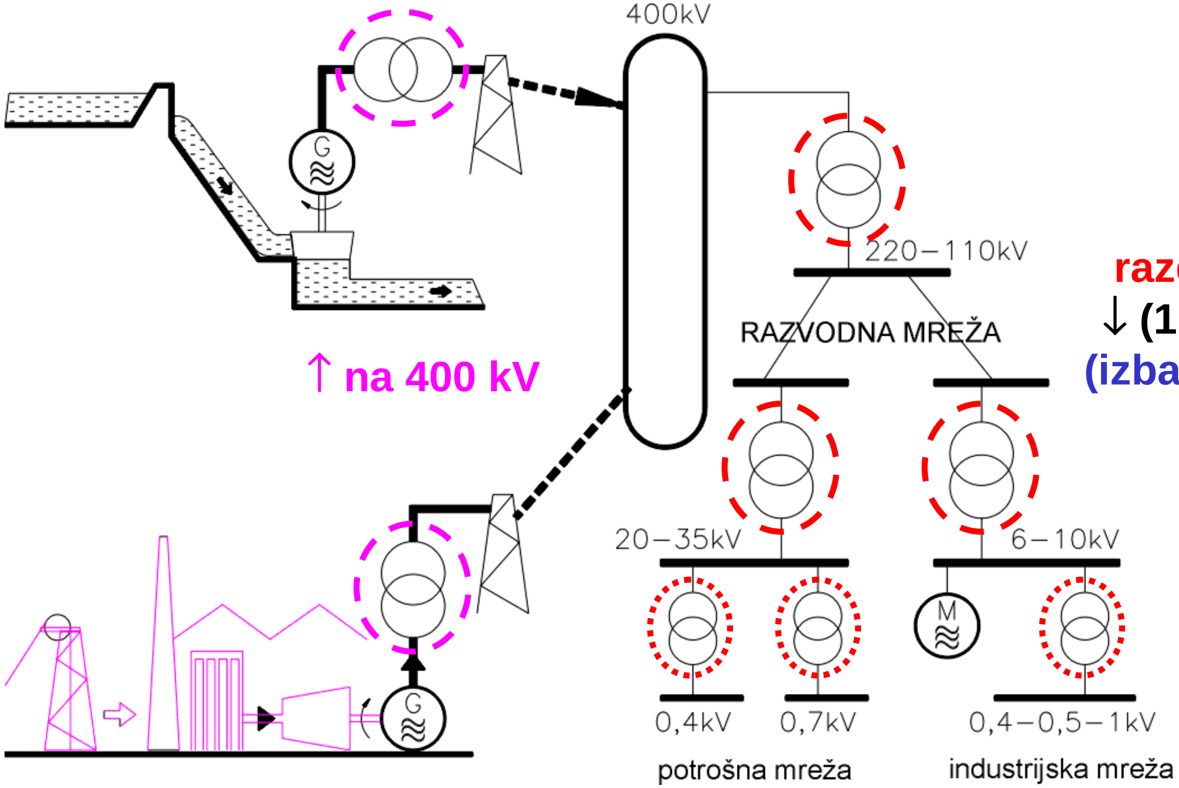
TRANSFORMATORI

opća mreža (400 kV - izbacivanje 220kV)



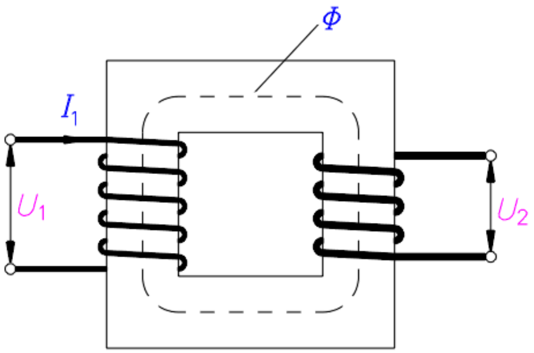
razdjelna mreža
↓ (110, 35, 20 kV)
(izbacivanje 10 kV)

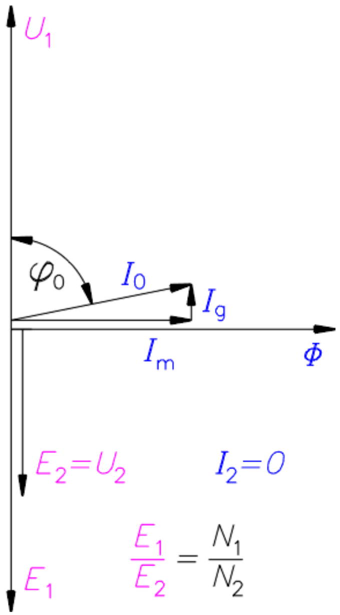
↓ potrošna **mreža**

Transformator u praznom hodu

N_1 - primarni

N_2 - sekundarni





GN - gornjeg napona

DN - donjeg napona

$$I_0 = \frac{U_1 - E_1}{Z_{TP}} = \sqrt{I_m^2 + I_g^2}$$

struja praznog hoda

U_1 - priključni napon

E_1 - inducirana protuelektromotorna sila

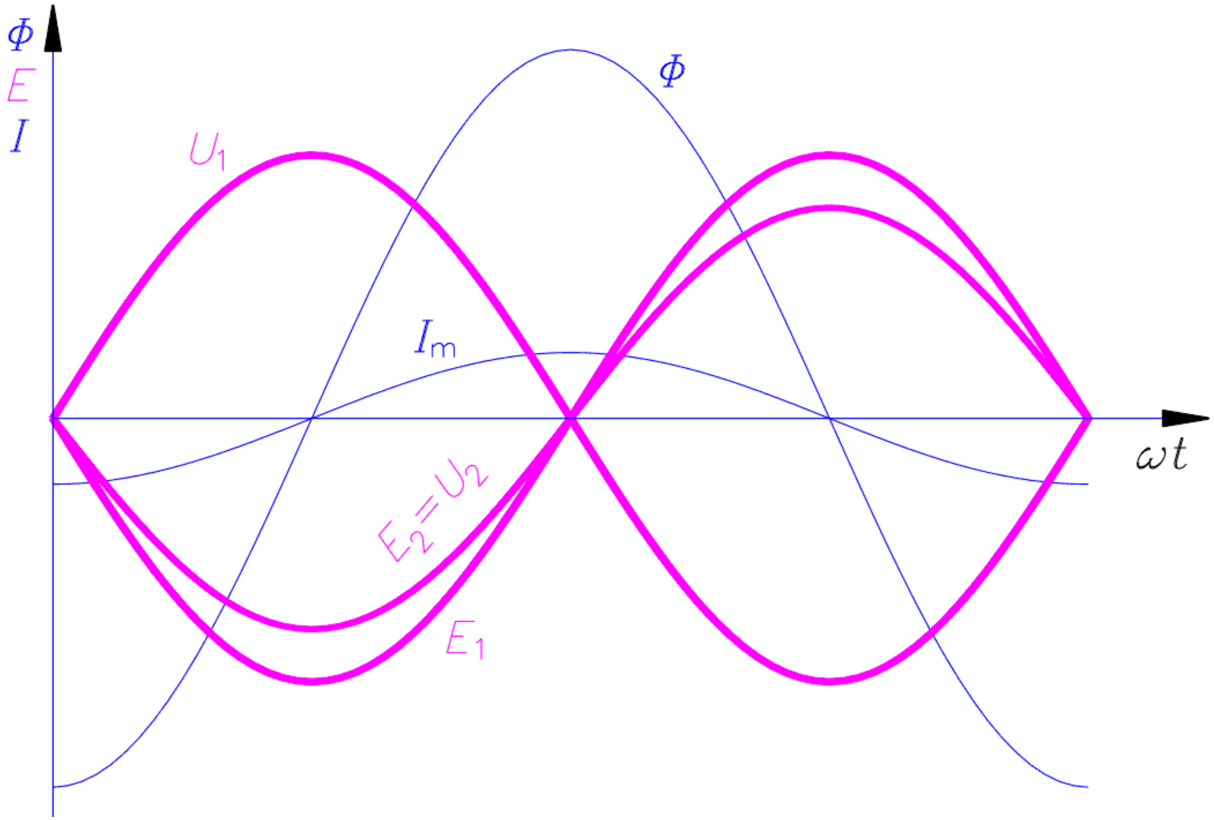
Z_{TP} - impedancija transformatora u praznom hodu

I_g - struja gubitaka praznog hoda

I_m - struja magnetiziranja

$$I_m = f(U_1 - E_1)$$

trenutne vrijednosti praznog hoda



$$\Phi = \Phi_m \sin \omega t$$

inducirani napon po zavoju

$$u = -\omega \Phi_m \cos \omega t$$

efektivna vrijednost za N zavoja

$$U_N = N \cdot \frac{\omega \Phi}{\sqrt{2}} = 4{,}44 \cdot N \cdot f \cdot \Phi$$

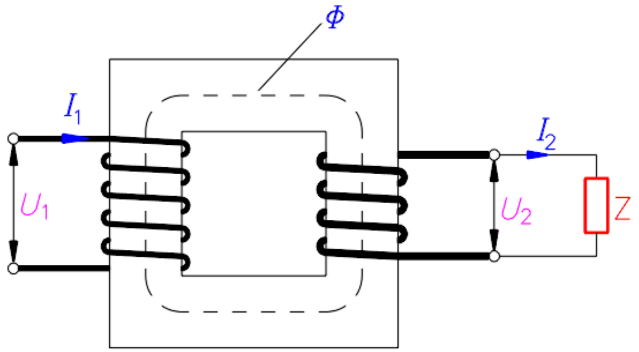
inducirani naponi u namotima $E_1 = N_1 \cdot u_i$ $E_2 = N_2 \cdot u_i$

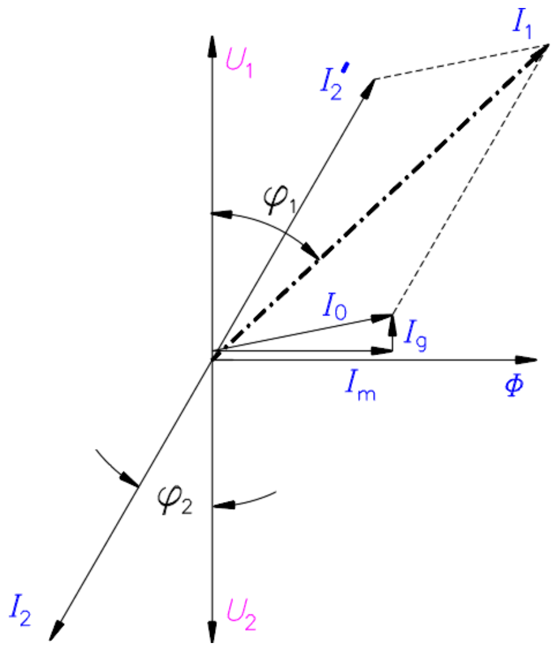
uz inducirani napon po jednom zavoju $u_i = 4{,}44 \cdot f \cdot \Phi$

$$\frac{E_1}{E_2} = \frac{U_1}{U_2} = \frac{N_1}{N_2} = n$$

prenosni omjer transformatora

Opterećeni transformator





za idealne svitke (zanemarene gubitke)

$$P_1 \approx P_2$$

P_1 **- snaga pimara**
P_2 **- snaga sekundara**

$$U_1 \cdot I_1 \cdot \cos\varphi_1 \approx U_2 \cdot I_2 \cdot \cos\varphi_2$$

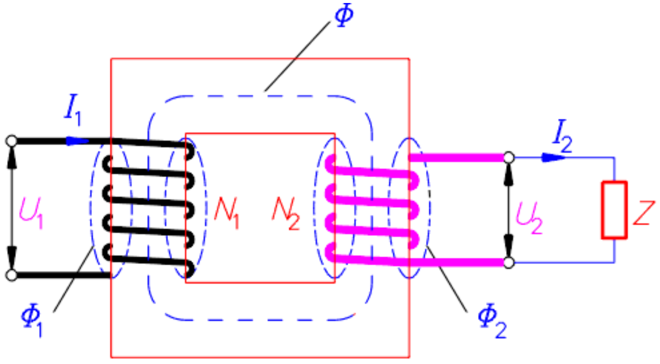
ako je

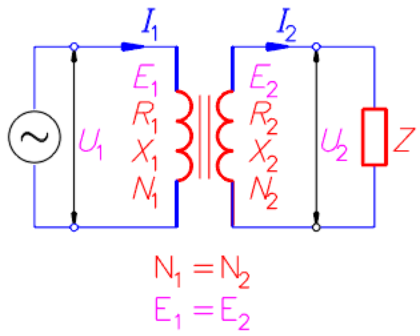
$$\varphi_1 = \varphi_2$$

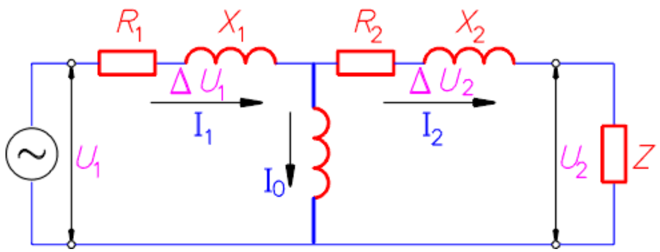
tada je

$$\frac{U_1}{U_2} \approx \frac{I_2}{I_1} \approx n$$

uz uzete u obzir impedancije svitaka



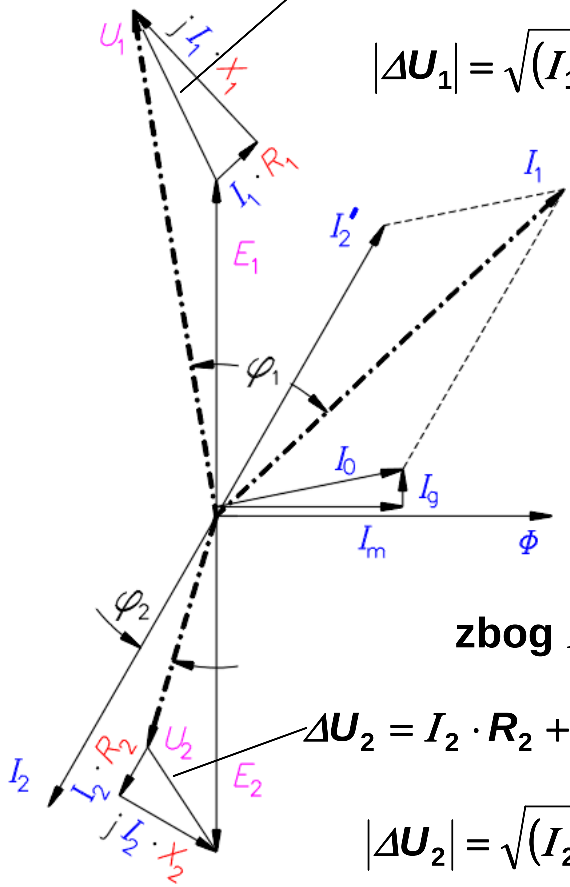




zbog I_1 pad U na N_1

$$\Delta U_1 = I_1 \cdot R_1 + jI_1 \cdot X_1 = I_1(R_1 + jX_1)$$

$$|\Delta U_1| = \sqrt{(I_1 \cdot R_1)^2 + (I_1 \cdot X_1)^2}$$



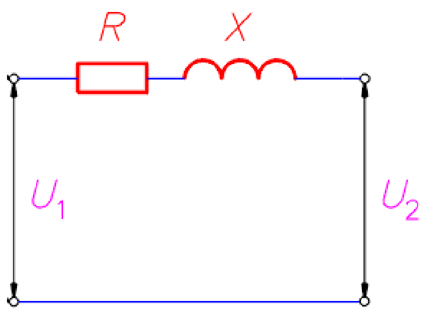
zbog I_2 pad U na N_2

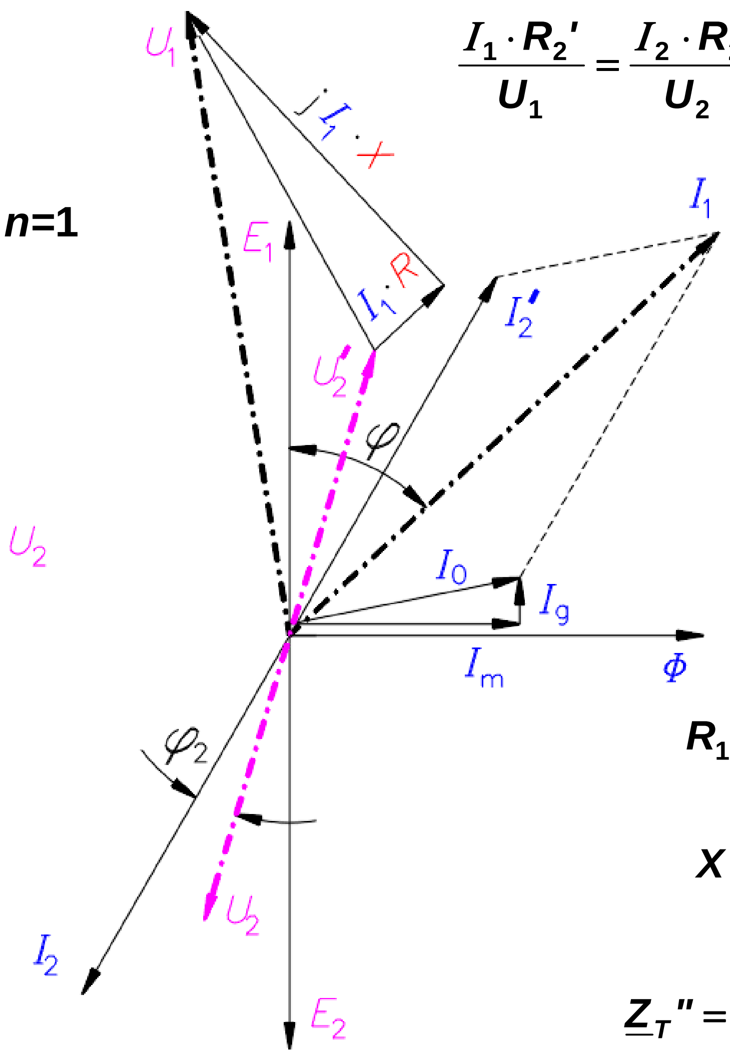
$$\Delta U_2 = I_2 \cdot R_2 + jI_2 \cdot X_2 = I_2(R_2 + jX_2)$$

$$|\Delta U_2| = \sqrt{(I_2 \cdot R_2)^2 + (I_2 \cdot X_2)^2}$$

(na jednu stranu sve impedancije) preračunavanje = reduciranje = preslikavanje

za $N_1=N_2$ odnsno $n=1$





na stranu primara

$$\frac{I_1 \cdot R_2'}{U_1} = \frac{I_2 \cdot R_2}{U_2} \qquad R_2' = R_2 \cdot n^2 \qquad R'_T = R_1 + n^2 \cdot R_2$$

$$\frac{I_1 \cdot X_2'}{U_1} = \frac{I_2 \cdot X_2}{U_2} \qquad X_2' = X_2 \cdot n^2$$

$$X'_T = X_1 + n^2 \cdot X_2$$

$$\underline{Z}'_T = R'_T + jX'_T$$

$$\left|Z'_T\right| = \sqrt{R'^2_T + X'^2_T}$$

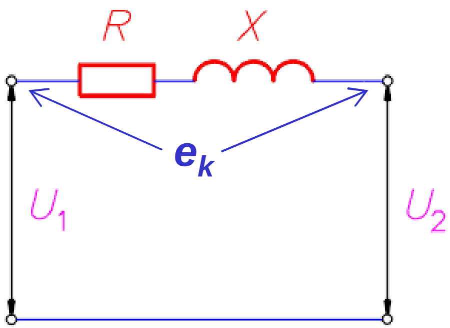
na stranu sekundara

$$R_1'' = \frac{R_1}{n^2} \qquad R_T'' = R_2 + \frac{R_1}{n^2}$$

$$X_1'' = \frac{X_1}{n^2} \qquad X_T'' = X_2 + \frac{X_1}{n^2}$$

$$\underline{Z}_T'' = R_T'' + jX_T'' \qquad \left|Z_T''\right| = \sqrt{R_T''^2 + X_T''^2}$$

pad napona na primarnoj strani



relativno gledano (jednake vrijednosti)

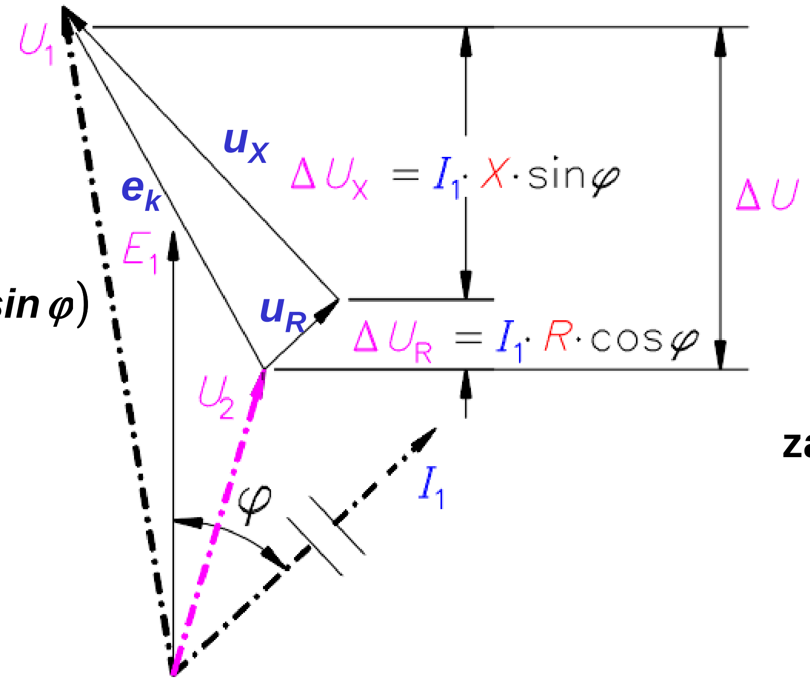
na primaru

$$\frac{I_1 Z_T'}{U_1} = \frac{I_1 R_T'}{U_1} + j\,\frac{I_1 X_T'}{U_1}$$

na sekundaru

$$\frac{I_2 Z_T''}{U_2} = \frac{I_2 R_T''}{U_2} + j\,\frac{I_2 X_T''}{U_2}$$

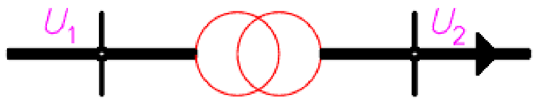
$$\Delta U_1 = I_1 (R \cdot \cos\varphi + X \cdot \sin\varphi)$$



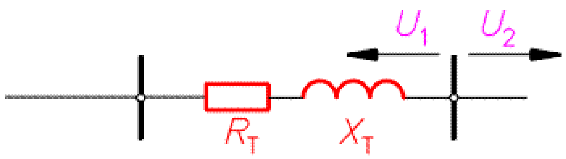
za oba slučaja (smjera) vrijedi

$$\underline{e}_k = u_R + j u_X$$

svaki transformator - jednaka impedanciju bez obzira na smjer gledanja

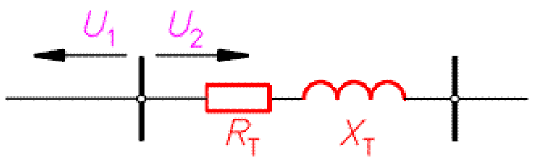


za $U_1 \neq U_2$ i $N_1 \neq N_2$ imamo:



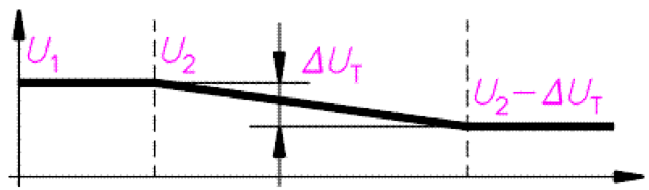
$$R_T' = R_1 + R_2\left(\frac{U_1}{U_2}\right)^2 \qquad X_T' = X_1 + X_2\left(\frac{U_1}{U_2}\right)^2$$

reducirano na primar
impedancija na strani izvor



$$R_T'' = R_2 + R_1\left(\frac{U_2}{U_1}\right)^2 \qquad X_T'' = X_2 + X_1\left(\frac{U_2}{U_1}\right)^2$$

reducirano na sekundar
impedancija na strani trošila



pad napona na transformatoru

$\Delta U_T \approx$ 5,0% U_n, za struju I_n

$U_{20} \approx U_2 - \Delta U_T$

U_2 - napon praznog hoda

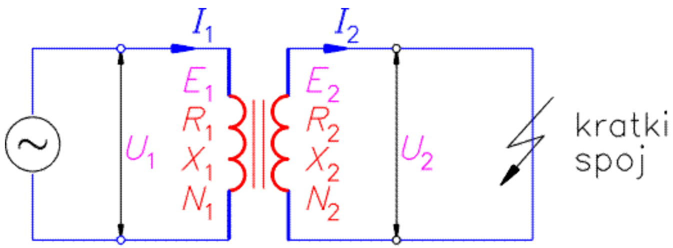
U_{20} - napon opterećenog trafa

ΔU_T - prosječno 5%

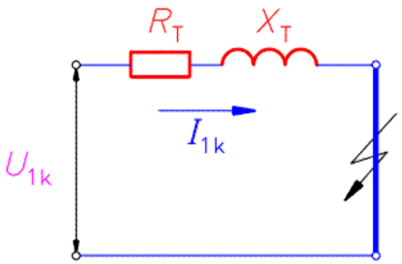
transformator u kratkom spoju

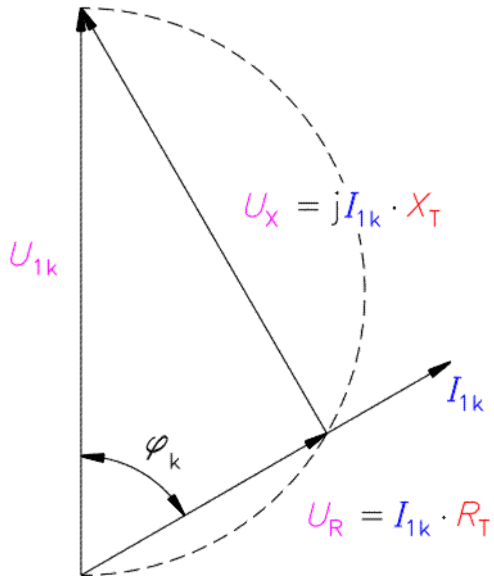
$\Delta U_T = u_R + j u_X = \underline{e}_k$

pad napona na transformatoru = naponu kratkog spoja
e_k - pri nominalnoj struji sekundara koji je u KS



U_1 - do vrijednosti za I_2 nominalno





pokus kratkog spoja

$$e_k = \frac{U_{1k}}{U_1} \cdot 100 \quad (\%)$$

gubici = gubici u *Cu*

$$u_R = \frac{P_{Cu}}{P} \cdot 100 \quad (\%)$$

pad napona u %

$$U_R = u_R \cdot \frac{U_1}{100} \quad (\%)$$

prema slici

$$U_R = I_{1k} \cdot R_T \quad (\mathrm{V})$$

prema slici je $$u_X = \sqrt{e_k^{\,2} - u_R^{\,2}} \quad (\%)$$

a prema tome je $$U_X = \sqrt{U_{1k}^{\,2} - U_R^{\,2}} = u_X \cdot \frac{U_1}{100} \quad (\mathrm{V})$$

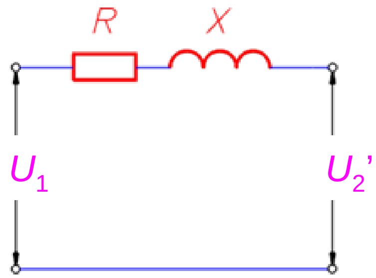
te je radna komponenta otpora

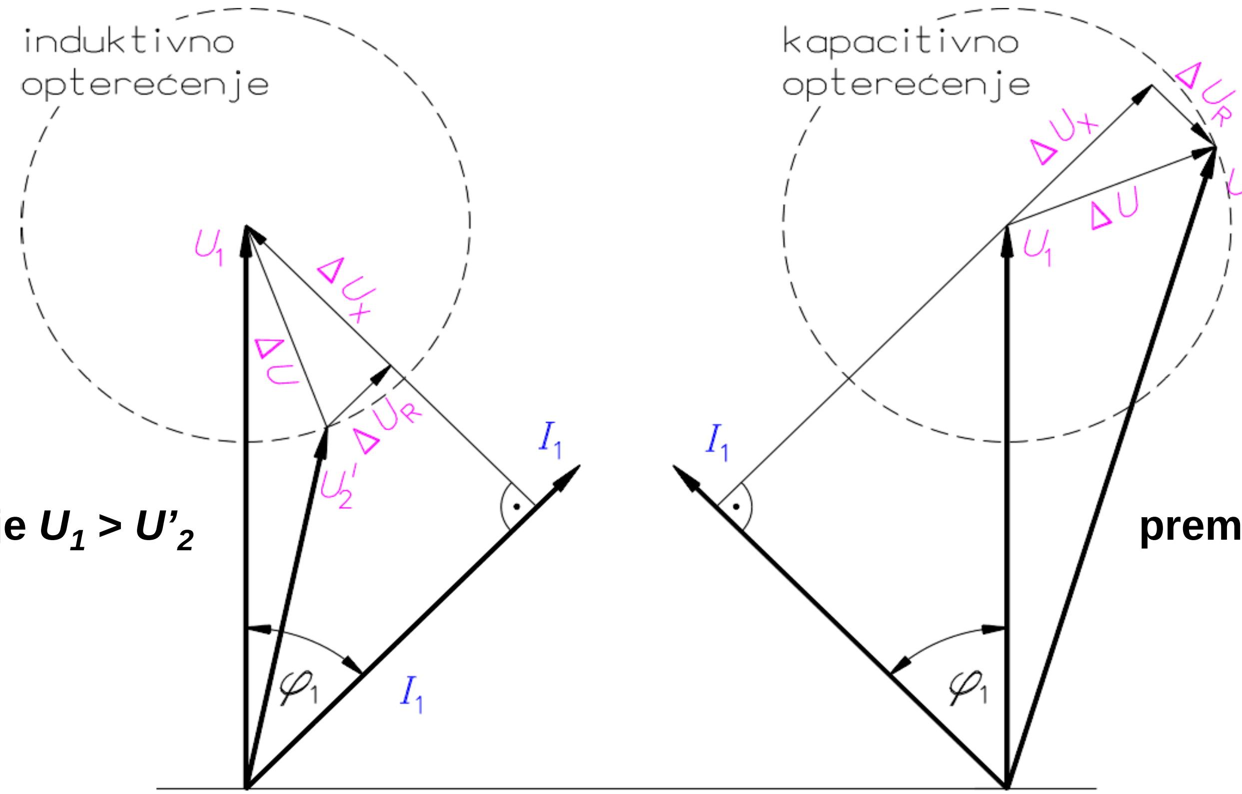
$$R_T = \frac{U_R}{I_{1k}} = \frac{u_R \cdot U_1}{100 \cdot I_{1k}} \quad (\Omega)$$

a induktivna komponenta otpora

$$X_T = \frac{U_X}{I_{1k}} = \frac{U_X \cdot U_1}{100} \quad (\Omega)$$

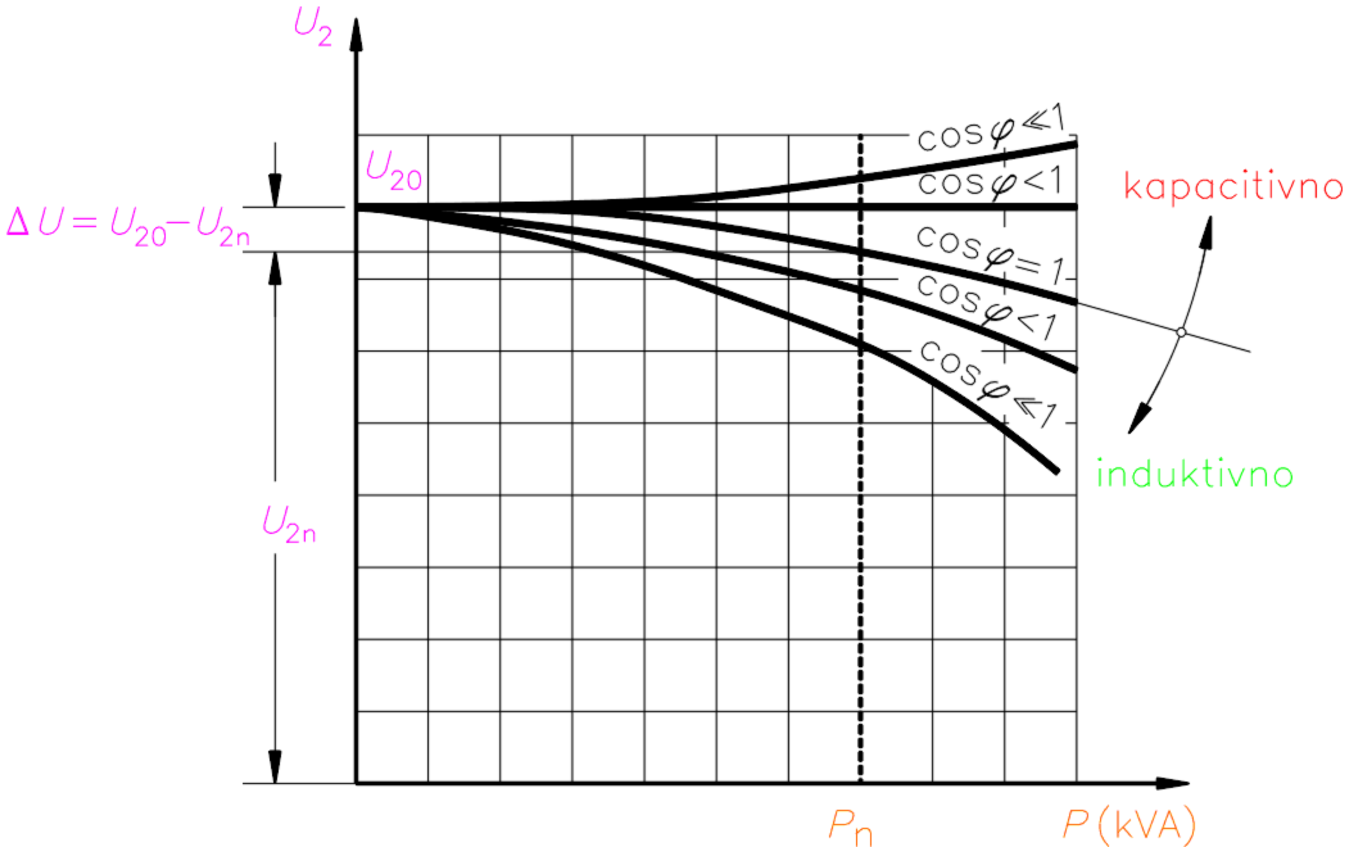
kazalični prikaza pada napona na transformatoru i utjecaj karaktera opterećenja





prema slici je $U_1 > U'_2$

prema slici je $U_1 < U'_2$



pad napona na transformatoru uz uzete u obzir sve utjecaje

$$\Delta U_1 = I_1(R_T \cdot \cos\varphi + X_T \cdot \sin\varphi) + \frac{1}{2U_1} \cdot I_1(X_T \cdot \cos\varphi + R_T \cdot \sin\varphi)^2 \quad (V)$$

kompliciranije a razlika oko 1% te se ne koristi

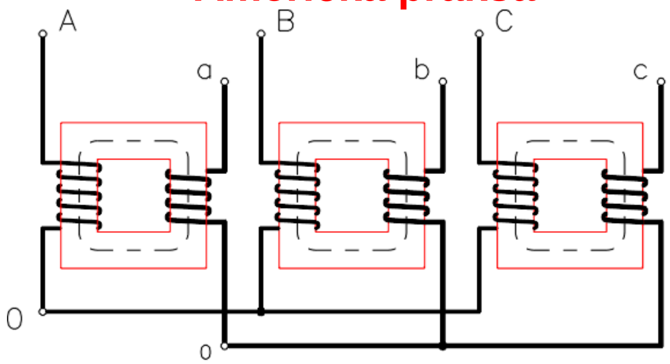
prazni hod ⇒ magnetska slika, inducirani naponi, gubici u željezu

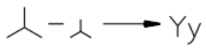
kratki spoj ⇒ strujna slika, gubici u bakru

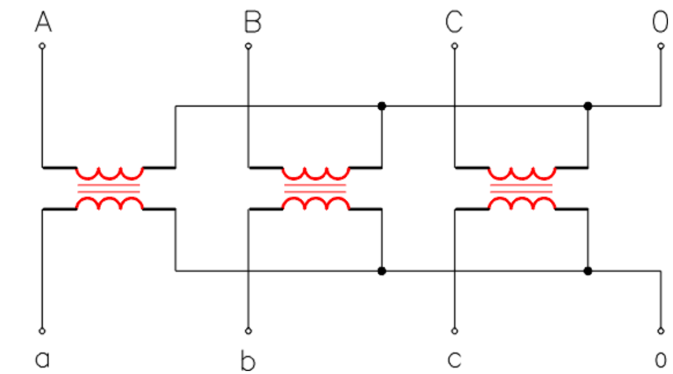
TROFAZNI TRANSFORMATORI

tri jednofazna

Američka praksa



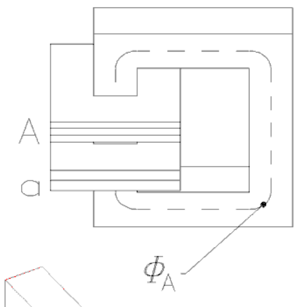


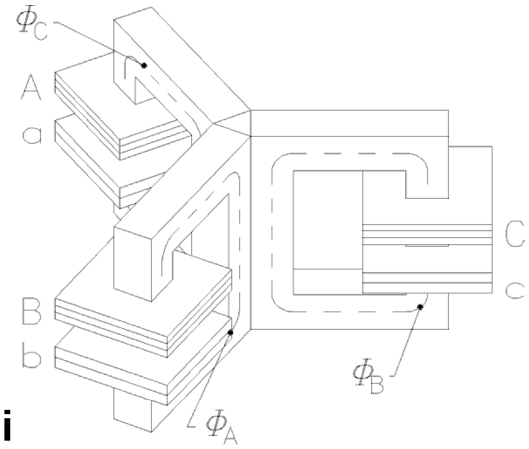


L₁ (A), L₂ (B), L₃ (C) - namoti višeg napona

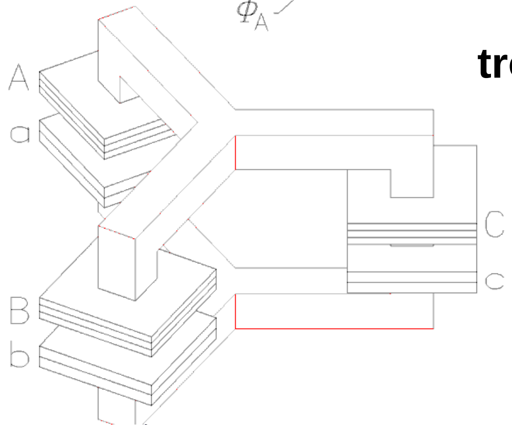
l₁ (a), l₂ (b), l₃ (c) - namoti nižeg napona

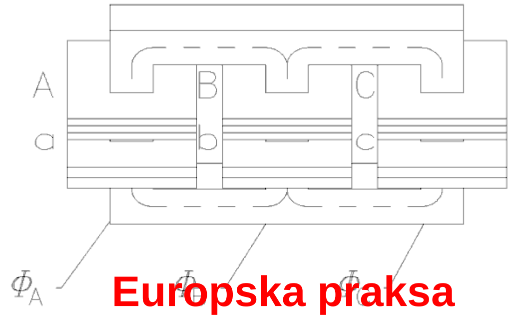
tok energije - od namota višeg prema namotima nižeg napona



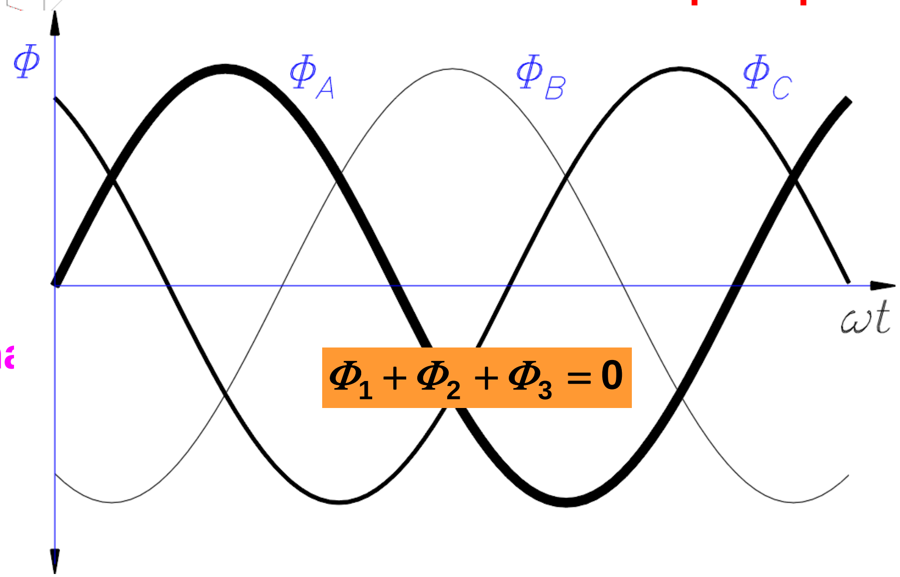


trofazni



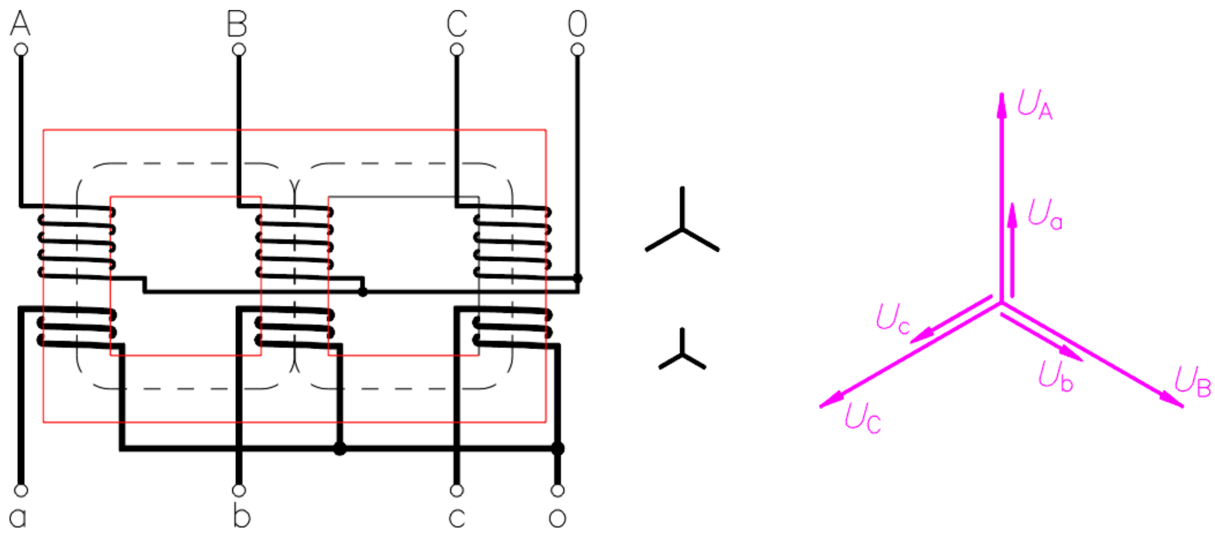


Europska praksa

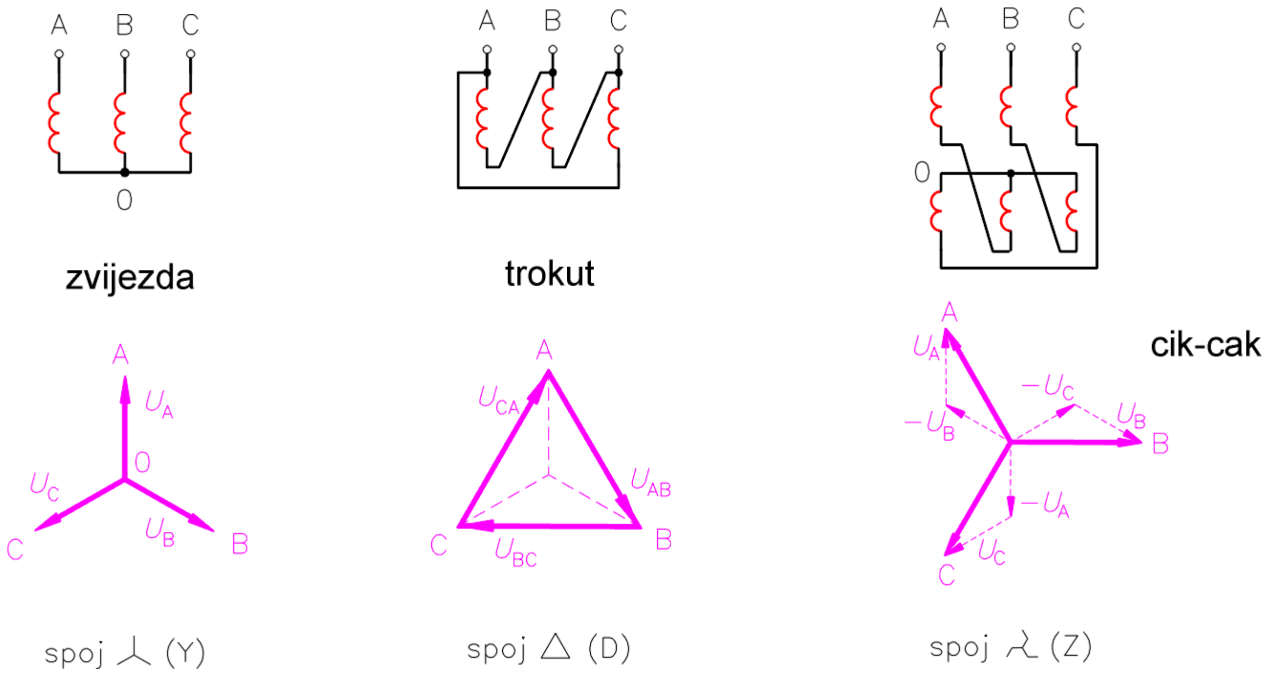


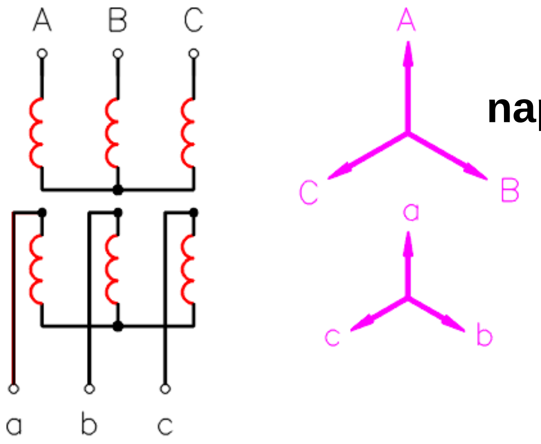
$$\Phi_1 + \Phi_2 + \Phi_3 = 0$$

istofazno spojeni namoti trofaznog transformatora



osnovni spojevi trofaznih transformatora



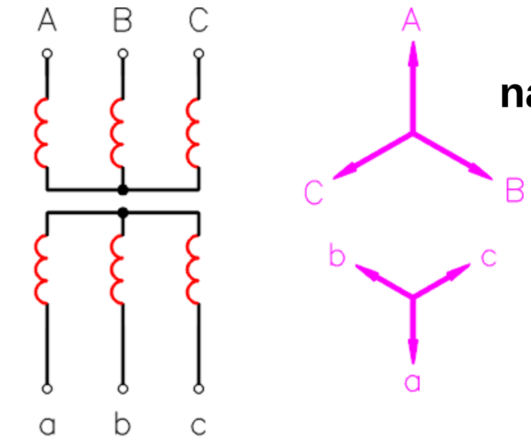


naponi u fazi

istovrsni spoj

Yy0:

grupa 0: $U_A / U_a \rightarrow 0°$

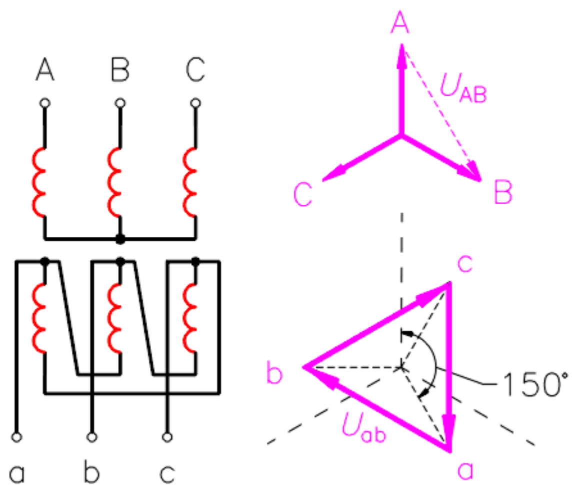


naponi u protufazi

Yy6:

grupa 6: $U_A / U_a \rightarrow 180°$

kombiniranje osnovnih spojeva omogućuje različite fazne pomake između primarnog i sekundarnog napona

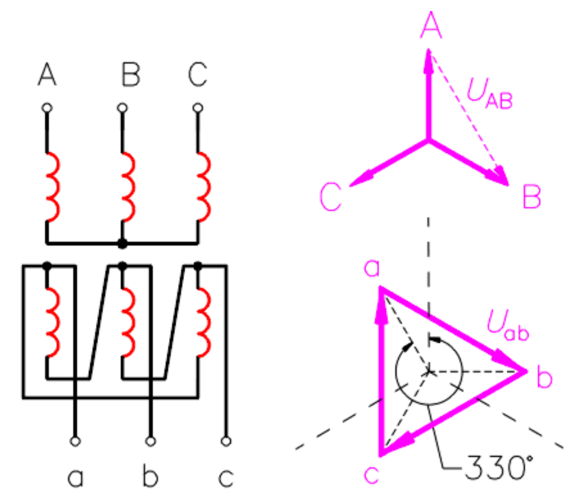


“referentna” faza

Yd5:

grupa 5: $U_{AC} / U_{ac} \rightarrow 150°$

raznovrsni spoj

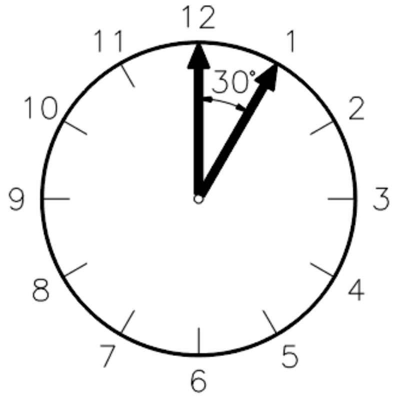


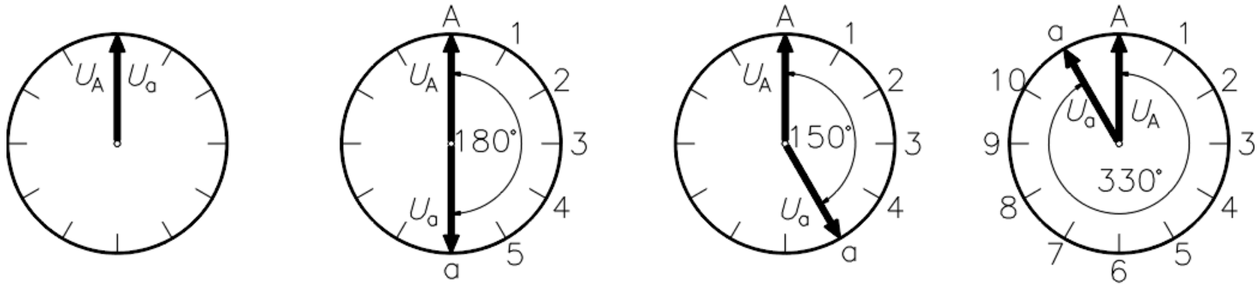
“protufaza”

Yd11:

grupa 11: $U_{AC} / U_{ac} \rightarrow 330°$

označivanje faznih pomaka - grupe spojeva - po 30° me đusobnog pomaka





Yy0 | Yy6 | Yd5 | Yd11

grupe0	**grupe6**	**grupe5**	**grupe11**
Dd0	**Dd6**	**Dy5**	**Dy11**
Yy0	**Yy6**	**Yd5**	**Yd11**
Dz0	**Dz6**	**Yz5**	**Yz11**

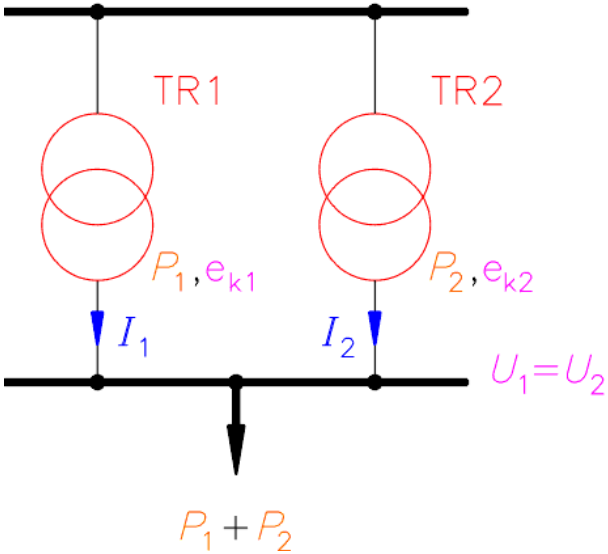
PARALELNI RAD TRANSFORMATORA

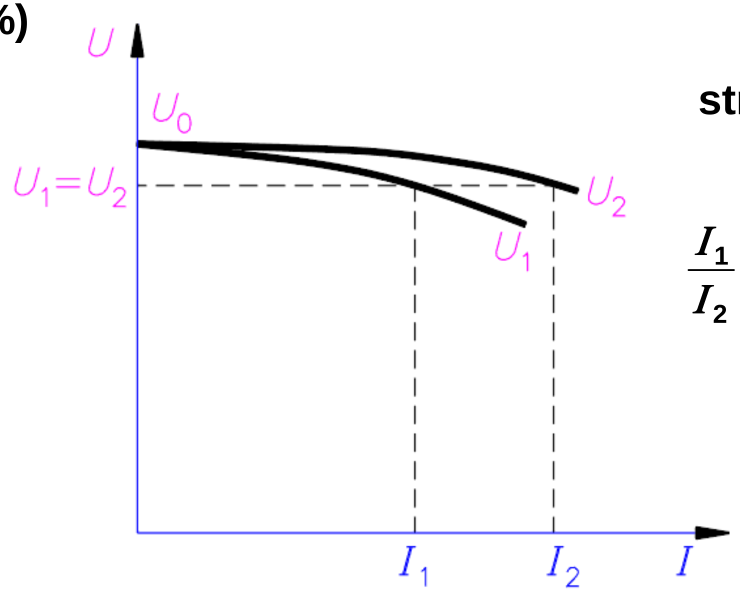
paralelno napajanje mreže

jednak *n* ; jednaka grupa spojeva (istofaznost)

mala razlika u snazi (izuzetak - usklađenost napona kratkog spoja)

≈ naponi kratkog spoja (Δ<10%)





strujno opterećenje je

$$\frac{I_1}{I_2} = \frac{Z_{k1}}{Z_{k2}}$$ **impedancije pri KS**

zbog toga što je

$$e_k = \frac{I_n \cdot Z_k}{U_n}$$

možemo izračunati impedancije kratkog spoja $Z_{k1} = \frac{U_{n1}}{I_{n1}} \cdot e_{k1}$ $Z_{k2} = \frac{U_{n2}}{I_{n2}} \cdot e_{k2}$

prema tome je $\frac{I_1}{I_2} = \frac{P_{n1} \cdot e_{k2}}{P_{n2} \cdot e_{k1}}$ **i stvarno opterečenje** $\frac{P_1}{P_{n1}} : \frac{P_2}{P_{n2}} = \frac{1}{e_{k1}} : \frac{1}{e_{k2}}$ **ili** $\frac{I_1}{I_{n1}} : \frac{I_2}{I_{n2}} = \frac{e_{k2}}{e_{k1}}$

$$P = \sum_{1}^{n} P_i \quad \left(\text{za } e_{k1} = e_{k2} = ...e_{ki}\right)$$

u VA ili kVA ili MVA

GUBICI TRANSFORMATORA

u željezu (magnetizacija, histereza, vrtložne struje)

$$P_h = k_h \cdot f \cdot B^{(1,6 \div 2)} \quad (\mathrm{W/kg})$$

k_h - koeficijent ovisi o kvaliteti materijala - površini histereze (od 0,01 do 0,02)

1,6 -2 - eksponent ovisan i indukciji (niže 1,6, više do 2)

f - frekvencija u Hz

B - magnetska indukcija u T

$$P_v = k_v \cdot f^2 \cdot B^2 \cdot b \quad (\mathrm{W/kg})$$

k_h - koeficijent ovisi o kvaliteti materijala (od 0,015 do 0,025)

f - frekvencija u Hz

B - magnetska indukcija u T

d - debljina lima u mm

$$P_{g(Fe)} \approx K \cdot B^2$$

u bakru (omski otpor)

za jednofazni trafo

$$P_{g(Cu)} = I_1^2 \cdot R_T$$

za trofazni trafo

$$P_{g(Cu)} = 3 \cdot I_1^2 \cdot R_T$$

I_1 - struja svitka višeg napona

R_T - radna komponenta impedancije transformatora

željezo - zbog B^2 za $\downarrow$ gubitke $\uparrow$ presjek jezgre $\rightarrow$ teži i skuplji transformator

bakar - zbog I^2 za $\downarrow$ gubitke $\uparrow$ presjek namota $\rightarrow$ teži i skuplji transformator

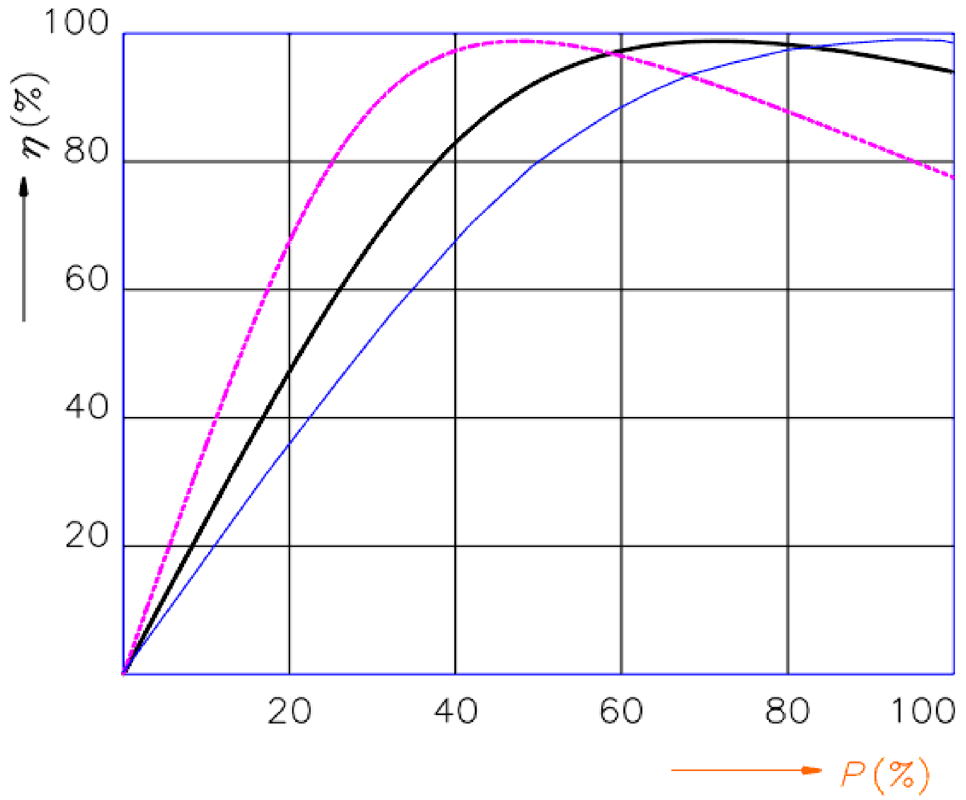
$$\eta = \frac{P_n \cdot \cos\varphi}{P_n \cdot \cos\varphi + P_{g_{Fe}} + P_{g_{Cu}}}$$ uz $x = \frac{P}{P_n}$ i stalan $\cos\varphi$

$P_{g_{Fe}} = k$ (konstanta)

$P_{g_{Cu}} = P_{g_{nCu}} \cdot x^2$

$P_{g_{Fe}} = P_{g_{Cu}}$ uvjet za η_{max}

ovisnost η o opterećenju



$$\frac{P_{g(Fe)}}{P_{g(Cu)}} \approx$$

- za 1,0 P_n
- za 0,75 P_n
- za 0,5 P_n

MJERNI TRANSFORMATORI

linearni prijenos mjernog podatka

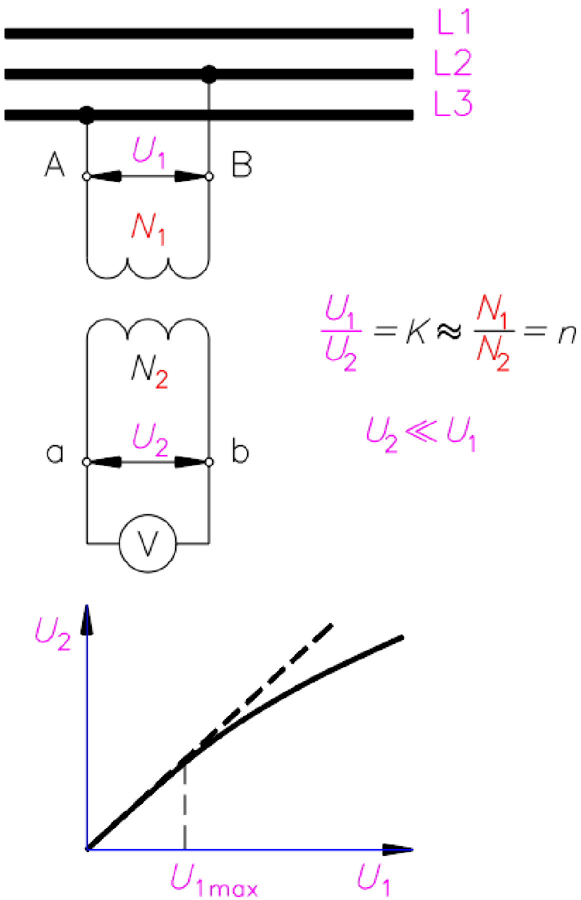
naponski

linearni dio karakteristike magnetiziranja

točnost ↑ ako opterećenje ↓

režim praznog hoda

za određenu snagu u VA



strujni

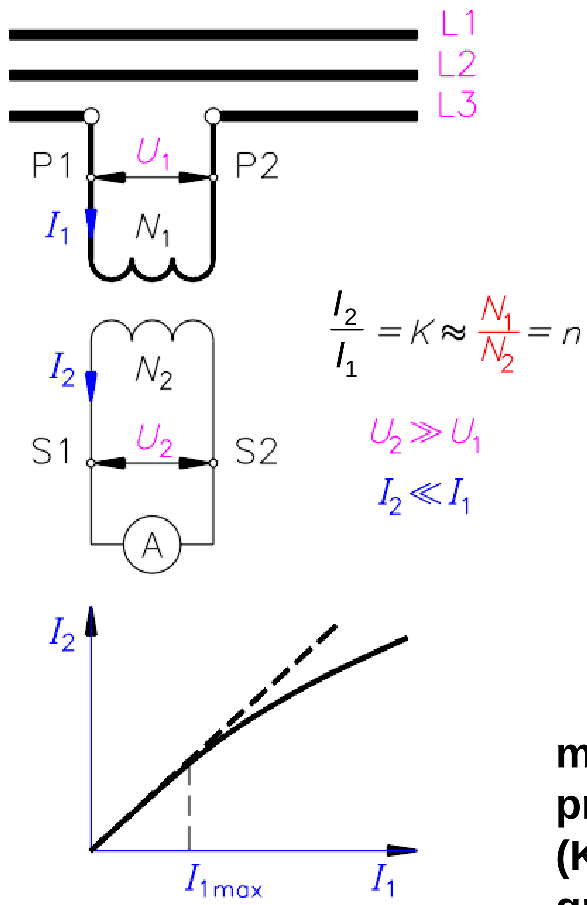
linearni dio karakteristike magnetiziranja

točnost ↑ ako opterećenje ↑

režim kratkog spoja

za određenu snagu u VA

mogućnost preopterećenja (KS i zasićenje uz grešku ≤ 10%)



Ft (faktor točnosti)< 5 točni i osjetljivi instrumenti

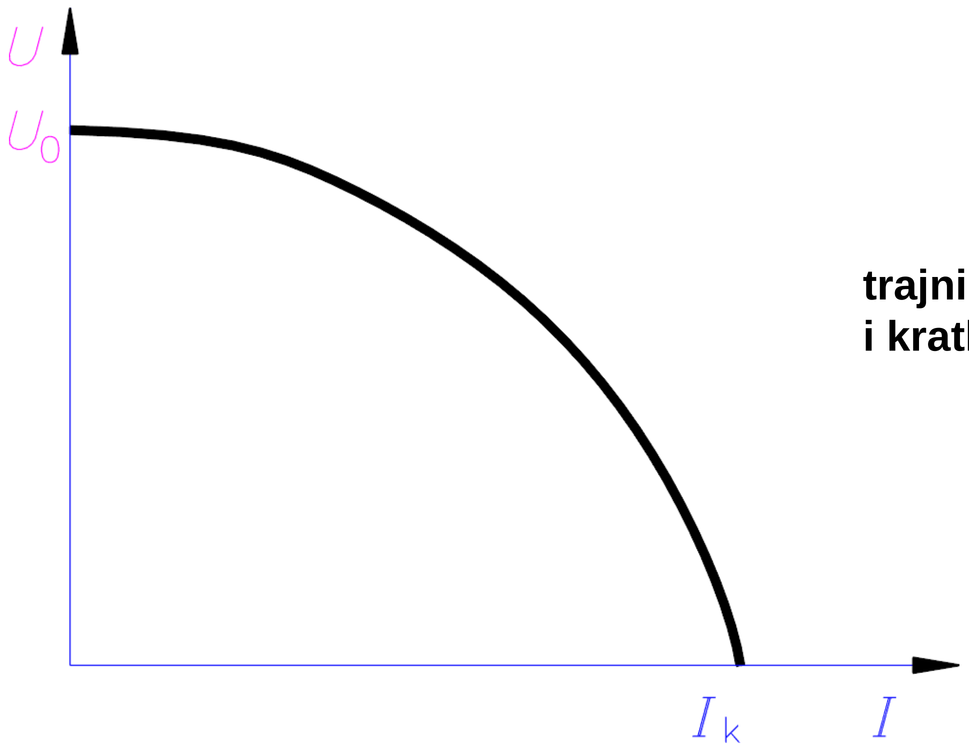
Ft < 10 pogonska mjerenja   Ft > 10 zaštitni releji

TRANSFORMATORI POSEBNE NAMJENE (IZVEDBE)

transformiranje (prilagođavanje) impedancije

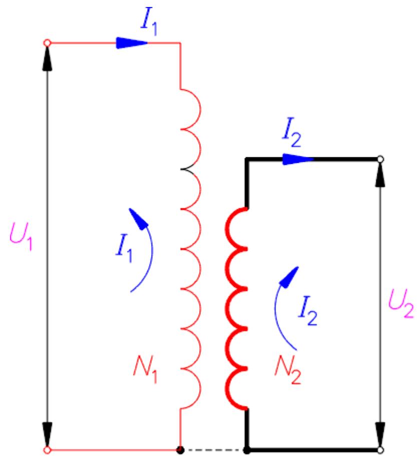
transformiranje malih snaga

prigušnice



trajni rad u praznom hodu
i kratkom spoju (zavarivanje)

TRANSFORMATOR U ŠTEDNOM SPOJU (AUTOTRANSFORMATOR)

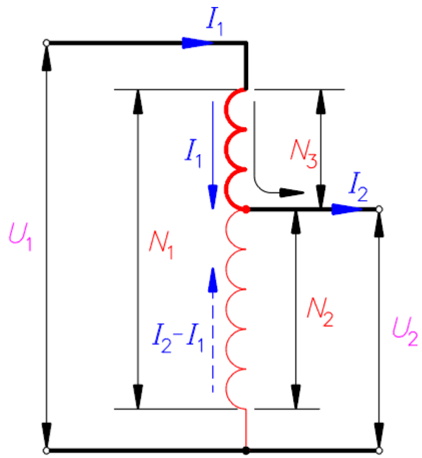


$$\frac{U_1}{U_2} = \frac{N_1}{N_2}$$

$S_{N1} \rightarrow I_1$

$S_{N2} \rightarrow I_2$

$I_2 > I_1 \rightarrow S_{N2} > S_{N1}$



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

$S_{N1} = S_{N2} + S_{N3}$

$S_{N3} \rightarrow I_1$

$I_2 \approx I_1 \rightarrow S_{N2} \ll S_{N1}$

snaga transformacije
snaga jezgre
tipska snaga

$$P_T = (U_1 - U_2) \cdot I_1 \approx (I_2 - I_1) \cdot U_2$$

$$P_T = P\left(1 - \frac{U_2}{U_1}\right) \quad \text{za} \quad U_1 > U_2$$

kada je $\frac{U_2}{U_1} \rightarrow 0,$ **slijedi** $P_T \rightarrow P$

kada je $\frac{U_2}{U_1} \rightarrow 1,$ **slijedi** $P_T \rightarrow 0$

ekonomski zanimljivo

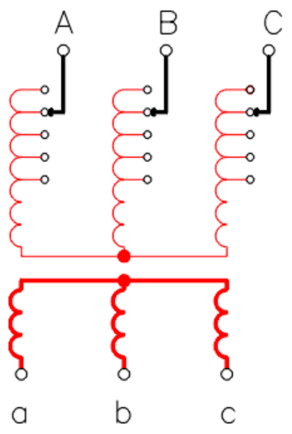
Zabranjena uporaba ako mreže moraju biti galvanski odvojene (PEX)

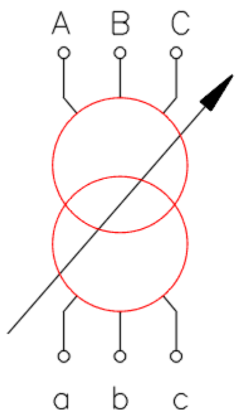
REGULACIJSKI TRANSFORMATOR

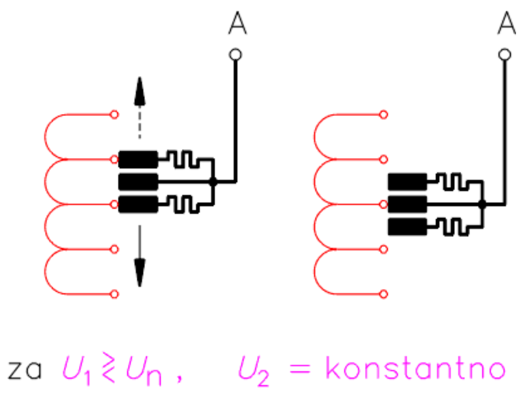
mogu raditi pri promjenjivim uvjetima napona mreže

obični trafo ima na primaru izvode s ± 4 do 5% za prilagođavanje u beznaponskom stanju

regulacijski trafo - prilagođavanje uz opterećenje (kod elektrodistribucijskih mreža)







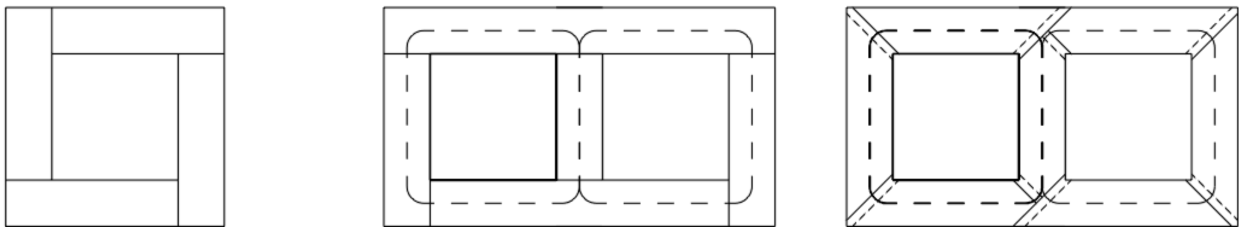
za snage > od 20 MVA

IZVEDBA TRANSFORMATORA

aktivni dijelovi - jezgra i namoti

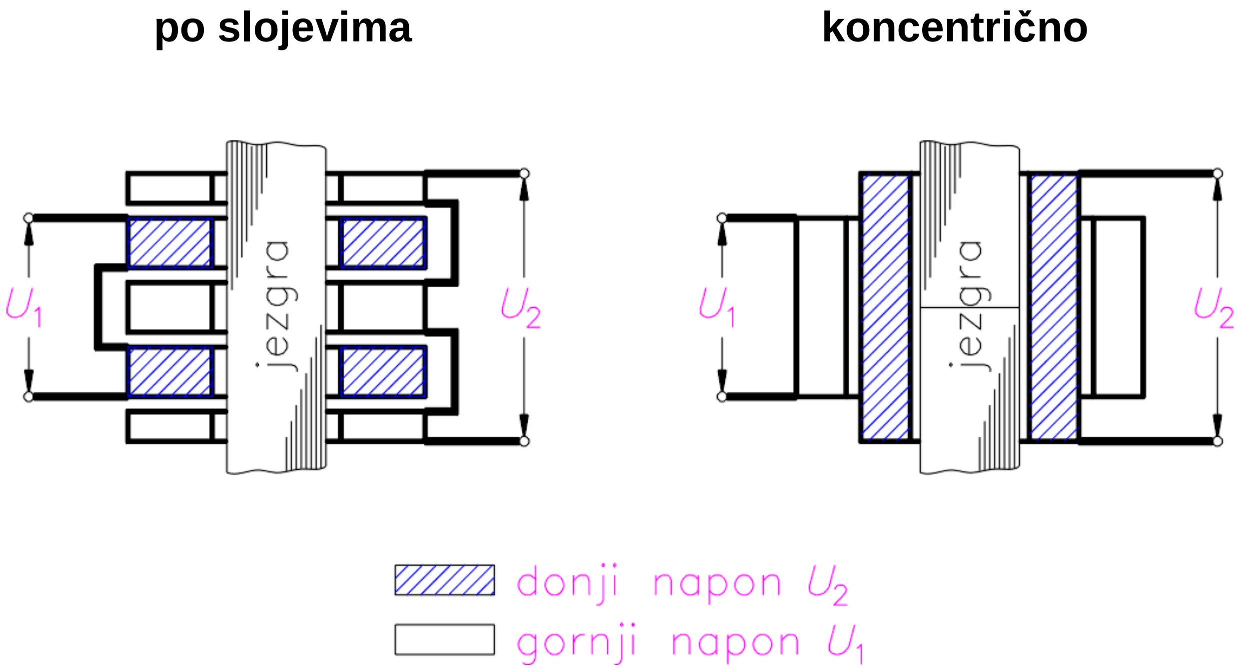
jezgra

- što bolje iskorištenje prostora



- što manji magnetski otpor (magnetski usmjereni limovi)

namoti



više kombinacija napona serijskim i paralelni spajanjem

bolja naponska odvojenost od jezgre

neaktivni dijelovi

- kotao
- medij za hlađenje
- zaštitni dijelovi
- provodni izolatori