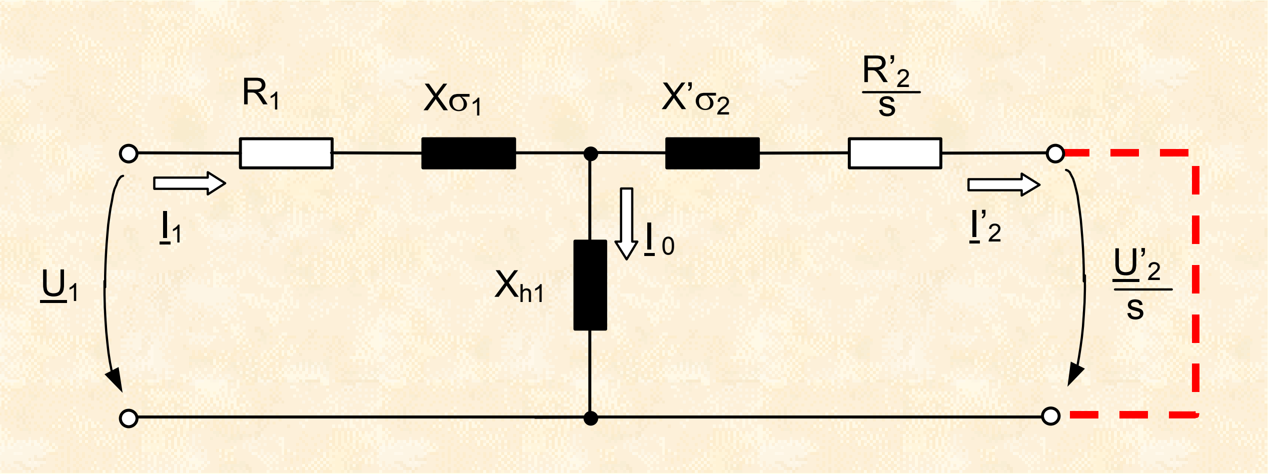
$X_{h1} = \omega_1 L_{h1}$ hoofdreactantie

$X_1 = \omega_1 L_{1=} X_{h1} + X_{\sigma 1}$	totale statorreactantie
$X_2' = \omega_1 L_2' = X_{h2}' + X_{\sigma 2}'$	op de stator betrokken totale rotorreactantie
$X_{\sigma 1}$	statorlekreactantie
$X_{\sigma 2}'$	op de stator betrokken rotorlekreactantie
$\underline{I}_0 = \underline{I}_1 - \underline{I}_2'$	nullaststroom

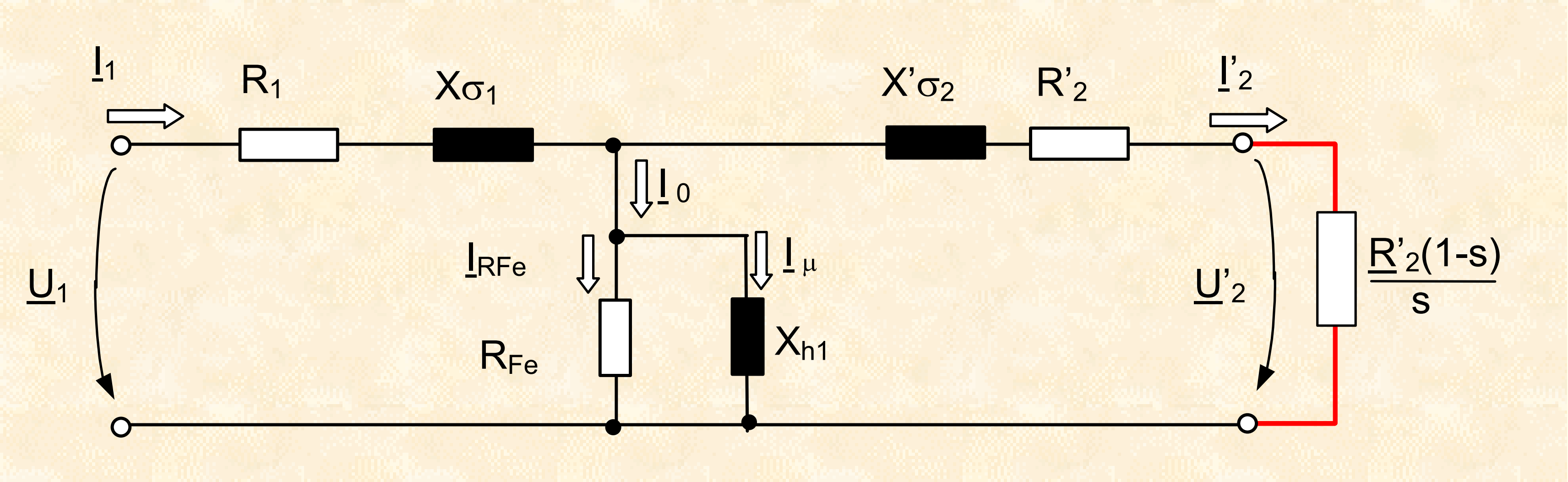
Galvanische koppeling

$$\underline{U}_1 = R_1\underline{I}_1 + jX_{\sigma 1}\underline{I}_1 + jX_{h1}\underline{I}_0$$

$$\frac{\underline{U}_2^{'}}{s} = -\frac{R_2^{'}}{s}\underline{I}_2^{'} - jX_{\sigma 2}^{'}\underline{I}_2^{'} + jX_{h1}\underline{I}_0$$



Met ijzerverliezen



Inductanties - Weerstanden

- Hoofdinductantie

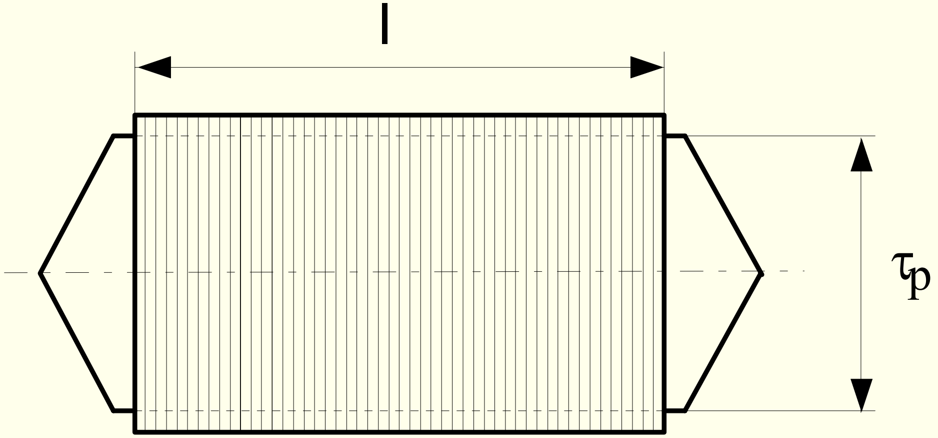
$$L_{h1} = \frac{X_{h1}}{\omega_1} = \frac{U_i}{\omega_1 I_1} = \frac{3}{2}\mu_0 \left(\frac{w_1 \xi_1}{p}\right)^2 \frac{2}{\pi}\frac{\ell D}{\delta}$$

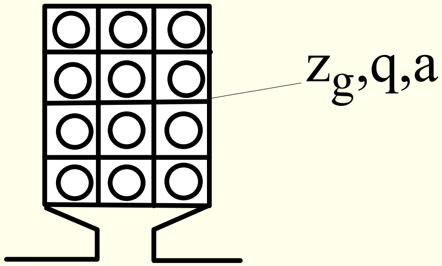
- Strooiinductanties

$$L_\sigma = L_{\sigma d.v.} + L_{\sigma g} + L_{\sigma s}$$

- Faseweerstand

$$R = \rho \frac{w\ell_g}{q}\left[1+\alpha\left(T-20\right)\right]$$





Gedrag van de machine

- Statorstroom
- Fasordiagram
- Vermogenverdeling en spanningsvergelijking
- Vermogenbilan
- Stationaire koppel-slip karakteristiek
- Formule van Kloss
- Samenvattende karakteristieken

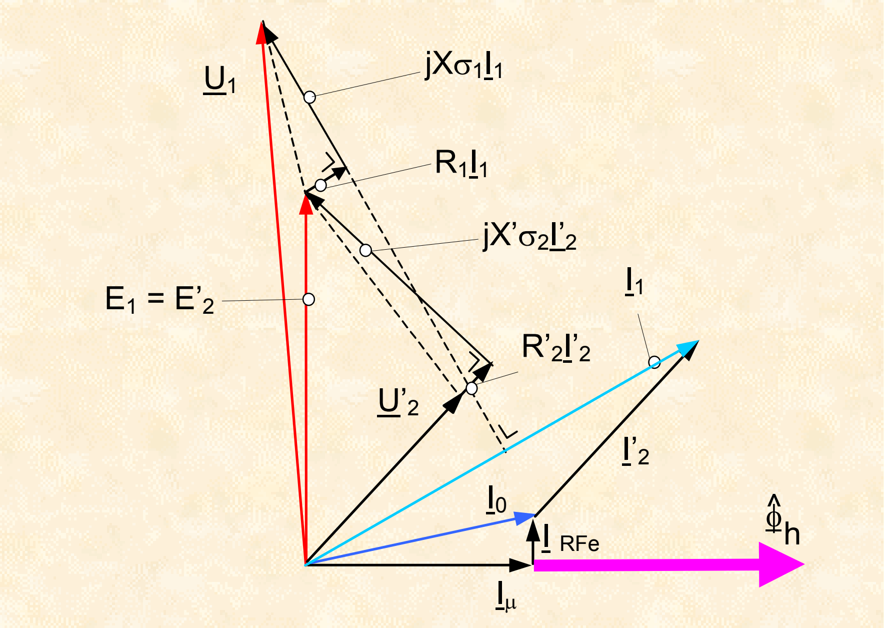
Statorstroom

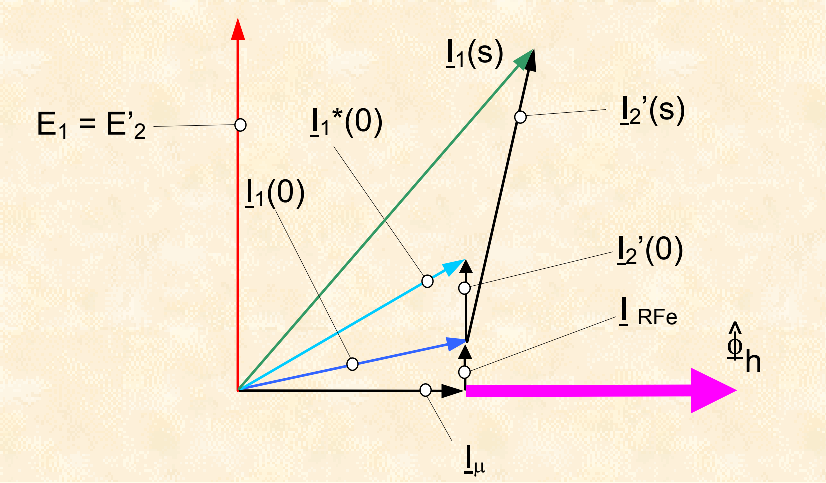
$$\underline{U}_2' = 0$$

$$\underline{U}_1 = R_1 \underline{I}_1 + jX_{\sigma 1} \underline{I}_1 + jX_{h1} \underline{I}_0$$

$$0 = -\frac{R_2'}{s} \underline{I}_2' - jX_{\sigma 2}' \underline{I}_2' + jX_{h1} \underline{I}_0$$

Fasordiagram





Normale werking Nullast

Vermogenverdeling - Stator

$$(3\underline{U}_1).\underline{I}_1 = (3R_1\underline{I}_1).\underline{I}_1 + (3j\omega_1 L_1\underline{I}_1).\underline{I}_1 - (3j\omega_1 L_{21}\underline{I}_2).\underline{I}_1$$

waarbij

$$(3\underline{U}_1).\underline{I}_1 = P_1 = 3U_1 I_1 \cos\varphi$$

totaal ingaand actief vermogen

$$(3R_1\underline{I}_1).\underline{I}_1 = 3R_1 I_1^2$$

statorjouleverliezen P_{j1}

$$-(3j\omega_1 L_{12}\underline{I}_2).\underline{I}_1 = +3\omega_1 L_{21}\left\{\left[j\underline{I}_1\right].\left[\underline{I}_2\right]\right\} = P_\delta$$

luchtspleetvermogen, m.a.w. het vermogen dat via de luchtpleet naar de rotor wordt overgedragen

$$(3j\omega_1 L_1\underline{I}_1).\underline{I}_1 = 0$$

Vermogenverdeling - Rotor

$$0 = -(3R_2\underline{I}_2).\underline{I}_2 - (3js\omega_1 L_2\underline{I}_2).\underline{I}_2 + (3js\omega_1 L_{12}\underline{I}_1).\underline{I}_2$$

$$P_{J2} = sP_\delta$$

$$0 = -(3R_2\underline{I}_2).\underline{I}_2 - \left(3\frac{R_2(1-s)}{s}\underline{I}_2\right).\underline{I}_2 - (3j\omega_1 L_2\underline{I}_2).\underline{I}_2$$

$$+(3j\omega_1 L_{12}\underline{I}_1).\underline{I}_2$$

Hierin is:

$$(3R_2\underline{I}_2).\underline{I}_2 = 3R_2I_2^2$$

Jouleverliezen
P_{J2} in de rotor

$$\left(3\frac{R_2(1-s)}{s}\underline{I}_2\right).\underline{I}_2 = 3\frac{R_2(1-s)}{s}I_2^2$$

Elektromechanische
vermogen P_{em}

$$(3j\omega_1L_{12}\underline{I}_1).\underline{I}_2 = 3\omega_1L_{21}\left\{\left[j\underline{I}_1\right].\left[\underline{I}_2\right]\right\} = P_\delta$$

Koppel en mechanisch vermogen

$$P_\delta = P_{J2} + P_{em}$$

$$P_{em} = (1-s)P_\delta$$

$$T = \frac{P_{em}}{\omega_m} = \frac{\left(1-s\right)P_\delta}{\frac{\omega_1}{p}\left(1-s\right)} = \frac{p}{\omega_1}P_\delta$$

$$T = \frac{p}{\omega_1}\frac{P_{J2}}{s}$$

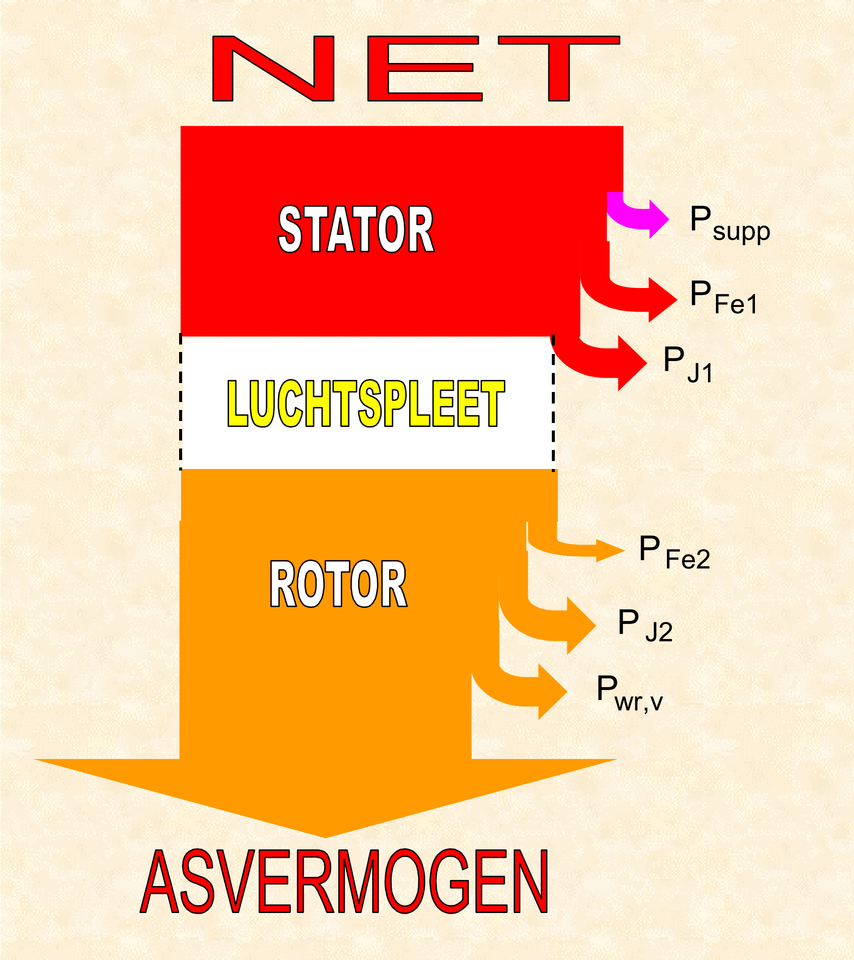
$$P_{J2} = 3R_2^{'}.I_2^{'\,2}$$

$$I_2^{'\,2} = \frac{U_1^{\,2}}{\left(R_1 + \frac{R_2^{'}}{s}\right)^2 + X_k^{\,2}}$$

$$X_k = X_{\sigma 1} + X_{\sigma 2}^{'}$$

$$T = \frac{3p}{\omega_1} U_1^{\,2} \frac{\frac{R_2^{'}}{s}}{\left(R_1 + \frac{R_2^{'}}{s}\right)^2 + \left(X_k\right)^2}$$

Vermogenbilan



Stationaire koppel-slipkarakteristiek

$$\underline{I}_1 = \frac{\left(\frac{R_2^{'}}{s} + jX_2^{'}\right).\underline{U}_1}{\left(R_1 + jX_1\right).\left(\frac{R_2^{'}}{s} + jX_2^{'}\right) + X_{h1}^2}$$

$$\underline{I}_2 = \frac{+jX_{h1}.\underline{U}_1}{\left(R_1 + jX_1\right).\left(\frac{R_2^{'}}{s} + jX_2^{'}\right) + X_{h1}^2}$$

$$X_1 = X_{\sigma 1} + X_{h1}$$

$$X_2' = X_{\sigma 2}' + X_{h1}$$

$$T = \frac{p}{\omega_1} P_\delta = \frac{p}{\omega_1} . \frac{P_{J2}}{s}$$

$$= \frac{3p}{\omega_1} \frac{R_2'}{s} \left| \underline{I}_2' \right|^2$$

$$= \frac{3p}{\omega_1} \frac{R_2' s X_{h1}^2 U_1^2}{R_1^2 R_2'^2 + R_2'^2 X_1^2 + 2sR_1R_2'X_{h1}^2 + s^2\left[\left(X_{h1}^2 - X_1X_2'\right)^2 + R_1^2 X_2'^2\right]}$$

Koppel zonder statorweerstand

$$T = \frac{3p}{\omega_1} \frac{R_2^{'} s X_{h1}^2 U_1^2}{R_2^{'2} X_1^2 + s^2 \left(X_{h1}^2 - X_1 X_2^{'} \right)^2}$$

Blondel $$\sigma = 1 - \frac{X_{h1}^2}{X_1 X_2^{'}}$$

$$T = \frac{3p}{\omega_1} \frac{\frac{R_2^{'}}{X_2^{'}} s \frac{U_1^2}{X_1} \left(1 - \sigma\right)}{\frac{R_2^{'2}}{X_2^{'2}} + s^2 \sigma^2}$$

$$I_0 = \frac{U_1}{X_1}$$

$$\beta = \frac{R_2^{'}}{X_2^{'}}$$

$$T = \frac{3p}{\omega_1} \frac{\beta s X_1 I_0^2 \left(1-\sigma\right)}{\beta^2 + s^2 \sigma^2}$$

$$s_{kip} = \frac{\beta}{\sigma} \cong \frac{R_2^{'}}{X_{\sigma 1} + X_{\sigma 2}^{'}}$$

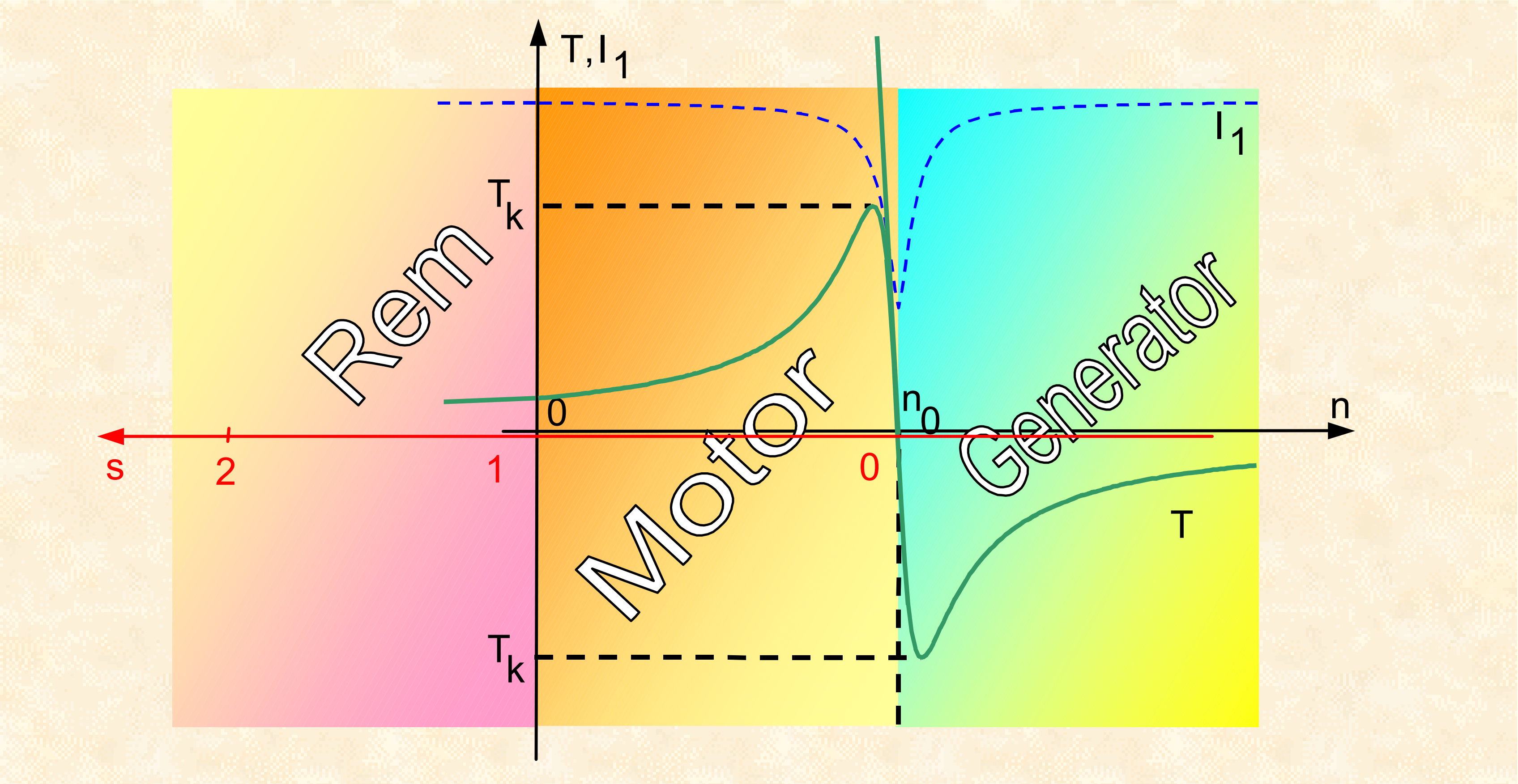
$$T_{kip} = \frac{3p}{\omega_1} \frac{X_1 \left(1-\sigma\right) I_0^2}{2\sigma} = \frac{3p}{2\omega_1} \frac{X_1^2 I_m^2}{X_{\sigma 1} + X_{\sigma 2}^{'}}$$

Verloop van T-s

$$\underset{s\to 0}{T(s)} \approx \frac{3p}{\omega_1} X_1 I_0^2 (1-\sigma)\frac{s}{\beta} = \frac{3p}{\omega_1} X_1 I_0^2 (1-\sigma)\frac{X_2^{'}}{R_2^{'}} s$$

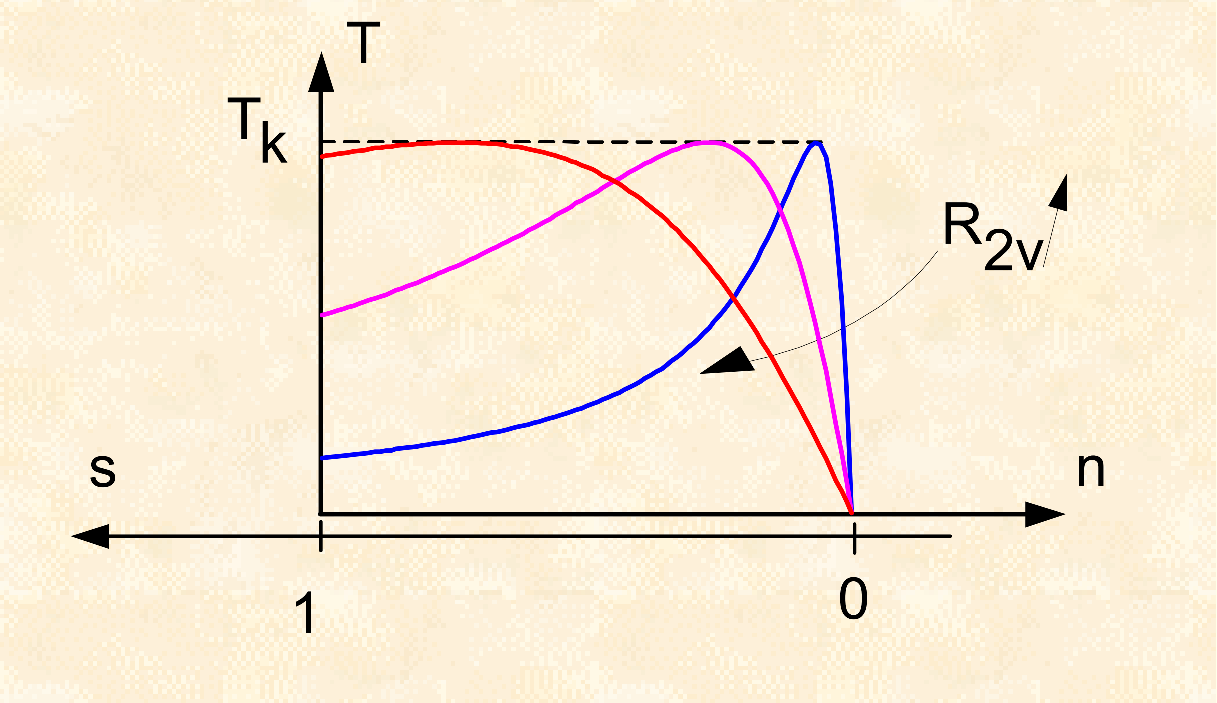
$$\underset{s\to\infty}{T(s)} \approx \frac{3p}{\omega_1} \beta X_1 I_0^2 \frac{(1-\sigma)}{\sigma^2}\frac{1}{s} = \frac{3p}{\omega_1}\frac{R_2^{'}}{X_2^{'}} X_2 I_0^2 \frac{(1-\sigma)}{\sigma^2}\frac{1}{s}$$

Koppel in functie van de slip en werkingsgebieden voor een inductiemachine



Voorschakelweerstand

$$\frac{T_k}{T_n} \geq 1,6$$



$$\underline{I}_2^{'} \sim \frac{s}{R_2^{'}}$$

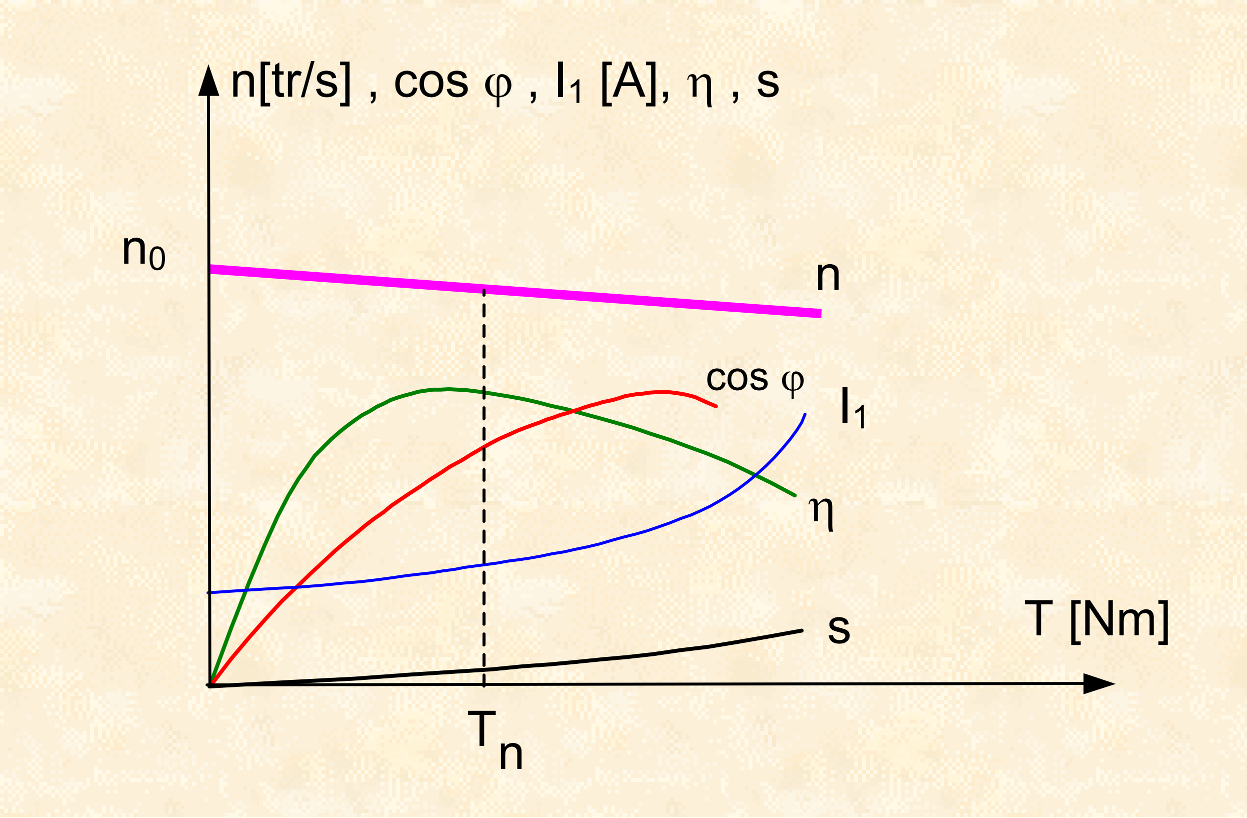
$$\underline{I}_2^{'} \sim \frac{s}{\sqrt{R_2^{'\,2} + \left(s\omega_1 \sigma L_2^{'}\right)^2}}$$

Formule van Kloss

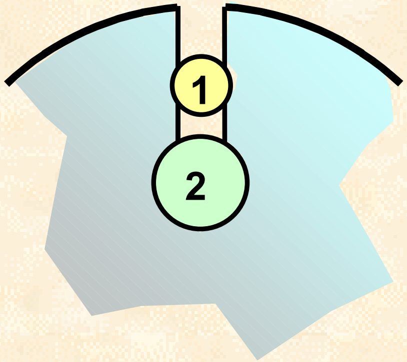
$$\frac{T}{T_k} = \frac{2}{\frac{s}{s_k} + \frac{s_k}{s}}$$

Belangrijkste karakteristieken

Belangrijkste karakteristieken van de inductiemotor



Dubbelkooirotor



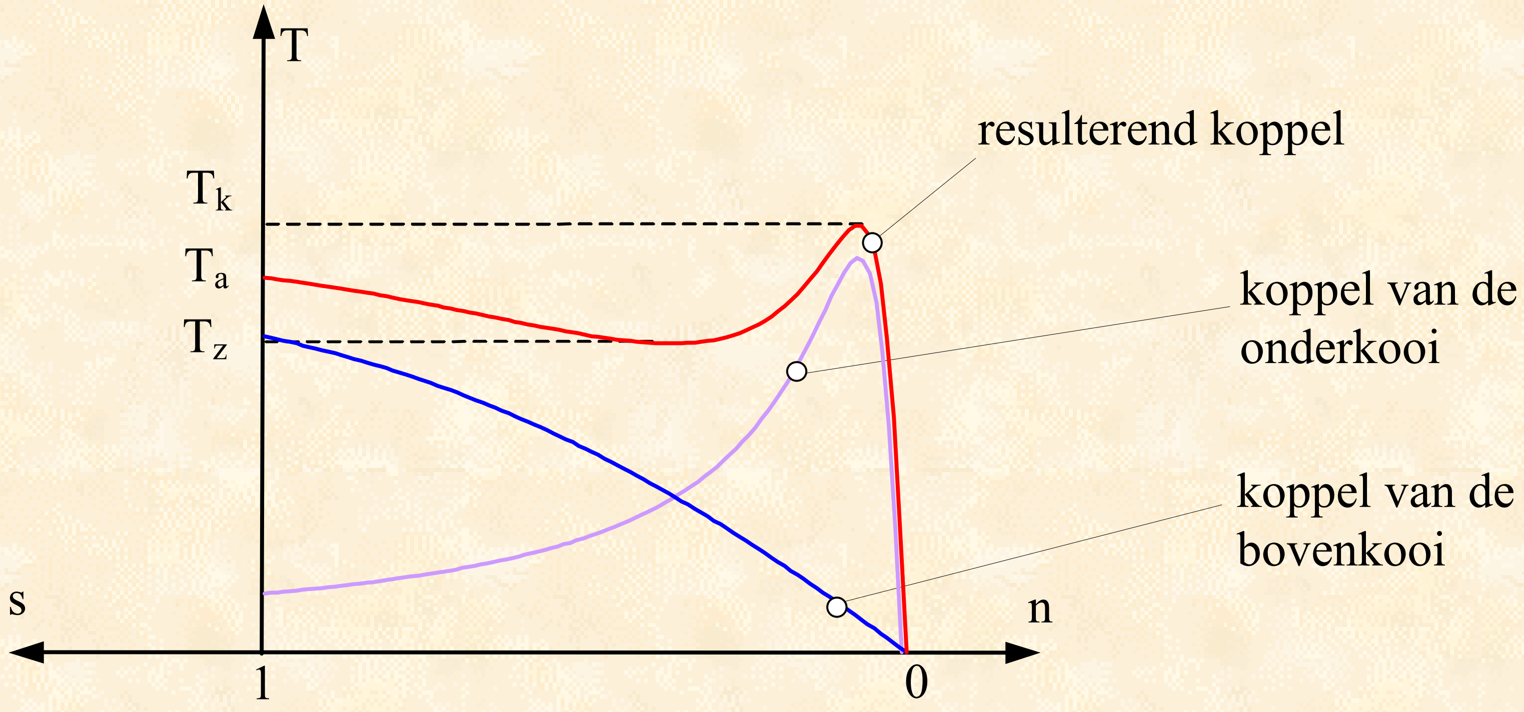
1 Buitenste kooi, bovenkooi of startkooi

2 Binnenste kooi, onderkooi of bedrijfskooi

$$\underset{(s=1)}{Z_{staaf}} = R_{staaf} + j\omega_2 L_{\sigma staaf} \approx j\omega_2 L_{\sigma staaf}$$

$$\underset{(s\approx 0)}{Z_{staaf}} = R_{staaf} + j\omega_2 L_{\sigma staaf} \approx R_{staaf}$$

Koppel-toerentalkarakteristiek

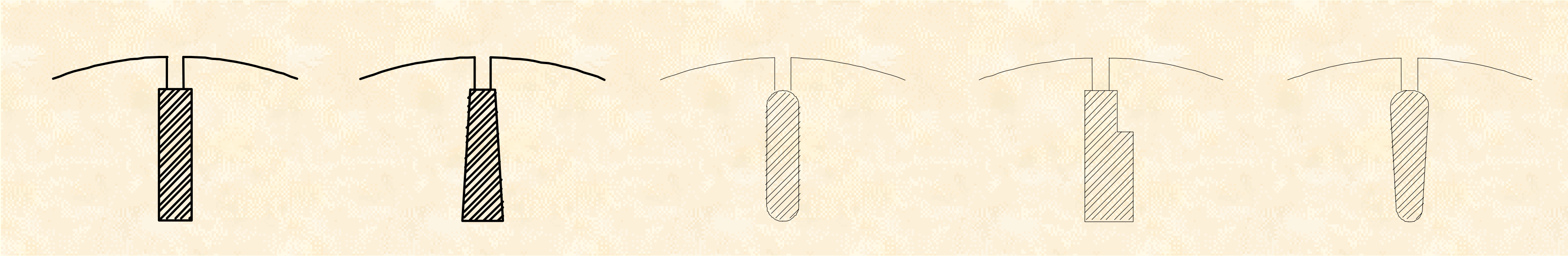


resulterend koppel

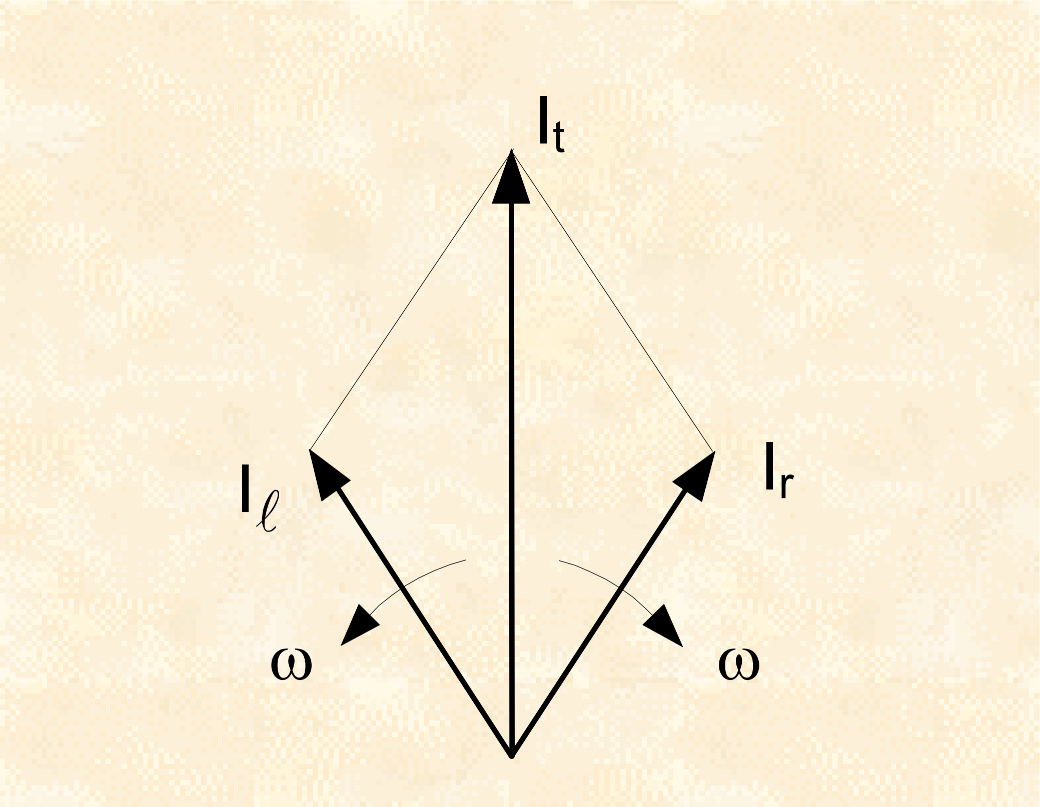
koppel van de onderkooi

koppel van de bovenkooi

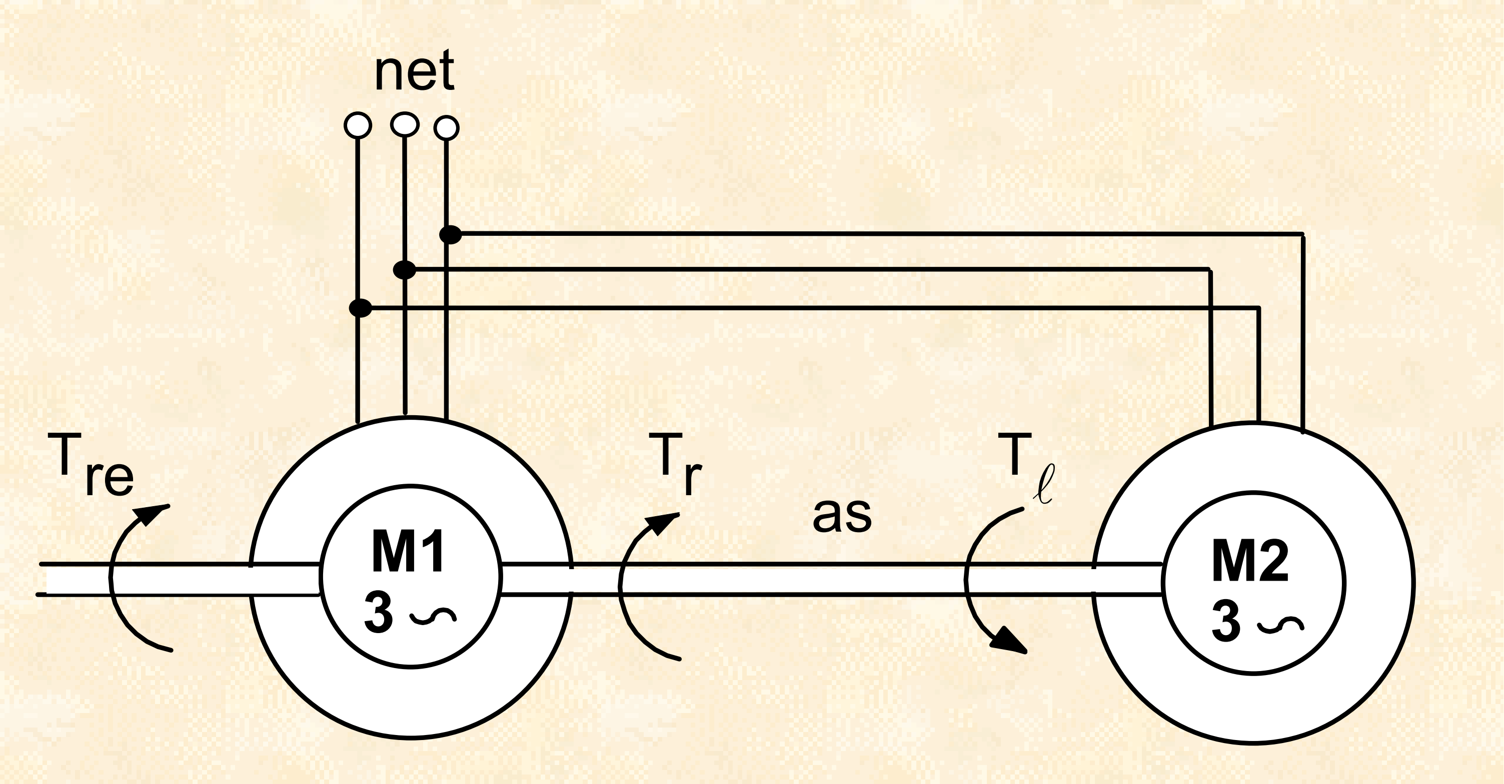
Stroomverdringingsrotor



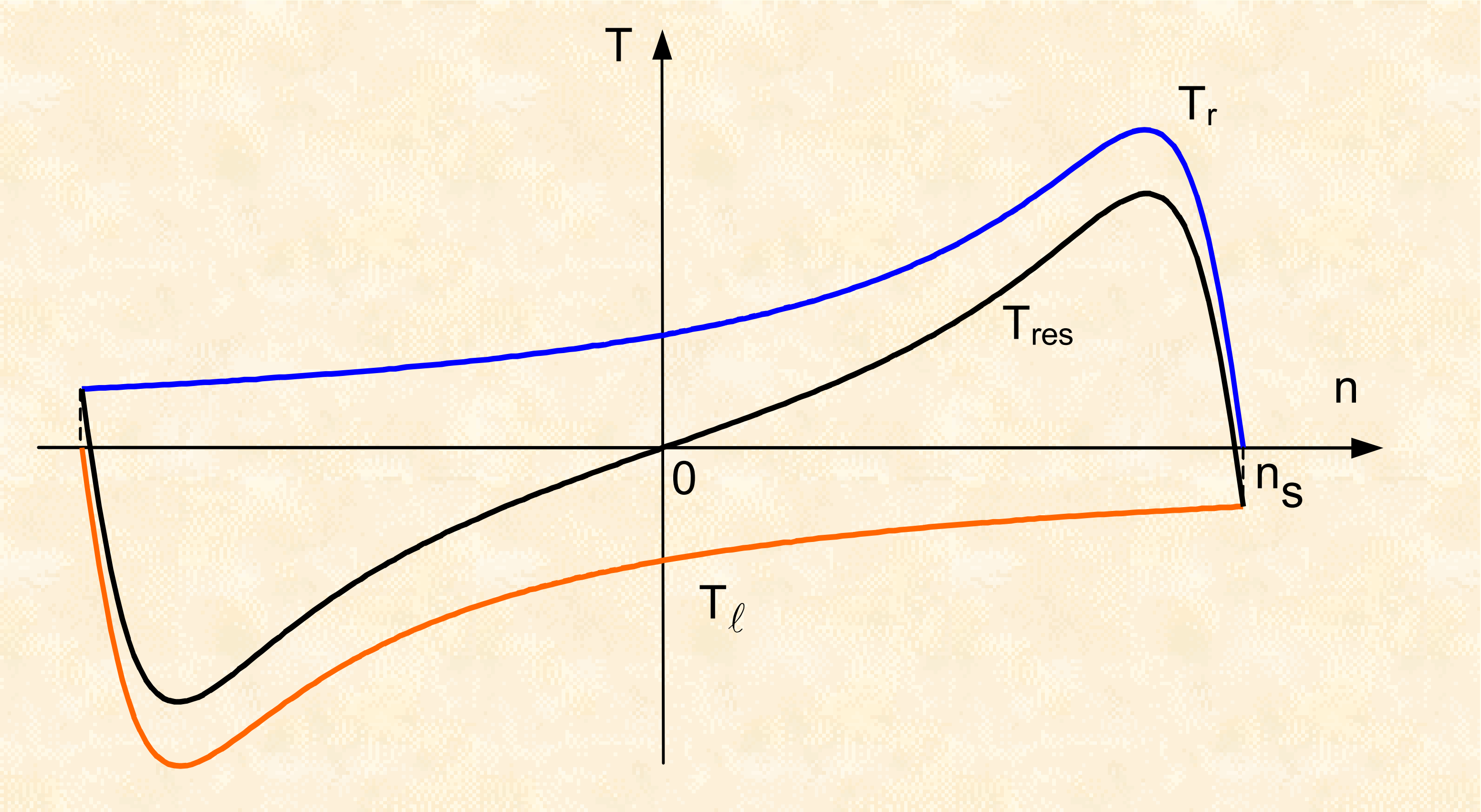
Eenfasige inductiemotor - Elliptisch draaiveld



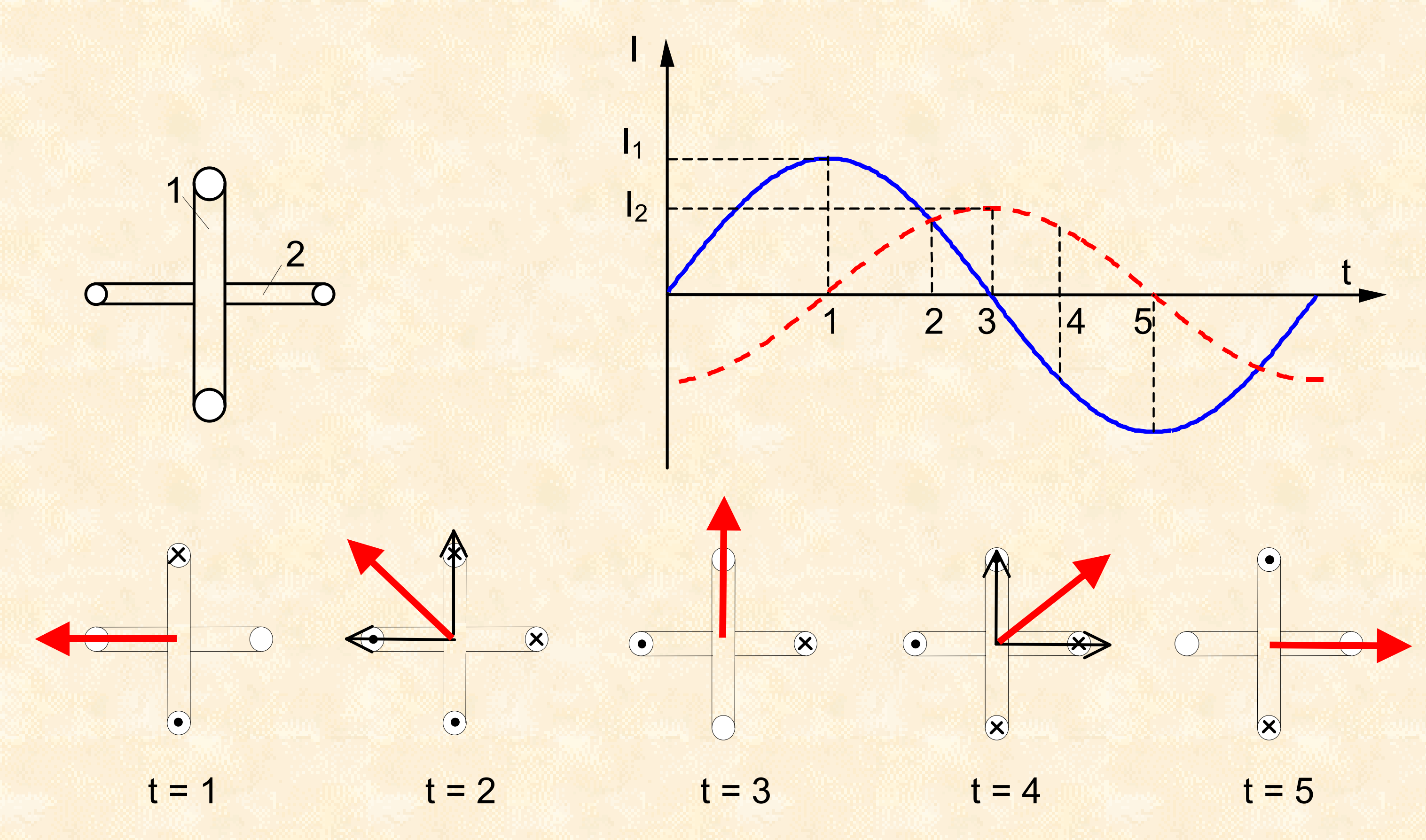
Gekoppelde driefasige machines als equivalent voor een eenfasige machine



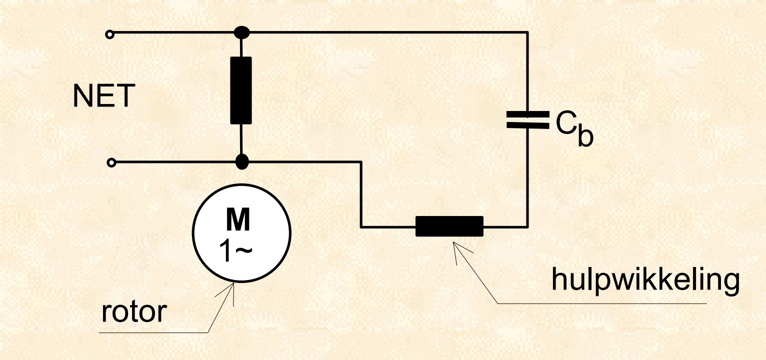
Koppel-toerentalkarakteristiek



Elliptisch draaiveld



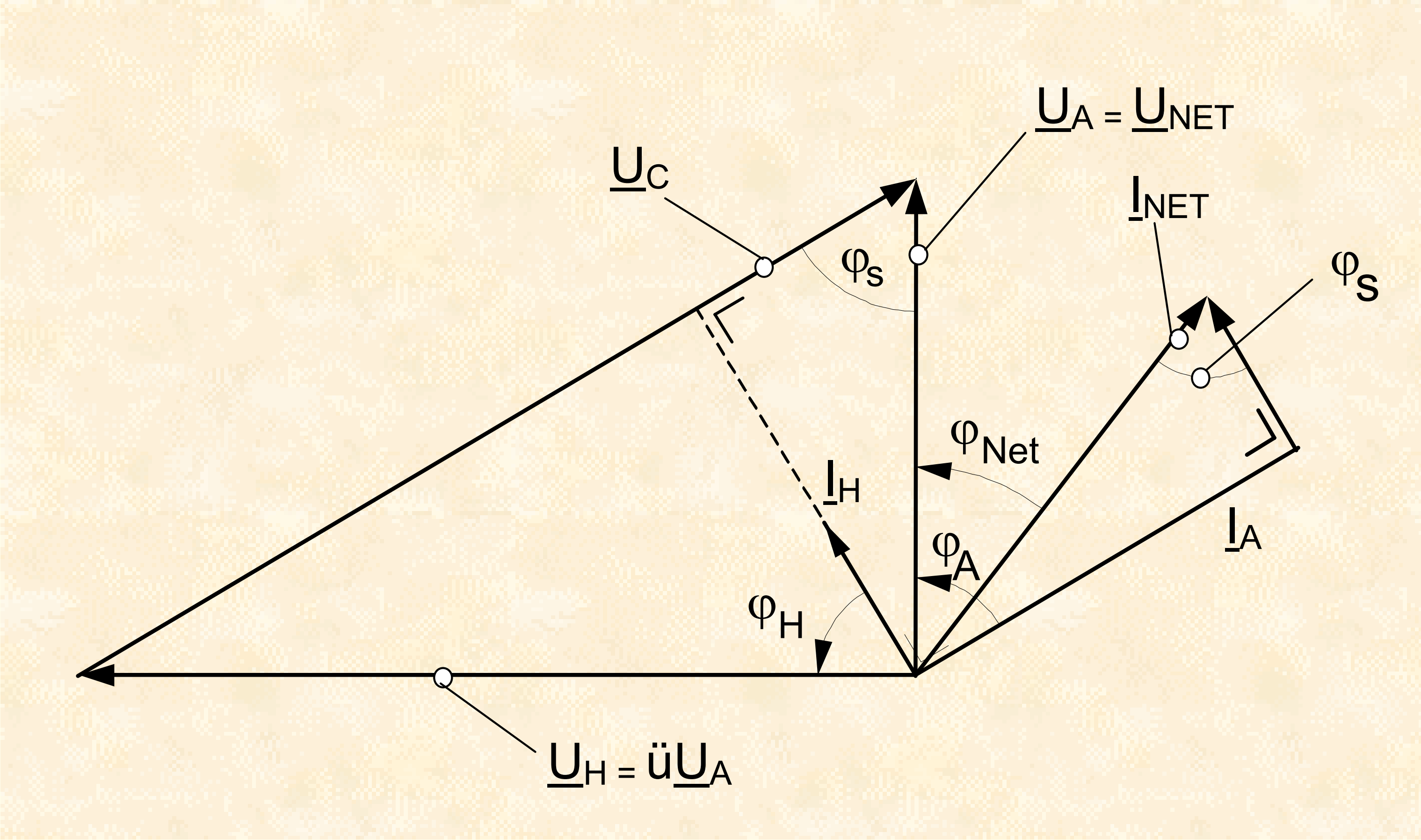
Condensator - Bedrijfscondensator

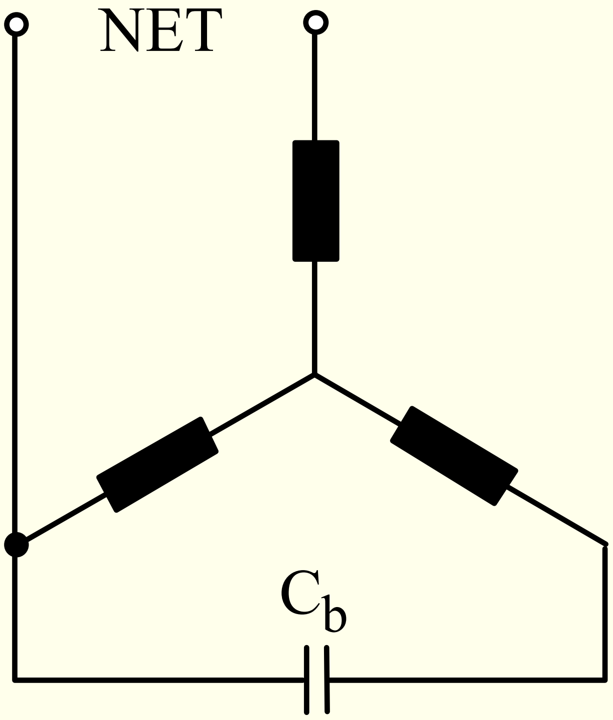


$$C_b = \frac{10^6}{2\pi f} \frac{P_2}{2U_N^2 u\,\eta} \quad [\mu\text{F}]$$

$$U_C = 1,2\sqrt{1+u^2}\,U_N$$

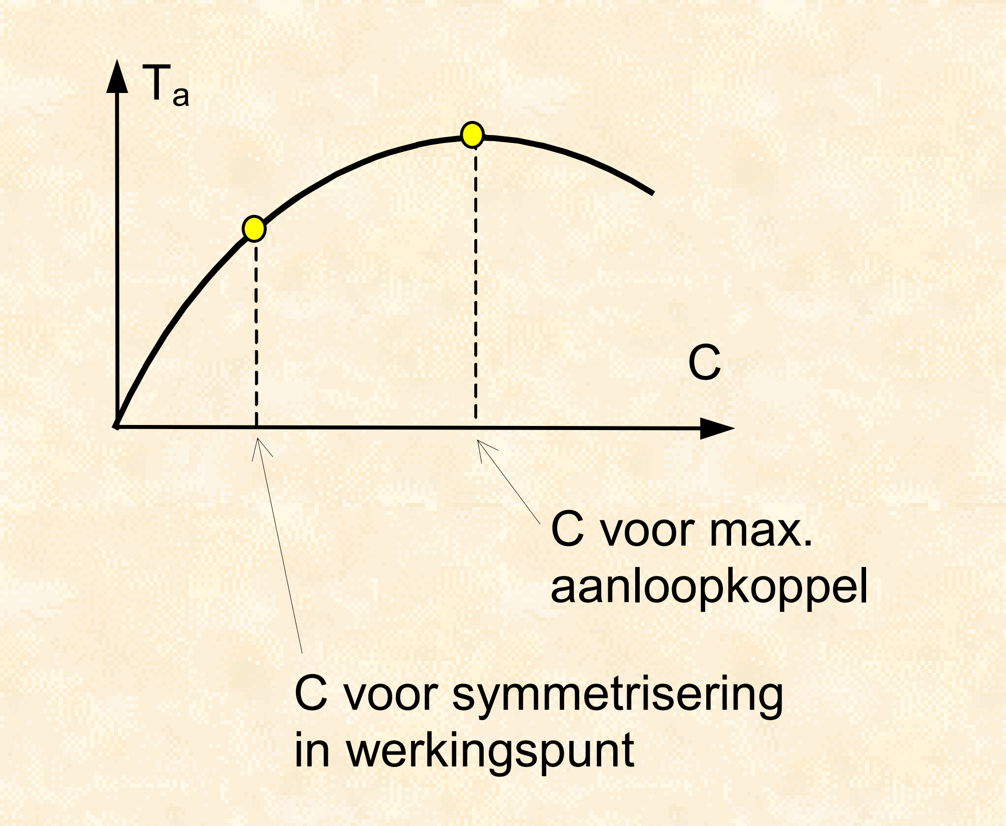
Fasordiagram





$$C_b = \frac{10^6}{2\pi f} \frac{P_2}{3.0,87\,U_N^2\,\eta} \qquad [\mu\text{F}]$$

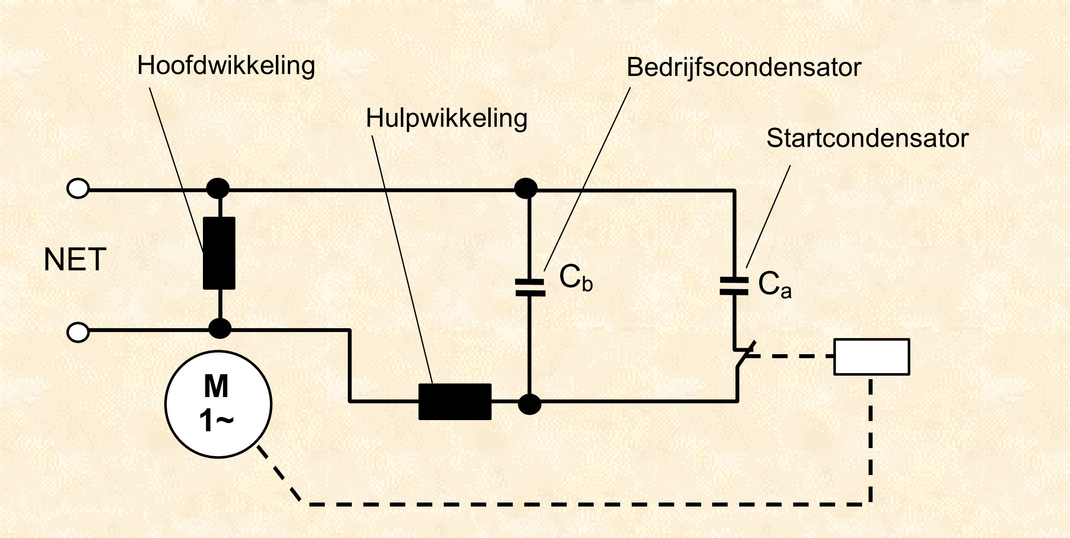
Condensatormotor: bedrijfs- en aanloopcondensator



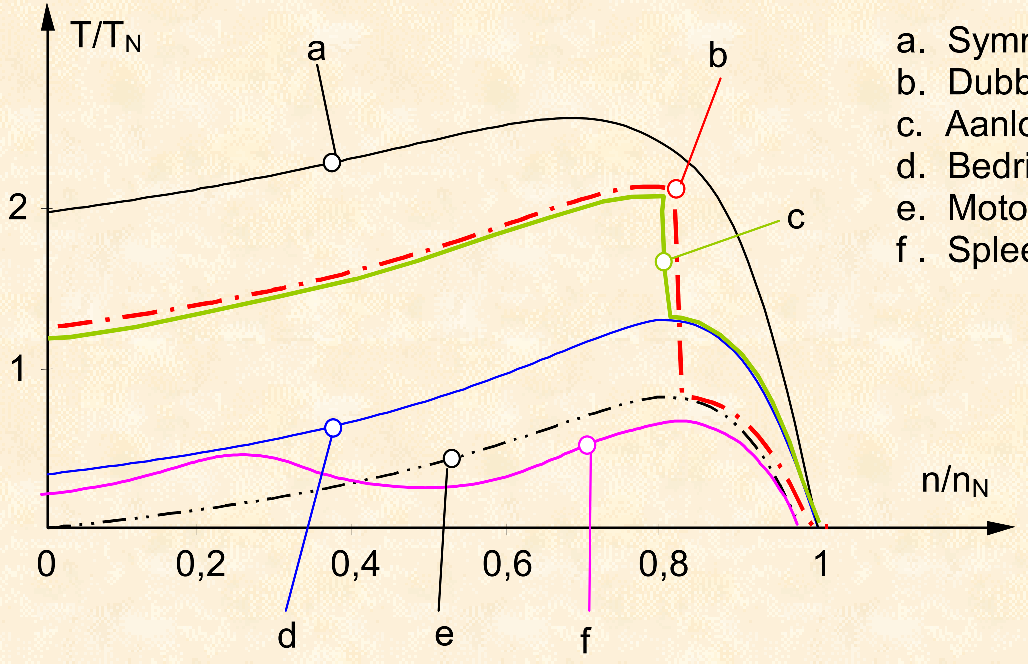
C voor max. aanloopkoppel

C voor symmetrisering in werkingspunt

Eenfasige motor met bedrijfs- en aanloopcondensator

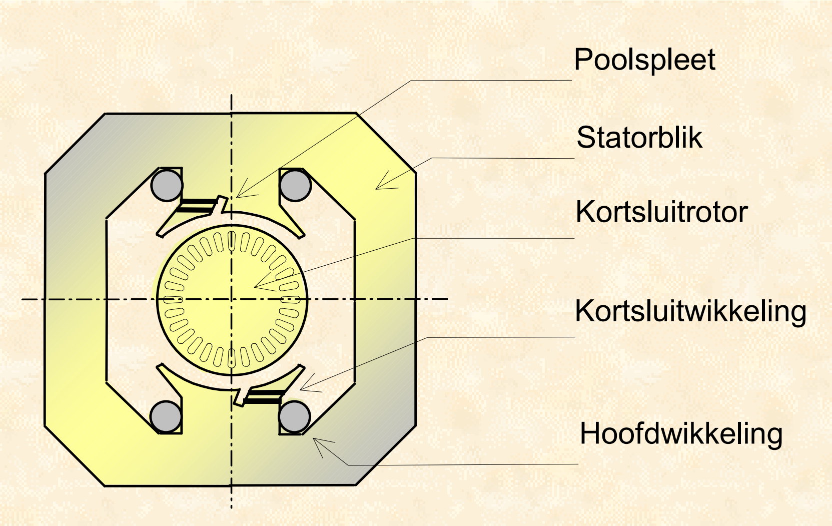


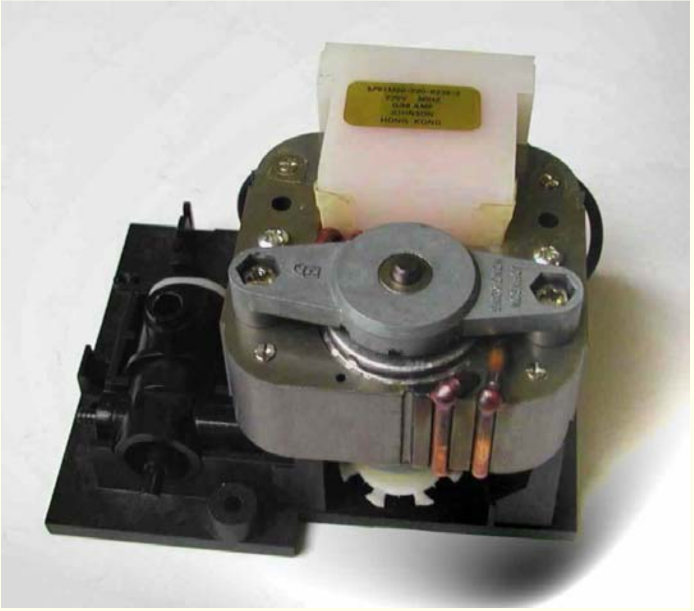
Koppel-toerentalkarakteristieken



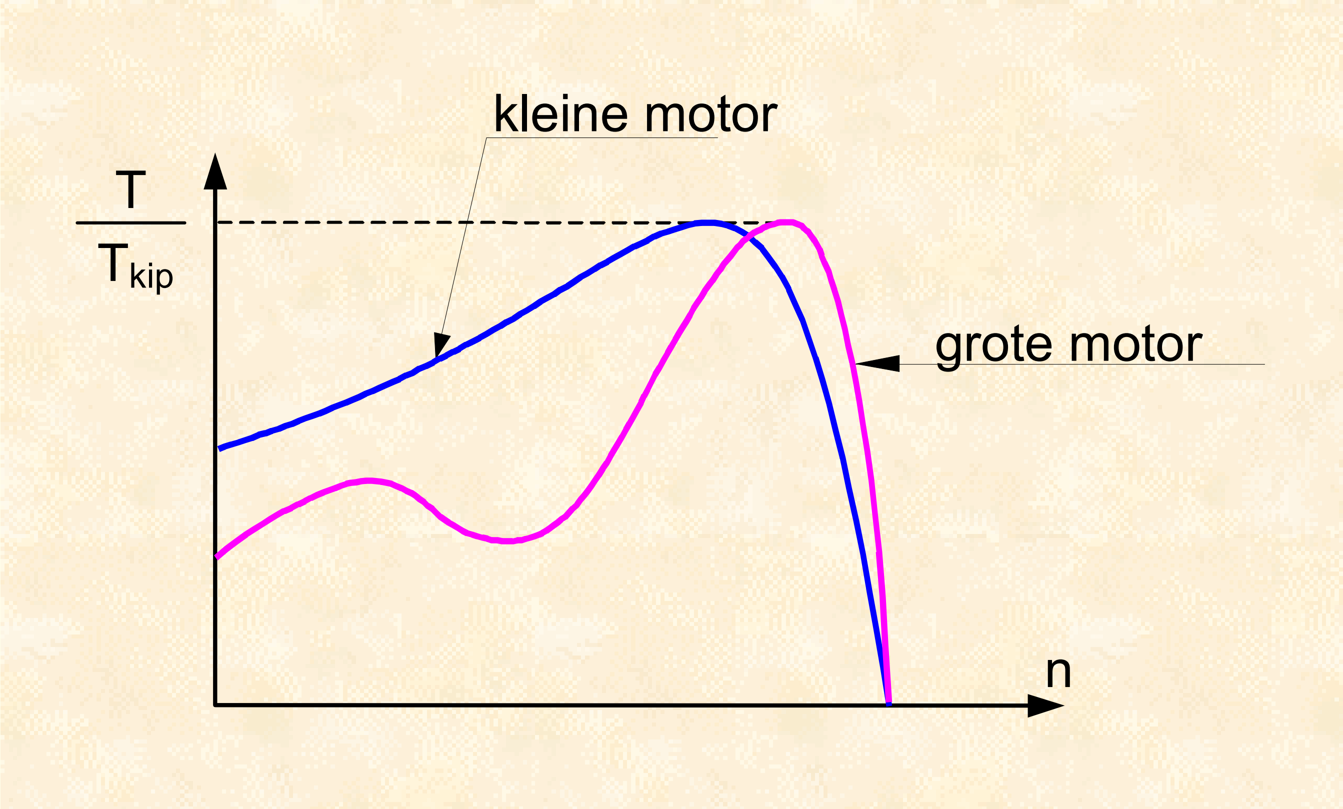
a. Symmetrische twee- of driefasige motor
b. Dubbelcondensatormotor
c. Aanloopcondensatormotor
d. Bedrijfscondensatormotor
e. Motor met 1 wikkelingsfase gevoed
f . Spleetpoolmotor

Spleetpoolmotor





Koppel-toerentalkarakteristiek van de spleetpoolmotor



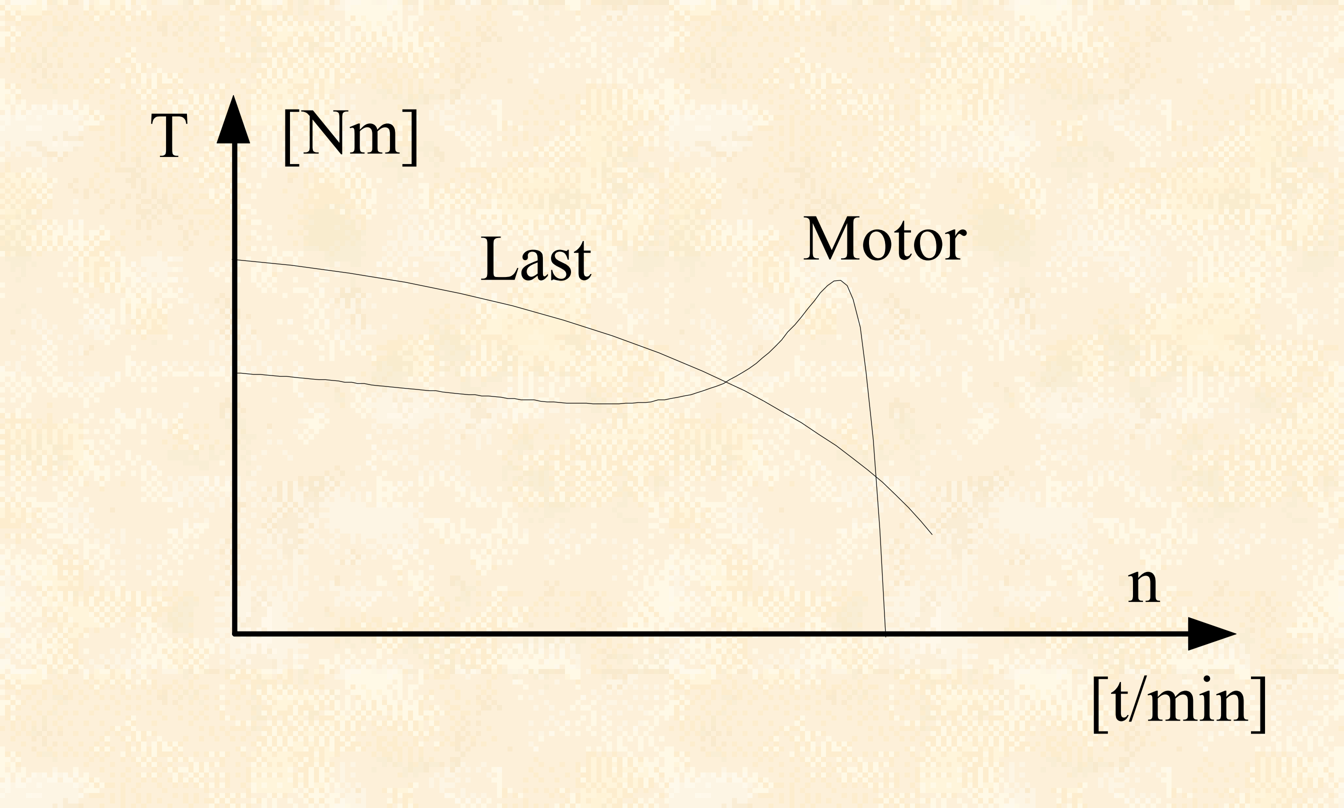
Gebruik van inductiemotoren

- Starten
- Remmen
- Toerentalregeling

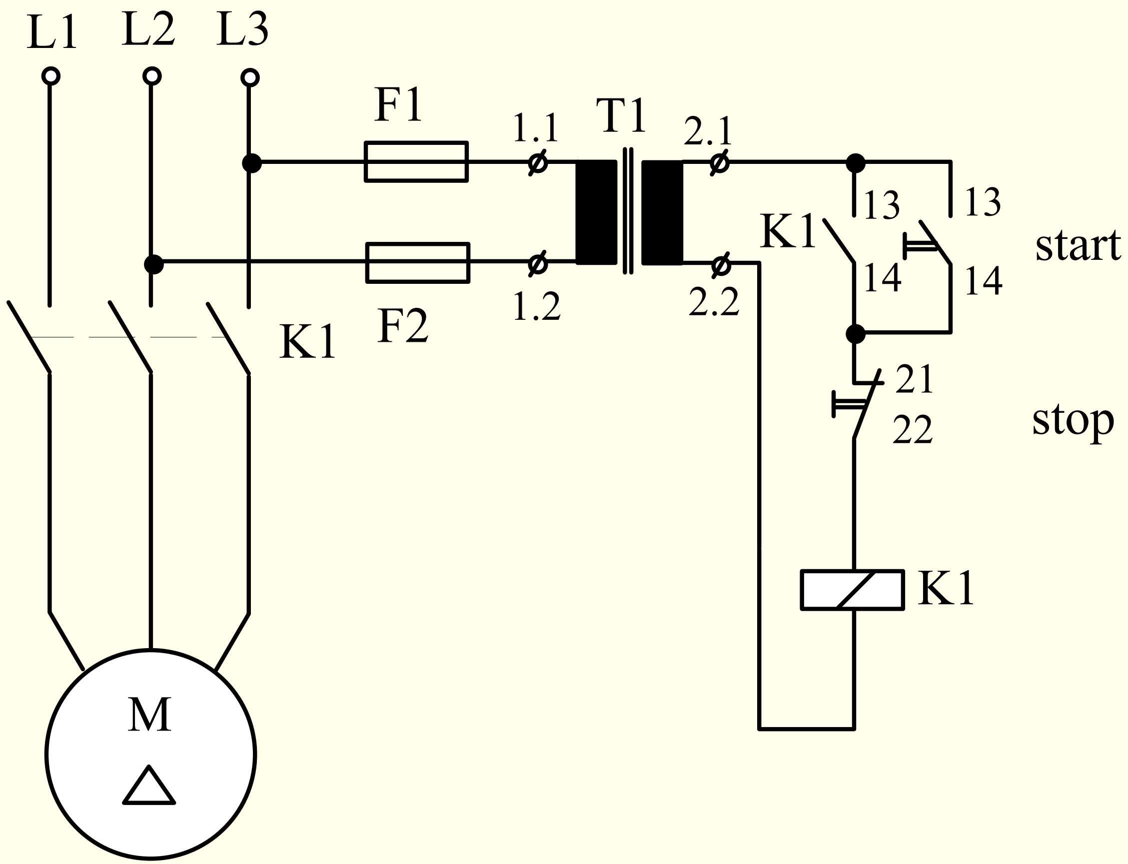
Starten

OPGENOMEN MOTORVERMOGEN (kVA)	**k**
tot 6 kVA: maar met een max. toegelaten nominale stroom van 23,7 A voor motoren gevoed met 230 V	6
van 3 t/m 4 kVA	3
van 4 t/m 10 kVA	2
boven 10 kVA	1,5

Aandrijfaggregaat met te hoog aanloopkoppel



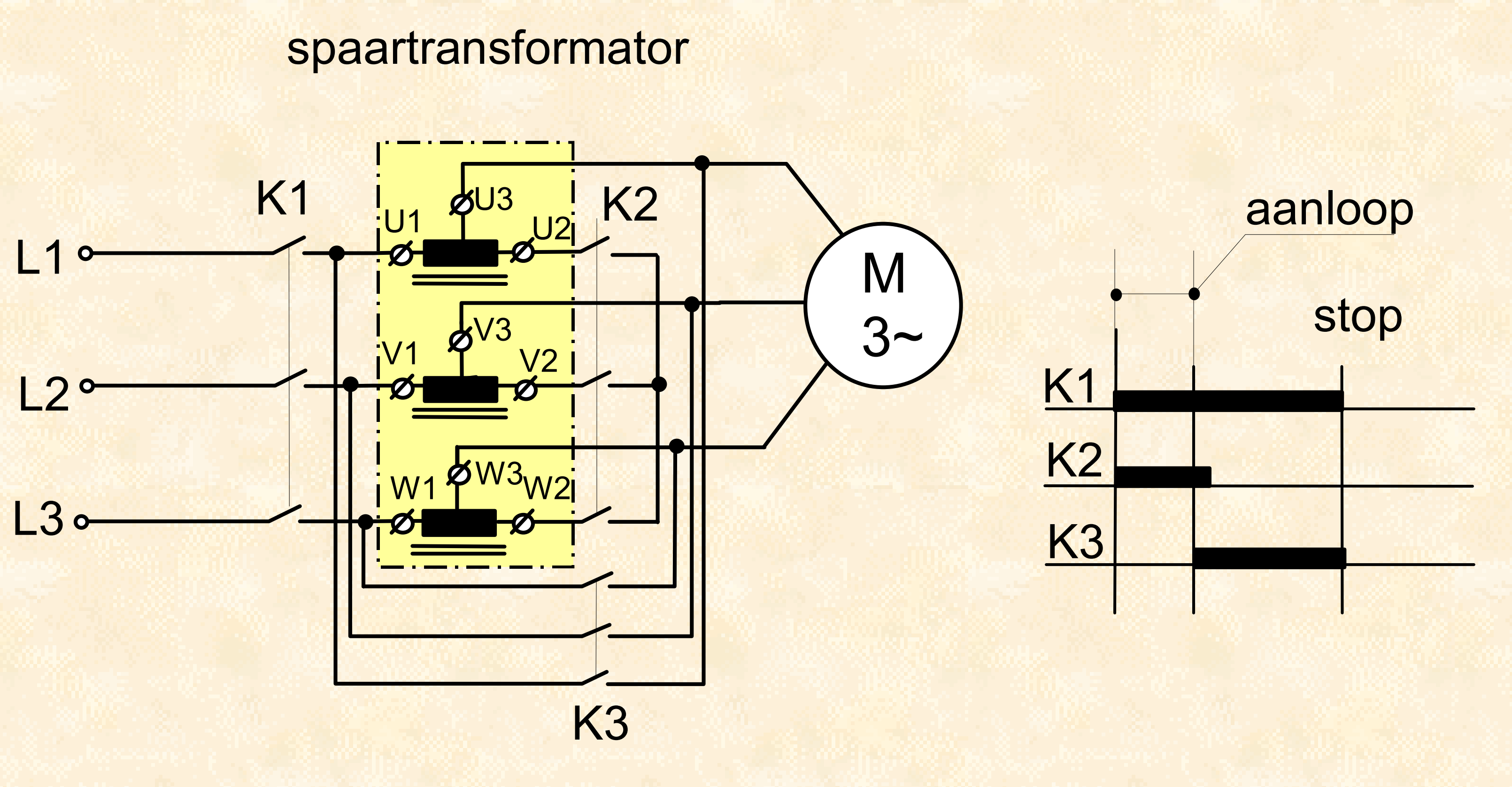
Directe aanloop



Verminderde spanning

- Spaartransformator
- Serie-impedanties
- Ster-driehoek aanloop
- Softstarter

Spaartransformator



$U_m = k_t U_N$ met $k_t < 1$

$$I_m = \frac{U_m}{\sqrt{3}\, Z_m} = \frac{U_N k_t}{\sqrt{3}\, Z_m}.$$

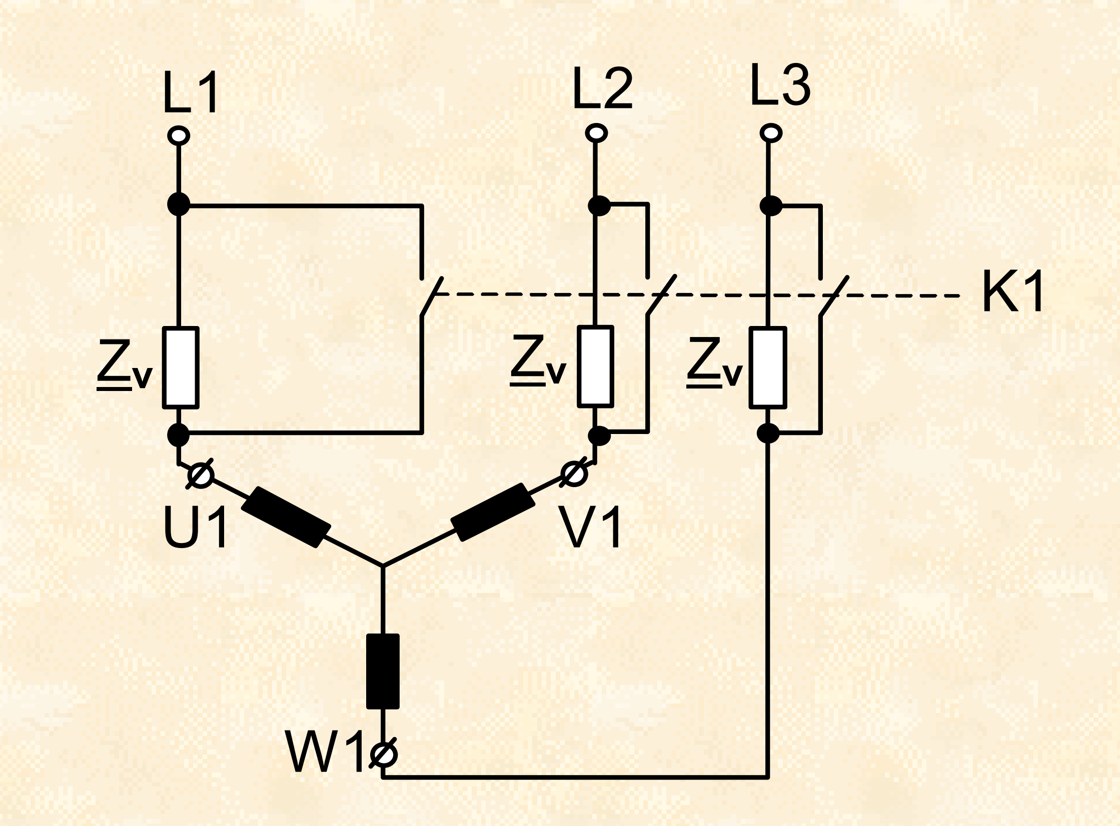
$$I_N = k_t I_m = k_t^2 I_{N1}$$

Voorschakelimpedanties

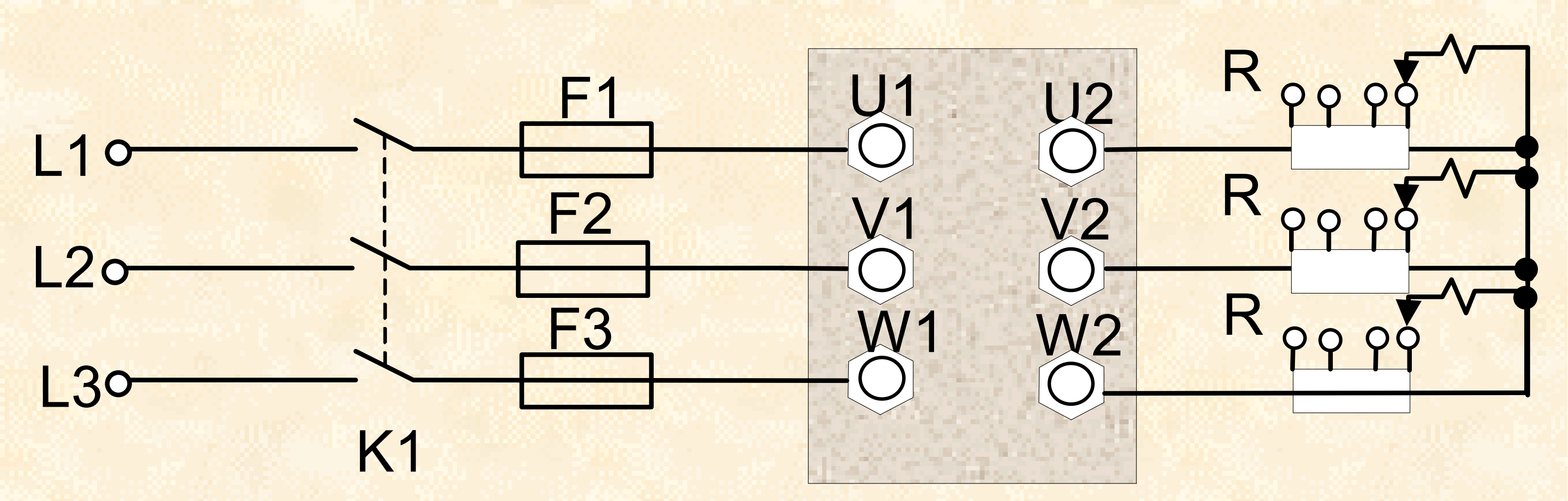
$$k_Z = \frac{U_m}{U_N} = \left| \frac{\underline{Z}_m}{\underline{Z}_m + \underline{Z}_V} \right| < 1$$

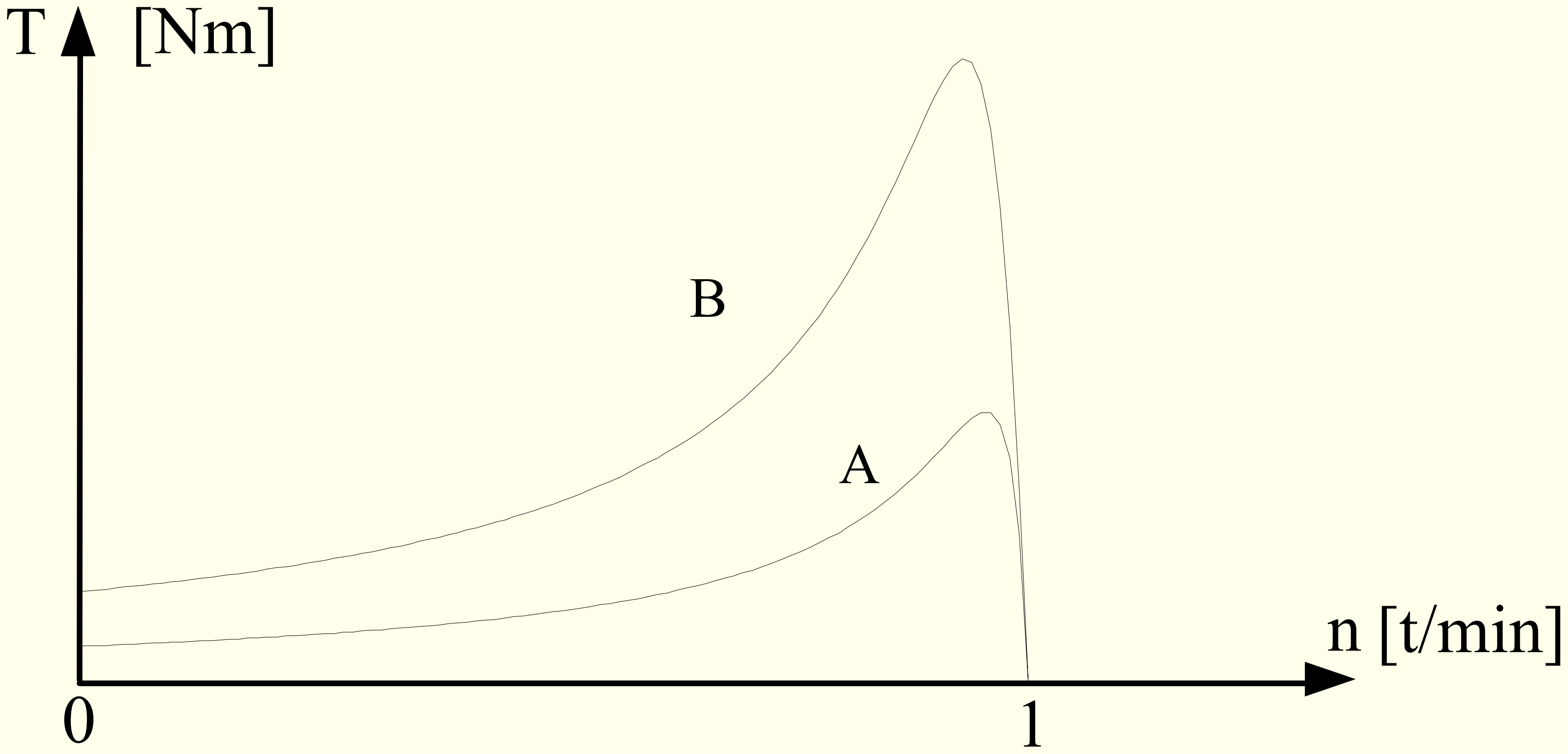
$$I_N = I_m = k_Z I_{N1}$$

Aanloop met statorvoorschakelimpedantie

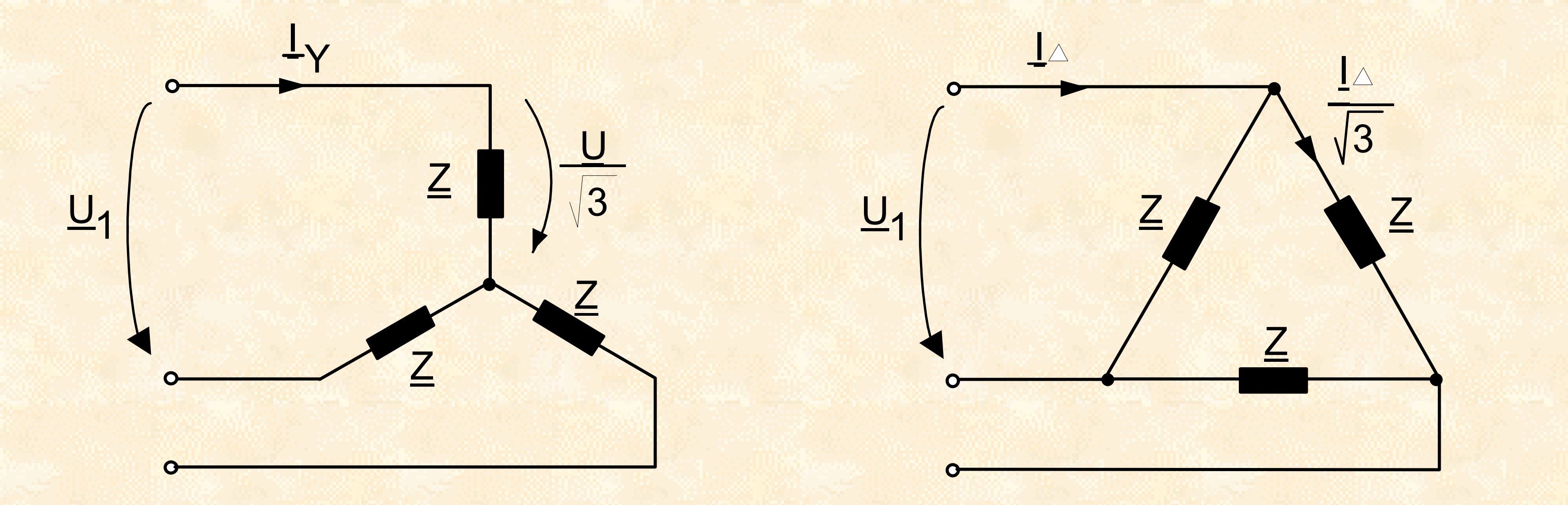


Statorvoorschakelweerstanden langs het sterpunt

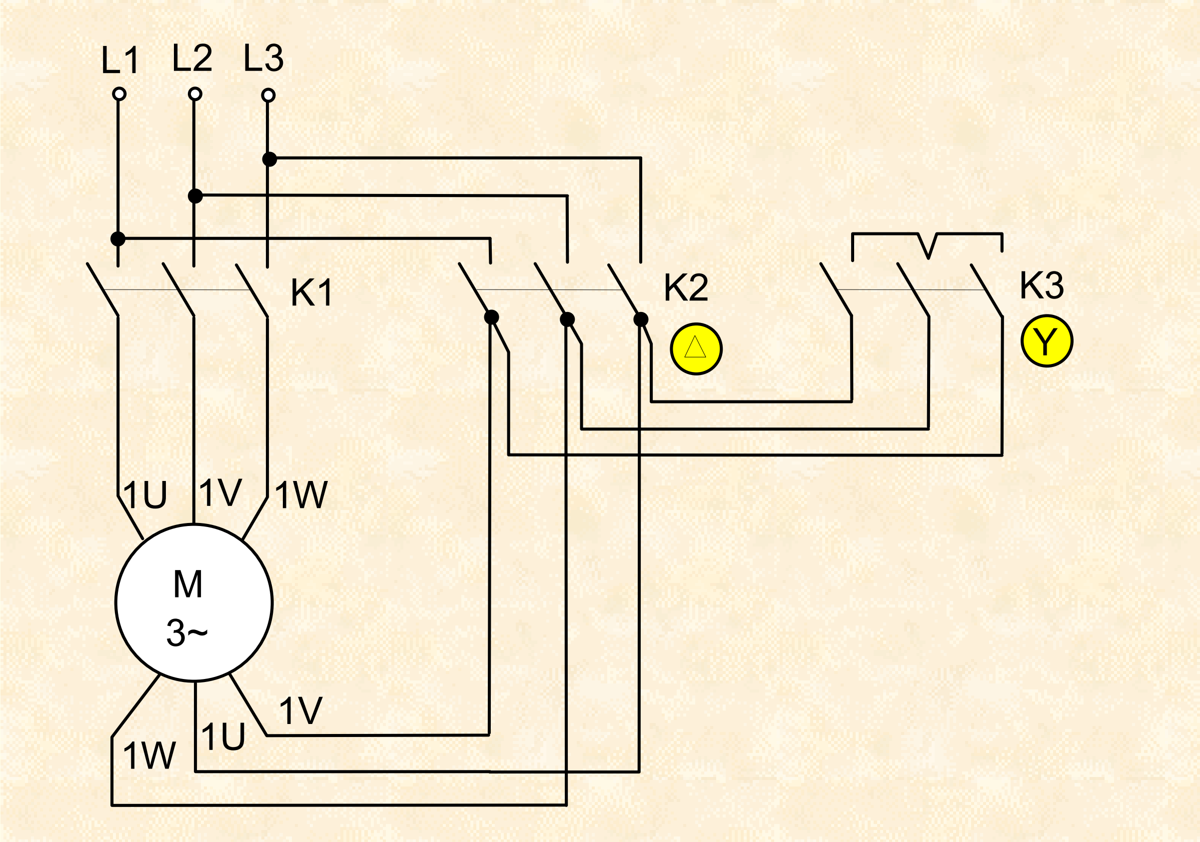


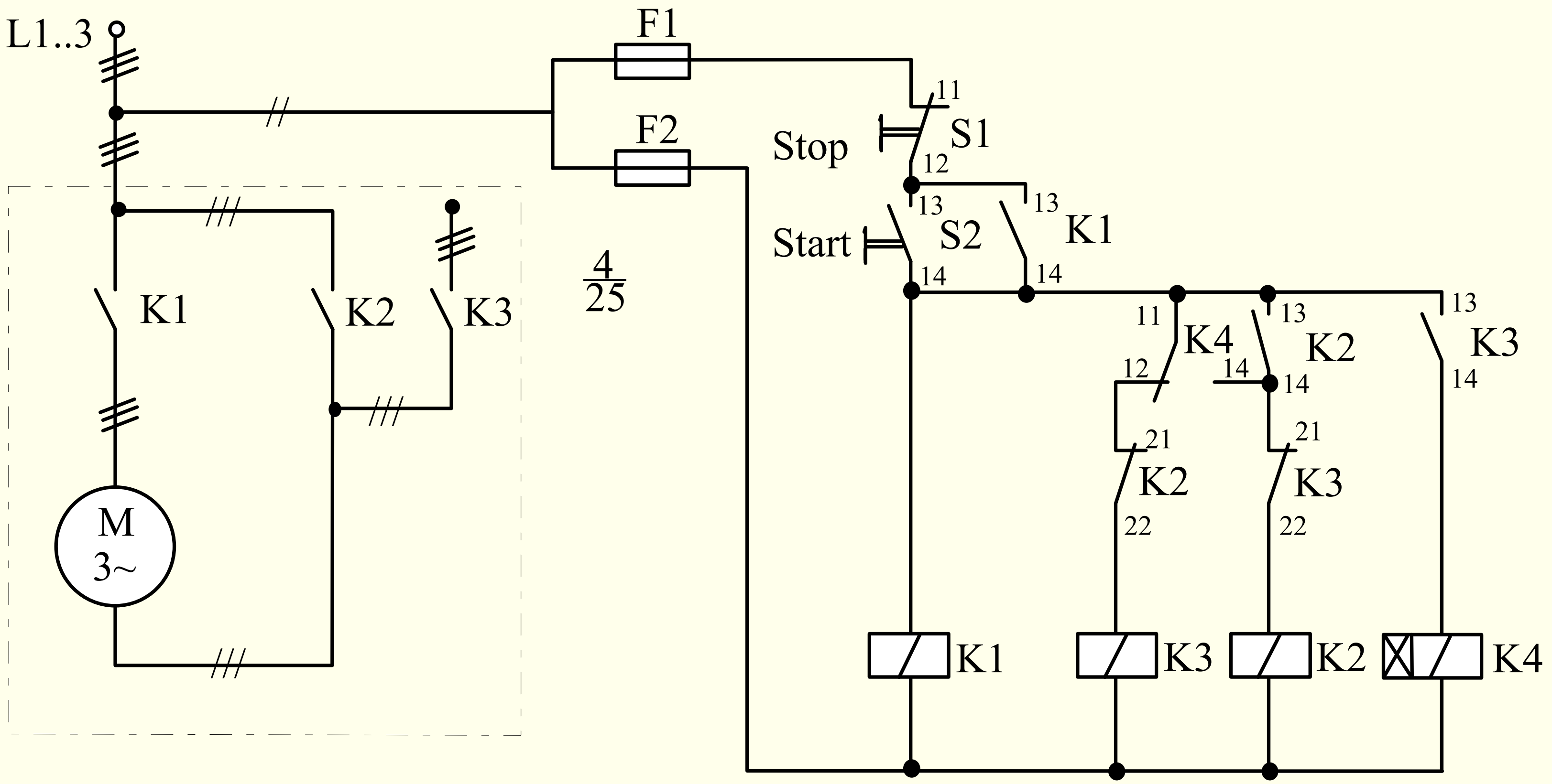

T [Nm]
B
A
n [t/min]
0
1

Ster-driehoekaanloop

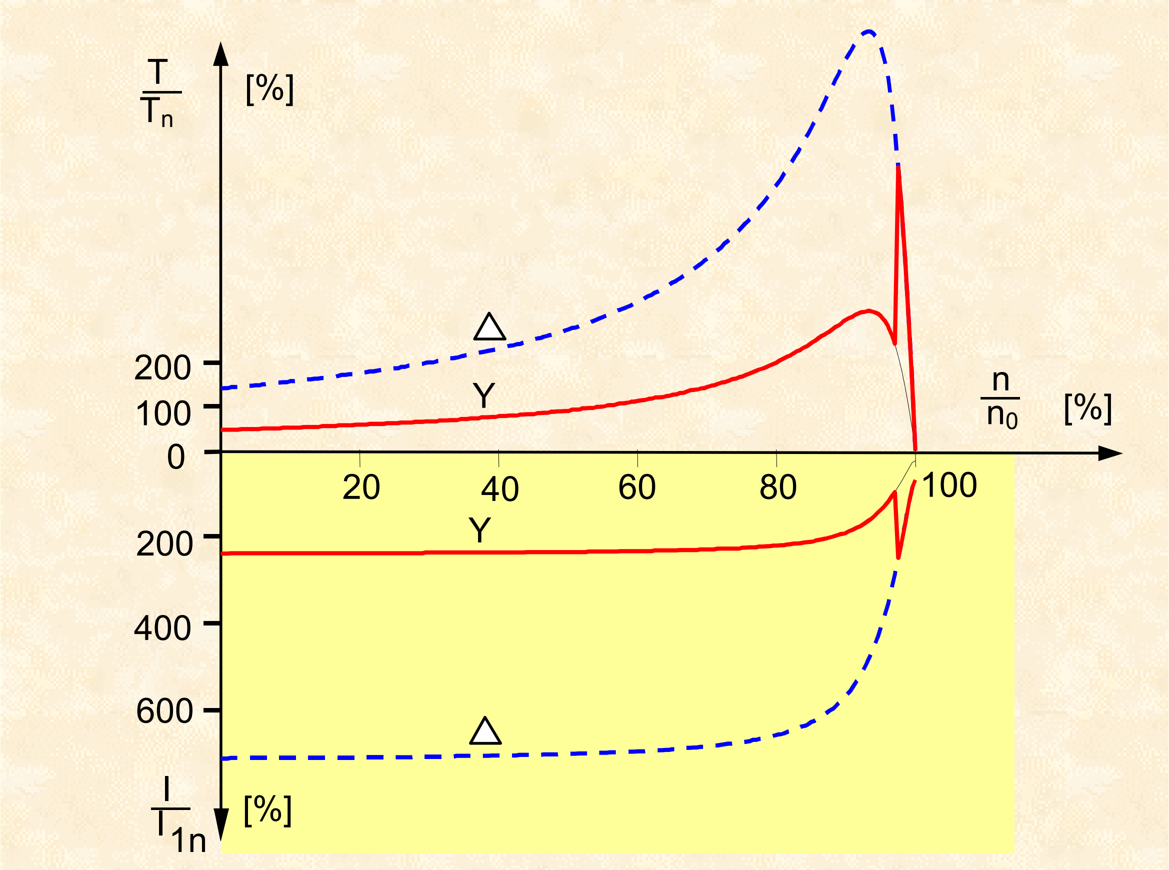


Schakelschema voor de Y-Δ aanloop

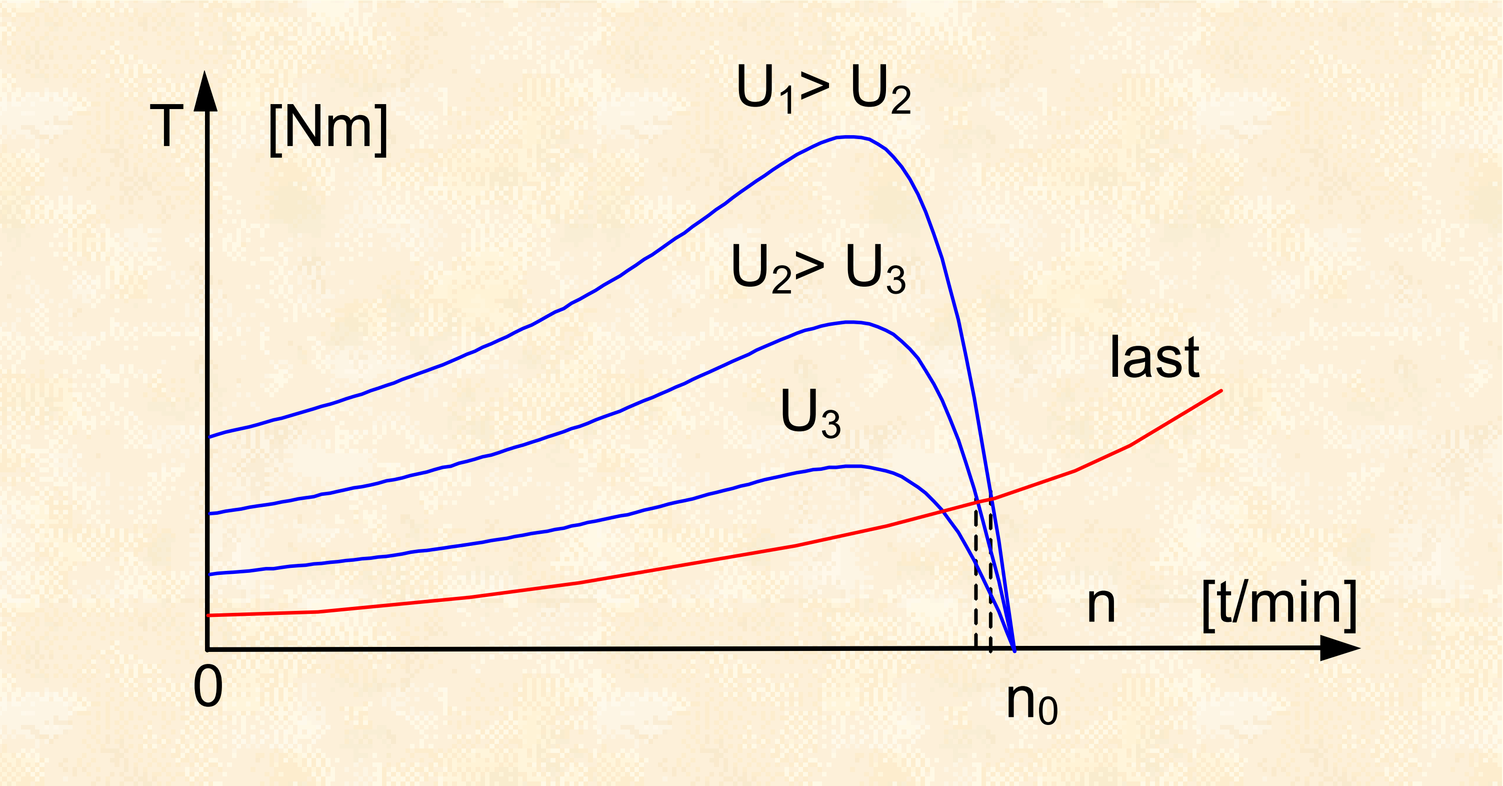



L1..3
F1
F2
Stop
S1
11
12
Start
S2
13
14
K1
13
14
K1
K2
K3
4
25
M
3~
11
K4
12
21
K2
22
13
K2
14
14
21
K3
22
13
K3
14
K1
K3
K2
K4

Stationaire koppel-toerental en stroom-toerental karakteristiek bij Y - Δ aanloop



Softstarter

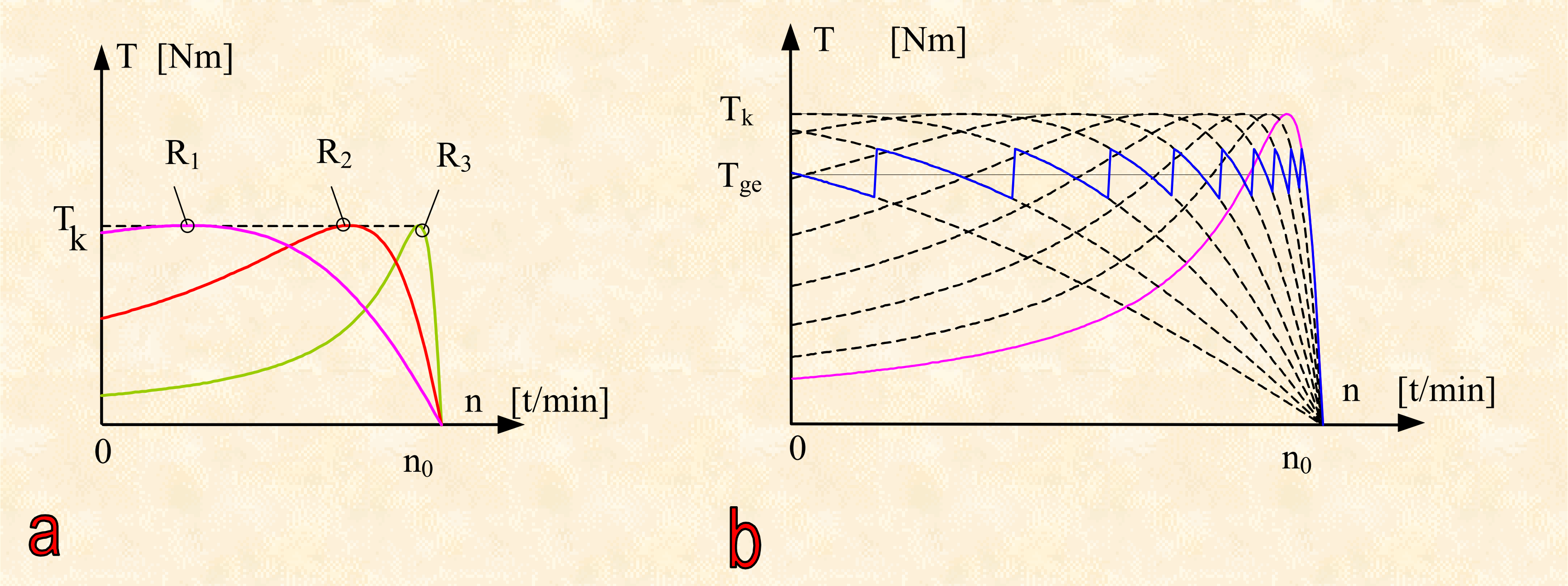


Rotorweerstanden

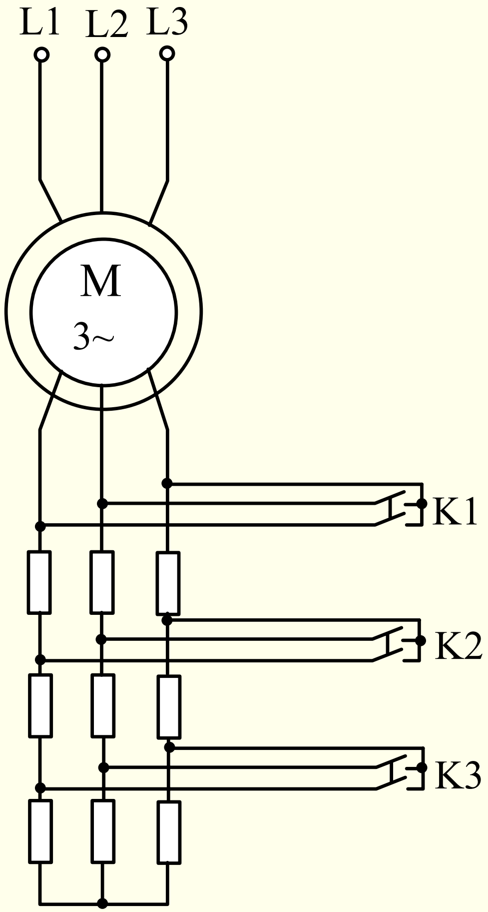
$$T_{kip} = \frac{3p}{2\omega_1} \frac{X_1 I_m^2}{X_{\sigma 1} + X_{\sigma 2}^{'}}$$

$$s_{kip} = \frac{\beta}{\sigma} \cong \frac{R_2^{'}}{X_{\sigma 1} + X_{\sigma 2}^{'}}$$

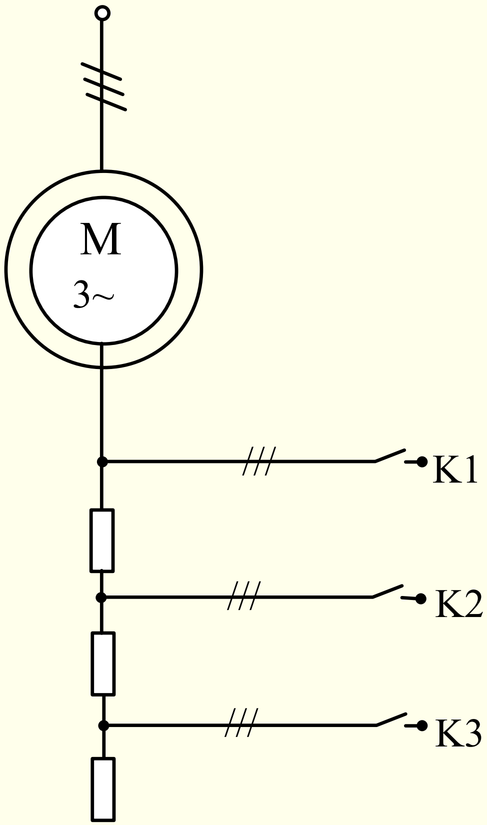
Koppel-toerentalkarakteristiek met rotor voorschakelweerstand



Praktische uitvoering

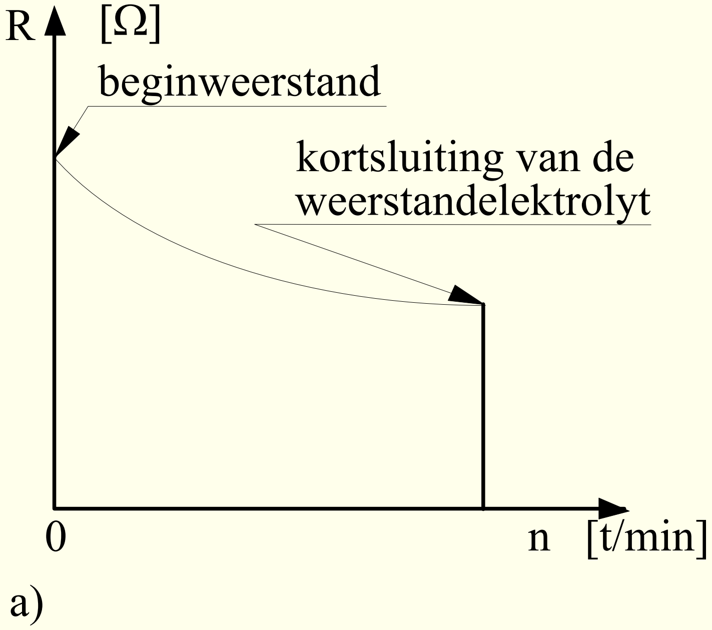


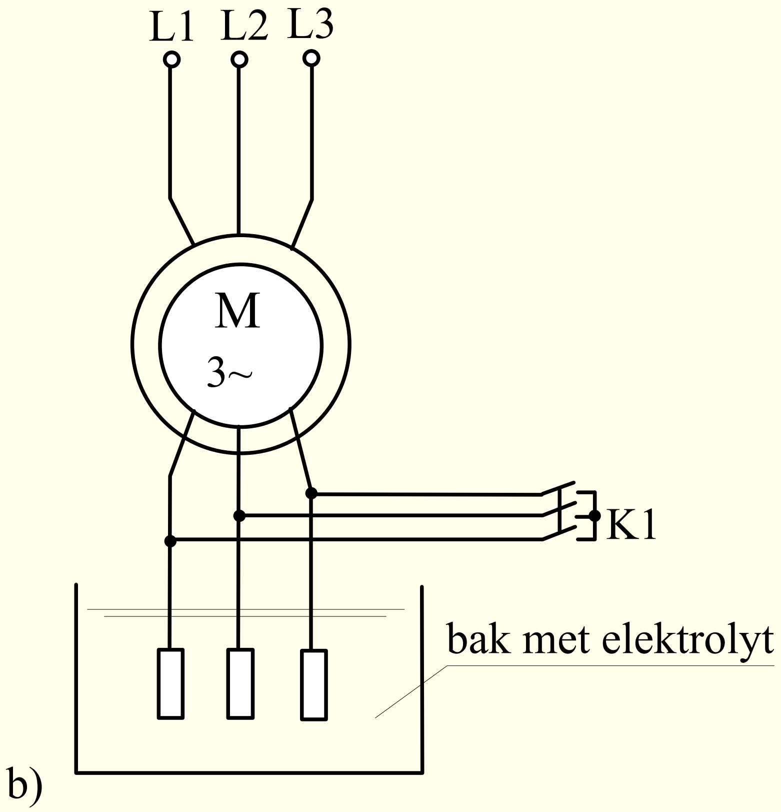
Schakelschema



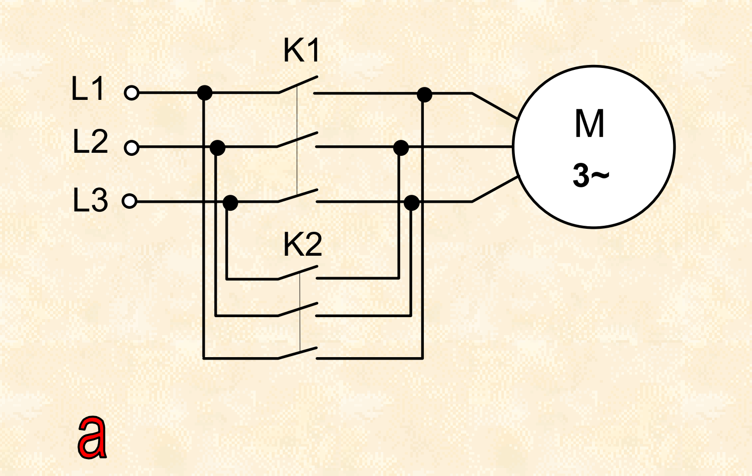
Eendraadsschema

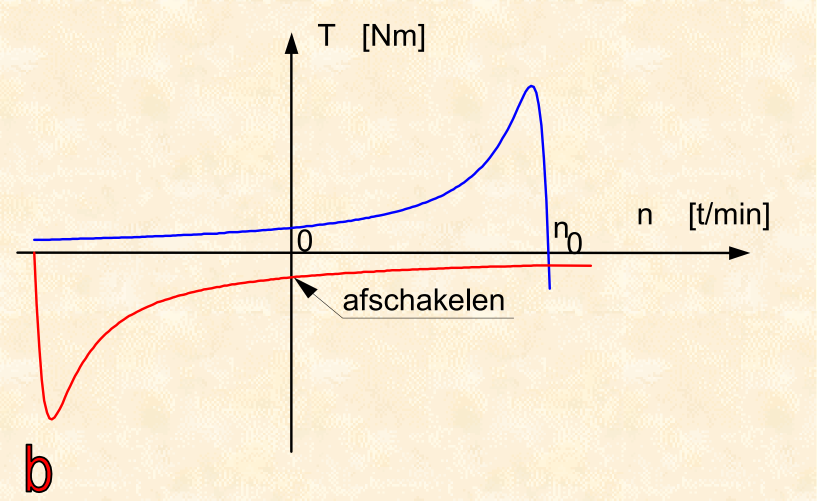
Vloeistofweerstand





Tegenstroomremming





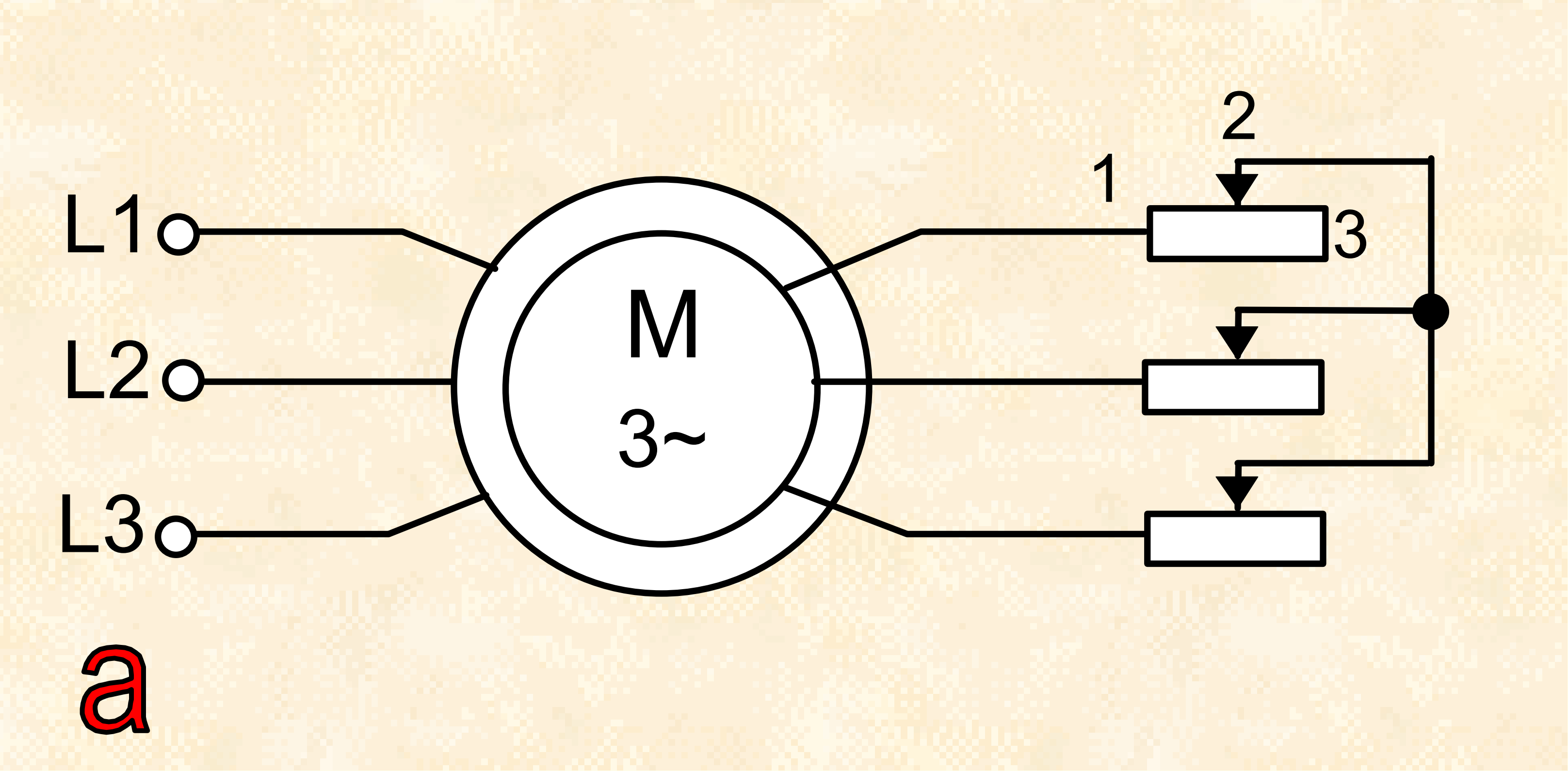
Oversynchrone remming

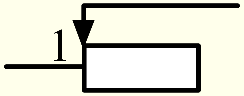
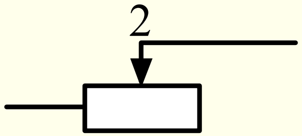
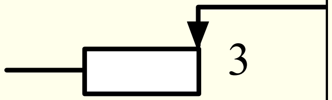
Toerentalregeling

$$\omega_m = \omega_0 (1 - s) = \frac{2\pi f_1}{p}(1 - s)$$

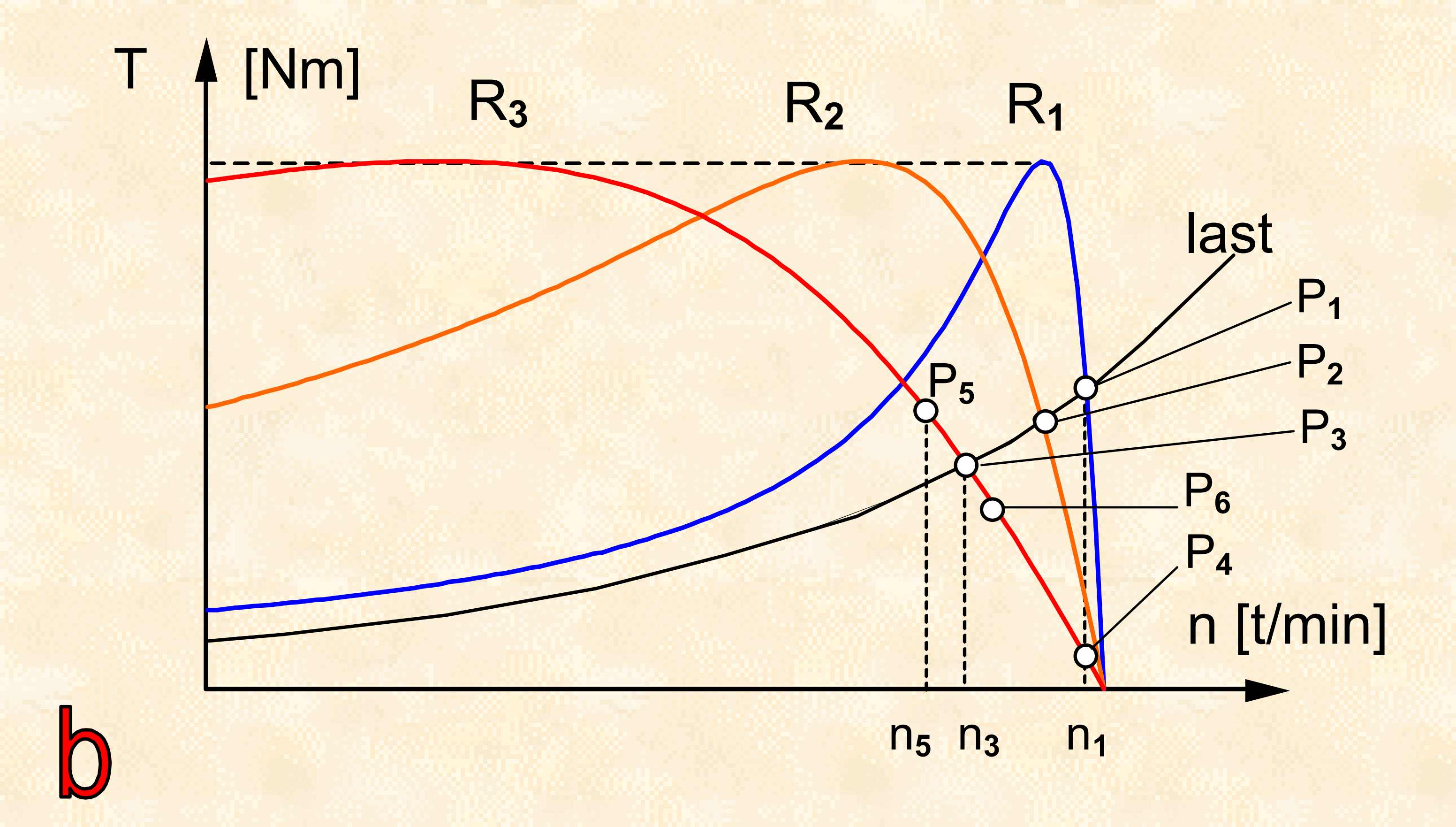
- poolpaartal
- slip
- frequentie
- mechanisch

Sleepringrotor – Weerstand I

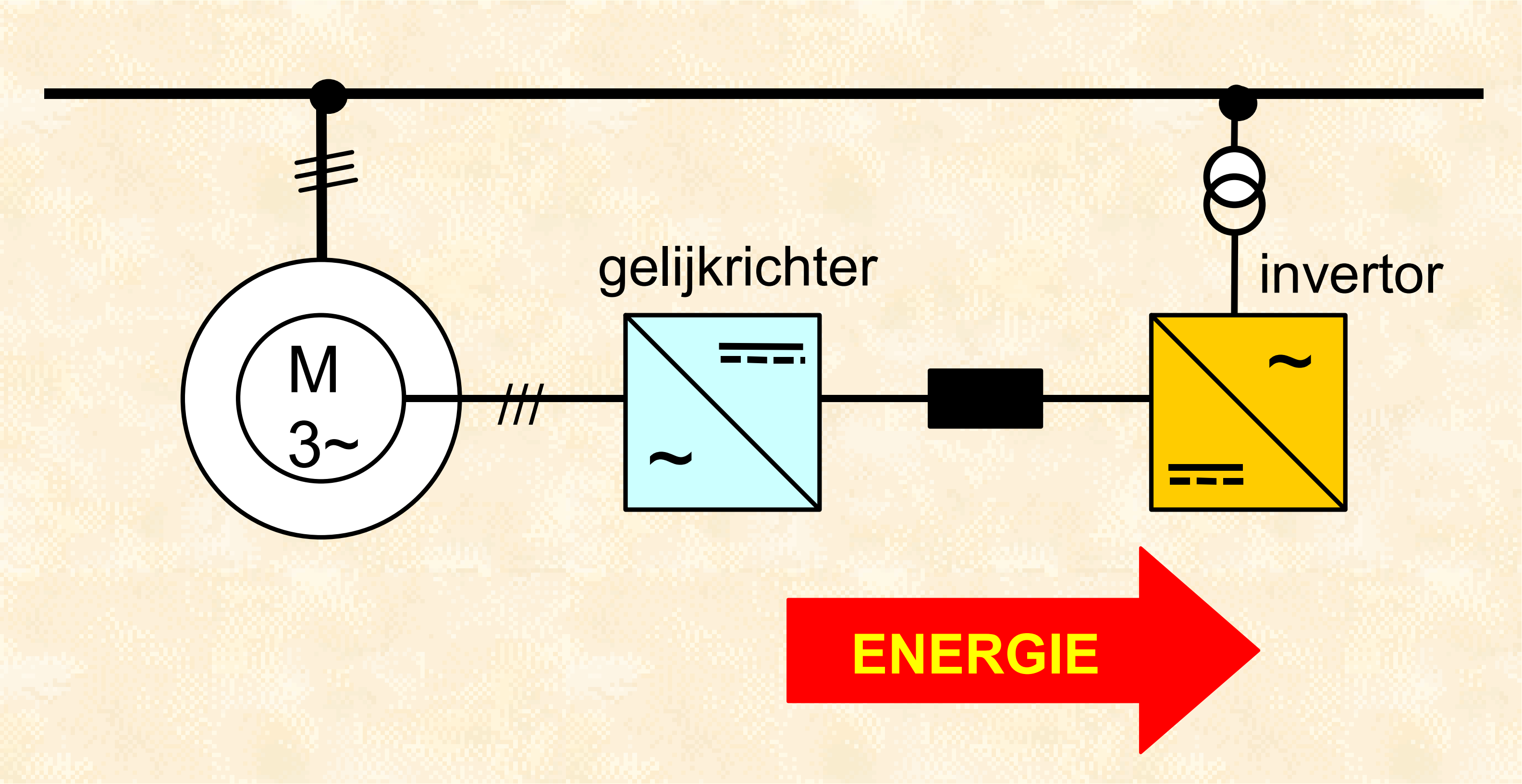


R1		geen bijkomende weerstand
R2		bijkomende rotorweerstand half ingeschakeld
R3		bijkomende rotorweerstand volledig ingeschakeld

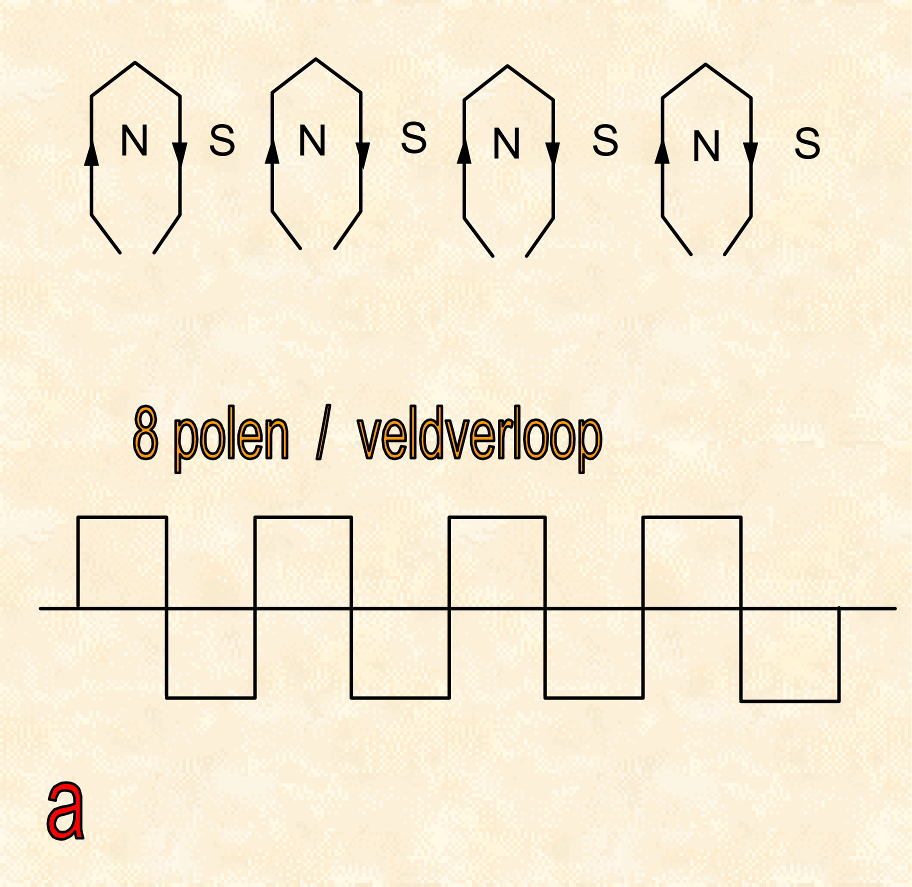
Sleepringrotor – Weerstand II



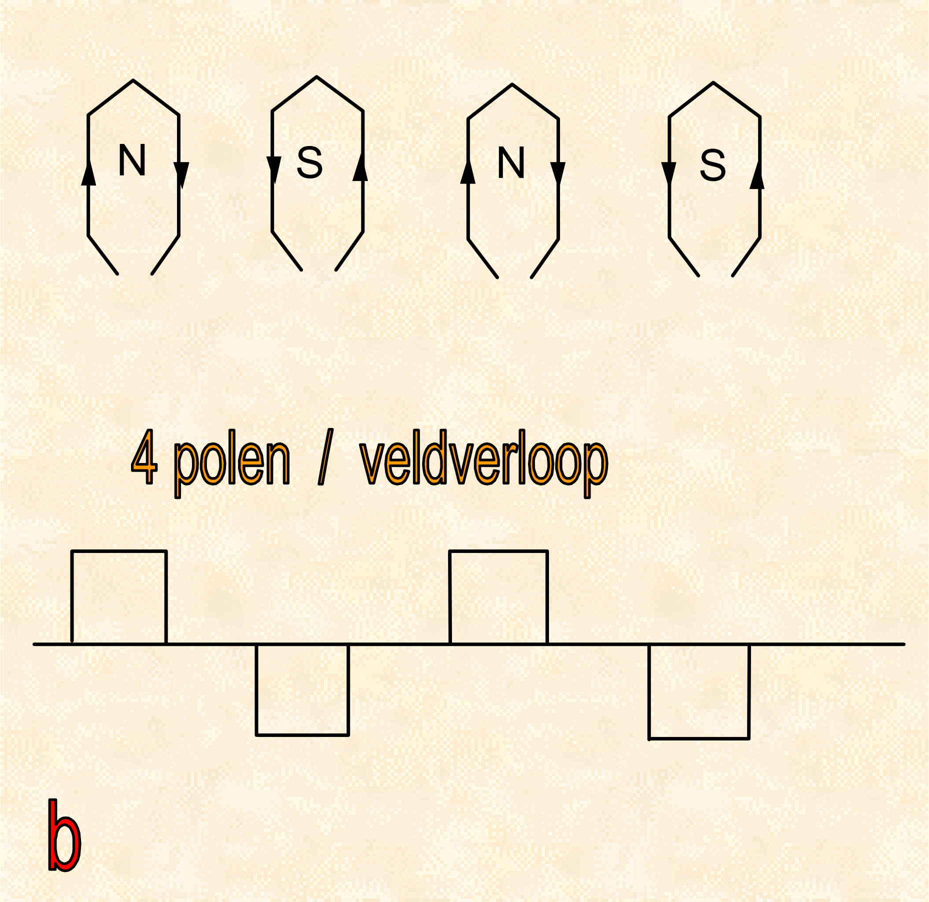
Sleepringrotor - Cascadeschakeling



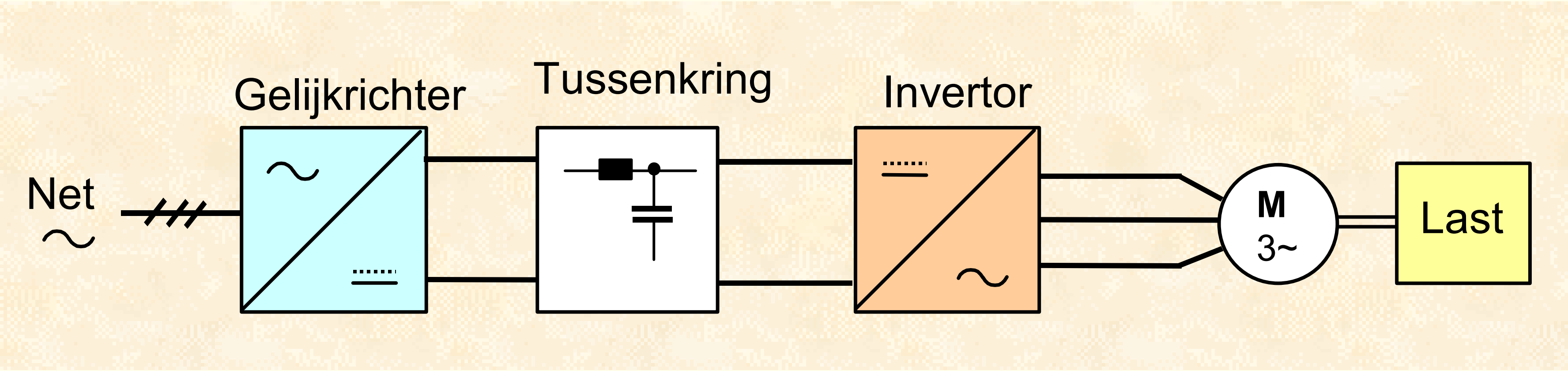
Poolpaartal – Dahlander I



Poolpaartal – Dahlander II



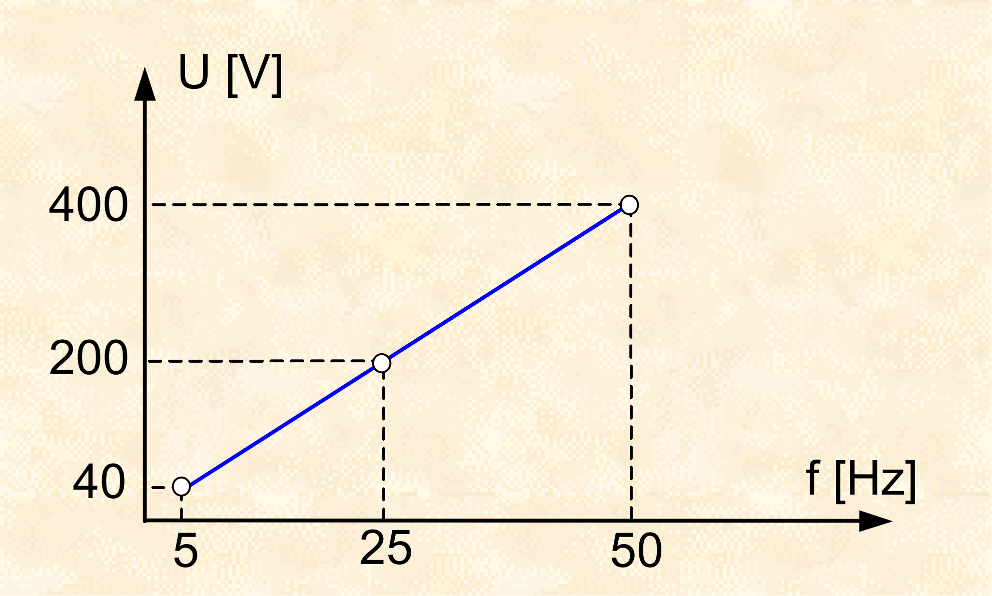
Frequentiesturing



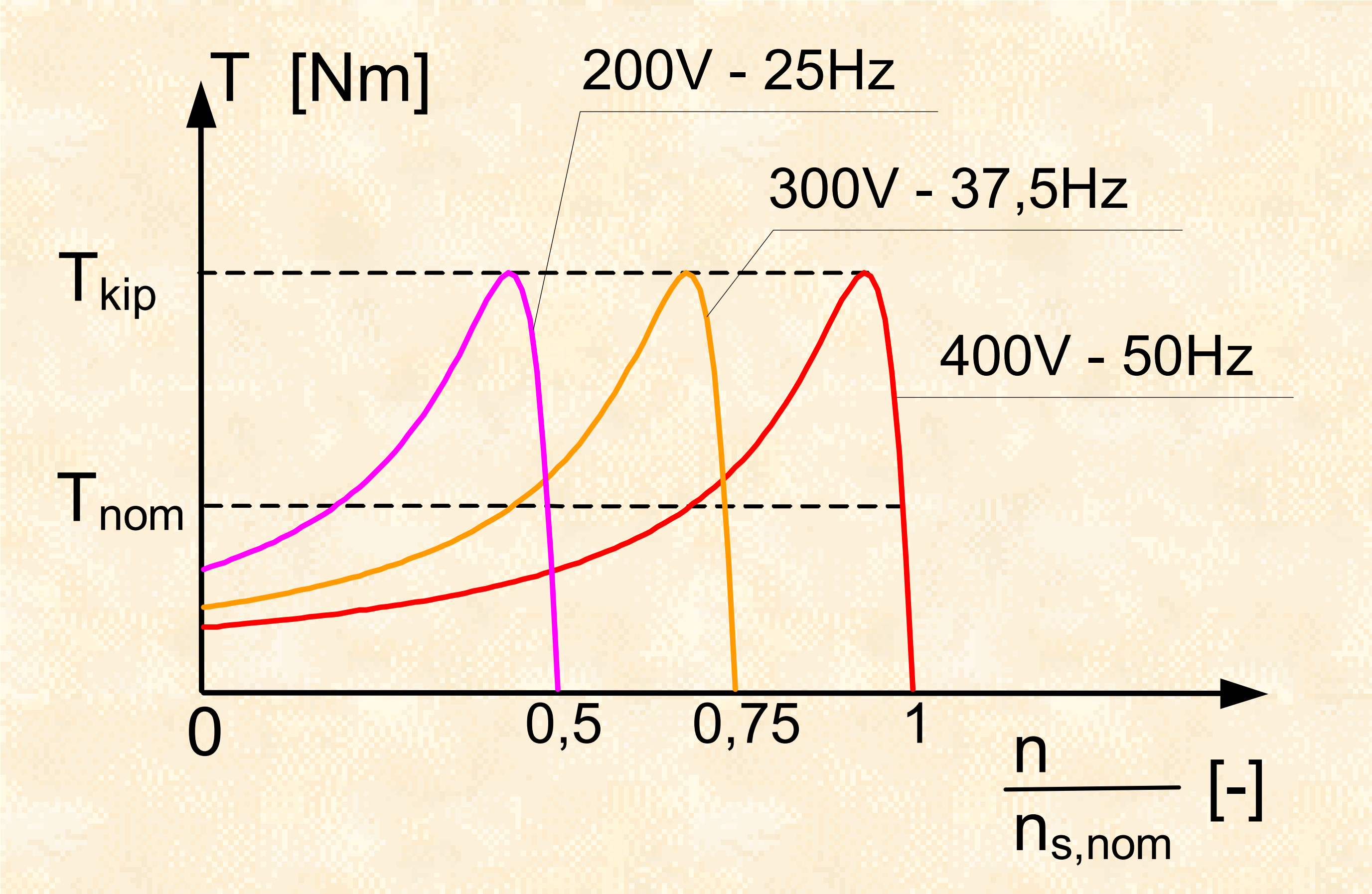
Verhouding spanning-frequentie

$$U_f = 4,44 . w_{eff} . f . \phi$$

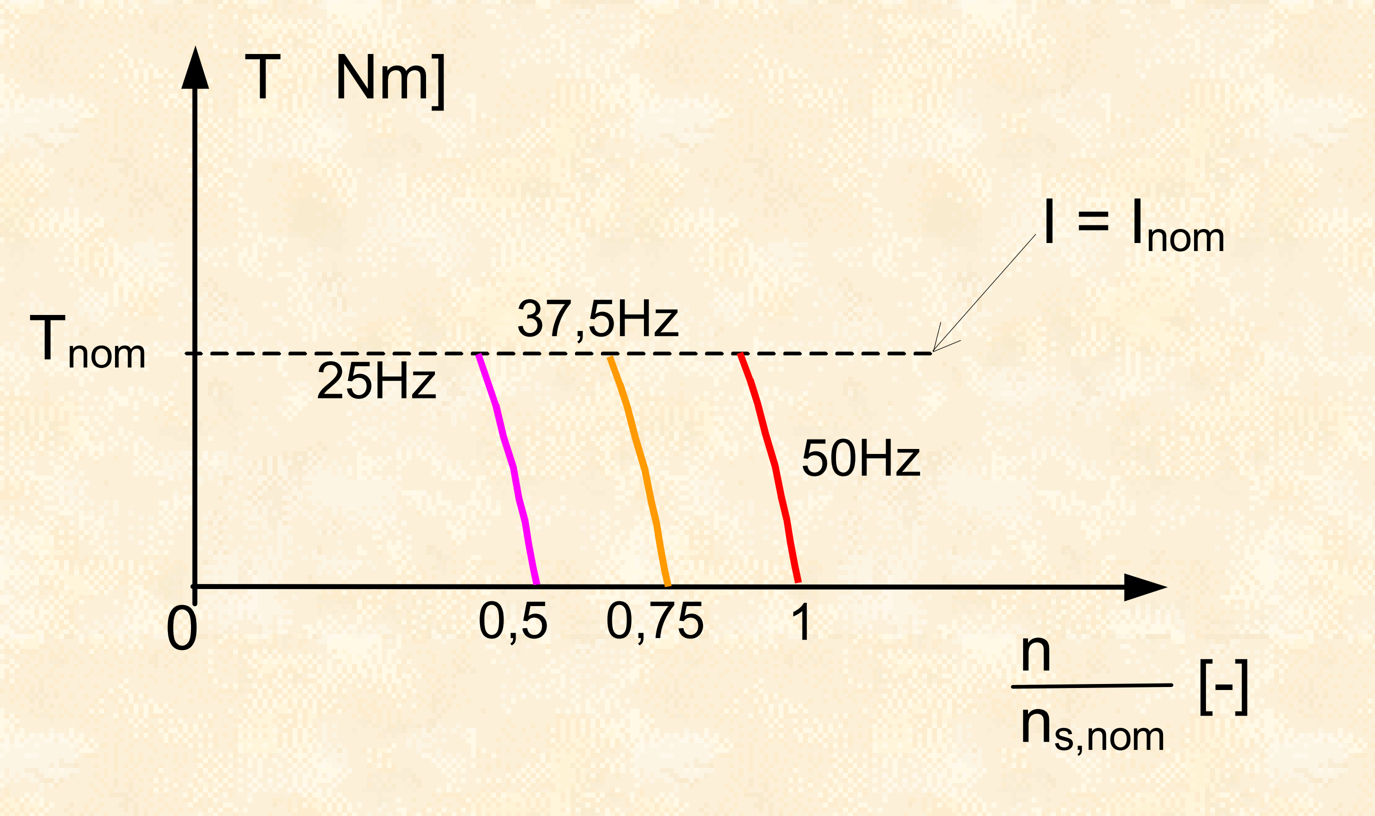
$$\frac{U_{f_1}}{U_{f_2}} = \frac{f_1}{f_2}$$



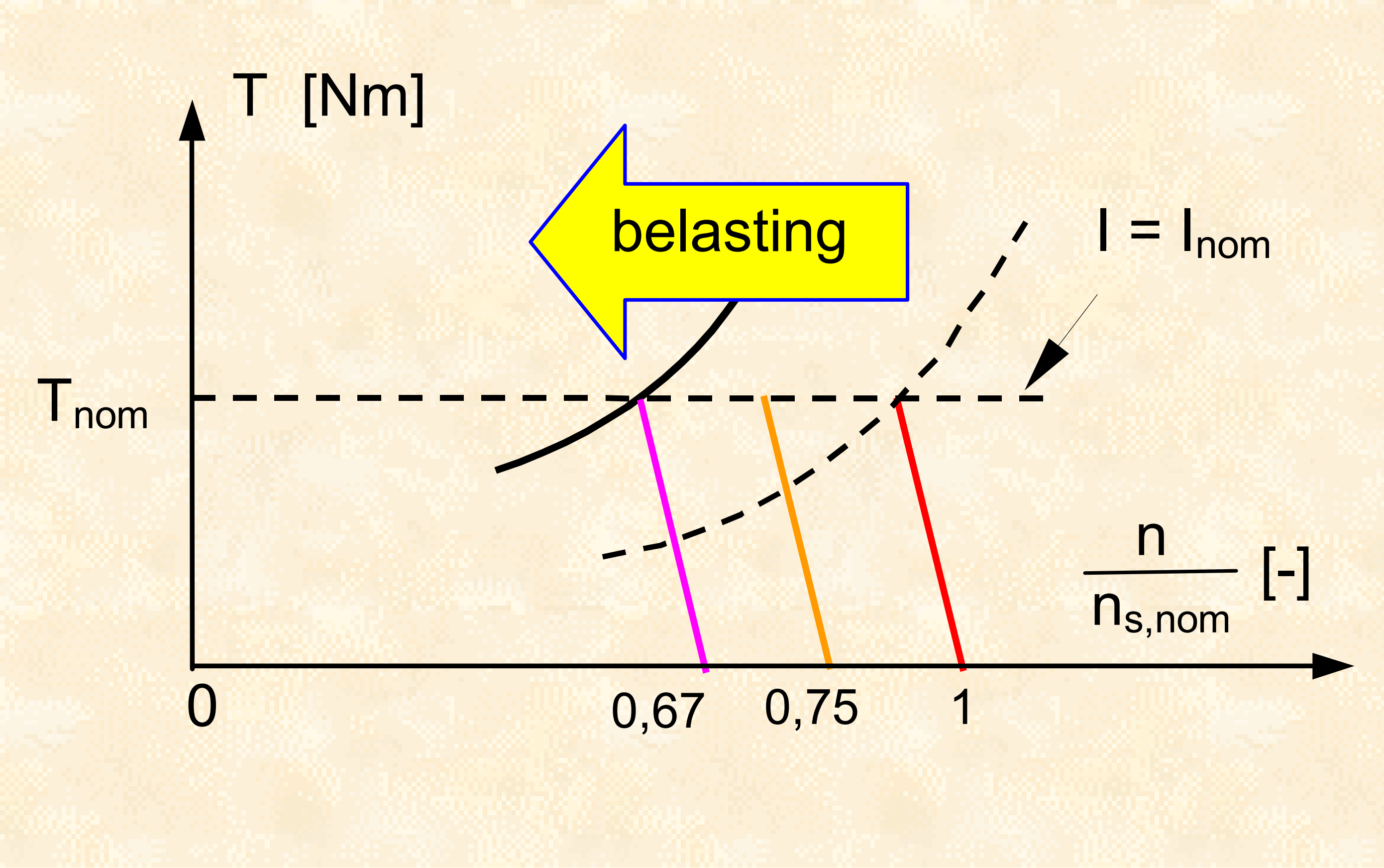
Koppel - Toerentalkarakteristiek



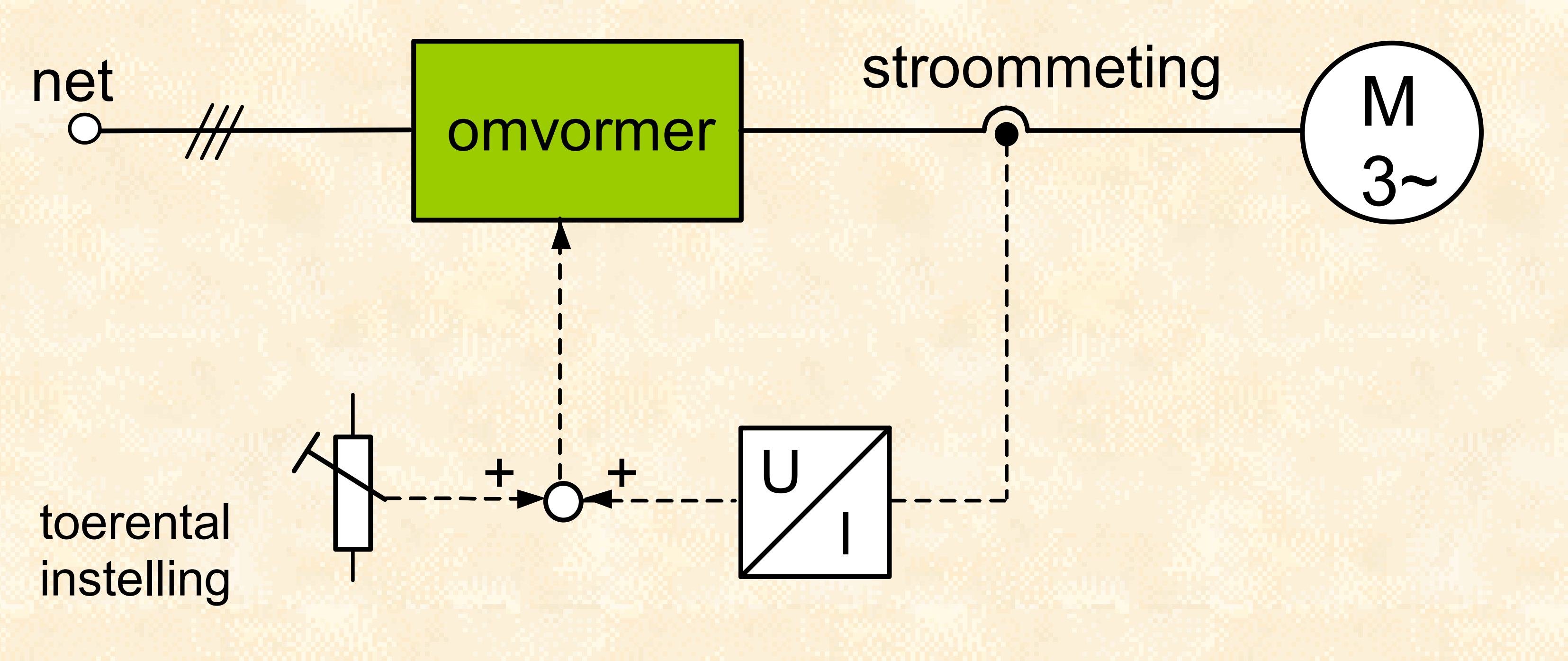
Stroombegrenzing I



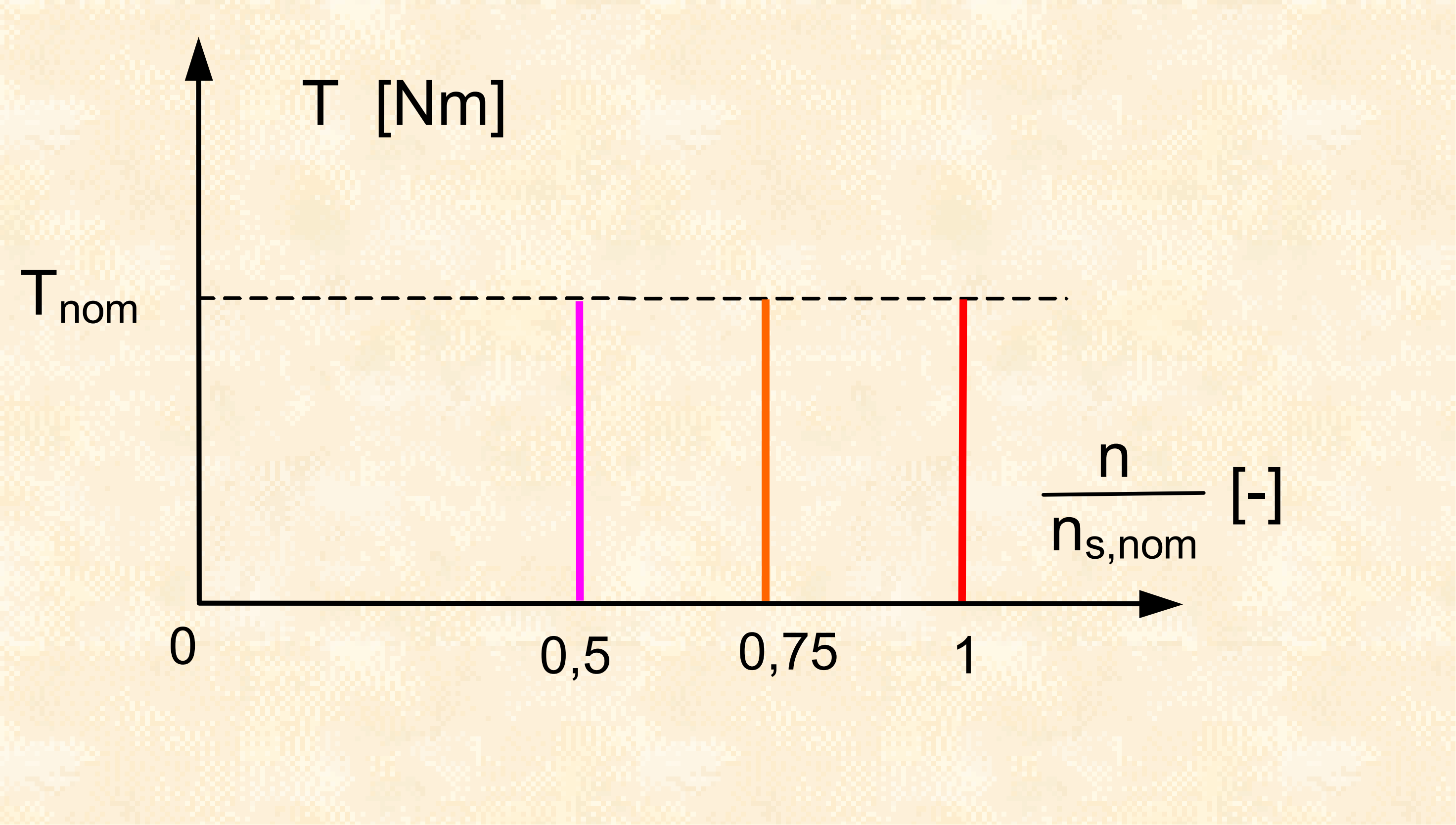
Stroombegrenzing II



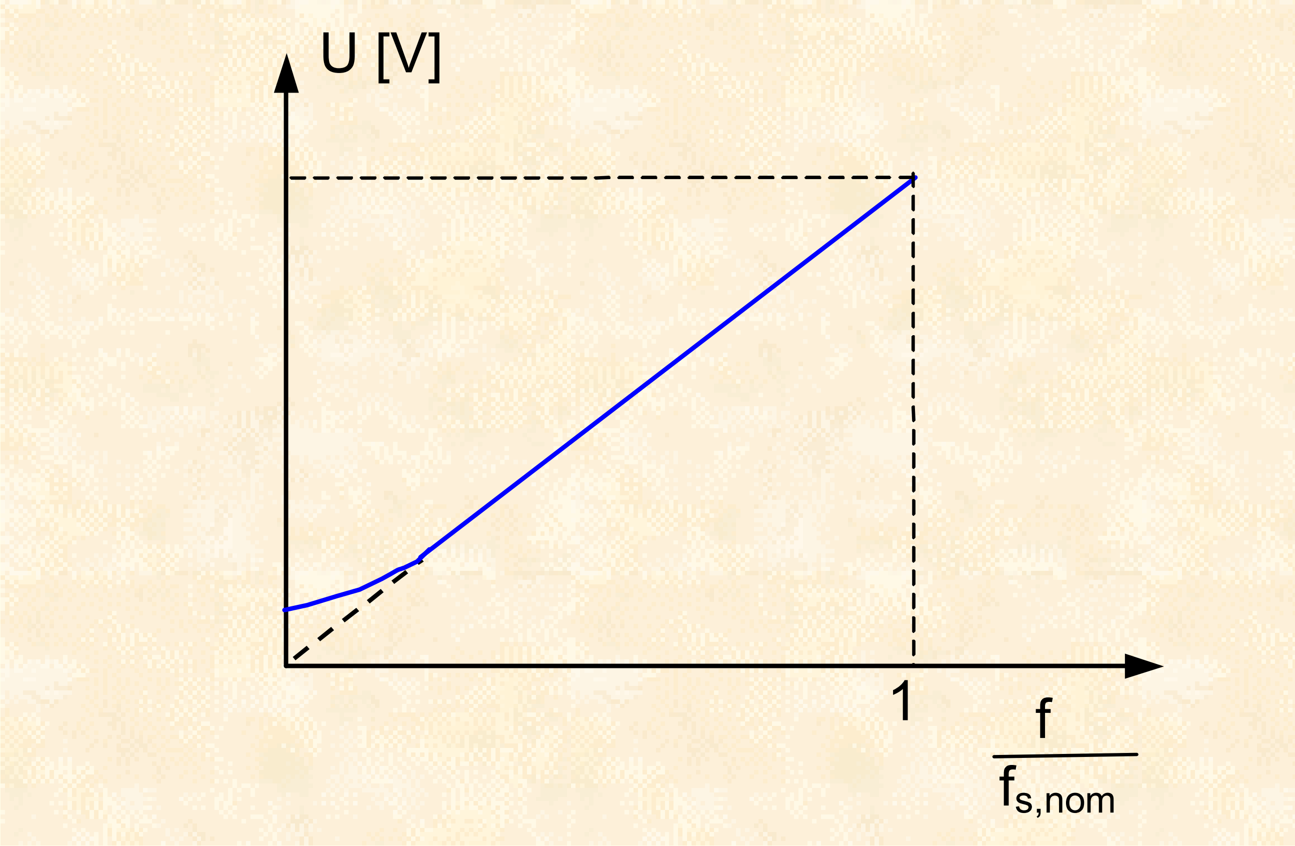
Slipcompensatie



Koppel-toerentalkarakteristiek met slipcompensatie



Statorweerstand



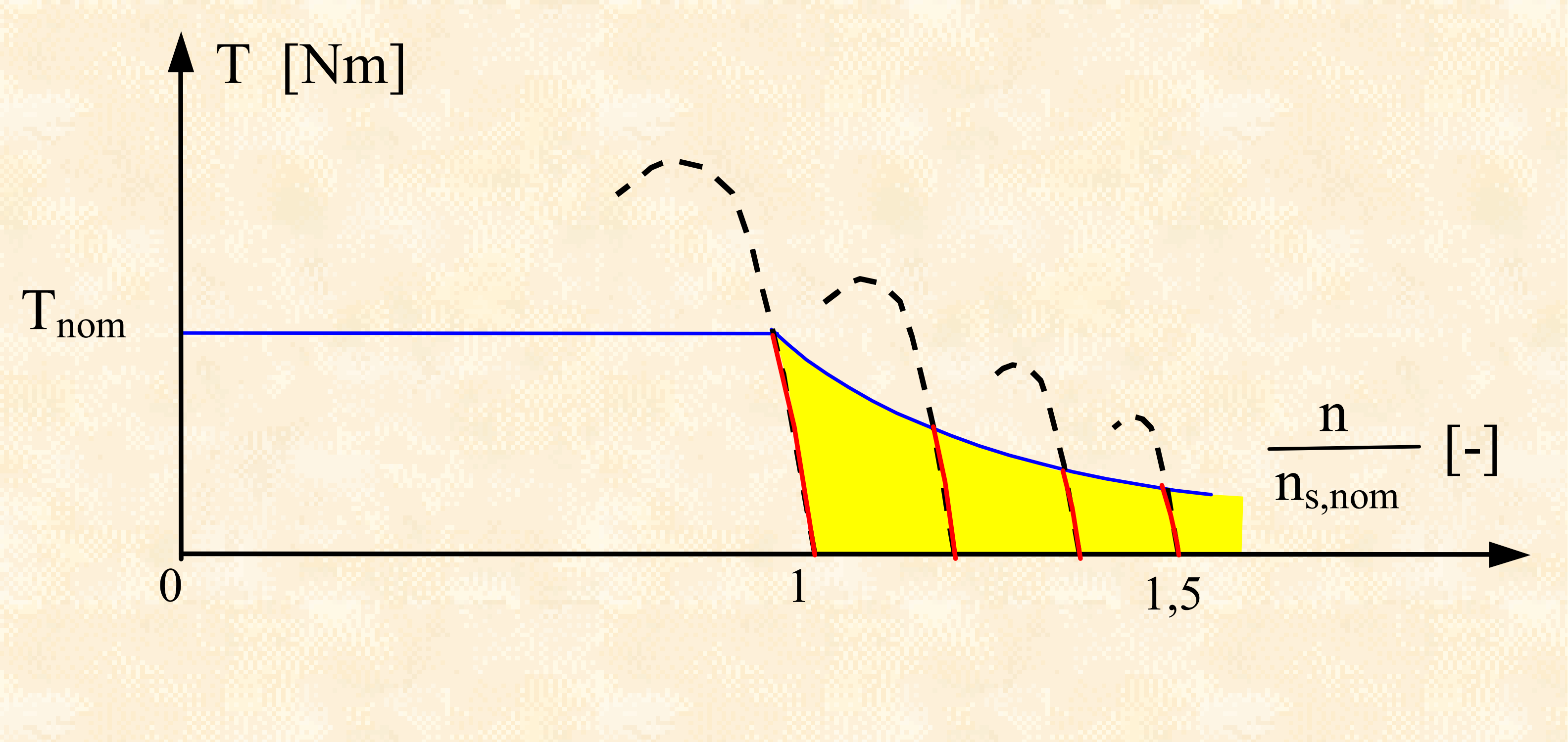
Veldverzwakking

$$P_1 = \sqrt{3}.U.I.\cos\varphi$$

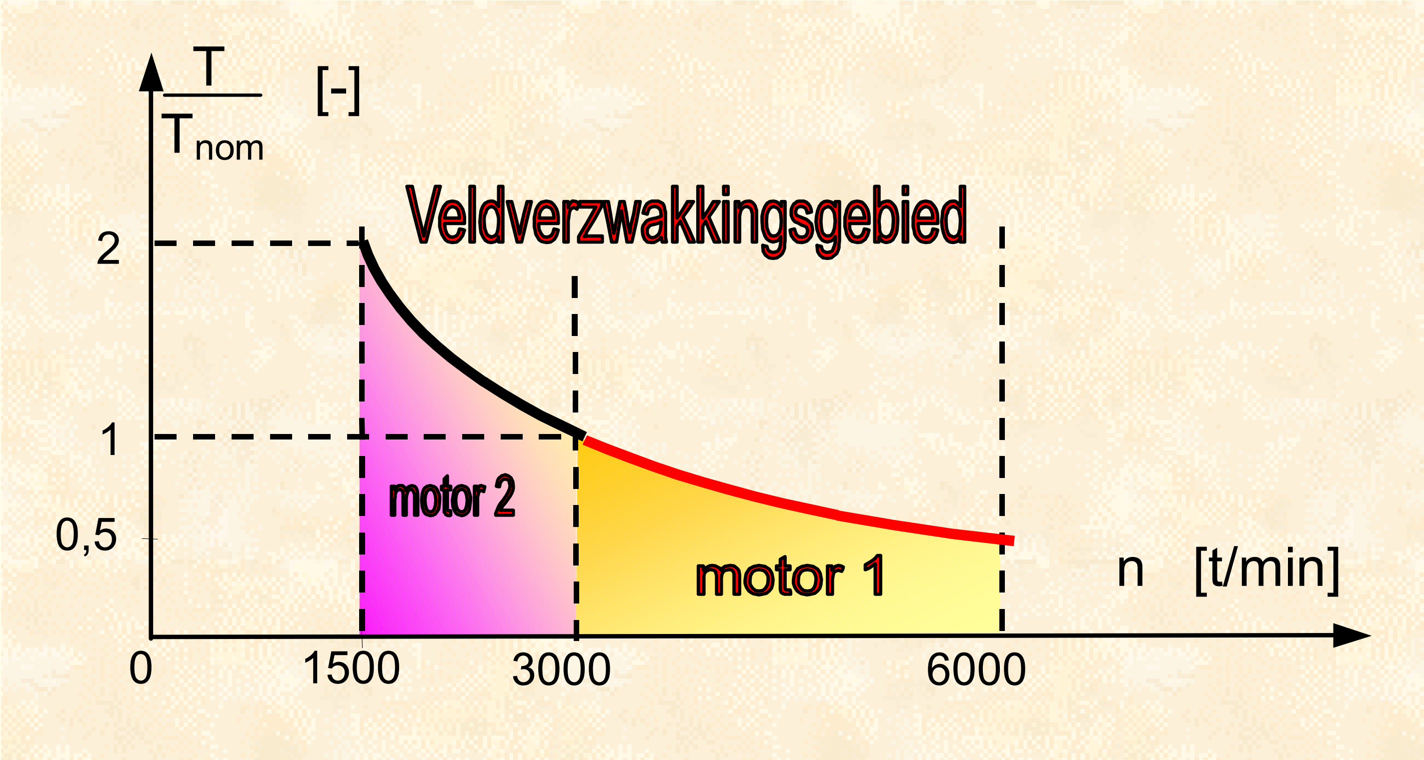
$$P_{as} = T.\omega$$

$$T = P_1.\frac{1}{\omega} = \frac{C}{n}$$

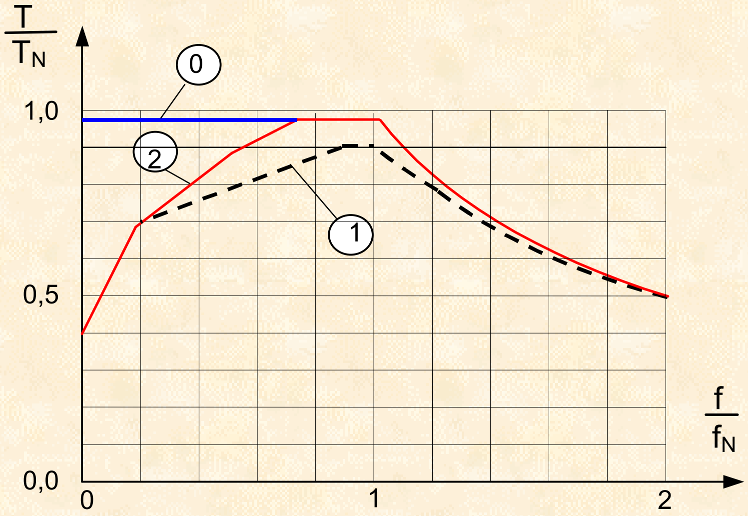
Veldverzwakking



Oversnelheid

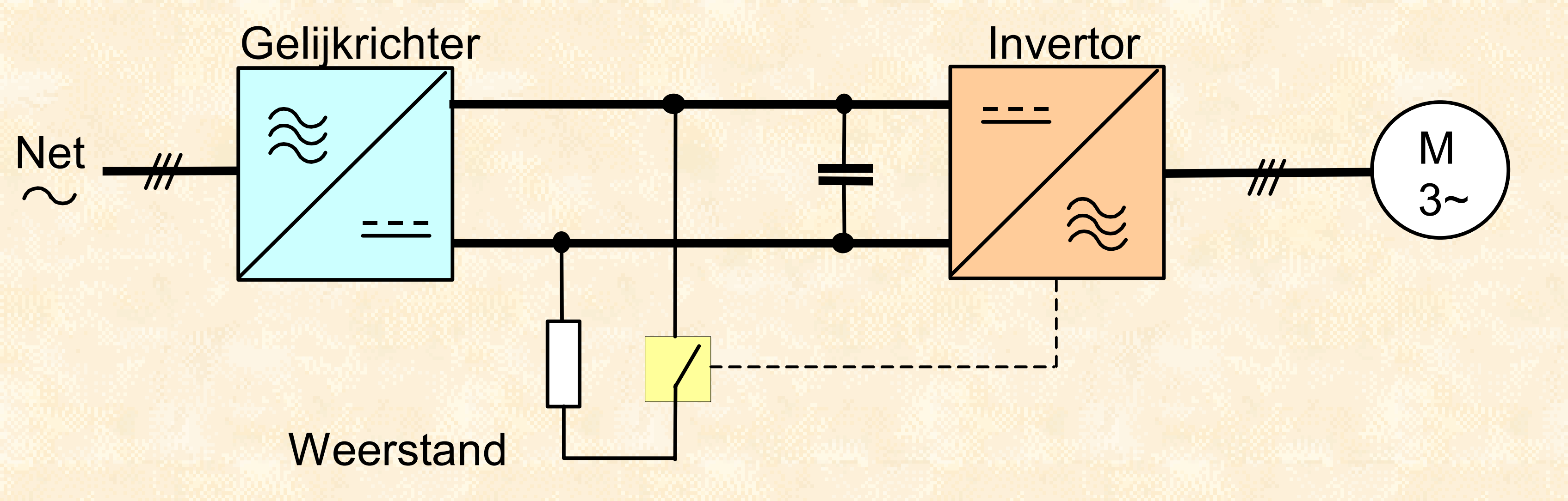


Motorbelasting, verliezen, koeling

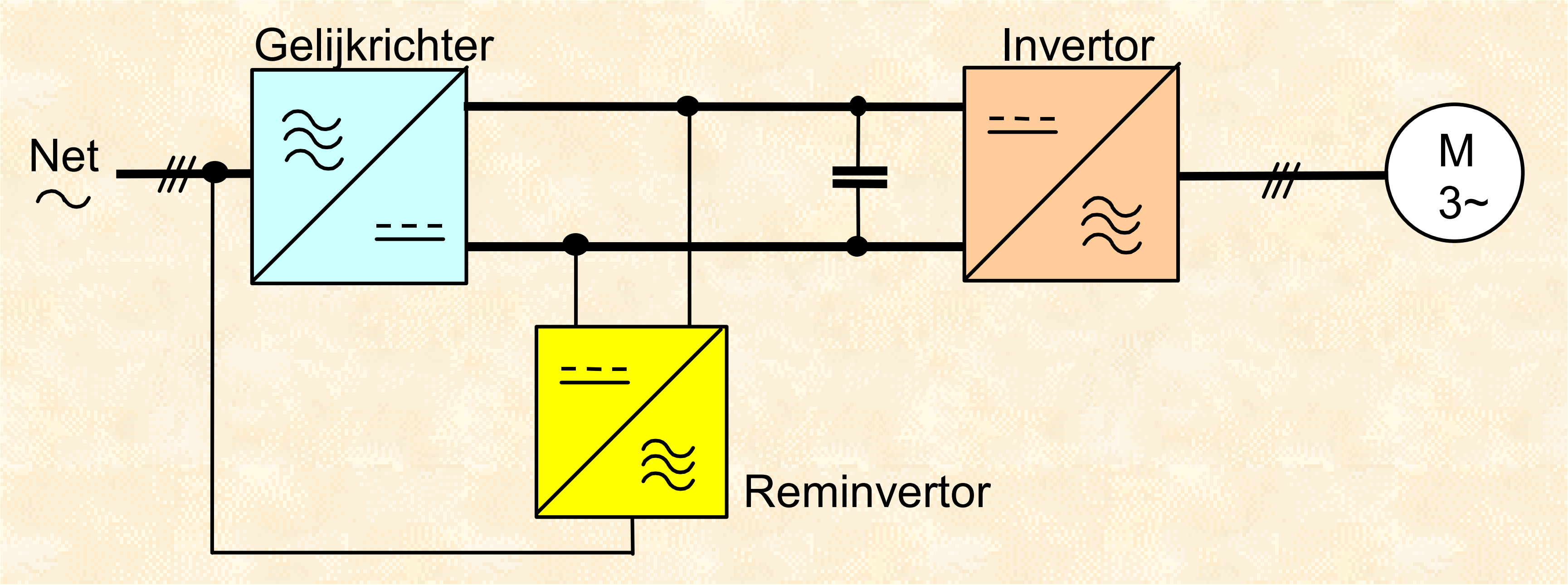


0 onafhankelijke ventilator
1 lage schakelfrequentie in de omvormer
2 hoge schakelfrequentie in de omvormer

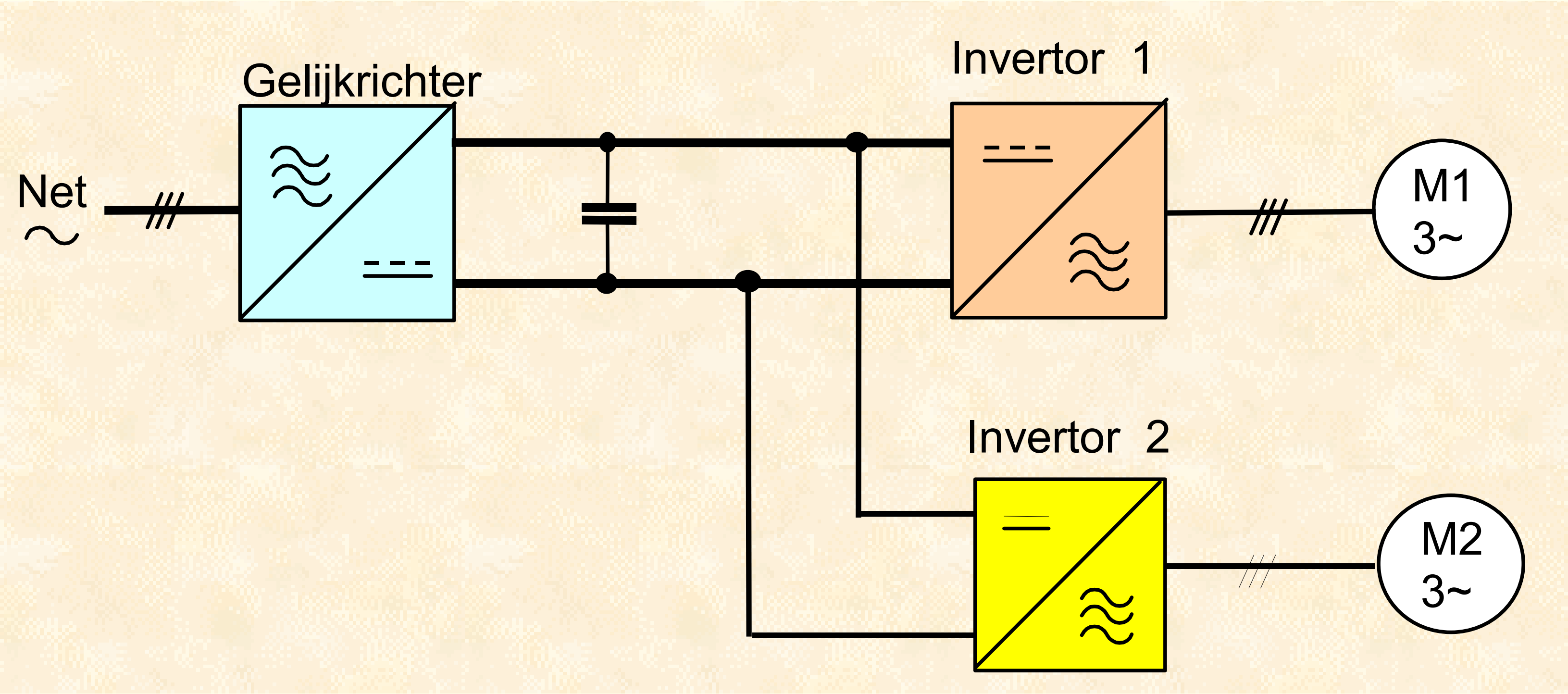
Weerstandsremming



Energierecuperatie



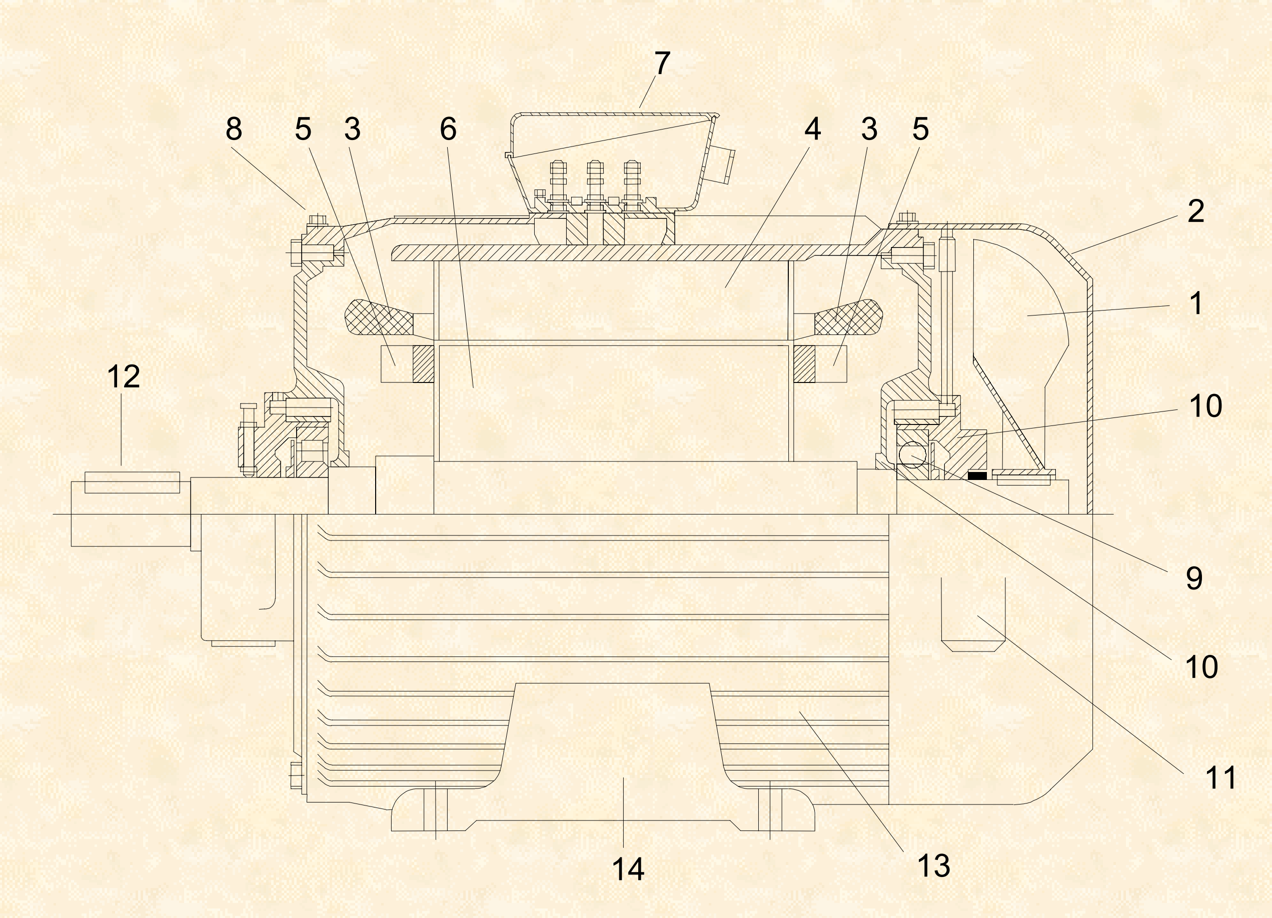
Common dc bus



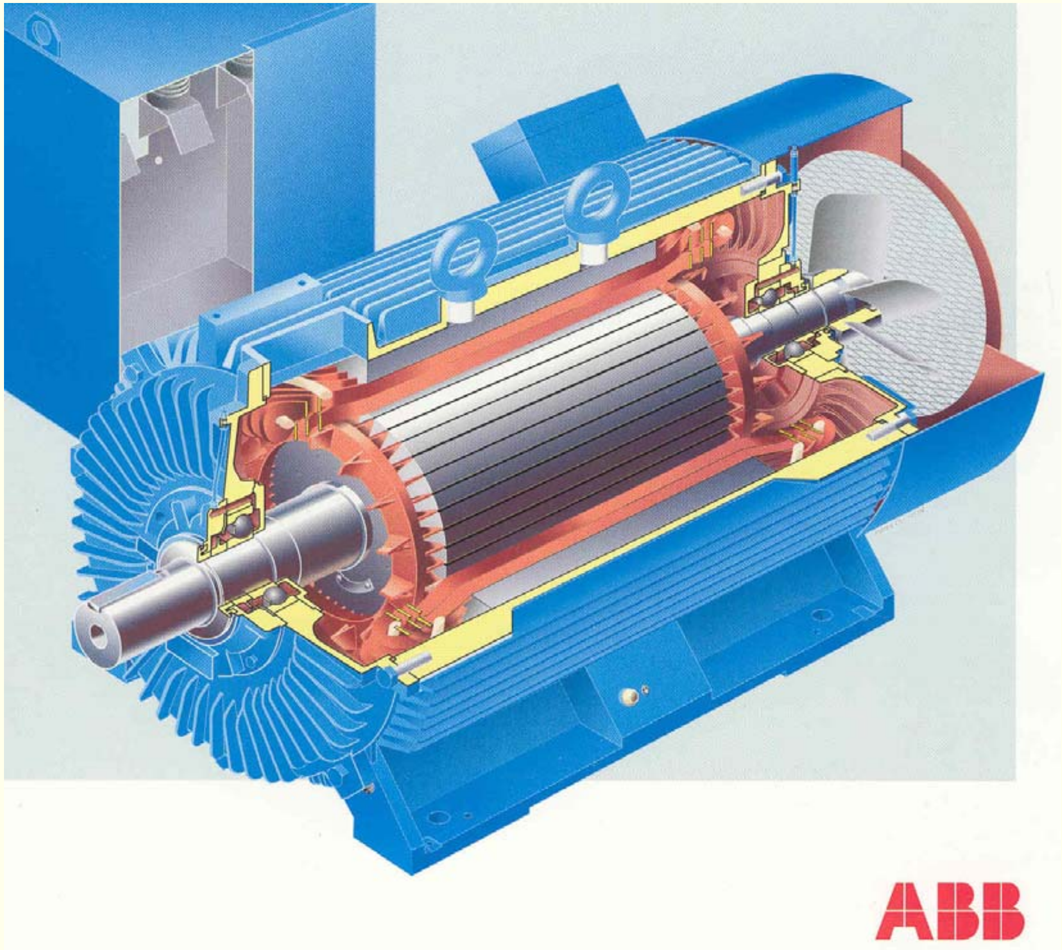
Constructie van inductiemotoren

- Inleiding
- Wikkelingen
- Stator- en rotorblikpakket
- Huis en lagers
- Constructienormen en mechanische uitvoeringen
- Mechanische bescherming
- Isolatieklassen
- Koeling

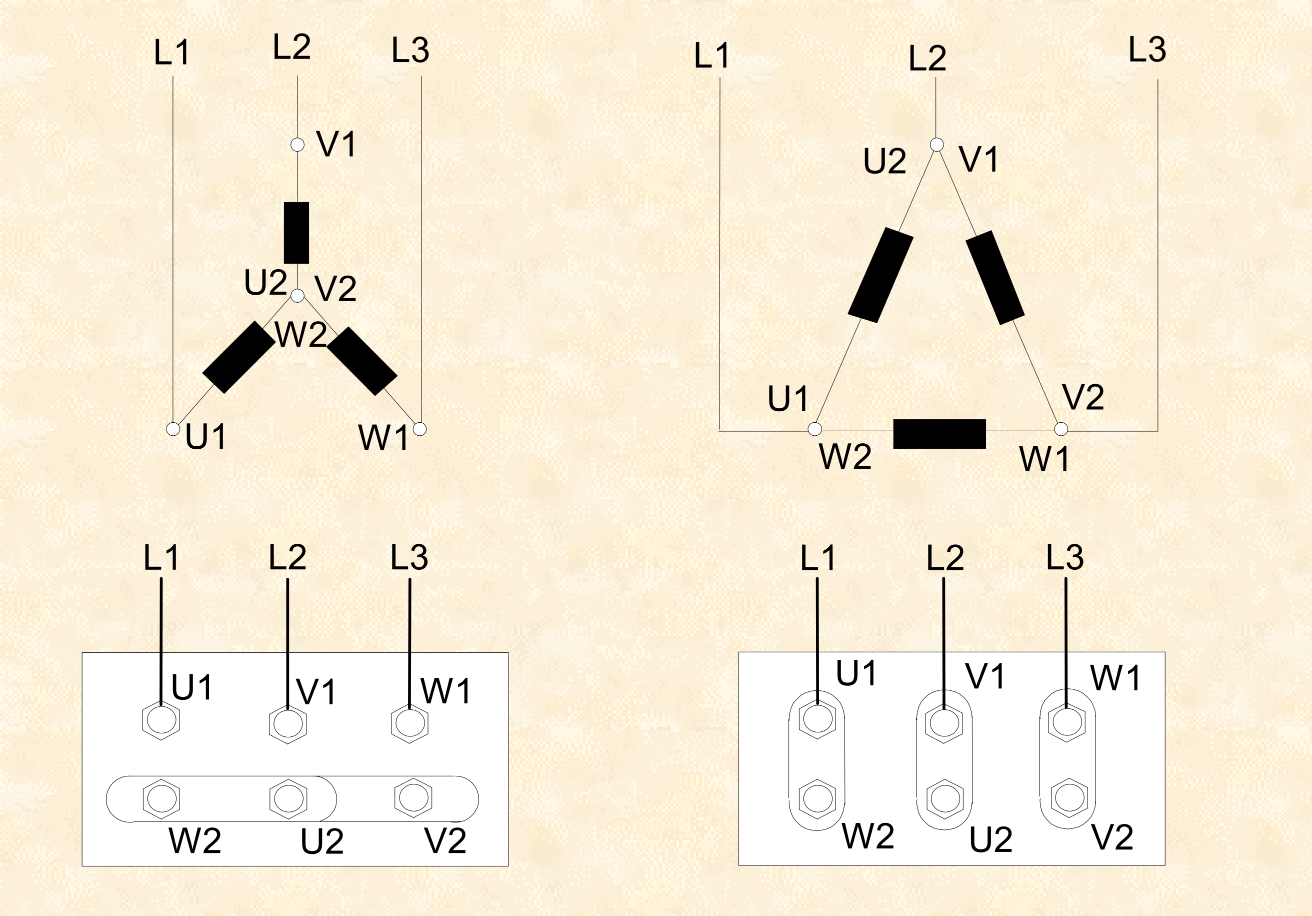
Driefasige inductiemotor met kooirotor I



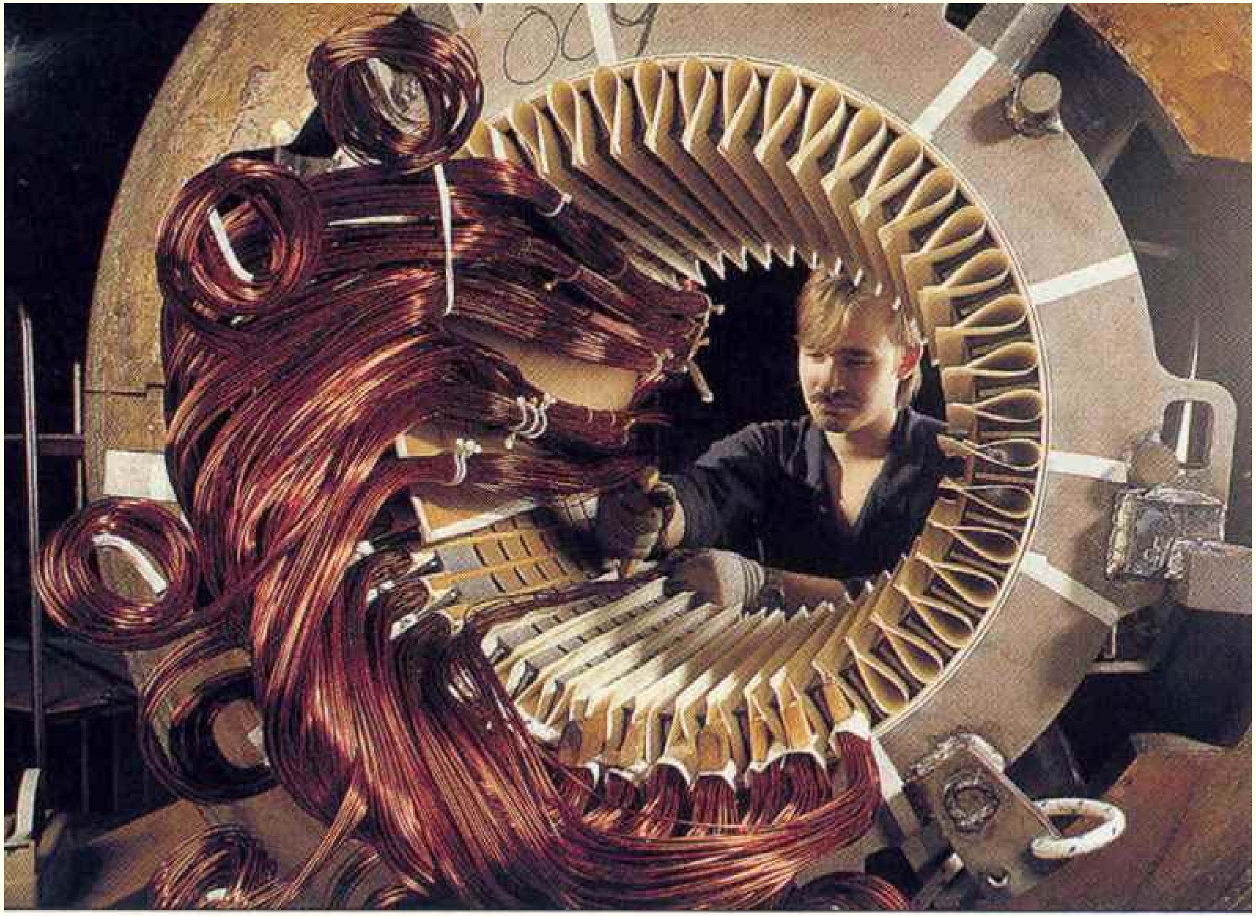
Driefasige inductiemotor met kooirotor II



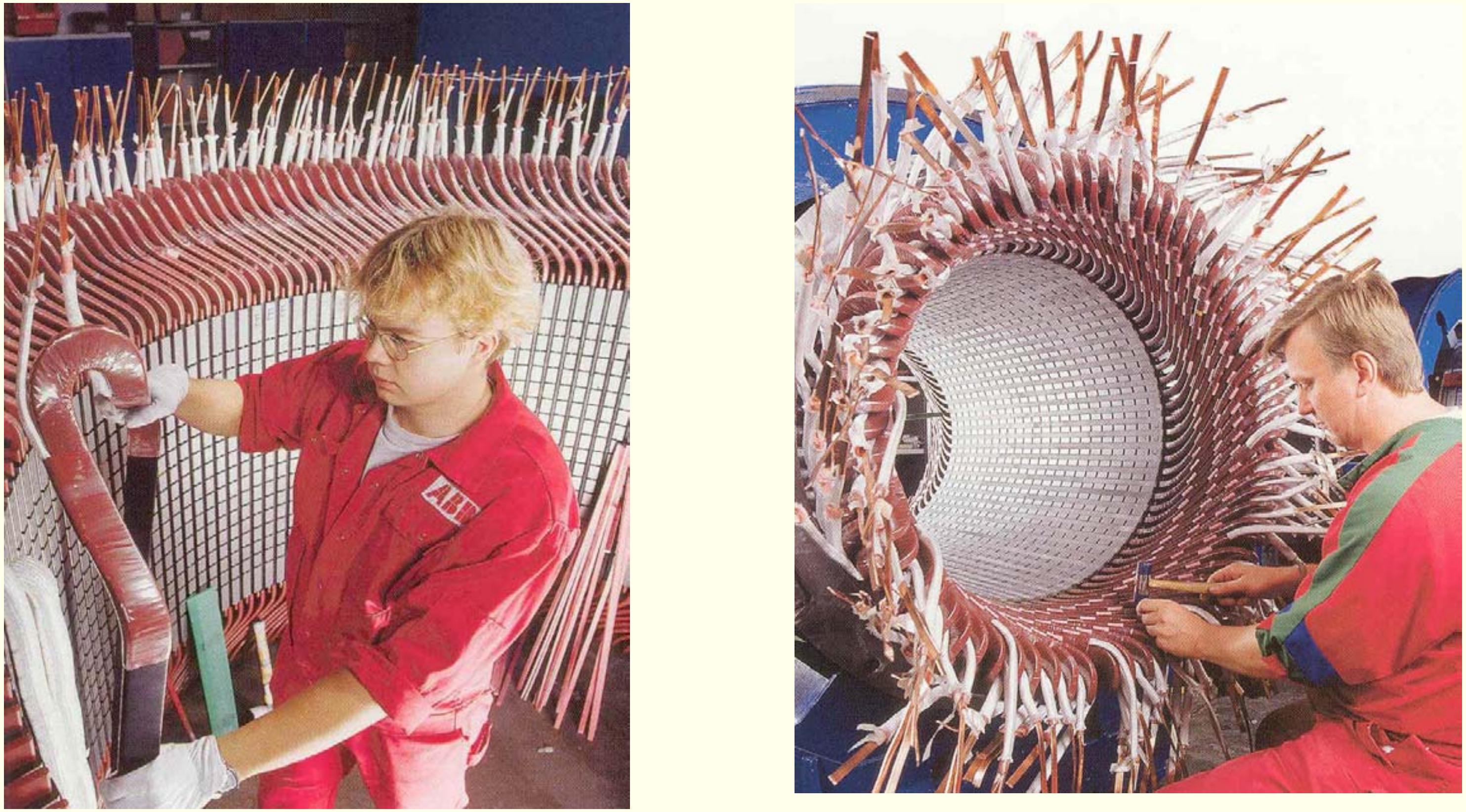
Ster-en driehoekschakeling



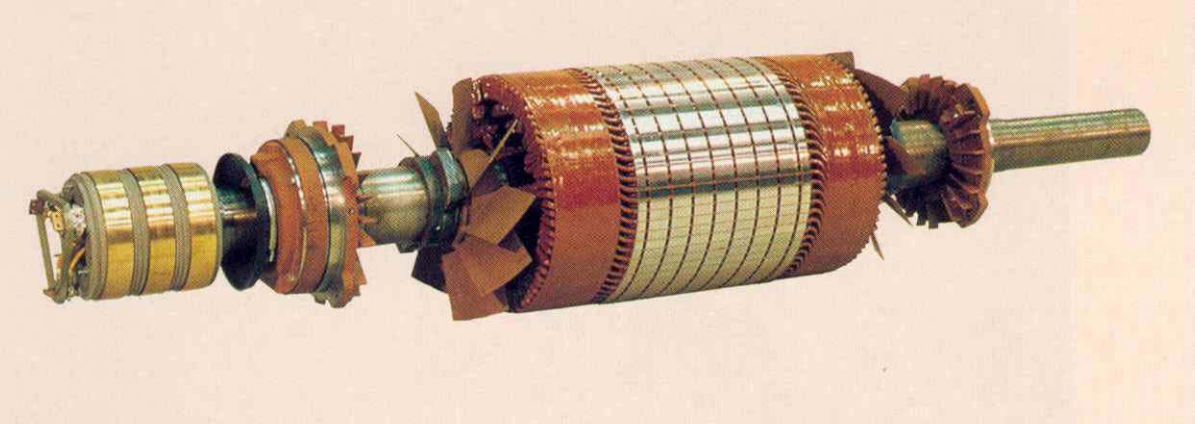
Spoelen in ronde wikkeldraad

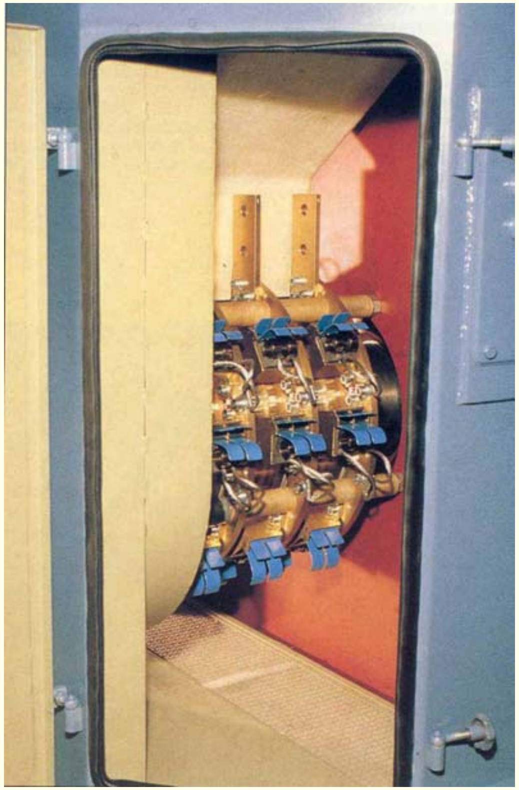


Voorgevormde spoelen voor een hoogspanningswikkeling

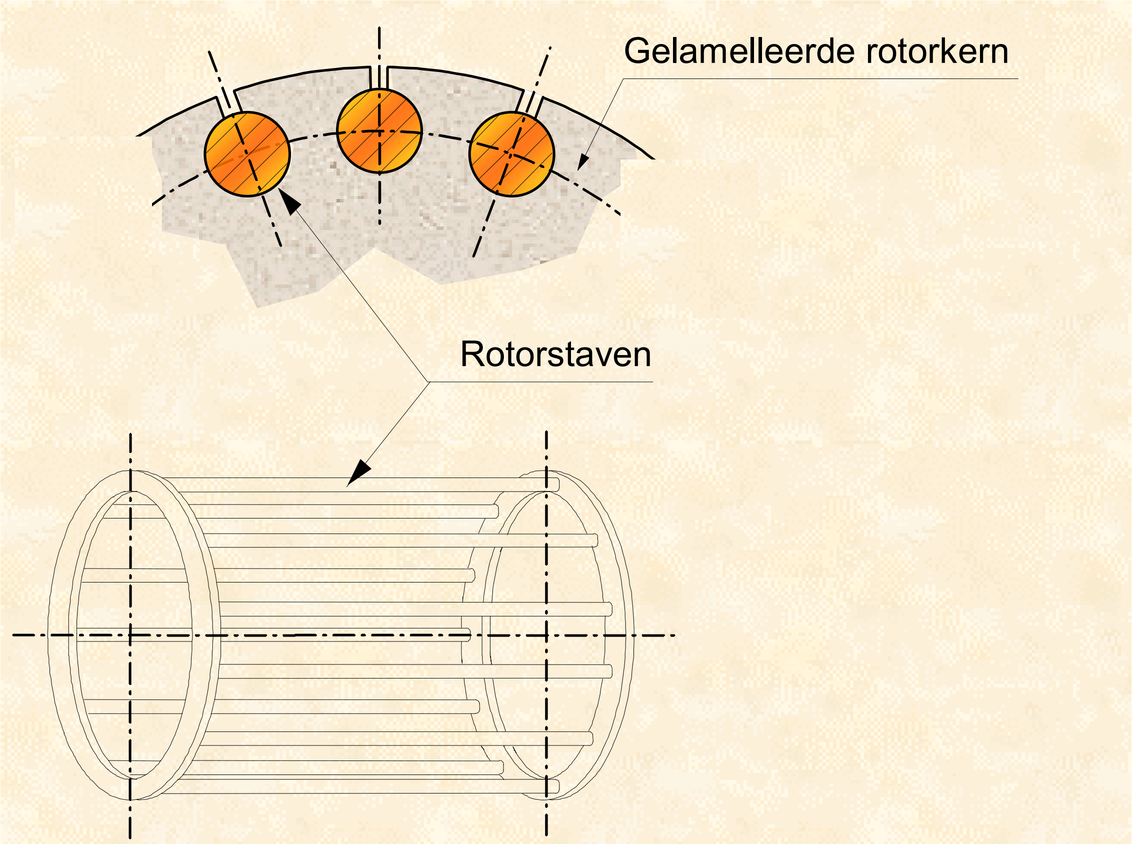


Sleepringrotor en borsteldrager

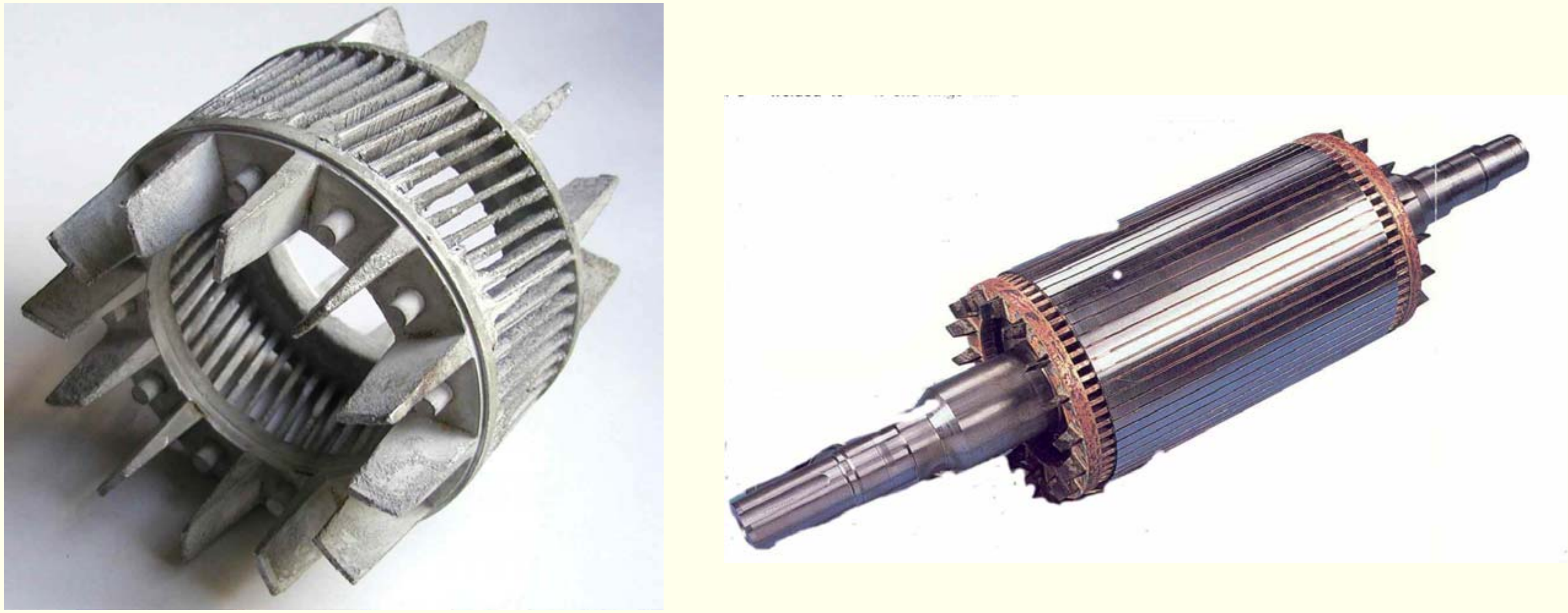




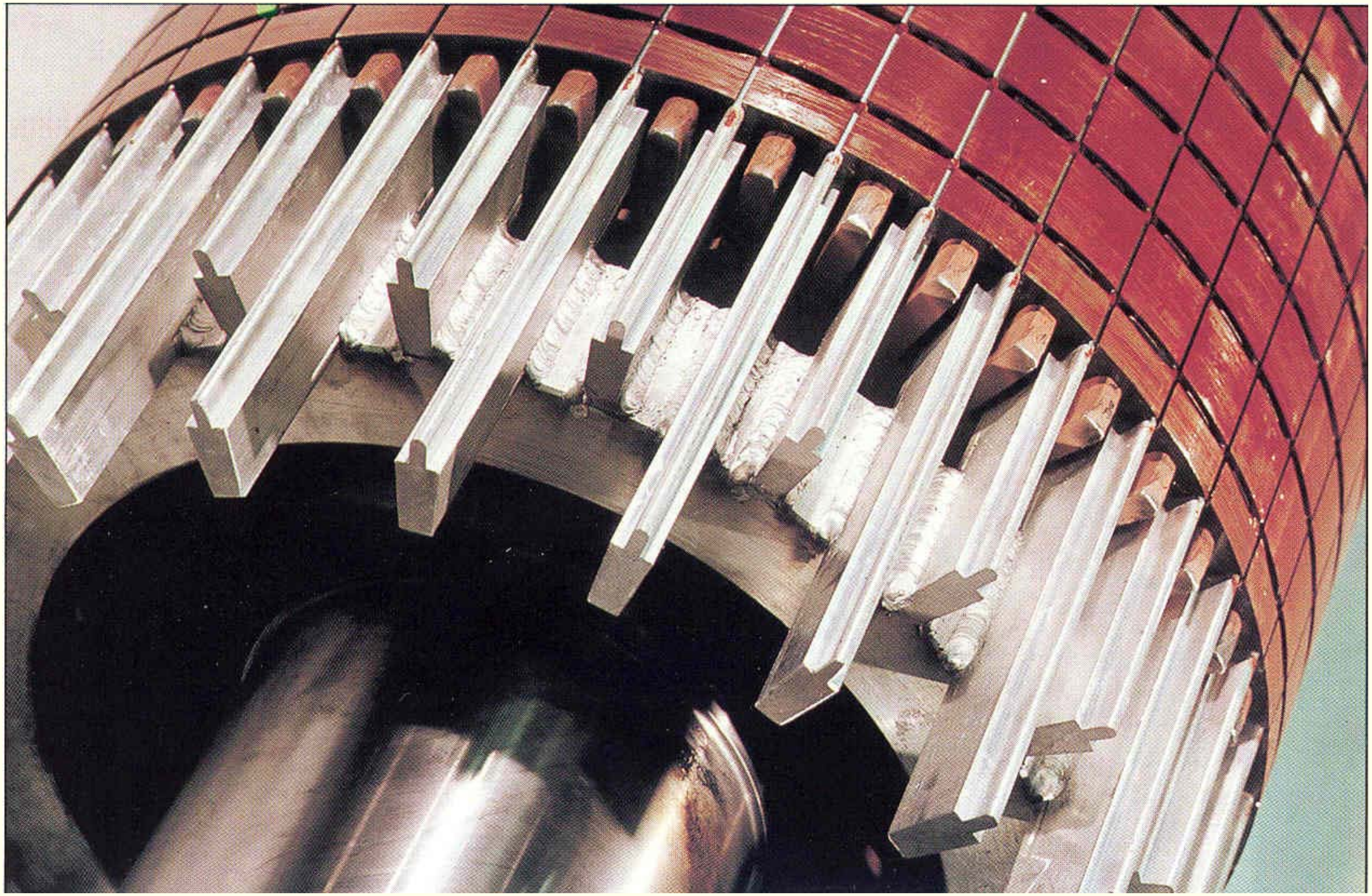
Enkelkooirotor



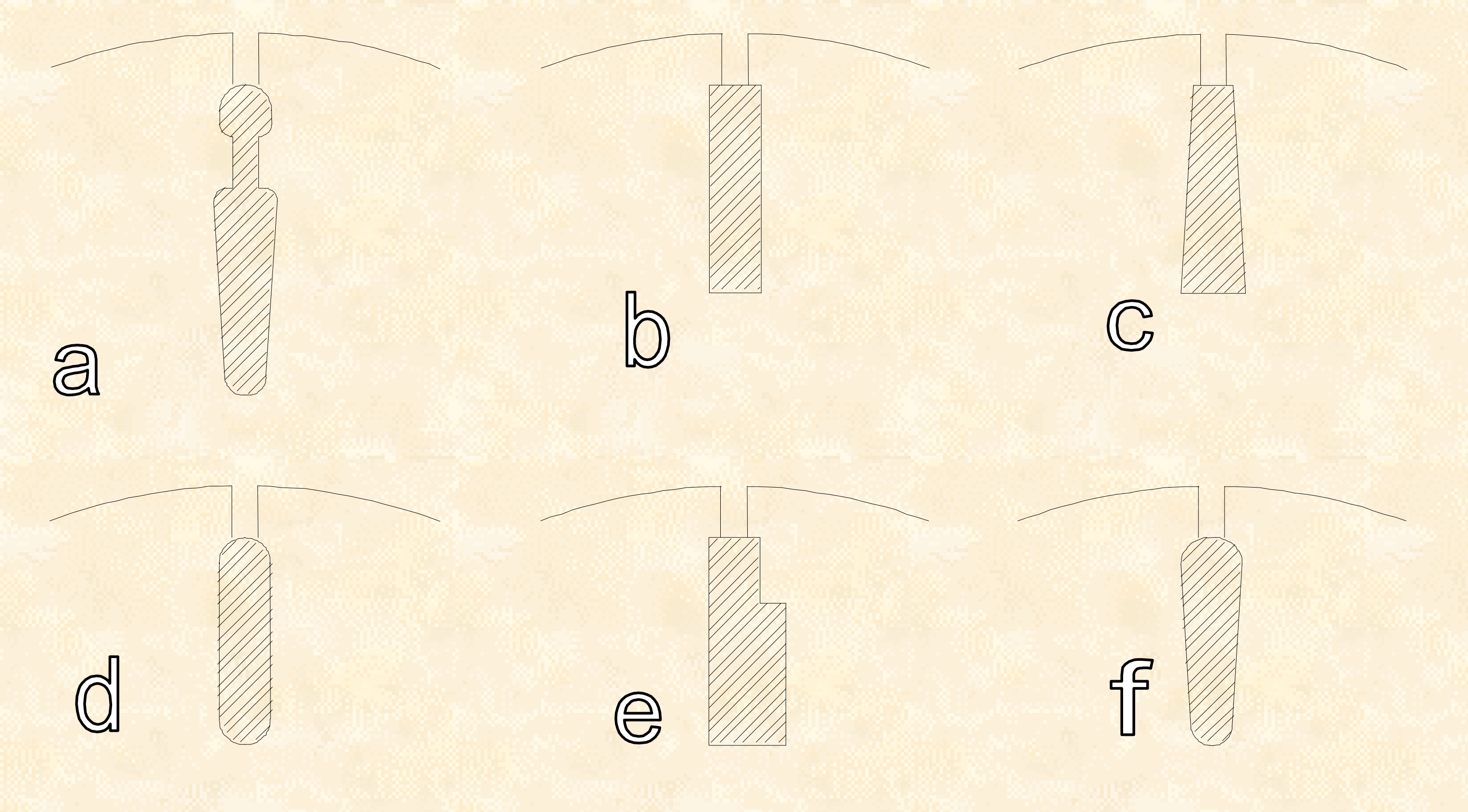
Enkelkooirotor zonder blik en rotor met gespoten Al kooi



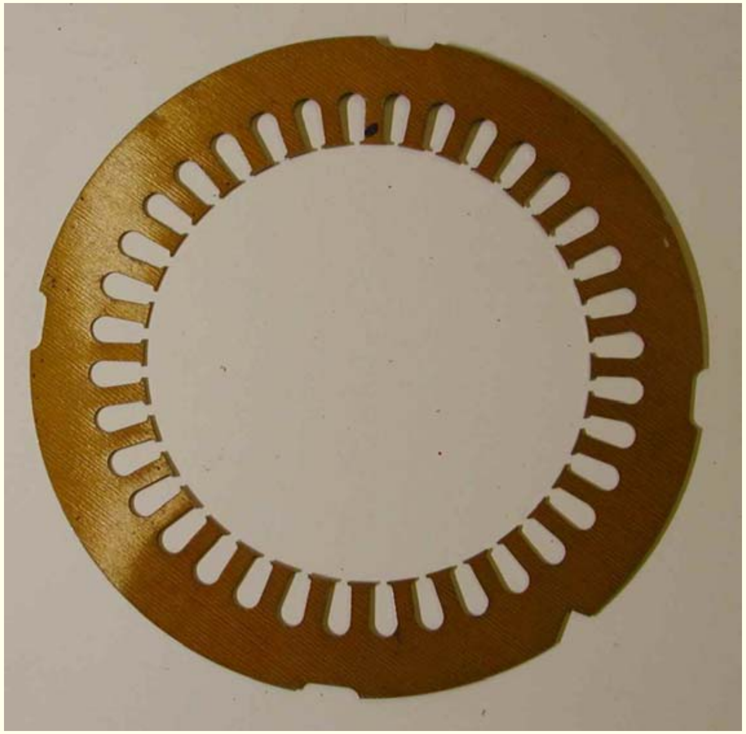
Rotoruiteinde met blikpakket

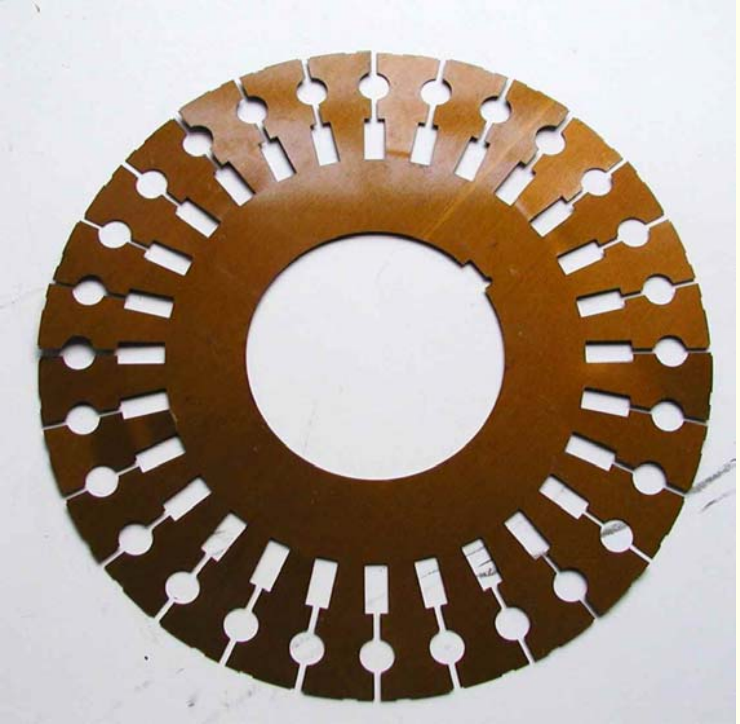


Kooirotorvormer

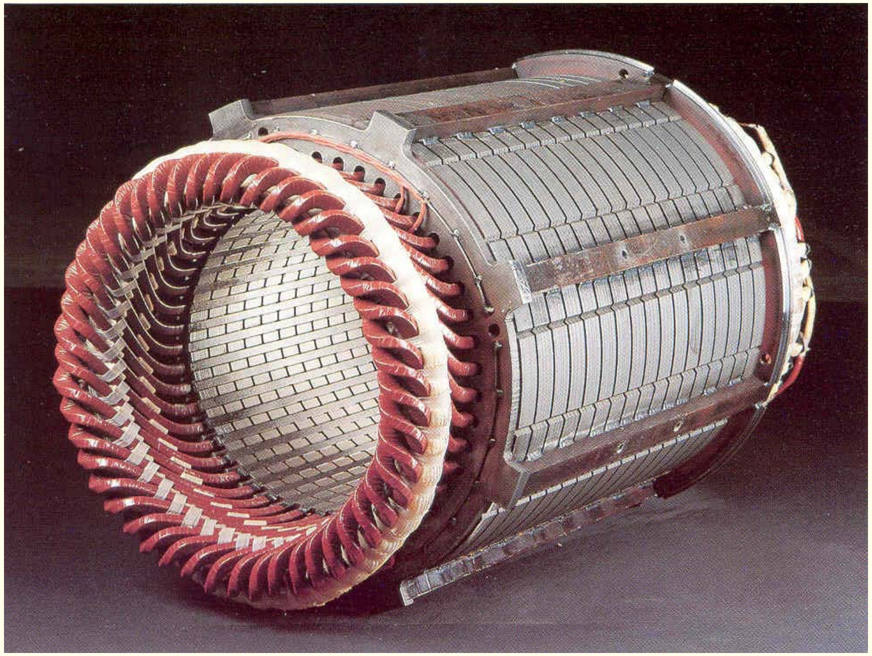


Stator- en rotorblik

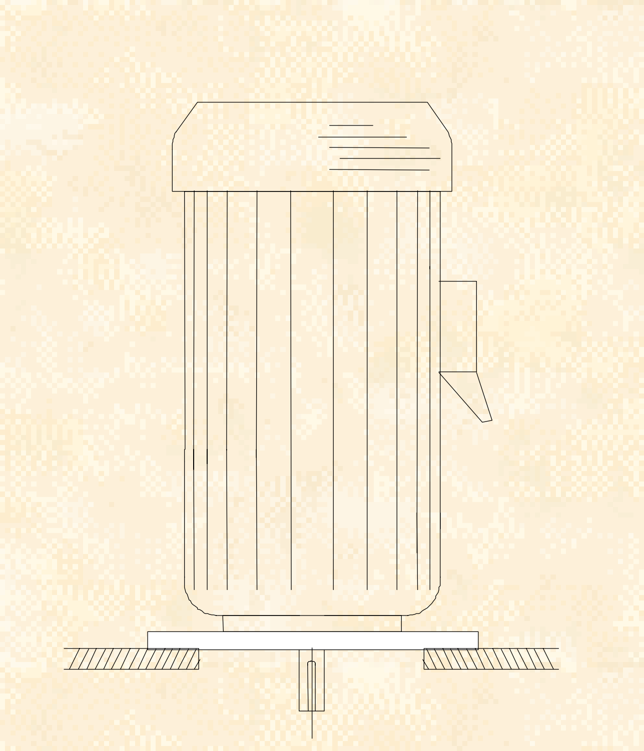


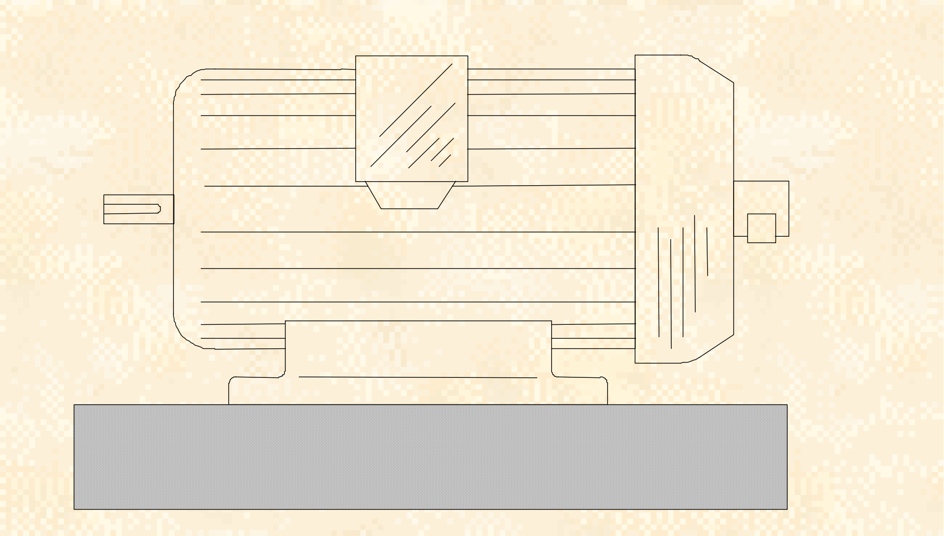


Statorbehuizing van een normmotor en statorblikpakket

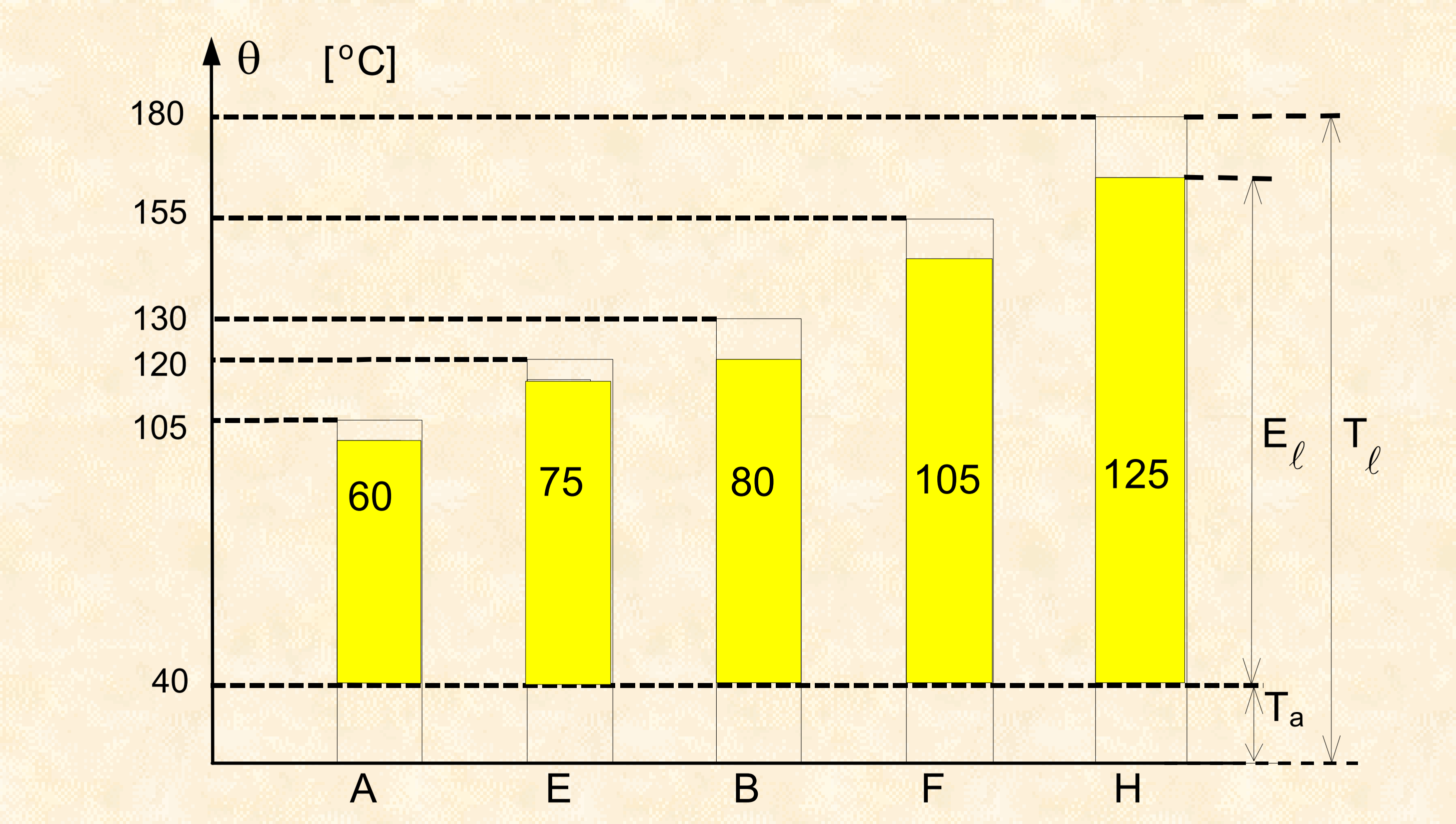


Verticale en horizontale uitvoeringsvorm

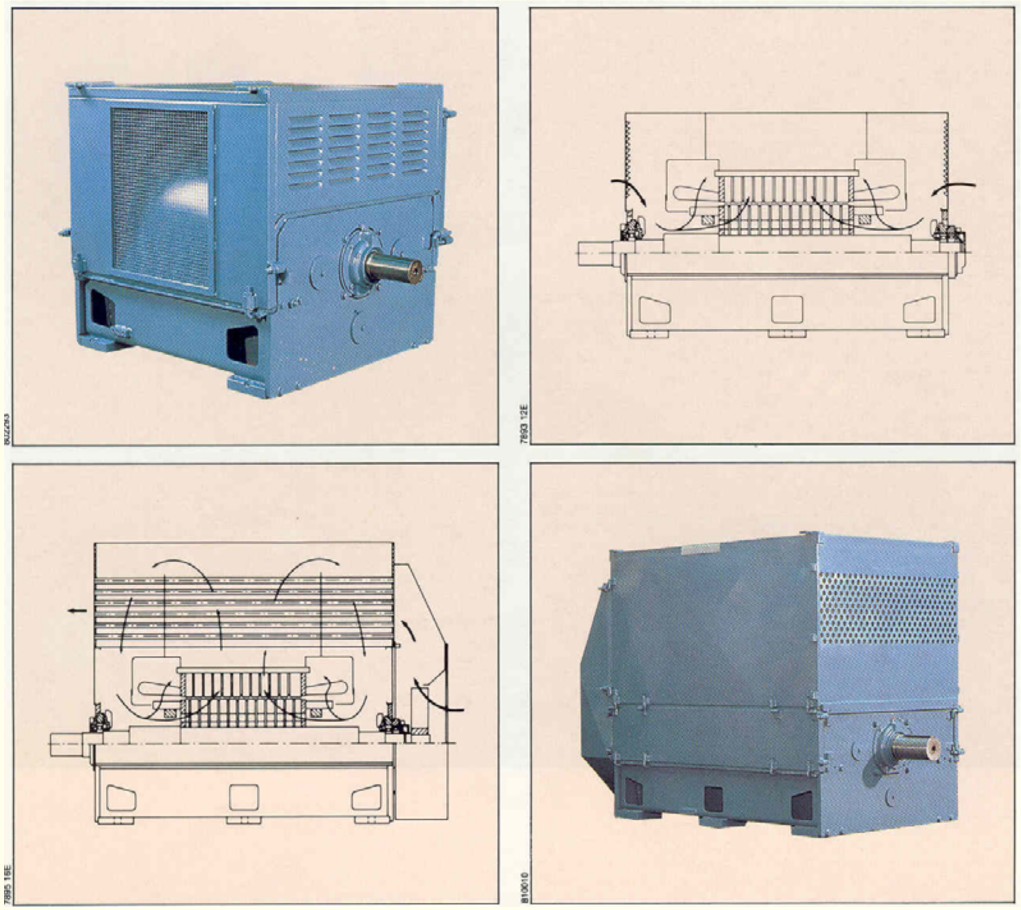




Grenstemperaturen voor isolatieklassen A, E, B, F en H



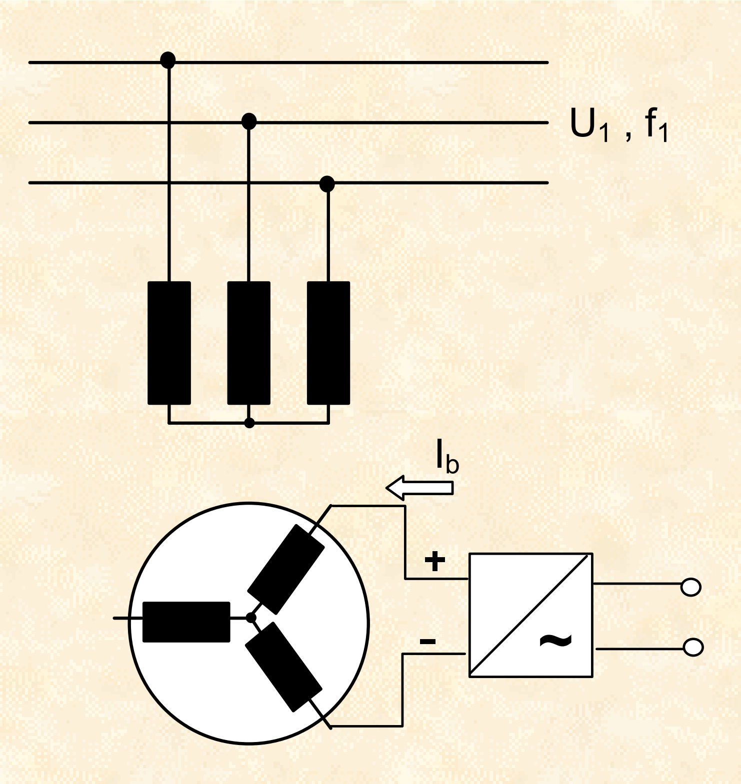
Inwendig gekoelde motor en motor met warmtewisselaar



Synchrone machines

- Equivalent schema
- Nullast en kortsluiting
- Koppeling met een star
- Machine met uitspringende polen

Sleepringmotor met gelijkstroomvoeding

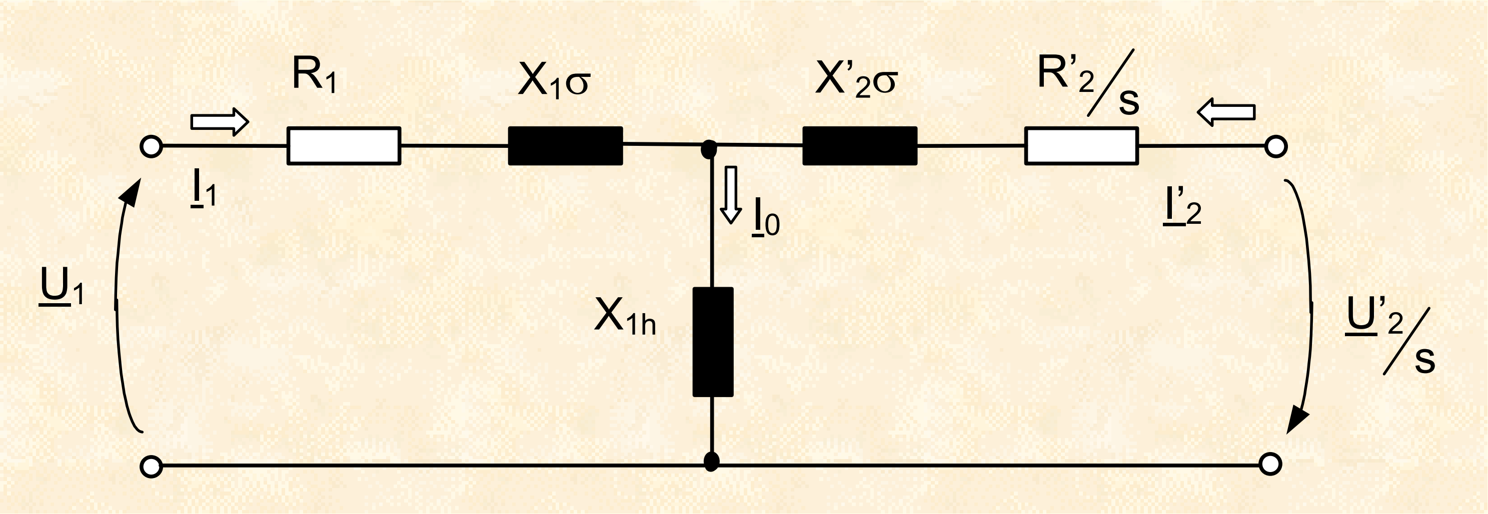


$$f_2 = sf_1 \qquad s = 0 \quad \text{of} \quad n = n_0 = \frac{f_1}{p}$$

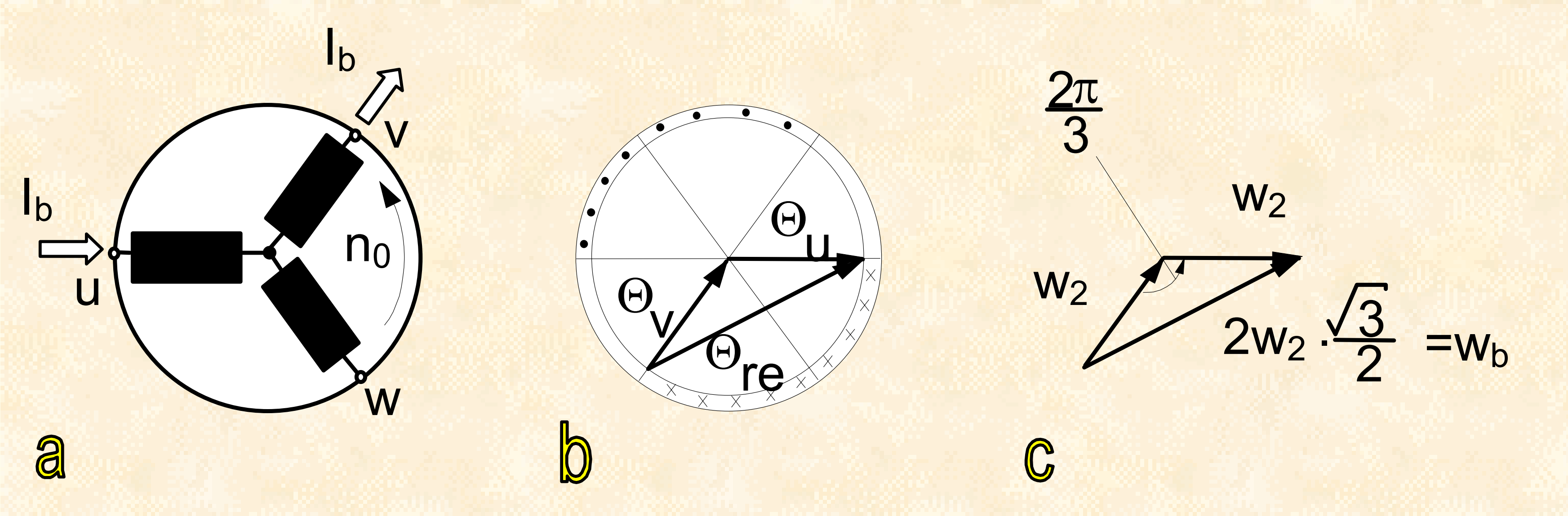
Equivalent schema

$$\underline{U}_1 + R_1\underline{I}_1 + j(X_{1\sigma} + X_{1h})\underline{I}_1 + jX_{1h}\underline{I}_2^{'} = 0$$

$$\underline{U}_2^{'} = R_2^{'}\underline{I}_2^{'}$$



Overgang van een driefasige rotorwikkeling naar een wikkeling

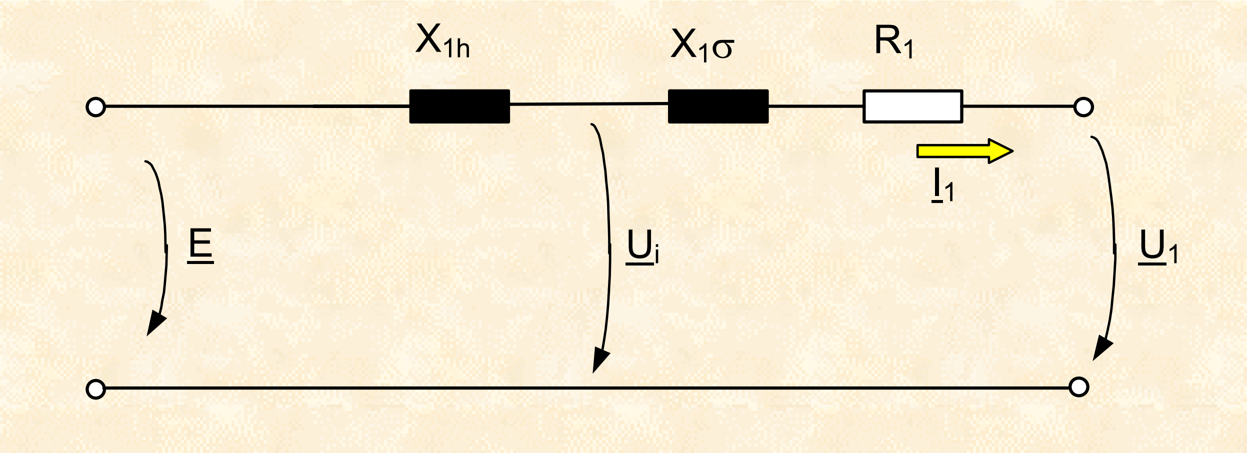


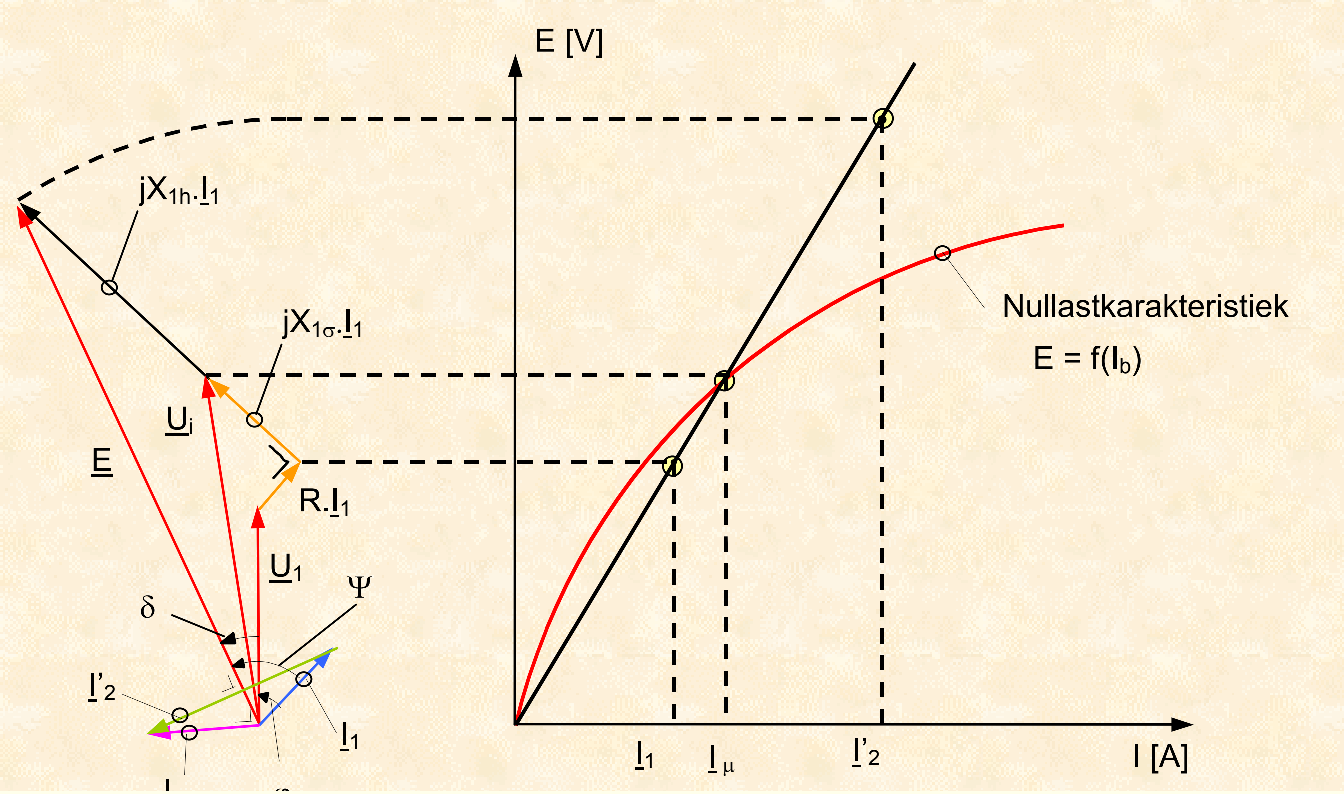
Equivalent schema

$$\underline{E} = -jX_{1h}\underline{I}_2^{'}$$

$$\underline{U}_1 + R_1\underline{I}_1 + j(X_{1\sigma} + X_{1h})\underline{I}_1 = \underline{E}$$

$$U_b = R_b I_b$$

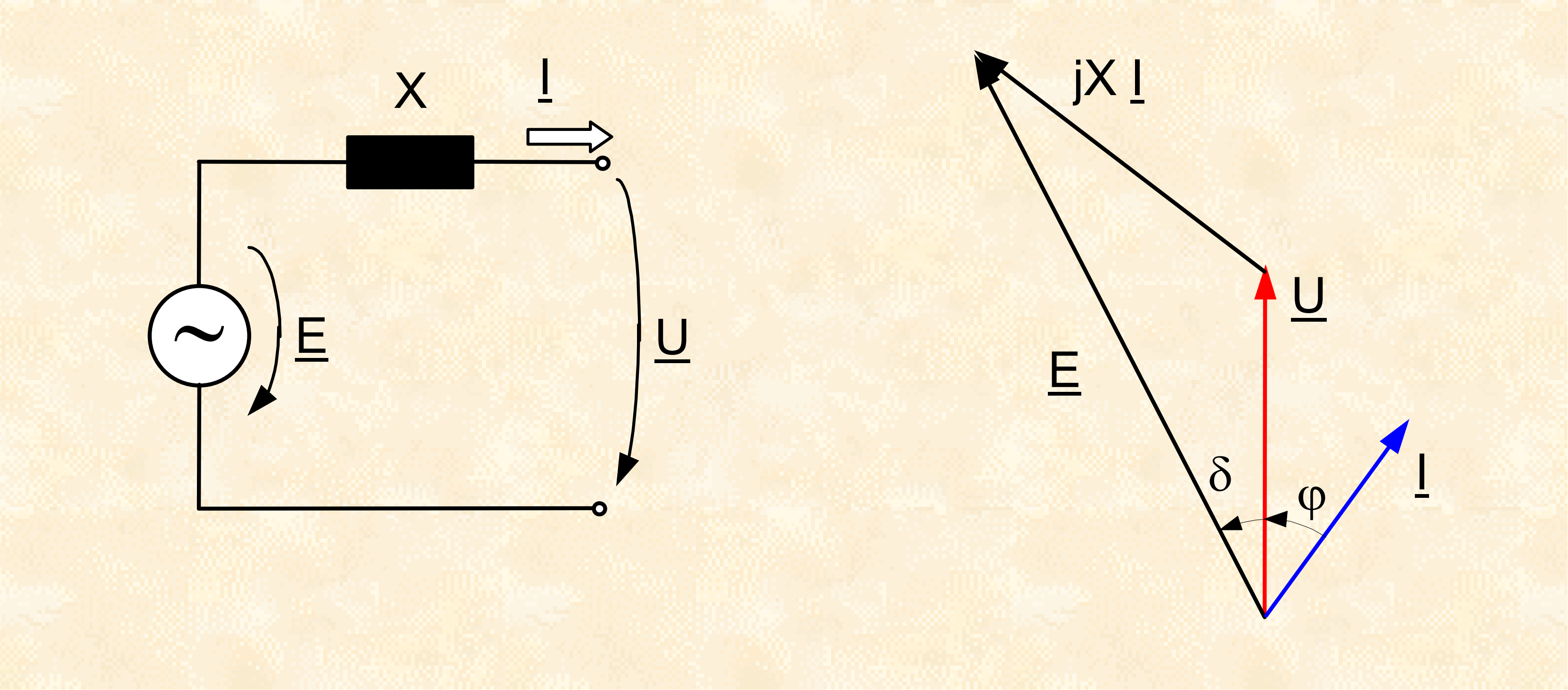




Fasordiagram van een inductief-resistief belaste synchrone generator

$$\underline{U}_i = -jX_{1h}\underline{I}_\mu \qquad \underline{E} = -jX_{1h}\underline{I}_2^{'}$$

Geen statorweerstand



Nullast en kortsluiting

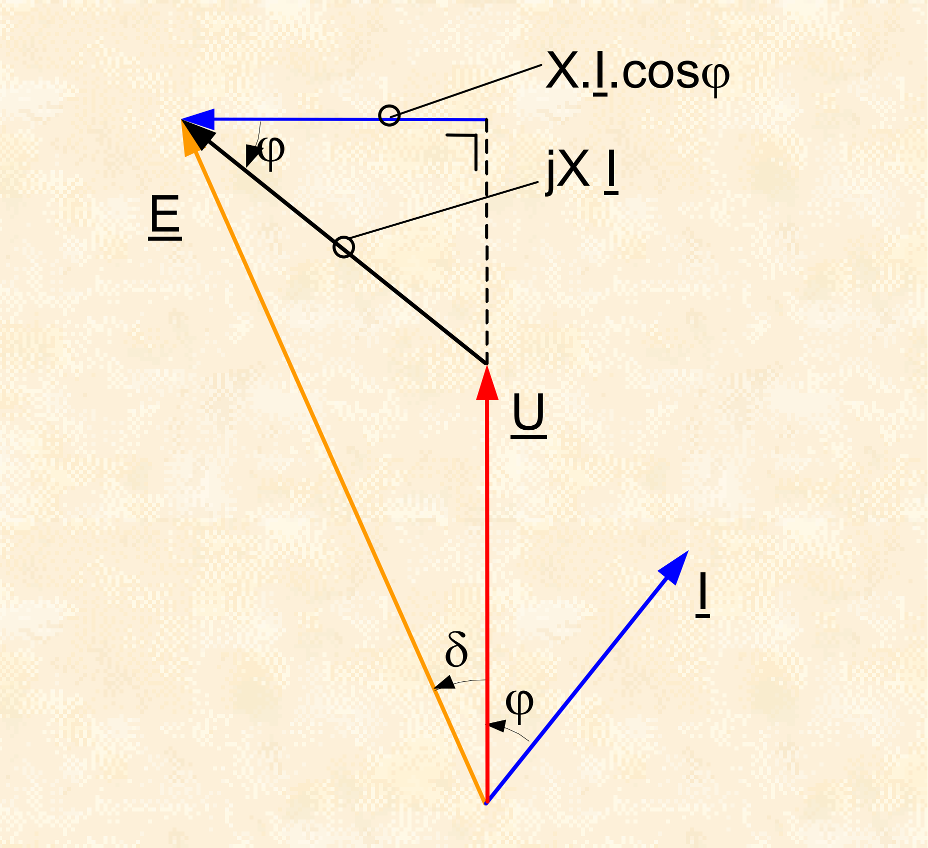
$$I = I_{k0} = \frac{U_{N,fase}}{X}$$

Star net - koppel

$$P_{mech} = \omega_0 . T = P_{elek} = \sqrt{3}.U_{lijn}.I.\cos\varphi$$

$$T = \frac{3.U.I.\cos\varphi}{\frac{\omega_1}{p}}$$

Spanningsval bij inductief-resistieve belasting

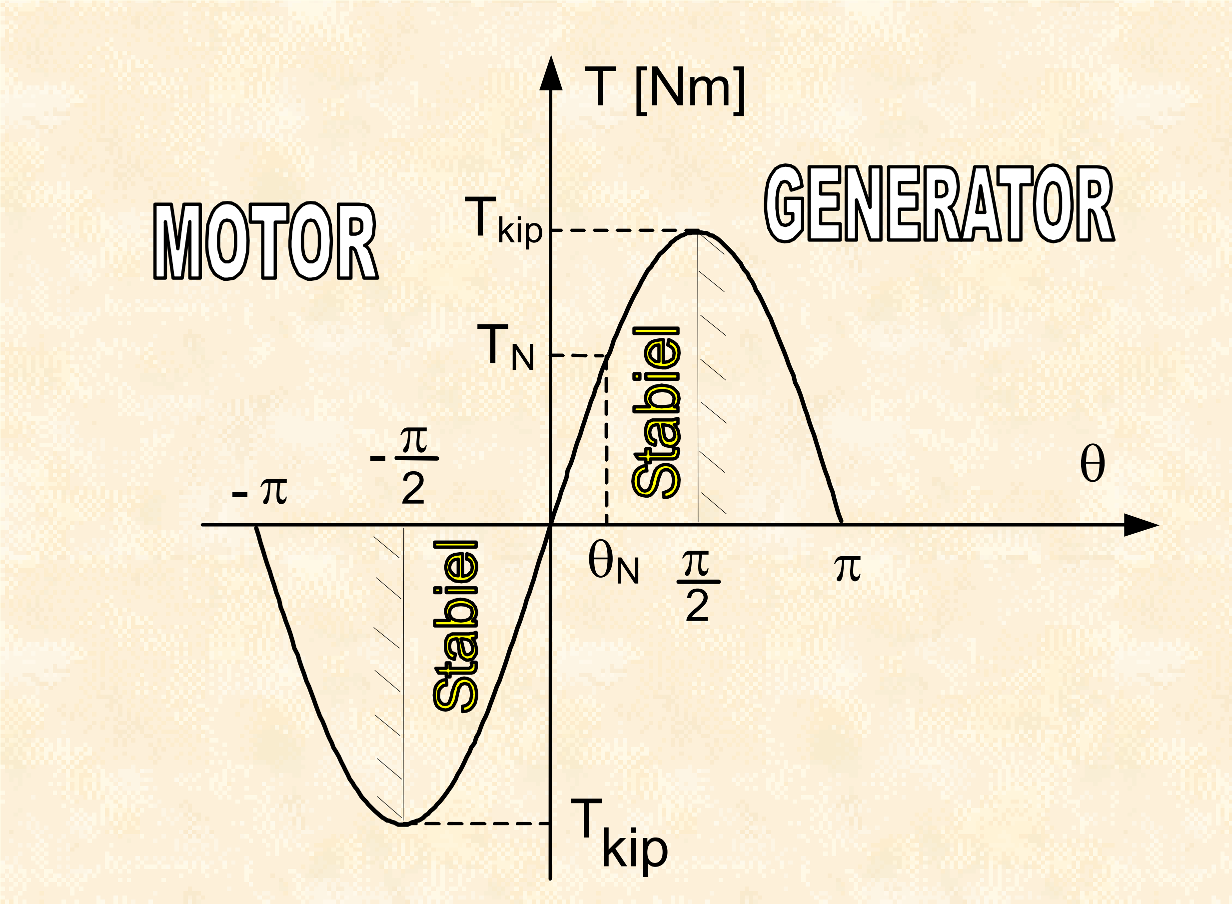


$$X.I.\cos\varphi = E.\sin\theta$$

$$I.\cos\varphi = \frac{E}{X}.\sin\theta$$

$$T = \frac{3.p.U.E}{\omega_1.X}.\sin\theta = T_{kip}.\sin\theta$$

Koppel-lasthoekkarakteristiek



Werkingsgebied

$$\underline{E} = Ee^{j\theta} = E(\cos\theta + j\sin\theta)$$

$$\underline{I} = Ie^{-j\varphi} = I\left(\cos\varphi - j\sin\varphi\right)$$

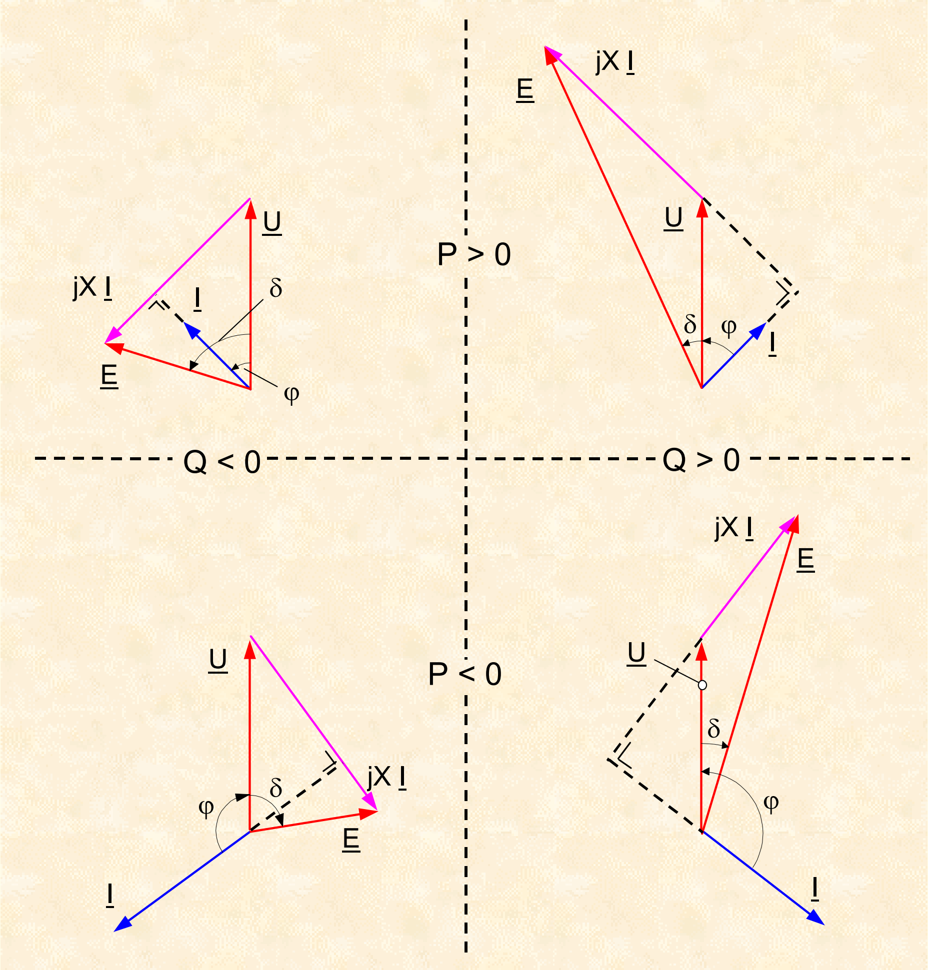
$$\underline{E} = \underline{U} + jX\underline{I}$$

$$E\left(\cos\theta + j\sin\theta\right) = U + jXI\left(\cos\varphi - j\sin\varphi\right)$$

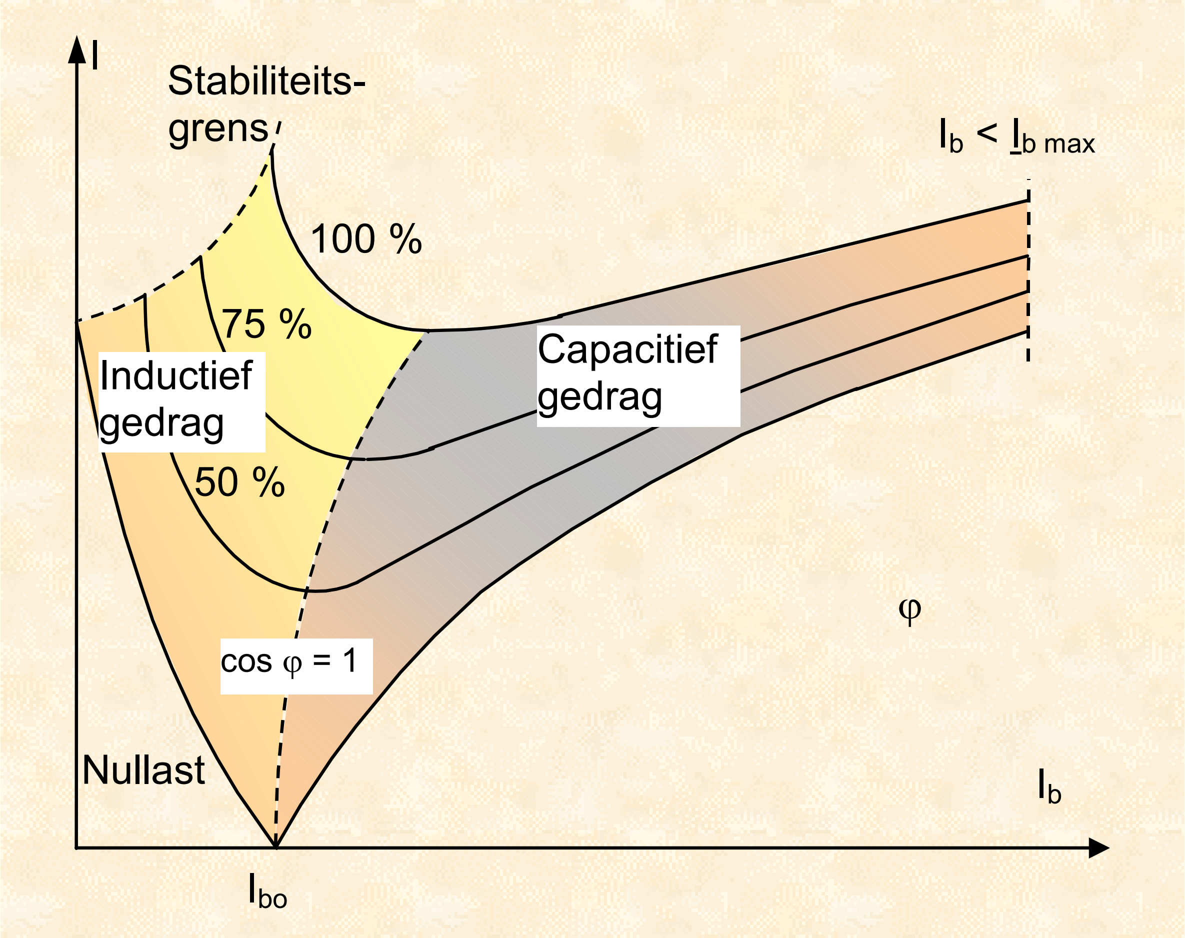
$$I\cos\varphi = \frac{E}{X}\sin\theta$$ (actieve stroom)

$$I\sin\varphi = \frac{E\cos\theta - U}{X}$$ (reactieve stroom)

Werkingsgebied



V-curves

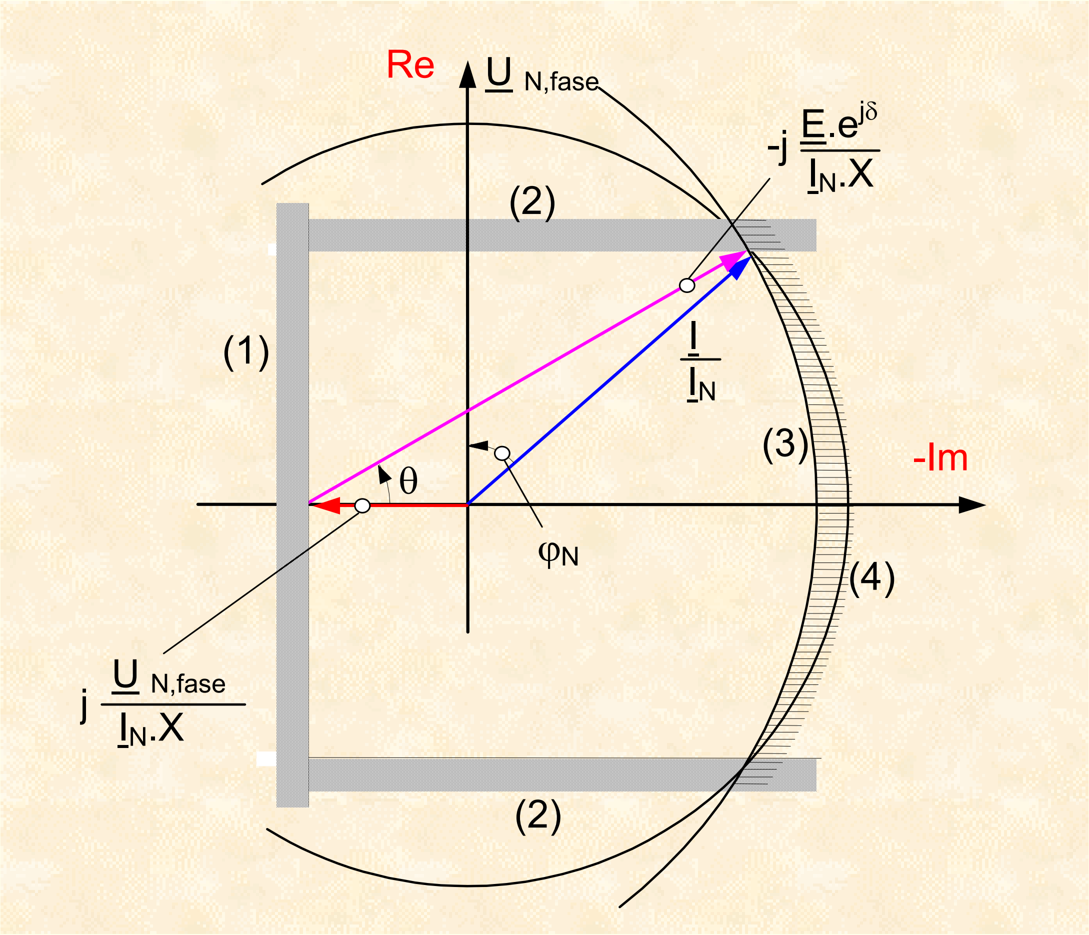

I
Stabiliteits-
grens
$I_b < I_{b\,max}$
100 %
75 %
Inductief
gedrag
Capacitief
gedrag
50 %
φ
cos φ = 1
Nullast
I_b
I_{bo}

Grenzen

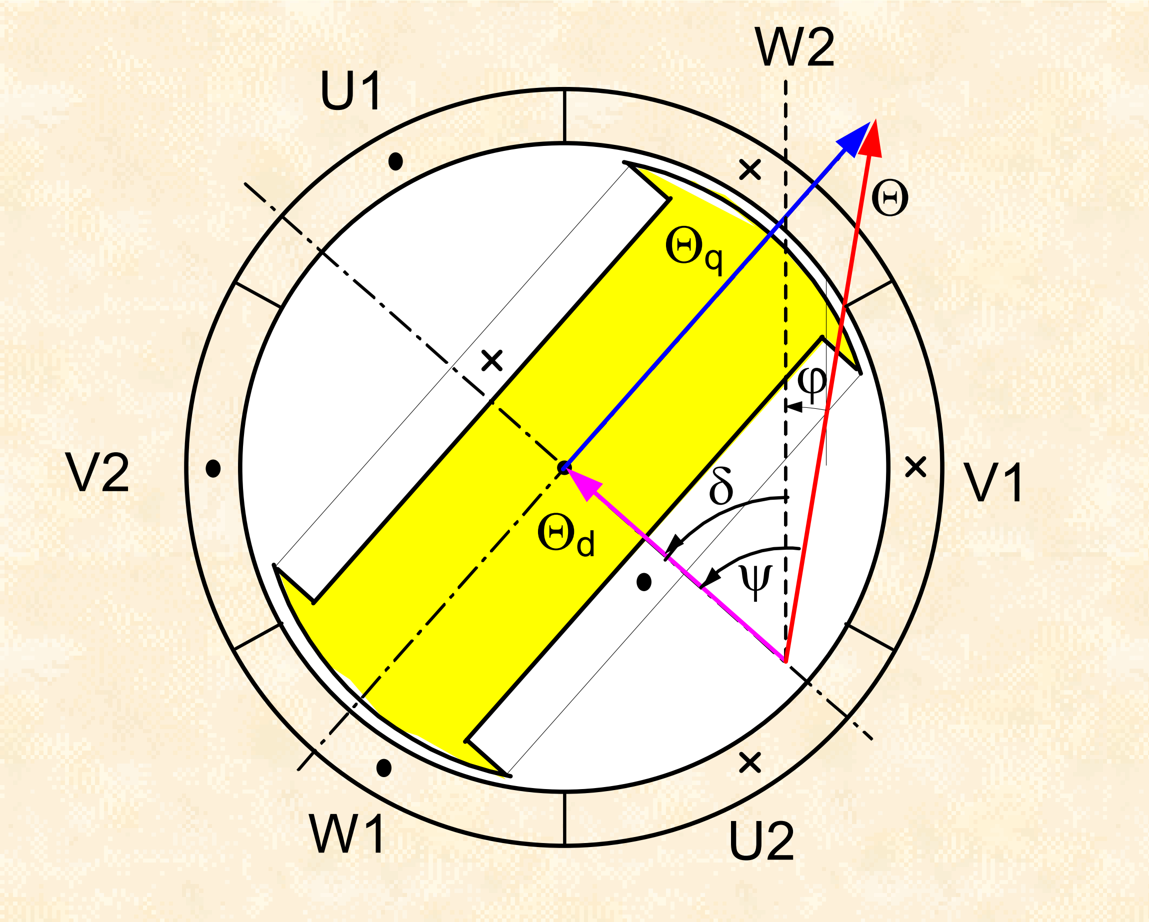
$$\underline{I} = \frac{E.e^{j\theta} - U_{N,fase}}{jX} = \frac{jU_{N,fase}}{X} - j\frac{E.e^{j\theta}}{X}$$

$$\frac{I}{I_N} = j\frac{U_{N,fase}}{I_N.X} - j\frac{E.e^{j\theta}}{U_{N,fase}}.\frac{U_{N,fase}}{I_N.X}$$

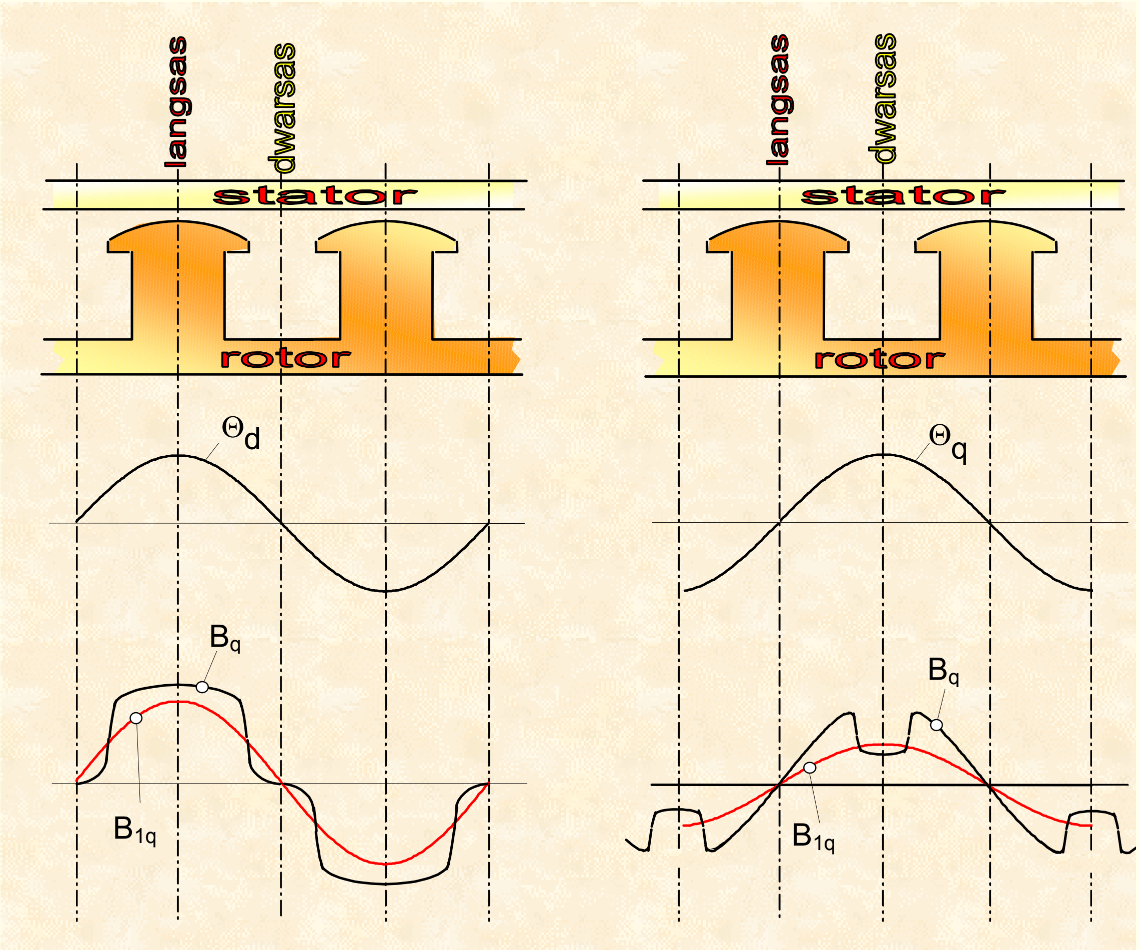
Grenzen voor het werkingsgebied



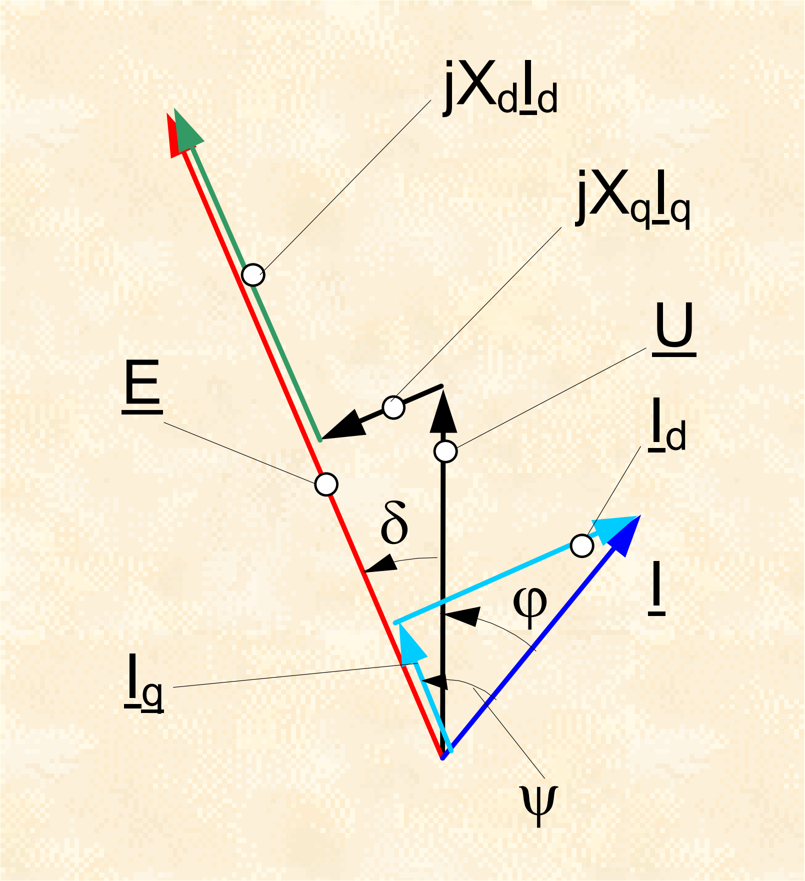
Machine met niet cilindrische rotor



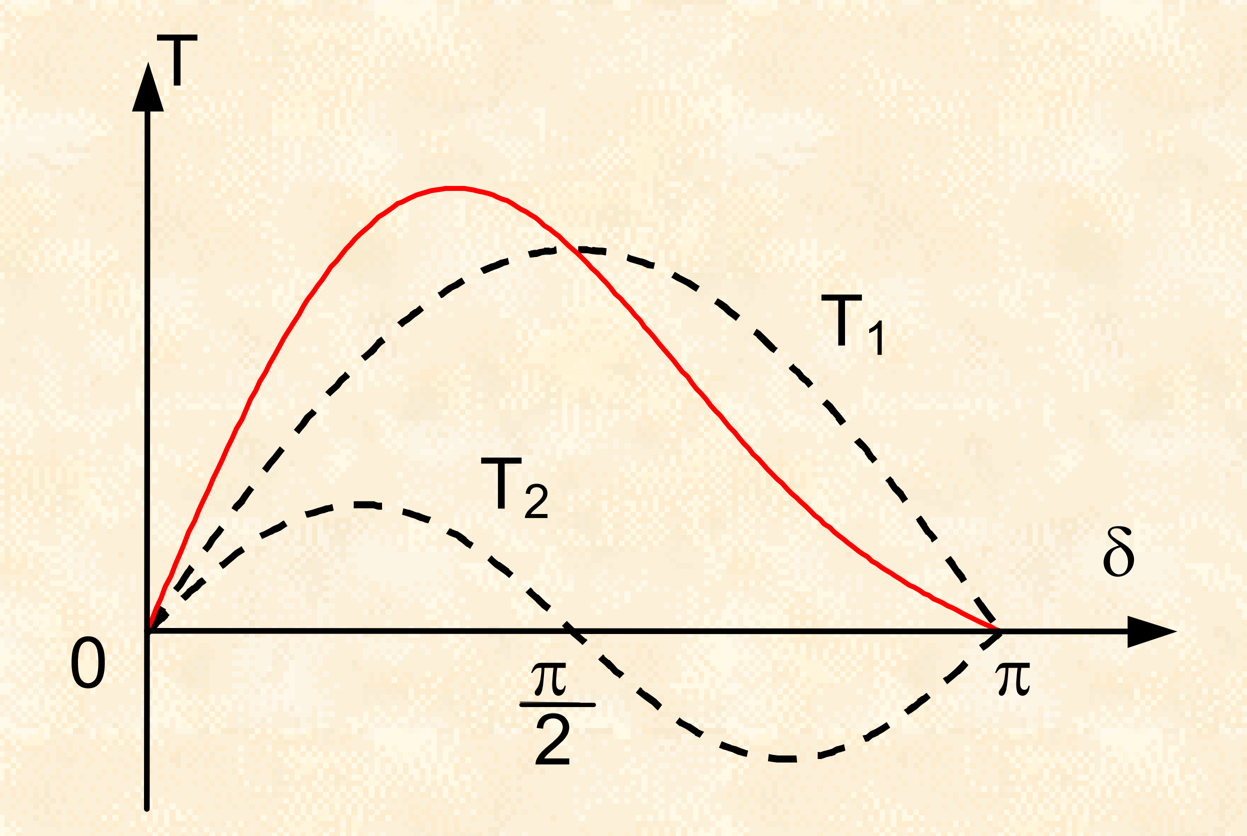
Direct en kwadratuurveld



Fasordiagram



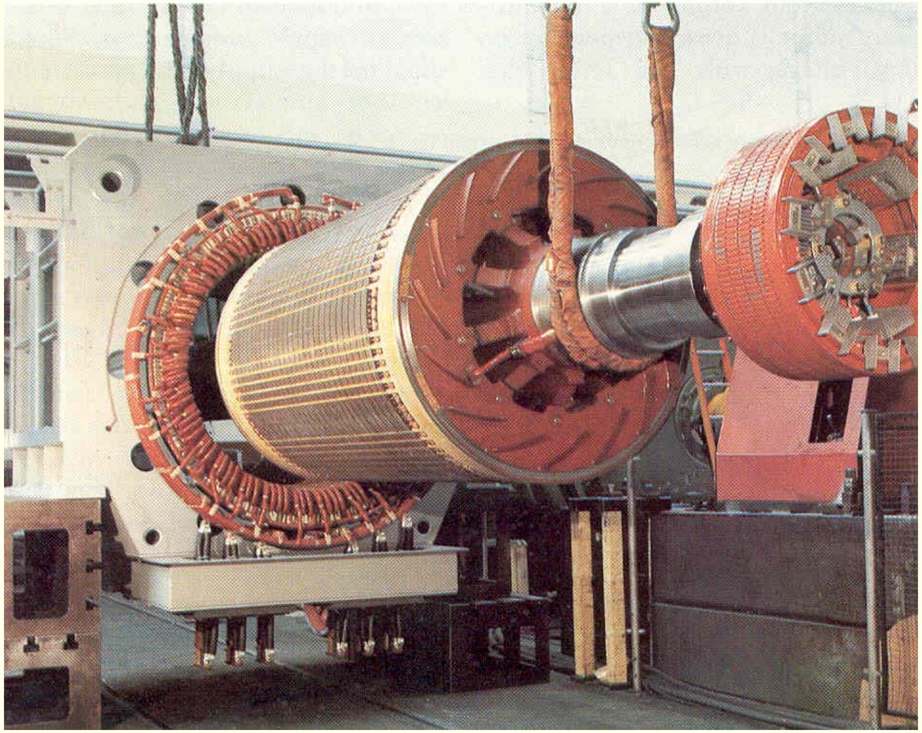
Koppel-lasthoekkarakteristiek

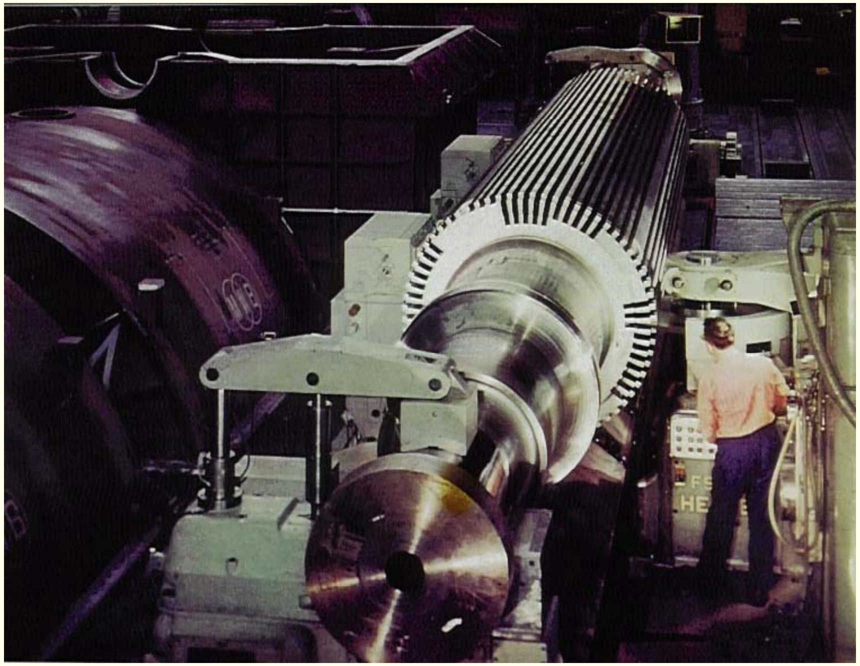


Gebruik en constructie van synchrone machines

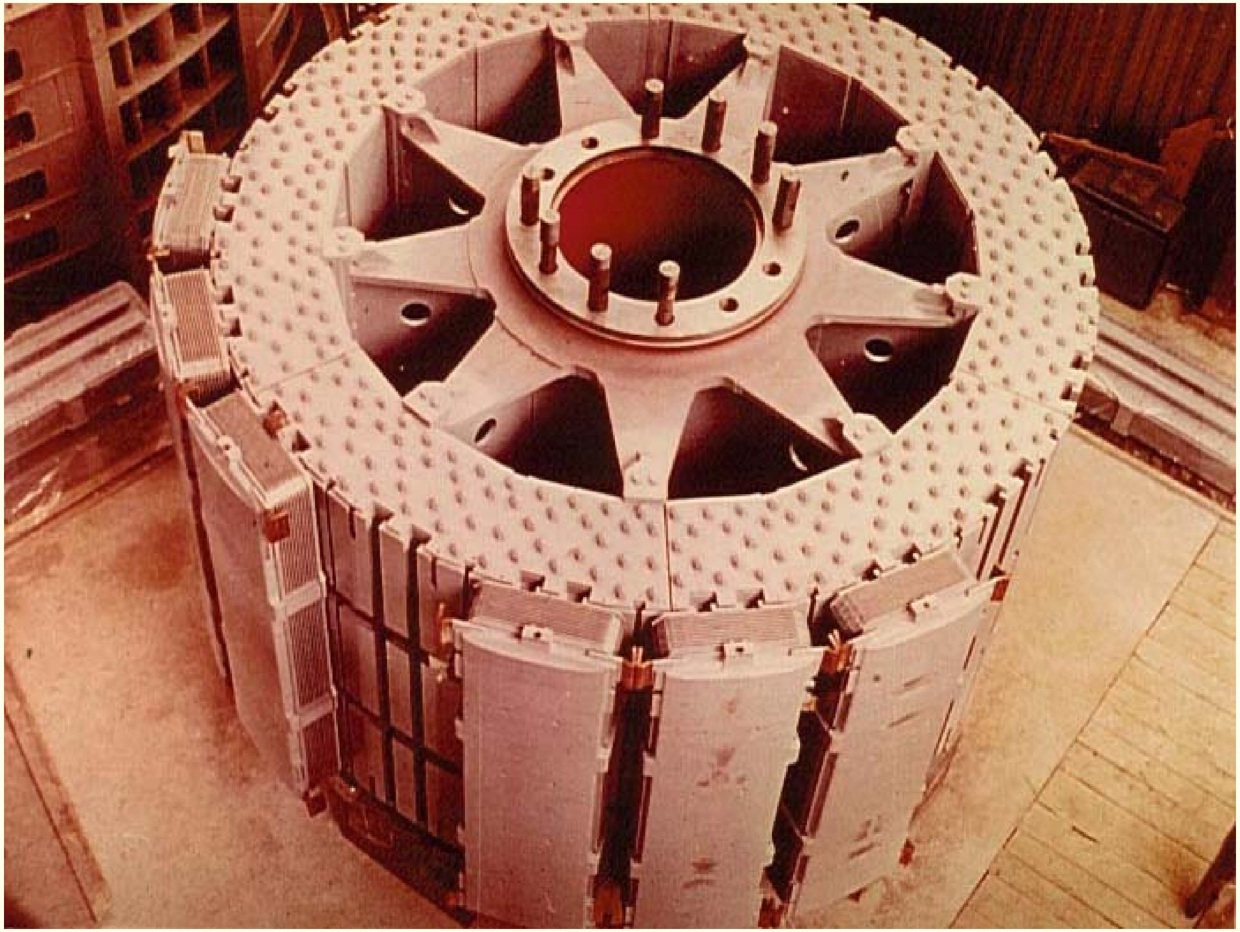
- Elektrisch bekrachtigde generator
- Klauwpoolgenerator
- Synchrone motor

Rotor voor een turbogenerator



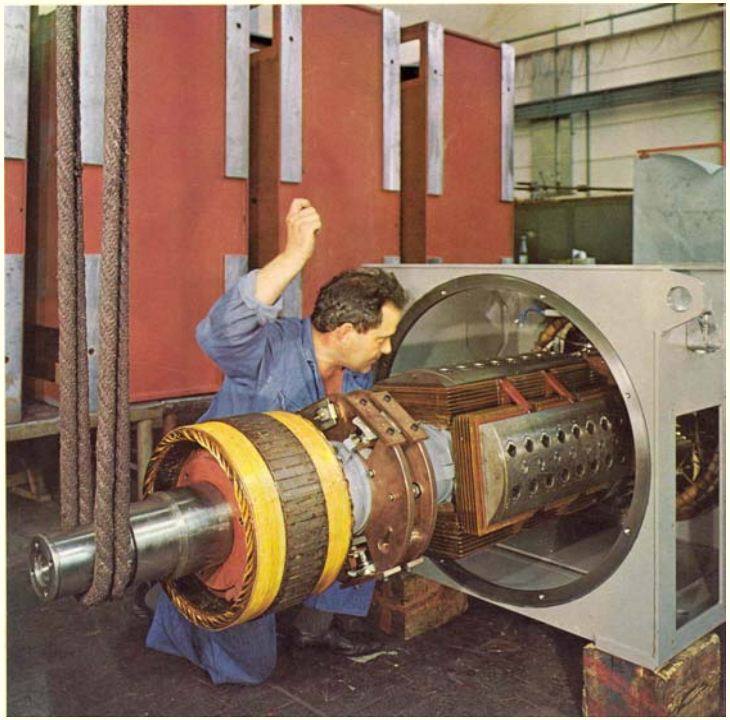


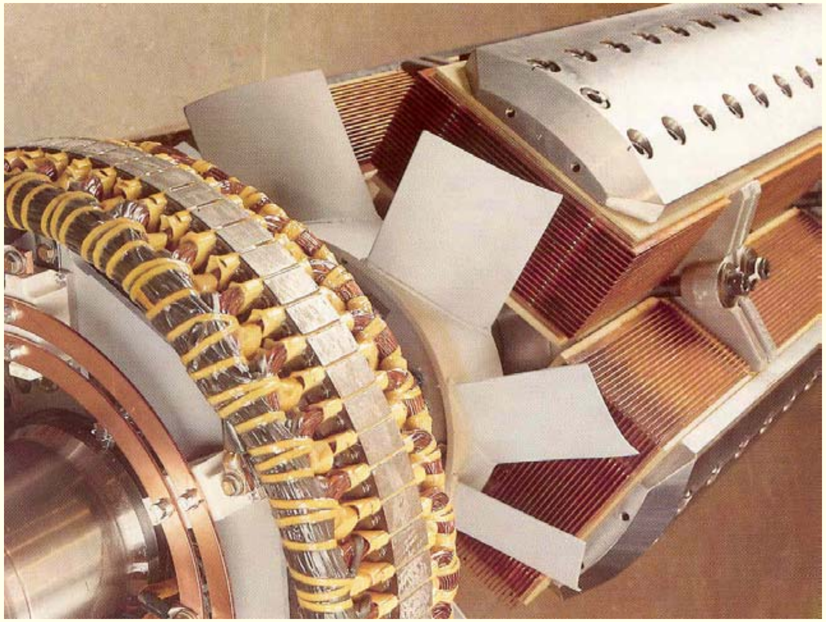
Gelaste rotorconstructie



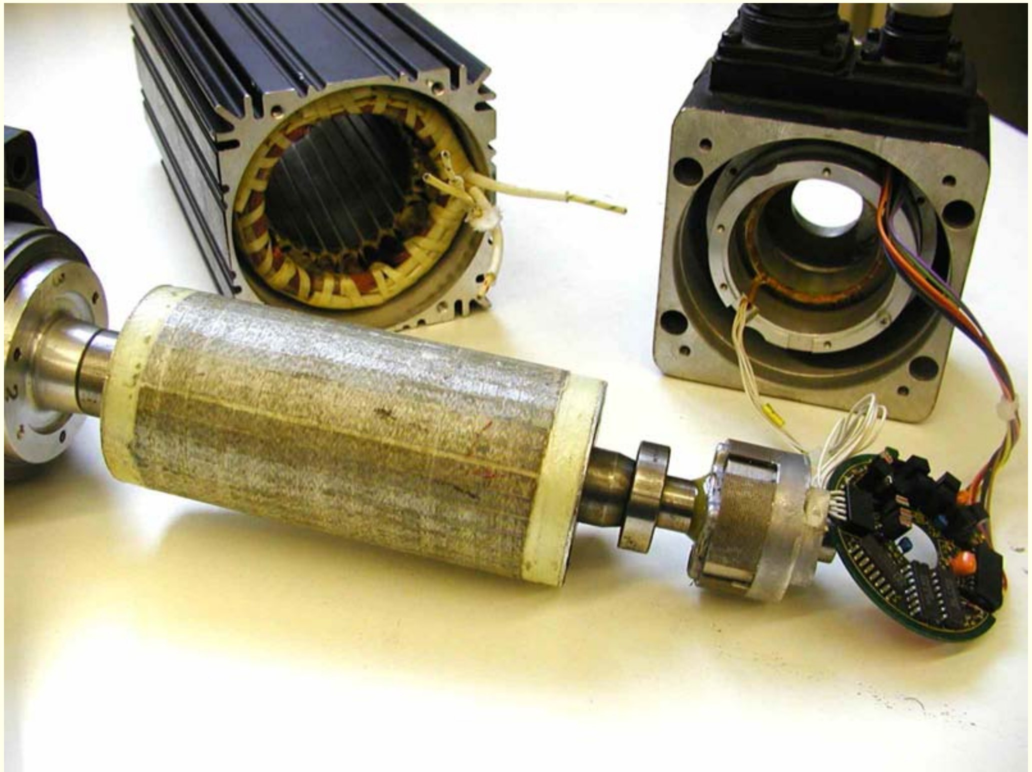
Klauwpoolalternator van een wagen

Rotor met uitspringende polen



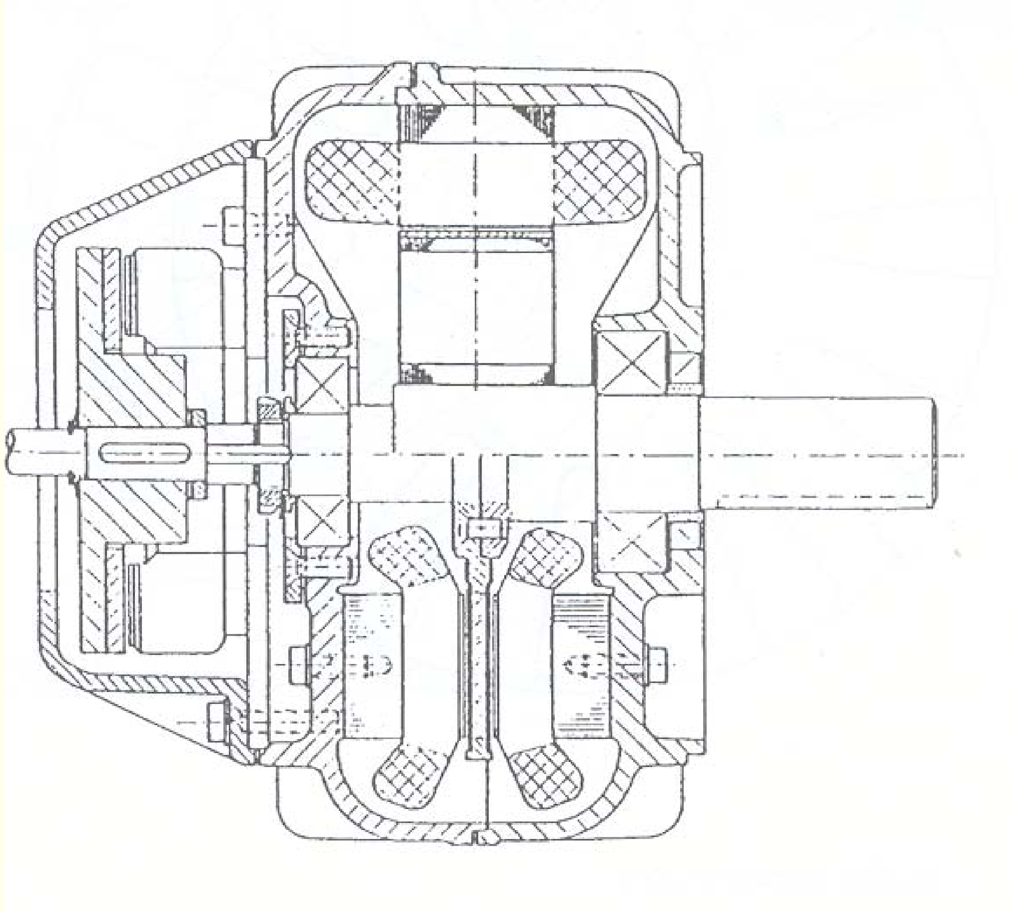


Borstelloze servomotor

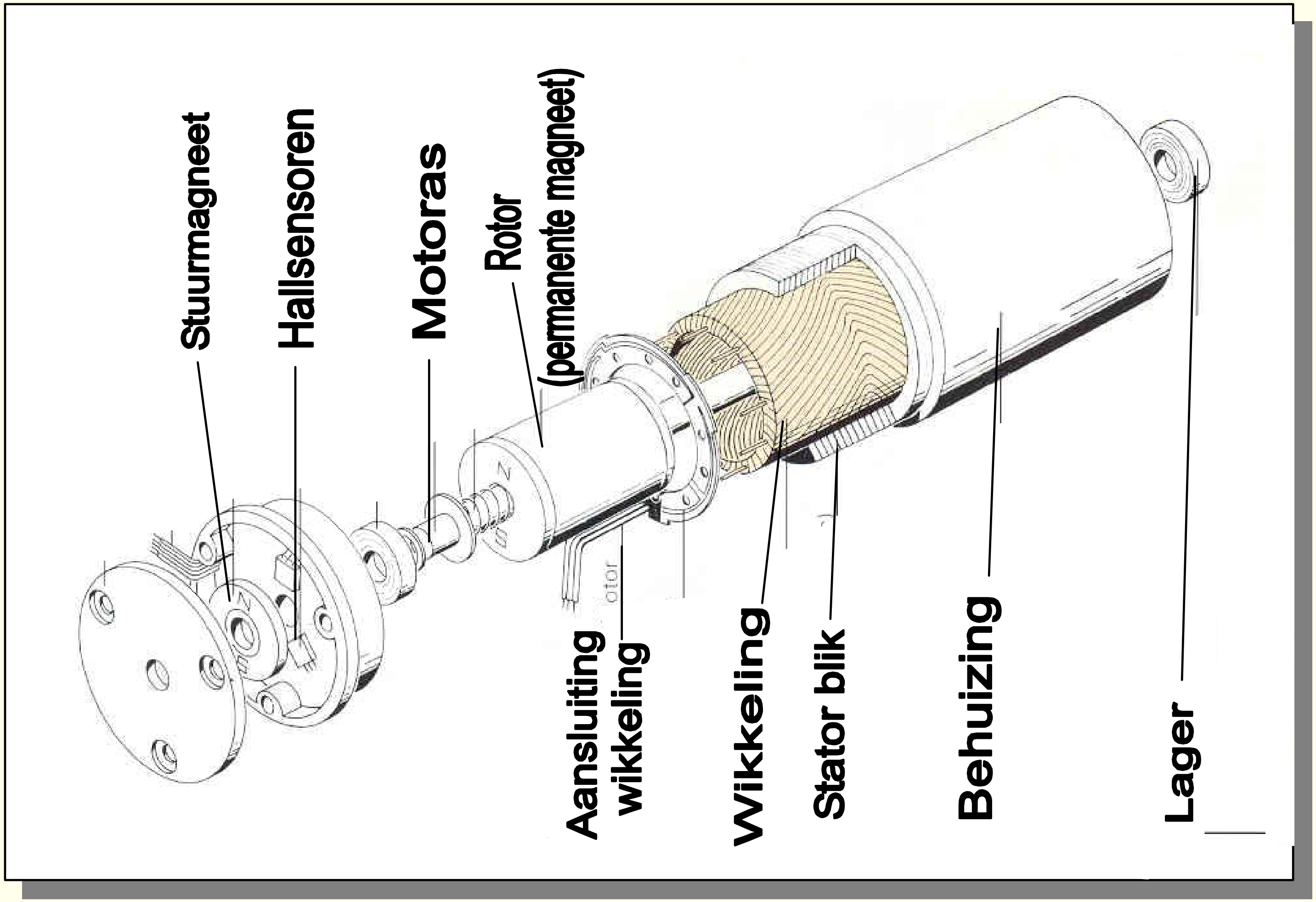


1. Rotor met permanente magneten.
2. Stator met driefasige wikkeling
3. Tachoanker en encoder
4 Lagerschild met tachowikkeling en aansluitstekkers

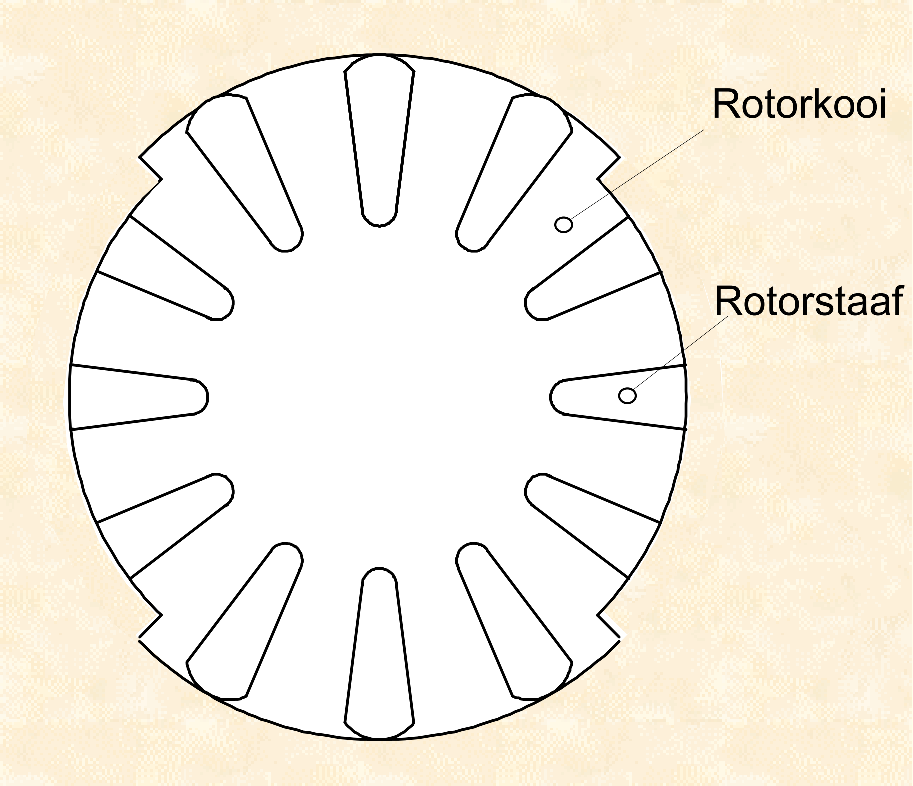
Borstelloze schijfrotormotor



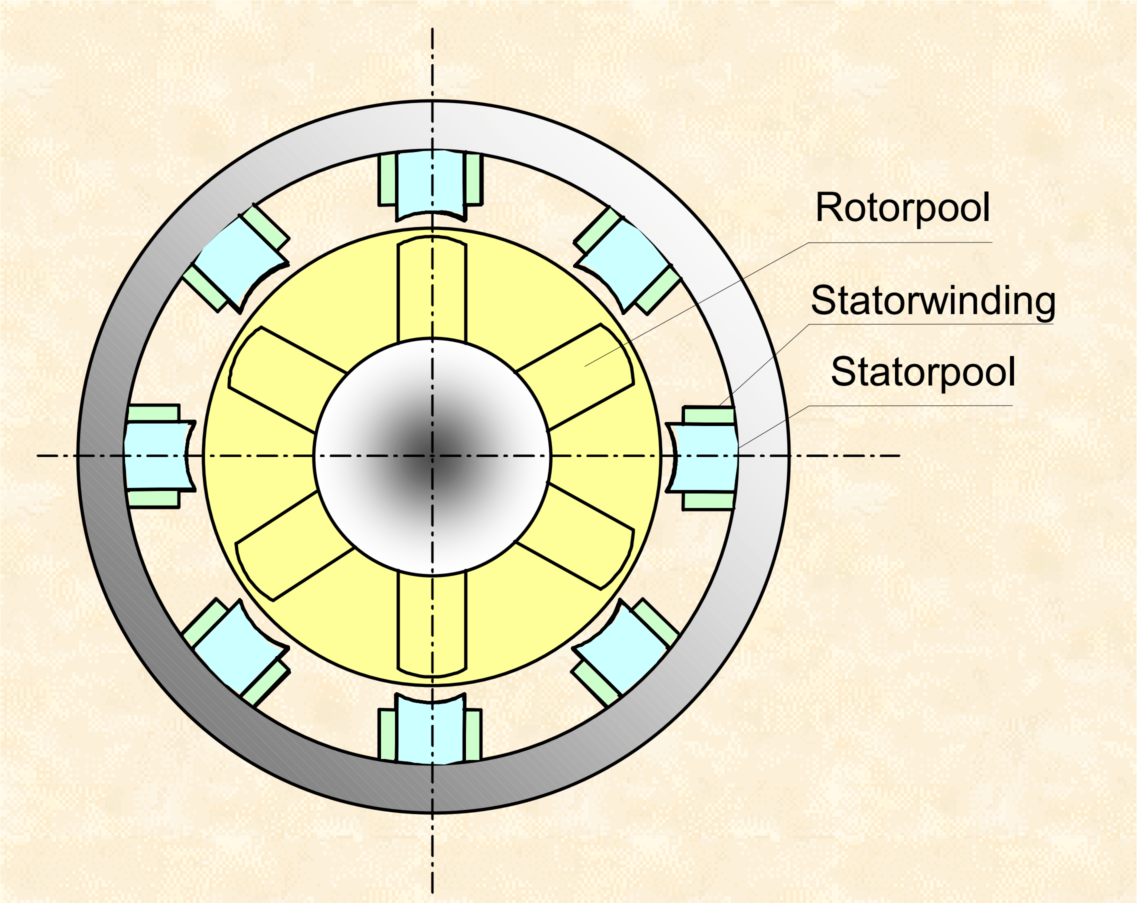
Maxon borstelloze motor



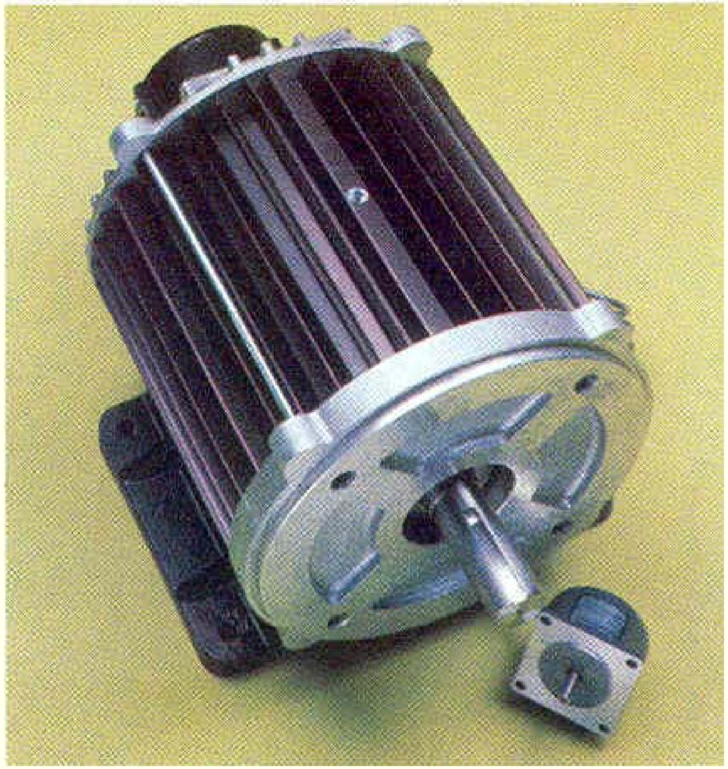
Reluctantiemotor

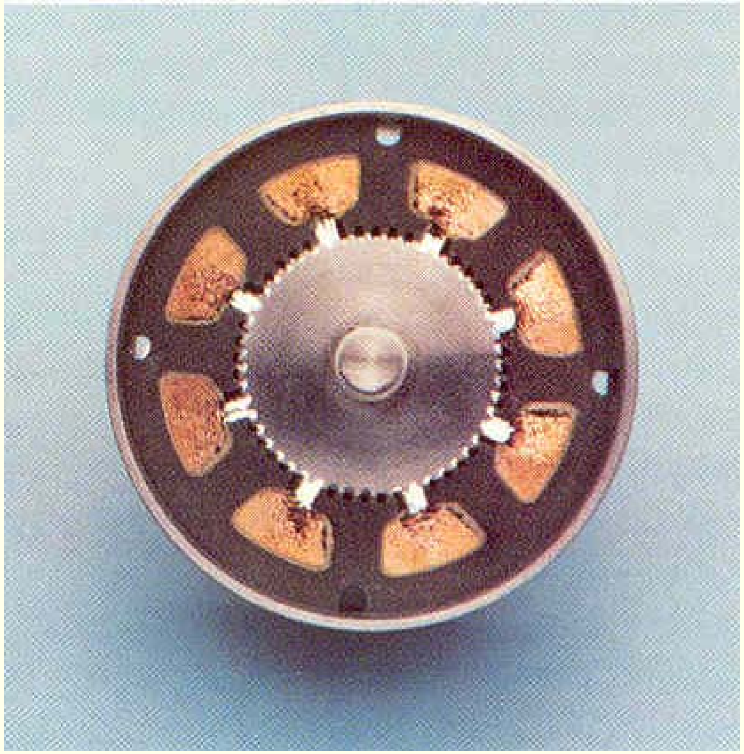


Geschakelde reluctantiemotor

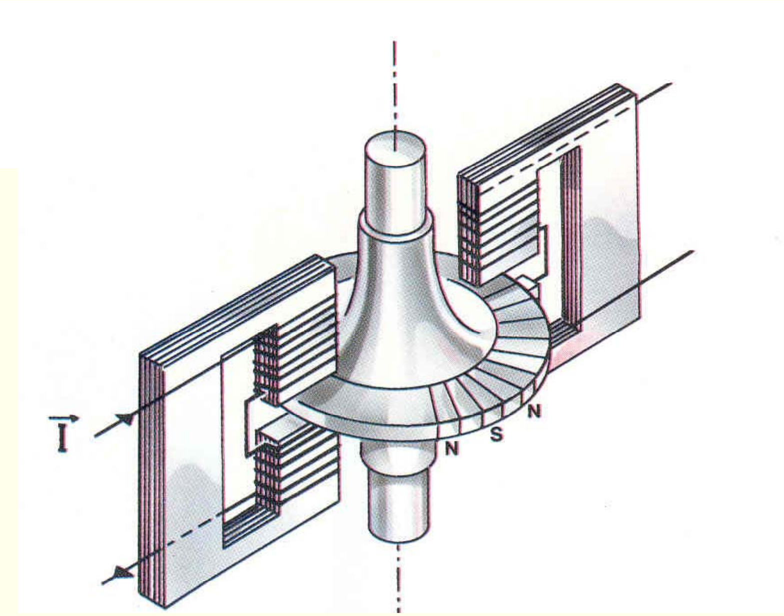


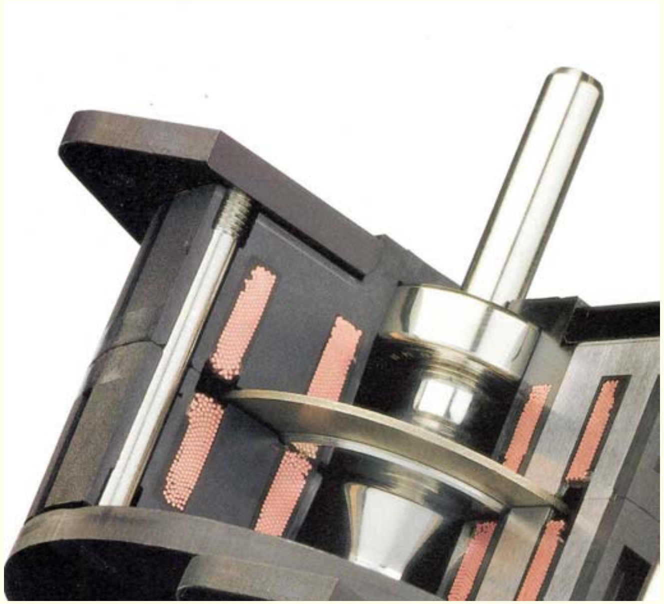
Stappenmotor I





Stappenmotor II





Stappenmotor III