1. Avditorne

Dobi na avditorne iz elektromagnetnih pretvorbi

pisalec 11-13 h

Rok 4.2 3F

1. 400 kVA

10 / 0.4 kV

50 Hz

YNd5

nazivni podatki kratkega spoja transformatorja

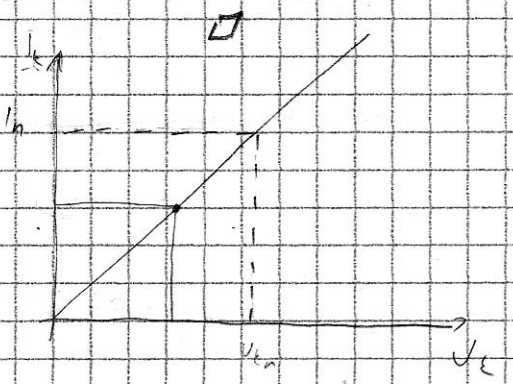
Prosimo izračunajte dol je to nazivna

Pks: (15 A) pri 500 V struja

Potek kratkega spoja

- sekundarno sekundarno kratko spojimo
- kontroliramo direkten napon na primaru dok nam krat primar (ali sekundar) ne teče nazivna struja, te stanemo
- prepoledamo do kojega smo napona dosli to nam je napon kratkega spoja

a) U_{kp} glede na primarno



$$I_{n1} = \frac{S_n}{\sqrt{3}\, U_{n1}} = \frac{400 \cdot 10^3}{\sqrt{3} \cdot 10^4} = 23.1\ A\ *$$

zakaj I_n je fazna struja

trafo je trafo transformator

U_k - napon kratkega spoja

v zadnje vrnjeti tudi LINIJSKE struje

$$\frac{I_k}{I_n} = \frac{U_k}{U_{kn}} \Rightarrow U_{kn} = U_k \cdot \frac{I_n}{I_k} = 500 \cdot \frac{23.1}{15} = 770\ V = U_k$$

Ovaj parametar nam je bitan

$$U_k\,\% = \frac{U_{kn}}{U_{n1}} = \frac{770}{10 \cdot 10^3} = 0.077 = 7.7\ \%$$

* ponekod zaradi omejitev izbora ne izberemo štrajc kratkega spoja za nazivno struja, ker nismo za znanem štrajc, ampak ker je linearna

b) bazna impedancija trofaznog transf. s primara i sa sekundara

? (λ) ZNd5

$$\boxed{Z_b = \frac{U_{nf}}{I_{nf}}}$$

$$Z_{b_p} = \frac{\frac{10000}{\sqrt{3}}}{23.1} = 249.9\ \Omega$$

λ $U_L = U_f \cdot \sqrt{3}$

Δ $I_L = I_f \cdot \sqrt{3}$

(Δ) ?

$$Z_{b_s} = \frac{U_{n2}}{\frac{S_n}{\sqrt{3}} \cdot \frac{1}{U_{n2}}} = \frac{U_{n2}^2}{\frac{S_n}{\sqrt{3}}} = \frac{3\,(U_{n2})^2}{S_n} = \frac{3 \cdot 400^2}{400 \cdot 10^3} = 1.2\ \Omega$$

$S_n = I_n \cdot U_n$

linijsko Δ $U_f = U_1$

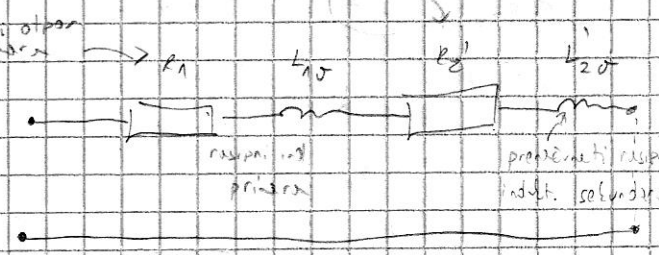
$$I_2 = \frac{S_n}{3\,U_{f2}}$$

c) Z kratkog spoja primara i sekundara

$$Z_{k\%} = \frac{U_{k\%}}{}$$

$$Z_{k\%} = U_{r\%} + j\,U_{\sigma\%}$$

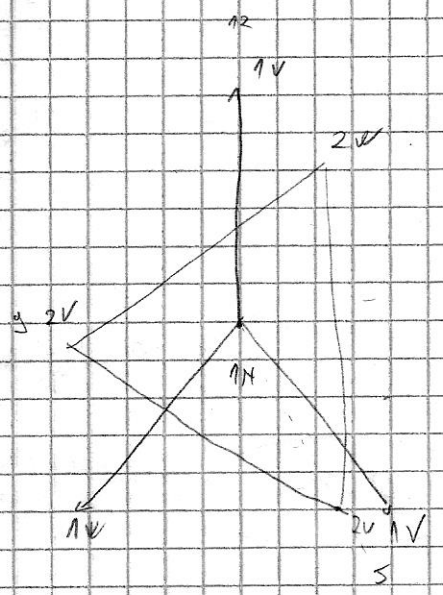
$= 7.7\ \%$



d) skicirati VD iz ostale grupe spoja

* Δ □ x ✓ sotni broj

Y N d 5



* (Y) → vrijednosni naznat spojen u λ

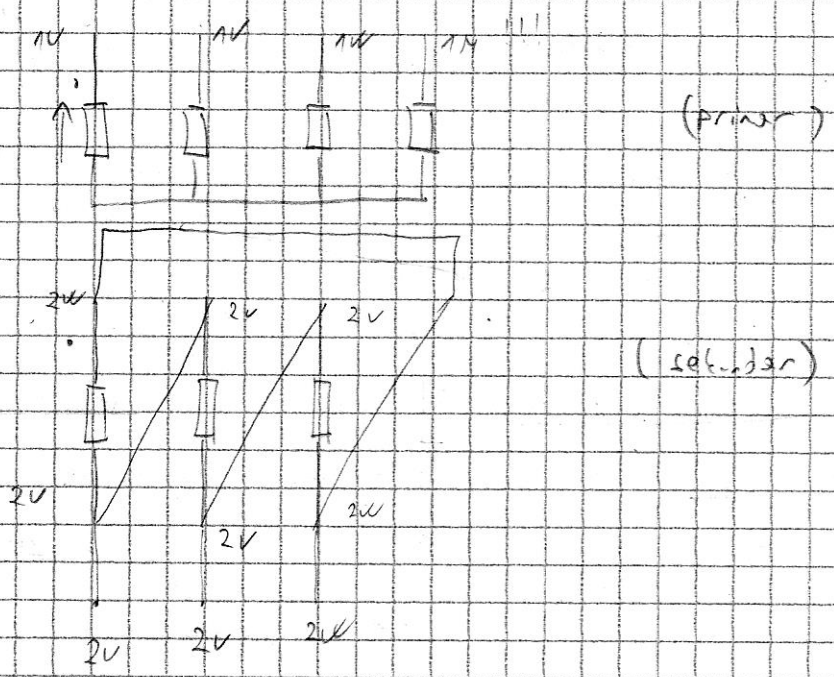
Δ(N) → imamo izvedenu tačku dijele

□ (d) → nizemnosni naznat (sekundar) spojen u trokut

x (5) - sotni broj

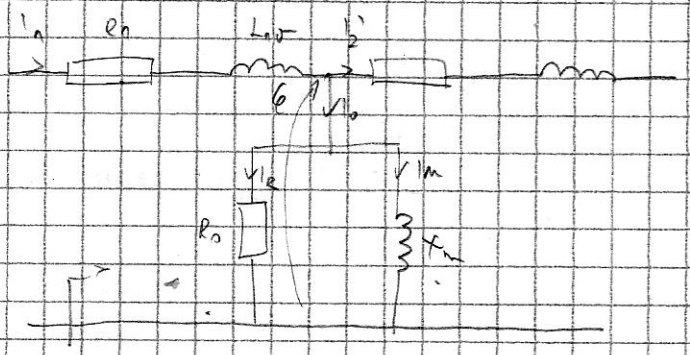
↳ fazni pomak između faza primara i sekundara

Shema spoja



Vektorski dijagram

(nadomjesna sheme)

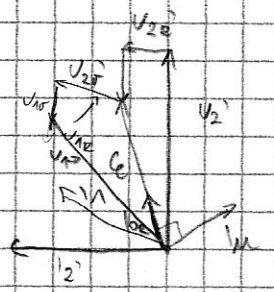


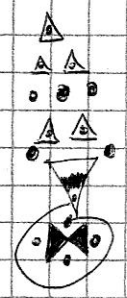
I_m - struja magnetiranja

I_{0R} - struja gubitaka u jezgri

fazorski dijagram

vektorski dijagram





ΔV $\quad > 0$ $\quad < 0$

2.4 iz zbirke

20 MVA

33/115 kV

Dyn11

P_k - snaga kratkog spoja
P_0 - snaga prazног hoda

Zadani transformator

75°; $P_k = 72.84$ kW $P_0 = 12.57$ kW

$v_k = 12.03\ \%$ $I_0 = 0.07\ \%\ I_n$

23°C $R_{ST1} = 0.155\ \Omega$
$R_{ST2} = 0.0157\ \Omega$

T na 75°C

Kod proračuna elemenata najjednostavnije sheme pravimo se da su svi namoti transformatora spojeni u Y (zanimaju nas parametri najjednostavnije zvijezde)

Rstezalki → u vezi za proračun elemenata $\frac{U_n}{\sqrt{3}}$

$R_{FY} = \frac{R_{ST}}{2}$ (zvijezda)

$I_{1n} = \frac{S_n}{\sqrt{3}\,U_{1n}} = \frac{20 \cdot 10^6}{\sqrt{3} \cdot 33 \cdot 10^3} = 349.9\ A$

$33 \cdot 10^3$

$I_{2n} = I_{1n} \cdot \frac{U_{1n}}{U_{2n}} = 100.1\ A$

$115 \cdot 10^3$

b - faktor promjene otpora s temp.

$b = \frac{235 + \vartheta_T}{235 + \vartheta_1} = \frac{235 + 75}{235 + 23} = 1.20155$

dodatni gubitci (struja ...) - pri izmjeničnoj struji

$P_{k,75°C} = P_{Cu} + P_{dod\,75}$

$P_{Cu} = P_{Cu1\,75°C} + P_{Cu2\,75°C}$

$P_{dod\,75} = P_{k,75} - P_{Cu1\,75} - P_{Cu2\,75}$

$= P_{k\,75} - \underbrace{3 \cdot I_{1n}^2 \cdot \frac{R_{ST1}}{2} \cdot b}_{P_{Cu1\,75}} - \underbrace{3 I_{2n}^2 \cdot \frac{R_{ST2}}{2} \cdot b}_{P_{Cu2\,75}}$

$= 72890 - \frac{3}{2} \cdot 1.20155 \cdot 0.155 \cdot 349.9^2 - \frac{3}{2} \cdot 1.20155 \cdot$

$\rightarrow 1034.12 \cdot 0.0152 = 10.159$ kW

$R_2' = R_{2Cu} + R_{dod}$

λ

Istosmjerna
napon

$Z_x = \lambda \quad I_k = I_1$

$U_1 = \sqrt{3} \cdot U_f$

$$\boxed{Z_b = \frac{U_{fn}}{I_{fn}} \overset{nap}{=} \frac{U_{1n}^2}{S_n}}$$

$Z_b = \frac{U_{1n}^2}{S_n} = \frac{33^2}{20} = 54.45\,\Omega$

$R_1 = R_{1Cu} = \frac{R_{ST1}}{2} \cdot b = \quad = 0.08312\,\Omega \qquad R_1\% = \frac{R_1}{Z_B} = 0.171\,\%$

$R_{2Cu}' = \frac{R_{ST2}}{2} \cdot b \cdot \lambda^2 = 0.017267\,\Omega$

$\downarrow$

$\left(\frac{U_{1n}}{U_{2n}}\right)^2$ (jer preračunavamo na primarnu stranu - prijenosni omjer)

$R_{dod} = \frac{\frac{P_{dod\,75}}{3}}{I_{1n}^2} = 0.027662\,\Omega$

$R_2' = R_{2Cu}' + R_{dod}' = 0.10533\,\Omega = 0.133\,\%$

$R_k = R_1 + R_2' = 0.364\,\%$

kako otpor kratkog spoja (horizontalna ljestvica)

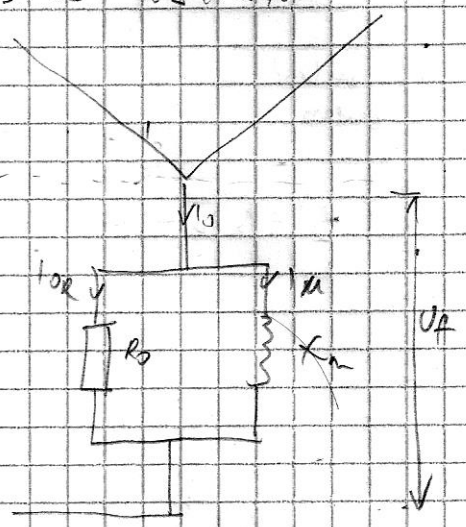
$U_{k75} = \sqrt{U_{k75}^2 - U_{R75}^2} = \sqrt{12.02^2 - 0.364^2} = 12.02\,\% = X_k$

$X_{1\sigma} = X_{2\sigma}' = \frac{X_k}{2} = 6.01\,\%$

linijski

$$R_0 = \frac{U_{1fn}^2}{\frac{P_0}{3}} = \frac{(\sqrt{3}\,U_{1fn})^2}{P_0} = \frac{U_{1n}^2}{P_0} = \frac{(33\cdot 10^3)^2}{12570} = 86635\,\Omega = 15\,108\,\%$$

za 1 fazo



$$I_{0R} = \frac{U_{1fn}}{R_0} = \frac{\frac{33\cdot 10^3}{\sqrt{3}}}{86635} = 0.212\ A = 0.06285\,\%$$

$$I_\mu = \sqrt{I_0^2 - I_{0R}^2} = \sqrt{0.07^2 - 0.06285^2} =$$

$$= 0.03082\,\%$$

$$X_0 = \frac{U_{1fn}}{I_\mu} = \frac{\frac{33000}{\sqrt{3}}}{0.00030082\cdot 34.4} = 1766\,71\,\Omega = 324462\,\%$$

Provizit te Oppo-a pri temperaturama

! Elementi poprečne grane se ne preračunavaju na toplo stanje

2.5 tB

$$\frac{U_{1n}}{U_{2n}} = \frac{380}{220}$$

50 Hz

$u_r = 2.5\,\%$

$u_k = 4.55\,\%$

$\Delta u = ?$

U_{2n} : u_r

a) $\cos\varphi = 0.8$ ind $\quad I_2 = I_{2n}$

$\cos\varphi = 0.6$ kap $\quad I_2 = 0.5\, I_{2n}$

$$\Delta u = \alpha \left[u_r \cos\varphi_2 + u_\sigma \sin\varphi_2 + 0.05\,\alpha \left(u_\sigma \cos\varphi_2 - u_r \sin\varphi_2 \right)^2 \right]$$

α - stupeň opterečenia $\quad \frac{S}{S_n} = \frac{I}{I_n}$

pokiaľ $u_k < 15\,\%$; ili $u_\sigma < 4\,\%$

$$\Delta u = \alpha \left[u_r \cos\varphi_2 + u_\sigma \sin\varphi_2 \right]$$

$$u_\sigma = \sqrt{u_k^2 - u_r^2} = \sqrt{4.55^2 - 2.5^2} = 3.8\,\%$$

$\alpha = 1$

a) $\Delta u = 1 \cdot (2.5 \cdot 0.8 + 3.8 \cdot 0.6) = 4.28\,\%$

?

$\Delta U = \Delta u \cdot U_{1n} = 16.26$ (úbytok na primáru)

pod napätím na primáru sec

$U_2 = 380 - 16.26\ V = 363.74\ V = 95.72\,\%$

$\Delta U = \Delta u \cdot U_{2n} = 0.0428 \cdot 220 = 9.42\ V$ (úbytok na sekundáru)

$U_2 = 220 - 9.42 = 210.58 = 95.72\,\%$

b) $\alpha = 0.5$ $\cos\varphi_2 = 0.6$ $\sin\varphi_2 = -0.8$! kap $\sin\varphi_2 < 0$

$$\Delta u = 0.5 \cdot \left[2.5 \cdot 0.6 - 3.8 \cdot 0.8 \right] = -0.75\ \%$$

4.2 3F transf

$S_n = 100\ kVA$

$P_0 = 350\ W$ (gubitci prazног hoda)

$P_{tn} = 1550\ W$ (gubitci u kratkom spoju $= P_k$)

$\cos\varphi = 0.8$

$\eta = ?$ a) $\alpha = 0.6$ b) $\alpha = 1$

α_{opt}? η_{max}?

$$\eta = 1 - \frac{P_0 + \alpha^2 P_{kn}}{\underbrace{\alpha \cdot S_n \cdot \cos\varphi}_{\text{ne bude sto manje} \rightarrow \text{tako samo } \cos\varphi_1}}$$

$$\frac{P_2}{P_n} = \frac{P_n - P_g}{P_n} = 1 - \frac{P_g}{P_1} = 1 - \frac{P_0 + \overbrace{\left(\frac{I}{I_n}\right)^2}^{\alpha^2} \overbrace{P_{tn}}^{I^2 R}}{\alpha \cdot S_n \cos\varphi} = 1 - \frac{P_0 + \alpha^2 P_{tn}}{\alpha S_n \cos\varphi}$$

vrijednosti

a) $\alpha = 0.6$

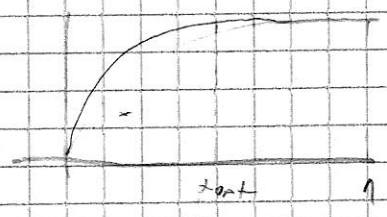
$$\eta = 1 - \frac{350 + 0.6^2 \cdot 1550}{0.6 \cdot 100 \cdot 10^3 \cdot 0.8} = 97.81\ \%$$

b) isto stvar

c) optimalna korisnost (maksimalna

$$\frac{d\eta}{d\alpha} = \qquad \alpha_{max} = \sqrt{\frac{P_0}{P_{tn}}}$$ pri tom opterećenju imamo α_{opt}

pri kojem dođe do najveće korisnosti



$$\alpha_{max} = \sqrt{\frac{350}{1450}} = 0.4237 = 42.37\%$$

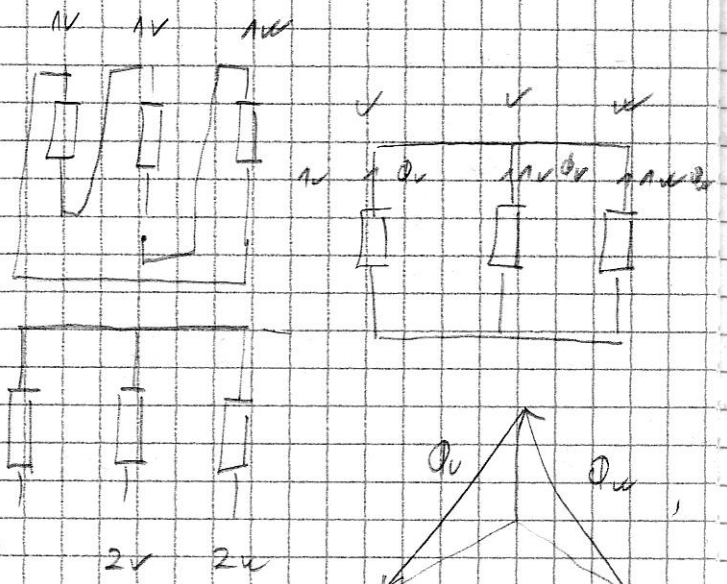
$$\eta_{max} = 1 - \frac{P_0 + \alpha_{opt}^2 \cdot P_k}{\alpha_{opt} \cdot S_n \cdot \cos\varphi} = 1 - \frac{350 - 0.4237^2 \cdot 1450}{0.4237 \cdot 100 \cdot 10^3 \cdot 0.8}$$

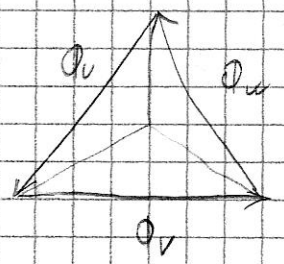
$$= 97.93\%$$

38. 3F trans

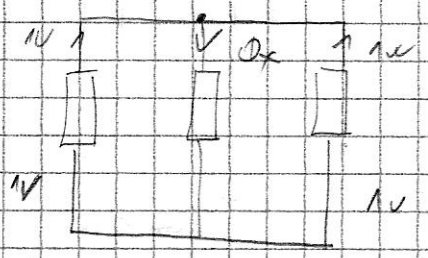
10/0.4 kV

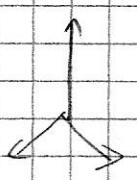
Dy5

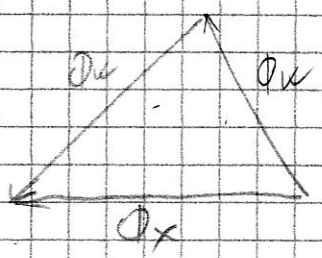


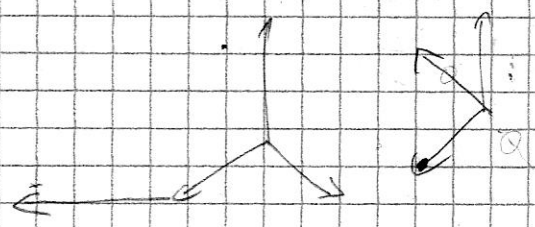


U ovoj točki se spoje da poništenje indukcije









Auditorne 4. tjedan

• Paralelni rad

- transformatore u paralelnom radu gradimo kao impedancije koje moraju imati slične snage i slične u_k

Zadatak: 6 jednakih trafa

$S_n = 400\ kVA$

$U_{1n}/U_{2n} = 10500/400\ V$

$P_0 = 2000\ W$

$\eta_n = 0.98$

Dz 6

Koliko ukupni ti paralelno ako se transformira

a) 900 kVA *

b) 1200 kVA

c) 1500 kVA

kad su jednaki transf. onda se jednoliko snaga raspoređuje po njima

Dalje da radе u z η_{max}. broj paralelnih transformatora?

$$\boxed{\eta = 1 - \frac{\sum_i P_{0i} + \sum_i \alpha_i^2 P_{ki}}{S \cdot \cos\varphi}}$$

za paralelni rad

$$\eta = 1 - \frac{P_0}{S_n} \Rightarrow P_0 = (1-\eta)\, S_n = (1-0.98)\ 400 \cdot 10^3 = 8\ kW$$

$\square\ \frac{S}{S_n} = \frac{I}{I_n}$

$$P_k = P_0 + P_k \rightarrow P_k = P_0 - P_0 = 6\ kW$$

Ukupna snaga koja se prenosi (zar. gotova)

S_n pojedinog transformatora

$$\eta = 1 - \frac{m \cdot P_0 + m \cdot \left(\frac{S}{m \cdot S_n}\right)^2 \cdot P_k}{S \cdot (\alpha)} = 1 - \frac{m \cdot P_0 + \frac{1}{m}\left(\frac{S}{S_n}\right)^2 P_k}{S}$$

paralelni rad u transf. $\quad$ 1 ← jer su svi trafo jednaki pa su 1 jednako opterećeni

(ako je zadano S i cos φ nije zadan onda je 1)

$$\frac{\partial \eta}{\partial m} = 0$$

$$-\frac{1}{S} \cdot \left(P_0 - \frac{1}{m^2} \cdot \left(\frac{S}{S_n}\right)^2 \cdot P_k\right) = 0$$

$$P_0 = \frac{1}{m^2} \cdot \left(\frac{S}{S_n}\right)^2 \cdot P_k \ \Big/ \sqrt{\ } \Rightarrow m = \left(\frac{S}{S_n}\right) \sqrt{\frac{P_k}{P_0}}$$

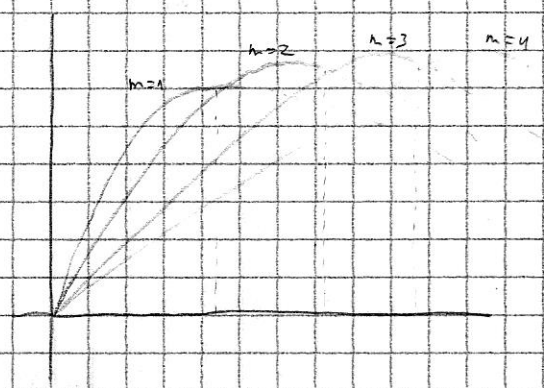
$$m = \frac{S}{400} \cdot \sqrt{\frac{6}{2}} = \frac{S}{400} \cdot \sqrt{3}$$

$$\boxed{m = \frac{S}{400} \cdot \sqrt{3}}$$

$$m = \frac{400}{400} \cdot \sqrt{3} = 3.4 \simeq 4$$

$\rightarrow 3 \qquad \eta_3 = 0.9820$

$\rightarrow 4 \qquad \eta_4 = 1 - \dfrac{4 \cdot 2 + \frac{1}{4} \cdot \left(\frac{400}{400}\right)^2 \cdot 6}{400} = 0.98267$



$$\eta = 1 - \frac{m \cdot P_0 + \frac{1}{m}\left(\frac{S}{S_n}\right)^2 \cdot P_t}{S}$$

$$\eta_4 = 1 - \frac{4 \cdot 2000 + \frac{1}{4}\left(\frac{1200}{400}\right) \cdot 6000}{400 \cdot \sqrt{3}} \qquad \frac{35}{\sqrt{3}}$$

b) $S = 1200 \ kVA$

$$m = \frac{1200}{400} \cdot \sqrt{3} = 5.19 \simeq 5$$

$\eta_4 = 0.94625$

$\eta_5 = 0.948$

c) $S = 1500 \ kVA$

$$m = \frac{1500}{400} \cdot \sqrt{3} = 6.49 \simeq 6$$

$\rightarrow \eta_5 = 0.9328$

$\eta_6 = 0.9348$

Zu Aabre odlicne

5.2

8 MVA

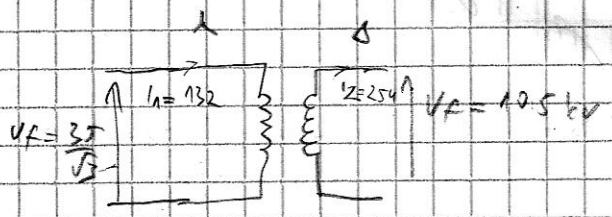
Yd5

35 / 10.5 kV

$P_0 = 9.4$ kW

$P_k = 54$ kW

$U_k = 7\%$



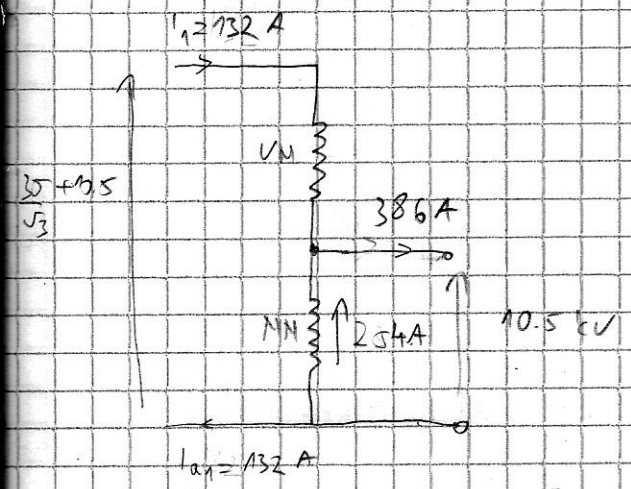
$$I_{1n} = \frac{S_n}{\sqrt{3}\cdot U_{1n}} = \frac{8000}{\sqrt{3}\cdot 35} = 131.37 \approx 132\ A$$

$$I_{2n} = \frac{S_n}{\sqrt{3}\cdot U_{2n}} = \frac{8000}{\sqrt{3}\cdot 10.5} = 439.89\ A$$

$$I_{2f} = \frac{I_{2n}}{\sqrt{3}} = 253.97\ A \approx 254\ A$$

Preračunajte na Y a D, S_n, U_{1a}/U_{2a}, η_a, U_{ka}

1) Shema



$$\eta = 1 - \frac{P_0}{S_n} = 1 - \left(\frac{9.4+54}{8000}\right) = 99.208\ \%$$

$$U_{12f} = \frac{35}{\sqrt{3}} + 10.5 = 30.71\ kV$$

$$U_{1an} = \sqrt{3}\cdot U_{12f} = \sqrt{3}\ 30.71\ kV = 53.19\ kV$$ (navitavo = linijski)

→ Y

$$I_{1a} = I_{1n} = 132$$

$$I_{2af} = 10.5\ kV \qquad I_{2n} = \sqrt{3}\cdot 10.5 = 18.19$$

Primerjava, ohišje

$$\alpha = \left(\frac{U_{1n}}{U_{2n}}\right)_a = \frac{53.19}{18.19}$$

$$S_a = \sqrt{3}\cdot U_{1a}\cdot I_{1a} = \sqrt{3}\cdot U_{2a}\cdot I_{2a} = \sqrt{3}\cdot 53.19\cdot 132 = 12.16\ MVA$$

$$S_2 = S_T \cdot \frac{U_{12}}{U_{12} - U_{22}} = 8 \cdot \frac{53.11}{53.11 - 18.11} = 12.16 \text{ MVA}$$

prividna snaga $S_T = S_n$ ako nema otvora i nema nametanja za redukcije

značajno kod

Manji autotransformatori – nema galvanskog odvajanja

$$u_k = u_{kZNT} \frac{U_{1n} - U_{2n}}{U_{1n}} = 7 \cdot \frac{53.11 - 18.11}{53.11} = 4.61\%$$

$$\eta = 1 - \frac{P_J}{S_{n2}} = 1 - \frac{P_0 + P_k}{S_{n2}} = 1 - \frac{1.4 + 5n}{12156.4} = 99.48\%$$

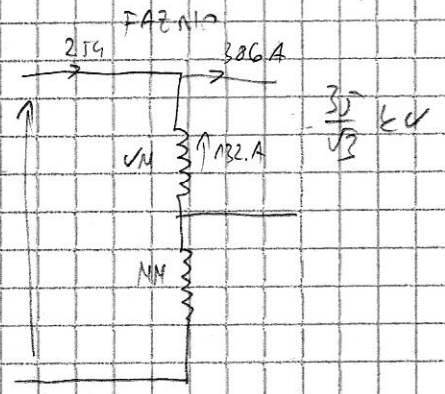
spoj

autotransformator

$S_2 \uparrow, u_k \downarrow, \eta \uparrow$

5. tjeban

5.2



Iz faze se prenese gdje dio preko autotransformatora

prelazi samo ono autotransformator

$$U_{1f} = \frac{35}{\sqrt{3}} + 10.5 = 30.71 \text{ kV}$$

podj 2 $\quad U_{12} = \sqrt{3}\, U_{1f} = \sqrt{3} \cdot 30.71 = 53.19 \text{ kV}$

$$I_{12} = I_{2n} = 254 \text{ A}$$

$$S_{2n} = \sqrt{3} \cdot U_{12} \cdot I_{12} = \sqrt{3} \cdot 53.19 \cdot 10^3 \cdot 254 = 23.4 \text{ MVA}$$

$$U_{22f} = \frac{U_{1n}}{\sqrt{3}} = \frac{35}{\sqrt{3}} = 20.21 \text{ kV}$$

$$U_{22} = 35 \text{ kV}$$

$$I_{22} = I_{1n} + I_{2f} = 132 + 254 = 386 \text{ A}$$

$$S_{22} = \sqrt{3} \cdot U_{22} \cdot I_{22} = \sqrt{3} \cdot 35 \cdot 10^3 \cdot 386 = 23.4 \text{ MVA}$$

$$S_2 = S_T \frac{U_{12}}{U_{12} - U_{22}} = 8 \cdot \frac{53.19}{53.19 - 35} = 23.4 \text{ MVA}$$

$$u_{2u} = u_k \cdot \frac{U_{12} - U_{22}}{U_{12}} = 7 \cdot \frac{53.19 - 35}{53.19} = 2.39\ \%$$

$$\eta = 1 - \frac{P_0}{S_{n2}} = 1 - \frac{9.4 + 54}{23.4 \cdot 10^6} = 99.73\ \%$$

5.5. $S_T = ?$

$S_n = 100\ MVA$ 123 / 14.4 kV

najvećeg iznosa ±5 %

$$S_T = S_n\left(1 + \frac{\overset{\text{poprečna}}{u\%} + \overset{\text{uzdužna}}{b\%}}{200} + \frac{S_3}{2S_n}\right)$$

snaga korisnika

$$S_T = 100 \cdot 10^6 \cdot \left(1 + \frac{5+5}{200}\right) = 100 \cdot \left(1 + \frac{10}{200}\right) = 105\ MVA$$

+5% napon kojeg dovodi za taljbu, ali nam taljin postaje isti

5.4 100/100/33 MVA (P S T)

da su iste snage onda bi bila dva sekundara

123/36.5/21 kV

VN reg. iznos +7.5% −5%

$u_{\%} = 7.5$

$b_{\%} = 5$

$S_3 = 33 \cdot 10^6$

$$S_T = 100 \cdot \left(1 + \frac{7.5+5}{20} + \frac{33}{200}\right) = 122.75\ MVA$$

na MI ice sati 1 zadatak iz paralelnog rada

Zagrzewanie transformatora

Zagrzewanie transformatora → traktujemy jako homogeny byt (bez 1 trójkąta)

powierzchnia przekazywania ciepła
traktujemy hladzi

$$mc\frac{dT}{dt} = P_{Cu} - A\cdot h\,(T - T_{otc})$$

spełnia rozpatrzeń

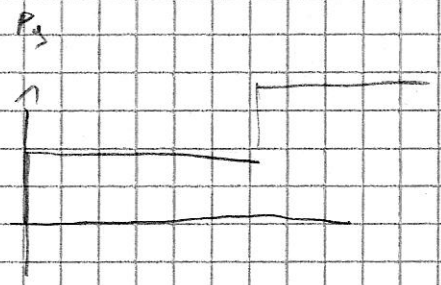
współczynnik przejmowania ciepła $\left[\frac{W}{m^2 K}\right]$

nadtemperatura

$$\vartheta = T - T_{otc}$$

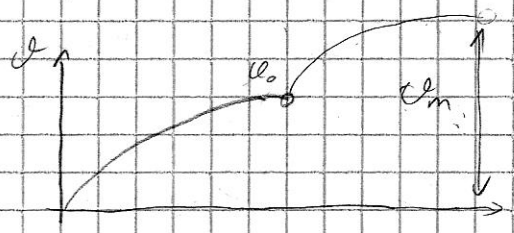
$$\vartheta = T - T_{otc} \quad \Big/ \frac{d}{dt}$$

$$\frac{d\vartheta}{dt} = \frac{dT}{dt}$$



$$mc\frac{d\vartheta}{dT} = P_{Cu} - A\,h\,\vartheta$$

$$\vartheta(t) = \vartheta_0 + (\vartheta_m - \vartheta_0)\left(1 - e^{-\frac{t}{T}}\right)$$



początkowa nadtemperatura
↓
nie można brać iż
wlodzaj strzaja

$$T = \frac{mc}{A\cdot h}$$

$$P_{Cu} \sim \vartheta_m$$

7.1.) Nakon 1.4 h $\vartheta = 30\,K$

$\vartheta_m = 60\,K$

$P_0 = 2.6\ kW \qquad P_t = 9.1\ kW$

a) $T = ?$ - ako je tijelo homogeno tijelo

b) $\alpha = 1.5 \qquad \vartheta_m = ?$

a) $\vartheta = \vartheta_m \left(1 - e^{-\frac{t}{T}}\right)$

$30 = 60 \left(1 - e^{-\frac{1.4h}{T}}\right) \Rightarrow T = -\dfrac{t}{\ln\left(1 - \frac{\vartheta}{\vartheta_m}\right)} = 2.02\ h$

b) $\vartheta_n = 80\,K$

$\alpha \qquad \vartheta_m = 60\,K$

ϑ_{m2} za $\alpha_2 = 1.5\,\alpha$

$\alpha^2 = 1$

$\dfrac{\vartheta_n}{\vartheta_m} = \dfrac{80}{60} = \dfrac{P_0 + P_t}{P_0 + \alpha^2 \cdot P_t}$

$\alpha = \sqrt{\dfrac{\vartheta_{m1}}{\vartheta_{m1}}\left(\dfrac{P_0}{P_t} + 1\right) - \dfrac{P_0}{P_t}}$

$\boxed{\dfrac{P_0 + \alpha_1^2 P_t}{P_0 + \alpha_2^2 P_t} = \dfrac{\vartheta_{m1}}{\vartheta_{m2}}}$

$\alpha = \sqrt{\dfrac{60}{80}\left(\dfrac{2.6}{9.1} + 1\right) - \dfrac{2.6}{9.1}}$

$\alpha = 0.8238$

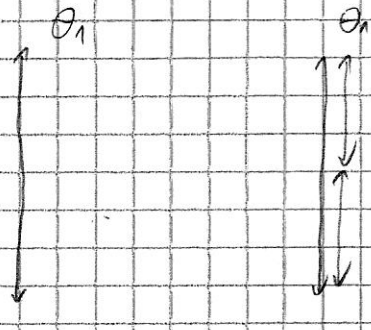
umjesto P_0 i P_t moje stati zadan i njihov omjer

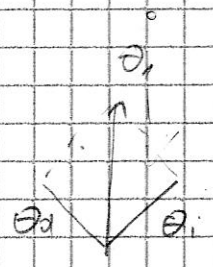
$\dfrac{\vartheta_{m2}}{\vartheta_{m1}} = \dfrac{P_0 + (1.5\alpha)^2 \cdot P_t}{P_0 + \alpha^2 P_t} = \dfrac{1 + (1.5\alpha)^2 \cdot \frac{P_t}{P_0}}{1 + \alpha^2 \cdot \frac{P_t}{P_0}}$

$= 1 \qquad = \dfrac{1 + (1.5 \cdot 0.8238)^2 \cdot \frac{9.1}{2.6}}{1 + 0.8238^2 \cdot \frac{9.1}{2.6}} = 1.88$

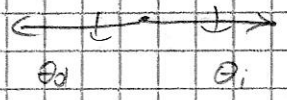
$\vartheta_{m2} = 1.88\ \vartheta_{m1} = 1.88 \cdot 60 = 112.78\ K$

Asimetrine struje





$\theta(t) = 0$



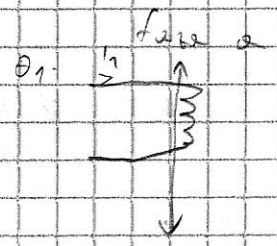
θ_d – u pos. smjeru

θ_i – u suprotnom smjeru kako se mijenja

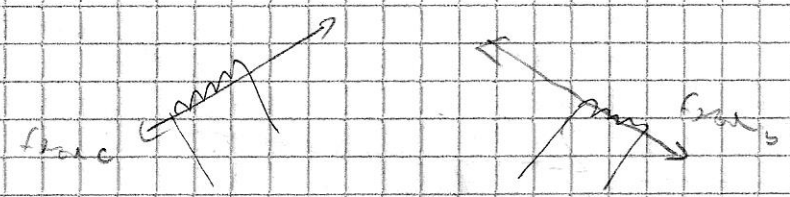
$\theta(t) = \theta_1 \cdot \cos(\omega t)$

$|\theta_d| = \frac{1}{2} |\theta_1|$

$|\theta_i| = \frac{1}{2} |\theta_1|$



Sustav s fazom statora pulsirajuće protjeranje



$\theta_{uk} = \frac{n}{2} \theta_1$

za 3-fazni sustav

$\theta_d = \theta_i = \frac{3}{2} \cdot \theta_1$ (protjeranje svih faza)

3. k direktni dodatk – faze, izmjenjuju se pozitivne

2 vrste protjecanja

- neizmjenično
- okretno

1.1. 3F 6 pol. stroj u

$B_{M1} = 0.4$ T

$\Theta_{M1} = ?$ $n = ?$

amplituda Fourier. niza

$\delta = 14$ mm

$f = 50$ Hz

$$n = \frac{60 \cdot f}{p} = \frac{60 \cdot 50}{3} = \frac{3000}{3} = 1000 \text{ okr/min}$$

za 1T u Z.R trosi 800 zavoja po mm

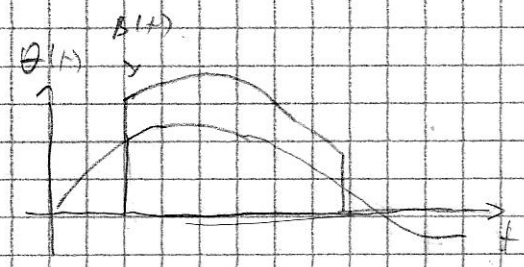
$$R_{m\delta} = \frac{1}{\Lambda} = \frac{\delta}{\mu_0} = \frac{\delta}{4\pi \cdot 10^{-7}} = 800 \cdot 10^3 \cdot \delta$$

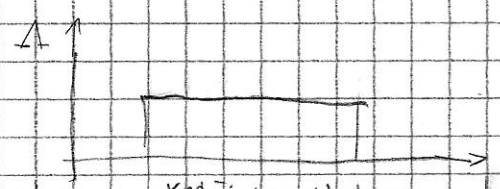
indukcija

magnetski otpor

vježba → $\Theta = B_\delta \cdot R_{m\delta}$

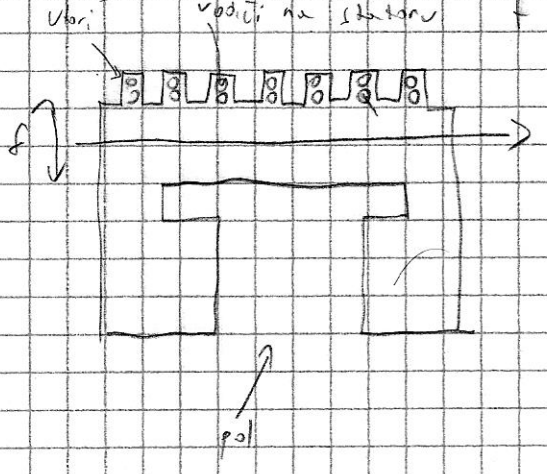
$B(\varphi) = \Theta(\varphi) \cdot \Lambda(\varphi)$





magnetska vodljivost

$\Lambda = \frac{\mu_0}{\delta}$



$\Theta_{vf} = B_\delta \cdot R_{-\delta} = B_\delta \cdot 800 \cdot 10^3 \cdot \delta = 0.1 \cdot 800 \cdot \cancel{10^3} \cdot 10 \cdot \cancel{10^{-3}} = 7700\,A$

vrijednost okretnog protjecanja

protjecanje

1 faze $\Theta_{1f} = \frac{2}{3} \cdot \Theta_{vf} = \frac{2}{3} \cdot 7700\ A$

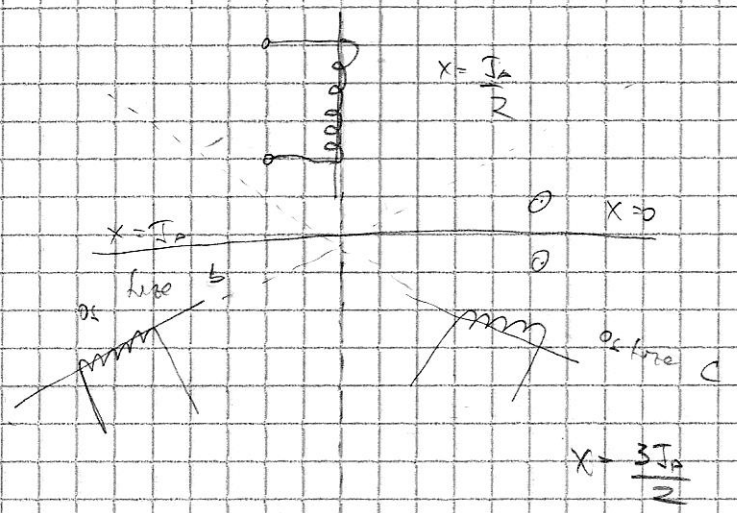
fazne struje ??

$\boxed{\Theta = NI}$

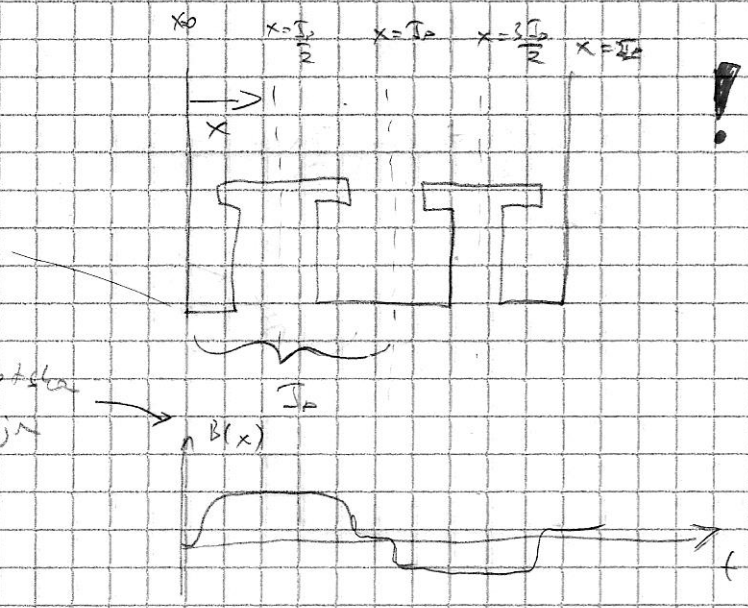
1.4.)

os faze a

τ_p - polni korak



$\boxed{A\bar{C}\ B\bar{A}\ C\bar{B}}$



τ_p - polni korak

! kod faze s istaknutim polovima postoji samo Θ_d

Protjecanje ima prostornu i vremensku ovisnost

$\tau_{re} = 180°$

$\tau_{pecom} = \frac{180}{2p}$

- prostorna → jer su osi faza pomaknute
- vremenska → struje koje teku su sinusi i mijenjaju se tokom vremena

$$\theta_A(x,t) = \theta_{1a} \cdot \cos(\omega t) \cdot \sin\left(\frac{\pi}{2p} x\right)$$

pokrenuti u prostoru za 120° $\left(\frac{2\pi}{3}\right)$

$$\theta_B(x,t) = \theta_{1b} \cdot \cos\left(\omega t - \frac{2\pi}{3}\right) \sin\left(\frac{\pi}{\tau_p} x - \frac{2\pi}{3}\right)$$

pulsirajuće protjecanje

zarotirajuće valovi

$$\theta_C = \theta_{1c} \cdot \cos\left(\omega t - \frac{4\pi}{3}\right) \cdot \sin\left(\frac{\pi}{2p} x - \frac{4\pi}{3}\right)$$

$\cos 0 = 1$

amplitude

$$\theta_{1a} = \theta_{1b} = \theta_{1c} = \theta_1$$

prva adicijska formula $(\cdot \to +)$

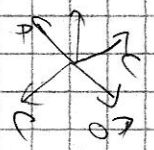
$$\cos(a) \cdot \sin(b) = \frac{1}{2}\left(\sin(a+b) + \sin(a-b)\right)$$

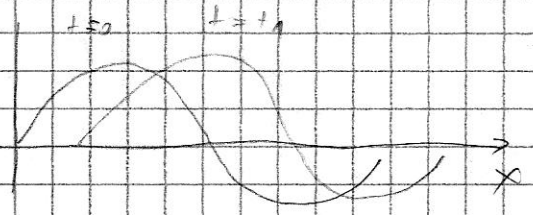
$$\theta_a(x,t) = \frac{1}{2}\theta_1 \cdot \sin\left(\frac{\pi}{\tau_p} x - \omega t\right) - \frac{1}{2}\theta_1 \sin\left(\frac{\pi}{\tau_p} x + \omega t\right)$$

$$\theta_b(x,t) = \frac{1}{2}\left(\theta_1 \sin\left(\frac{\pi}{\tau_p} x - \omega t\right) + \frac{1}{2}\theta_1 \sin\left(\frac{\pi}{\tau_p} x + \omega t - \frac{4\pi}{3}\right)\right)$$

$$\theta_c(x,t) = \frac{1}{2}\theta_1 \sin\left(\frac{\pi}{\tau_p} x - \omega t\right) + \frac{1}{2}\theta_1 \sin\left(\frac{\pi}{\tau_p} x + \omega t - \frac{2\pi}{3}\right)$$

$\sin(k \cdot x - \omega t)$ $\frac{3}{2}$ jednostbna valna





$$\theta_{uz}(x,t) = \theta_d + \underbrace{\theta_{in}}_{0} = \underbrace{\frac{3}{2} \cdot \sin\left(\frac{\pi}{\tau_p} x - \omega t + 0\right)}_{\theta_d}$$

Direktna protjecanja su uvijek u smjeru max stroje odnosno

$$x = \frac{11\tau_p}{6}$$

$$\sin\left(\frac{\pi}{\tau_p} \cdot \frac{11\tau_p}{6} - \frac{4\pi}{3}\right)$$

max struja faze C je za $\omega t = \frac{4\pi}{3}$

$$\frac{11\pi}{6} - \frac{4\pi}{3} = \frac{1}{2}\pi \qquad \underline{\underline{\sin 90 = 1}}$$

Treba nađi struju s istaknutim polom

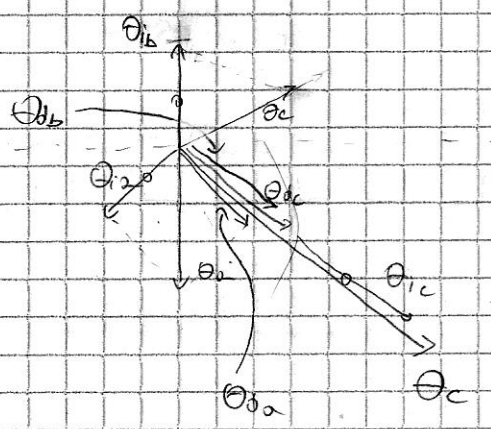
struja faze c maksimalna

nacrtati Θ_d i Θ_i

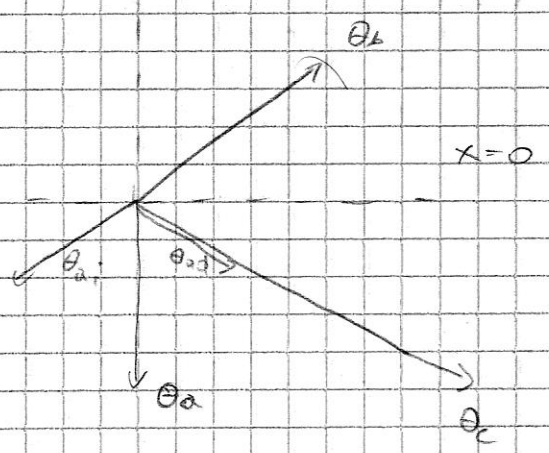
faza c ima maksimum za $\omega t = \frac{4\pi}{3}$ * | prebaciti 2 f i uzeti podatke iznad

$$\boxed{\begin{aligned} \Theta_{1c} &= \Theta_1 \\ \Theta_{1a} = \Theta_{1b} &= -\frac{\Theta_1}{2} \end{aligned}}$$

$\cos 120 = -\frac{1}{2}$



Θ_1 sve se nadosadno poklopiti jer su pod 120°
↳ najbrži rezultat je 0



1.11.

2-pólový stroj

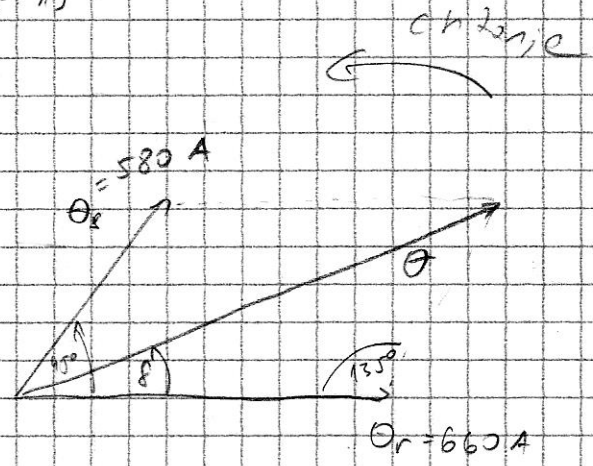
$D = 0.466$ m

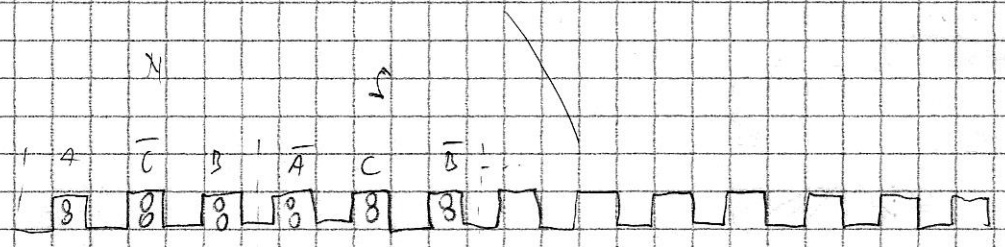
$l = 0.235$ m

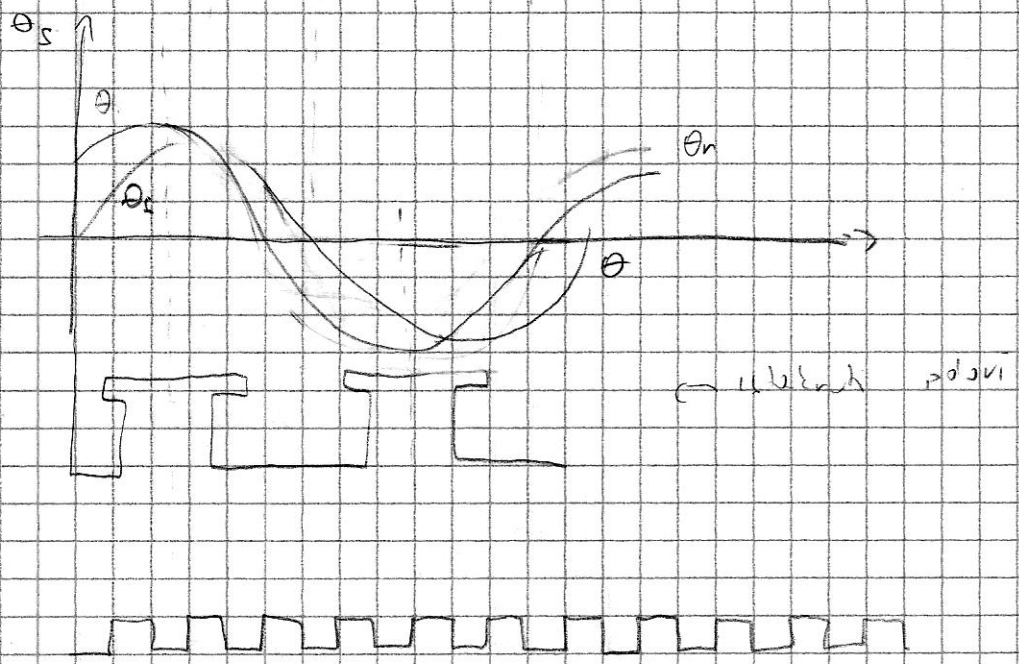
$\delta = 1.5$ mm $= 1.5 \cdot 10^{-3}$

$\mu = n$

kotva jako generátor







$$M_r = \frac{D_p \pi \cdot l}{2} \cdot B \cdot \Theta_r \cdot \sin\delta$$

$$\Theta = \sqrt{\Theta_r^2 + \Theta_s^2 - 2\,\Theta_r \cdot \Theta_s \cdot \cos 135^\circ}$$

$$\Theta = \sqrt{660^2 + 580^2 - 2 \cdot 660 \cdot \cos 135}$$

$$\Theta = 1146\,A$$

$$B = \frac{\mu_0}{\delta}\,\Theta = \frac{4\pi \cdot 10^{-7}}{0.015} \cdot 1146 = 0.96\,T$$

$$\delta = \operatorname{atan}\frac{\Theta_s \cdot \sin 45^\circ}{\Theta_r + \Theta_s \cos 45^\circ}$$

$$= \operatorname{tg}^{-1}\frac{580 \cdot \sin 45}{660 + 580 \cdot \cos 45^\circ} = 20.97^\circ$$

$$M_r = \frac{D_p \pi l}{2} B \Theta_r \sin\delta$$

$$M_r = \frac{0.466 \cdot 1 \cdot \pi \cdot 0.235}{2} \cdot 0.96 \cdot 660 \cdot \sin(20.97^\circ)$$

$$= 39\,Nm$$

protjecanje statora prije protjecanja rotora
↳ motorski rad

protjecanje rotora prije protjecanja statora
↳ generatorski rad

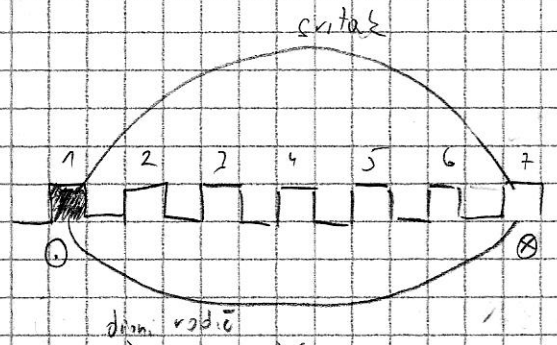
stroj se vrti pozitivno (u lijevo)

NAMOTI

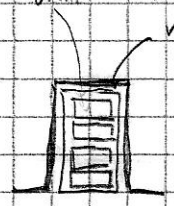
5 predavanje (3)

- jednoslojni
- dvoslojni

y - broj svitka



$y = 6$

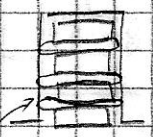


① dioni vodiči spojeni u paralelu

vodiči spojeni u seriju

y - broj svitka [nakon kolko utora formirano svitak]

jednoslojni namot

② 

4 vodiča u utoru (nema dionih vodiča)

izolacija

između vodiča nije se uvijek mora nalazit izolacija

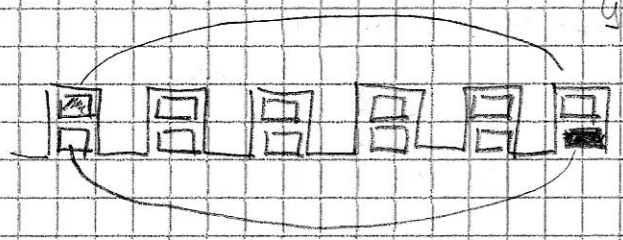
dioni vodič → vodič → žavoj → W_{sr} → svitak → namot

jednoslojni → 1 svitak po utoru

DVO-SLOJNI

dvoslojni → dva odvojena svitka

$y=5$



dvoslojni

dioni vodič

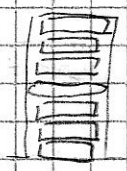
izolacija

2 vodiča po utoru,
vodiči imaju isti potencijal, broj

⇓

broj zavoja po svitku je 1

$w_{sv}=1$



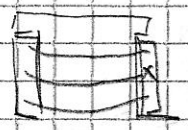
6 vodiča po utoru, 3 zavoja po svitku

$w_{sv}=3$

Namoti:

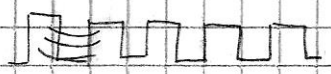
1) koncentrični [vrlo dobri namoti kod istaknutih polova]

2) raspodijeljeni (prije nacrtani)



$y=1$

koncentrični namot



- Sheme namotaja

(1)

→ 4 - pola

→ $N_v = 24$ vodiča

→ dvoslojni

→ dijametralni sitak → $y = \tau_p$

a)

$$y = \frac{N}{2p} = \frac{24}{2 \cdot 2} = 6 \quad (1 \to 7)$$

b) skraćeni sitak $y < 6$ $(y = 5)$

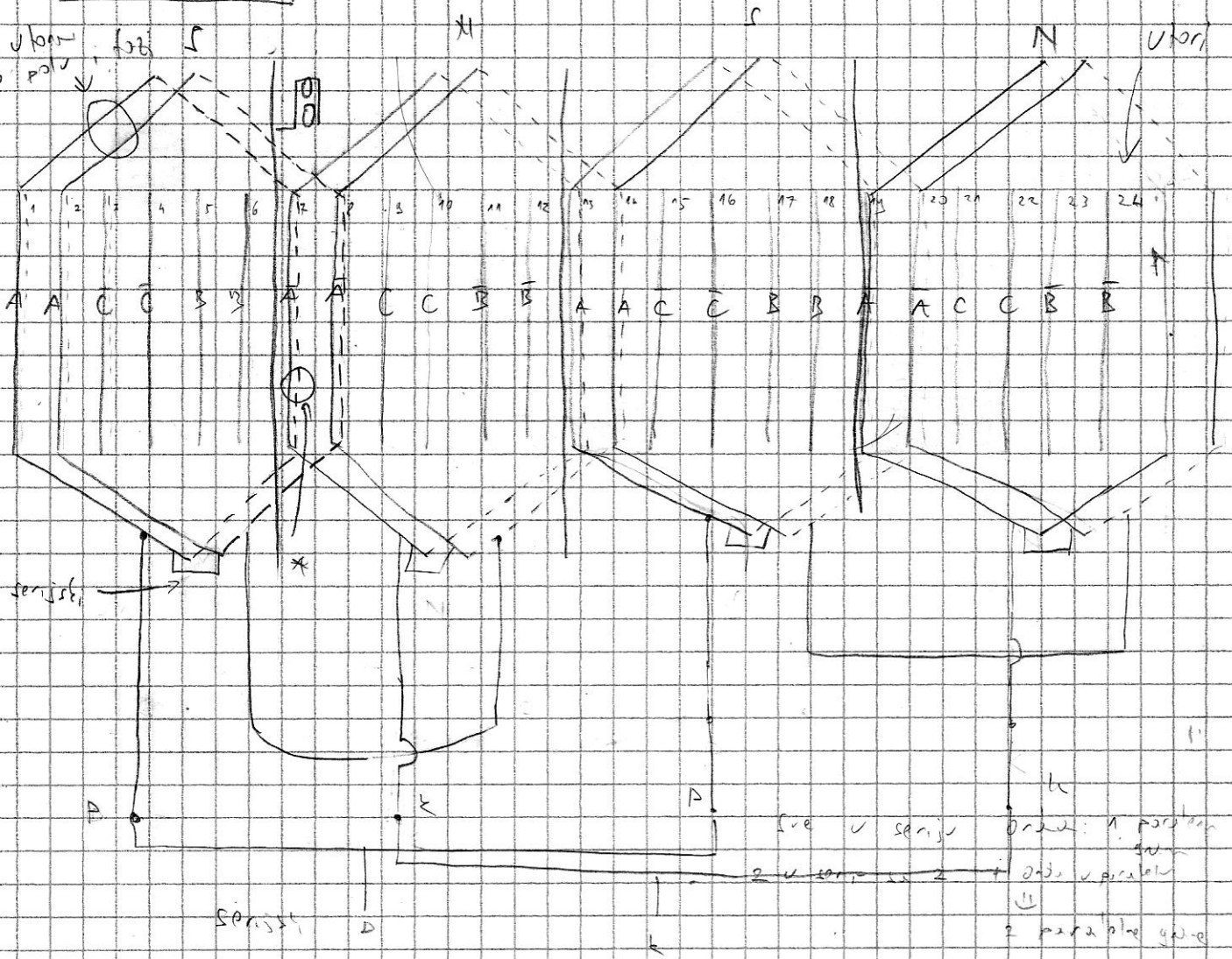
τ_p - polni korak (razmak u utorskim koracima)

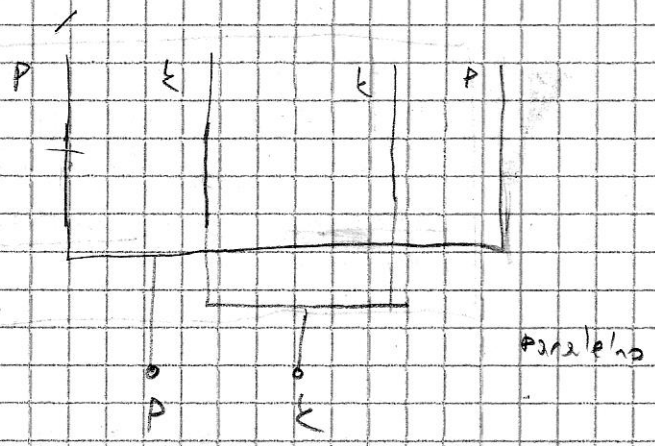
koliko sitaka moramo spojiti da formiramo namot

→ q - broj utora po polu i fazi

$$\boxed{q = \frac{N_v}{2 \cdot p \cdot m}} = \frac{24}{2 \cdot 2 \cdot 3} = 2 \quad \text{(jednoslojni)}$$

broj faza

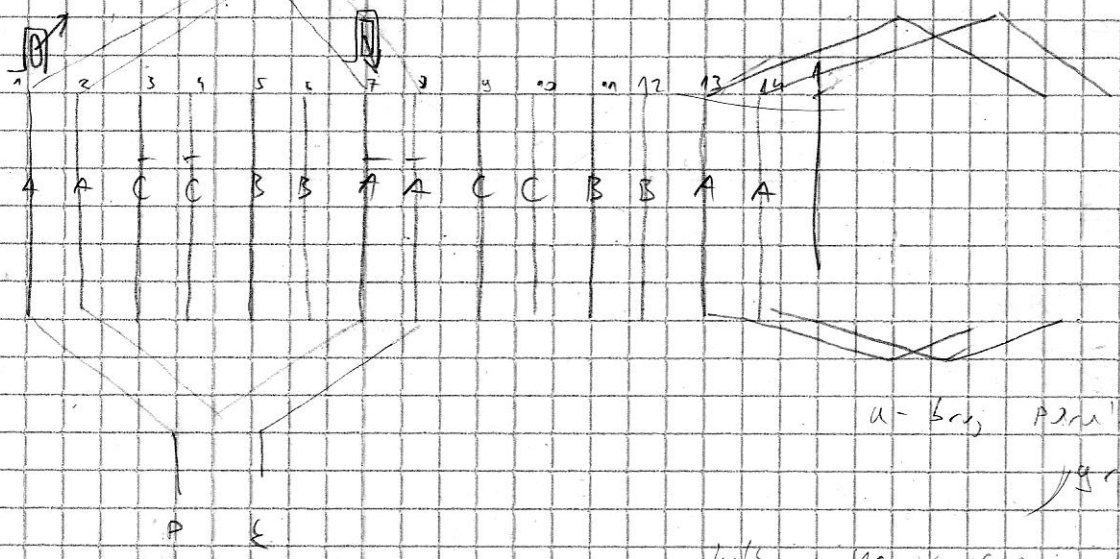

2 utora po polu i fazi
S
N
S
N
utori
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
A A C C B B A A C C B B A A C C B B A A C C B B
serijski
*
P
k
P
k
sve u serije
2 u seriju
2 u seriju
2 u seriju



פרלל

$\boxed{y = I_P}$ jednoslojni

jednoslojni



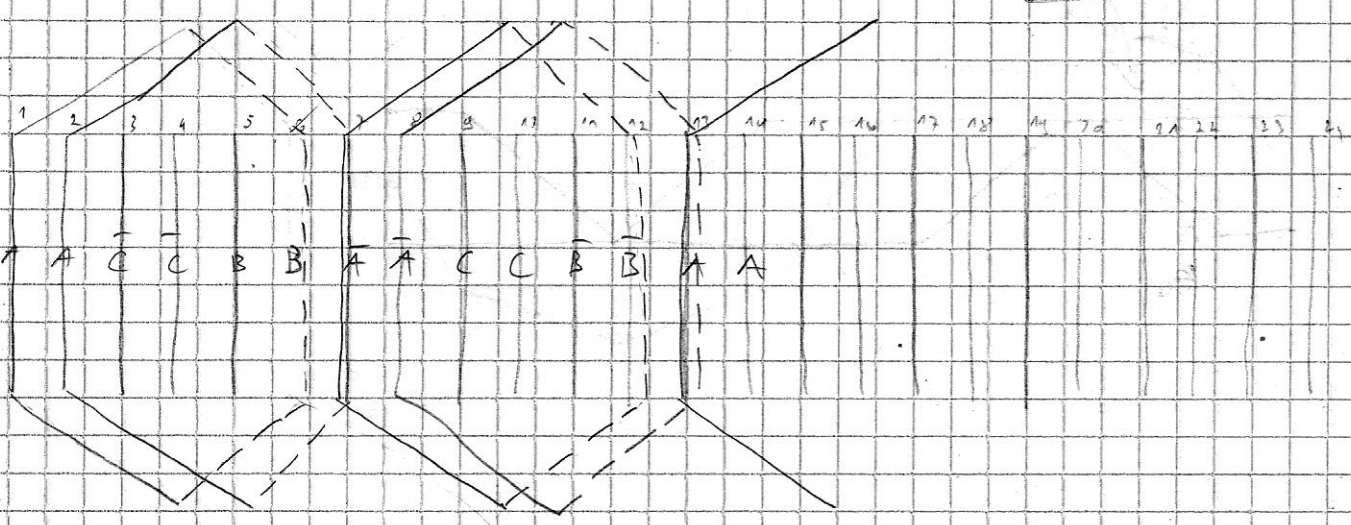
u-broj פרלל

שמאלי

שרטוט

שרטוט

שרטוט $y = 5$



6. Auditorne (3)

1.a

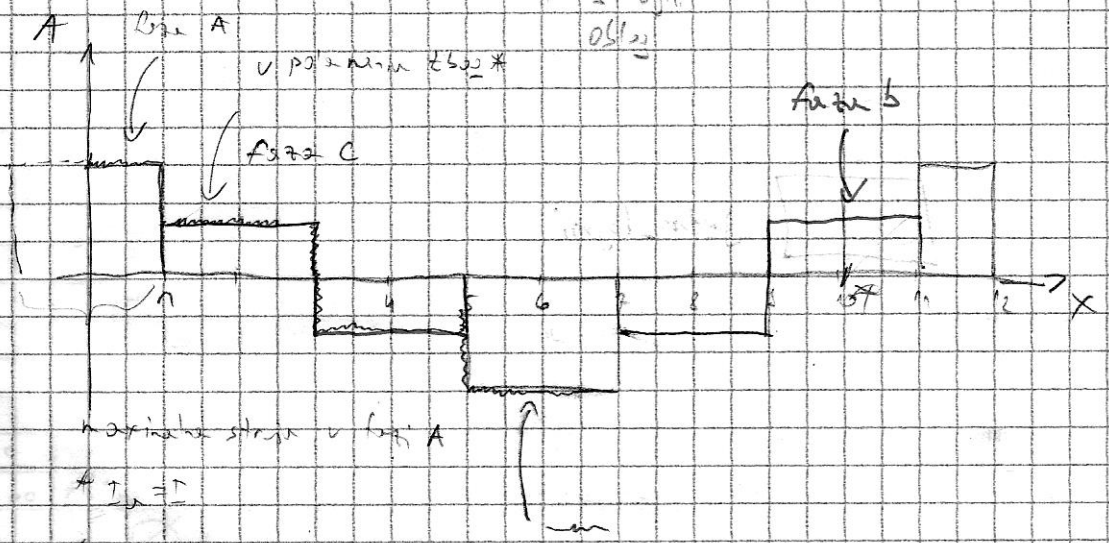
raspodjela struje duž A

raspodjela protjecanja Θ_a

kada je struja faze A maksimalna

Kad je struja jedne faze max kroz prošlih dvije faze teče polovina struje suprotnog smjera

Raspodjela



početak crtanja od sredine stražnje zone*

maksimalna struja u fazi A

* $I_a = I$

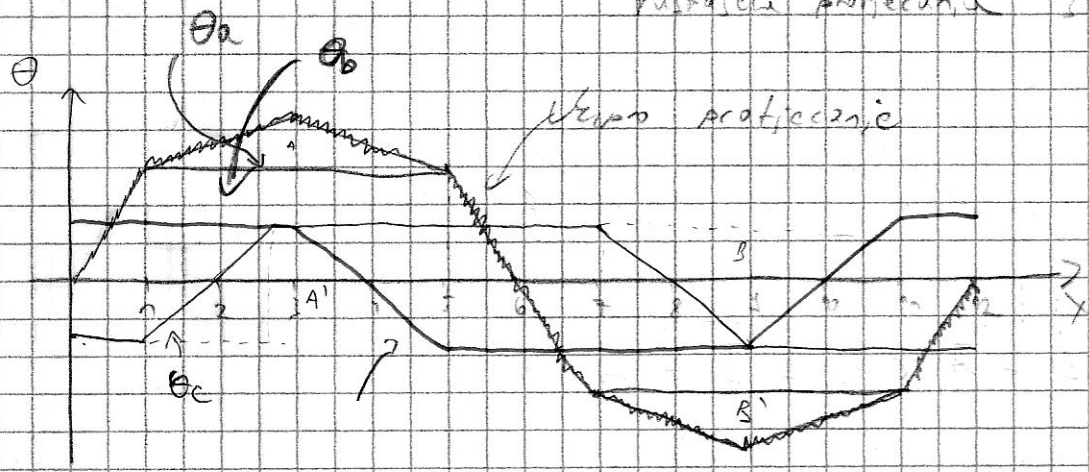
* $I_b = I_c = -\frac{I}{2}$

a vrijedno

$$\Theta(l_P) = \int_{l_0} A(x)\,dx$$

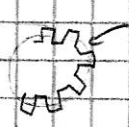
! l_0 - sredina stražnje zone

raspodjela protjecanja strujnih obloga



A i A' te B i B' bi zapravo trebale biti iste površine

Stroj: $N_v = 36$ (broj vretena)

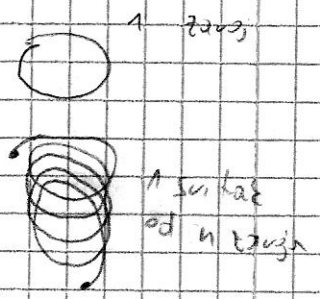


(2) 4 faze ($z_p = 2$)

$W = 72$ (broj u sporu spojenih zavojnica 1 faze)

Za isti stroj gledamo da:

- 1 S
- 2 S



a) broj svitaka u fazi N_{sv}?

b) broj zavojnica po svitku W_{sv}

c) broj vodiča u vretenu z_v?

- **1 S**: broj svitaka po fazi — 1 svitak traži 2 vretena (1 svitak traži 2 vretena)

$$N_{sv} = \frac{N_v}{3} \cdot \frac{1}{2} = \frac{36}{3} \cdot \frac{1}{2} = \frac{36}{6} = 6$$ (broj svitaka po fazi)

ima 3 faze

broj zavojnica po svitku

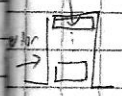
$$W_{sv} = \frac{W}{N_{sv}} = \frac{72}{6} = 12$$

broj svitaka 72
broj zavojnica 6

⇓

broj svitaka po zavojnici 12

vodič



$z_v = W_{sv}$

6 svitka ⇒ 12 svitaka
3 faze

⇓

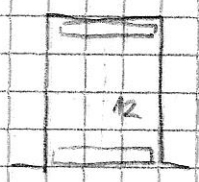
12 zavojnica po svitku

$$\frac{12 \cdot 12 \cdot 2}{36} = 12$$

⇓

1 zavoj u 2 vretena

Kolko je broj vodiča u vretenu

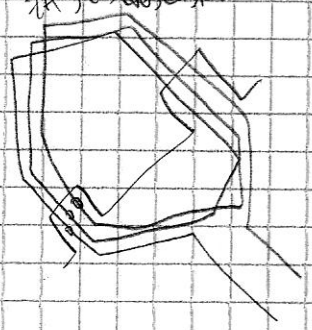


12 vodiča u vretenu

Koliko nije to Aranžmana 1, a za 2 aranžmana 2 vodiča po vretenu?

$W_{sv} = 12$

ZA JEDNOSLOJNI

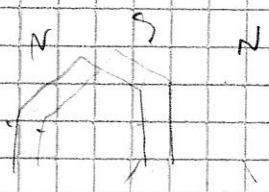


$W_{sv} = 5$

36/6 jednoslojni

$$q = \frac{36}{6 \cdot 3} = 2 \quad W = 30$$

$$y = \tau_p = \frac{36}{6} = 6 \quad (1 \to 7)$$



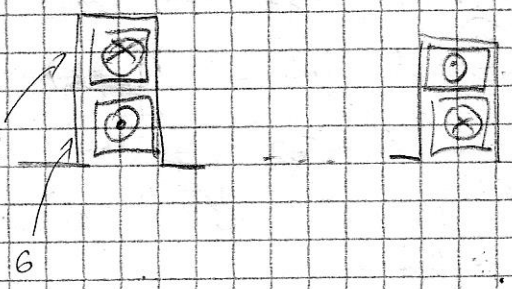
2 S:

jedan svitak čuvena uzeo 1 vlak

$$N_{sv} = \frac{N_v}{3} \cdot 1 = \frac{36}{3} = 12$$

$\frac{1}{2}$ kad idu i pole svi se vraca

broj svitka 1 faze



$$w_{sv} = \frac{W}{N_{sv}} = \frac{72}{12} = 6$$

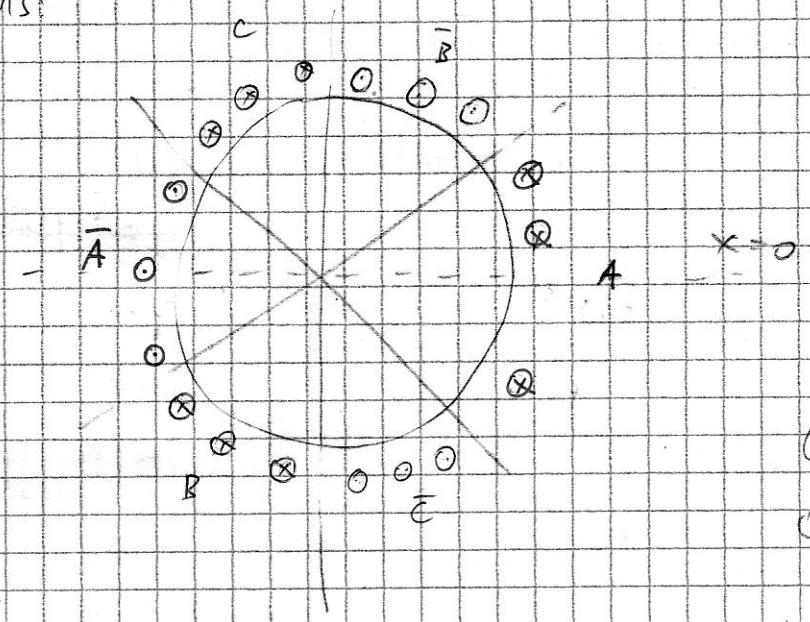
$$z_v = 2 \cdot w_{sv} = 2 \cdot 6 = 12$$

→ za 2 pola naćerati struju A i ⊖ za fazu A

kad je $I_a = I_{max}$

FA 1S:

objasniti sliku



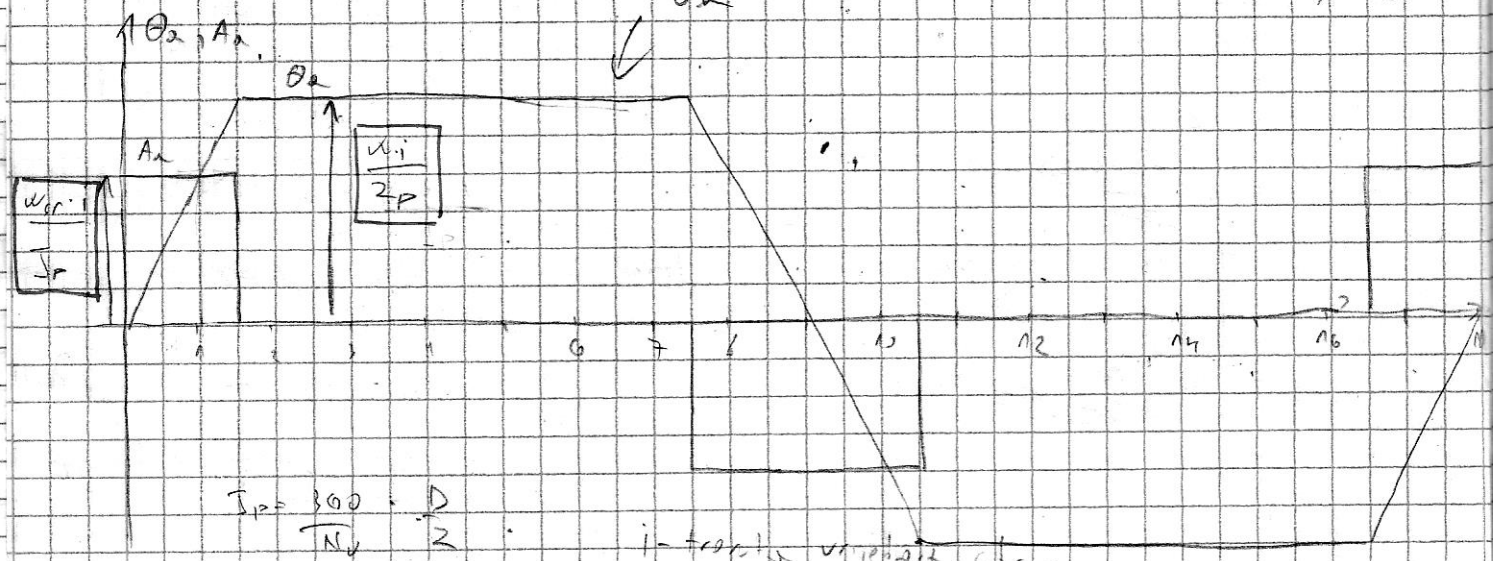
⊗ pozitivno

⊙ negativno

$$y = \frac{N_v}{m \cdot 2p} = \frac{36}{3 \cdot 4} = 3$$

(k za dvosloj.) da ima promenu slike bi bila kvadratna po x-u

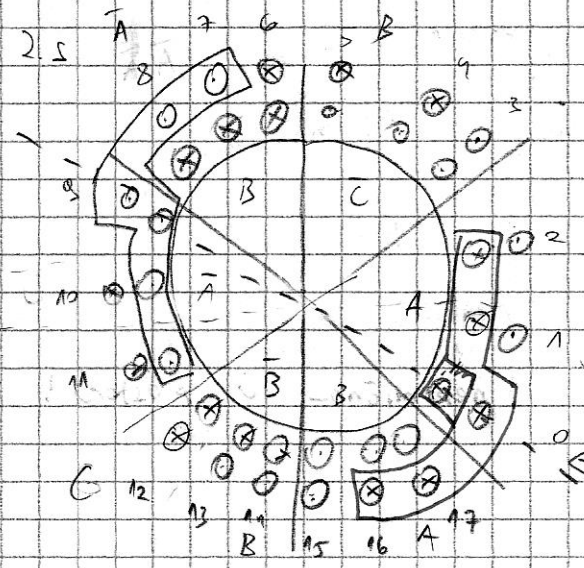
Θ_a



$$J_p = \frac{300}{N_v} \cdot \frac{D}{2}$$

i - trenutna vrijednost struje

2.5



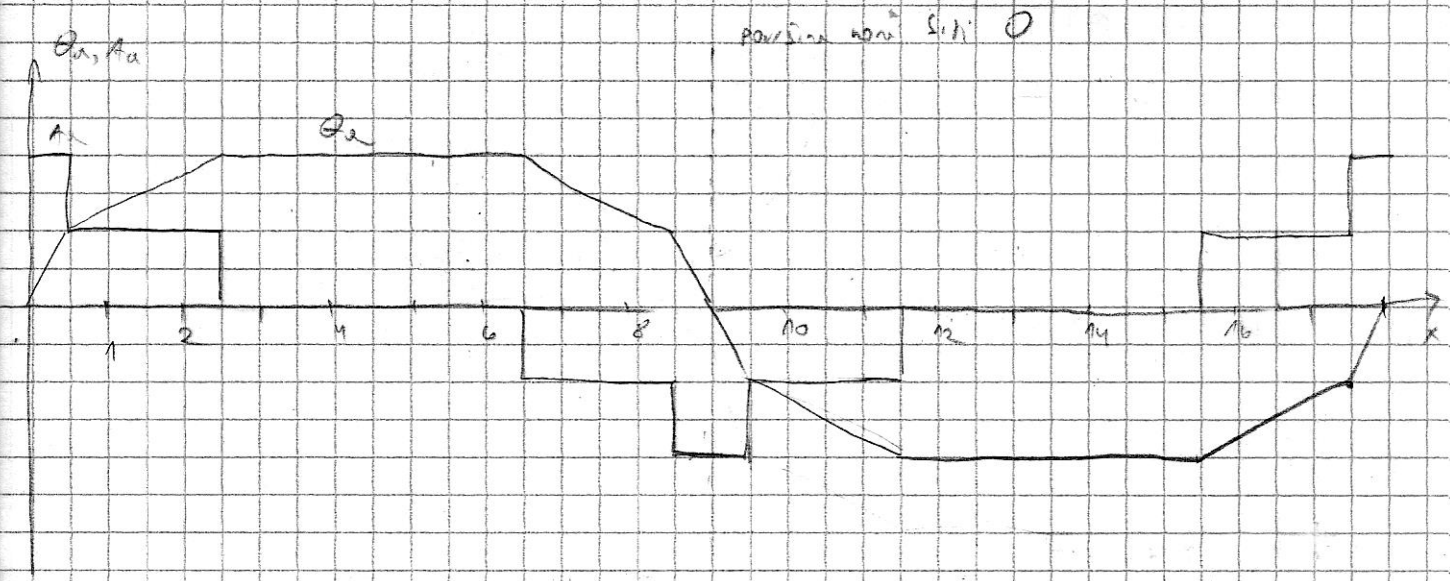
razlika $y - z = 2$

sredina statorja tvori (prvi) krak sredine (sinica)

$J_p = \frac{36}{y} = 4$ pda kmalu je 4 utorska

$y = 7$ (kmalu sistem poveljnt)

$J_p = 4$ skrajšali na $J_p = 7$



povišana nori sili O

7 predavanje (7.tj)

Kriteriji el. neh pretvorbe

$$f^R = \pm f^s \pm f_m$$
$$f_a^R = f_m$$
$$f_b^R = f_m$$
$$f_a^R = \pm f_b^R \pm 2 f_m$$

! Da bi postojao EM moment okretnog protjecanja statora i rotora kombinacija s vremenom nakon bit nepomične u prostoru!
tj. bili su iste frekvencije i išli u istom smjeru

fi da bi imali elektromagnetski moment

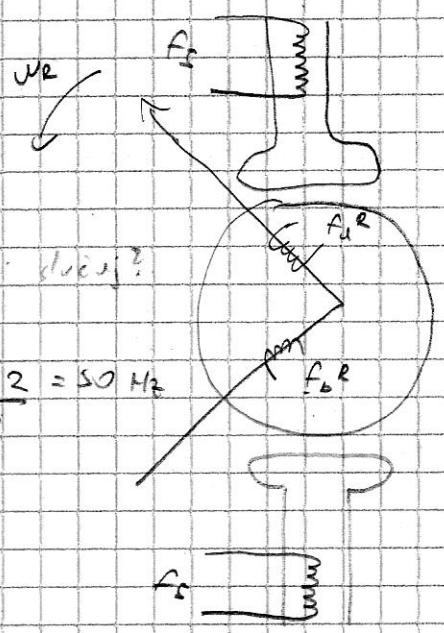
1.) 4 pola

$n_r = 1500\ min^{-1}$

$f^s = 50\ Hz$

$f_a^R, f_b^R = ?$ koji stroj ima sustav struja?

$$n_s = \frac{60 \cdot f_m}{p} \qquad f_m = \frac{n_s \cdot p}{60} = \frac{1500 \cdot 2}{60} = 50\ Hz$$



dvopolni opći stroj

1. kriterij

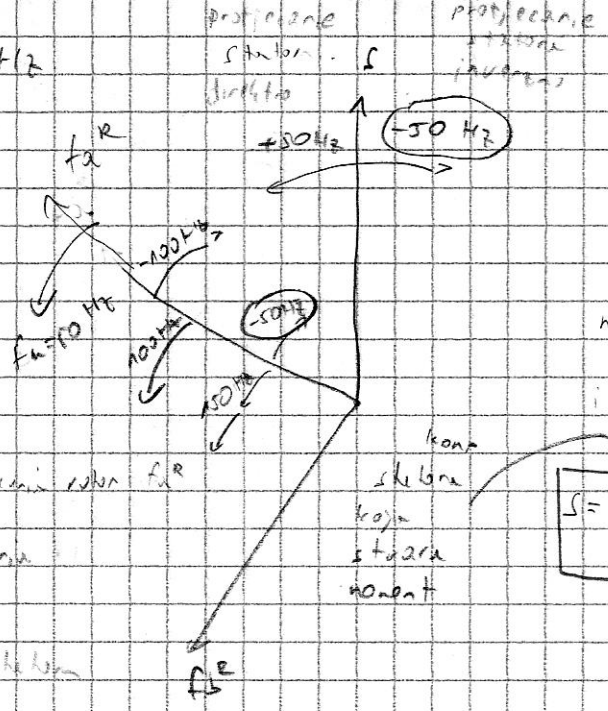
$$f_R = \pm f_s \pm f_m$$
$$f_R = \pm 50 \pm 50$$

(gled samo pozitivne f i 0)

$f_{R1} = 0\ Hz$

$f_{R2} = 100\ Hz$

$f^R = 100\,Hz$

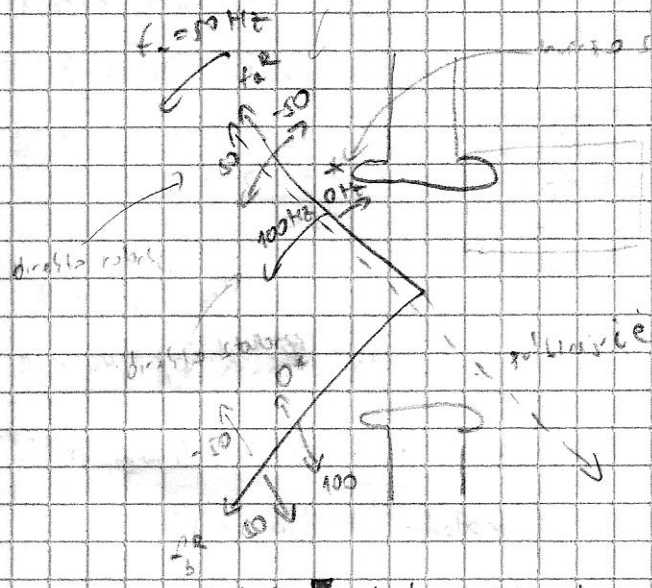


kroz prostorne dva kriterija isto isti rezultantni stroj

2) $f_a^R = f_m = 50$ Hz

3) $f_b^R = f_m = 50$ Hz

} rezultantni stroj



* inaco pulsirajuće rotiranje jer je frekvencija u statoru 0 Hz, te ono nastaje rotacijom rotora u položaj izlaznih polova (treba dobiti ukupno protjecanje koje je pulsirajuće $f=0$)

postoji moment koji teži ukleniti rotor u položaj izlaznih polova

2. i 3 kriterij ! kod rezultantnog stroja želimo dobiti pulsirajuće protjecanje

pulsirajuće protjecanje ima rezultantnu frekvenciju od 0 Hz (ne okreće se)

4. Crit

$f_a^R = \pm f_b^R \pm 2 f_m$

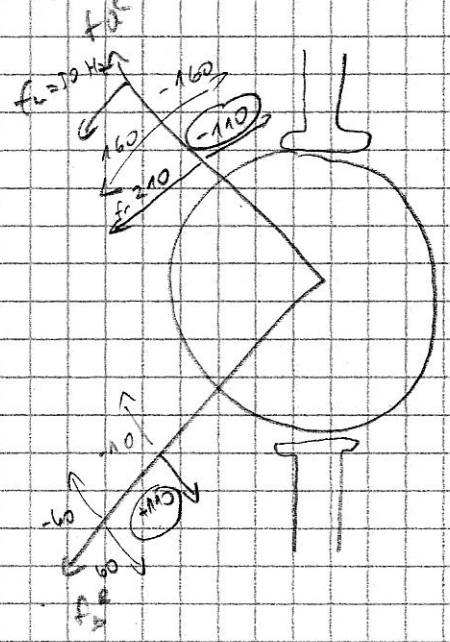
$f_a^R = \pm f_b^R \pm 100$

(imamo beskonačno mnogo rješenja)

npr $f_b = 60$

$f_a^R = 160$ Hz $\qquad$ $f_a^R = 40$ Hz

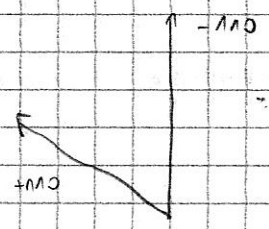
$f_2^R = 160$ Hz



Indukcijski motor radi kao mali

drugi polovnik cijelo radi mala

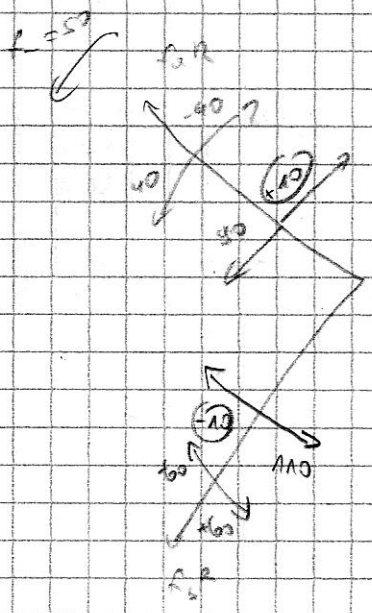
i ima polovnik koji dakle proizvodi



Imamo pulsirajuće protjeranje tj. reluktantni moment

↳ nastoji se stroj postaviti u položaj istaknutih polova

$f_2^R = 40$



Komponenta momenta je reluktantni moment

Za četverpol ne treba napisat koji je stroj

Ne postoji takav stroj

4. 4 polova

$n = 1200\ min^{-1}$ $f_m = 40\ Hz$

$f_a = 60\ Hz$

$f_a^R = f_b^R = 60\ Hz$

$f_s = ?$ vrsta stroja za sve kriterije

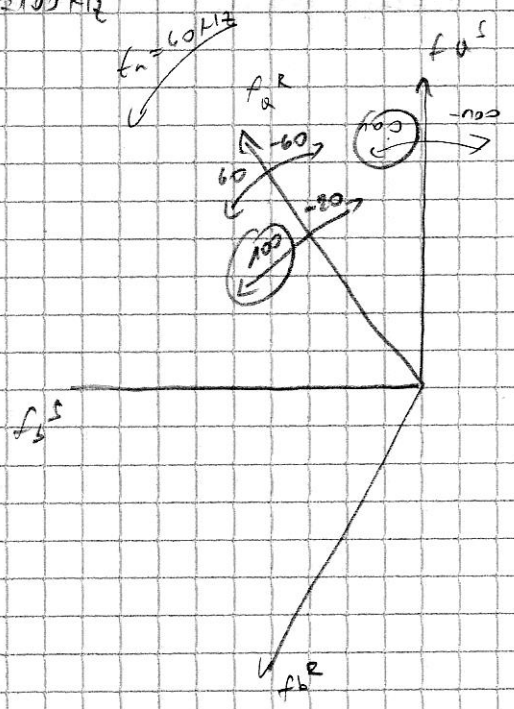
1.) $f^R = \pm f_s \pm f_m$ f_a^S mora biti jednak kao f_a^R

$60 = \pm f_s \pm 40$

$f_{s_1} = 100\ Hz$

$f_{s_2} = 20\ Hz$ (samo pozitivne vrijednosti)

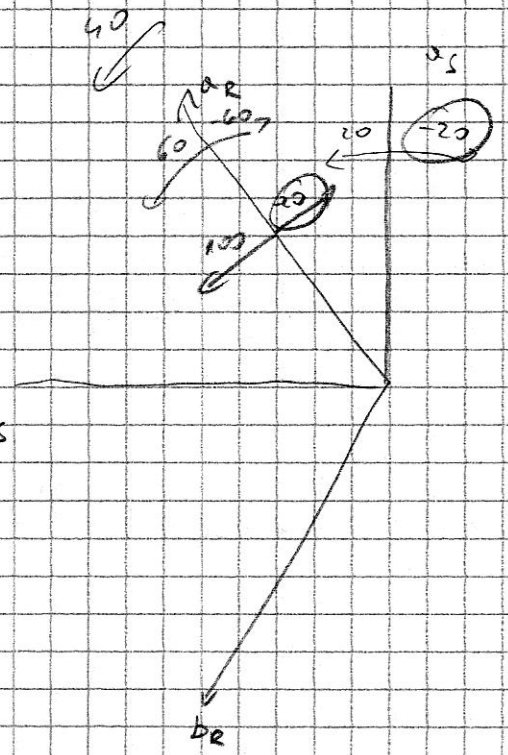
$f_s = 100\ Hz$



$s = \frac{f_s - f_m}{f_s} = \frac{100 - 40}{100} = 0.6$

Asinkroni stroj, motorski režim

$f_1 = 20$ Hz



$$s = \frac{-20 - 40}{-20} = 3$$

asinkroni motor u prostu strujnom kočenju

2)

$f_R^* = f_m$

$60 \neq 40$ ne nastaje moment ne možemo priključiti kočnicu

3) -||-

4) $-60 = \pm 60 \pm 2 \cdot 40$

ne možemo priključiti

postoje sinkroni i rezultantni moment

* nacrtati napajanje mosta

2 transformator

1

1 protitlačna napajanja chopper protheca,*

1 ona u kaskaderiji

8. Auditorne (nekoliko prepisane)

$$\Theta(\varphi) = \int^{\varphi} A(x)\, dx$$

!! φ - sredina strujne zone

A - strujni oblog

strujni oblog (ili linijska gustoća struje $\left[\frac{A}{m}\right]$)

↳ određuje magnetsko polje u trajnom razporu

$$A_{max} = \frac{w_{sv} \cdot i}{\tau_p}$$

w_{sv} - broj zavoja po svitku

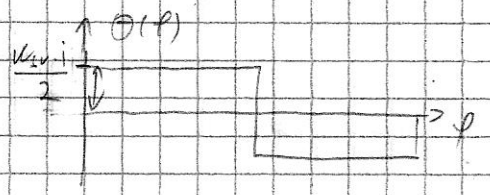
w - broj vodiča spojenih u seriju

i - struja vodiča

$$\Theta_{max} = \frac{w \cdot i}{2p}$$

protjecanje → suma obuhvaćenih struja

Dijametralni svitak



$$\Theta_{sv,max} = \frac{w_{sv} \cdot i}{2}$$

$$\Theta_{sv} = \frac{4}{\pi} \frac{w_{sv} \cdot i}{2}$$

$$f_z = \frac{\sin\left(\alpha \cdot \frac{\alpha_{el}}{2}\right)}{q \sin\left(\frac{\alpha_{el}}{2}\right)}$$

$$f_t = \sin\left(\frac{q}{\tau_p} \frac{\pi}{2}\right)$$

$$\Theta_{1k} = \sum_{\text{dij po fuži/paru polova}} |\Theta_{sv,k}| \cdot f_{uk}$$

$$f_{uk} = f_z \cdot f_t$$

f_z → zbog distr. namota

f_t → zbog skraćenja

jednoslojni

dvoslojni

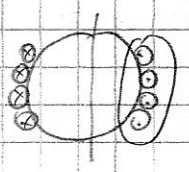
$$\Theta_{1f} = \frac{4}{\pi} \frac{w_{sv} \cdot i}{2} \cdot q \cdot f_{uk}$$

$$\Theta_{1f} = \frac{4}{\pi} \frac{w_{sv} \cdot i}{2} \cdot 2p \cdot f_{uk}$$

broj utora po fazi u zoni pod polom

m broj faza

$\frac{w}{p}$ → broj u seriju spojenih zavoja po paru polova



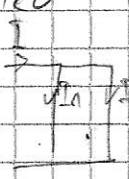
$q = 4$

$$\Theta_{1f} = \frac{4}{\pi} \frac{w}{p} \frac{i}{2} f_{uk}$$

kod inverzno paralelne grane → struja vk je a puta veća od struje u svitku

$I\sqrt{2}$

$$\boxed{\Theta_{1f} = \frac{4}{\pi}\,\frac{w}{p\,a}\,\frac{I}{2}\,f_{uk}}$$



$I = I_1 + I_2$

$$\Theta_{uk} = \frac{3}{2}\cdot\frac{4}{\pi}\,\frac{w}{p\,a}\,\frac{I}{2}\,f_{uk} \qquad \Theta_{uk} = \frac{3}{2}\,\Theta_{1f}$$

1.) Stroj $36/6$ (N / 2p) $y = 4$ $w_{sv} = 10$ $I = 4.5\,A$ $a = 2$

protjecanje jedne faze i ukupno kk dvosloj. namot

$$\Theta_{f1} = \frac{4}{\pi}\,\frac{I\sqrt{2}}{2a}\,\frac{w}{p}\,f_n$$

broj utora po fazi u zoni pol. pola

$$f_z = \frac{\sin\left(\alpha\cdot\frac{\alpha}{2}\right)}{\alpha\cdot\sin\left(\frac{\alpha}{2}\right)}$$

$$\boxed{\alpha = \frac{N}{2p\cdot m}} = \frac{36}{6\cdot 3} = 2$$

broj faza

$$\boxed{\alpha_{el} = \frac{2\pi\cdot p}{N}} = \frac{2\pi\cdot 3}{36} = \frac{\pi}{6} = 30^\circ$$

$$f_z = \frac{\sin\left(2\cdot\frac{\pi}{2\cdot 6}\right)}{2\sin\left(\frac{\pi}{2\cdot 6}\right)} = 0.965925$$

$$\tau_p = \frac{N_u}{2p}$$

$$f_t = \sin\left(\frac{y}{\tau_p}\cdot\frac{\pi}{2}\right) = \sin\left(\frac{4}{6}\cdot\frac{\pi}{2}\right) = 0.866025$$

$$\boxed{f_{uk} = f_n = f_t\cdot f_z} = 0.965925\cdot 0.866025 = 0.836515\,59$$

$$\boxed{w = \frac{N}{3}\cdot w_{sv}} = \frac{36}{3}\cdot 10 = 120$$ (dvosloj.)

$$\Theta_{f1} = \frac{4}{\pi}\cdot\frac{4.5}{2}\,\frac{\sqrt{2}}{2}\cdot\frac{120}{3}\cdot 0.83655159 = 67.784\,A$$

$$\Theta_{uk} = \frac{3}{2}\,\Theta_{1f} = 101.677\,A$$

2) za jednovrstvinu navinut $y = 6$ $\alpha = 1$

$$k_z = \frac{\sin\left(q \cdot \frac{\alpha}{2}\right)}{q \sin\left(\frac{\alpha}{2}\right)}$$ ostaje isti kao prije

$k_z = 0.965925$

$w = \frac{N}{3 \cdot 2} \quad w_{sv} = \frac{36}{6} \cdot 10 = 60$

$k_t = \sin\left(\frac{y}{\tau_p} \cdot \frac{\pi}{2}\right) = \sin\left(\frac{6}{6} \cdot \frac{\pi}{2}\right) = 1$

$\Theta_{f1} = \frac{4}{\pi} \cdot \frac{4.5}{2} \cdot \frac{\sqrt{2}}{1} \cdot \frac{60}{3} \cdot 0.965925 = 78.2674 \text{ A}$

$\Theta_{uk} = 1.5 \, \Theta_{1p} = 117.4 \text{ A}$

Inducirani napon

a) u jednom vodiču

maksimalna vrijednost indukcije u zračnom nasporu

$$E_{v1} = \frac{1}{\sqrt{2}} B_\delta l v$$ ← obodna brzina

magnetski tok po jednom polu

$$\Rightarrow \phi = \int_0^{\tau_p} B_\delta \sin\left(\frac{\pi}{\tau_p} x\right) l \, dx = \frac{2}{\pi} B_\delta \tau_p l = \frac{\cancel{2}}{\cancel{\pi}} \cdot B_\delta \cdot \frac{D \cancel{\pi}}{\cancel{2} p} = \phi$$

$$\boxed{B_\delta = \frac{\phi \cdot p}{D l}}$$

$$v = R \omega_m = \frac{D}{2} \cdot \frac{n \pi}{30}$$

$$E_{v1} = \frac{1}{\sqrt{2}} \frac{\phi p}{D \cancel{l}} \cdot \frac{\cancel{D}}{2} \frac{n \pi}{30} = \frac{\pi}{\sqrt{2}} \phi \cdot \overbrace{\frac{p n}{60}}^{f}$$

$$n_s = \frac{60 f}{p}$$

$$E_{v1} = \frac{\pi}{\sqrt{2}} \cdot \phi \cdot f$$

b) u jednom svitku

$$E_{sv} = 2 E_{v1} \cdot w_{sv} \cdot f_n$$

c) u spoju sa w svitaka spojenih u seriju (namot)

$$E = 2 \cdot \frac{w}{a} E_{v1} \cdot f_n = \underbrace{2 \cdot \frac{w}{2} \cdot \frac{\pi}{\sqrt{2}}}_{4.44} \cdot \phi \cdot f \cdot f_n = \boxed{4.44 \, f \cdot f_n \cdot \frac{w}{a} \cdot \phi}$$

broj faza

$$\boxed{\begin{aligned} w &= \frac{N}{3} \cdot w_{sv}, && (2\text{-slojni}) \\ w &= \frac{N}{3 \cdot 2} w_{sv} && (1\text{-slojni}) \end{aligned}}$$

$$\boxed{\begin{aligned} w &= 2p \, q \cdot w_{sv} && \text{za } (2\text{-slojni}) \\ w &= p \cdot q \cdot w_{sv} && \text{za } (1\text{-slojni}) \end{aligned}}$$

w – broj svitaka jedne faze, neovisno o paralelnim granama

a – broj paralelnih grana u namotu

(3) Broj $D = 0.80$ m $l = 0.3$ m $N = 72$ vodiča 6 polova

$w_{sv} = 5$ $a = 6$ namot sferičan ka 1 vlor

$B = 0.85$ T $f = 50$ Hz

$E_e = ?$

$$\Phi = B_\delta \frac{D l}{p} = 0.85 \cdot \frac{0.8 \cdot 0.3}{3} = 0.068 \text{ Vs}$$

$$E_{v1} = \frac{\pi}{\sqrt{2}} \Phi \cdot f = 5.3407 \text{ Hz}$$

$$f_z = \frac{\sin\left(q \cdot \frac{\alpha}{2}\right)}{q \sin \frac{\alpha}{2}} = \frac{\sin\left(4 \cdot \frac{15}{2}\right)}{4 \sin\left(\frac{15}{2}\right)}$$

$$q_p = \frac{N}{2p} = \frac{72}{6} = 12$$

$$y = 11$$

$$q = \frac{N}{2pm} = \frac{72}{6 \cdot 3} = 4$$

$$\alpha = \frac{360 \cdot p}{N} = 15^\circ$$

$$f_z = 0.95766$$

$$f_z = \sin\left(\frac{11}{12} \cdot 90\right) = 0.99144$$

$$f_n = f_z \cdot f_v = 0.95766 \cdot 0.99144 = 0.94946$$

$$w = \frac{N}{3} \cdot w_{sv} = \frac{72}{3} \cdot 5 = 120$$

$$E = 4.44 \frac{w}{2} \cdot f \cdot \overset{f_{vl}}{f_n} \cdot \Phi =$$

$$= 4.44 \cdot \frac{120}{6} \cdot 50 \cdot 0.94946 \cdot 0.068 = 286.661 \text{ V} \quad (\text{fazno})$$

$$E_{linijski} = \sqrt{3}\, E = 496.51 \text{ V}$$

koji harmonik se najbolje prigušuje

$$\boxed{y = \left(1 - \frac{1}{\nu}\right) \tau_p}$$

$\nu = 12$ — 11, 13

ν-ti harmonik

5) Koliki mora biti korak sita da se najbližnji privuči 7 harmonik?

$$y = \left(1 - \frac{1}{7}\right) T_0 = \left(1 - \frac{1}{7}\right) \cdot 12 = 10{,}28571 \approx \underline{\underline{10}}$$

1. ob. tarne

Faktori navoja za više harmonike

$$f_{zv} = \frac{\sin\left(q \cdot \frac{v\alpha}{2}\right)}{q \cdot \sin\left(\frac{v\alpha}{2}\right)}$$

$$f_{tv} = \sin\left(v \frac{y}{\tau_p} \cdot \frac{\pi}{2}\right)$$

$$f_{uv} = f_{zv} \cdot f_{tv}$$

$$y = \left(1 - \frac{1}{v}\right) \tau_p$$ za uklanjanje harmonika

korak svitka

$\tau_p = 12$; $72/6$ (vrh, polova)

kolko mora biti skraćen svitak da se poništi 7 harmonik $y = ?$

$$\boxed{\tau_p = \frac{N}{2p}} = \frac{72}{6} = 12$$

korak svitka mora biti cijeli broj

$$y = \left(1 - \frac{1}{7}\right) \cdot 12 = 10.2857 \approx 10$$

za 10 redni harmonik neće biti skraćen poništen

Stroj 36/4

izračunati faktore za 1, 3, 5, 17, 19 harmonik

$m = 3$

$p = 2$

$$\boxed{q = \frac{N}{2pm}} = \frac{36}{4 \cdot 3} = 3$$

$\alpha = 20°$

$$\tau_p = \frac{N_u}{2p} = \frac{36}{4} = 9$$

$$\frac{y}{\tau_p} = \frac{7}{9} \quad \square$$

$$y = \left(1 - \frac{1}{\nu}\right)\tau_p \Rightarrow \frac{7}{9} = 1 - \frac{1}{\nu} \qquad \nu = 4.5 \rightarrow 4 \rightarrow 5$$

s ovim $\square$ izrazom najbolje se prigušuje 5. harm.

↳ kod stroja su svi parni harmonici najčešće prigušeni

$$f_{z\nu} = \frac{\sin\left(\nu \cdot q \cdot \frac{\alpha}{2}\right)}{q \cdot \sin\left(\nu \cdot \frac{\alpha}{2}\right)} = \frac{\sin\left(\nu \cdot 3 \cdot \frac{20°}{2}\right)}{3 \cdot \sin\left(\nu \cdot \frac{20°}{2}\right)}$$

$$f_{t\nu} = \sin\left(\nu \cdot \frac{y}{\tau_p} \cdot \frac{\pi}{2}\right) = \sin($$

viši harmonici

	1	3	5	17	19
$f_{z\nu}$	0.96	0.667	0.218	0.96	0.96
$f_{t\nu}$	0.9397	0.5	0.174	0.9397	-0.9397
f_{ν}	0.902	0.333	0.038	0.902	-0.902

vtorski harmonski - imajo komponente $6q \pm 1$

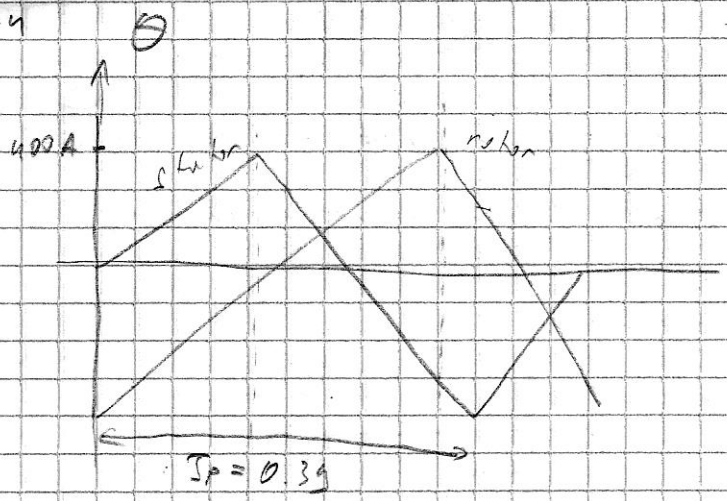
- nanoje se poniščati skrčenjem ali drugim odstranitvi navitja

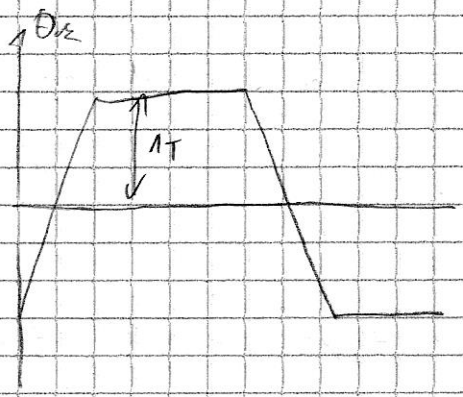
- nastanejo zobni i vtorki

(- možno ih pobit skošenjem)

v wolfu 8.10

$2p = 4$





$B = \Theta_{vz}$

$\Theta_z = 400\ A$

$\delta = 0.5\ mm$

$\tau_p = 0.3\,m$

B, A_s, A_r

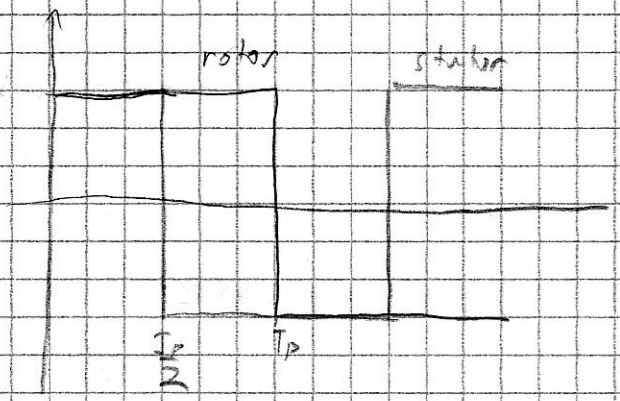
$$B(x) = \frac{\mu_r\ \Theta(x)}{\delta} \qquad \left(B(x) = \Theta(x) \cdot \underbrace{\Lambda(x)}_{\frac{\mu_0}{\delta(x)}} \right)$$

$$\boxed{B_\delta(x) = \frac{\mu_0\ \Theta(x)}{\delta}}$$

$$B_\delta(x) = \frac{4\pi \cdot 10^{-7} \cdot 400}{0.5 \cdot 10^{-3}} = 1\ T$$

$$\Theta = \int A\,dx$$

$$A = \frac{\partial \Theta}{\partial x}$$



$$\boxed{\Theta_m = \frac{A \cdot \tau_p}{2}} \Rightarrow A = \frac{2\,\Theta_m}{\tau_p} = \frac{2 \cdot 400}{0.32} = 2081 \ A/m$$

8.11

$l = 0.3$

kolik je obodová síla a kolik moment na statoru i rotoru

$F = ?$

$M = ?$

$$\boxed{M = F \cdot \frac{D}{2}}$$

$$\boxed{F = 2p \cdot \int_0^{\tau_p} A_n(x) \cdot B(x) \cdot l \, dx} = 2 \cdot p \cdot B \cdot A \cdot \frac{\tau_p}{2} \cdot l = 2 \cdot 2 \cdot 1 \cdot 2051 \cdot \frac{0.39}{2} \cdot 0.3 = 480 \text{ N}$$

$$\tau_p = \frac{D \cdot \pi}{2p} \qquad D = \frac{2p \cdot \tau_p}{\pi} = \frac{2 \cdot 2 \cdot 0.39}{\pi} = 0.5 \text{ m}$$

$$M = 480 \cdot \frac{0.5}{2} = 120 \text{ Nm}$$

vypočítat kolik dosáhne τ_p

↳ zadání je v přednáškovém zápisu

Proračun momenta pomoću volumena

8.12 motorski način rada

$2p = 4$

Θ_r = raspoređeno na raspodjelu indukcije na $\frac{1}{12}$ obodu stroja

$\Theta_r = 2200\ A$ rotorska protjeranica koja za stupnjem protjecanja

$B = 0.9\ T$ Motorski rad

$D = 0.4\ m$

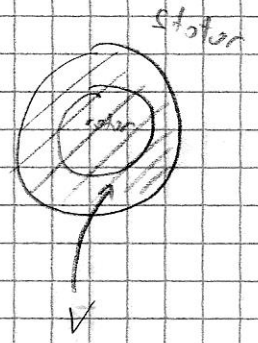
$l = 0.18\ m$

$M = ?$ generatorski ili motorski ?

volumen rotora

$$\boxed{M = \frac{\pi}{\tau_p} \cdot V \cdot B \cdot \Theta_r \cdot \sin(\delta_{el})}$$

kut opterećenja
kut između rotorskog protjecanja i indukcije u trenutku nastupa



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

$V = \frac{D^2 \pi}{4} \cdot l$

$$\boxed{\delta_{el} = p \cdot \delta_{mech}}$$

Θ_r raspoređen na $\frac{1}{12}$ od B

$\delta_{el} = 2 \cdot \frac{360}{12} = 60°$

$$M = \frac{\pi \cdot 2p}{D\pi} \cdot \frac{D^2 \cdot \pi \cdot l}{4} \Theta_r \cdot \sin(p \cdot \delta_{el})$$

$$= \frac{\pi}{2} \cdot 2 \cdot 0.4 \cdot 0.18 \cdot 0.9 \cdot 2200 \cdot \sin\left(2 \cdot \frac{360}{12}\right) = 388\ Nm$$

kad vlastno protjecanje prethodi rotacijom protjecanj => (14)

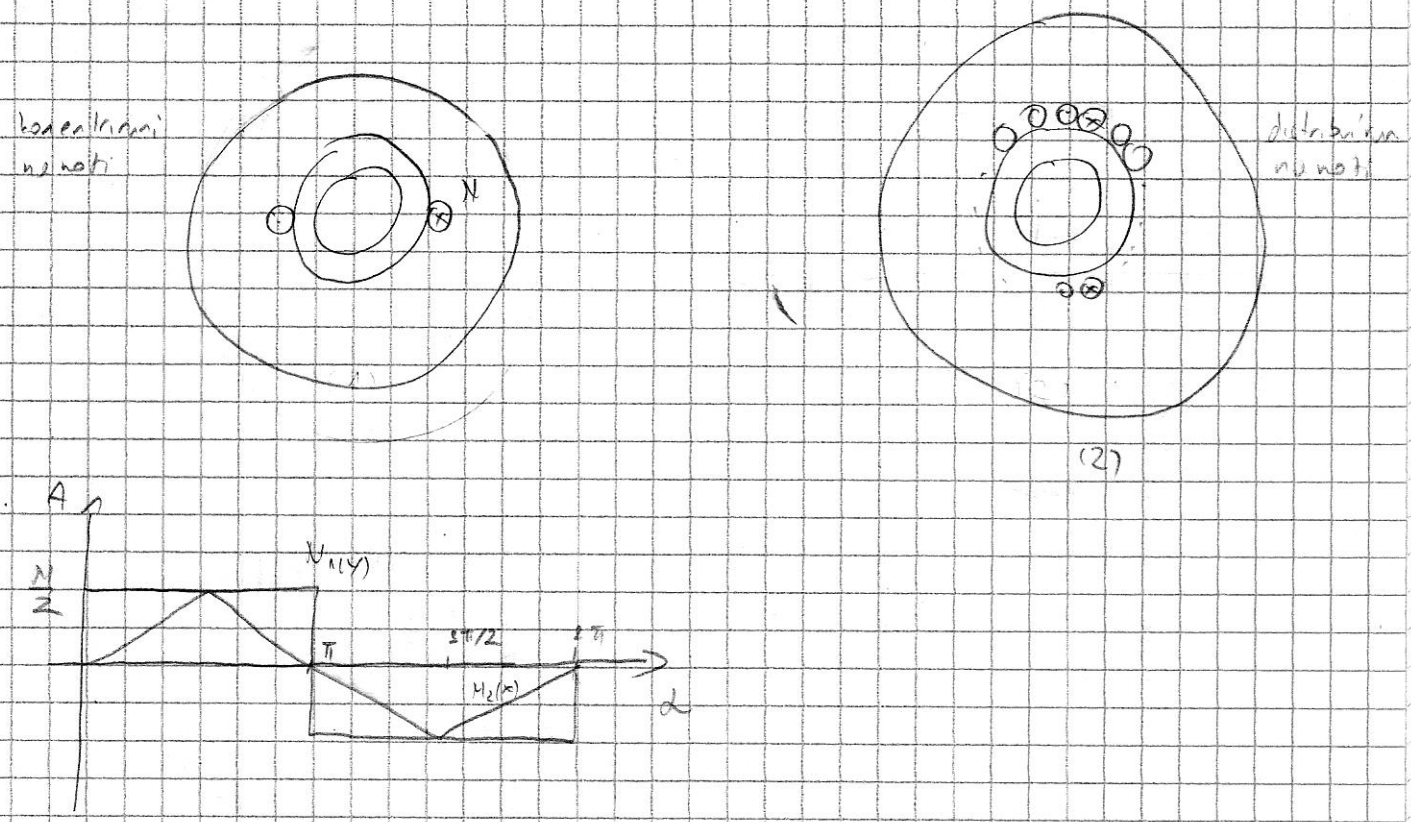
kada rotacijsko protjecanje prethodi vlastnom protjecanju (indukcija) (6)

10. Avdibrne

Induktivni stroj

$$N(\alpha) = \frac{\Theta(\alpha)}{I} \qquad L = \frac{\mu_0 \cdot r \cdot l}{\delta} \int_0^{2\pi} \frac{(N(\alpha))^2}{\delta(\alpha)} d\alpha \qquad M = \mu_0 \cdot r l \cdot \int_0^{2\pi} N_1 N_2$$

a) $\frac{L_1}{L_2}$



$$L_1 = \frac{\mu_0 \cdot r l}{\delta} \int_0^{2\pi} N_1^2(\alpha)\, d\alpha = \frac{4 \mu_0 \cdot r l}{\delta} \int_0^{\pi/2} \left(\frac{N}{2}\right)^2 d\alpha$$

$$= \frac{\mu_0 \cdot r \cdot l}{\delta} \cdot N^2 \cdot \frac{\pi}{2}$$

$$L_2 = \frac{\mu_0 \cdot r l}{\delta} \int_0^{2\pi} N_2^2(\alpha)\, d\alpha = \frac{4 \mu_0 \cdot r \cdot l}{\delta} \int_0^{\pi/2} \left(\frac{N}{2} \alpha\right)^2 \cdot d\alpha$$

pravc

$$L = \frac{\mu_0 \cdot r l}{\delta} \cdot N^2 \cdot \frac{\pi}{6}$$

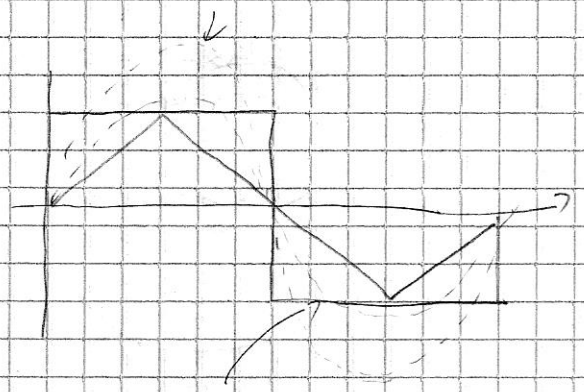
$$\frac{L_1}{L_2} = \frac{\frac{\mu_0 \cdot l \cdot r}{\delta} \cdot N^2 \cdot \frac{\pi}{2}}{\frac{\mu_0 \cdot l \cdot r}{\delta} \cdot N^2 \cdot \frac{\pi}{6}} = 3$$

1. harm.

b) $\frac{L_{1n}}{L_{2n}}$

rozdělení rozpadájící protiřezání rozpadající harm.

$M_{1n}(\alpha) = N_{1n} \cdot \sin\alpha$



$M_{2n}(\alpha) = N_{2n} \cdot \sin(\alpha)$

$$M_{1n} = \frac{1}{\pi} \int_0^{2\pi} M_1(\alpha) \cdot \sin\alpha = \dots = \frac{4}{\pi} \frac{N}{2} = \frac{2}{\pi} \cdot N$$

$$M_{2n} = \frac{1}{\pi} \int_0^{2\pi} N_2(\alpha) \cdot \sin(\alpha) = \dots = \frac{4}{\pi} \int_0^{\frac{\pi}{2}} \frac{N}{2} \alpha \cdot \sin(\alpha) = \frac{4}{\pi^2} N$$

$$L_{1n} = \frac{\mu_0 \cdot l \cdot r}{\delta} \int_0^{2\pi} (N_{1n} \sin(\alpha))^2 = d\alpha = \frac{\mu_0 \cdot r \cdot l}{\delta} \cdot N_{1n}^2 \int_0^{2\pi} \frac{1 - \cos 2\alpha}{2}$$

$$= \frac{\mu_0 \cdot r \cdot l}{\delta} \cdot \frac{4 N^2}{\pi}$$

$N = f_n \cdot$

$$L_{2n} = \frac{\mu_0 \cdot l \cdot r}{\delta} \int_0^{2\pi} (N_{2n} \sin(\alpha))^2 = \frac{\mu_0 \cdot l \cdot r}{\delta} \cdot M_{2n}^2 \cdot \pi$$

$$= \frac{\mu_0 \cdot l \cdot r}{\delta} \cdot \frac{16 N^2}{\pi^3}$$

$$\frac{L_{1n}}{L_{2n}} = \frac{\frac{\mu_0 \cdot r \cdot l}{\delta} \cdot \frac{4N^2}{4}}{\frac{\mu_0 \cdot r \cdot l}{\delta} \cdot \frac{16N^2}{\pi^2}} = \frac{\pi^2}{4} \approx 2.4674$$

c) $\frac{i_1}{i_2} = 1$ zato ito su iste max vrijednosti funkcije nemoka => isto protjecanje => iste indukcije

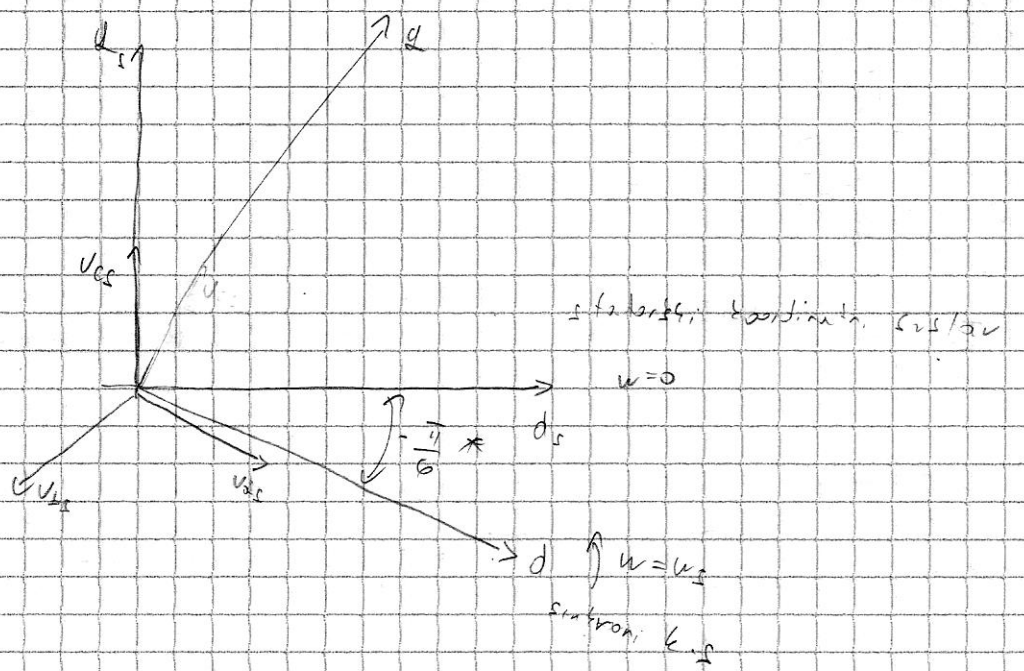
ASINKRONI STROJ (vrlo 1 min)

2.1 $i_n = 400\,V$ $f = 50\,Hz$

$U_{dq_s}^s$, V_{dq_s} sinkronom brzinom Ω_s

s statorski

$U_{a_s} = V_m \cdot e^{-j \cdot (\pi/6)}$ (faznoj naponu)



s statorski koordinatni sustav

u) statorski koordinatni sustav (trošilo nešto na pomu)

$$V_{dq_s}^s = \overbrace{V_{s+}\, e^{j w_s t}}^{\text{direktno}} + \overbrace{V_{s-}^*\, e^{-j w_s t}}^{\text{inverzno}}$$

direktna komponenta $\overline{V_{s+}} = \frac{1}{3}\left(\overline{V_{as}} + \overline{V_{bs}}\, a + a^2\, \overline{V_{cs}}\right)$ $a = e^{j\frac{2\pi}{3}}$

inverzna komponenta $\overline{V_{s-}} = \frac{1}{3}\left(\overline{V_{as}} + a^2\, \overline{V_{bs}} + a\, \overline{V_{cs}}\right)$

* positive sequence - direktna komponenta

fazno max linijski

$$\overline{U_{as}} = \sqrt{2}\,\frac{U}{\sqrt{3}}\, e^{-j\frac{\pi}{6}}$$

pomaz

$$\overline{U_{bs}} = \sqrt{2}\,\frac{U}{\sqrt{3}} \cdot e^{-j\frac{\pi}{6}} \cdot e^{-j\frac{2\pi}{3}}$$

$$\overline{U_{cs}} = \frac{\sqrt{2}\cdot U}{\sqrt{3}} \cdot e^{-j\frac{\pi}{6}} \cdot e^{-j\frac{4\pi}{3}}$$

nesimetrični 3-fazni sustav rastavljamo u 3 simetrična trofazna sustava (direktni, inverzni i nulti)

kasnijenje faze b kasnijenje faze c

$$\overline{U_{sr}} = \frac{1}{3}\left[\frac{\sqrt{2}\cdot U}{\sqrt{3}} \cdot e^{-j\frac{\pi}{6}}\left(1 + \underbrace{e^{j\frac{2\pi}{3}}}_{a} \cdot e^{-j\frac{2\pi}{3}} + \underbrace{e^{j\frac{4\pi}{3}}}_{a^2} \cdot e^{-j\frac{4\pi}{3}}\right)\right]$$

$$= \frac{\sqrt{2}}{\sqrt{3}}\, U \cdot e^{-j\frac{\pi}{6}}$$

(direktna komponenta gleda u smjeru faze a)

za simetrični sustav

$$\overline{U_{sn}} = 0$$

$$e^{j\omega t} = \cos(\omega t) + j\sin(\omega t)$$

$\overline{U_{sr}}$ okreće sinkrono

$$\overline{U_{d_{\alpha\beta}}^{s}} = \frac{\sqrt{2}}{\sqrt{3}} \cdot U \cdot e^{-j\frac{\pi}{6}} \cdot e^{j\omega_s t}$$

$$= \sqrt{\frac{2}{3}} \cdot U \cdot e^{j(\omega_s t - \frac{\pi}{6})} = \sqrt{\frac{2}{3}} \cdot 400 \cdot e^{j(\omega_s t - \frac{\pi}{6})} = 326.6 \cdot e^{j(\omega_s t - \frac{\pi}{6})}$$

$$\overline{U_{d_{\alpha\beta}}^{s}} = \underbrace{U_{d_s}^{s}}_{real} + j\,\underbrace{U_{q_s}^{s}}_{imag} \Rightarrow \quad \overline{U_{d_s}^{s}} = 326.6 \cdot \cos\left(\omega_s t - \frac{\pi}{6}\right)$$

$$\overline{U_{q_s}^{s}} = 326.6 \cdot \sin\left(\omega_s t - \frac{\pi}{6}\right)$$

5) sinkroni koordinatni sustav

$$\boxed{\overline{U_{d_{dq_s}}} = \overline{U_{d_{\alpha\beta_s}}^{s}} \cdot e^{-j(\omega_s t - \frac{\pi}{6})}}$$

ako su 2 ks u fazi nema ovog člana

$$\overline{U_{d_{dq_s}}} = \sqrt{\frac{2}{3}} \cdot e^{j(\omega_s t - \frac{\pi}{6})} \cdot e^{-j(\omega_s - \frac{\pi}{6})}$$

$$= \sqrt{\frac{2}{3}} \cdot U = 326.6\ V$$

sinkron. ks dobijemo iz statorskog ako ga pomnožimo s $e^{-j(\omega_s t + \varphi(\text{sinh. ks, stat. ks}))}$

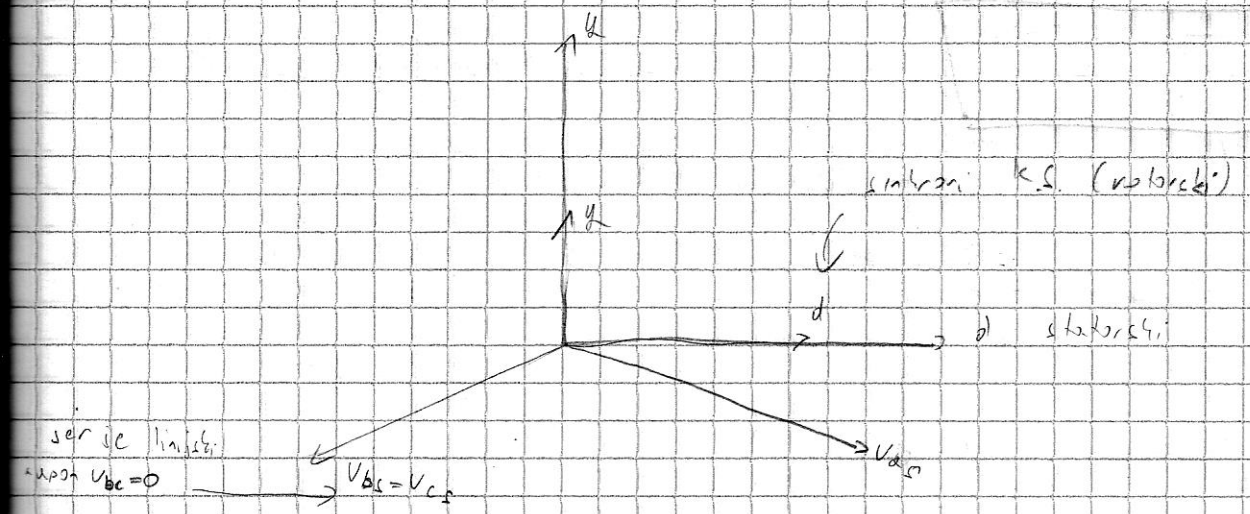
$V_{dS} = 326.6\,V$ (realna vrij.)

$V_{qS} = 0\ V$ (imaginarna vrij.)

d komponenta statora u sinkronom k.s.

2.2.

$V_{ab} = V_{ac}$ i $V_{bc} = 0$ fazor a zaostaje $\angle -30°$ u odnosu na statorski k.s., za rotorski k.s. d-os je u d-osi statorskog k.s.



$$\overline{V_{sn}} = \frac{1}{3}\left(V_{as} + a^2 \cdot V_{bs} + a \cdot V_{cs}\right) = 188.56$$

$$\overline{V_{dq}^s} = 188.56 \cdot e^{j\omega_s t} - 188.56\, e^{-j\omega_s t}$$

$$\overline{V_{d_s}^s} = 377.12 \cdot \cos(\omega_s t)$$

$$\overline{V_{q_s}^s} = 0$$

b) sinkroni koordinatni sustav

$$\boxed{\overline{V_{dq_s}} = \overline{V_{dq_s}^s} \cdot e^{-j\omega_s t}}$$

sinkroni koordinatni sustav

$$= \left(188.56 \cdot e^{j\omega_s t} + 188.56\, e^{-j\omega_s t}\right) \cdot e^{-j\omega_s t}$$

$$= 188.56 \cdot \left(1 + e^{-2j\omega_s t}\right)$$

$$V_{ds} = 188.56 \cdot \left(1 + \cos(2\omega_s t)\right)$$

nije više konstantna vrijednost

$$V_{qs} = -188.56 \sin(2\omega_s t)$$

11. auditorne vježbe

2.4 $P_{2n} = 100\,kW$ $U_n = 400\,V$ $f_n = 50\,Hz$ $2p = 4$

$r_s = 0.015$ $x_{\sigma s} = 0.09$ $r_r' = 0.017$ $x_{\sigma r}' = 0.08$ $x_m = 3.2$

$P_B = P_{2n} = 100\,kW$

$U_B = \frac{400}{\sqrt{3}} = 230\,V$

$I_B = \frac{P_B}{3U_B} = 144.33$

$\omega_B = 2\pi f = 100\pi$ rad/s

$\omega_{mB} = \frac{\omega_B}{p} = 157.08$ rad/s

$Z_B = \frac{U_B}{I_B} = 1.6\,\Omega$ $Z_B = \frac{3U_{fn}^2}{P_{2n}}$

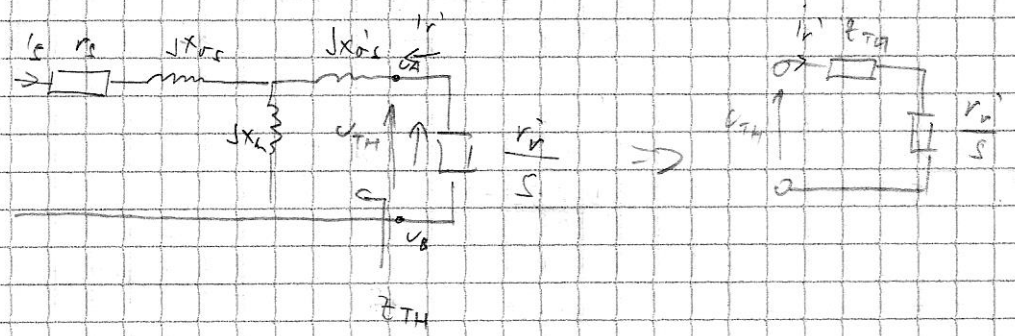
$M_B = \frac{P_B}{\omega_{mB}} = 636.6$ Nm

$Z_B = \frac{U_B}{I_B} = 1.6\,\Omega$

$M_B = \frac{P_B}{\omega_{mB}}$

$M_B \neq M_n$

a)



$$Z_{TH} = jx_{\sigma r}' + \frac{jx_m \cdot (r_s + jx_{\sigma s})}{jx_m + r_s + jx_{\sigma s}} = 0.172 \angle 85.45$$

$$= 0.0142 + j0.1776$$

$U_s = 1 \angle 0°$

$U_{TH} = U_{AB}$

$$U_{TH} = \frac{jX_m}{jX_m + jX_{\sigma s} + r_s} \cdot U_s = 0.9726 \angle 0.26°$$

(bilo bi moment u AM moženo proglasiti nativni, i onda za taj moment računamo nativno klizanje

$$M_n = |I_r'|^2 \cdot \frac{r_r'}{s_n} = \frac{1}{1 - s_n}$$

$$I_r' = \frac{|U_{TH}|}{\sqrt{\left(r_{TH} + \frac{r_r'}{s_n}\right)^2 + X_{TH}^2}}$$

Z_{TH} nastavimo na r_{TH} i X_{TH}

$$\frac{U_{TH}^2}{\left(R_{TH} + \frac{r_r'}{s_n}\right)^2 + X_{TH}^2} \cdot \frac{r_r'}{s_n} = \frac{1}{1 - s_n}$$

$$= 0.0478 \cdot s_n^2 - 0.0156\, s_n + 2.84 \cdot 10^{-4} = 0$$

$$\underline{s_n = 0.0197}$$

$$M_n = \frac{1}{1 - s_n} = \frac{1}{1 - 0.0197} = 1.02 \text{ p.u}$$

$$\omega_{rmn} = 1 - s = 1 - 0.0197 = 0.9803 \text{ p.u}$$

$$Z = r_s + jX_{\sigma s} + \frac{jX_m \cdot \left(jX_{\sigma r}' + \frac{r_r'}{s_n}\right)}{jX_m + jX_{\sigma r}' + \frac{r_r'}{s_n}} = 0.8657 \angle \underbrace{25.88°}_{\varphi_n}$$

$$I_s = \frac{|U_s|}{Z} = \frac{1}{0.8657} = 1.155$$

$$\cos \varphi_n = \cos(25.88°) = 0.9$$

$$M_n = M_B \cdot M_{n(p.u)} = 1.02 \cdot 636.6 = 649.3 \text{ Nm}$$

jesto dobar ✓ ispitna

$$\omega_{rmn} = \omega_{mB} \cdot \omega_{rmn(p.u)} = 157.08 \cdot 0.9803 = 153.98 \text{ rad/s}$$

$$|I_{sn}| = I_B \cdot |I_{sn}|_{p.u} = 144.93 \cdot 1.155 = 167.4 \text{ A}$$

$$a = \frac{X_{sn}}{X_n} \cdot \frac{\left(\frac{\omega_s \cdot f_{ns}}{\omega_r \cdot f_{nr}}\right)^2}{\left(\frac{\omega_s \cdot f_{ns}}{\omega_r \cdot f_{nr}}\right)^2} = \frac{X_m \cdot \frac{\omega_r \cdot f_{nr}}{\omega_s \cdot f_{ns}} \cdot \left(\frac{\omega_s \cdot f_{ns}}{\omega_r \cdot f_{nr}}\right)^2}{X_r'}$$

X_{sn}, X_r'

$$\boxed{a = \frac{X_m}{X_r'} \cdot \frac{\omega_s \cdot f_{ns}}{\omega_r \cdot f_{nr}}}$$

a tub si inel rasporenie

A2 - odibrne

$$a X_{sn} = \frac{X_m}{X_r'} \cdot \frac{\omega_s \cdot f_{ns}}{\omega_r \cdot f_{nr}} \cdot X_{sn} = \frac{X_m}{X_r'} \cdot \frac{\omega_s f_{ns}}{\omega_r f_{nr}} \cdot \frac{3}{2} k \left(\omega_s \cdot f_{ns} \cdot \omega_r f_{nr}\right)$$

$$= \frac{X_m}{X_r} \cdot \frac{3}{2} k \left(\omega_s f_{ns}\right)^2 = \frac{X_m^2}{X_r}$$

$$\frac{a^2 r_r}{s} = \left(\frac{X_m}{X_r'}\right)^2 \left(\frac{\omega_s \cdot f_{ns}}{\omega_r \cdot f_{nr}}\right)^2 \cdot \frac{r_r}{s} = \frac{r_r'}{s} \left(\frac{X_m}{X_r'}\right)^2$$

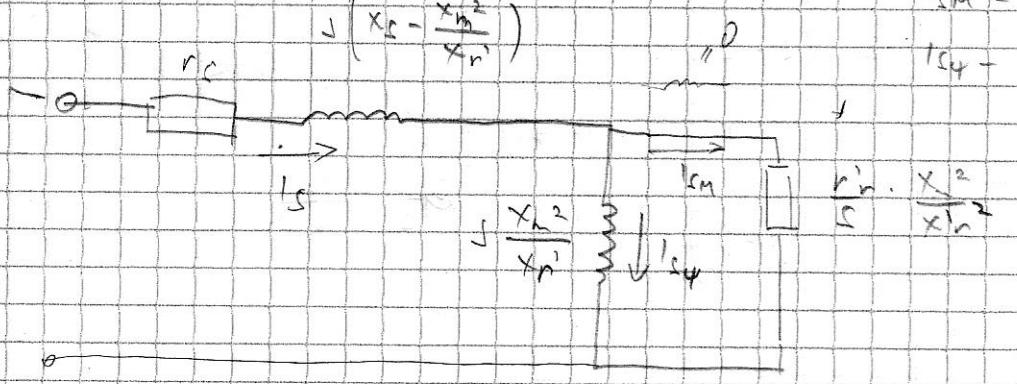
r_r'

$$\boxed{X_r' = X_{\sigma r}' + X_m} = 0.1 + 3 = 3.1 \text{ p.u}$$

$$\boxed{X_s = X_{\sigma s} + X_m} = 0.1 + 3 = 3.1 \text{ pu}$$

I_{sm} - komponenta struje koja teče u mreži

$I_{s\psi}$ - -||- I_{0s}



$f = 1$ p.u.

$$M_n = \frac{1}{1-s_n} = \frac{1}{1-0.0177} = \underline{1{,}018}$$

$$M_n = |I_{sMn}|^2 \cdot \underbrace{\frac{r_r'}{s_n}\frac{X_m^2}{X_r'^2}}_{\text{otporniki}} \Rightarrow I_{sMn} = \frac{X_r'}{X_m}\sqrt{M_n \frac{s_n}{L_r'}} = 1.1326$$

! • Moment odgovara struji I_{sM}

$$|Z| = \left| r_s + j\left(X_s - \frac{X_m^2}{X_r'}\right) + \frac{j\frac{X_m^2}{X_r'}\cdot\frac{r_r'}{s_n}\left(\frac{X_m^2}{X_r'}\right)}{j\frac{X_m^2}{X_r'} + \frac{r_r'}{s_n}\left(\frac{X_m^2}{X_r'}\right)} \right| = 0.8524 \text{ (p.u)}$$

$$\underline{I_{sn}} = \frac{|U_s|}{|Z|} = \frac{1}{0.8524} = 1.173 \text{ p.u.}$$

$$\underline{I_{s\varphi n}} = \sqrt{|I_{sn}|^2 - (I_{sMn})^2} = \sqrt{1.173^2 - 1.1326^2} = 0.3056 \text{ p.u.}$$

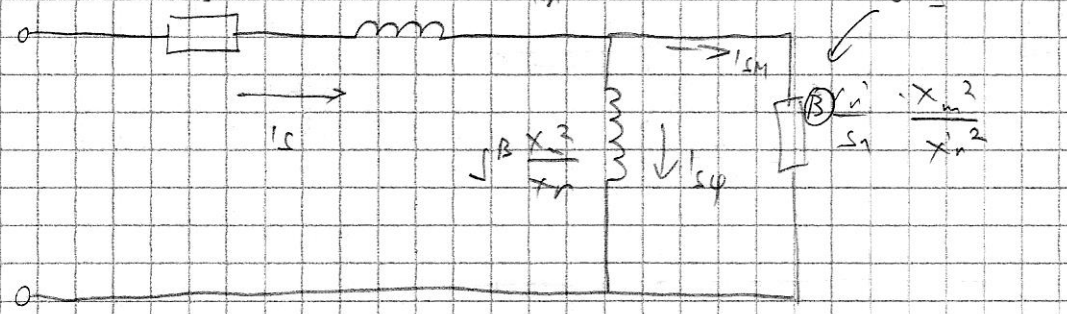
za $f = 0.25$ p.u $= B$

p.u vrijednosti $\Rightarrow$ vrijednosti za nazivnu frekvenciju

$X_{pu,\, f=B} = B \cdot X_{pu,\, f=f_n}$

sve reaktancije množiti sa B

! za vekt. upravl. f_r = konstanta $\Rightarrow s_n \cdot 1 = s \cdot B$ $\quad s = \frac{s_n}{B}$



$$M = M_n = \frac{|I_{sn}|^2 \cancel{B}\,\frac{r_r'}{s_n}\cdot\frac{X_m^2}{X_r'^2}}{\cancel{B}} = \left(\frac{P_{0\xi}}{\omega_s}\right)$$

$$= |I_{sn}|^2 \cdot \frac{r_r' X_m^2}{s_n \cdot X_r'^2} \Rightarrow I_{sM} = I_{sMn} = 1.132 \text{ p.u.}$$

! $M_{,\, f=B} = M_n \Rightarrow I_{sM,\, f=B} = I_{sM}$

$|I_{s\psi}| = |I_{s\psi n}| = 0.03056$ p.u (u trodelu: tok mora ostati isti za $f=1$, $f=0.25$)

$$|I_s| = \sqrt{|I_{sm}|^2 + |I_{s\psi}|^2} = 1.173 \text{ p.u}$$

- promjenom f:
- $\overline{I_s}, \overline{I_{sm}}, \overline{I_{s\psi}}$ ostaju isti
- mijenja se $|Z|$ (smanjuje se) => struja je i $|U_s|$ manji

$$|Z| = \left| r_s + jB\left(x_s - \frac{x_m^2}{x_r'}\right) + \frac{j \cdot B \frac{x_m^2}{x_r'} \cdot \frac{r_r'}{s_n} \cdot B \cdot \left(\frac{x_m}{x_r'}\right)^2}{j \cdot B \cdot \frac{x_m^2}{x_r'} + B \cdot \frac{r_r'}{s_n} \cdot \left(\frac{x_m}{x_r'}\right)^2} \right|$$

$$= 0.2231 \text{ p.u}$$

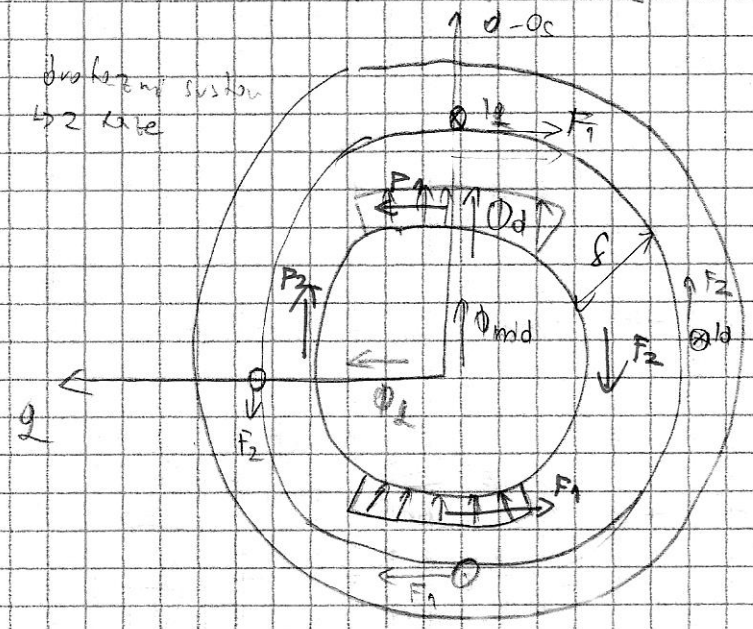
$$|U_s| = |I_s| \cdot |Z| = 1.173 \cdot 0.2231 = 0.2617 \text{ p.u}$$

12 a.d.bere 23 min

Sinkron. motori s trajnim magnetom (SPMP)

$\vec{F} = L \times \vec{B}$

dvoosni sustav
↳ 2 kate



$\delta = konst$ $\mu_{PM} \approx 1$

d su magneti d-os
q-os prolaziti d-osi

Sile na rotor
↳ sile na stator s obrnutim predznakom (akcija)

doprinos toku: magnet i trajnica

zbroj toka magneta i armature

$$M = (\overbrace{w \cdot f_n \cdot \Phi_{dvq}}^{\psi} \cdot I_q - \overbrace{w \cdot f_n \cdot \Phi_{qvd}}^{\psi} \cdot I_d) \cdot p \cdot \frac{3}{2}$$

✓ sinusoidi, inv. 3 faze a ne 2

$$M = \frac{3}{2} p \cdot (\psi_d \cdot I_q - \psi_q \cdot I_d)$$

cilj: inverz toka → pustiti struju
↓
dobijemo silu

$$\begin{cases} \psi_d = \psi_{md} + I_d \cdot L_d \\ \psi_q = I_q \cdot L_q \end{cases}$$

$$M = \frac{3}{2} p \left[(\psi_{md} + L_d \cdot I_d) I_q - (L_q \cdot I_q) I_d \right]$$

$E_0 = w \cdot \psi_{md}$

$X_d = w \cdot L_d$

$X_q = w \cdot L_q$

kod motora s PM ne treba nam struja u d-osi jer imamo permanentne magnete koji stvaraju tok

$$\boxed{M = \frac{3}{2} \frac{p}{w_s} \left[\underbrace{E_0 \cdot I_{qs}^r}_{\text{sinkroni moment}} + \underbrace{(X_d - X_q) I_{ds}^r \cdot I_{qs}^r}_{\text{reluktantni moment}} \right]}$$

$i_d = I_s \cdot \sin\gamma$

$\gamma = \measuredangle(I_s, y\text{-osi})$

$I_q = I_s \cdot \cos\gamma$

$X_s = \sqrt{I_d^2 + I_q^2}$

$$\boxed{M = \frac{3}{2} \cdot \frac{p}{\omega_s} \left[E_0 \cdot I_s \cdot \cos\gamma + \frac{1}{2} \cdot (X_d - X_q) \cdot I_s^2 \cdot \sin 2\gamma \right]}$$

(PM: $L_d = L_q$ (magneti na površini rotora)

$I_d = 0$ do $\omega = \omega_n$

$M \sim I_q$

(ako sinkroni motor)

IPM: (magneti ubačeni u jezgru rotora)

$L_d < L_q$

sinkroni + reluktantni

MTPA: $\gamma_{opt} < 0$

Maximum torque per ampere

Objašnjenje

E_0 - inducirani napon u armaturi stroja kod praznog hoda

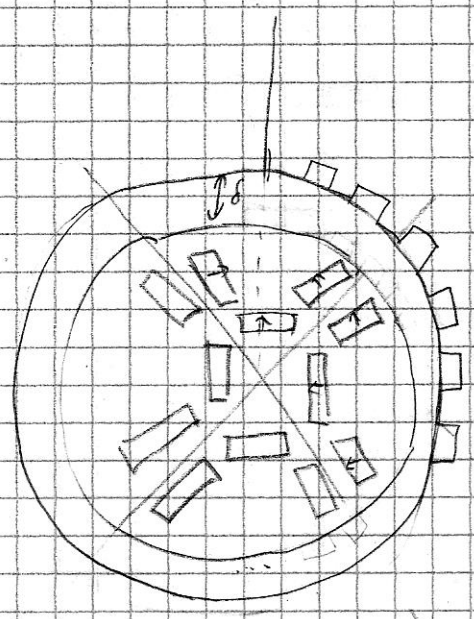
13. Aud. torque SMPM

SPM – mag na powierzchni rotora

przenikalność względna magnesu 1.05

$L_d = L_q$

IPM



$L_q > L_d$

$$\boxed{U_d = R_c \cdot I_d - X_q I_q}$$

$$\boxed{U_q = I_s R_c + X_d I_d + E_0}$$

$$\boxed{E_0 = \omega \cdot \Psi_{md}}$$

bez tej stałej magnes tad nema drugich pobudz

$X_q = \omega L_q$

$X_d = \omega L_d$

$X_{du} = \omega X_{dn}$

$X_{qu} = \omega \cdot X_{qn}$

1.1. 150 kW

400 V

50 Hz

$2p = 4$

$R_s = 0.03$ $X_{\sigma s} = 0.03$ $X_{md} = 0.2$ $X_{mq} = 0.5$ $U_s = 1$

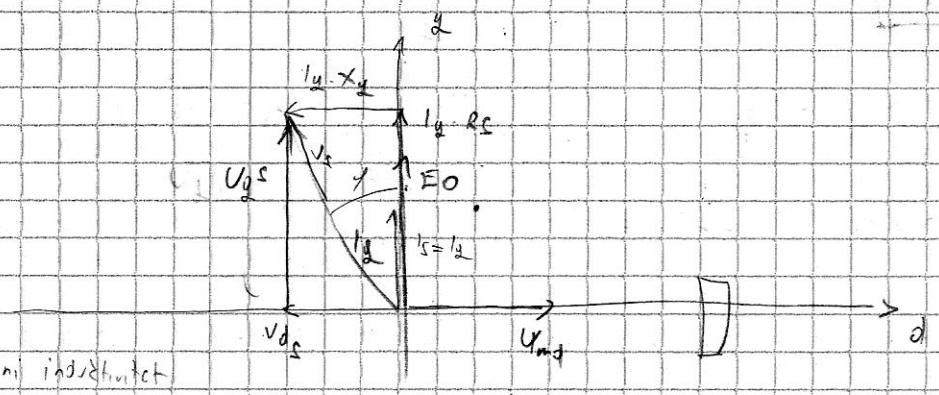
$\underbrace{\qquad\qquad\qquad\qquad}_{\text{svi vrednosti stroja p.u.}}$

$\underset{\cdot}{t}$ i $\underset{\cdot}{q}$-osi

a) $I_d = 0$ $(\gamma = 0)$

$I_s = I_q$

$M = ?$ $\cos\varphi = ?$ $E_0 = ?$ za $f = 1$ i $U = 1$ p.u.



X_σ – rasipni induktivitet

$$\boxed{X_d = X_{md} + X_{\sigma s}} = 0.2 + 0.05 = 0.25 \text{ p.u.}$$

$$\boxed{X_q = X_{mq} + X_{\sigma s}} = 0.5 + 0.05 = 0.55 \text{ p.u.}$$

} IPM

$$E_0 = \sqrt{U_s^2 - (I_q \cdot X_q)^2} - I_s \cdot R_s$$

$$\sqrt{1 - (1 \cdot 0.55)^2} + 1 \cdot 0.03 = 0.805 \text{ p.u.}$$

$$M = \underbrace{\frac{1}{\omega} E_0}_{U_{md}} \cdot I_q = \frac{1}{1} \, 0.805 \cdot 1 = 0.805$$

$$\cos\varphi = \frac{E_0 + I_q \cdot R_s}{U_s} = \frac{0.805 + 1 \cdot 0.03}{1} = 0.835$$

b) $I_s = 1$

I_d, I_q, γ za maksimalni moment M_{max}

<0

$$M = \frac{1}{m}\left[\underbrace{E_0 \cdot I_s \cdot \cos\gamma}_{\text{sinkroni } M} + \underbrace{\frac{1}{2}(X_d - X_q)\, I_s^2 \cdot \sin 2\gamma}_{\text{reluktantni } M}\right]$$

zašto ne

3.P 777 γ - kut između struje i q-osi

kod IPM možemo dio M dobiti na račun reluktantnog momenta!

MTPA (max torque per ampere), ali ne slijedi kao SPM-a sam je $X_d = X_q$

$$\boxed{\frac{dM}{d\gamma} = 0}$$

$$\frac{dM}{d\gamma} = \frac{1}{m}\cdot\left(-E_0 \cdot I_s \sin\gamma + (X_d - X_q)\, I_s^2 \cdot \cos 2\gamma\right)$$

<0

$\cos(2\gamma) = \cos^2\gamma - \sin^2\gamma = 1 - 2\sin^2\gamma$ $\qquad \sin^2(x) = 2\sin(x)\cos(x)$

$$2(X_d - X_q)\, I_s^2 \cdot \sin^2\gamma + E_0 I_s \sin\gamma - (X_d - X_q)\, I_s^2 = 0$$

$$0.6 \sin^2\gamma - 0.805 \sin\gamma - 0.3 = 0$$

$$\sin\gamma = -0.3049 \Rightarrow \gamma = -17.61$$

! γ nema veći sl. manji od 0 za max M

$$M_{em} = \frac{1}{m}\left[E_0 I_s \cos\gamma + \frac{1}{2}(X_d - X_q)\sin 2\gamma\right] = \ldots = 0.8533$$

$I_d = I_s \cdot \sin\gamma = -0.3049$ (- za motorski R.R)

$I_q = I_s \cdot \cos\gamma = 0.9527$ (+ za motorski R.R)

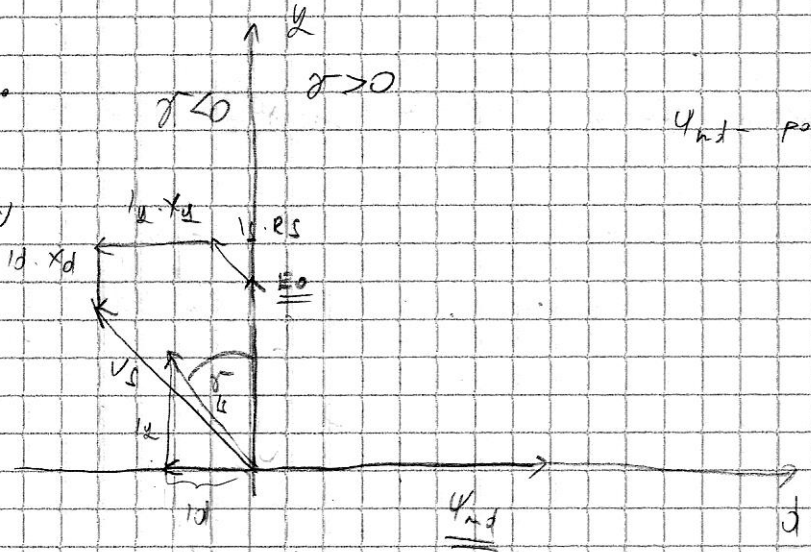
$$V_s = \sqrt{\underbrace{(E_0 + I_q \cdot R_s - I_d \cdot X_d)^2}_{V_q} + \underbrace{(I_d \cdot R_s - I_q \cdot X_q)^2}_{V_d}} = \ldots = 0.9264$$

I faznog napona

motorski rad: $I_d < 0$

$I_q > 0$

Id ponešto za 90° zbog Xd



Ψ_{md} – polje permanentnog magneta

- magnet stvara polje u d-osi
- za $I_d < 0$ slabi se polje magneta, ujedno iskorištavamo reluktantni moment

$$\boxed{E_0 = \omega \cdot \Psi_{md}}$$

U_s želimo postaviti kako god hoćemo pomoću frekvenc. pretvarača
↳ pomoću U_s upravljamo strujama na Id i Iq

smanjenje Ψ želimo poveć[illegible]

uli imamo manji Id tj. manji moment

Ψ ↓ s Id<0 a time ω(n) ↗

nedostatak: manji Id → manji M

↳ ako stavimo struju u negativnu d-os da bi smanjili Ψ i povećali brzinu, manje struje nam ostaje za Iq pa time imamo manji moment

↳ nikad se ne stavlja struja u q-os Iq>0 (dobili bi reluktantni moment u suprotnu stranu od smjera)

dobra strana IPM-a: slabimo polje i iskorištavamo M reluktantno u isto vrijeme

12 SPM 120 Hz

12 kW, 400 V, 28 A, ~~50 Hz~~, 2p = 8 $n_n = 1800\ min^{-1}$

$L_d = L_q = 2.6\ mH$ SPM

statorski otpor zanemariti $X_q = X_d$

a) $X_d = ?$ v p.u.

$S_B = \sqrt{3}\ U_n \cdot I_n = \sqrt{3} \cdot 400 \cdot 28 = 19\,399\ VA$

$V_B = \frac{U_n}{\sqrt{3}} = \frac{400}{\sqrt{3}} = 230\ V$ (bazni napon fazni napon)

$I_B = \frac{S_B}{3 \cdot V_B} = \frac{19\,399}{3 \cdot 230} = 28\ A$

$f = \frac{p \cdot n}{60} = \frac{4 \cdot 1800}{60} = 120\ Hz$

X_d kod SPM-a rel. mali jer je struja napon velik (u zr. nas se koristi smjesta nazivna)

$\omega_B = 2\pi f = 2\pi \cdot 120 = 754\ rad/s$

$Z_B = \frac{U_B}{I_B} = \frac{230\ V}{28\ A} = 8.2478\ \Omega$

$\boxed{X_d = \frac{L_d \cdot \omega_B}{Z_B}} = 0.2377$ p.u. $\boxed{X_q = \frac{L_q \cdot \omega_B}{Z_B}}$

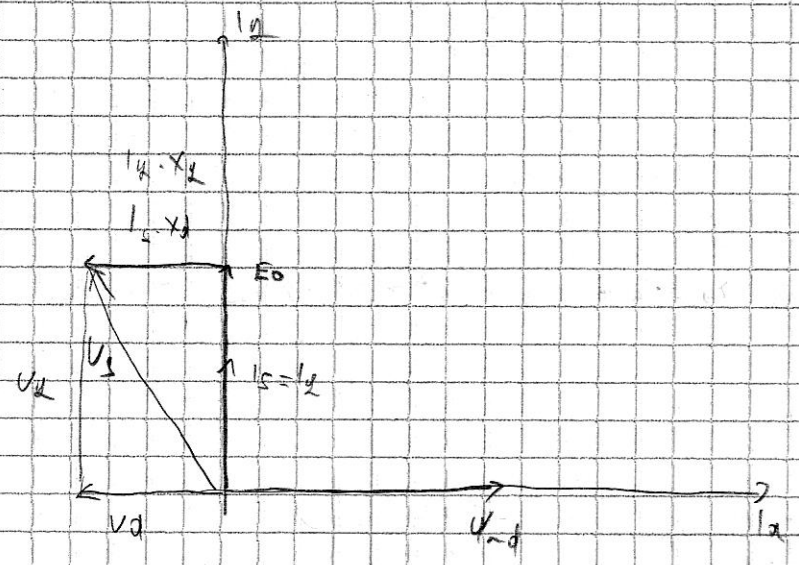
baze vrijednosti za lakšu preračunavanje iz stvarnih vrijednosti u pu

b) $I_{ds} = 0$ $\gamma = 0$

$I_s = I_q$

$E_0 = ?$ $M = ?$

sincrono



$$E_0 = \sqrt{U_s^2 - (I_q \cdot X_d)^2} = \sqrt{1 - 1 \cdot 0.2377} = 0.9713$$

(ako je $m = 1$, $\Psi_{md} = 0.9713$ pu)

$$M_{em} = \frac{E_{0n} \cdot I_q}{m} = 0.9713$$

$$M = \Psi_{md} \cdot I_q$$

$$E_0 = \Psi_{md} \cdot \omega_e \Rightarrow \Psi_{md} = \frac{E_0}{\omega}$$

c) Izbljeđenje polja: I_d, I_q?

$$E_0 = \Psi_{md} \cdot \omega_e$$

$\omega \nearrow$: $E_0 \nearrow$

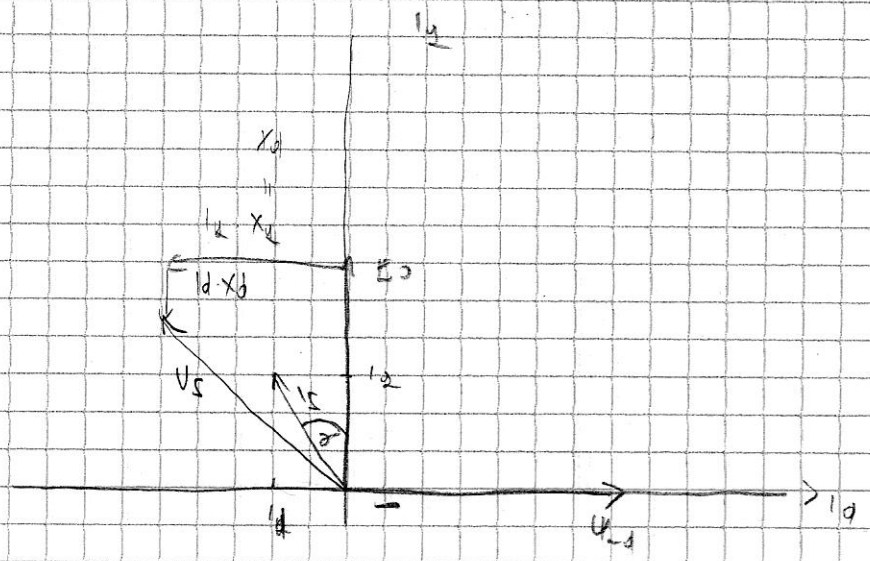
$n = 2430$ o/min

$$\omega = \frac{\omega_m}{\omega_{mB}} = \frac{n}{n_n} = \frac{2430}{1800} = 1.35 \text{ pu}$$

$$E_{0\omega} = E_{0n} \cdot \omega = 0.9713 \cdot 1.35 = 1.311 \text{ p.u.}$$

(nazivna prostorna brzina)

$$X_{d\omega} = X_{dn} \cdot \omega = 0.2377 \cdot 1.35 = 0.3209 \text{ pu}$$



$$V_s = E_{0w} + I_d \cdot X_{dw}$$

$$I_s^2 = I_d^2 + I_q^2 \quad \Rightarrow \quad I_q^2 = I_s^2 - I_d^2$$

$$V_s = E_{0w}^2 + 2\, E_{0w}\, X_{dw}\, I_d + X_{dw}^2\, I_d^2 + \left(I_s \cdot X_{dw}\right)^2 - X_{dw}^2 \cdot I_d^2$$

$$I_d = -0.9766$$

$$I_d = \frac{V_s^2 - E_{0w}^2 - (I_s \cdot X_{dw})^2}{2\, E_{0w}\, X_{dw}} = -0.9766 \text{ p.u.}$$

$$I_q = \sqrt{I_s^2 - I_d^2} = \sqrt{1 - 0.9776^2} = 0.215 \text{ p.u}$$

$$M = \frac{E_{0w} \cdot I_q}{w} = \frac{1.1311 \cdot 0.215}{1.35} = 0.209 \text{ p.u}$$

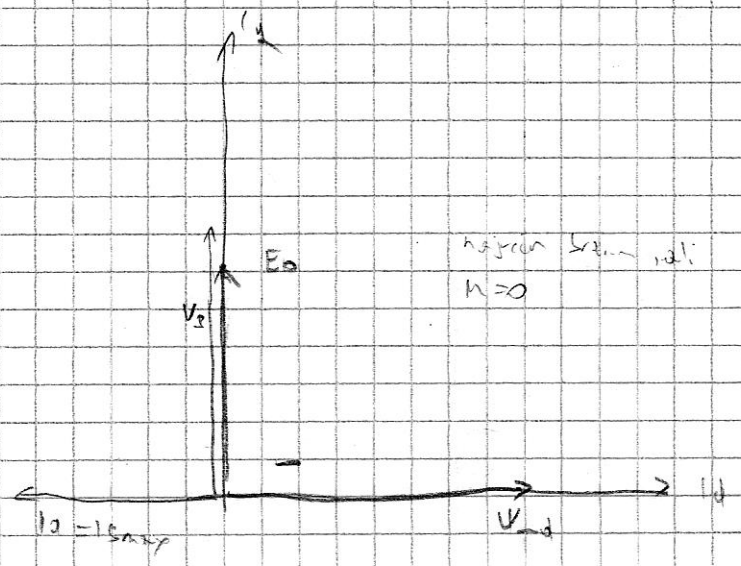
na velikoj brzini imamo manji M

1.5.) $E_0 = 0.8$ p.u. $\quad X_d = 0.4$ p.u $\quad R_s = 0.05$ p.u $\quad X_q = 0.04$ p.u $\quad w_s = 1$ p.u

$V_s = 1$ p.u. $\quad I_{s_{max}} = 1.25$ p.u

a) $\gamma = 0$ $\quad w_{max} = ?$

nemoćno slabit polje

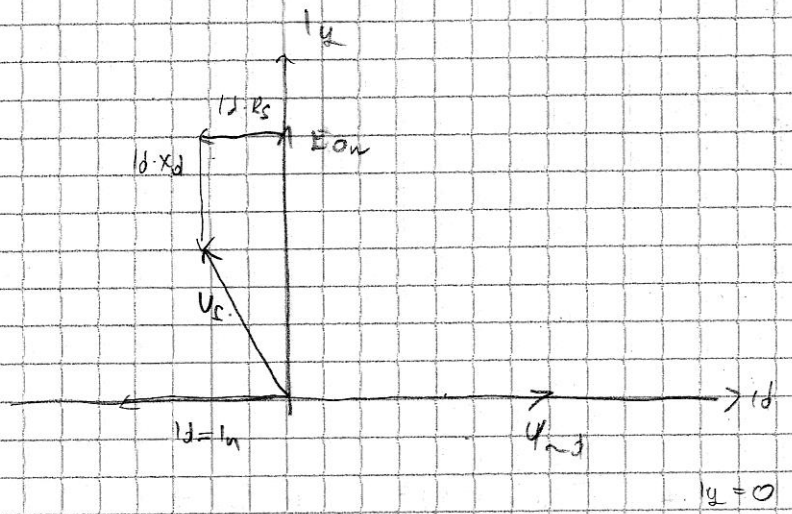


$U_{max} = E_{0n} = E_0 \cdot w_{max}$

$$w_{max} = \frac{U_s}{E_0} = \frac{1}{0.8} = 1.25 \text{ pu} \Rightarrow n = 0$$

c) najveća moguća brzina u praznom hodu σ to w_{max}

→ slabimo polje maksimalno



$$(E_{0w})^2 - (I_d \cdot X_{dw})^2 + (I_d \cdot R_s)^2 = U_s^2$$

$E_{0w} = E_{0n} \cdot w$

$X_{dw} = w \cdot X_{dn}$

$$w^2 (E_0 - I_d \cdot X_d)^2 + (I_d R_s)^2 = U_s^2$$

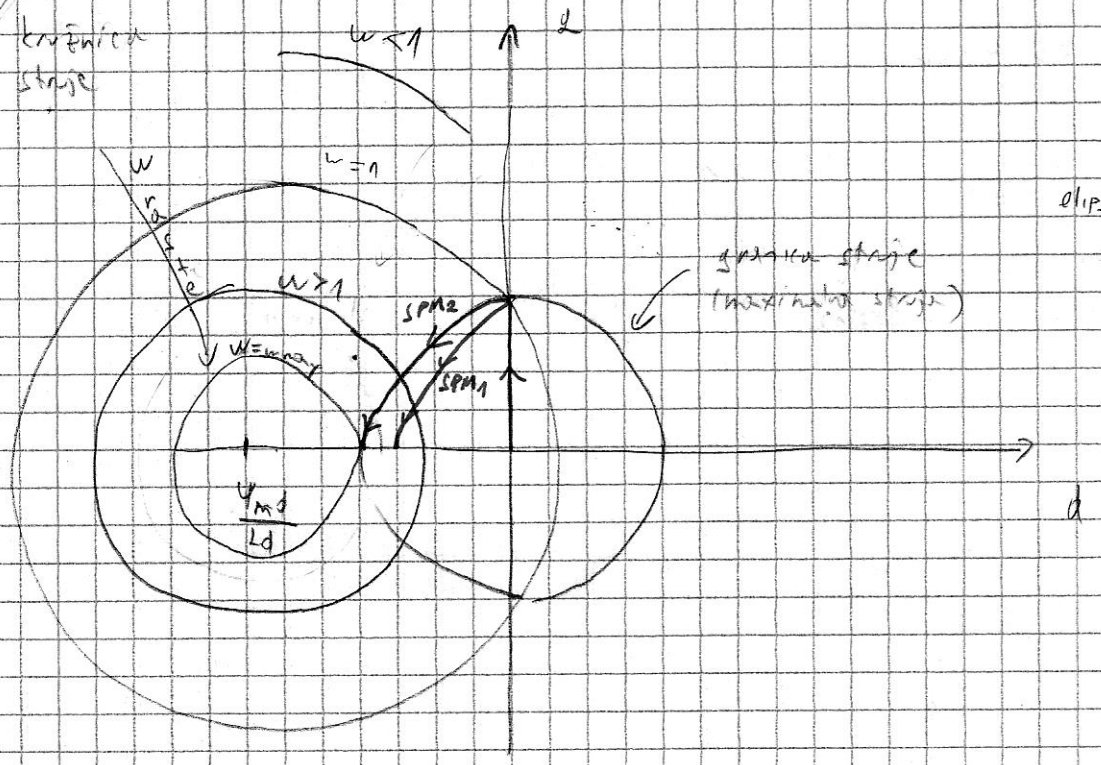
$$w = \frac{\sqrt{U_s^2 - (I_d \cdot R)^2}}{E_0 - I_d X_d} = \frac{\sqrt{1^2 + (1.25 \cdot 0.05)^2}}{0.8 - 1.25 \cdot 0.4} = 3.33 \text{ pu}$$

kružnica struje

SPM

$L_d = L_q$ $(\xi = 1)$

elipsa prelazi u kružnicu



ω^2 skraćuju u nazivniku nazivnika

$\rightarrow I_s^2 = I_d^2 + I_q^2$

$\rightarrow V_{s\,max}^2 = V_d^2 + V_q^2 = \omega^2 (L_q I_q)^2 + \omega^2 (\psi_{md} + I_d L_d)^2 \quad / V_{s\,max}$

transformirano statorski otpor RS

$$1 = \frac{(L_q \cdot I_q)^2}{\frac{V_{s\,max}^2}{\omega^2}} + \frac{(\psi_{md} + I_d L_d)^2}{\frac{V_{s\,max}^2}{\omega^2}}$$

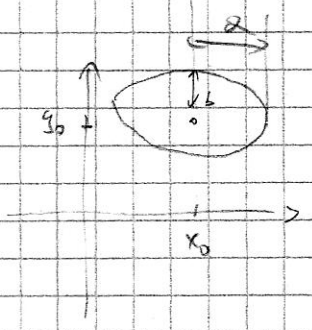
(L_d skraćuju u nazivniku nazivnika)

I_c – karakteristična struja

$$\frac{\left(I_d + \frac{\psi_{md}}{L_d}\right)^2}{\frac{V_{s\,max}^2}{\omega^2 L_d^2}} + \frac{(I_q + 0)^2}{\frac{V_{s\,max}^2}{\omega^2 L_q^2}} = 1$$

(jednadžba elipse)

x, x_0, y, y_0



x_0, y_0 – koord. središta

$$\frac{x - x_0}{a^2} + \frac{y - y_0}{b^2} = 1$$ jed. elipse

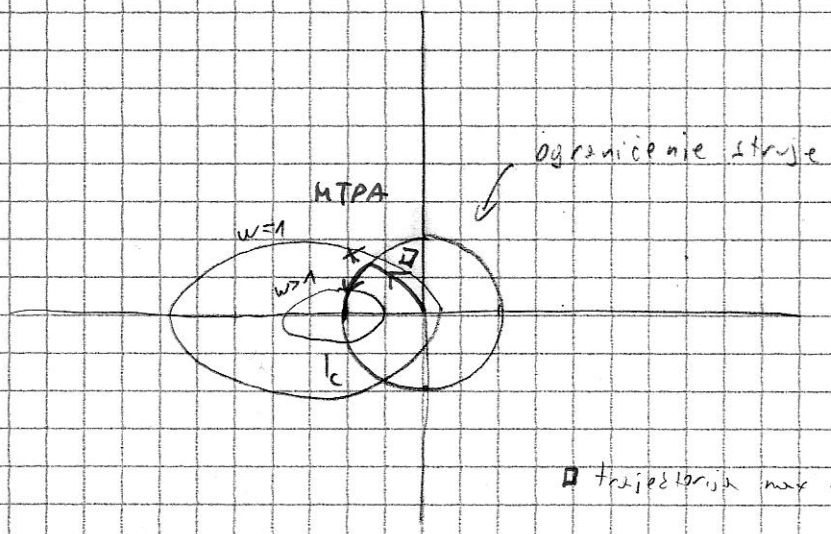
SPM: – I_c uvijek veći od 1

↳ kuli L_d velik ψ_{md} lagano slabiti struju, da se može ići do beskonačne brzine

IPM

MTPA nije ovisna o ω

- $I_c = 1$



$I_c = \frac{\psi_{md}}{L_d} = 1$

* trajektorija struje u režimu slabljenja polja

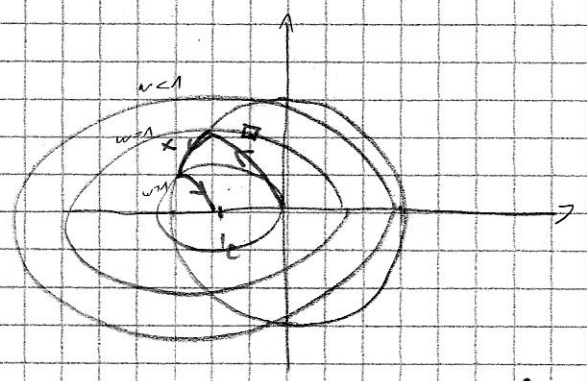
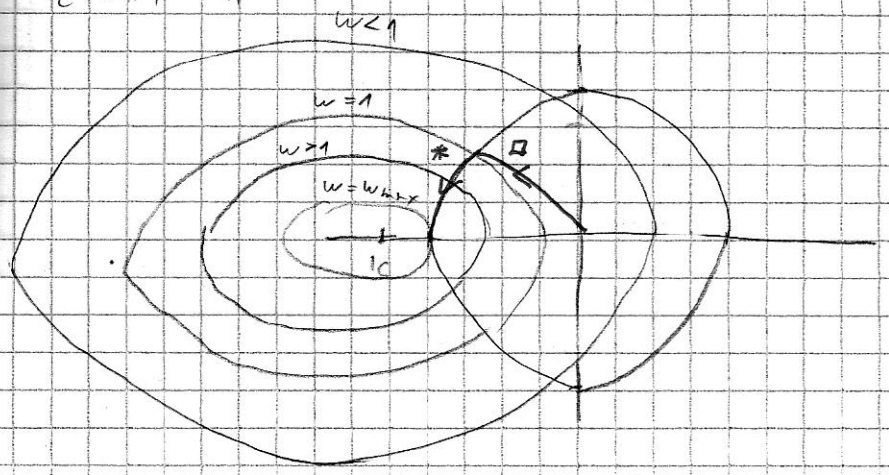
□ trajektorija max okretnog momenta i struje

općenito

IPM nisko ograničili s brzinom → lošiko ići na "proizvoljne" brzine
→ npr 20 000 rpm (prednost IPM-ova)
↳ kako struja bude jednaka ili manja kružnice struje

IPM - ograničenje struje promjera 1 sa središtem u k.s (uvijek)

$I_c = 0.6 < 1$



$I_c = 1.4 > 1$