Transformatoren

R. BELMANS

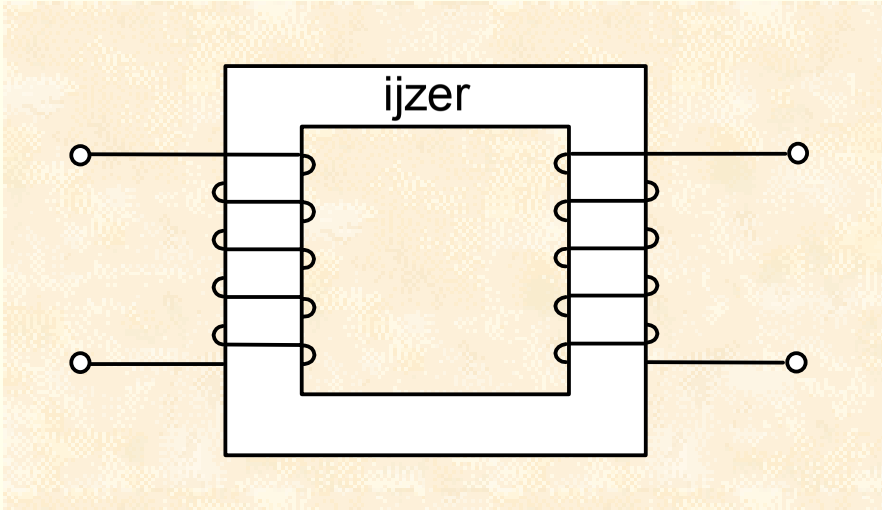
Overzicht

- Fundamentele studie van de eenfasige transformatoren
- Bedrijfstoestanden van de eenfasige transformator
- Driefasige transformatoren
- Parallelwerking van transformatoren
- Speciale transformatoren
- Aspecten van constructie

Fundamentele studie van het gedrag

- Principiële bouw van een transformator
- Ideale transformator
- Reële of technische transformator

Principiële bouw van een transformator



$$\Re = \frac{\ell}{\mu S}$$

$$\mu = \mu_0 . \mu_r$$

Ideale transformator

$\mu_{Fe} \to \infty$ geen lekflux

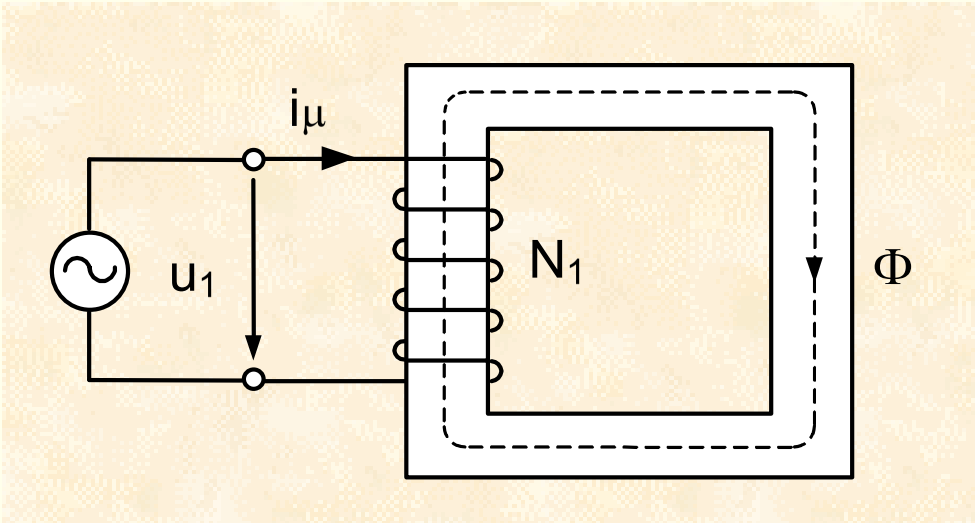
geen ijzerverliezen

$R_1 = R_2 = 0$

Ijzeren kern met spoel

- Verband spanning-flux
- Verband magnetiseringsstroom-flux
- Verband spanning-magnetiseringsstroom

Verband spanning-flux



$$u_1 = U_1\sqrt{2}\cos\omega t$$

$$\oint \vec{E}.d\vec{\ell} = -N_1\frac{d\phi}{dt}$$

$$\psi = N_1 \phi$$

$$\oint \vec{E}.d\vec{\ell} = 0 - u_1$$

$$u_1 = N_1 \frac{\mathrm{d}\phi}{\mathrm{dt}}$$

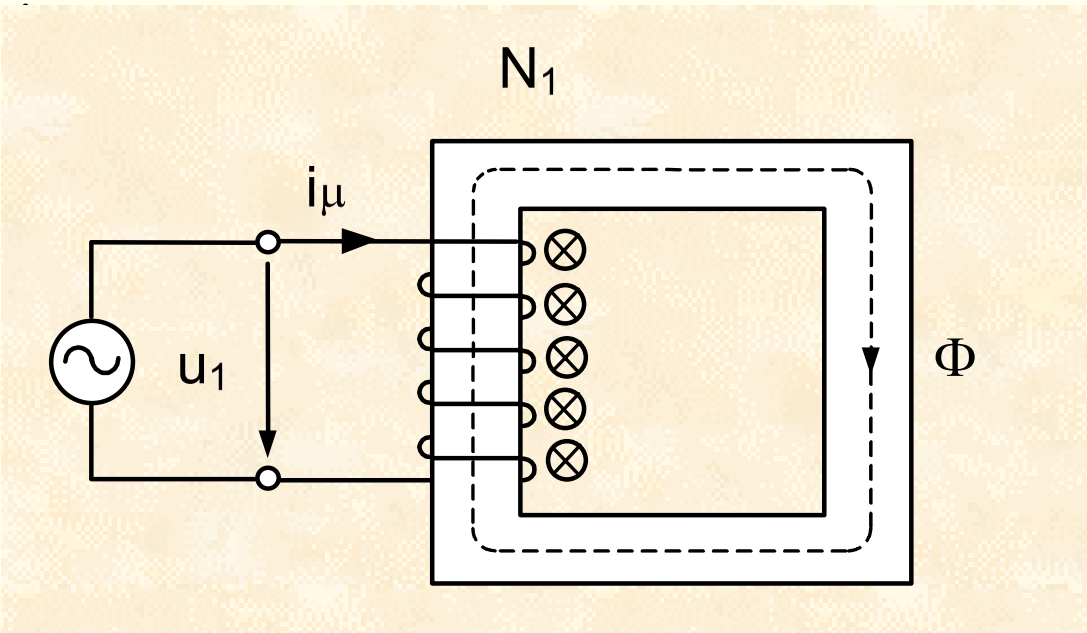
$$\phi = \int \frac{\mathrm{u}_1}{N_1} dt$$

$$\phi = \hat{\phi}.\sin \omega t + C$$

$$\hat{\phi} = \frac{\sqrt{2}\,U_1}{2\pi f\, N_1} \cong \frac{U_1}{4{,}44 N_1 f}$$

$$U_1 = 4{,}44 N_1 f \hat{\phi}$$

Magnetiseringsstroom-flux



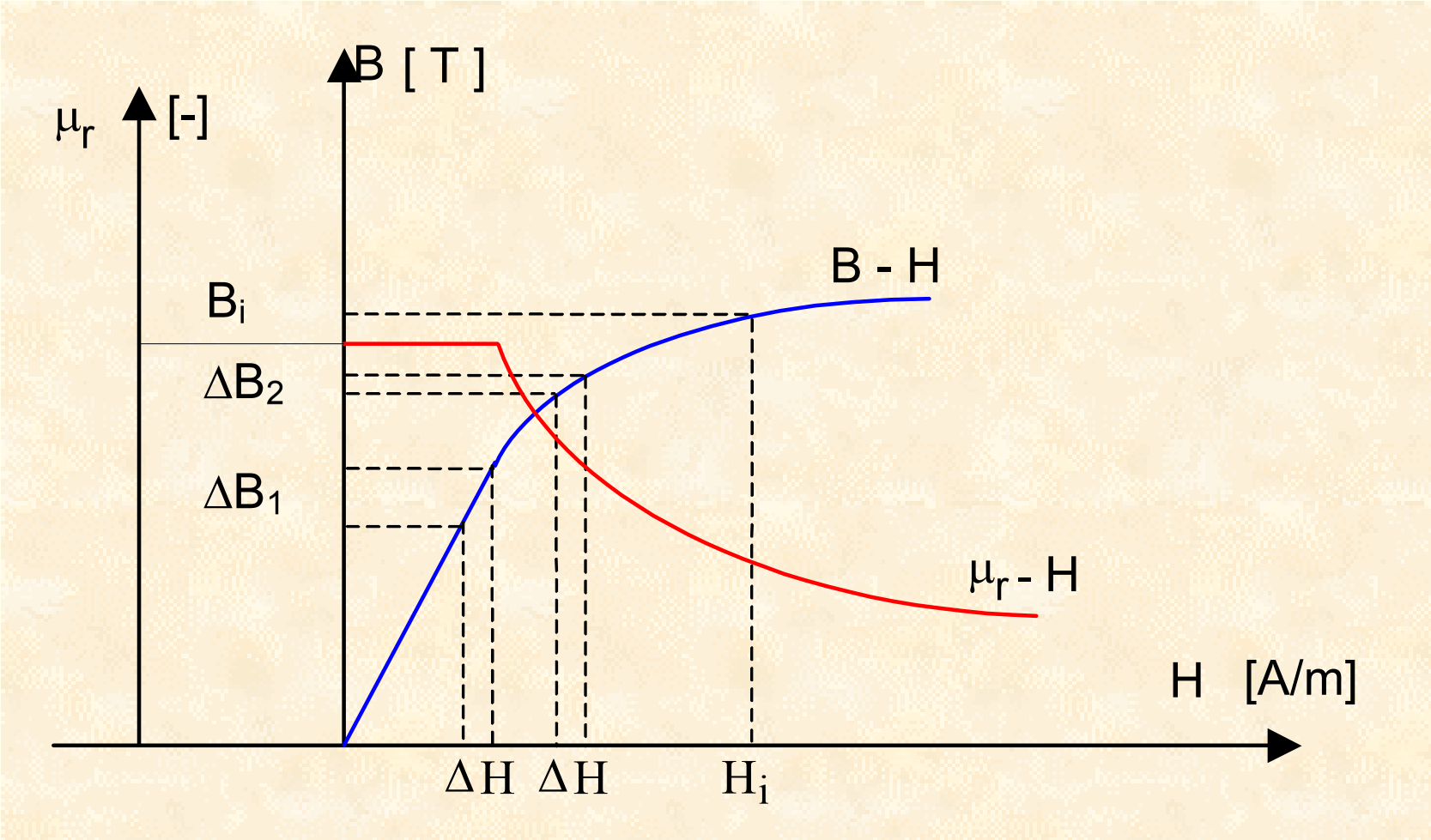
$$\oint \vec{H}\, d\vec{\ell} = \iint_S \vec{J}\, d\vec{S} = \Theta$$

$$B_i = \frac{\phi}{S_i}$$

$$B = \mu H = \mu_0 \mu_r H$$

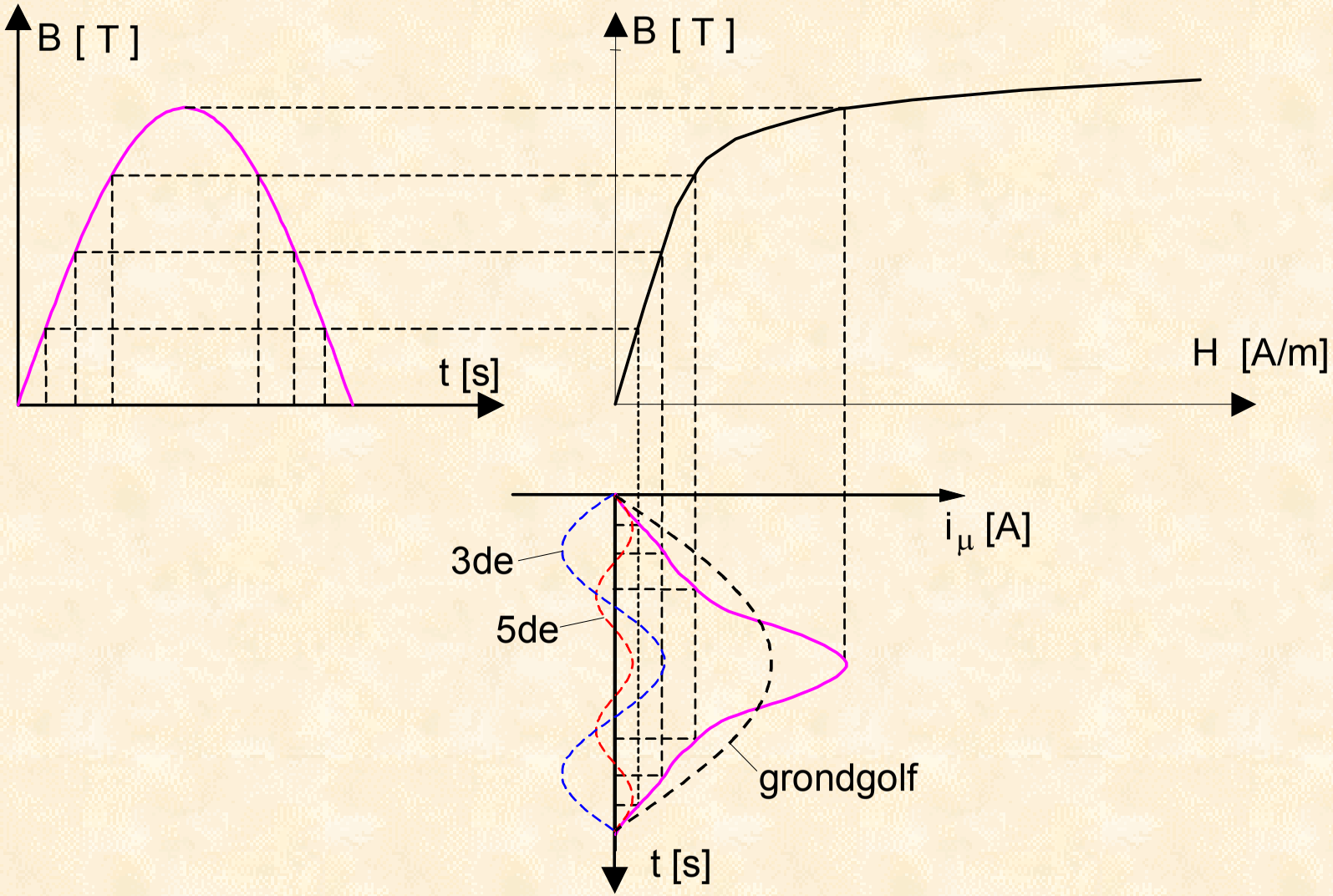
$$\oint \vec{H}\, d\vec{\ell} = \sum_i H_i \ell_i$$

$$\sum_i H_i \ell_i = 2H_b \ell_b + 2H_j \ell_j + H_\delta \ell_\delta$$


B [T]
μr
[-]
B - H
Bi
ΔB2
ΔB1
μr - H
H [A/m]
ΔH
ΔH
Hi

$$i_{\mu 1} = \frac{\sum_i H_i \ell_i}{N_1}$$

$$i_{\mu 1} = \frac{\sum_i \frac{\phi \, \ell_i}{\mu_0 \mu_{r_i} S_i}}{N_1}$$

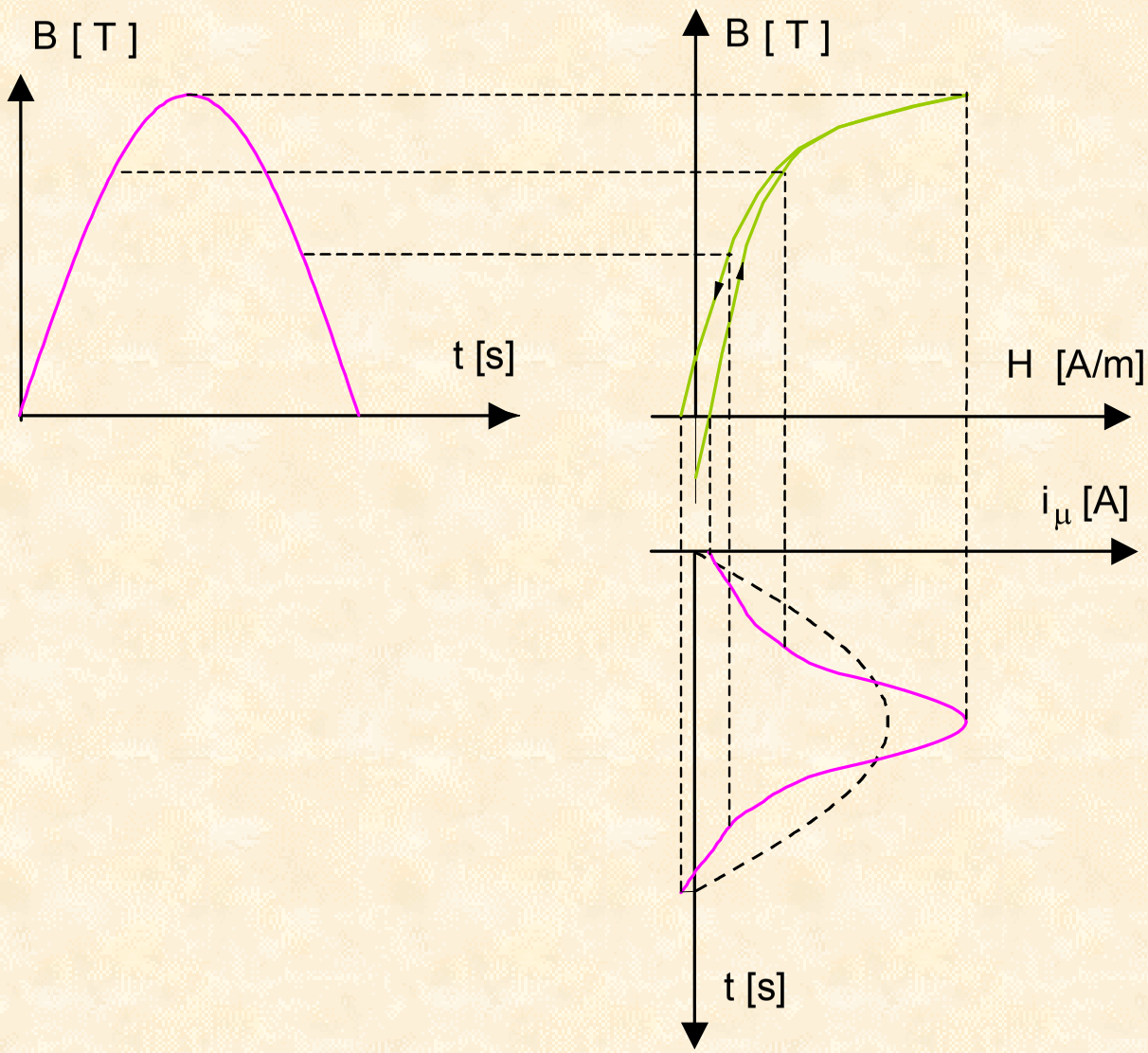

B [T]
t [s]
B [T]
H [A/m]
i μ [A]
3de
5de
grondgolf
t [s]

$$i_{\mu 1} = \sqrt{2} I_{\mu 11} \sin \omega t + \sqrt{2} I_{\mu 13} \sin 3\omega t$$

$$+ \sqrt{2} I_{\mu 15} \sin 5\omega t + \ldots + \sqrt{2} I_{\mu 1 \nu} \sin \nu \omega t + \ldots$$

$$i_{\mu 1}(t) = - i_{\mu 1}\left(t + \frac{T}{2}\right)$$

$$I_{\mu 1} = \sqrt{\left(I_{\mu 11}\right)^2 + \left(I_{\mu 13}\right)^2 + \left(I_{\mu 15}\right)^2 + \ldots + \left(I_{\mu 1 \nu}\right)^2 + \ldots}$$


B [T]
t [s]
B [T]
H [A/m]
i_μ [A]
t [s]

Verband spanning-magnetiseringsstroom

$$N_1 i_{\mu 1} = \phi \sum_i \frac{\ell_i}{\mu_0 \mu_{r_i} S_i} = \phi \, \Re_m^*$$

$$\Re_m^* = \sum_i \frac{\ell_i}{\mu_0 \mu_{r_i} S_i}$$

$$\Lambda^* = \frac{1}{\Re_m^*}$$

$$\phi = \frac{\Theta}{\Re_m^*} = \Theta\Lambda^* = N_1 i_{\mu 1}\Lambda^*$$

$$N_1\phi = \psi = N_1\,\Theta\,\Lambda^* = N_1^2 i_{\mu 1}\Lambda^*$$

$$u_1 = N_1\frac{d\phi}{dt} = N_1^2\frac{d(\Lambda^* i_{\mu 1})}{dt}$$

Spannings-differentiaalvergelijking

$$u_1 = N_1^2 \Lambda^* \frac{di_{\mu 1}}{dt} = L_{h1}^* \frac{di_{\mu 1}}{dt}$$

$$L_{h1}^* = N_1^2 \Lambda^* = \frac{N_1^2}{\sum_i \frac{\ell_i}{\mu_0 \mu_{r_i} S_i}}$$

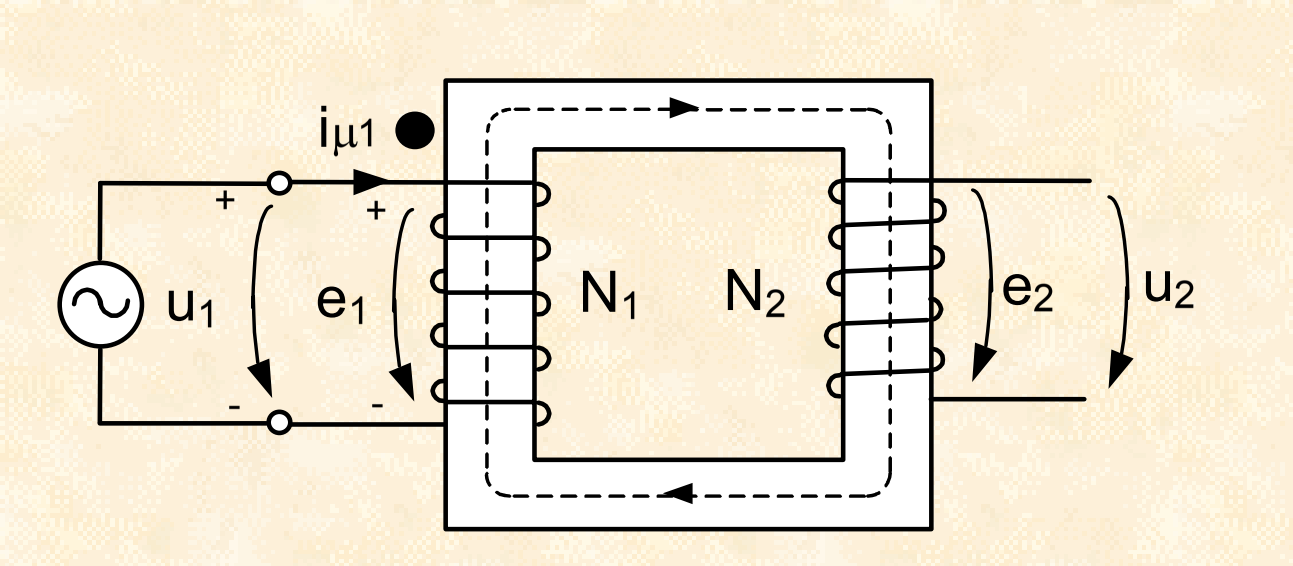
$$\psi = L_{h1}^* \, i_{\mu 1}$$

$$i_{\mu 1} = \frac{1}{L_{h1}^*} \int u_1 dt = \frac{U_1 \sqrt{2}}{\omega L_{h1}^*} \sin \omega t + C$$

$$i_{\mu 1} = \frac{U_1 \sqrt{2}}{\omega N_1^2 \Lambda^*} \sin \omega t = \frac{U_1 \sqrt{2}}{\mu_0 \omega N_1^2 S} \left(\frac{\ell_{tot}}{\mu_r} + \ell_\delta \right) \sin \omega t$$

$$L_{h1}^* = \frac{U_1}{\omega I_{\mu 1}}$$

Ideale transformator bij nullast



$$-u_1 + e_1 = 0$$

$$e_1 = u_1 = N_1 \frac{d\phi}{dt} = \frac{d\psi_1}{dt}$$

$$e_2 = u_2 = N_2 \frac{d\phi}{dt} = \frac{d\psi_2}{dt}$$

$$\frac{u_1}{u_2} = \frac{N_1}{N_2} = \ddot{u}$$

$$e_2 = u_2 = N_1 N_2 \Lambda^* \frac{di_{\mu 1}}{dt}$$

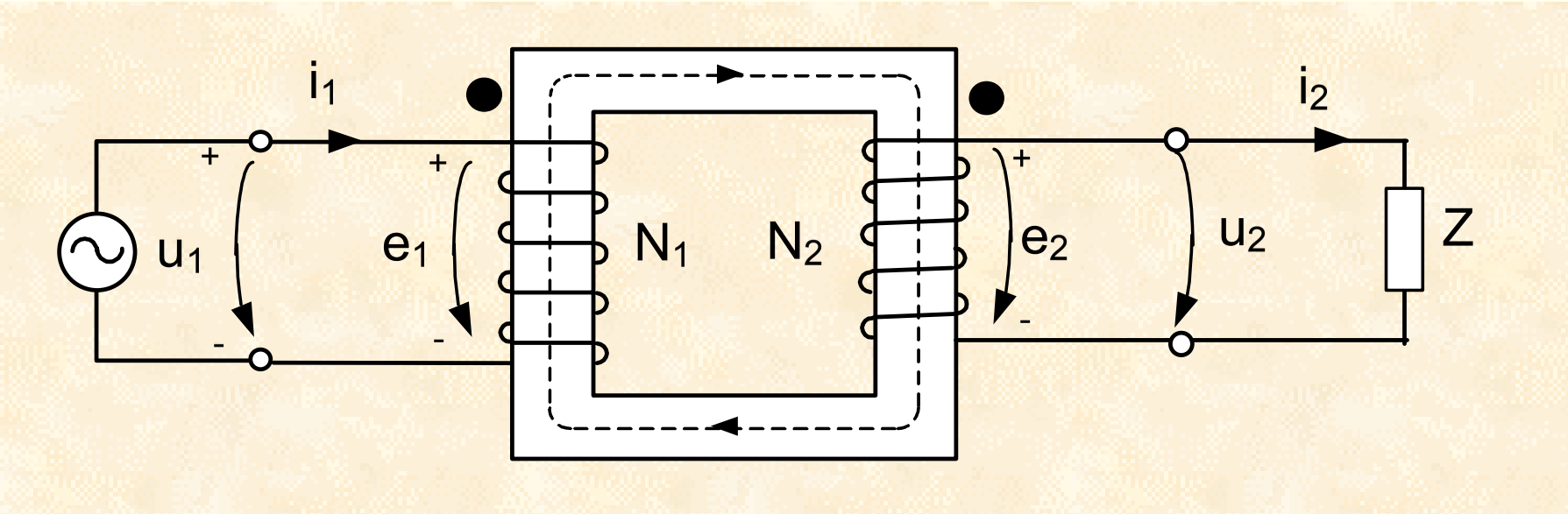
$$M_{21}^* = N_1 N_2 \Lambda^*$$

$$M_{21}^* = N_1 N_2 \Lambda^* = \frac{N_2}{N_1} L_{h1}^*$$

$$\psi_2 = N_2\phi = N_1 N_2 \Lambda^* i_{\mu 1} = M_{21}^* i_{\mu 1}$$

$$M_{21}^* = \frac{\psi_2}{i_{\mu 1}}$$

Ideale transformator bij belasting



$$u_1 = N_1 \frac{d\phi_x}{dt}$$

$$\phi_x = \phi$$

$$\Theta = N_1 i_1 - N_2 i_2$$

$$N_1 i_1 - N_2 i_2 = N_1 i_{\mu 1}$$

$$i_1 = i_{\mu 1} + \frac{N_2}{N_1} i_2$$

Twee componenten: magnetiseringsstroom
belastingsstroom

$$\frac{i_1^*}{i_2} = \frac{N_2}{N_1}$$

$$i_1 \cong i_1^* = i_2 \frac{N_2}{N_1}$$

$$u_1 = L_{h1}^* \frac{d\left(i_1 - i_2 \frac{N_2}{N_1} \right)}{dt}$$

$$u_1 = L_{h1}^* \frac{di_1}{dt} - L_{h1}^* \frac{N_2}{N_1} \frac{di_2}{dt}$$

$$M_{12}^* = \frac{N_2}{N_1} L_{h1}^* = M_{21}^*$$

Spanningsvergelijkingen

$$u_1 = L_{h1}^* \frac{di_1}{dt} - M_{12}^* \frac{di_2}{dt}$$

$$u_2 = M_{21}^* \frac{di_1}{dt} - L_{h2}^* \frac{di_2}{dt}$$

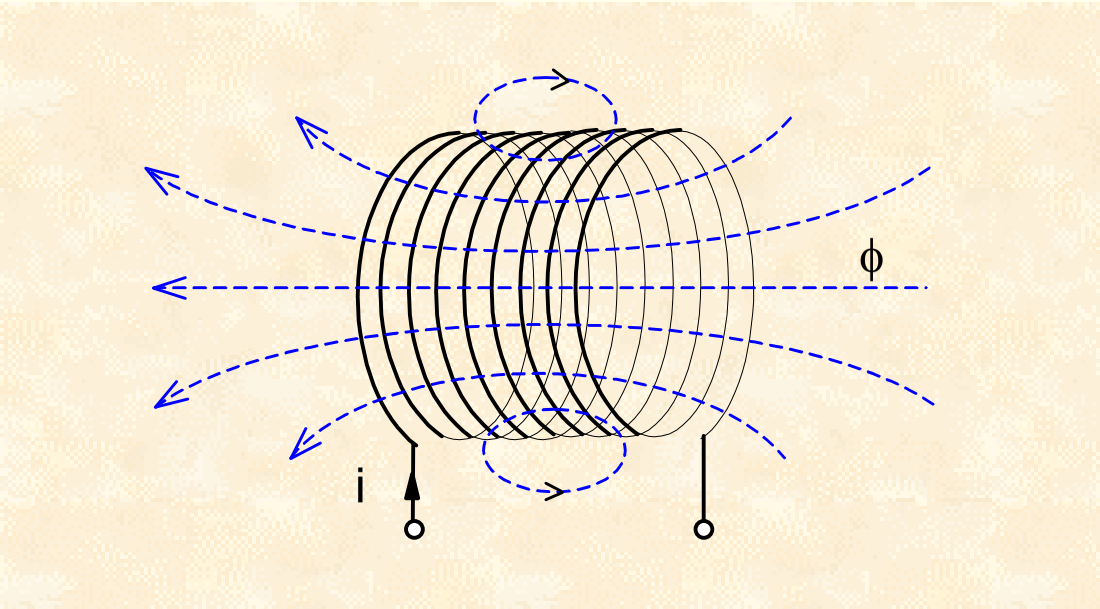
$$M_{12}^* M_{21}^* = L_{h1}^* L_{h2}^*$$

Hoofdinductanties

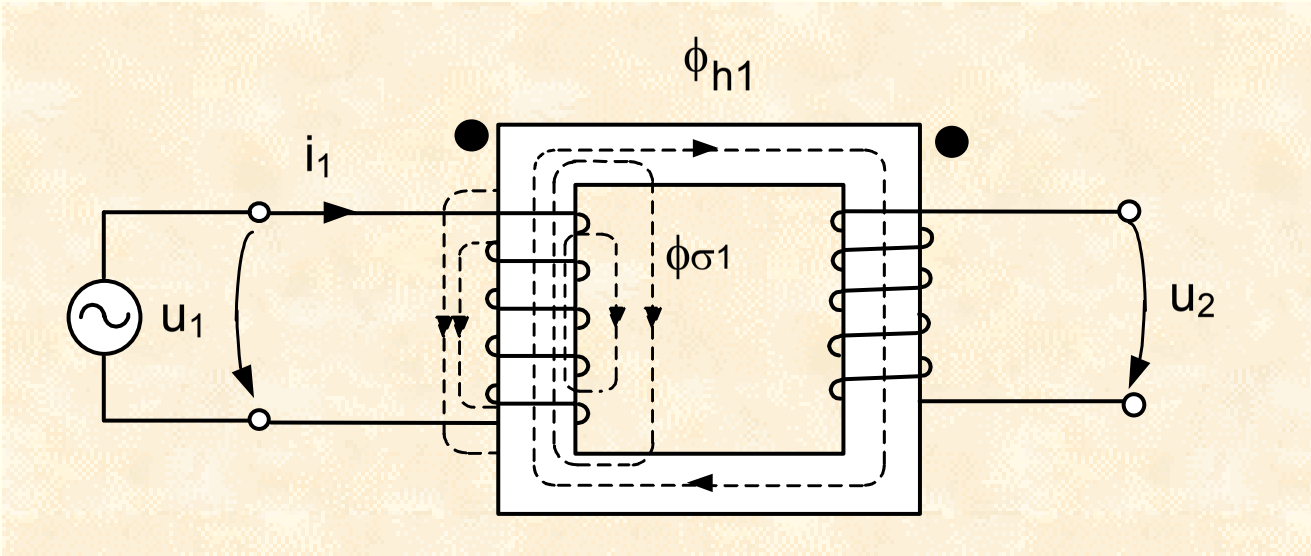
Wederzijdse inductanties

Reële transformator

- Verschillen met de ideale transformator
  - eindige permeabiliteit-lexflux

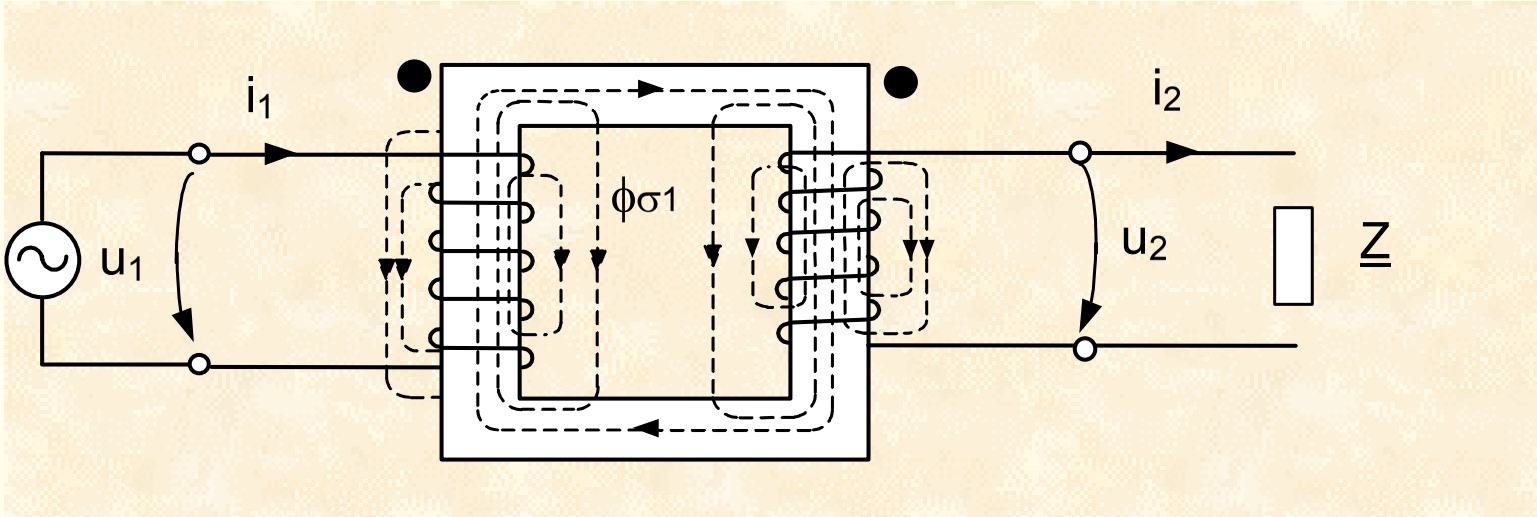


$$\psi = \int_0^N \phi \, dN$$



– Wervelstroom- en hysteresisverliezen
– jouleverliezen

Spannings-differentiaalvergelijkingen



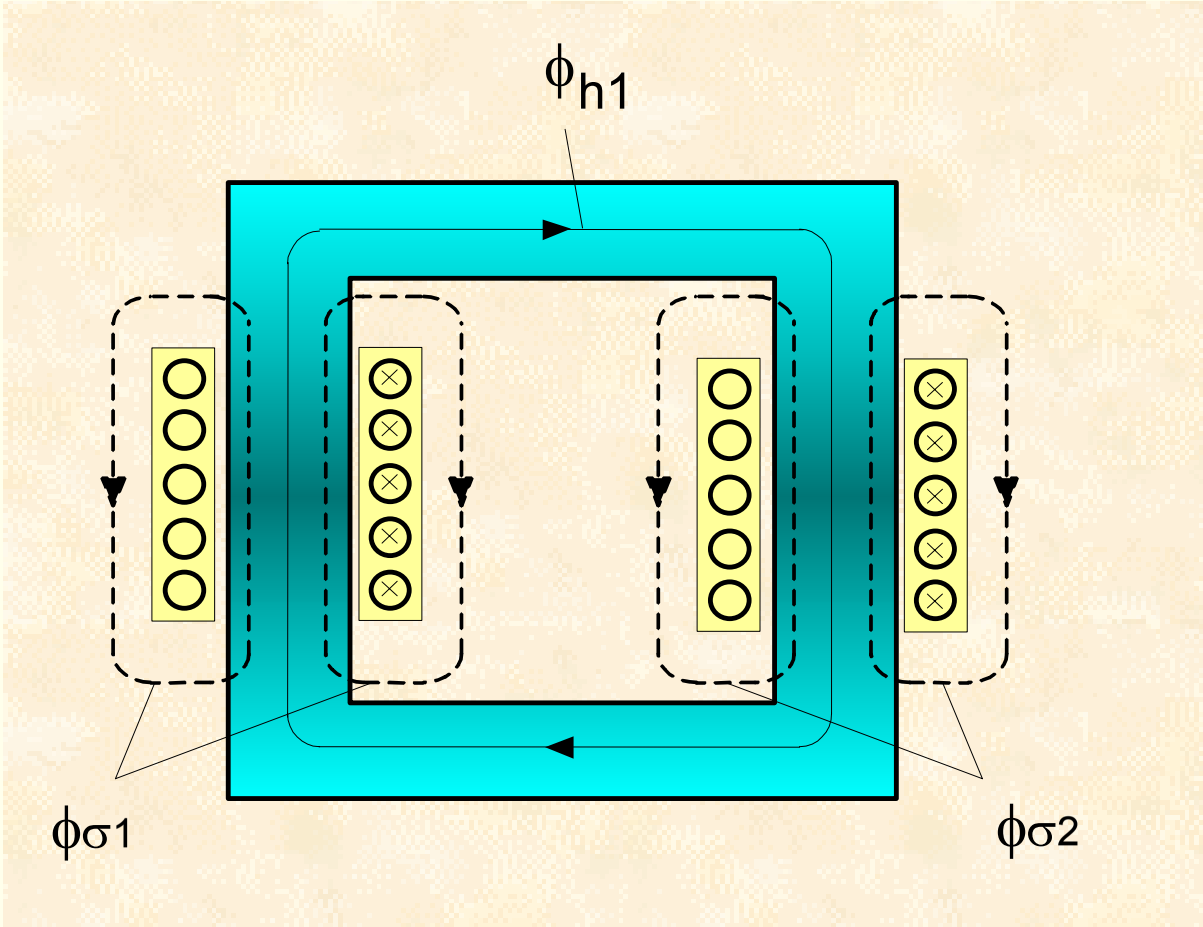
$$\oint \vec{E} \cdot d\vec{\ell} = i_1 R_1 - u_1$$

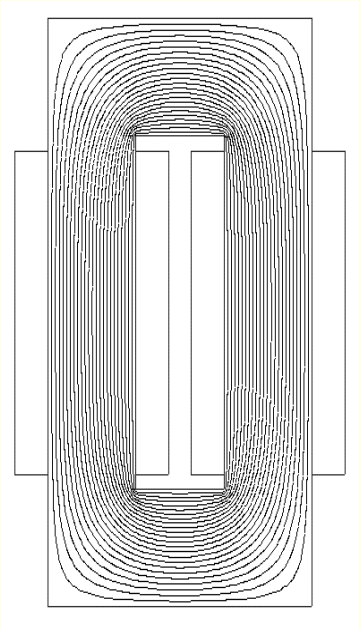
$$\psi_1 = \mathrm{L_1 i_1} - \mathrm{M i_2}$$

$$u_1 = i_1 R_1 + L_1 \frac{di_1}{dt} - M \frac{di_2}{dt}$$

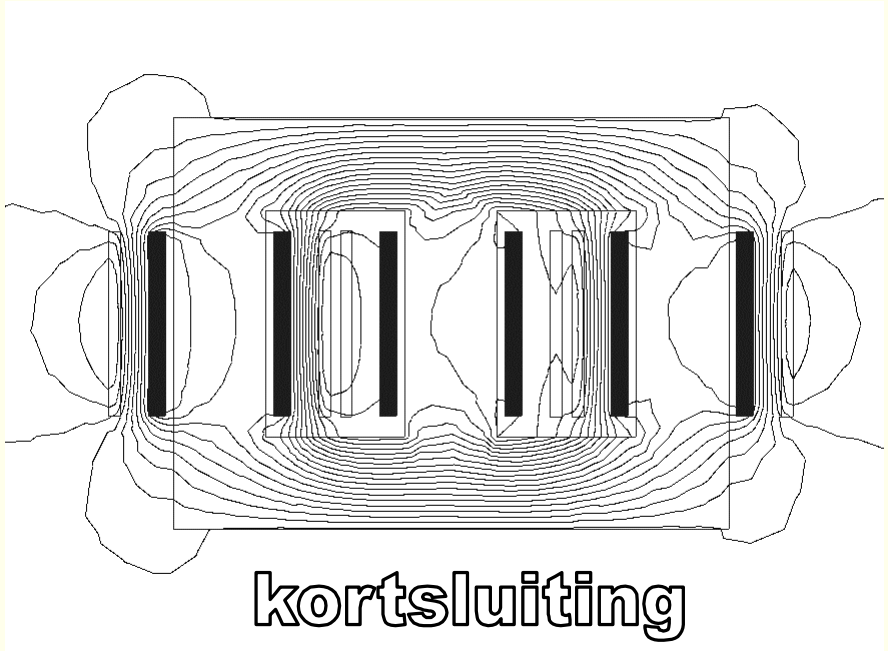
$$u_2 = -i_2 R_2 - L_2 \frac{di_2}{dt} + M \frac{di_1}{dt}$$

Hoofdinductanties en lek- en strooiinductanties





nullast



kortsluiting

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

$$\psi_1 = L_1 i_1 - M i_2$$
$$\psi_2 = M i_1 - L_2 i_2$$

$$\psi_1 = L_{\sigma 1} i_1 + \left(L_{h1} i_1 - M i_2 \right)$$
$$\psi_2 = -L_{\sigma 2} i_2 + \left(M i_1 - L_{h2} i_2 \right)$$

$$\phi_{\sigma 1} = \frac{L_{\sigma 1} i_1}{N_1}$$

$$\phi_{\sigma 2} = \frac{L_{\sigma 2} i_2}{N_2}$$

$$\phi_h = \frac{L_{h1} i_1}{N_1} - \frac{M i_2}{N_1} = -\frac{L_{h2} i_2}{N_2} + \frac{M i_1}{N_2} = \frac{M i_1}{N_2} - \frac{M i_2}{N_1}$$

$$\psi_1 = N_1 \phi_{\sigma 1} + N_1 \phi_h$$

$$\psi_2 = -N_2 \phi_{\sigma 2} + N_2 \phi_h$$

$$L_{h1} \cong L_{h1}^*$$

Equivalent schema

$$u_1 = R_1 i_1 + \frac{d\psi_1}{dt}$$

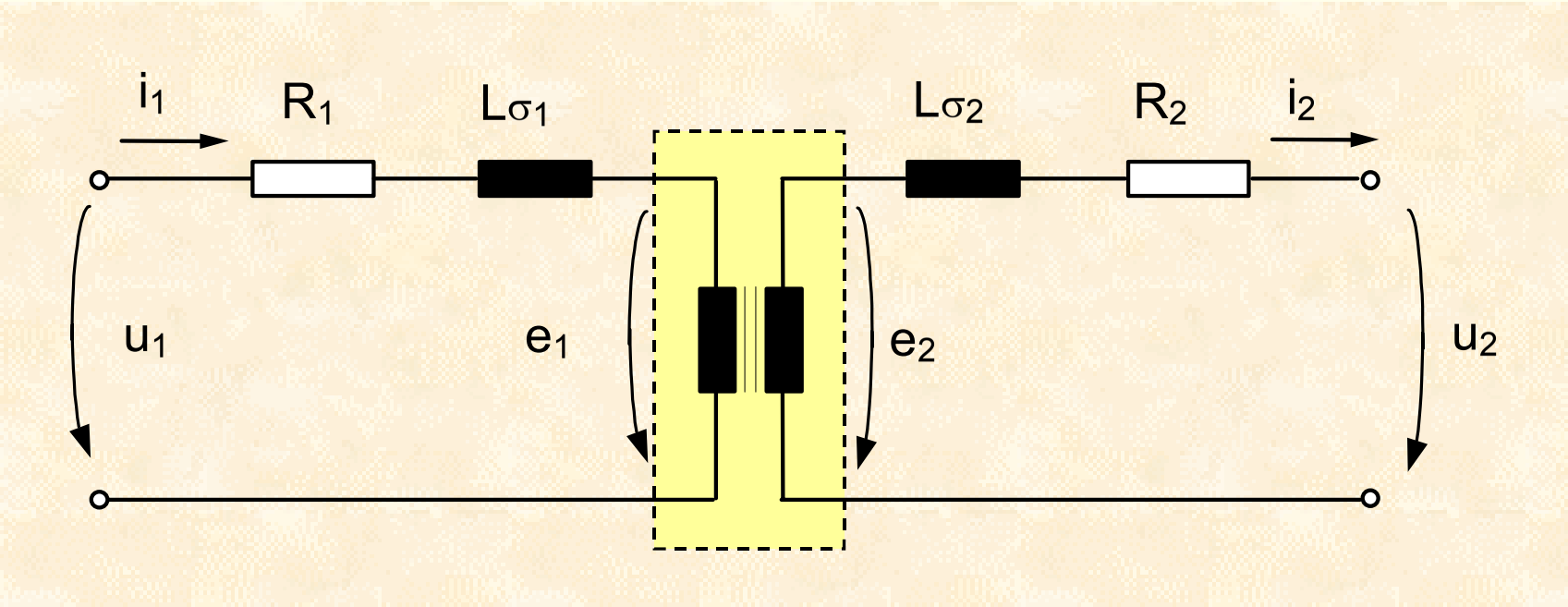
$$u_2 = -R_2 i_2 + \frac{d\psi_2}{dt}$$

$$u_1 = R_1 i_1 + L_{\sigma 1} \frac{di_1}{dt} + L_{h1} \frac{di_1}{dt} - M \frac{di_2}{dt}$$

$$u_2 = -R_2 i_2 - L_{\sigma 2} \frac{di_2}{dt} - L_{h2} \frac{di_2}{dt} + M \frac{di_1}{dt}$$

$$e_1 = L_{h1}\frac{di_1}{dt} - M\frac{di_2}{dt}$$

$$e_2 = -L_{h2}\frac{di_2}{dt} + M\frac{di_1}{dt}$$


i1
R1
Lσ1
Lσ2
R2
i2
u1
e1
e2
u2

Identieke vermogen

- Magnetische koppeling
- Galvanische koppeling

$$\ddot{u}.e_2 = e_2' = e_1$$

$$\frac{i_2}{\ddot{u}} = i_2'$$

$$e_2' = \frac{N_1}{N_2} e_2 = -\frac{N_1}{N_2} L_{h2} \frac{N_1}{N_2} \frac{di_2'}{dt} + \frac{N_1}{N_2} M \frac{di_1}{dt}$$

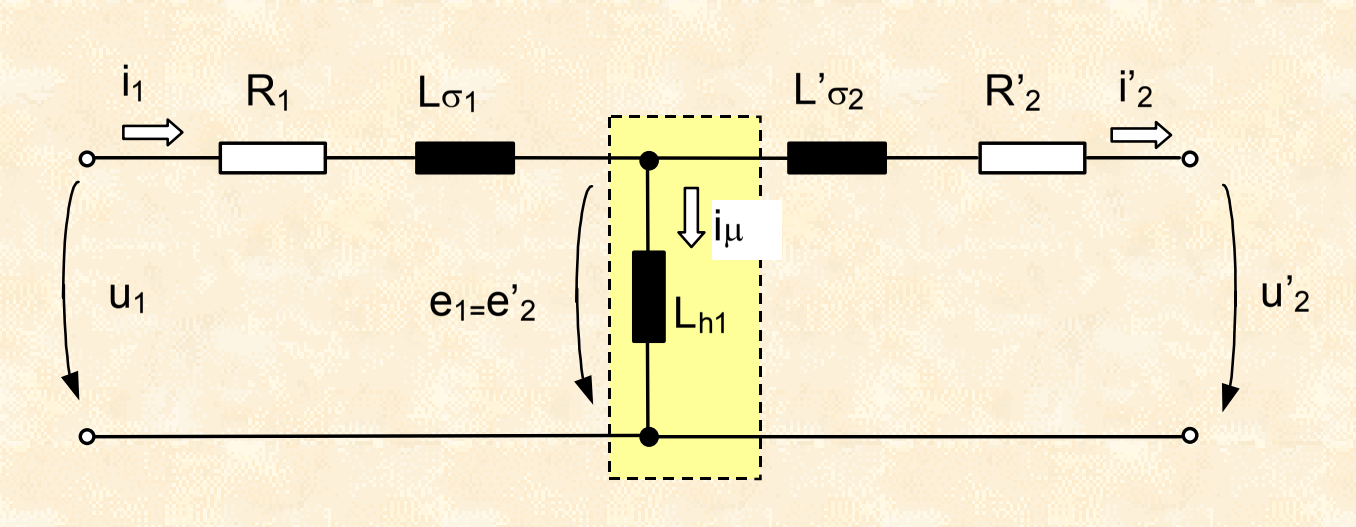
$$e_2' = L_{h1} \left(\frac{di_1}{dt} - \frac{di_2'}{dt} \right)$$

$$e_1 = L_{h1} \left(\frac{di_1}{dt} - \frac{di_2'}{dt} \right) = e_2'$$

$$e_1 = e_2' = L_{h1} \frac{di_{\mu 1}}{dt}$$

$$i_{\mu 1} = i_1 - i_2'$$

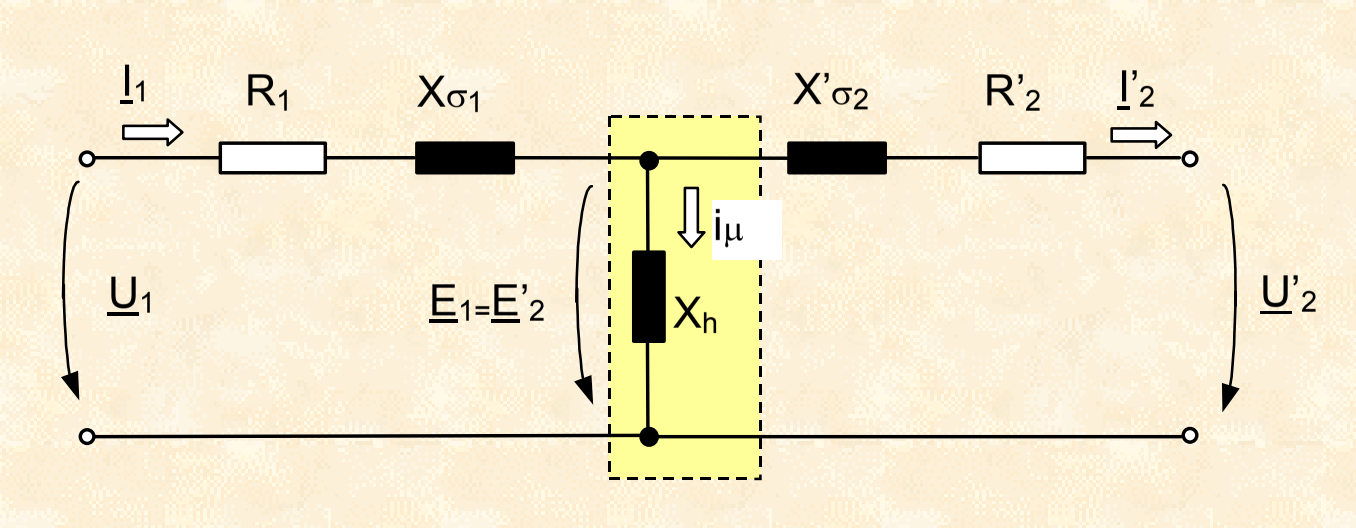
Equivalent schema



$$u_1 = R_1 i_1 + L_{\sigma 1}\frac{di_1}{dt} + L_{h1}\frac{di_{1\mu}}{dt}$$

$$u_2^{'} = -R_2^{'} i_2^{'} - L_{\sigma 2}^{'}\frac{di_2^{'}}{dt} + L_{h1}\frac{di_{1\mu}}{dt}$$

Stationaire toestand

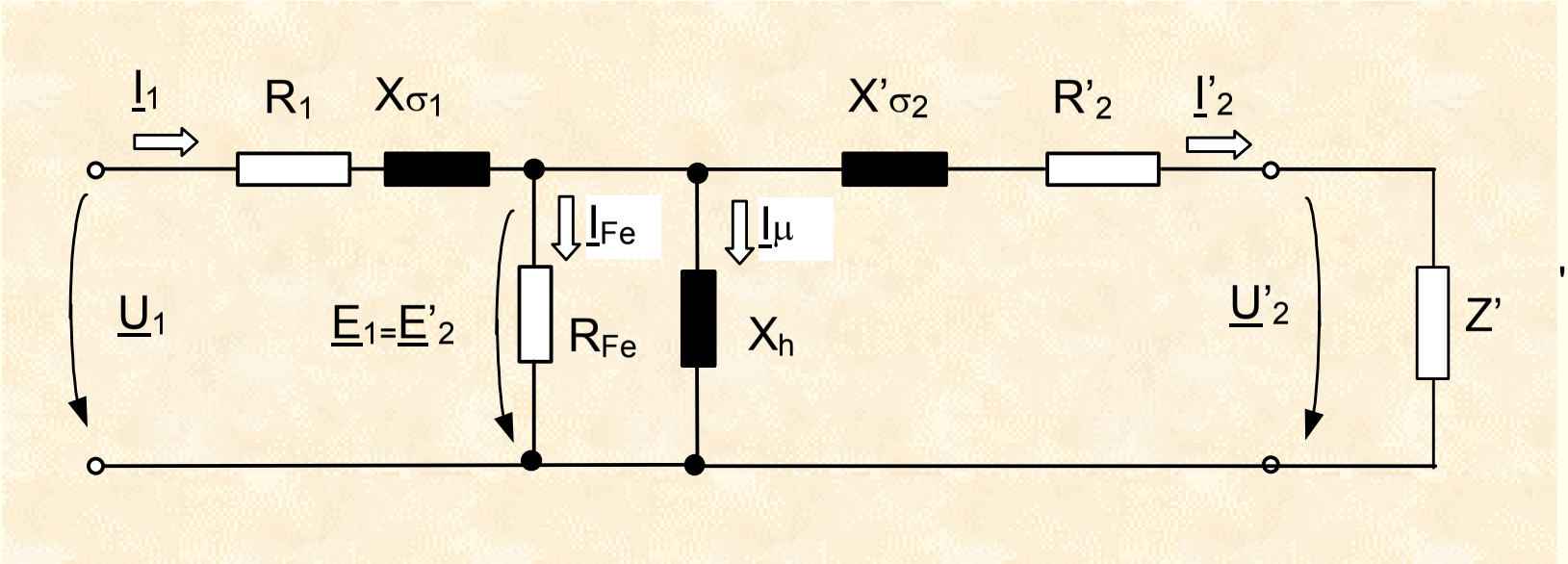


$$\underline{U}_1 = R_1 \underline{I}_1 + jX_{\sigma 1} \underline{I}_1 + jX_h \underline{I}_\mu$$

$$\underline{U}_2^{'} = -R_2^{'} \underline{I}_2^{'} - jX_{\sigma 2}^{'} \underline{I}_2^{'} + jX_h \underline{I}_\mu$$

$$\underline{I}_\mu = \underline{I}_1 - \underline{I}_2^{'}$$

Ijzerverliezen



Fasordiagram

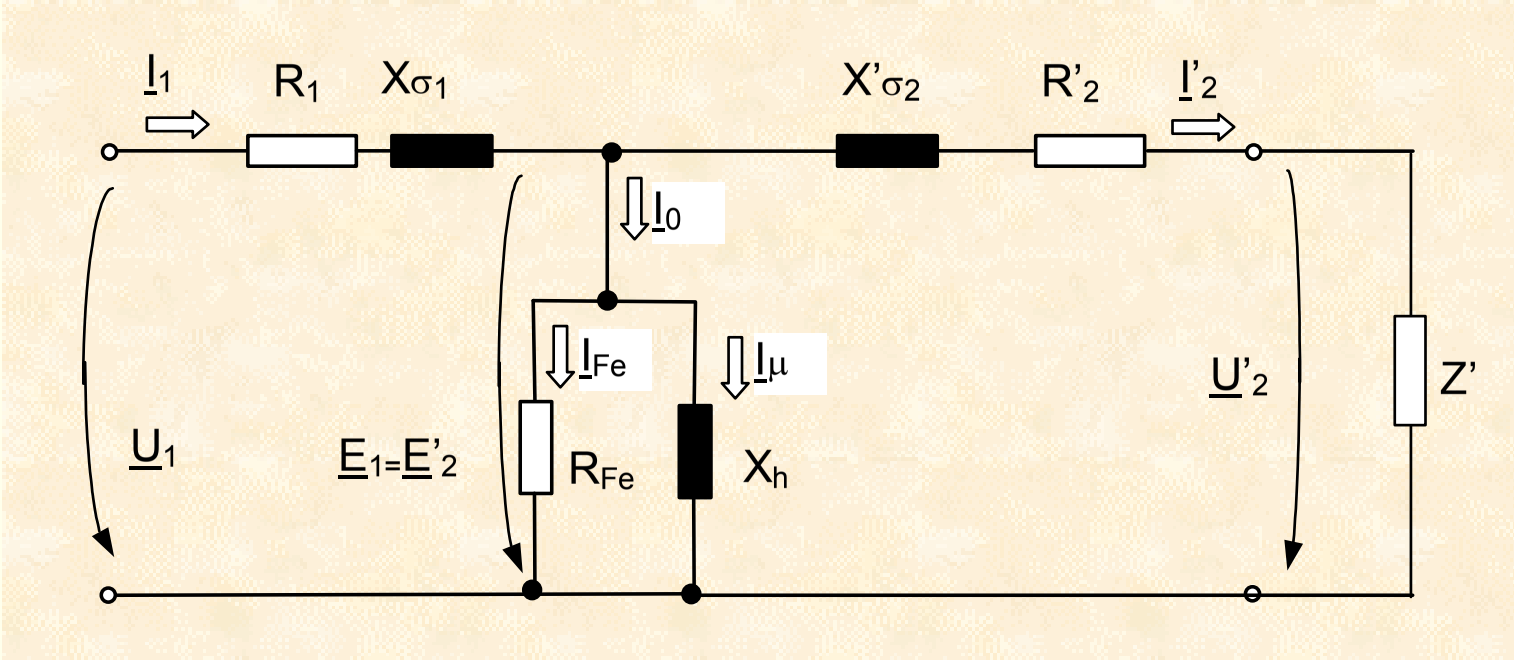
$$\underline{U}_1 = R_1 \underline{I}_1 + jX_{\sigma 1} \underline{I}_1 + \underline{E}_1$$

$$\underline{U}_2' = -R_2' \underline{I}_2' - jX_{\sigma 2}' \underline{I}_2' + \underline{E}_2'$$

$$\underline{E}_1 = \underline{E}_2' = jX_h \underline{I}_\mu = R_{Fe} \underline{I}_{Fe}$$

$$\underline{I}_1 - \underline{I}_2' = \underline{I}_0 = \underline{I}_{Fe} + \underline{I}_\mu$$

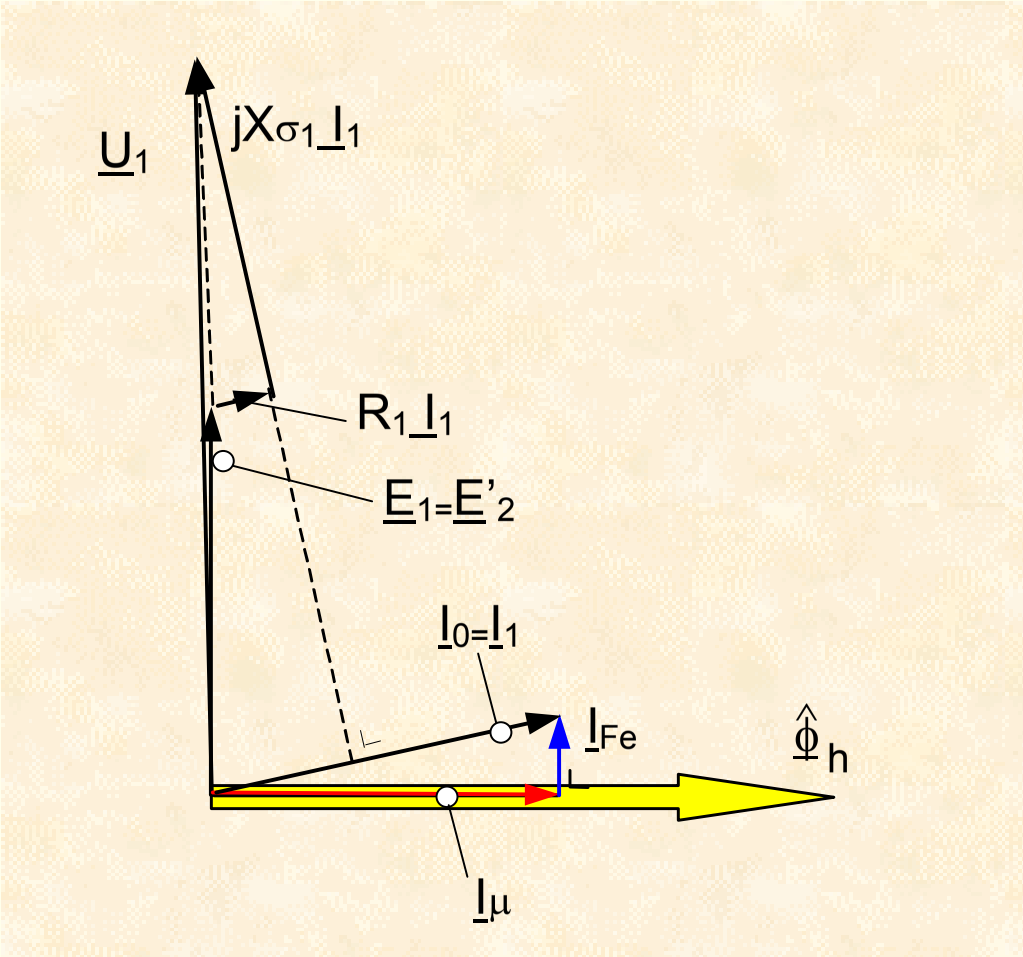
$$\underline{U}_2' = \underline{I}_2' \underline{Z}'$$



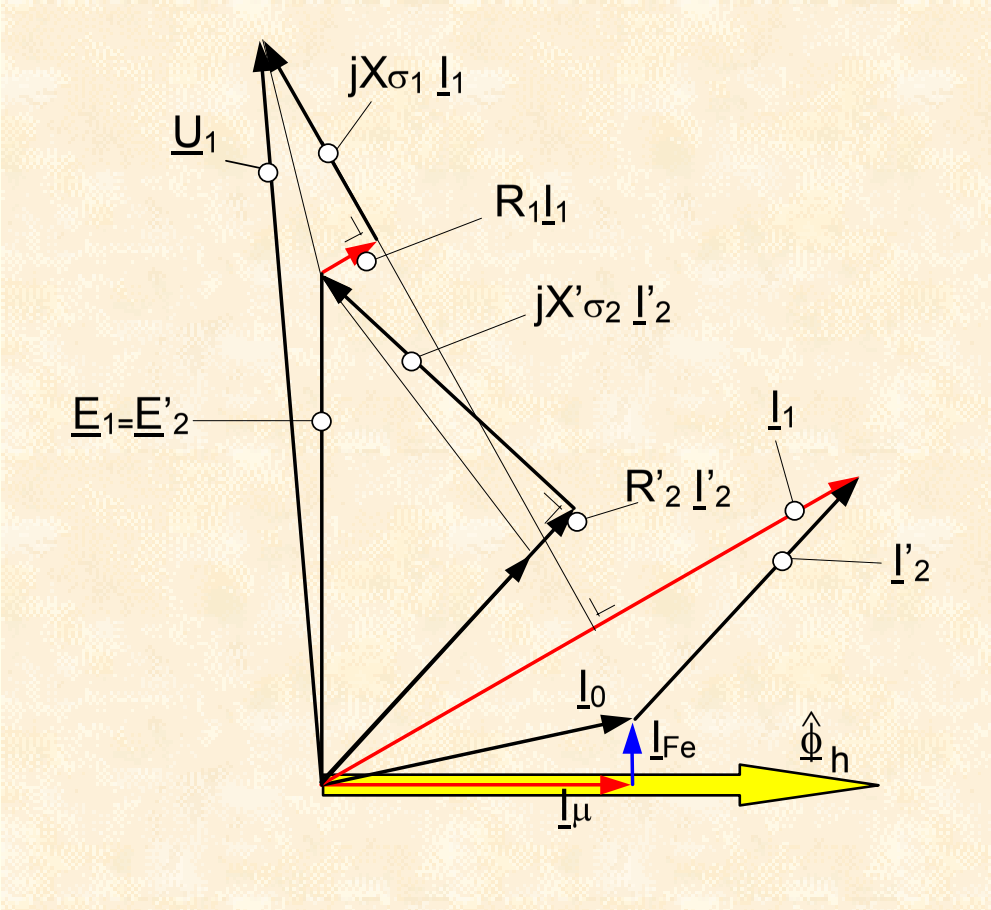
$$\underline{E}_1 = j4,44 N_1 f \hat{\phi}_h$$

$$\underline{I}_1 = \underline{I}_\mu + \underline{I}_{Fe} = \underline{I}_0$$

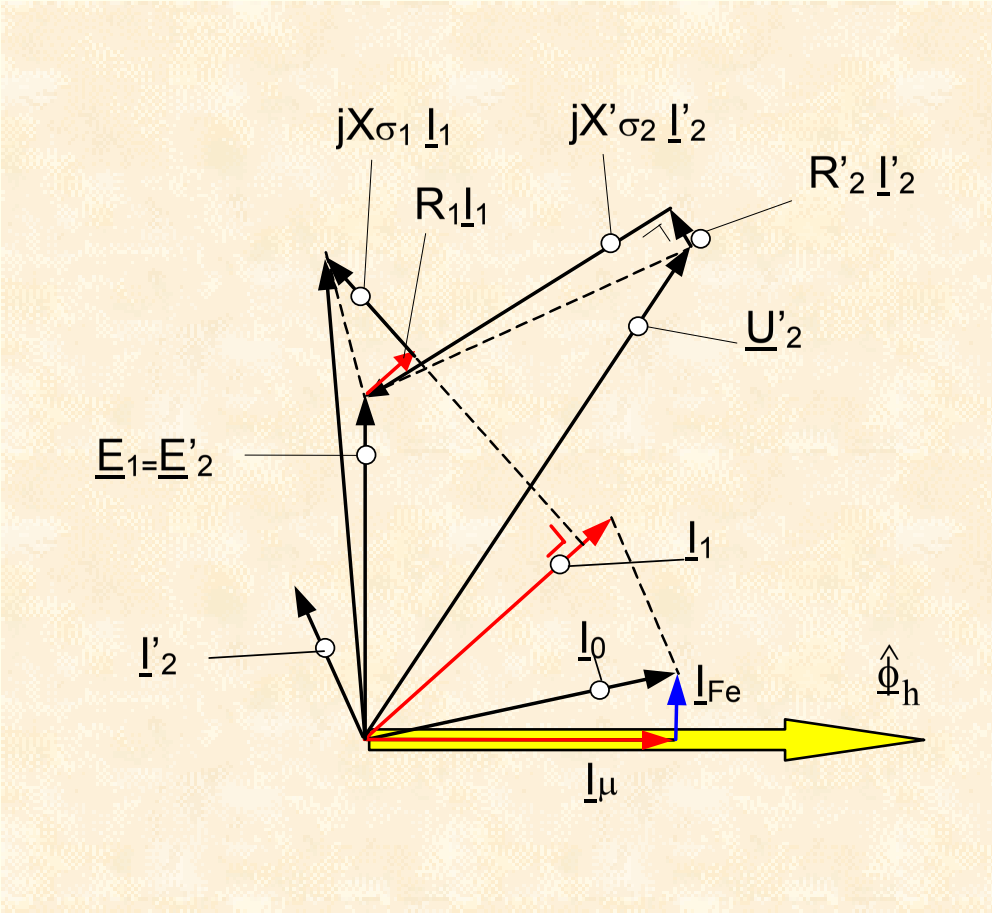
Fasordiagramma bij nullast



Fasordiagramma bij ohmse belasting



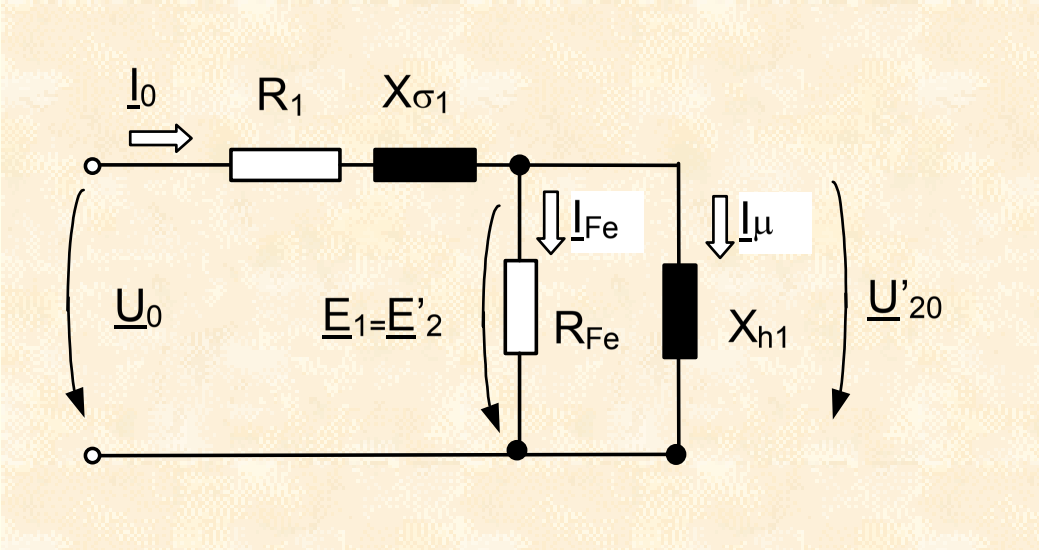
Fasordiagramma bij resistieve-capacitieve belasting

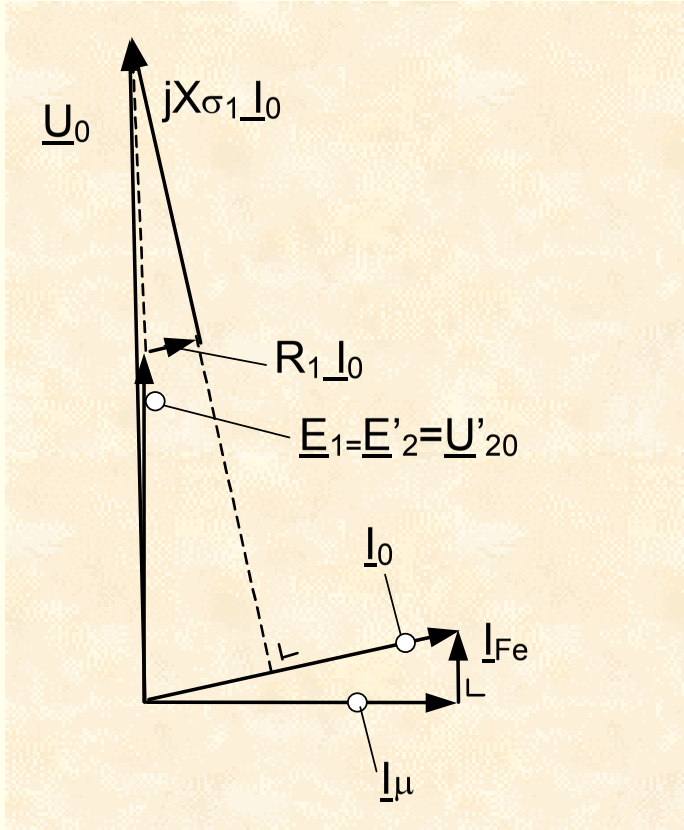


Bedrijfstoestanden van de eenfasige transformator

- Nullast
- Kortsluiting
- Belasting
- Overgangsverschijnselen
- Verliezen, rendement en groeiwetten
- Invloed van de harmonische netvervuiling

Nullast - Kenmerken





$$\underline{I}_0 = \frac{\underline{U}_0}{R_1 + jX_{\sigma 1} + j\dfrac{X_{h1}R_{Fe}}{R_{Fe} + jX_{h1}}}$$

$$P_0 = P_{J10} + P_{Fe}$$

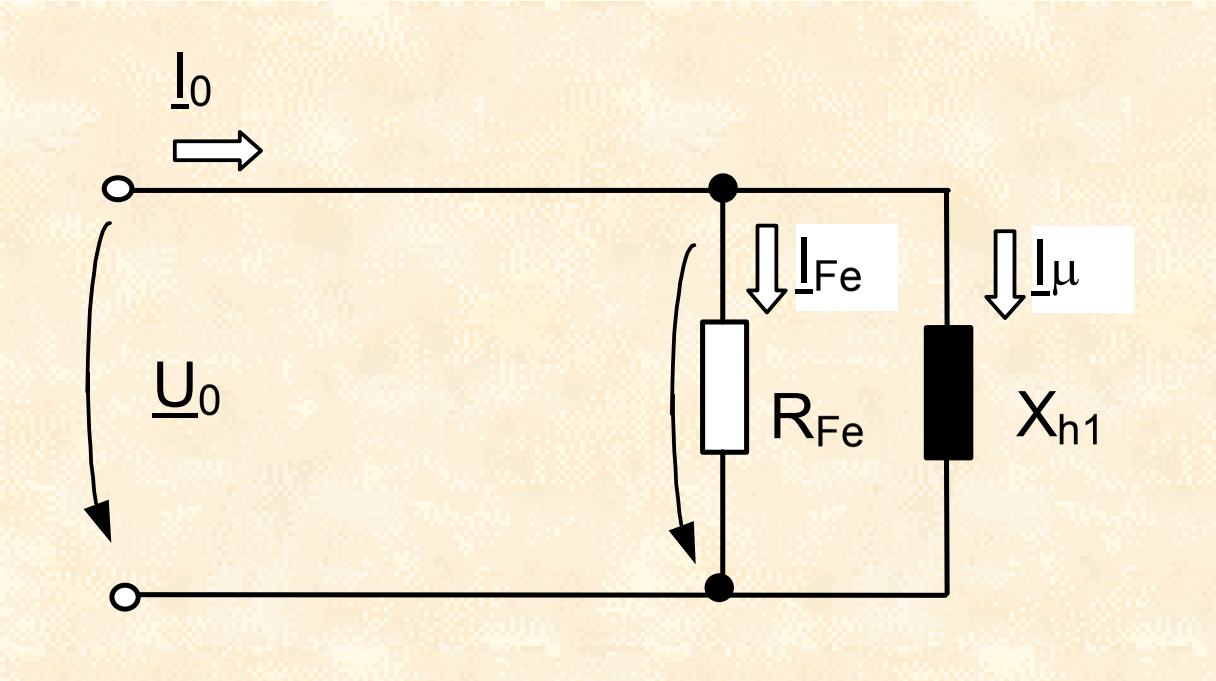
$$\underline{I}_\mu \approx \frac{\underline{U}_0}{jX_{h1}} = -j\frac{\underline{U}_0}{X_{h1}}$$

$$\underline{I}_{Fe} \approx \frac{\underline{U}_0}{R_{Fe}}$$

$$\underline{I}_0 = \underline{I}_\mu + \underline{I}_{Fe}$$

kleine 1-fasige transformatoren			3-fasige transformatoren		
S_n [VA]	i_{10} [%]	$\cos\varphi_0$	S_n [kVA]	i_{10} [%]	$\cos\varphi_0$
25	22	0,28 ... 0,35	10	3	0,35 ... 0,4
125	16		50	1,5	
250	15		100	0,8	
500	14		1000	0,5	
1000	13		10000	0,3	
2000	11		100000	0,21	
4000	8		300000	0,18	

Nullastproef



$$\cos\varphi_0 = \frac{P_0}{U_0 I_0}$$

$$I_{Fe} = I_0 \cos \varphi_0$$

$$I_{\mu} = I_0 \sin \varphi_0$$

$$R_{Fe} = \frac{U_0}{I_{Fe}} = \frac{U_0}{I_0 \cos \varphi_0}$$

$$X_{h1} = \frac{U_0}{I_{\mu}} = \frac{U_0}{I_0 \sin \varphi_0}$$

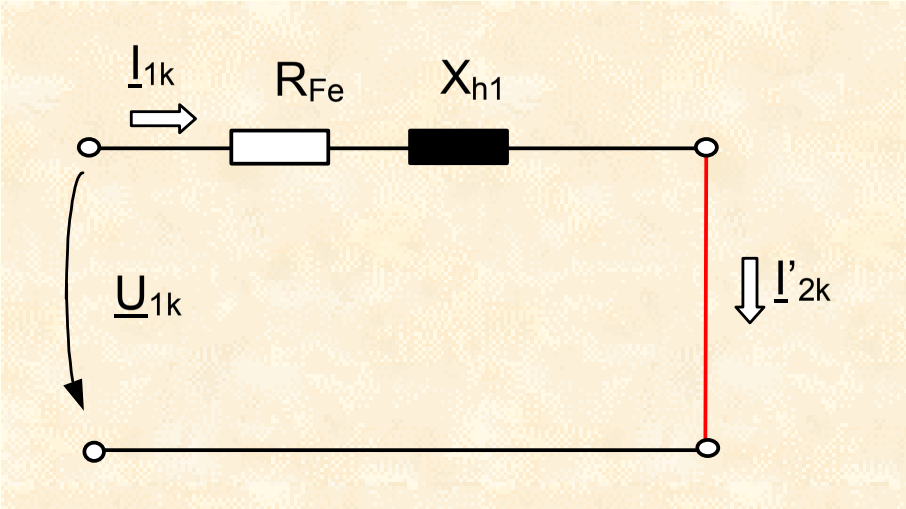
Kortstluiting - Stationair

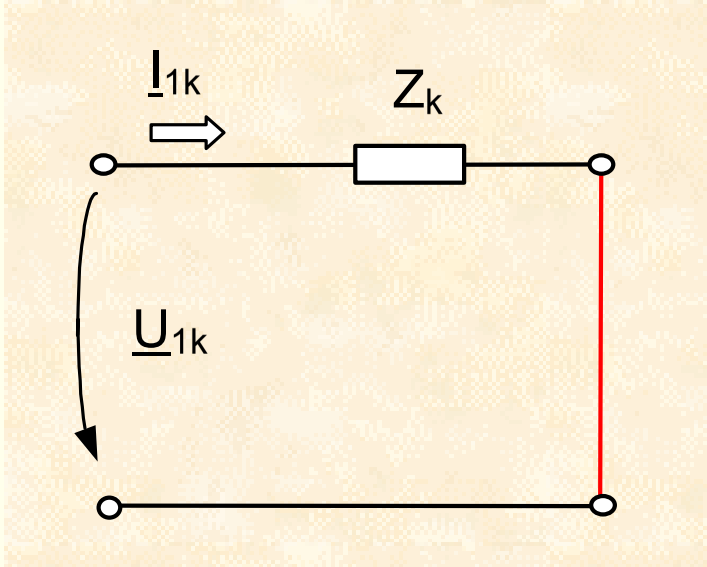
$$R_k = R_1 + R_2^{'}$$

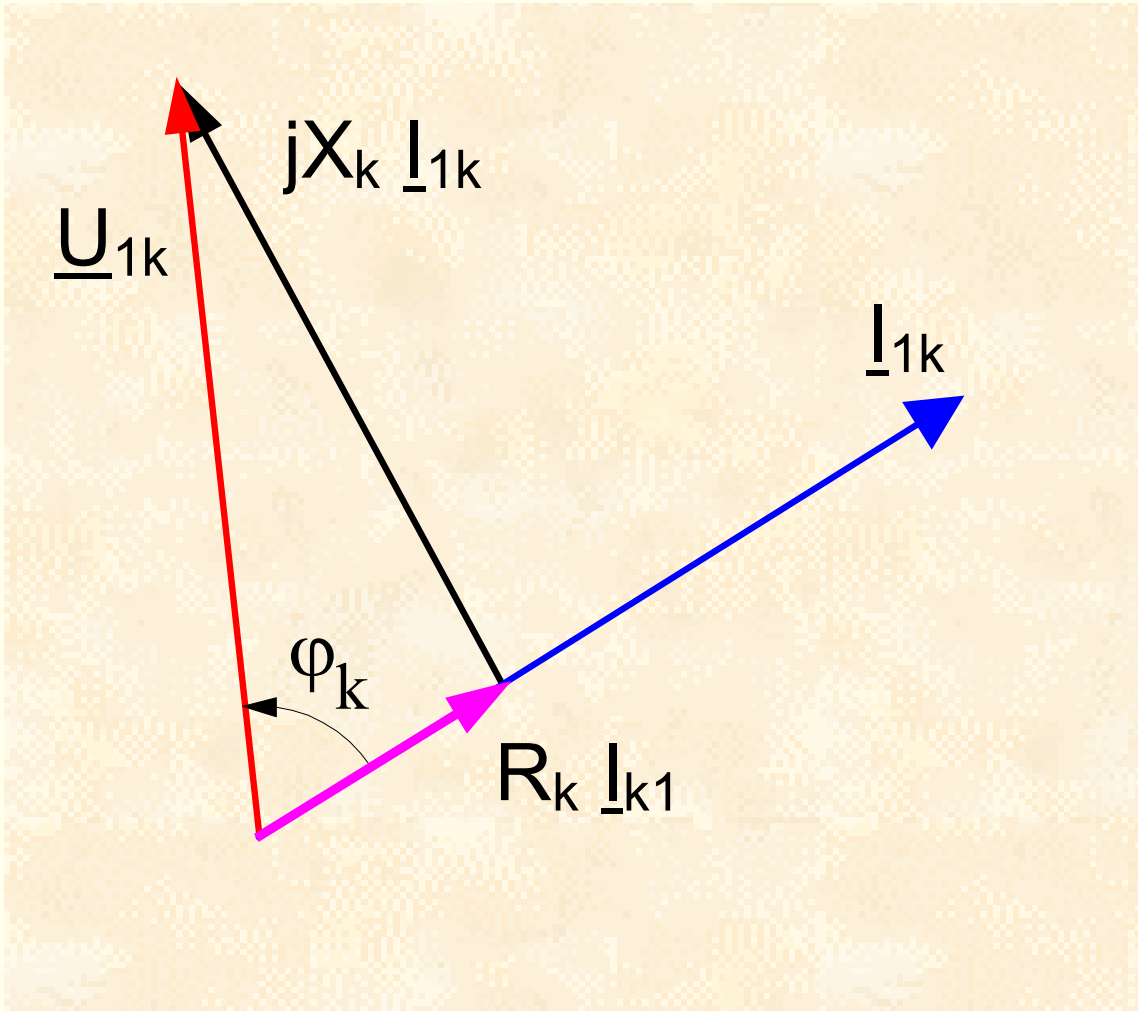
$$X_k = X_{\sigma 1} + X_{\sigma 2}^{'}$$

$$\underline{Z}_k = R_k + jX_k$$

$$\underline{I}_{1k} = \frac{\underline{U}_{1k}}{\underline{Z}_k}$$


I1k
RFe
Xh1
U1k
I'2k


I1k
Zk
U1k


jXk I1k
U1k
I1k
φk
Rk Ik1

Kortsluitstroom

- Invloed van de strooiing
- Procentuele kortsluitspanning

$$\underline{U}_k = \underline{I}_N \underline{Z}_k$$

$$u_k = \frac{U_k}{U_N}$$

$$u_k(\%) = \frac{U_k}{U_N}.100$$

kleine 1-fasige transformatoren			3-fasige transformatoren		
S_n [VA]	u_k [%]	$\cos\varphi_k$	S_n [VA]	u_k [%]	$\cos\varphi_k$
25	15,5	0,96	10	3	0,66
125	7,7	0,93	50	3,5	0,43
250	6,2	0,89	100	4	0,3
500	4,4	0,84	1000	5	0,14
1000	2,6	0,77	10000	8,4	0,06
2000	2,4	0,54	100000	13	0,025
4000	2,2	0,43	300000	17,5	0,013

$$I_{kN} = \frac{U_N}{Z_k} = \frac{U_N I_N}{Z_k I_N} = \frac{U_N}{U_k} I_N$$

$$Z_k = \sqrt{R_k^2 + X_k^2}$$

$$\frac{I_{kN}}{I_N} = \frac{U_N}{U_k} = \frac{1}{u_k}$$

$$u_R = \frac{U_R}{U_N} = \frac{R_k I_N}{U_N} = \frac{R_k I_N^2}{U_N I_N} = \frac{P_J}{S_N}$$

$$u_X = \frac{X_k I_N}{U_N}$$

$$u_k = \sqrt{u_R^2 + u_X^2}$$

$$tg\,\varphi_k = \frac{u_X}{u_R}$$

Kortsluitproef

$$Z_k = \frac{U_k}{I_k}$$

$$P_k = R_k I_k^2$$

$$R_k = \frac{P_k}{I_k^2}$$

$$X_k = \sqrt{Z_k^2 - R_k^2}$$

$$R_1 = R_2^{'} = \frac{1}{2} R_k$$

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

Equivalent schema

$$\ddot{u} = \frac{U_1}{U_2} \approx \frac{e_1}{e_2} \approx \frac{N_1}{N_2}$$

Nominale toestand

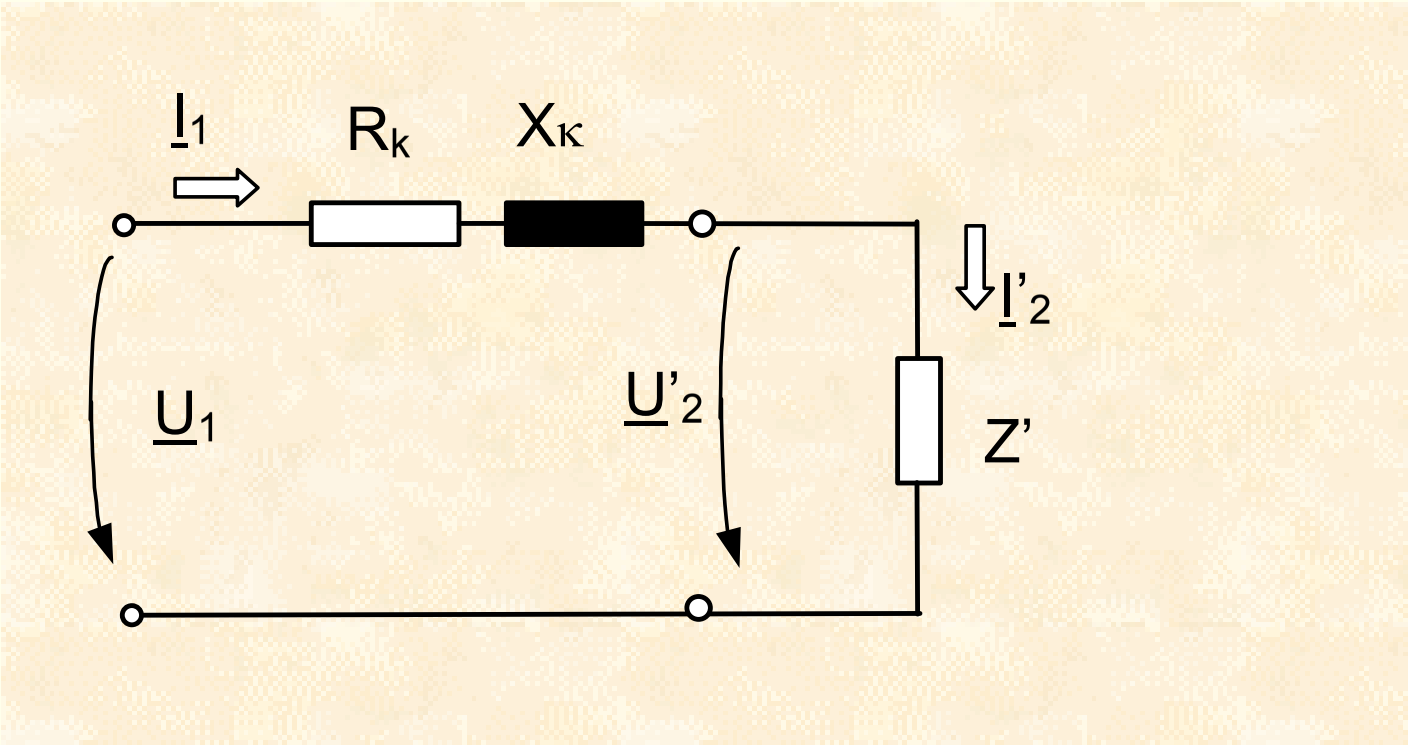
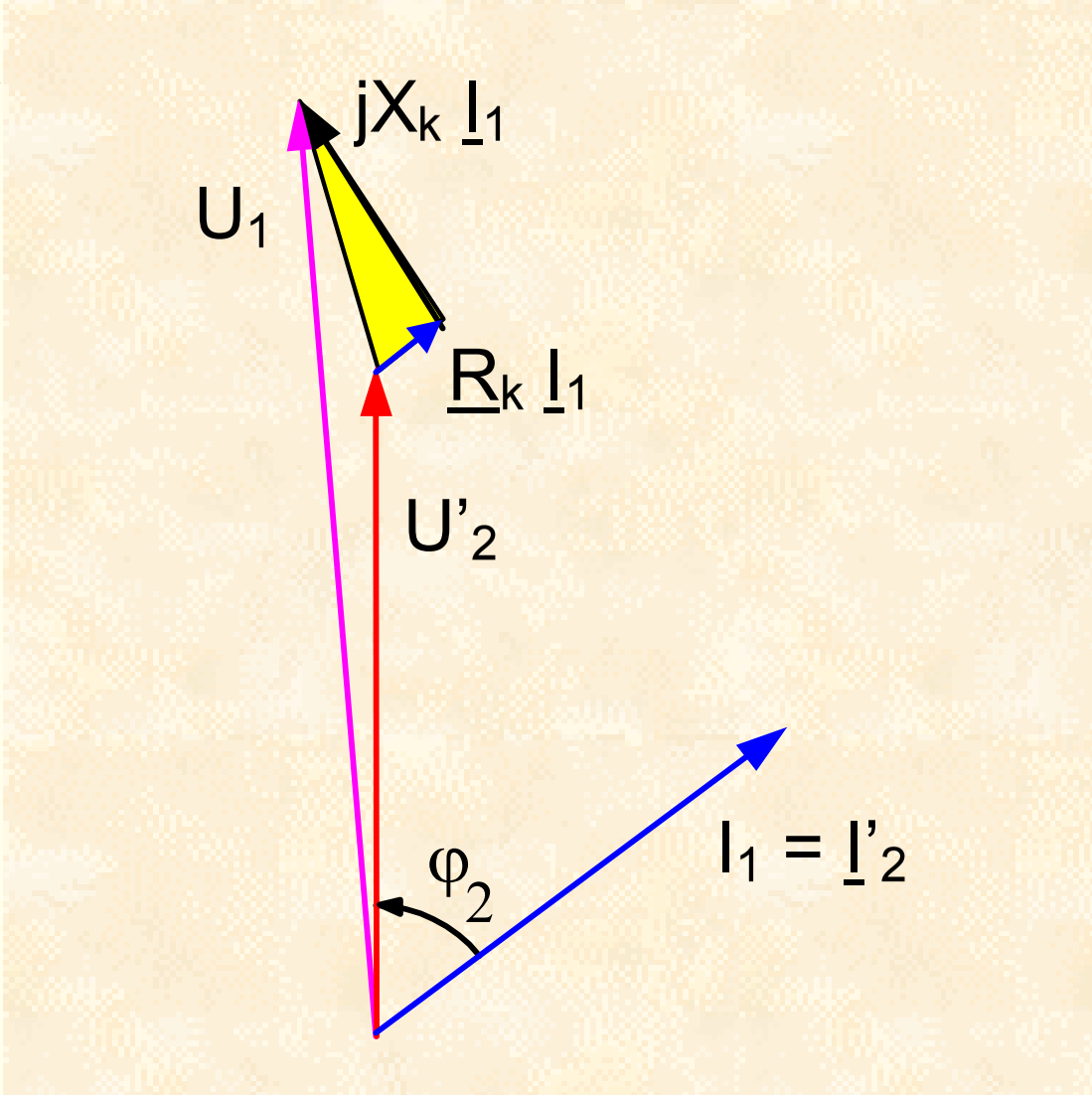


Diagramma van Kapp

$$\underline{I}_2' = \underline{I}_1$$

$$\underline{U}_1 = \underline{U}_2' + R_k \underline{I}_1 +$$



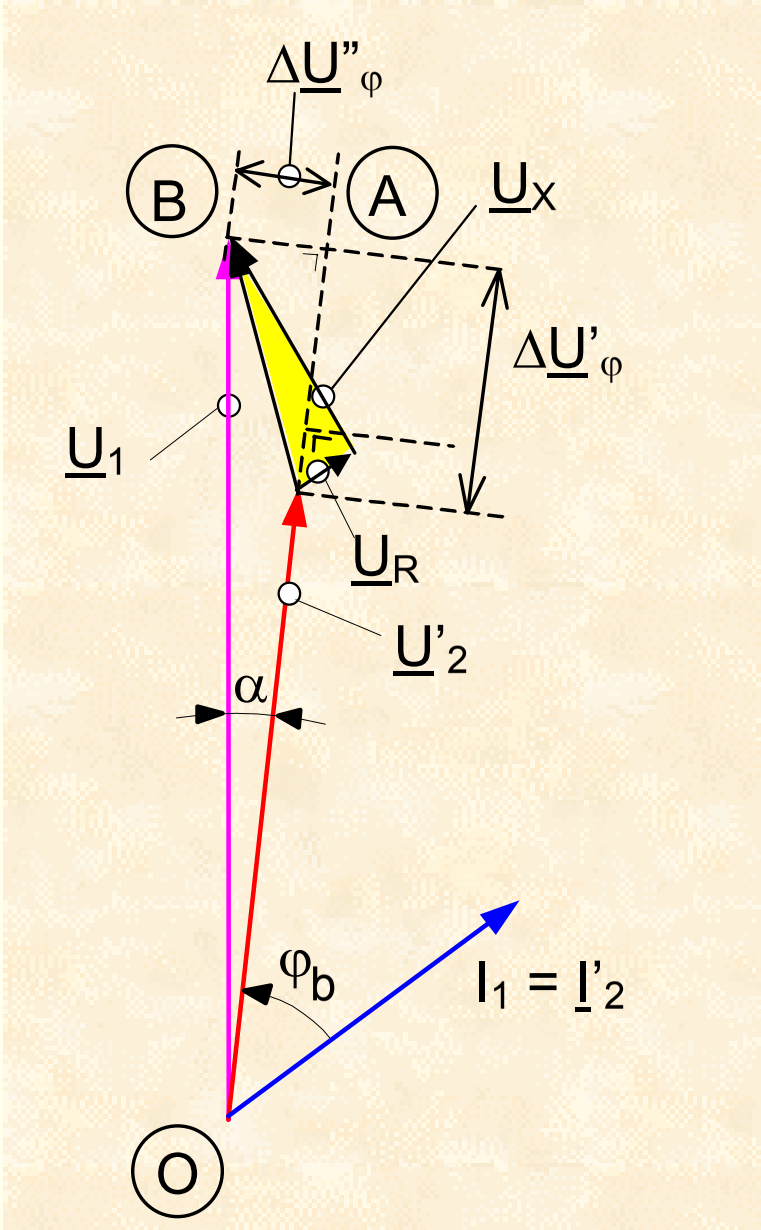
Spanningsverandering bij belasting

$$\underline{\Delta U} = \underline{U}_1 - \underline{U}_2'$$

$$\Delta U_\varphi' = U_R \cos\varphi_b + U_X \sin\varphi_b$$

$$\Delta U_\varphi'' = U_X \cos\varphi_b - U_R \sin\varphi_b$$

Spanningsval bij belasting



$$U_1^2 = \left(U_2^{'} + \Delta U_\varphi^{'}\right)^2 + \left(\Delta U_\varphi^{''}\right)^2$$

$$U_2^{'} = \sqrt{U_1^2 - \Delta U_\varphi^{''\,2}} - \Delta U_\varphi^{'}$$

$$U_2^{'} = U_1\sqrt{1 - \left(\frac{\Delta U_\varphi^{''}}{U_1}\right)^2} - \Delta U_\varphi^{'}$$

$$U_2^{'} = U_1 - \frac{1}{2}\frac{\Delta U_\varphi^{''\,2}}{U_1} - \Delta U_\varphi^{'}$$

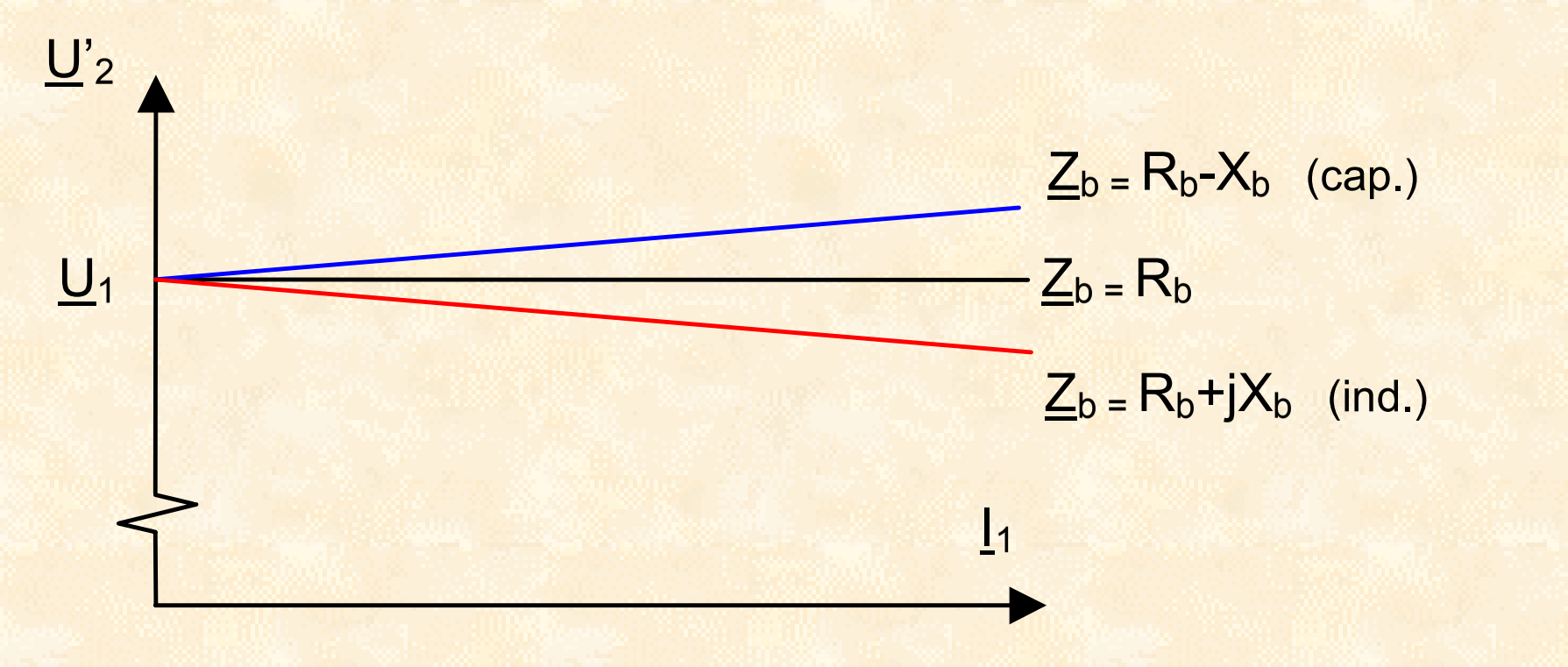
$$\Delta U = U_1 - U_2' = \Delta U_\varphi' + \frac{1}{2}\frac{\Delta U_\varphi''^{\,2}}{U_1}$$

$$\Delta u = \frac{\Delta U}{U_1} = \frac{U_1 - U_2'}{U_1} = \frac{\Delta U_\varphi'}{U_1} + \frac{1}{2}\frac{\Delta U_\varphi''^{\,2}}{U_1^2}$$

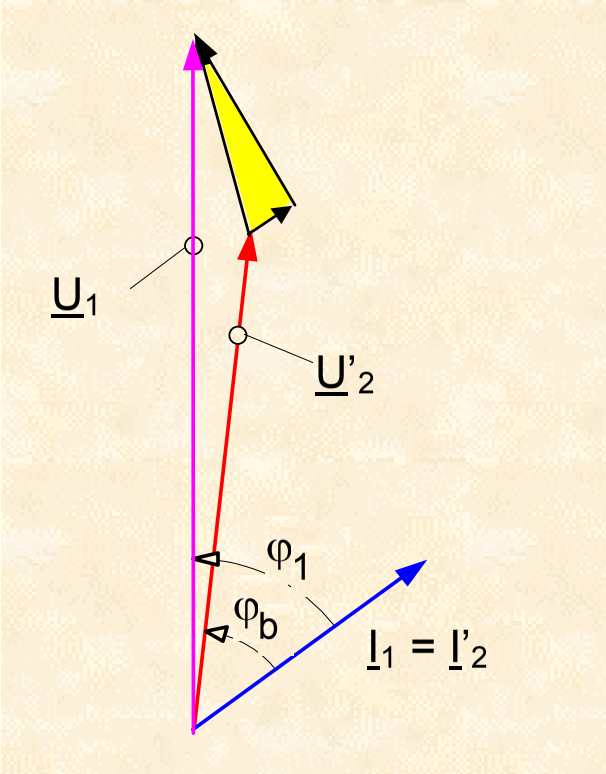
$$= \Delta u_\varphi' + \frac{1}{2}\Delta u_\varphi''^{\,2}$$

$$\Delta u = \Delta u_\varphi' = u_R \cos\varphi_b + u_X \sin\varphi_b$$

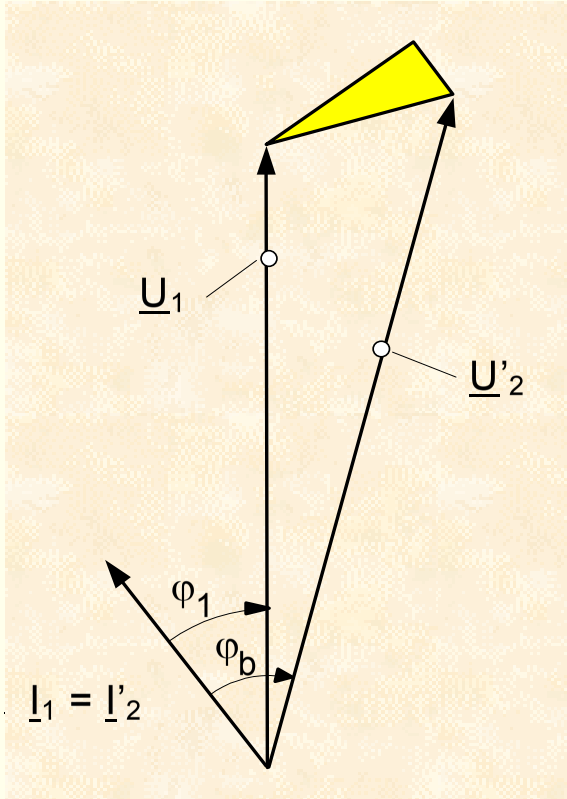
Spanningsverandering



Fasordiagram



R-L



R-C

Overgangsverschijnselen

- Inschakelstroom
- Stootkortsluiting

Inschakelstroomstoot

$$u_1 = R_1 i_1 + N_1 \frac{d\phi}{dt}$$

$$u_1 = \sqrt{2}\, U_1 \sin\left(\omega t + \alpha\right)$$

$$\frac{d\phi}{dt} = \sqrt{2}\frac{U_1}{N_1}\sin\left(\omega t + \alpha\right) - \frac{R_1}{N_1} i_1$$

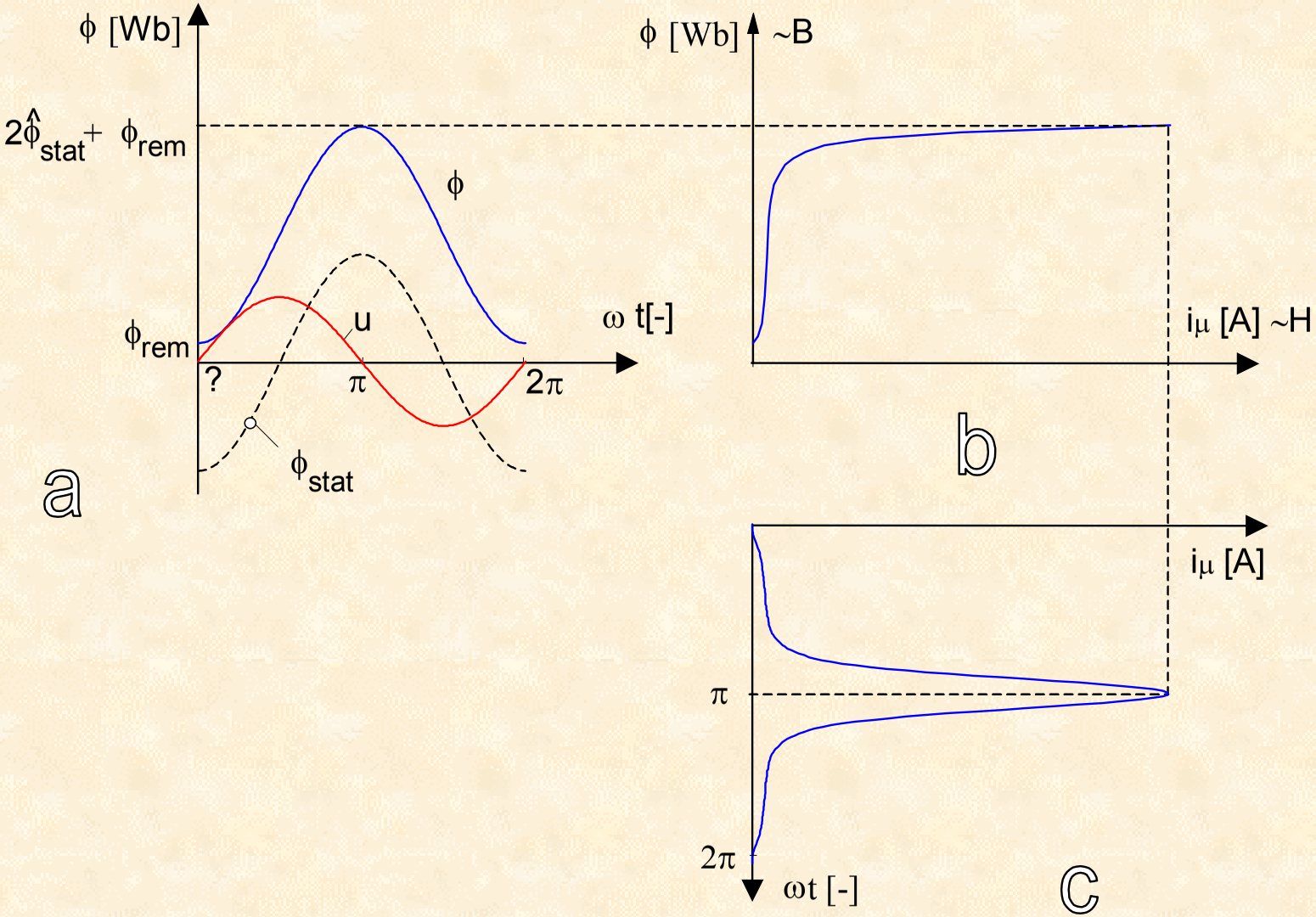
$$\phi\left(t\right) = -\frac{\sqrt{2}U_1}{\omega N_1}\cos\left(\omega t + \alpha\right) - \frac{R_1}{N_1}\int i_1 dt + C$$

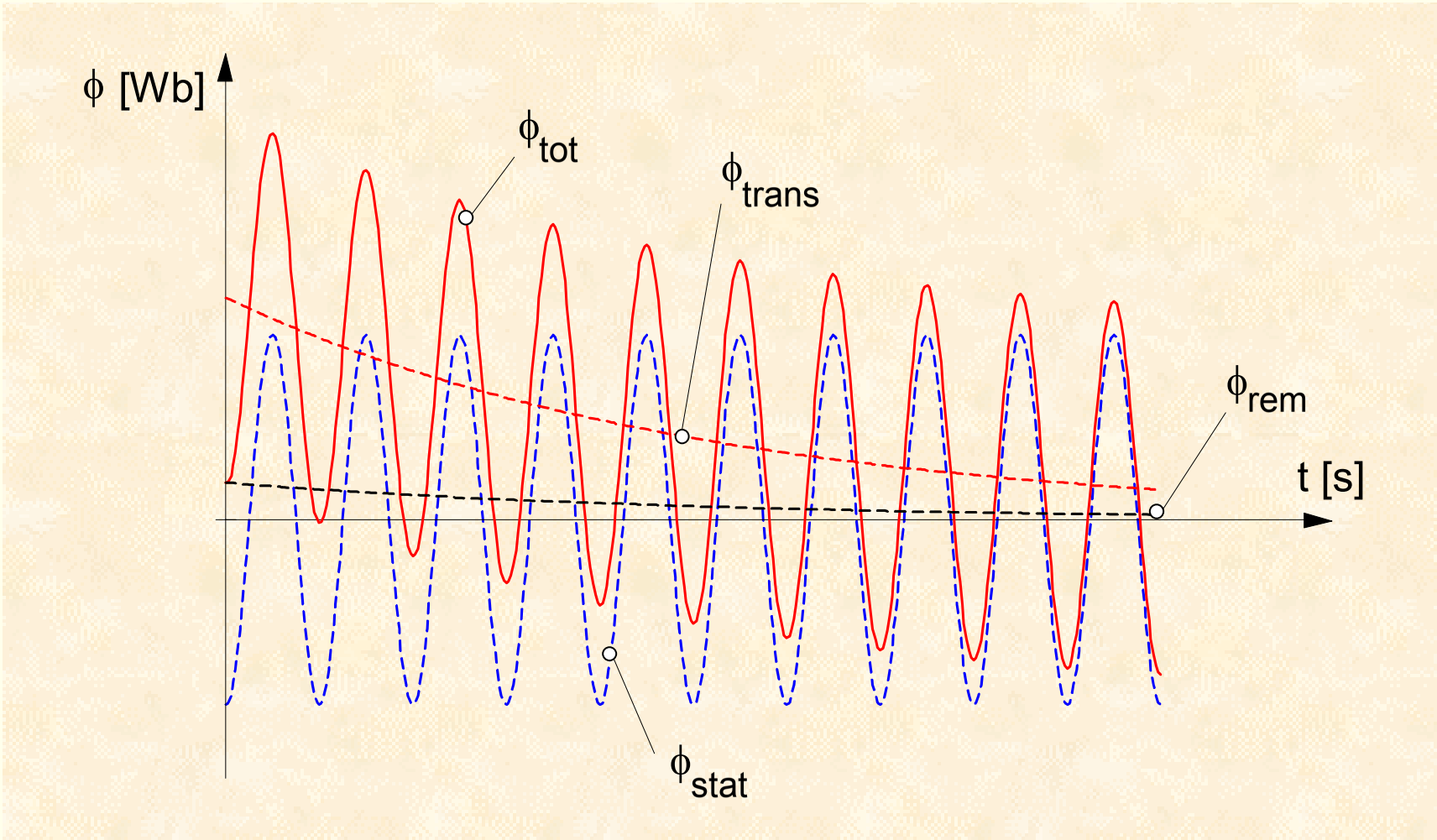
$$C = \phi_{rem} + \frac{\sqrt{2}U_1}{\omega N_1}\cos\alpha$$

$$\phi(t) = \phi_{rem} + \frac{\sqrt{2}U_1}{\omega N_1}\left[\cos\alpha - \cos(\omega t + \alpha)\right] - \frac{R_1}{N_1}\int i_1 dt$$

$$\phi(t) = \phi_{rem} + \hat{\phi}\left[\cos\alpha - \cos(\omega t + \alpha)\right]$$

	Verhouding inschakelstroom tot nominale stroom	
Trafo-vermogen	Hoogspanning	Laagspanning
500 kVA	11	16
5 MVA	6	10
50 MVA	4,5	9


ϕ [Wb]
2ϕ̂stat + ϕrem
ϕrem
ϕ
u
ω t[-]
?
π
2π
ϕstat
a
ϕ [Wb] ~B
iμ [A] ~H
b
iμ [A]
π
2π
ωt [-]
c


ϕ [Wb]
ϕtot
ϕtrans
ϕrem
t [s]
ϕstat

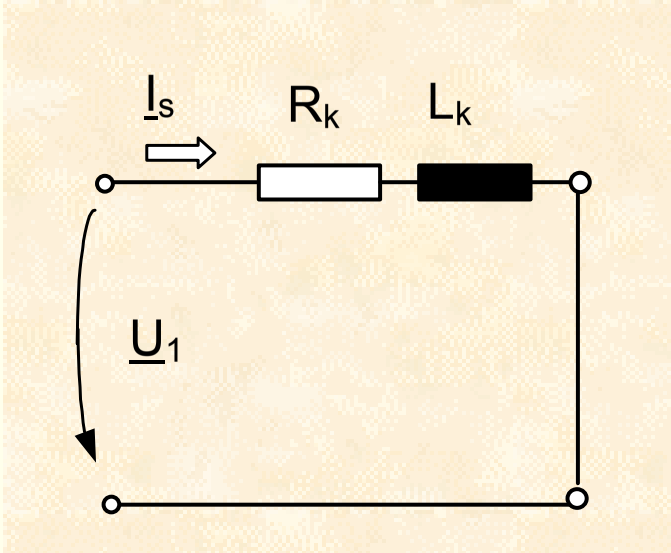
$$\phi(t) = \phi_{rem}\, e^{-t/\tau_1} - \hat{\phi}\left[\cos(\omega t + \alpha) - \cos\alpha\, e^{-t/\tau_1}\right]$$

$$\phi(t) = \phi_{stat} + \phi_{trans}$$

$$L_1 = L_{\sigma 1} + L_{h1}$$

$$\tau_1 = \frac{L_1}{R_1}$$

Stootkortsluiting



$$u_1 = U_1\sqrt{2}\sin\left(\omega t + \alpha\right) = R_k i_s + L_k \frac{di_s}{dt}$$

$$i_s(t=0) = 0$$

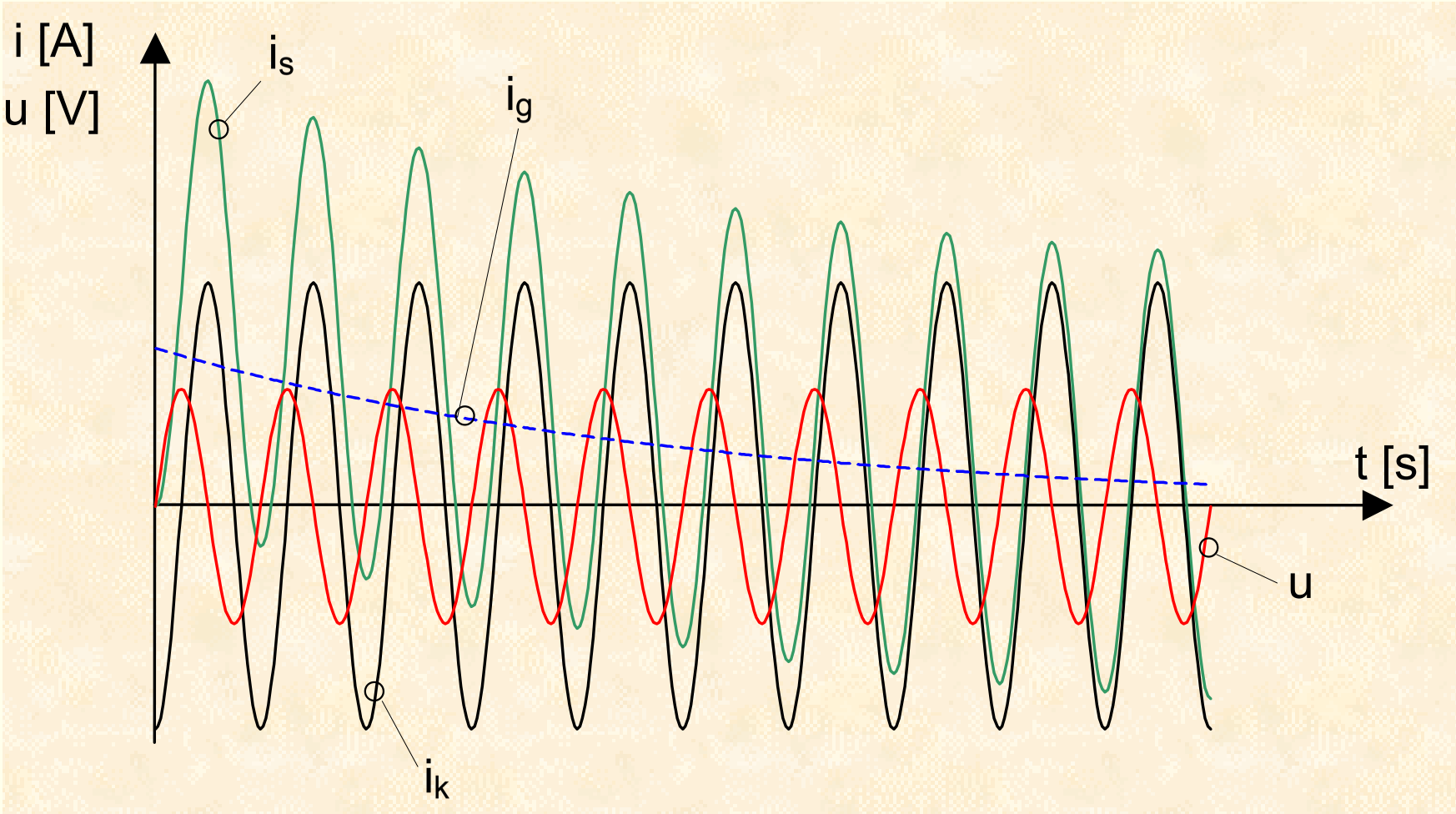
$$i_s = I_k \sqrt{2} \sin\left(\omega t + \alpha - C\right) - I_k \sqrt{2}\, e^{-\frac{R_k}{L_k} t} \sin\left(\alpha - \varphi_k\right)$$

$$i_s = i_k + i_g$$

$$I_k = \frac{\mathrm{U}_1}{\sqrt{\mathrm{R}_\mathrm{k}^2 + (\omega L_k)^2}}$$

$$\varphi_k = bgtg \frac{\omega L_k}{R_k}$$

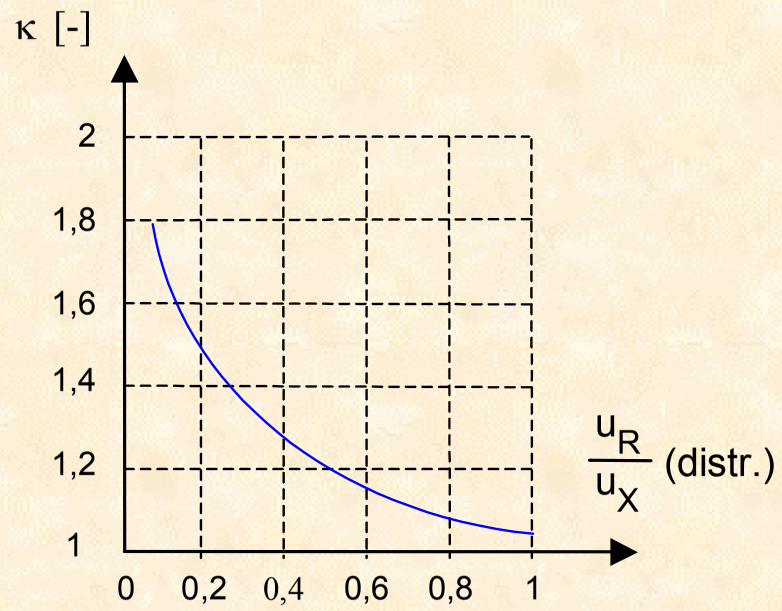
$$\tau_s = \frac{L_k}{R_k} = \frac{X_k}{\omega R_k} = \frac{1}{\omega} \frac{u_X}{u_R}$$

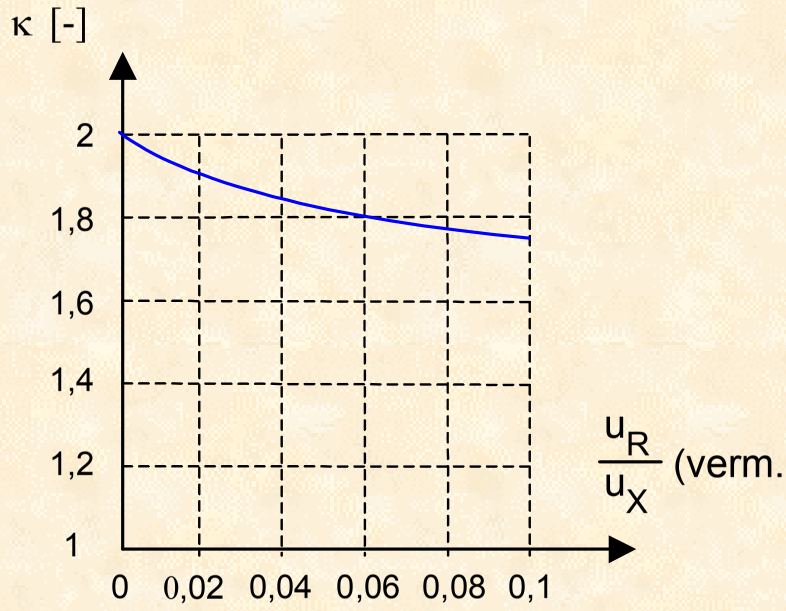

i [A]
u [V]
i_s
i_g
t [s]
u
i_k

$$i_s = I_k \sqrt{2} \left(-\cos \omega t + e^{-\frac{R_k}{L_k} t} \right)$$

$$\hat{I}_s = \sqrt{2} I_k \left(1 + e^{-\frac{R_k}{X_k} \pi} \right)$$

$$\kappa = 1 + e^{-\frac{R_k}{X_k} \pi} = 1 + e^{-\frac{u_R}{u_X} \pi}$$


κ [-]
2
1,8
1,6
1,4
1,2
1
0
0,2
0,4
0,6
0,8
1
$\frac{u_R}{u_X}$ (distr.)

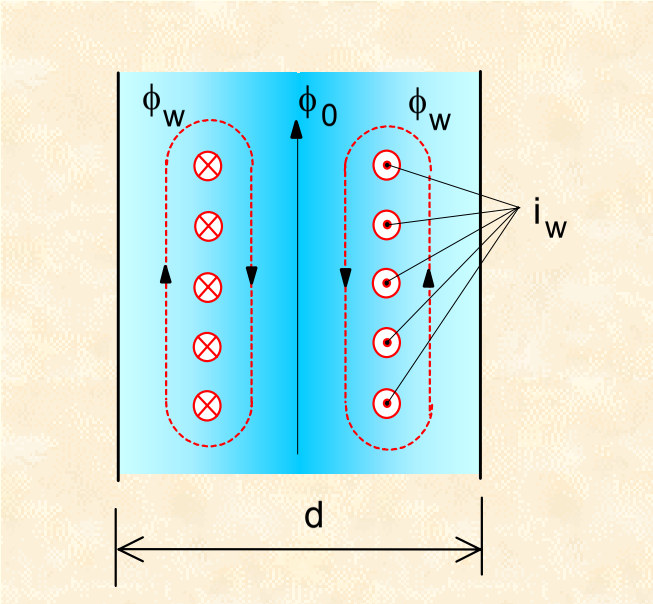

κ [-]
2
1,8
1,6
1,4
1,2
1
0
0,02
0,04
0,06
0,08
0,1
$\frac{u_R}{u_X}$ (verm.

Verliezen

- Ijzerverliezen
  - Wervelstroomverliezen
  - Hysteresisverliezen
- Wikkelingsverliezen of belastingsverliezen
- Rendement
- Groeiwetten

Wisselstroomverliezen

- $P_w \sim \sigma d^2 f^2 B^2$
  - Dikte beperkt
  - Elektrische geleidbaarheid te hoog



Hysteresisverliezen

$$P_h \sim f\,\hat{B}^{1,6}$$

Globale ijzerverliezen

$$P_{Fe} = P_w + P_h$$

$$P_{Fe} \cong P_{Fe0}\left(\frac{U}{U_N}\right)^2$$

Wikkelingsverliezen

$$P_J = R_1 I_1^2 + R_2 I_2^2 = R_1 I_1^2 + R_2' I_2'^2 \approx R_k I_1^2$$

$$P_J \cong P_{JN} \left(\frac{I}{I_N} \right)^2$$

Rendement

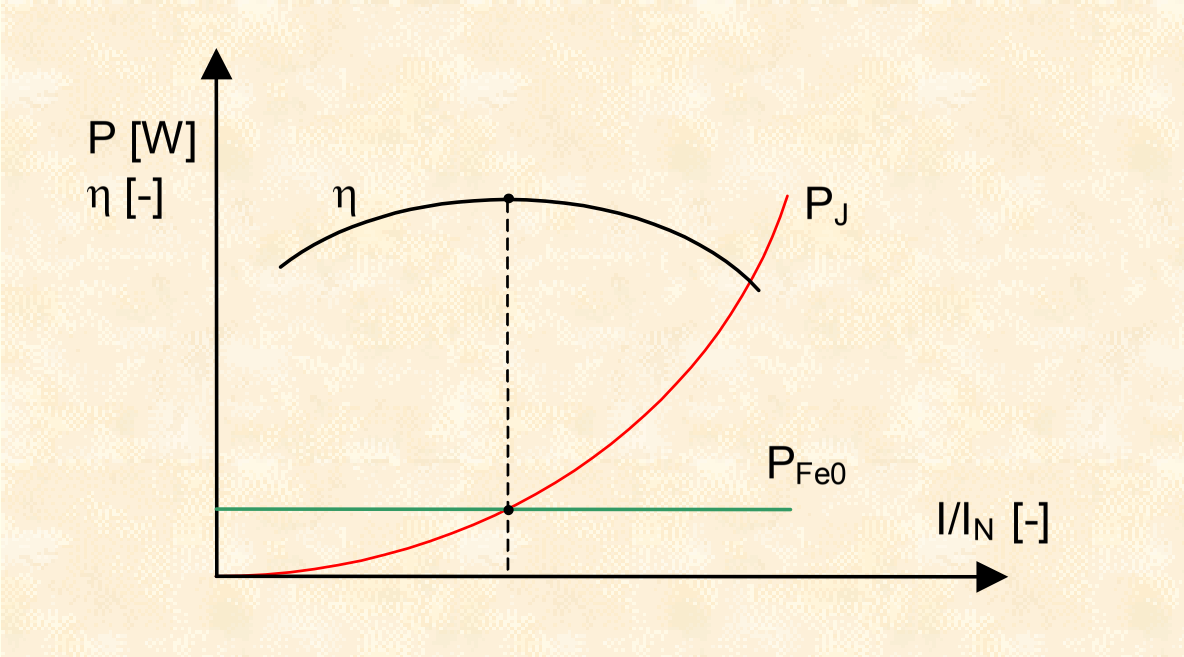
$$\eta = \frac{P_2}{P_1} = \frac{P_1 - P_{Fe} - P_J}{P_1} = 1 - \frac{P_{Fe} + P_J}{P_1}$$

$$P_1 = U_1 I_1 \cos\varphi_1$$

$$\eta = 1 - \frac{P_{Fe} + P_{JN}\left(\frac{I_1}{I_N}\right)^2}{U_1 I_1 \cos\varphi_1}$$

$$\frac{I_1}{I_N} = \sqrt{\frac{P_{Fe}}{P_{JN}}}$$

$$P_{Fe} = P_{JN}\left(\frac{I_1}{I_N}\right)^2 = P_J$$



Groeiwetten

$$S_N = U_N I_N$$

$$S_N = 4,44\, N_1 f\, \hat{\phi}_N I_N$$

$$S_N = 4,44\, f\, \hat{\mathbf{B}} S_{Fe} J\, S_g$$

$$S_N \sim L^4$$

$$G \sim L^3$$

$$P_v \sim L^3$$

$$P_J = RI^2 = \frac{\rho \ell}{S_g} J^2 S_g^2 = \rho J^2 \ell S_g \sim L^3$$

$$S_{koel} \sim L^2$$

Prijs: $\frac{\text{prijs}}{\text{vermogen}} \sim \frac{\text{gewicht}}{\text{vermogen}} \sim \frac{L^3}{L^4} \sim \frac{1}{L}$

Rendement: $\eta = 1 - \frac{P_v}{P} = 1 - \frac{P_v}{S\cos\varphi} \sim 1 - \frac{1}{L}$

Koeling

Invloed van de harmonische netvervuiling

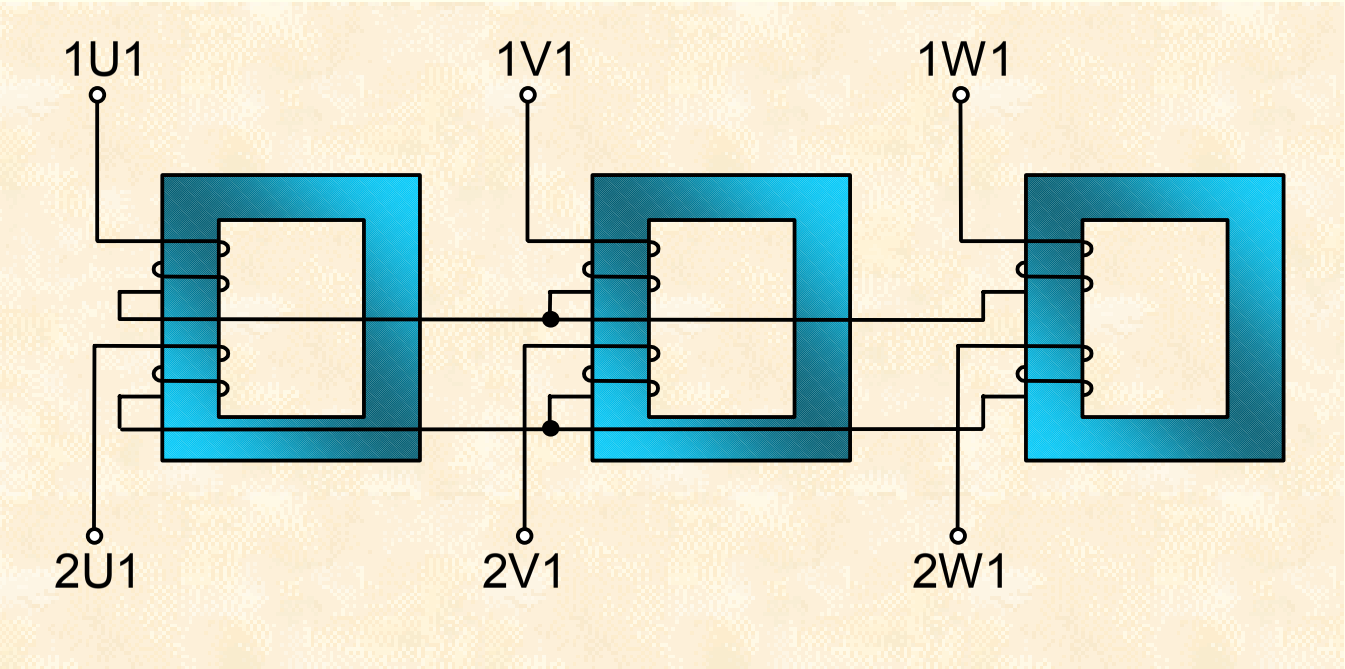
- Harmonische netvervuiling
- Invloed van harmonischen op een transformator

Driefasige transformatoren

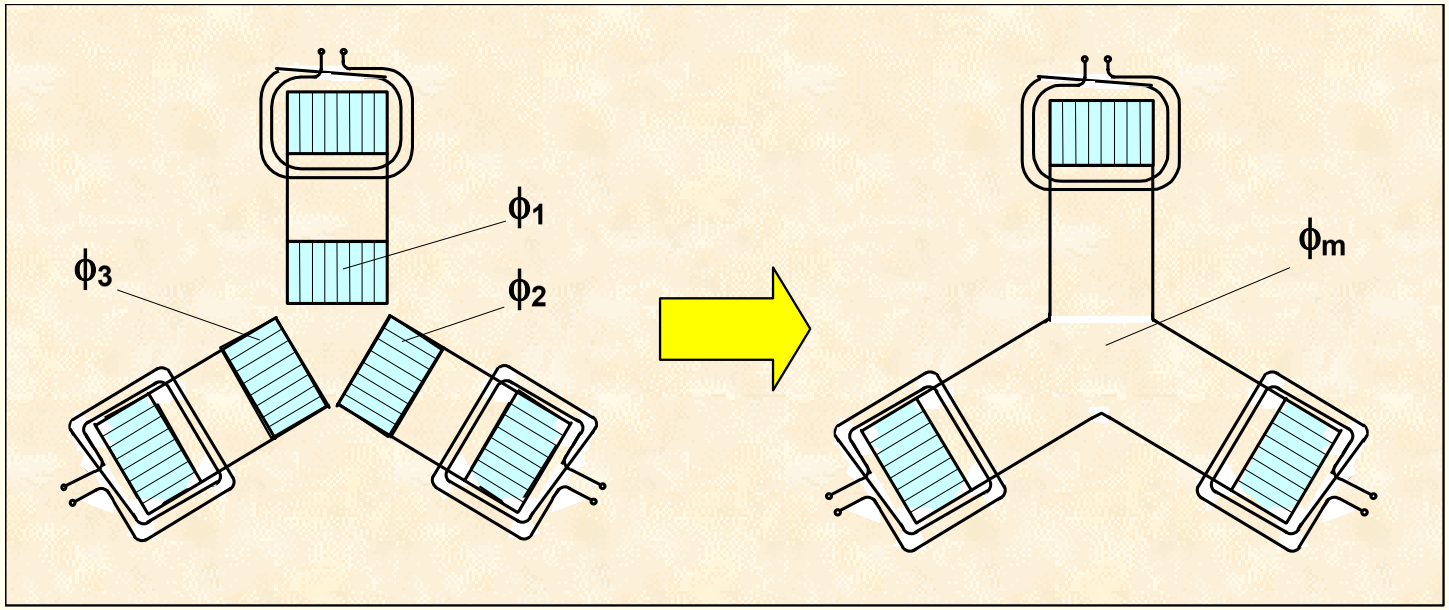
- Principiële bouw
- Spanningsvergelijkingen van de driefasige transformator
- Schakelgroepen
- Equivalent schema

Principiële bouw

- Onafhankelijke magnetische ketens

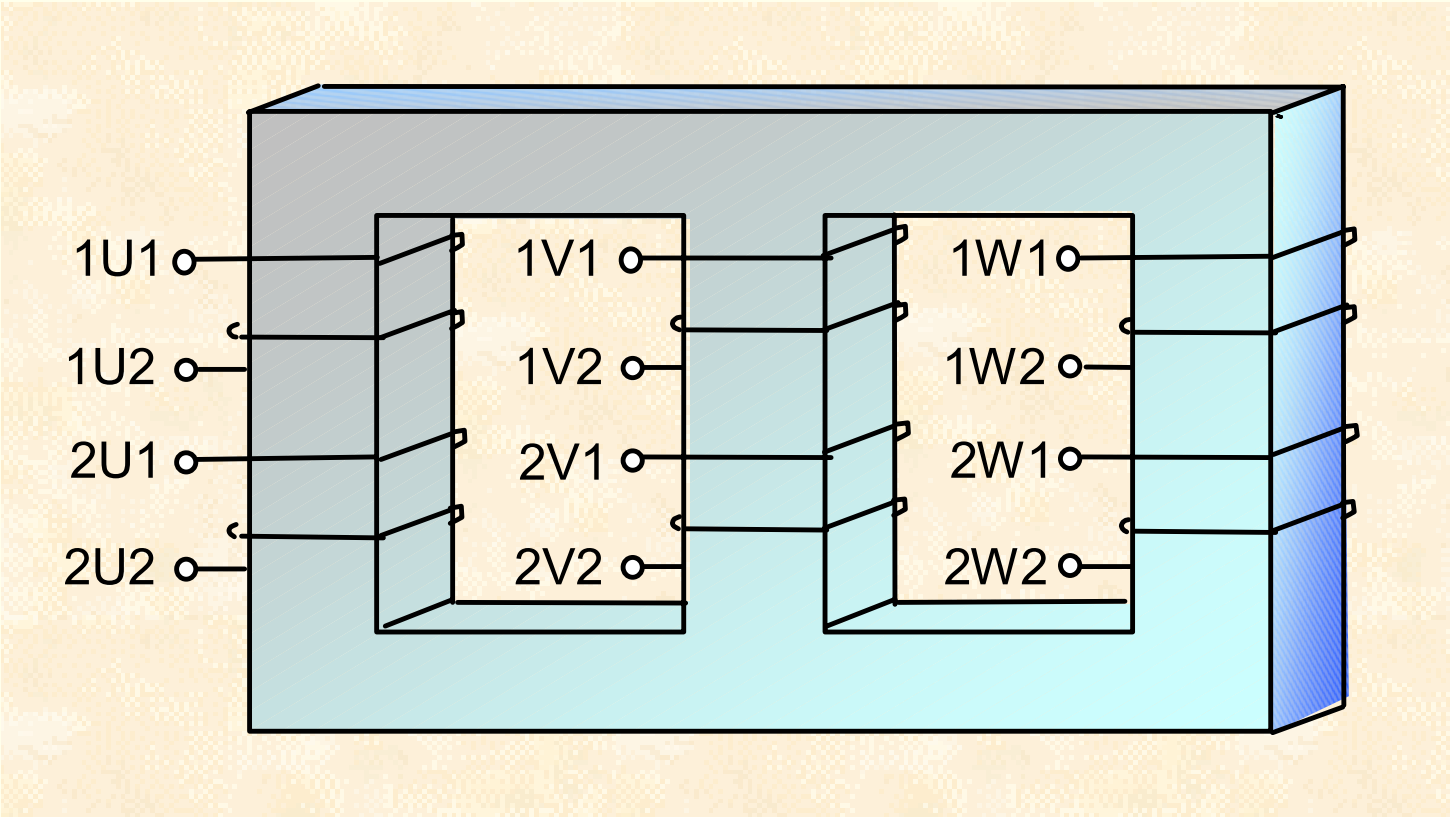


Verbonden magnetische keten

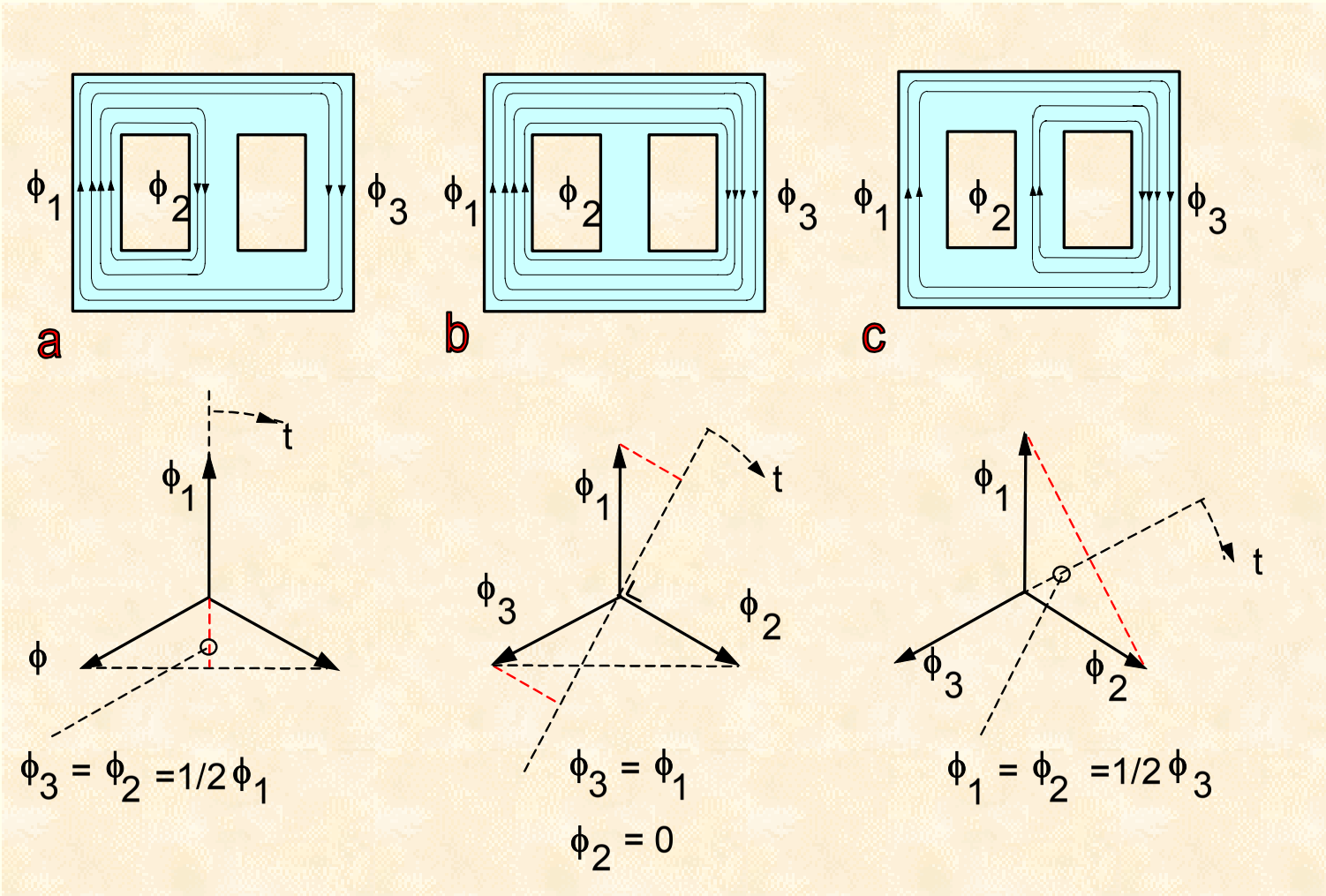


$$\phi_m(t) = \phi_1(t) + \phi_2(t) + \phi_3(t) = 0$$

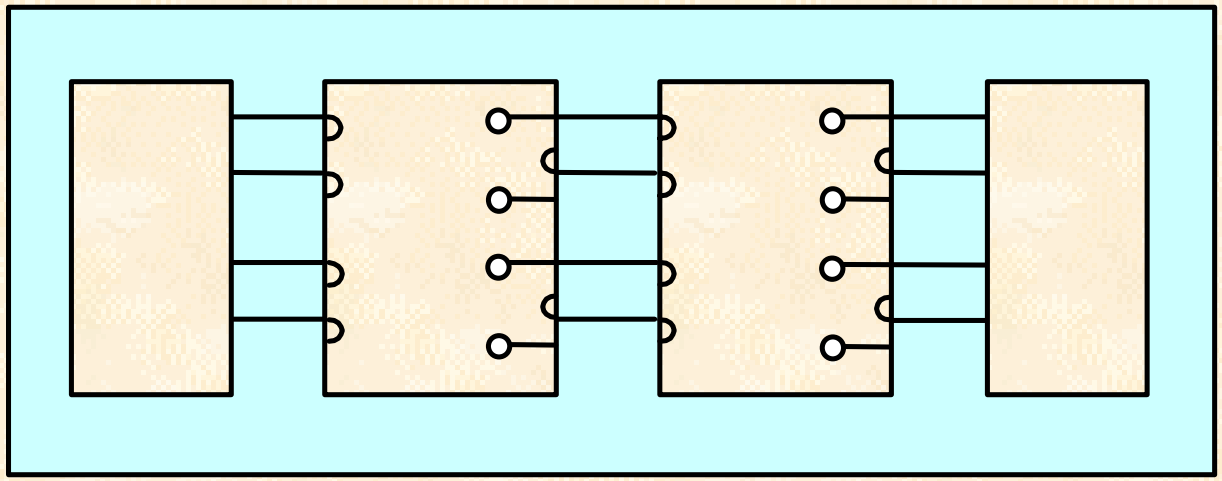
Klassieke driefasige kerntransformator



Fluxverloop



Kern met vijf benen



Spanningsvergelijkingen

$$\underline{U}_{1U} = R_{1U}\underline{I}_{1U} + j\omega L_{\sigma 1U}\underline{I}_{1U} + j\omega L_{h1U}\underline{I}_{1U} + j\omega M_{1U1V}\underline{I}_{1V} + j\omega M_{1U1W}\underline{I}_{1W} + j\omega M_{1U2U}\underline{I}_{2U} + j\omega M_{1U2V}\underline{I}_{2V} + j\omega M_{1U2W}\underline{I}_{2W}$$

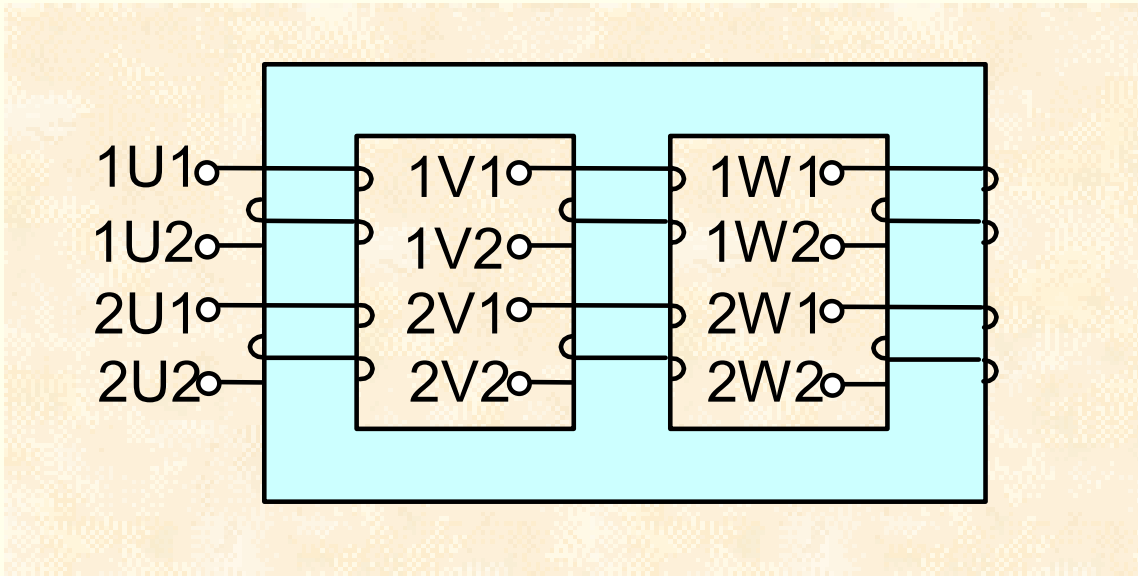
$$L_{\sigma 1U} = N_1^2 \Lambda_{\sigma 1}$$

$$L_{h1U} = N_1^2 \Lambda_h$$

$$L_{1U2U} = N_1 N_2 \Lambda_h$$

$$M_{1U1V} = M_{1U1W} = -\frac{1}{2} L_{h1U}$$

$$\mathrm{M_{1U2W}} = -\frac{1}{2} \mathrm{M_{1U2U}}$$



$$\underline{I}_{1U} + \underline{I}_{1V} + \underline{I}_{1W} = \underline{I}_{2U} + \underline{I}_{2V} + \underline{I}_{2W} = 0$$

$$\underline{U}_{1U} = R_{1U}\,\underline{I}_{1U} + j\omega L_{\sigma 1U}\,\underline{I}_{1U} + j\omega L_{h1U}\left(\underline{I}_{1U} - \frac{1}{2}\left(\underline{I}_{1V} + \underline{I}_{1W}\right)\right)$$

$$+ j\omega M_{1U\,2U}\left(\underline{I}_{2U} - \frac{1}{2}\left(\underline{I}_{2V} + \underline{I}_{2W}\right)\right)$$

$$\underline{U}_{1U} = R_{1U}\,\underline{I}_{1U} + j\omega L_{\sigma 1U}\,\underline{I}_{1U} + j\frac{3}{2}\omega L_{h1U}\,\underline{I}_{1U} + j\frac{3}{2}\omega M_{1U\,2U}\,\underline{I}_{2U}$$

$$\underline{I}_{2U} = \frac{N_1}{N_2}\,\underline{I}'_{2U} \approx \frac{1}{k}\,\underline{I}'_{2U}$$

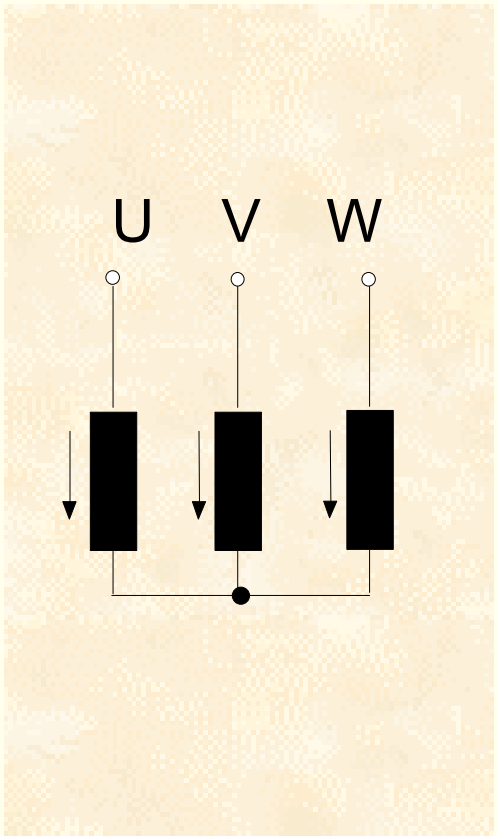
$$\underline{U}_{1U} = R_{1U}\,\underline{I}_{1U} + j\omega L_{\sigma 1U}\,\underline{I}_{1U} + j\frac{3}{2}\omega L_{h1U}\,(\underline{I}_{1U} + \underline{I}'_{2U})$$

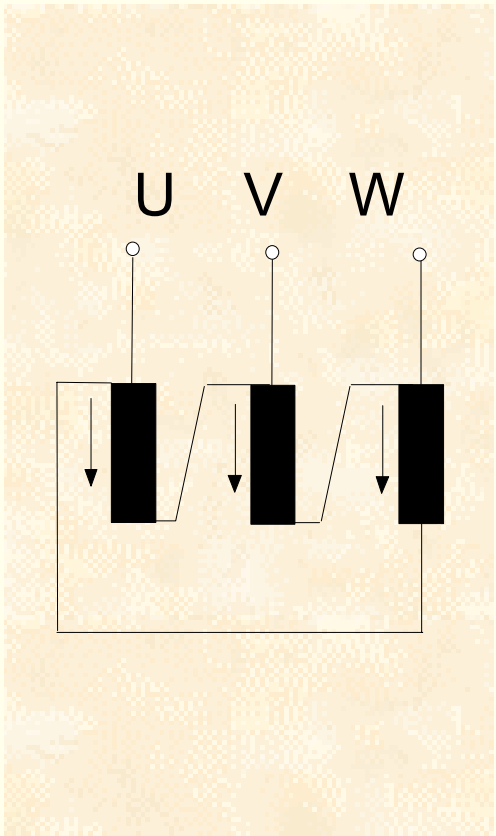
$$= \left(R_{1U} + jX_{\sigma 1U}\right)\underline{I}_{1U} + j\frac{3}{2}X_{h1U}\,\underline{I}_{0}$$

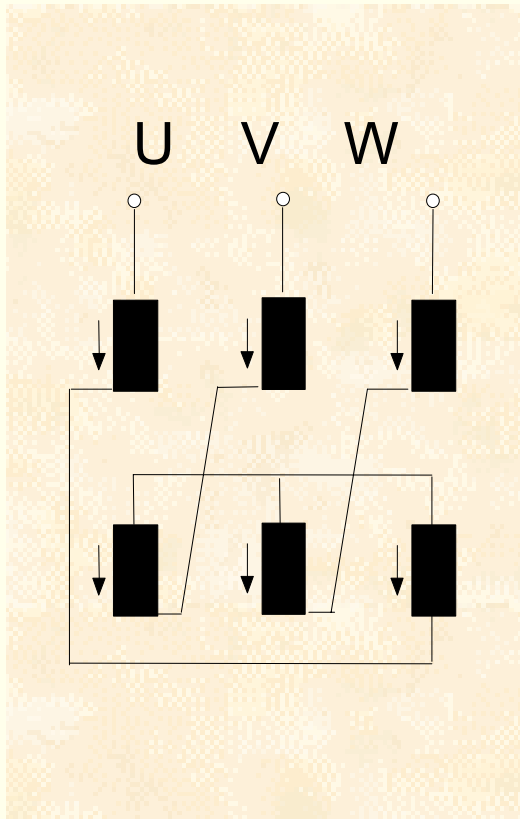
$$X_{h3f} = \frac{3}{2}X_{h1U}$$

$$S = 3U_{1f}I_{1f} = \sqrt{3}U_{1L}I_{1L}$$

Schakelgroepen



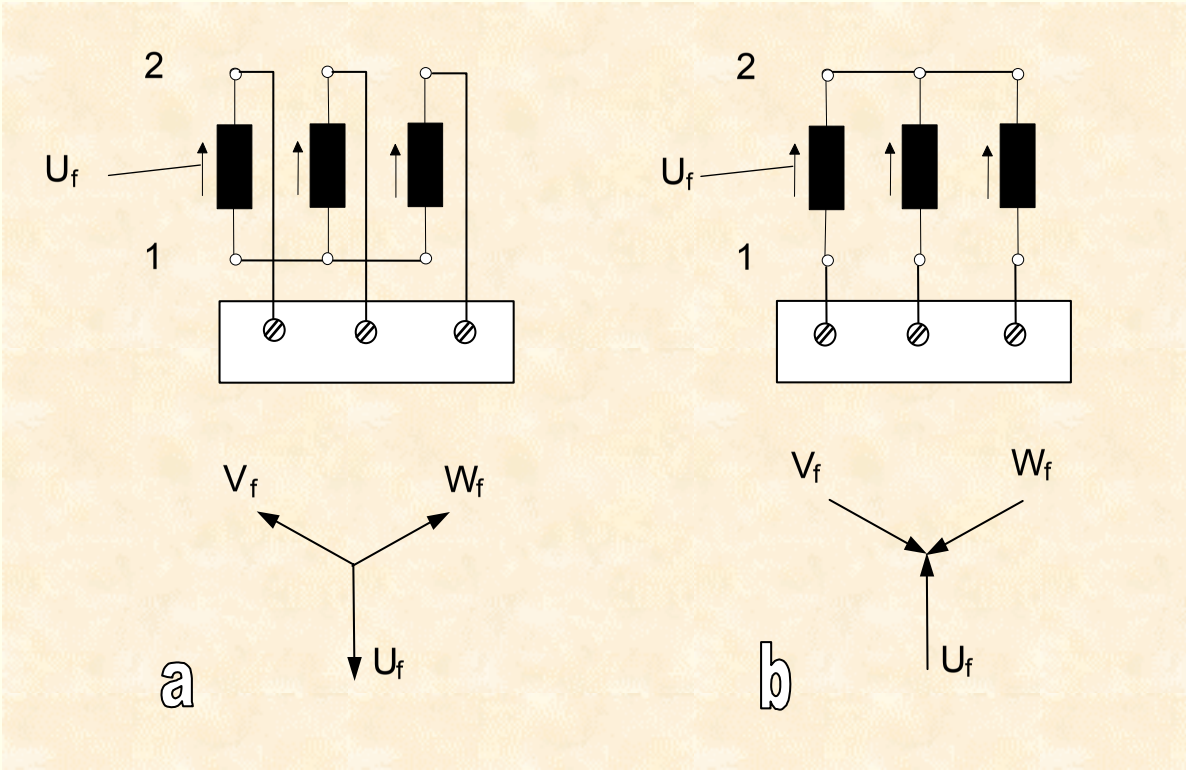




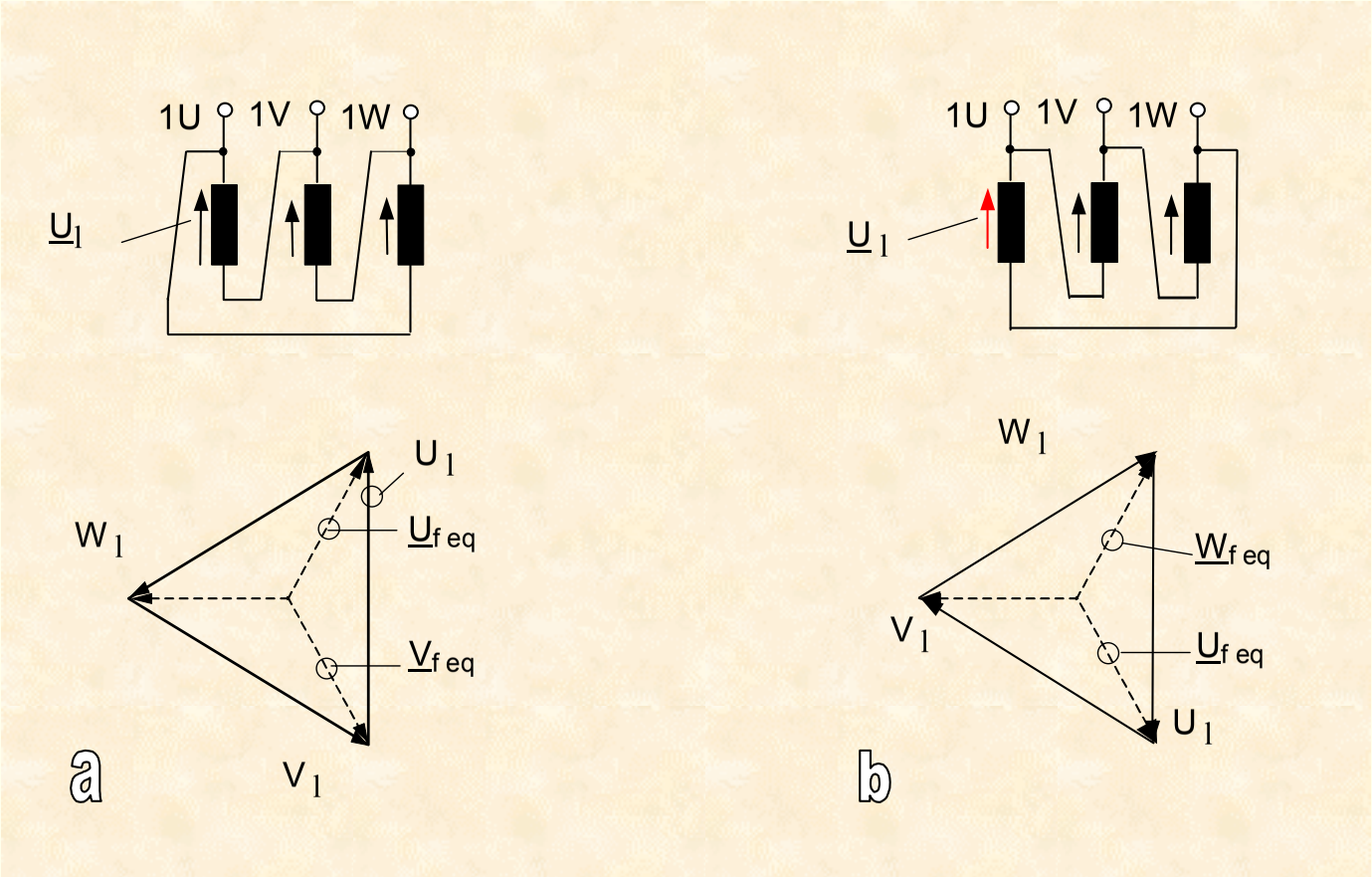
	ster	driehoek	zig-zag
U_{fase}	1	1	$\frac{\sqrt{3}}{2}$
U_{lijn}	$\sqrt{3}$	1	$\frac{3}{2}$

Y,y sterschakeling
D,d driehoekschakeling
z zigzagschakeling

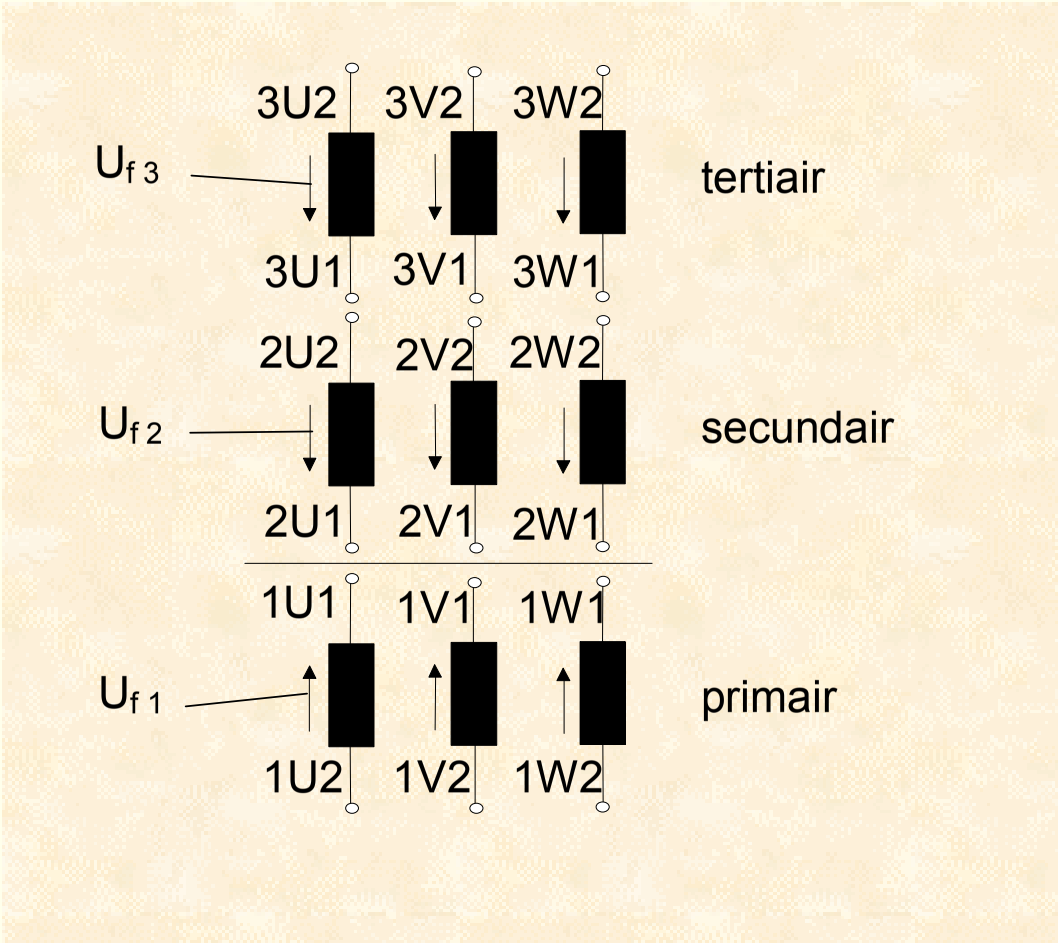
Spanningsconventie voor een wikkeling in ster

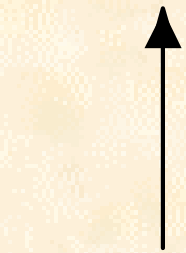


Spanningsconventie voor een wikkeling in driehoek

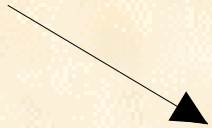


Spanningsconventie

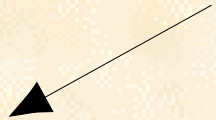




eerste been
(U)

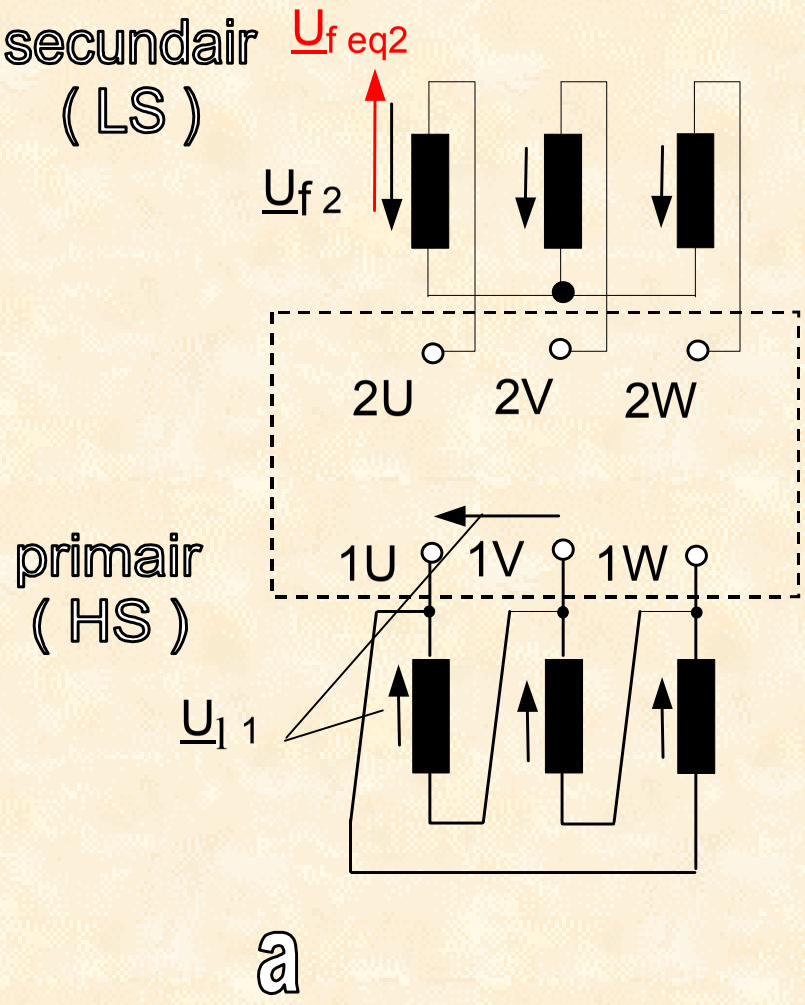


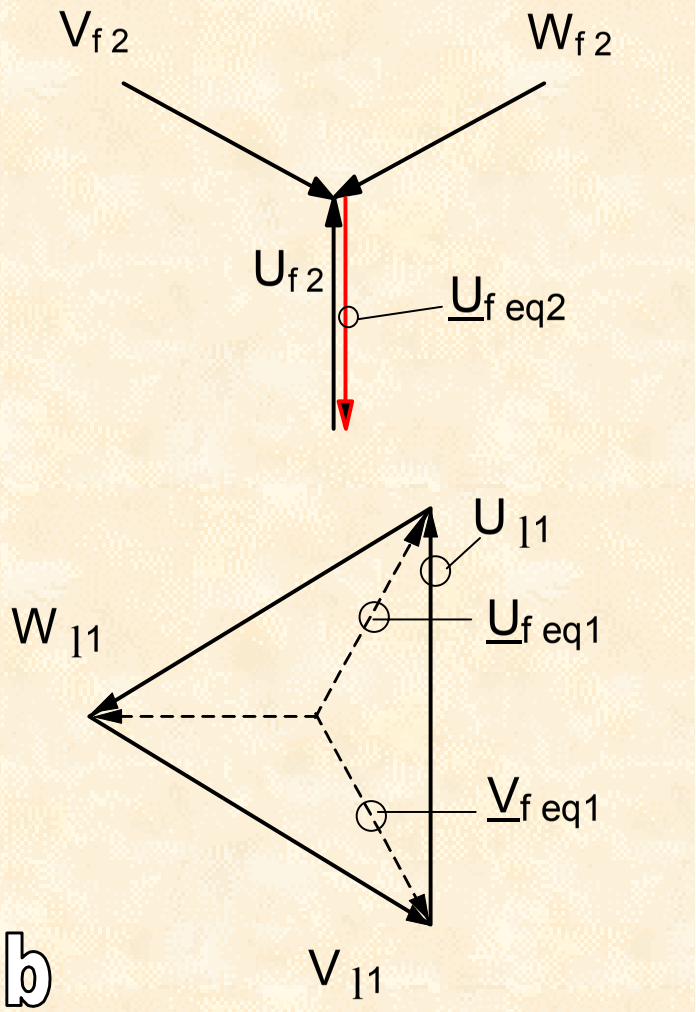
tweede been
(V)

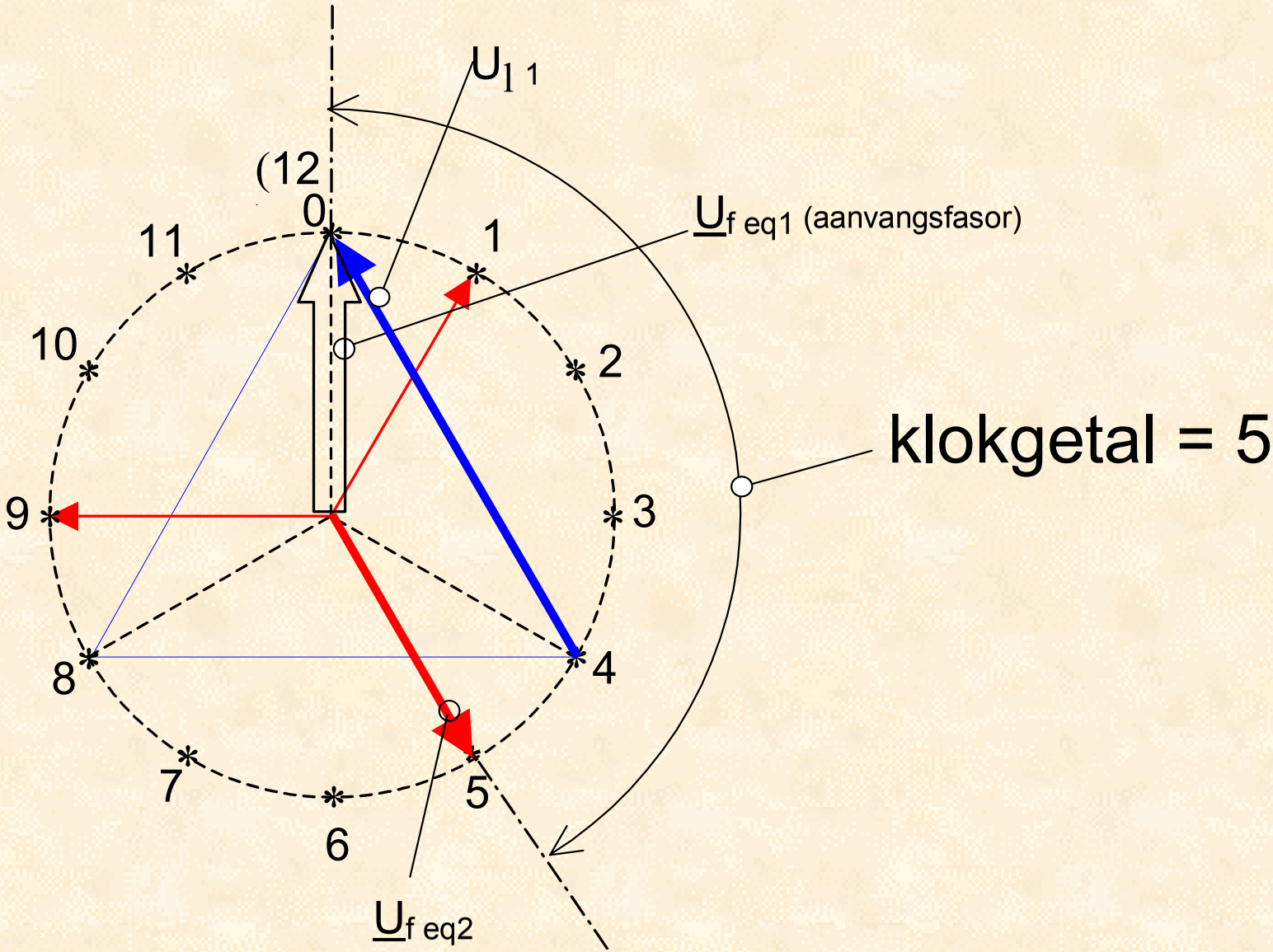


derde been
(W)

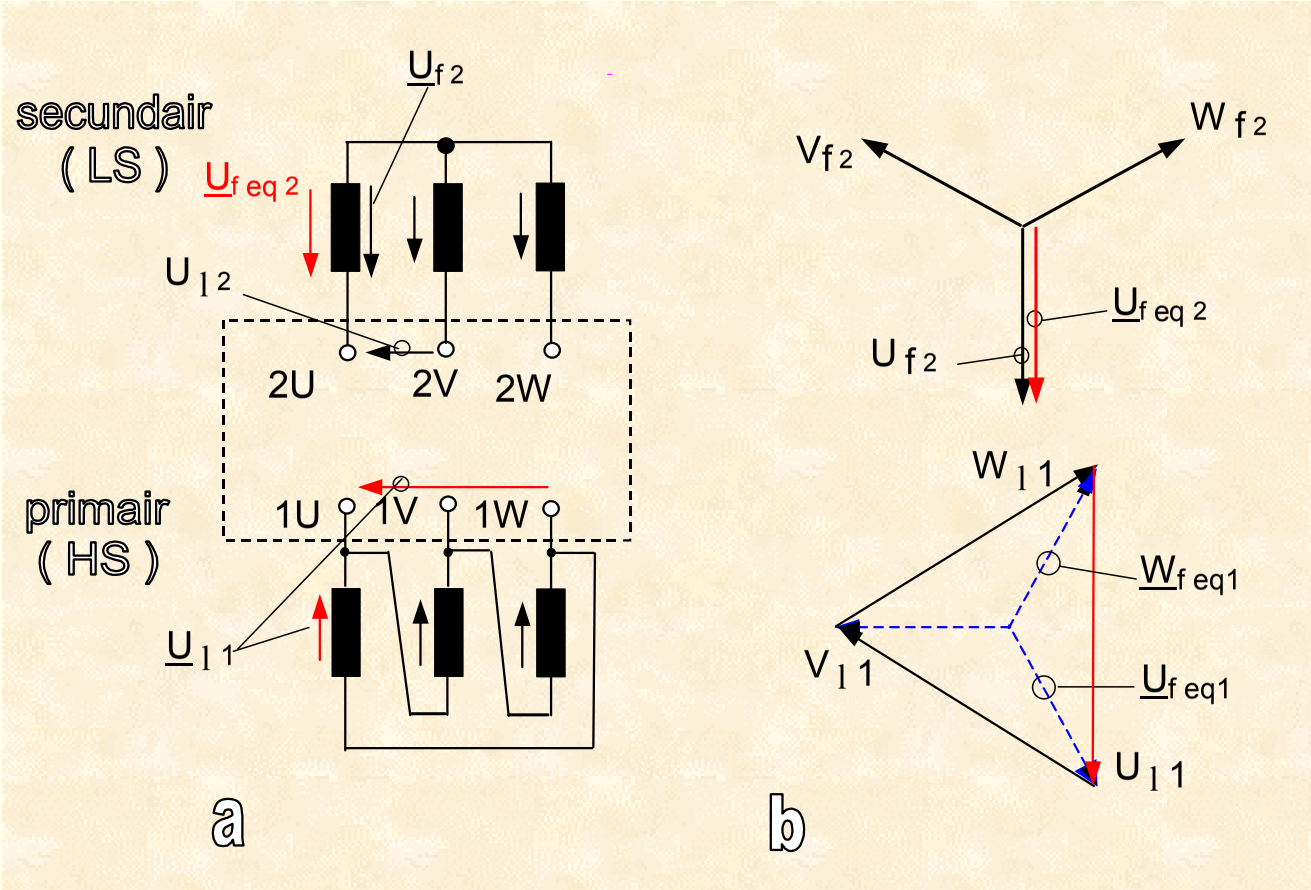
Dy5


secundair
(LS)
$\underline{U}_{f\,eq2}$
$\underline{U}_{f\,2}$
2U
2V
2W
primair
(HS)
1U
1V
1W
$\underline{U}_{l\,1}$
a

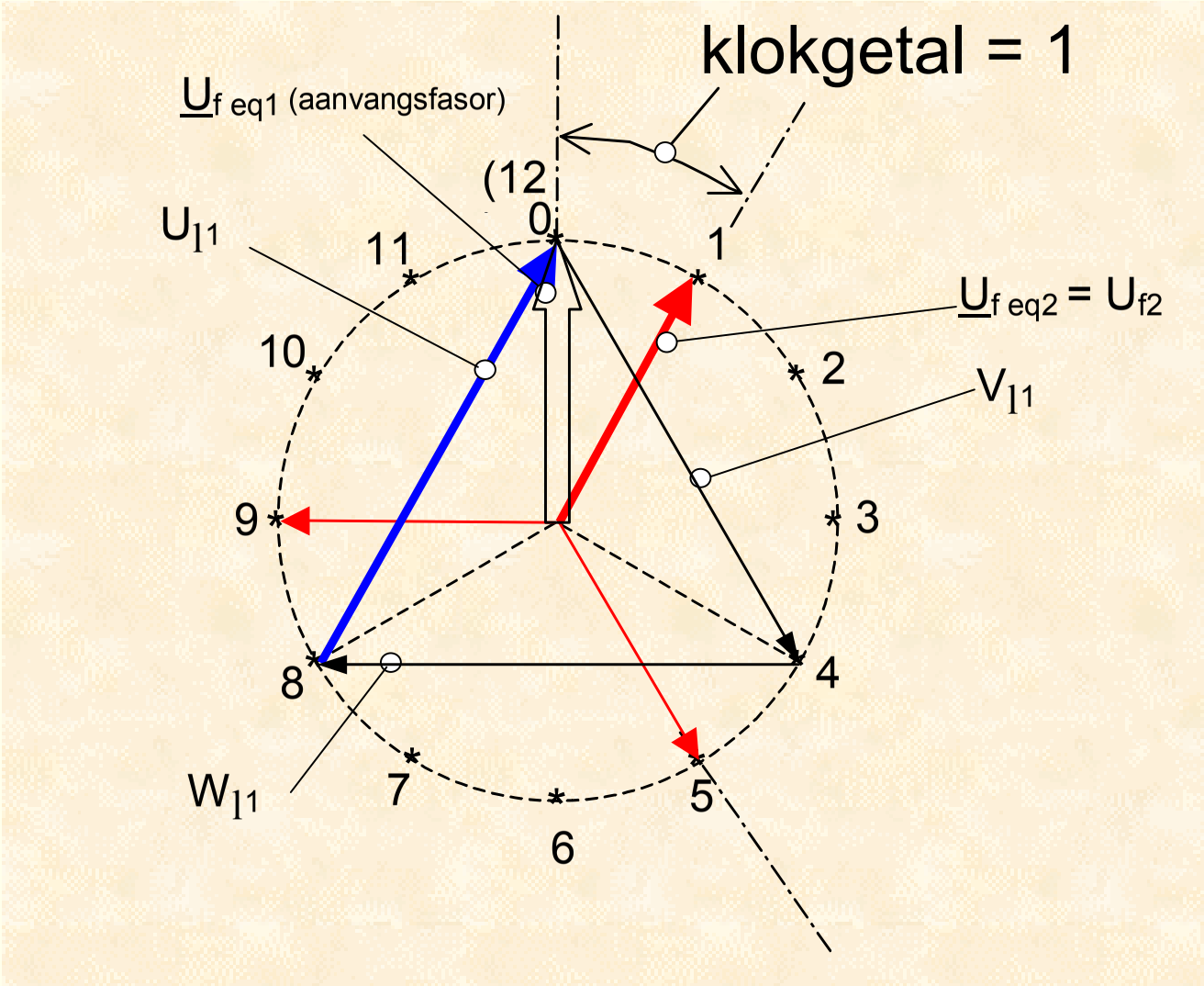

$V_{f\,2}$
$W_{f\,2}$
$\underline{U}_{f\,2}$
$\underline{U}_{f\,eq2}$
$U_{l\,1}$
$W_{l\,1}$
$\underline{U}_{f\,eq1}$
$\underline{V}_{f\,eq1}$
$V_{l\,1}$
b


U l 1
(12
0
1
2
3
4
5
6
7
8
9
10
11
U f eq1 (aanvangsfasor)
U f eq2
klokgetal = 5

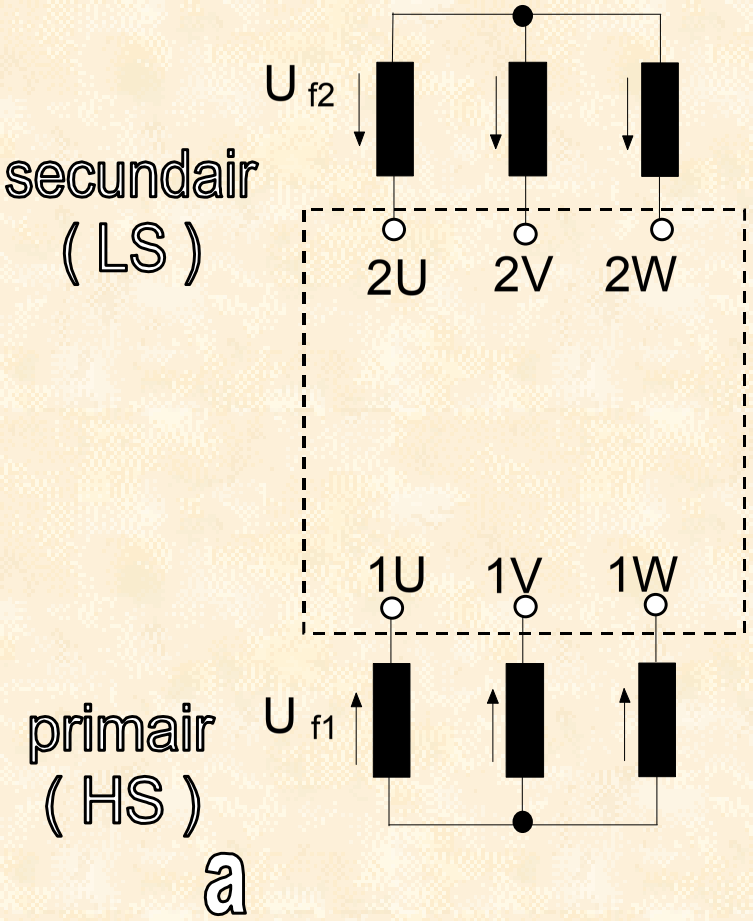
Schakelgroep Dy1

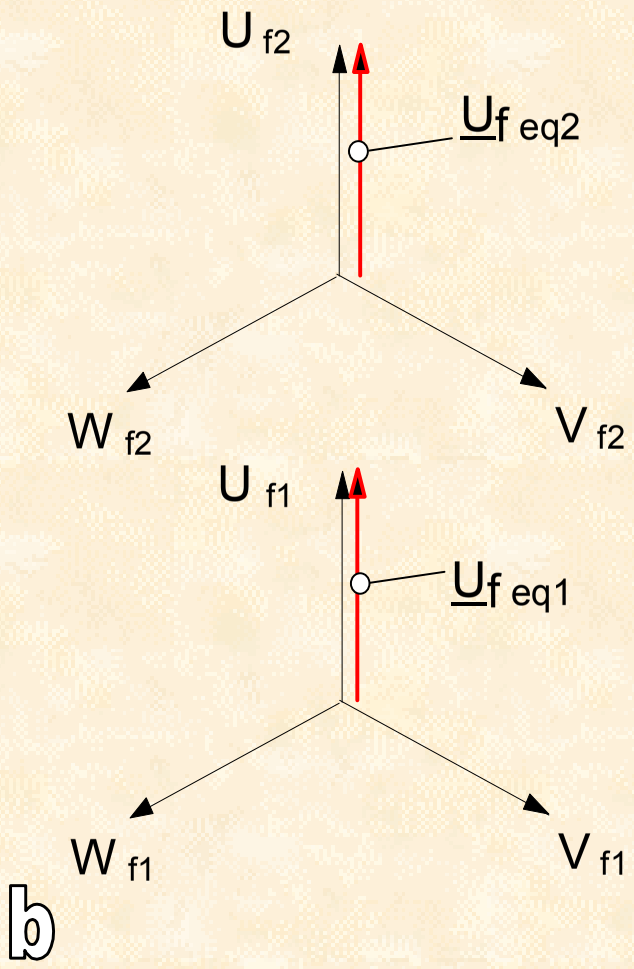


Dy1

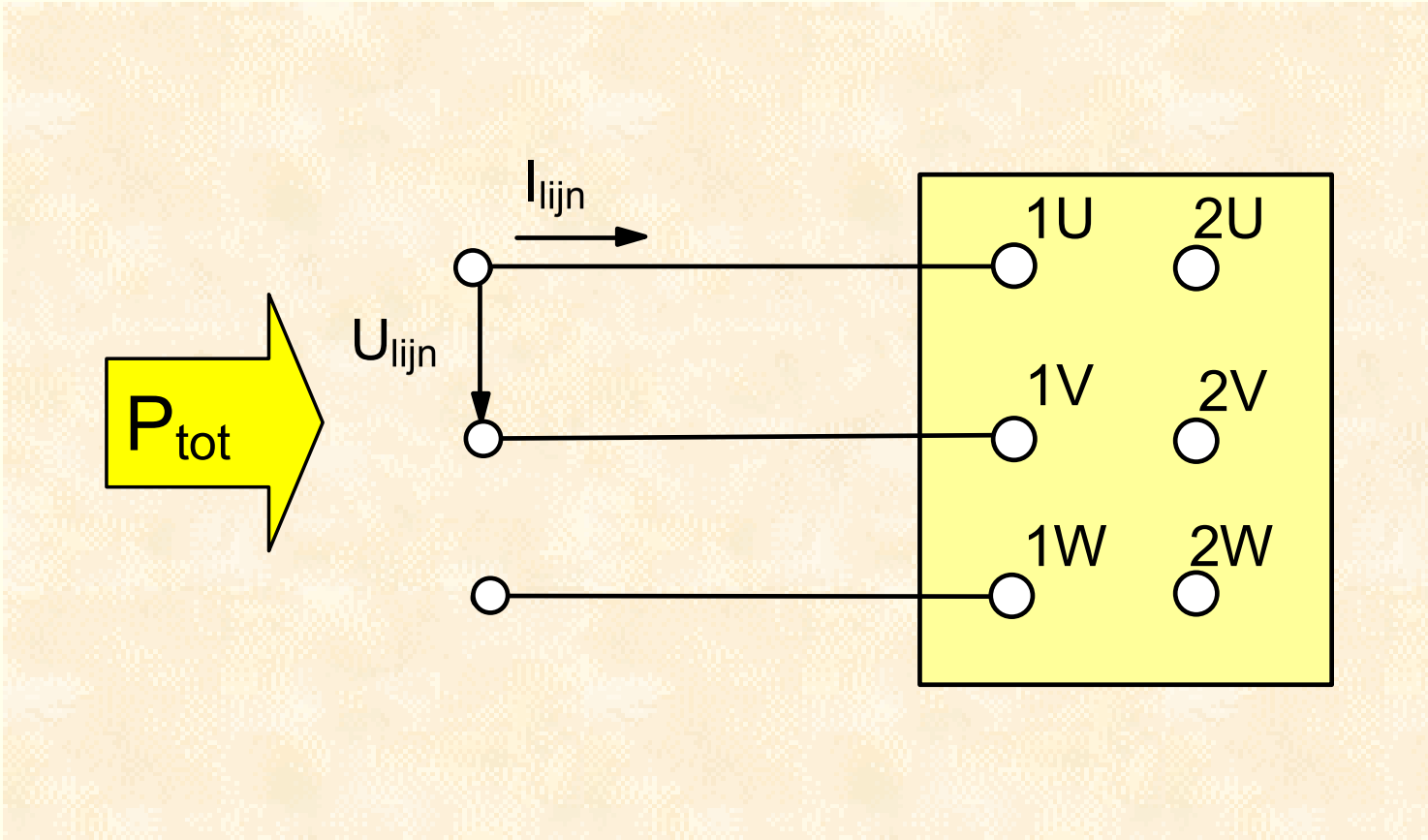

klokgetal = 1
$\underline{U}_{f\,eq1}$ (aanvangsfasor)
(12
0
1
U_{l1}
11
2
$\underline{U}_{f\,eq2} = U_{f2}$
10
V_{l1}
9
3
8
4
W_{l1}
7
5
6

Yy0


secundair
(LS)
U f2
2U
2V
2W
1U
1V
1W
U f1
primair
(HS)
a

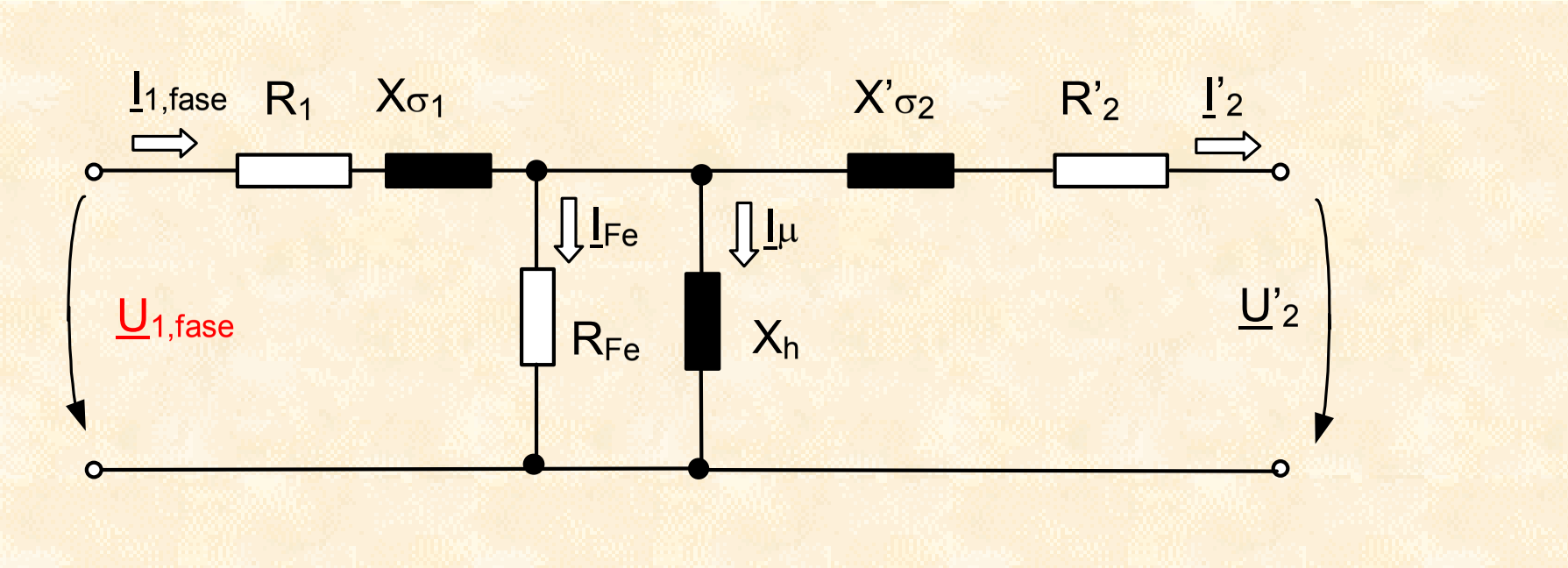

U f2
Uf eq2
W f2
V f2
U f1
Uf eq1
W f1
V f1
b

Equivalent schema



Meetopstelling

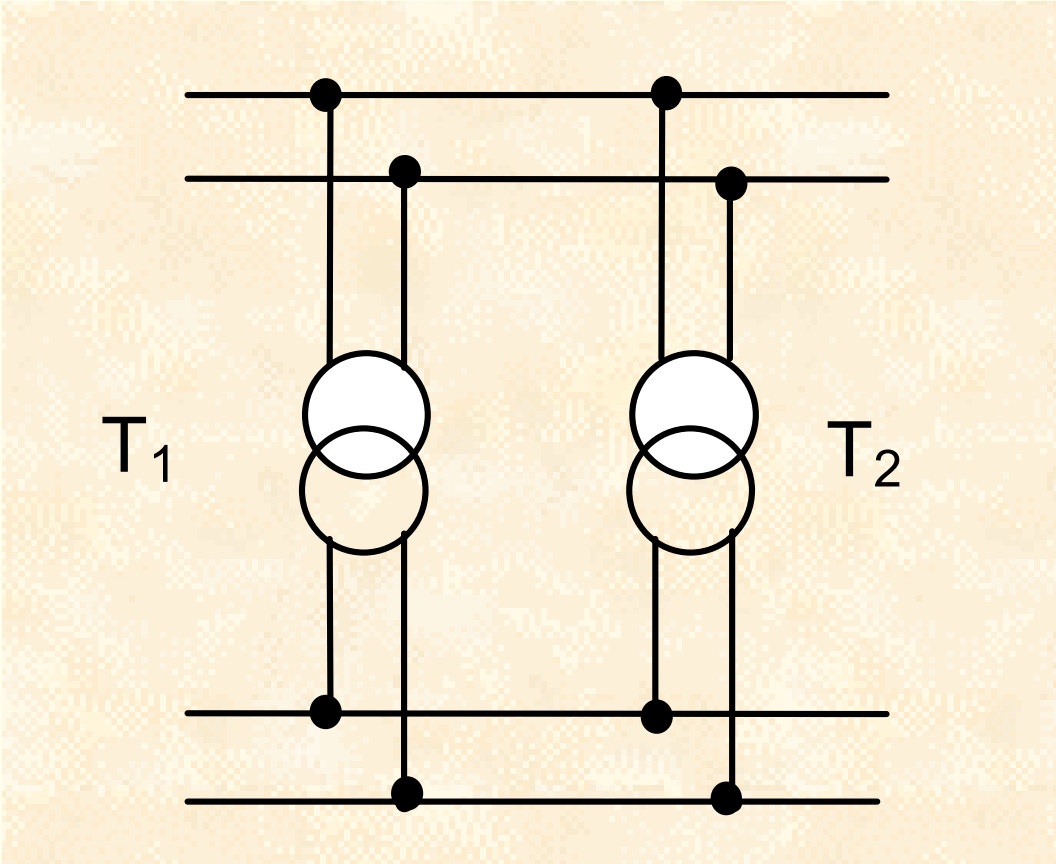
Eenfasig equivalent schema

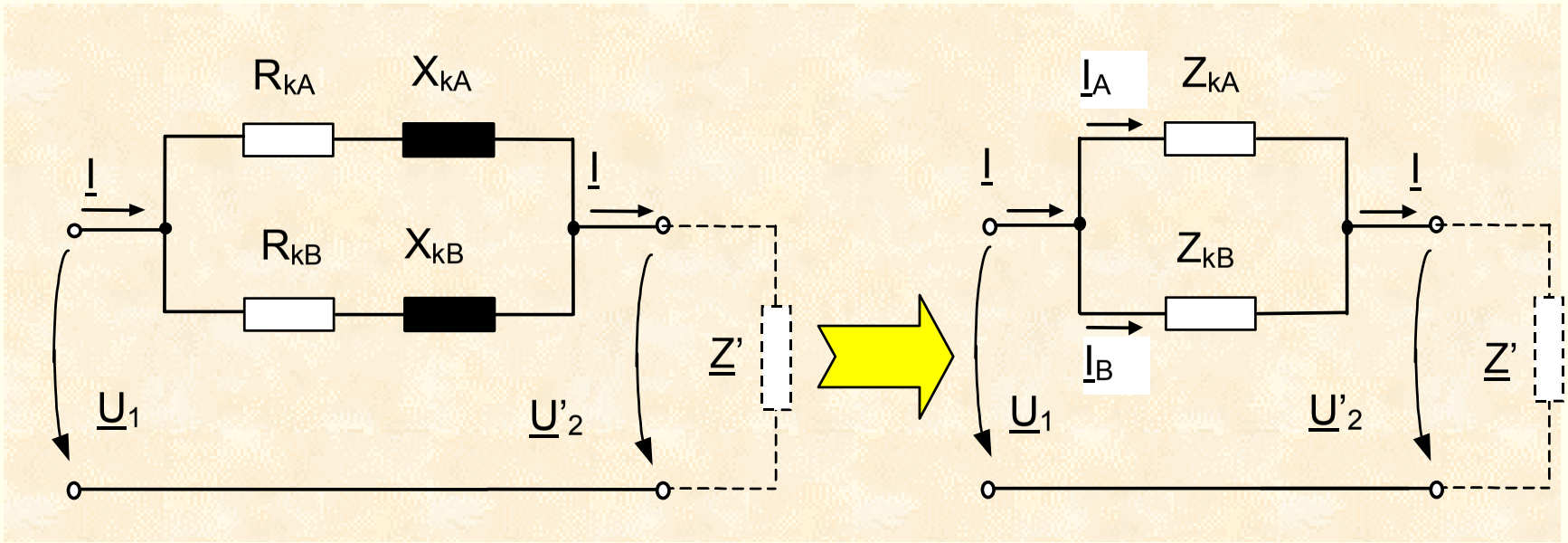


Parallelwerking

- Belastingsverdeling
- Voorwaarden voor parallelschakeling

Belastingsverdeling




R_{kA}
X_{kA}
$\underline{I}$
$\underline{I}$
R_{kB}
X_{kB}
$\underline{Z}'$
$\underline{U}_1$
$\underline{U}'_2$
$\underline{I}_A$
Z_{kA}
$\underline{I}$
$\underline{I}$
Z_{kB}
$\underline{I}_B$
$\underline{Z}'$
$\underline{U}_1$
$\underline{U}'_2$

$$\underline{Z}_{kA}\underline{I}_A = \underline{Z}_{kB}\underline{I}_B$$

$$\underline{Z}_{kA} = R_{kA} + jX_{kA}$$

$$\underline{Z}_{kB} = R_{kB} + jX_{kB}$$

$$Z_{kA}I_A = Z_{kB}I_B$$

$$\frac{I_A}{I_{AN}} \cdot \frac{I_{AN}Z_{kA}}{U_{1N}} = \frac{I_B}{I_{BN}} \cdot \frac{I_{BN}Z_{kB}}{U_{1N}}$$

$$\frac{I_A / I_{AN}}{I_B / I_{BN}} = \frac{u_{kB}}{u_{kA}}$$

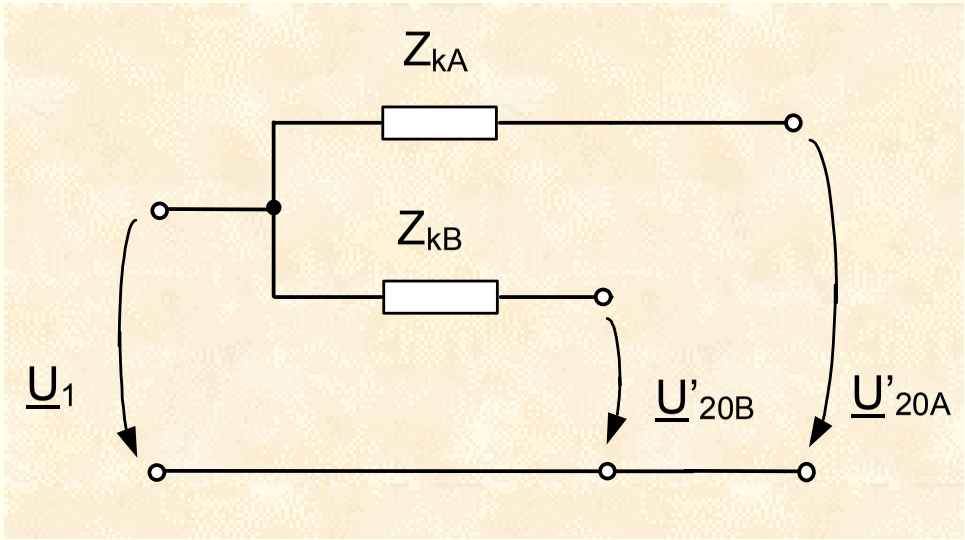
Voorwaarden

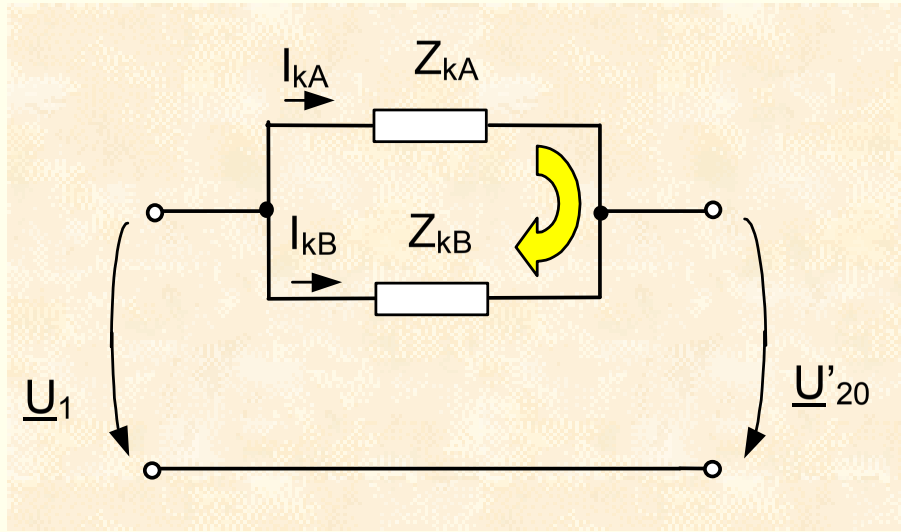
- Gelijke spanning in grootte en fase

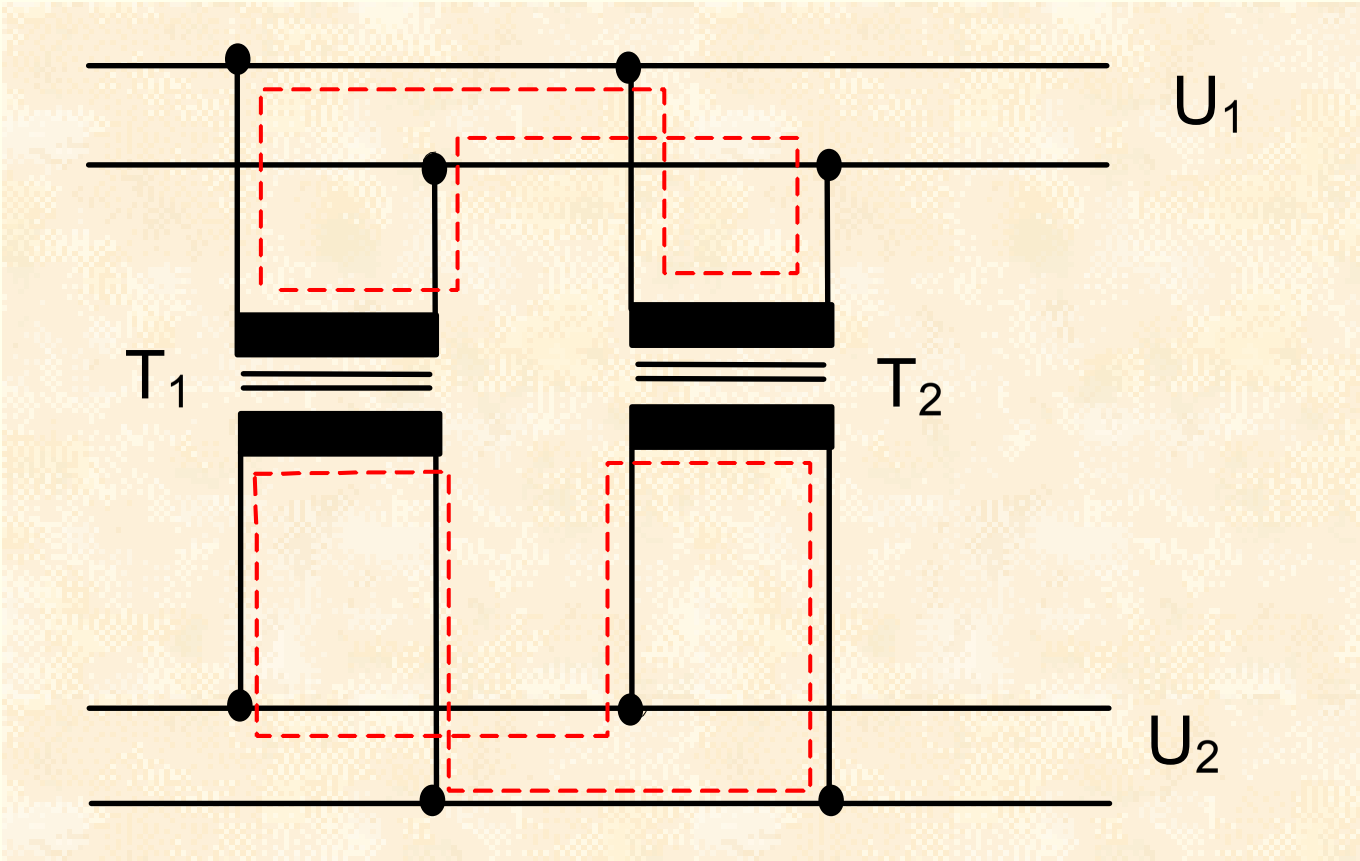
$$\Delta \underline{U} = \underline{U}'_{20A} - \underline{U}'_{20B} \neq 0$$

$$\underline{I}_{kA} = -\underline{I}_{kB} = \frac{\Delta \underline{U}}{\underline{Z}_{kA} + \underline{Z}_{kB}}$$

Gelijkstromen





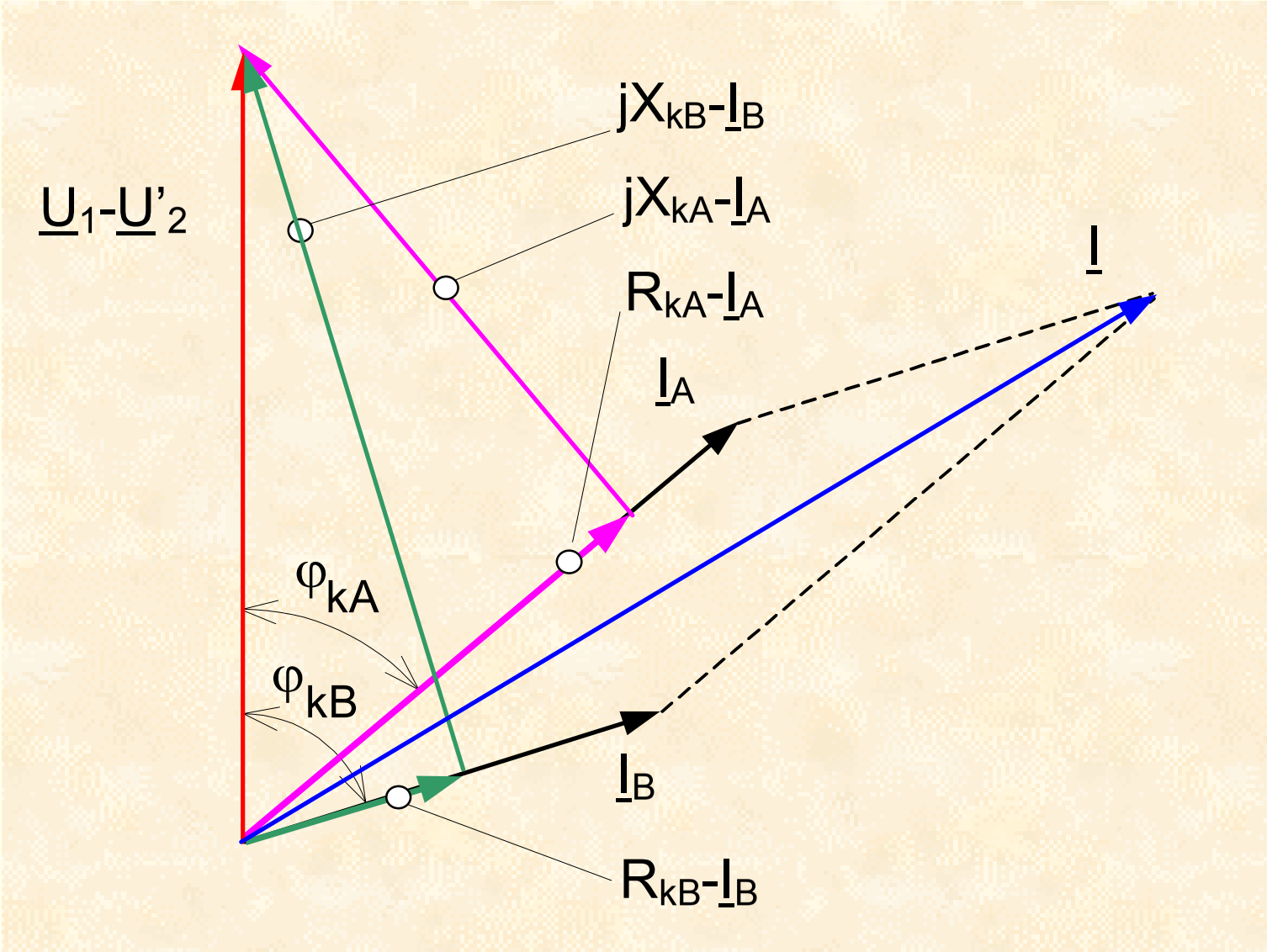

U1
T1
T2
U2

Procentuele kortsluitspanning

$$u_{kA} \approx u_{kB}$$

Driefasige: -schakelgroep
-fasevolgorde

$$\frac{X_{kA}}{R_{kA}} = \frac{X_{kB}}{R_{kB}}$$


$\underline{U}_1-\underline{U}'_2$
$jX_{kB}-\underline{I}_B$
$jX_{kA}-\underline{I}_A$
$R_{kA}-\underline{I}_A$
$\underline{I}$
$\underline{I}_A$
φ_{kA}
φ_{kB}
$\underline{I}_B$
$R_{kB}-\underline{I}_B$

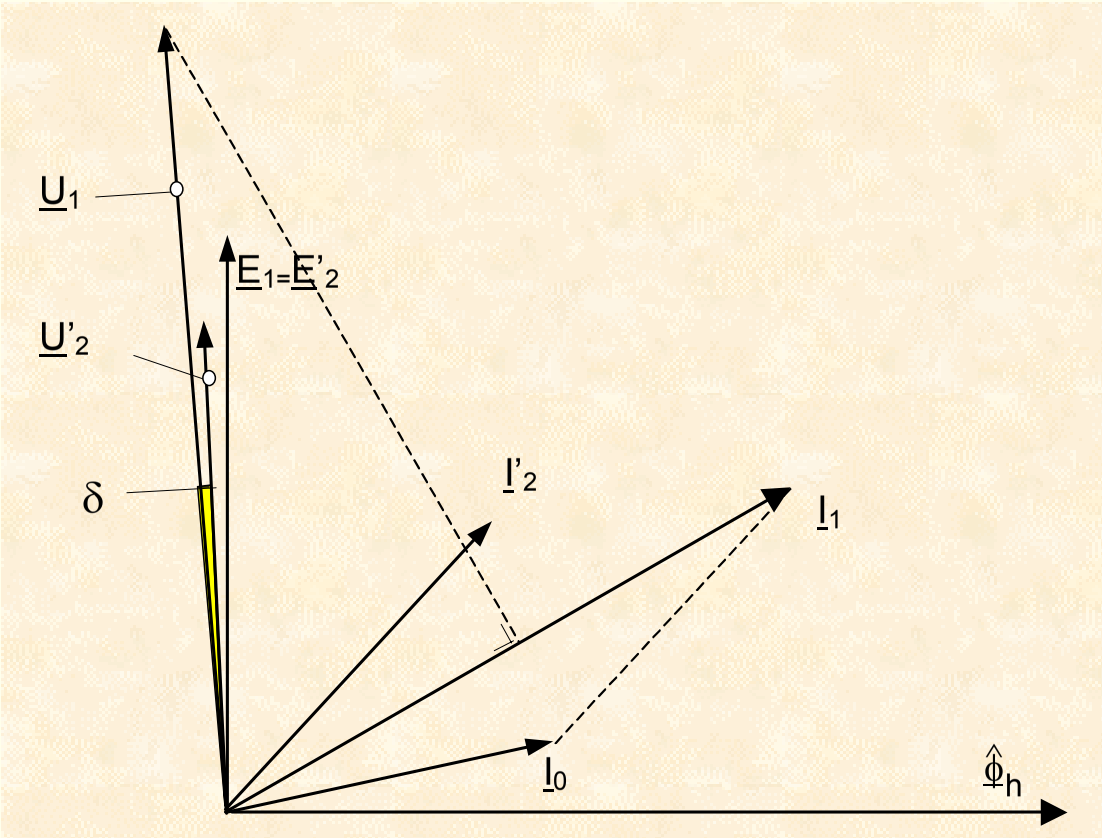
Speciale transformatoren

- Meettransformator
- Spaartransformator
- Veiligheidstransformator
- Verliesstroomschakelaar

Meettransformator

- Spanningsmeettransformator
- Stroommeettransformator

Spanningsmeettransformator

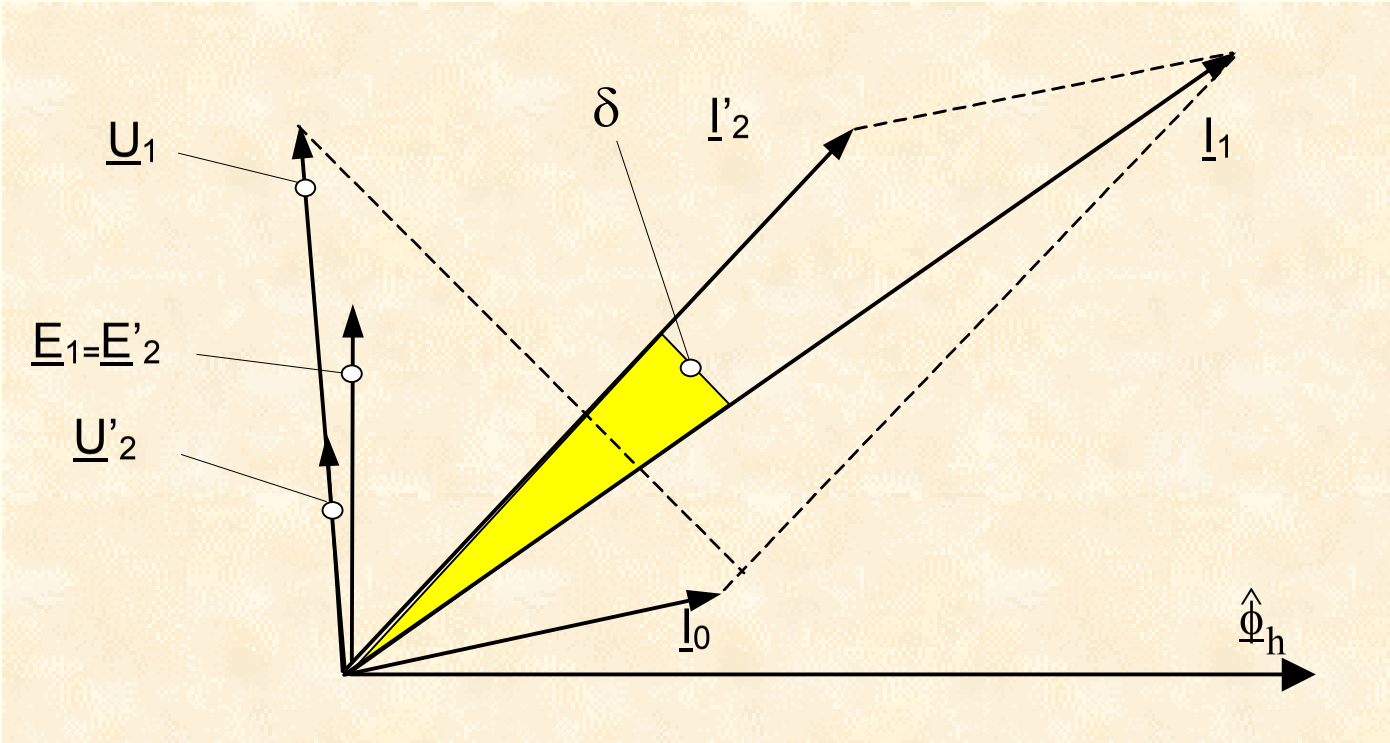


$$j\omega L_{h1}\underline{I}_{\mu} = -\left(j\omega L'_{2\sigma} + R'_{2}\right)\underline{I}'_{2}$$

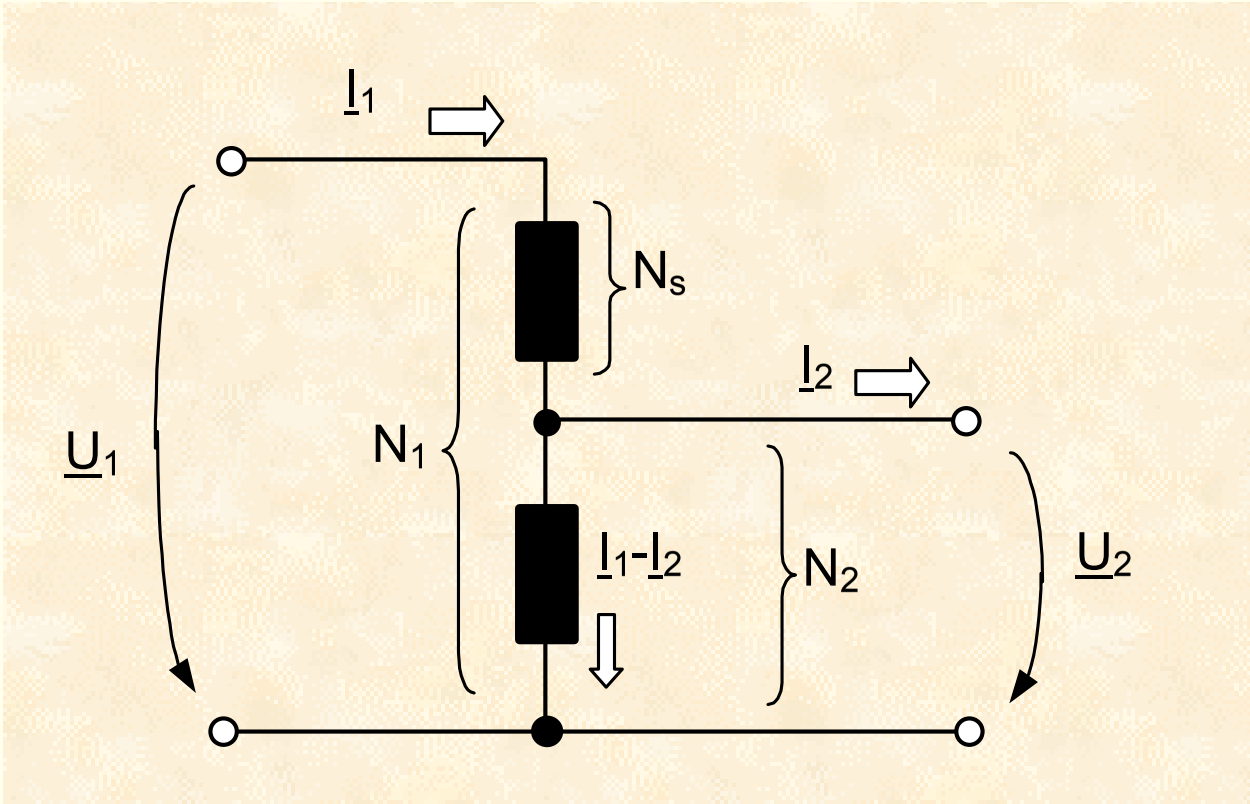
$$\underline{I}_{1} = -\underline{I}'_{2}\left(1 + \frac{j\omega L'_{2\sigma} + R'_{2}}{j\omega L_{h1}}\right)$$

$$\underline{I}_{1} \approx -\underline{I}'_{2} = -\underline{I}_{2}\frac{N_{2}}{N_{1}}$$

Stroomtransformator



Spaartransformator I



$$\frac{U_1}{U_2} = \frac{N_1}{N_2}$$

$$N_s = N_1 - N_2$$

$$\underline{I}_1 N_s + \left(\underline{I}_1 - \underline{I}_2\right) N_2 = 0$$

$$\underline{I}_1 = \frac{N_2}{N_1} \underline{I}_2$$

$$S_1 = mU_1I_1 = S_2 = mU_2I_2 \cong S_d$$

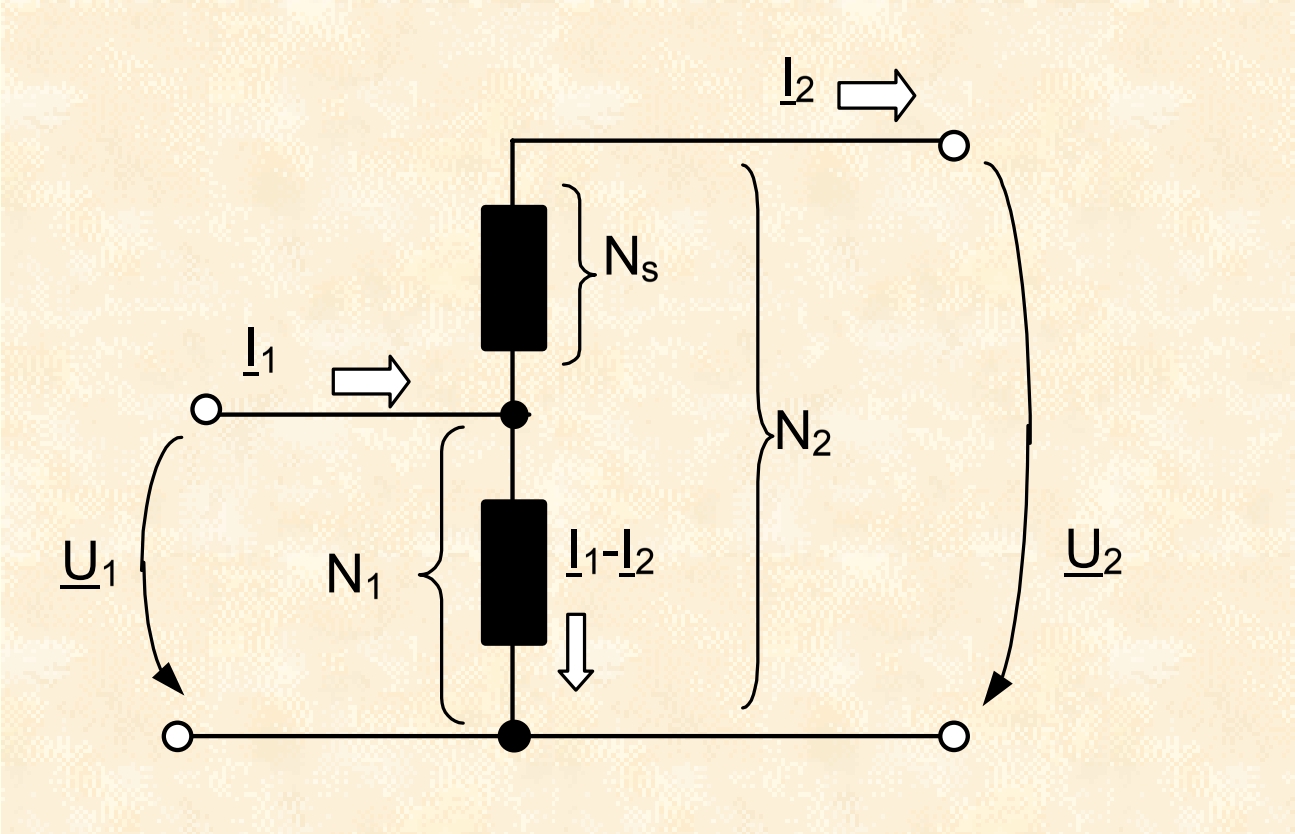
$$S_e = m\left(U_1 - U_2\right)I_1 = mU_2\left(I_1 - I_2\right)$$

$$= m\frac{N_s}{N_1}U_1I_1 = \frac{U_1 - U_2}{U_1}mU_1I_1$$

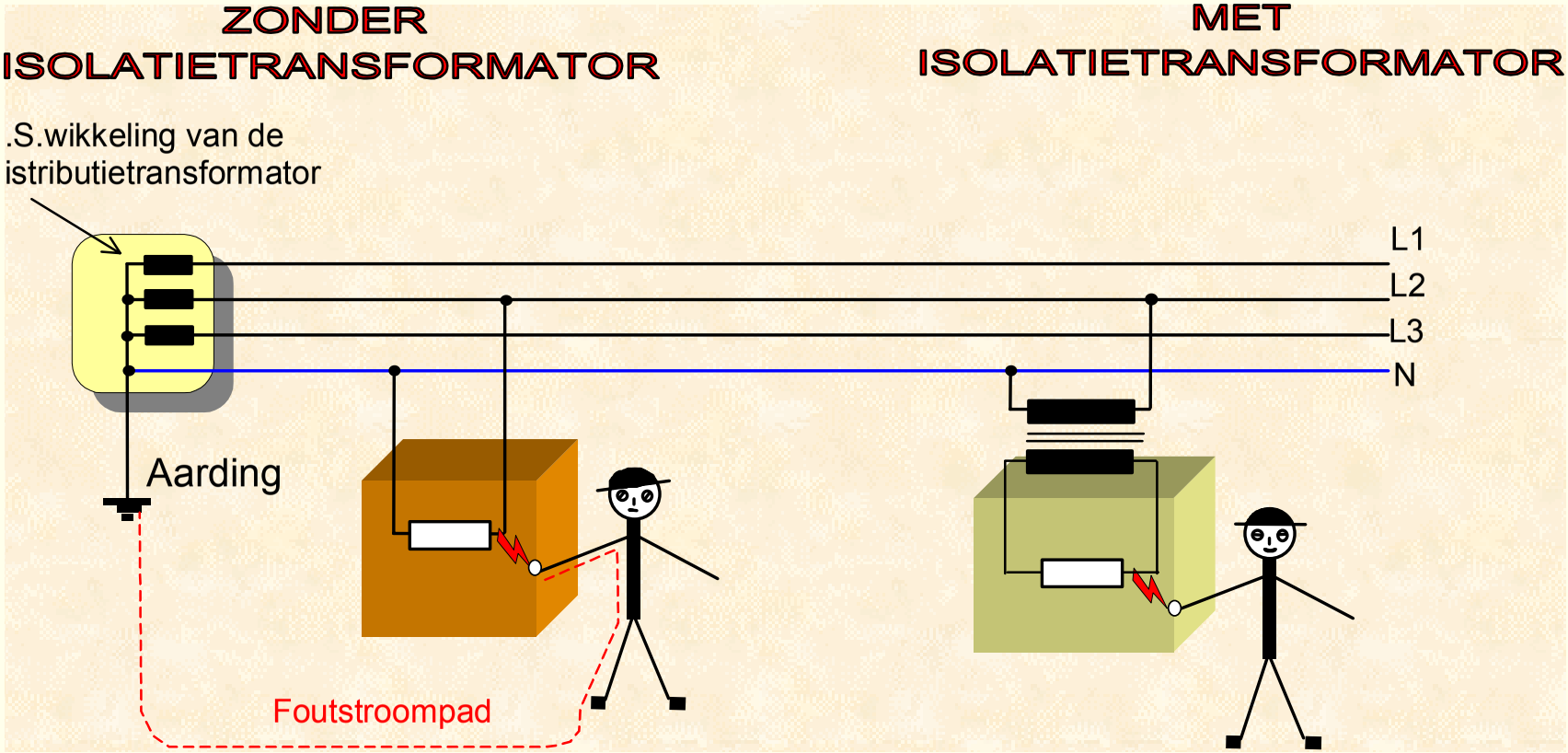
$$\frac{S_e}{S_d} = \frac{U_1 - U_2}{U_1}$$

$$\frac{S_e}{S_d} = \frac{U_2 - U_1}{U_2}$$

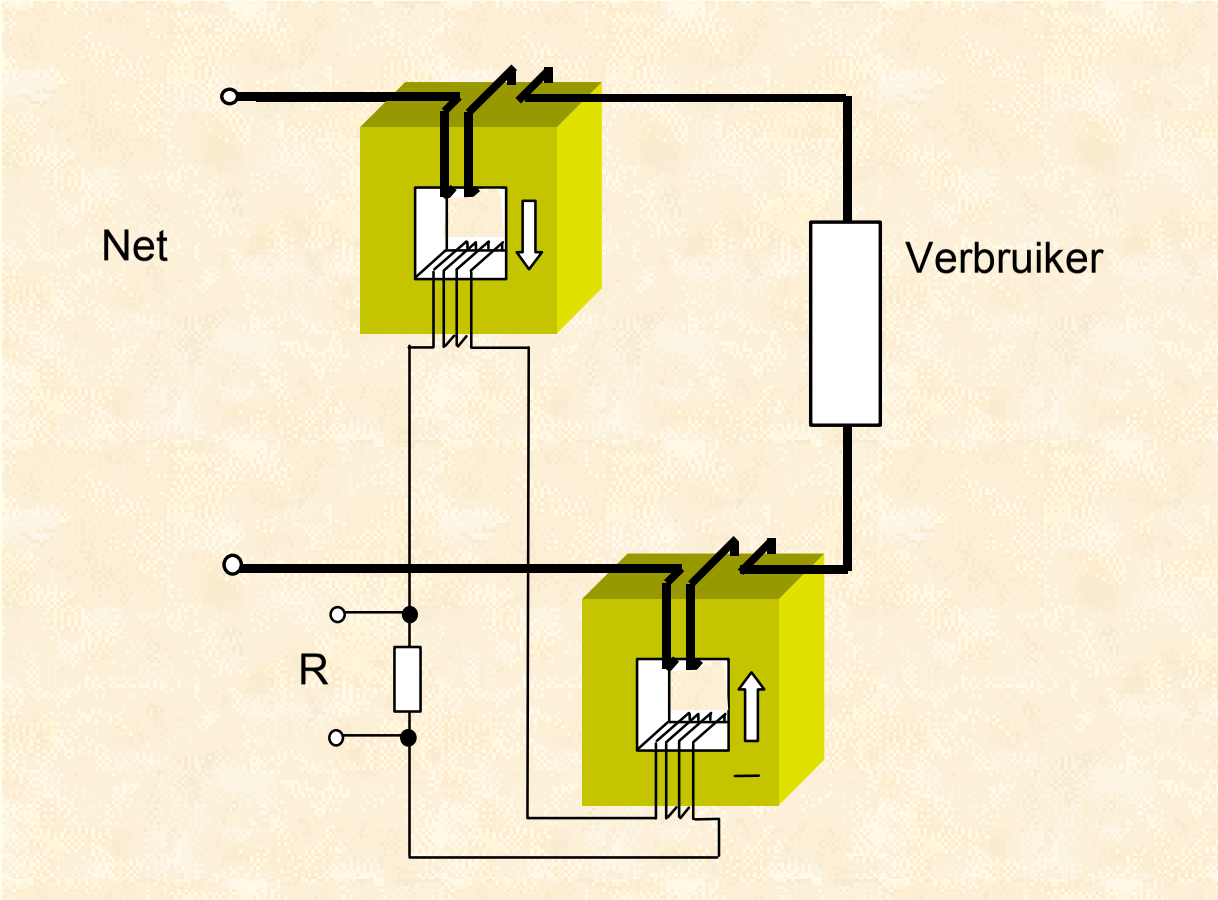
Spaartransformator II

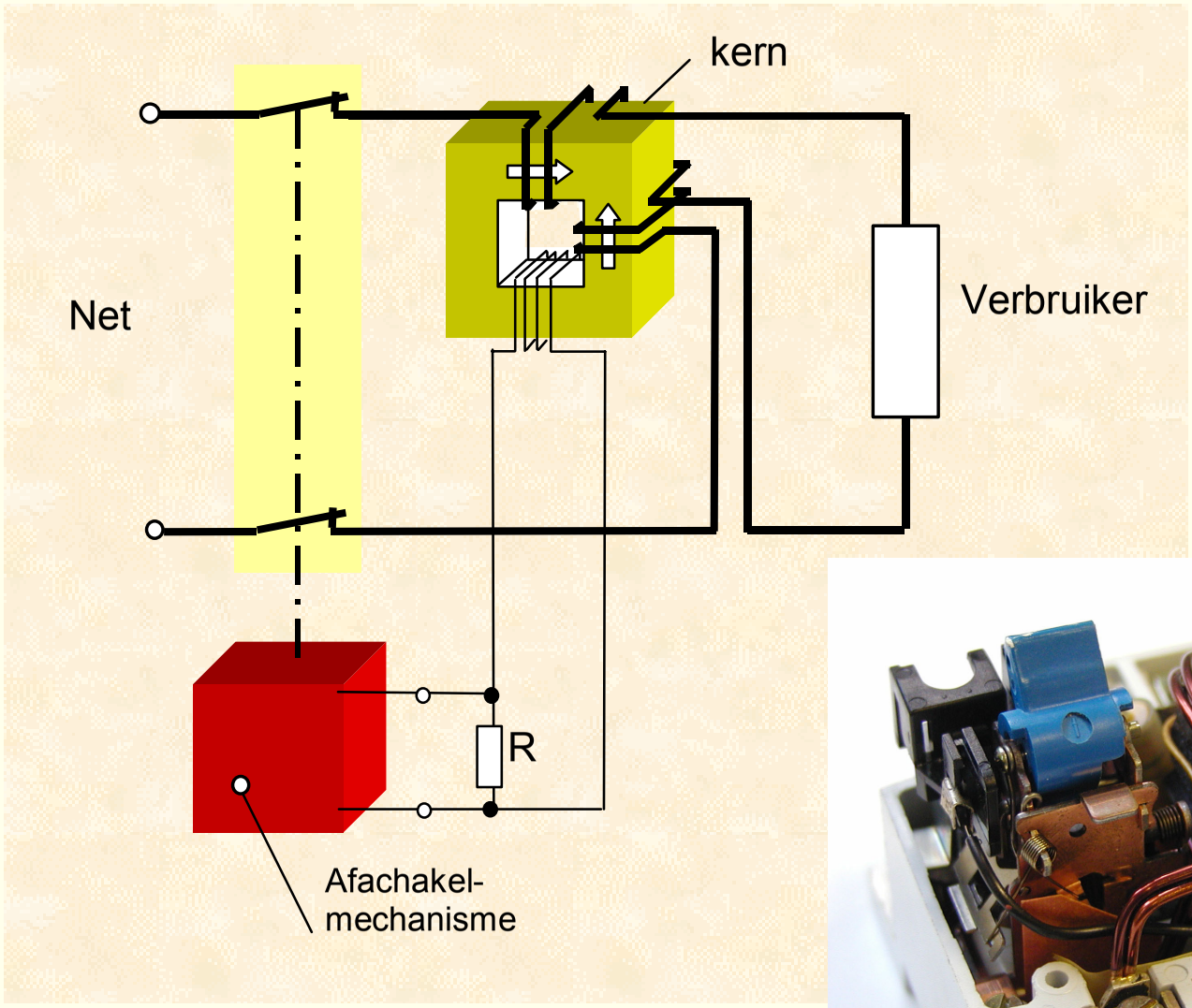


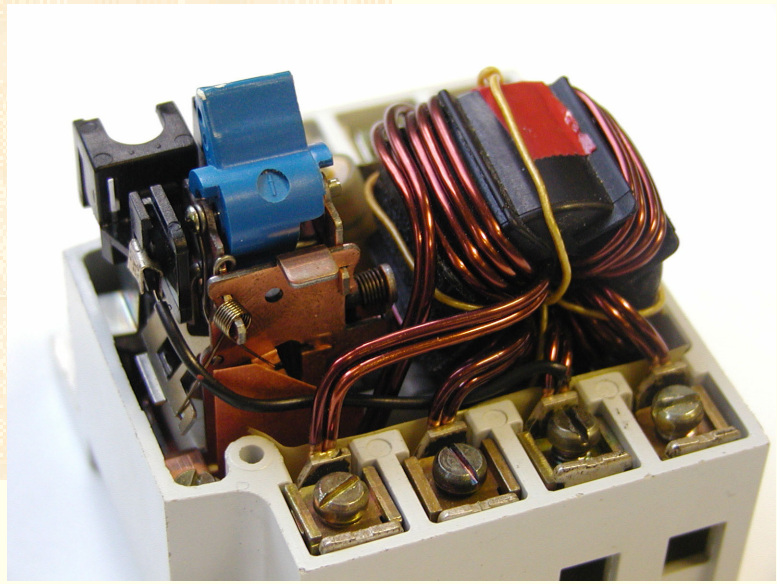
Veiligheidstransformator



Verliesstroomschakelaar



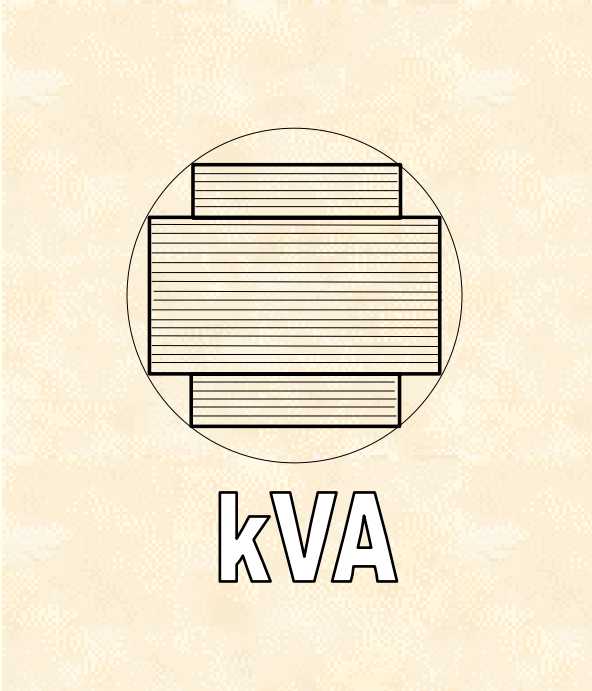

kern
Net
Verbruiker
R
Afachakel-
mechanisme

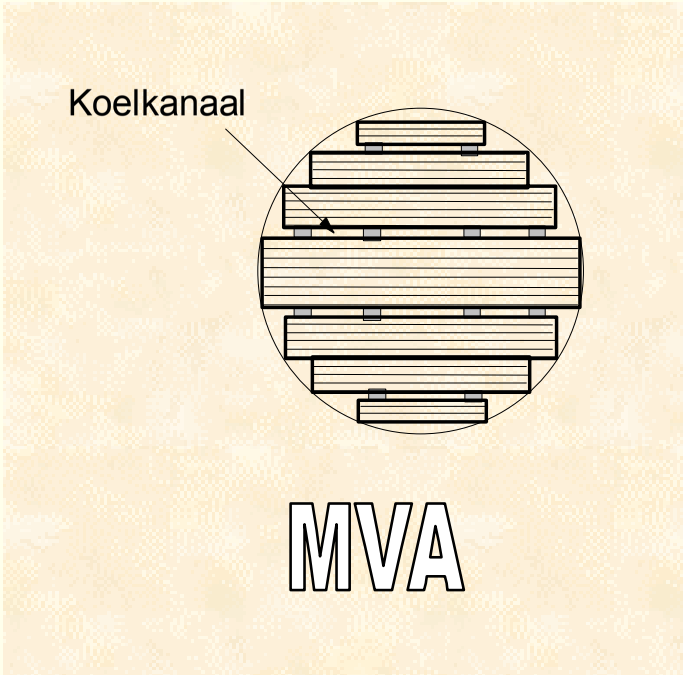


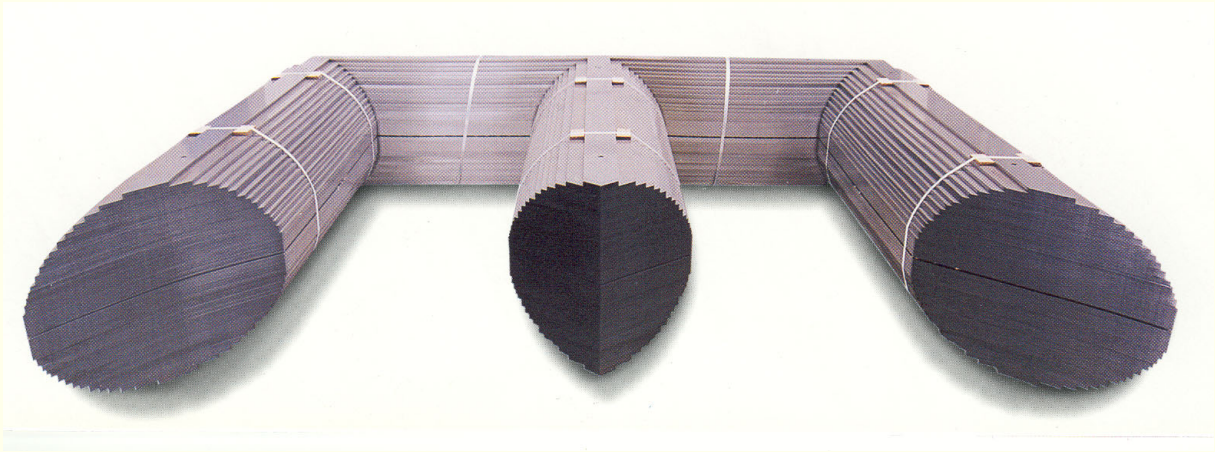
Aspecten van constructie en problemen eigen aan transformatoren

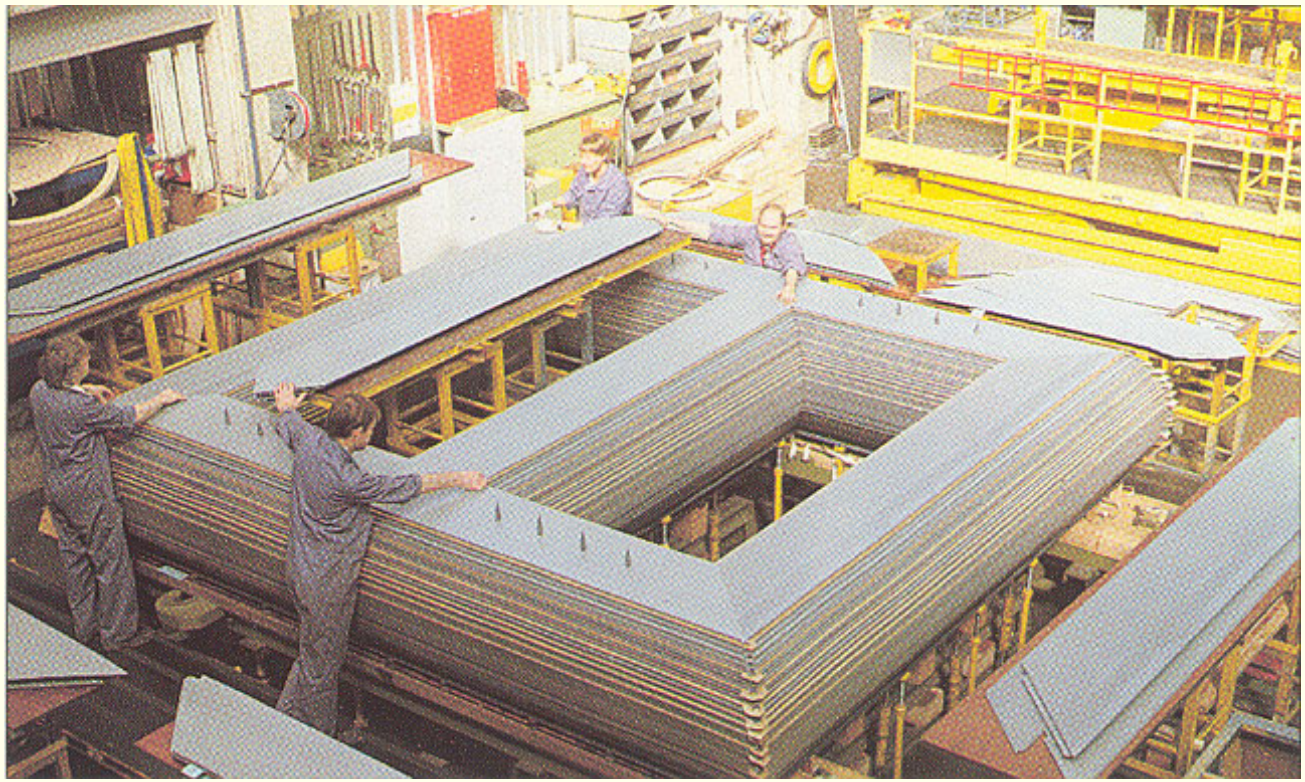
- Magnetische kern
- Wikkelingen
- Olie, kuip en koelsystemen
- Niet-oliehoudende transformatoren
- Regeling van de transformatieverhouding

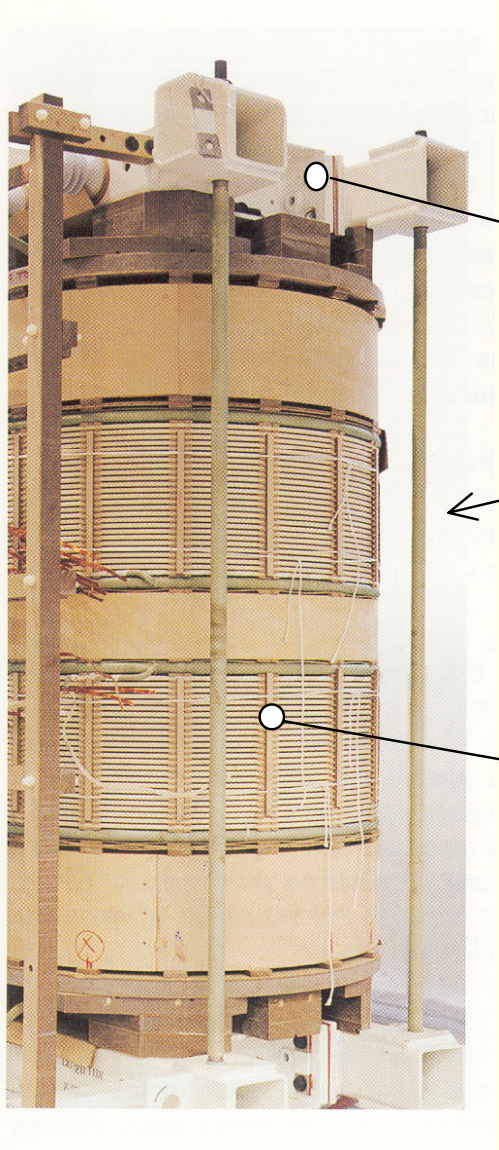
Magnetische kern



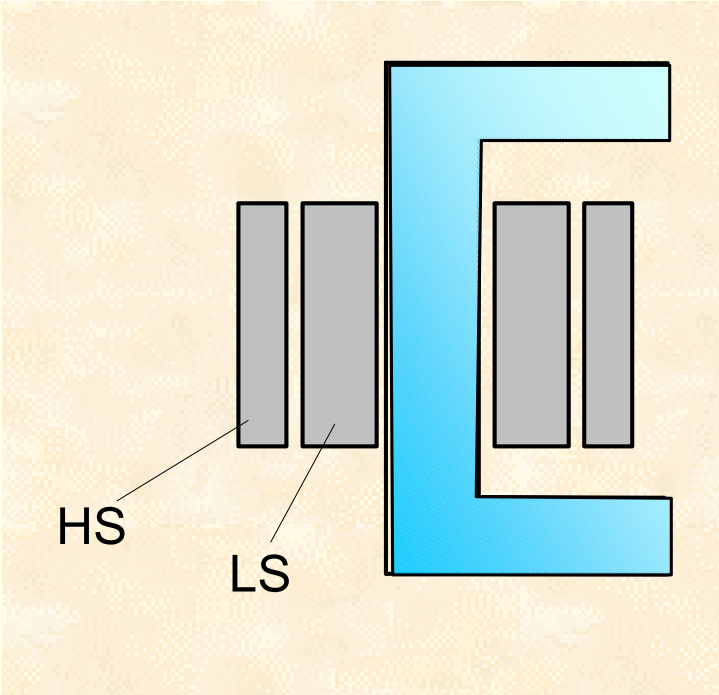


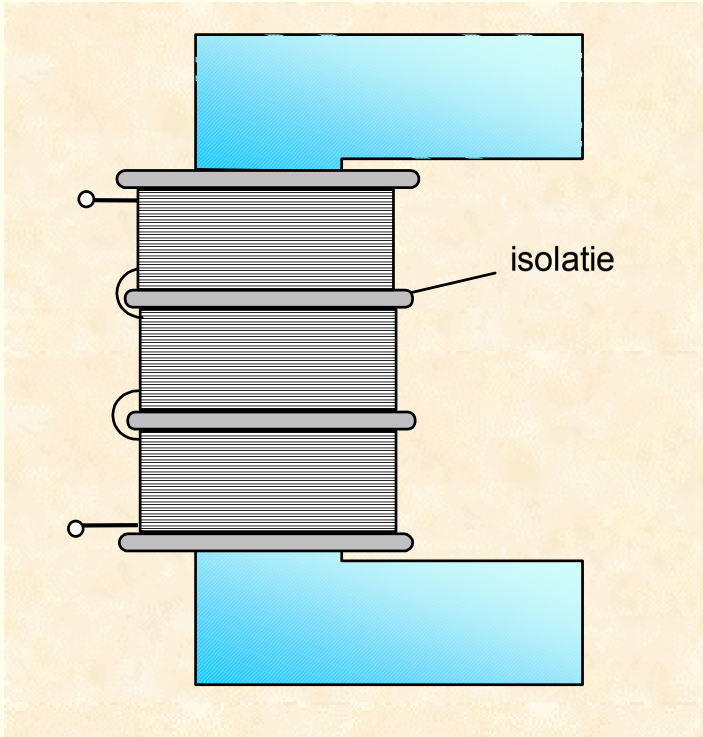


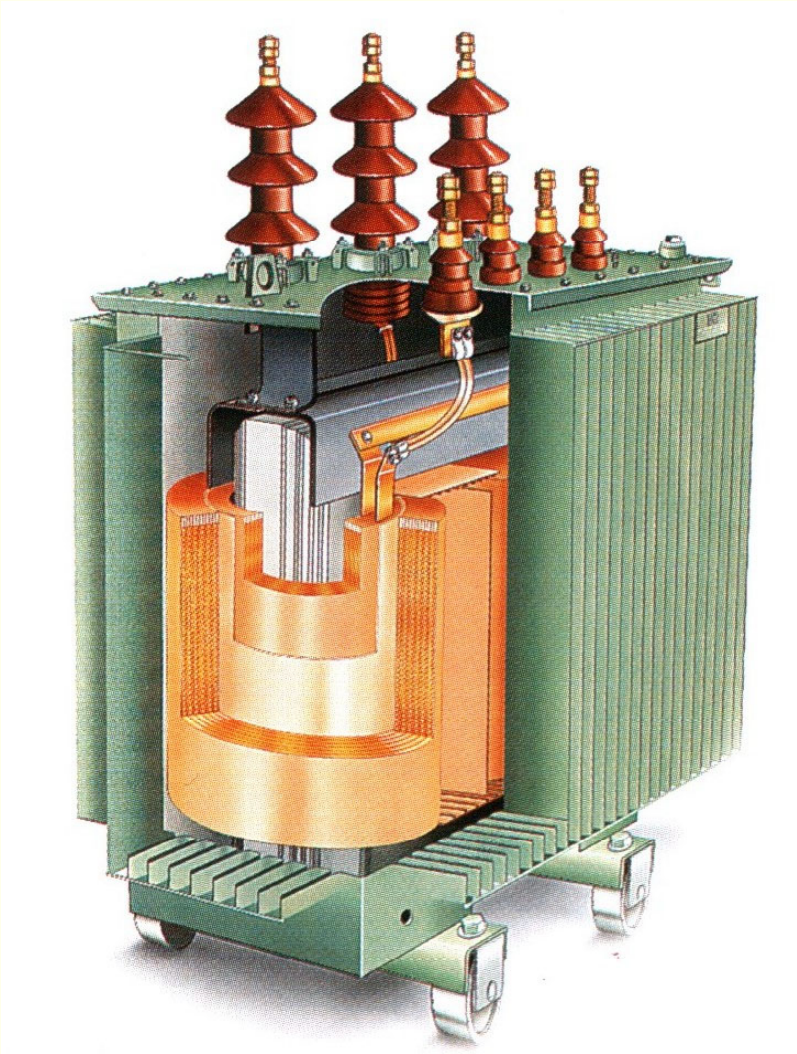


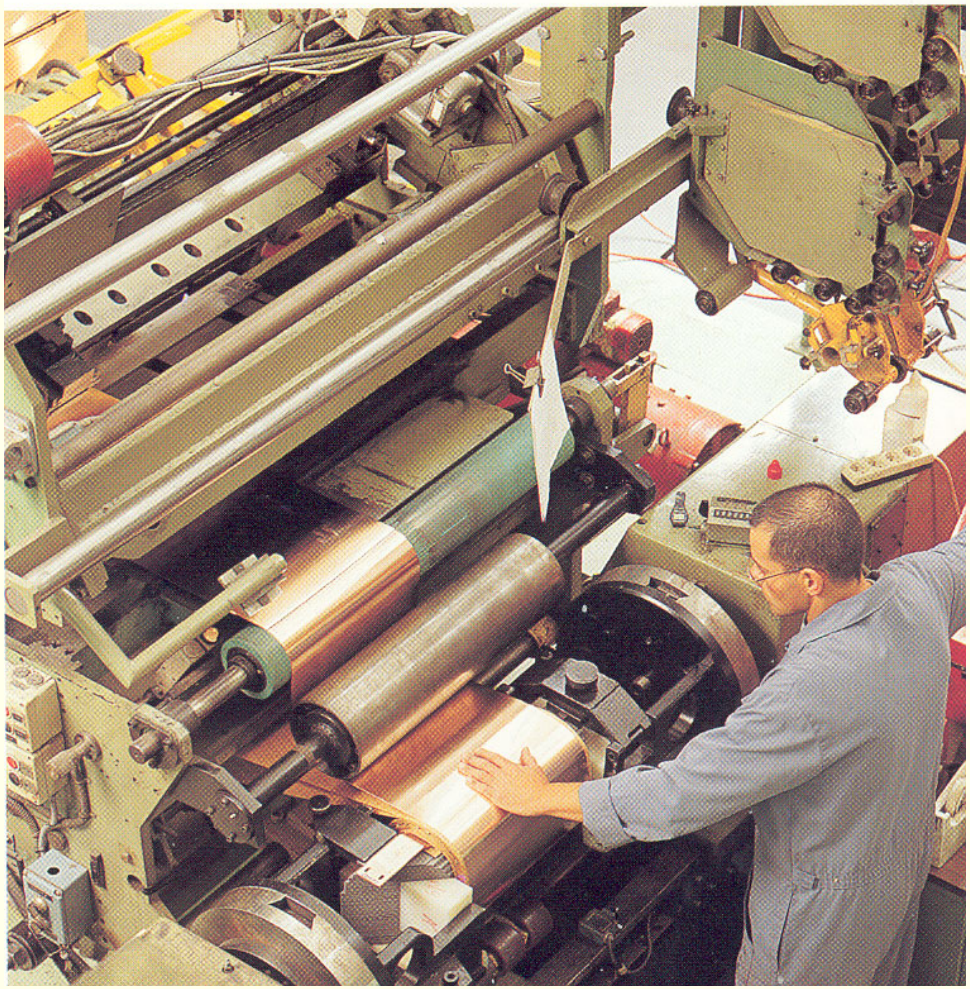

Jukbalk
Trekstang
HS-wikkeling

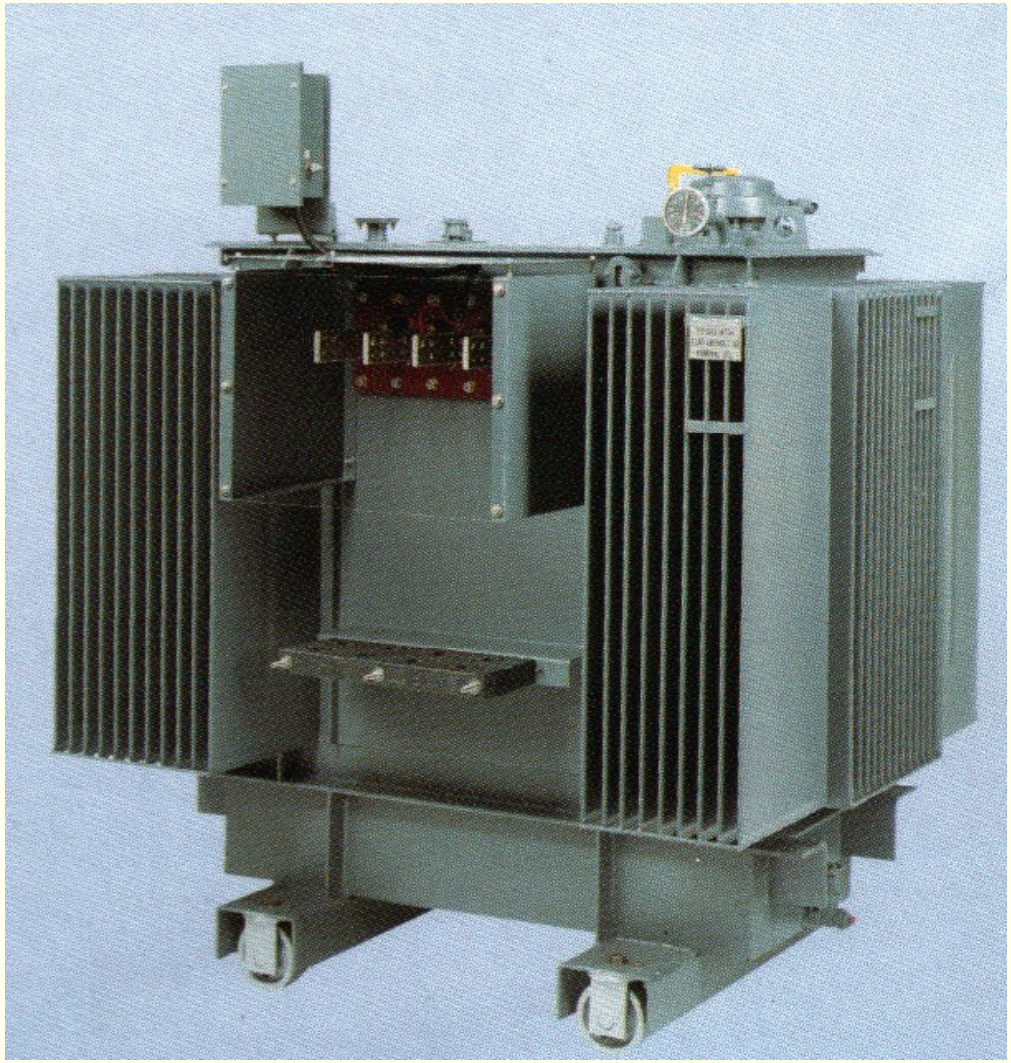
Cilinder- en schijfwikkeling

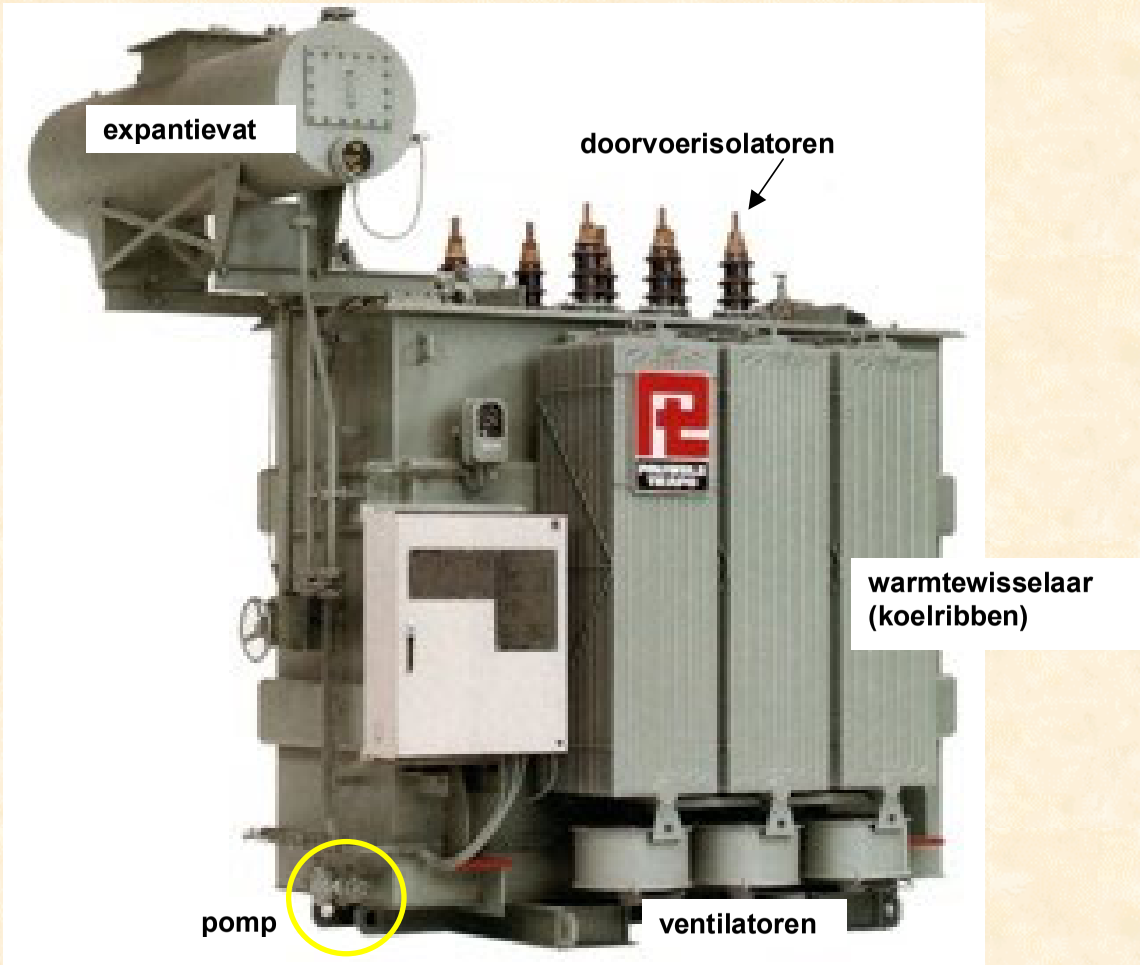




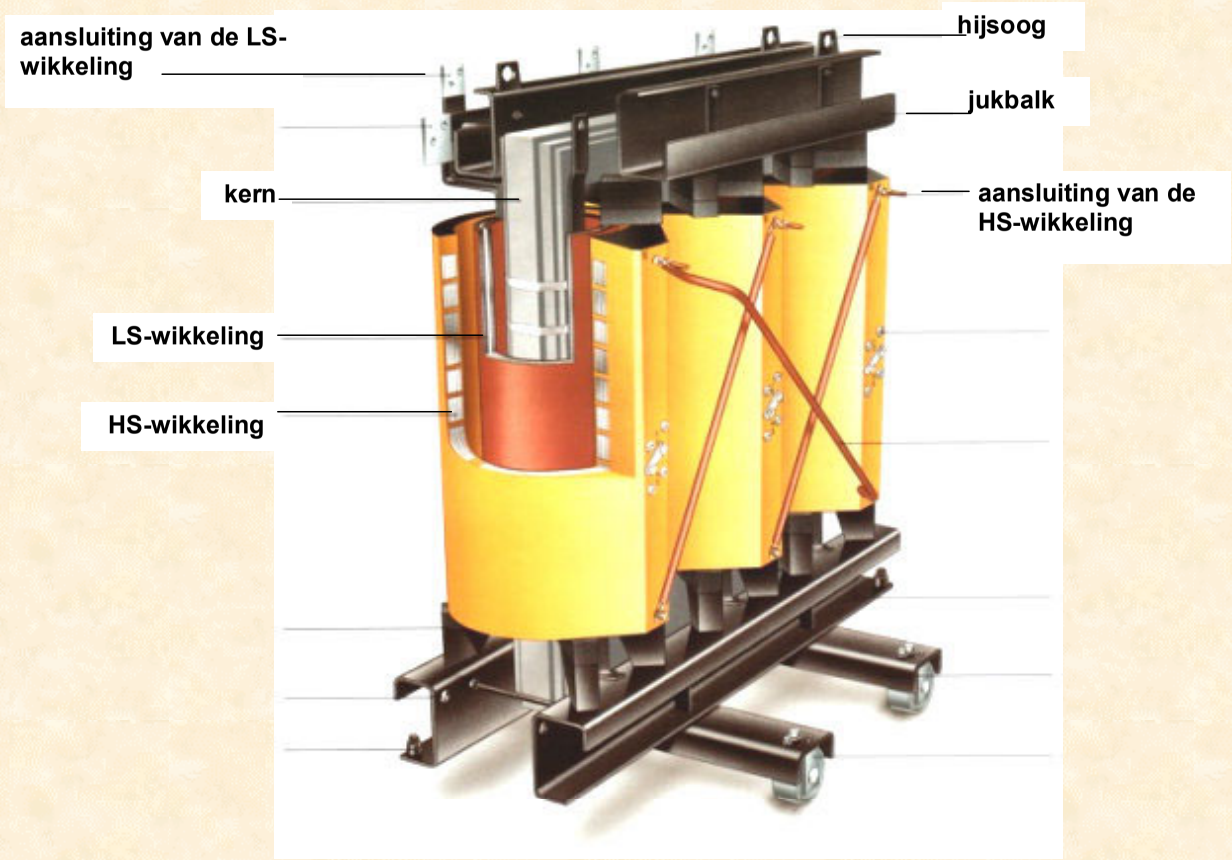







expantievat
doorvoerisolatoren
warmtewisselaar
(koelribben)
pomp
ventilatoren

Gietharstransformator



Regeling van de transformatieverhouding