Zadatak 1

Neki elektroenergetski sustav (50 Hz) sastoji se od 5 elektrana s karakteristikama prema tablici 1. Ovaj sustav može se aproksimirati s dinamičkim modelom prema slici 1 u kojem su sve termoelektrane, hidroelektrane i potrošači agregirani u jedan stroj ukupne konstante tromosti H i regulacijske energije potrošnje $D = 2$ p.u.. Agregirani sustav sastoji se od jedne ekvivalentne parne turbine s pregrijanjem pare i jedne ekvivalentne hidroturbine s ekvivalentnim statičnostima σ_T i σ_H. Potrebno je:

a) Odrediti ukupnu konstantu tromosti sustava u normalnom pogonskom stanju.

b) Odrediti ekvivalentnu statičnost sustava u normalnom pogonskom stanju.

c) Izvesti izraz za odstupanje frekvencije u Laplaceovoj domeni i izračunati odstupanje frekvencije u stacionarnom stanju nakon ispada elektrane E3 koja je prije ispada radila s 50% nazivne snage.

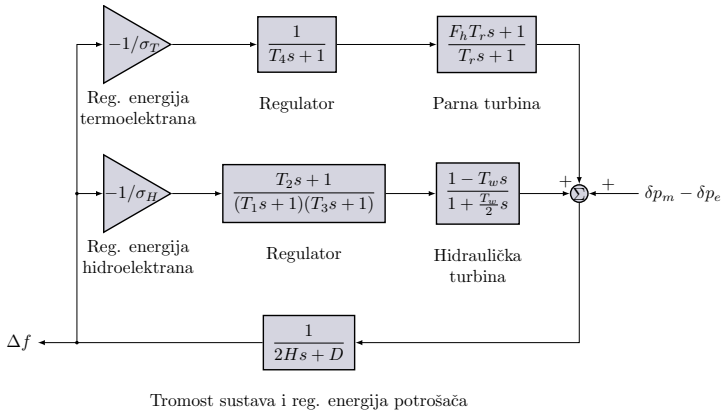
d) Izračunati za koliko se promijeni snaga potrošnje sustava nakon poremećaja iz c).

e) Izračunati početni RoCoF ($t = 0^+$) neposredno nakon poremećaja iz c).

Koristiti $S_b = 1000$ MVA.
(10 bodova)

Tablica 1: Podaci o agregatima u elektranama

Elektrana	Vrsta	Moment tromosti [kgm^2]	Broj polova	Nazivna snaga [MVA]	Statičnost [%]
E1	Termo	$10 \cdot 10^3$	2	100	5
E2	Termo	$25 \cdot 10^3$	2	200	6
E3	Termo	$50 \cdot 10^3$	2	400	∞
E4	Hidro	$1000 \cdot 10^3$	20	200	2
E5	Hidro	$500 \cdot 10^3$	18	100	4



Slika 1: Dinamički model sustava

Zadatak 2

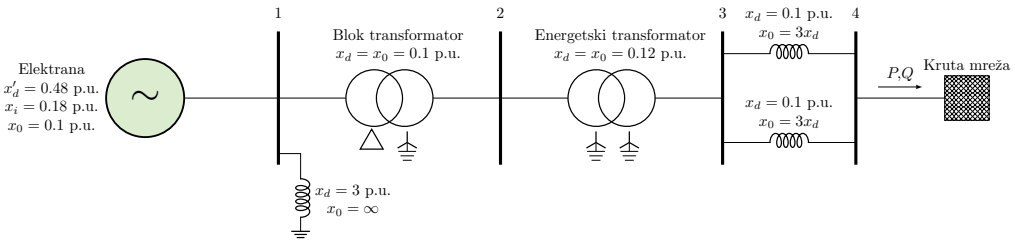
Neka elektrana spojena je na krutu mrežu preko blok-transformatora, energetskog transformatora i dvostrukog dalekovoda prema slici 2. Generator na vlastitim sabirnicama snabdijeva pomoćne asinkrone motore sa strujom magnetiziranja. Motori su trenutno neopterećeni i modelirani su kao pasivni potrošač jalove snage s konstantnom impedancijom. Zvjezdište asinkronog motora nije uzemljeno. Agregat u mrežu predaje snagu $P = 0.9$ p.u. pri $\cos\varphi = 1.00$. Napon krute mreže iznosi $1\angle 0^\circ$ p.u. Na 5% duljine jednog od dva paralelna voda (gledano od sabirnice 3) nastaje dvopolni kratki spoj sa zemljom. Potrebno je 1) odrediti kritični kut uklanjanja kvara i 2) nacrtati nadomjesnu shemu sustava sa slike 2 te odrediti izraz i skicirati krivulje za prijenos električne snage između elektrane i krute mreže za slučajeve:

a) prije nastanka kratkog spoja;

b) tijekom kratkog spoja;

c) nakon isključenja voda u kvaru.

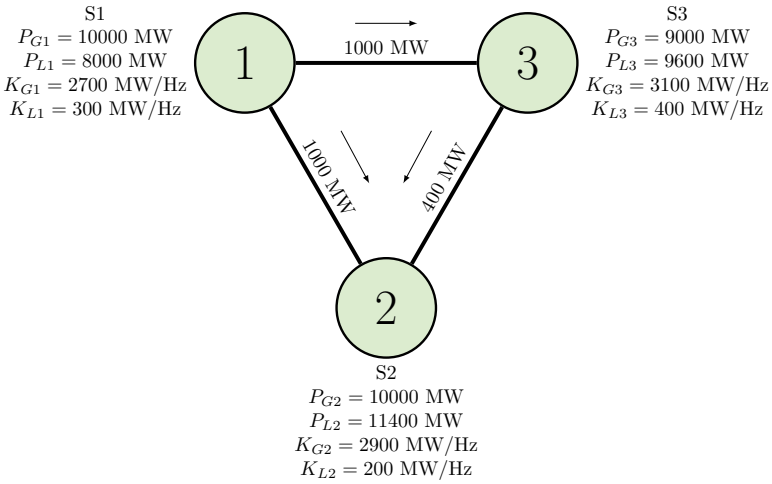
(9 bodova)



Slika 2: Spoj elektrane s krutom mrežom

Zadatak 3

Tri sustava rade u interkonekciji (Slika 3). Jože je dispečer u operatoru sustava 1. Joži je ispao tanjur s buncekom, pečenicama i kuhanim krumpirom na tipkovnicu i slučajno je isključio vod između sustava 1 i 3. Sekvencijalno opišite što će se dogoditi od tog trenutka pa sve do konačnog stacionarnog stanja. Navedite i naznačite sva međustanja. Potrebno je izračunati konačno stanje u svim sustavima te sva međustanja kroz koja sustavi prolaze. Maksimalno dozvoljeno opterećenje vodova 1–2 i 1–3 iznosi 1500 MW, dok je prijenosna moć voda 2–3 zbog radova smanjena i iznosi 500 MW. Preopterećeni vod prekostrujna zaštita automatski isključuje. Svi sustavi jednako sudjeluju u sekundarnoj regulaciji. Dozvoljena su odstupanja između proizvodnje i potrošnje do 100 MW zbog numeričke nepreciznosti tijekom proračuna.
(6 bodova)



Slika 3: Tri sustava u interkonekciji

Zadatak 4

Nacrtajte blok dijagram dinamičkog sustava opisanog jednadžbama (1)–(2), gdje su T_1, H, D i R konstante, a $\Delta p_e(t)$ je step poremećaj amplitude A. Matematički dokazati da smanjenje statičnosti uzrokuje smanjenje odstupanja brzine vrtnje u stacionarnom stanju nakon poremećaja, odnosno: $R \to 0^+ \implies [\Delta\omega(t \to \infty)] \to 0$.

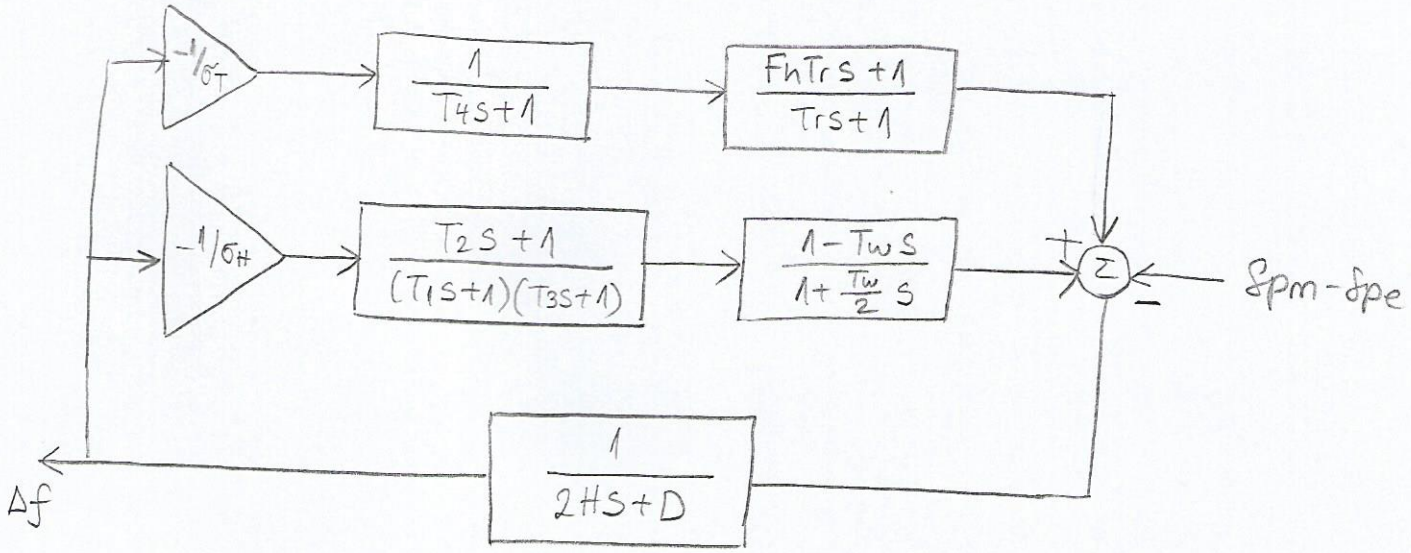
$$2H\frac{d\Delta\omega}{dt} + D\Delta\omega = \Delta p_m(t) - \Delta p_e(t) \tag{1}$$

$$T_1\frac{d\Delta p_m(t)}{dt} + \Delta p_m(t) = -\frac{1}{R}\Delta\omega \tag{2}$$

(5 bodova)

1. ZADATAK

Elektrana	Vrsta	J [kgm²]	Br. polova	Sn [MVA]	Statičnost [%]
E1	Termo	$10 \cdot 10^3$	2	100	5
E2	-11-	$25 \cdot 10^3$	2	200	6
E3	-11-	$50 \cdot 10^3$	2	400	∞
E4	Hidro	$1000 \cdot 10^3$	20	200	2
E5	-11-	$500 \cdot 10^3$	18	100	4



$D = 2$ p.u.

a) $H_{UK} = ?$

$S_B = 1000$ MVA

$$H = \frac{E_{kin}}{S_B} = \frac{J\omega_m^2}{2S_B} \qquad H_{UK} = \sum \frac{J_i \left(\frac{\omega_{ei}}{p_i}\right)^2}{2S_B} = \frac{\sum J_i \left(2\pi \frac{f}{p_i}\right)^2}{2S_B}$$

$$H_{UK} = (2\pi f)^2 \frac{\sum J_i \left(\frac{1}{p_i}\right)^2}{2S_B}$$

$$H_{UK} = \frac{(2\pi \cdot 50)^2}{2 \cdot 1000M} \left[\frac{10 \cdot 10^3}{1} + \frac{25 \cdot 10^3}{1} + \frac{50 \cdot 10^3}{1} + \frac{1000 \cdot 10^3}{10^2} + \frac{500 \cdot 10^3}{9^2} \right]$$

$H_{UK} = 4{,}99\,s \approx 5\,s$

b) $\sigma_{UK} = ?$

$$\sigma_1' = \sigma_1 \frac{S_B}{S_{n1}} = 0{,}05 \frac{1000}{100} = 0{,}5 \qquad \sigma_4' = 0{,}02 \frac{1000}{200} = 0{,}1$$

$$\sigma_2' = 0{,}06 \frac{1000}{200} = 0{,}3 \qquad \sigma_5' = 0{,}04 \frac{1000}{100} = 0{,}4$$

$\sigma_3' = \infty$

$$K_{UK} = \sum \frac{1}{\sigma_i'} = 17{,}83\,pu$$

$$\sigma_{UK} = \frac{1}{K_{UK}} = \frac{1}{17{,}83} = 0{,}056\ p.u.$$

c) Izvesti izraz za odstupanje fr. u Laplaceovoj domeni

$$\Delta f = \frac{1}{2Hs+D}\left[\Delta f\left(-\frac{1}{\sigma_T}\right)G_T(s)+\Delta f\left(-\frac{1}{\sigma_H}\right)G_H(s)+\delta p_m-\delta p_e\right]$$

$$\Delta f\left[2Hs+D+\frac{1}{\sigma_T}G_T(s)+\frac{1}{\sigma_H}G_H(s)\right]=\delta p_m-\delta p_e$$

$$\Delta f=\frac{\delta p_m-\delta p_e}{2Hs+D+\frac{1}{\sigma_T}G_T(s)+\frac{1}{\sigma_H}G_H(s)}$$

Ispad elektrane E3 koja je prije ispada radila s 50% Sn

$$\Delta f(t\to\infty)=\lim_{s\to 0} s\cdot\Delta f=\lim_{s\to 0} s\,\frac{\frac{\delta p_m-\delta p_e}{s}}{2Hs+D+\frac{1}{\sigma_T}G_T(0)+\frac{1}{\sigma_H}G_H(0)}$$

($2Hs\to 0$, $G_T(0)\to 1$, $G_H(0)\to 1$)

$$\Delta f(t\to\infty)=\frac{\delta p_m-\delta p_e}{D+\frac{1}{\sigma_T}+\frac{1}{\sigma_H}}=\frac{-0,2}{2+\frac{1}{0,5}+\frac{1}{0,3}+\frac{1}{0,1}+\frac{1}{0,4}}=-0,01\ \text{p.u.}\ /\cdot 50\text{Hz}$$

$$\Delta f(t\to\infty)=-0,5\ \text{Hz}$$

d) $\Delta P_m = D\cdot\Delta f = 2\cdot(-0,01)=-0,02$ p.u.

$=-20$ MVA

e) $\frac{df}{dt}(t=0^+)=?$

$$\left.\frac{df}{dt}\right|_{t=0^+}=\lim_{s\to\infty}s^2\Delta f(s)=\lim_{s\to\infty}s^2\,\frac{\frac{\delta p_m-\delta p_e}{s}}{2Hs+D+\frac{1}{\sigma_T}G_T+\frac{1}{\sigma_H}G_H}=$$

$$=\lim_{s\to\infty}\frac{\delta p_m-\delta p_e}{2H+\frac{D}{s}+\frac{1}{s\sigma_T}G_T+\frac{1}{s\sigma_H}G_H}=\frac{\delta P}{2H}=\frac{-0,2}{2\cdot 2,526}=-0,0396\ \frac{\text{pu}}{\text{s}}$$

$$=-1,98\ \frac{\text{Hz}}{\text{s}}$$

(*) $H=H_{uk}-H_3=4,993-\frac{50\cdot 10^3\left(2\pi\cdot\frac{50}{1}\right)^2}{2\cdot 1000\text{M}}=2,526\,\text{s}$

M1 2020/2021.

2. ZADATAK

$P = 0,9$ p.u.

$\cos\varphi = 1$

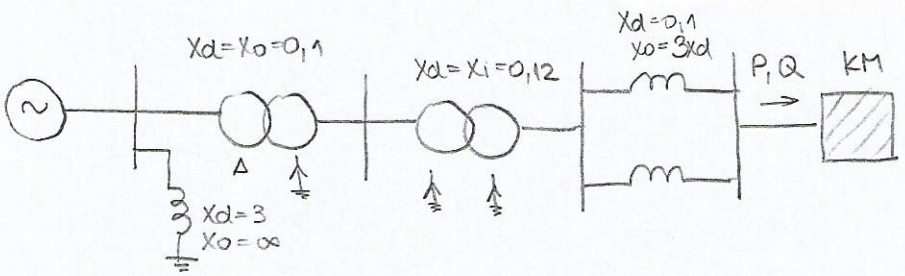
$U_{\infty} = 1\angle 0°$

2KSZ, 5% dv

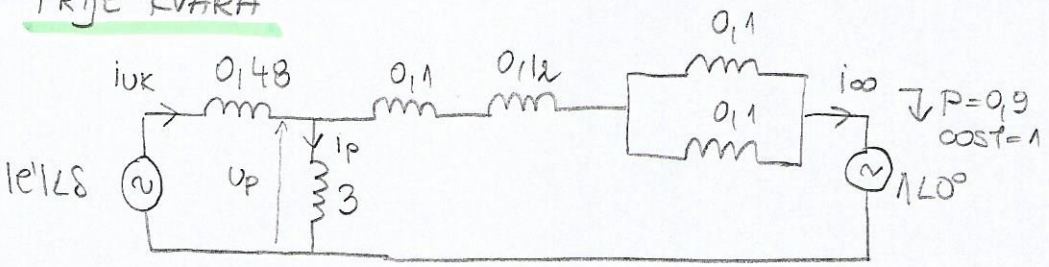
$X_d' = 0,48$

$X_i = 0,18$

$X_o = 0,1$



PRIJE KVARA



$X_L = 0,27$

$X_D = 0,48$

$X_{DO} = 3$

$$i_{\infty} = \left(\frac{S_{\infty}}{U_{\infty}}\right)^* = 0,9 \text{ p.u.}$$

$$\left.\begin{aligned} U_p &= U_{\infty}\angle 0° + j i_{\infty} \cdot X_L \\ U_p &= i_p \cdot X_p \end{aligned}\right\} \quad i_p = \frac{U_{\infty}\angle 0° + i_{\infty} \cdot X_L}{X_p} = \frac{1\angle 0° + 0,9 \cdot 0,27\angle 90°}{3\angle 90°} =$$

$$U_p = 1,029\angle 13,66°$$

$$= \frac{1,029\angle 13,66°}{3\angle 90°} = 0,343\angle -76,34° =$$

$$i_{uk} = i_p + i_{\infty} = 0,081 - j0,333 + 0,9 \quad = 0,081 - j0,333$$

$$= 0,981 - j0,333 = 1,036\angle -18,75°$$

$$1e'1\angle\delta = U_p + j\, i_{uk} \cdot X_d' = 1,029\angle 13,66° + 1,036\angle -18,75° \cdot 0,48\angle 90° =$$

$$= 1 + j0,243 + 0,1598 + j0,471 = 1,362\angle 31,62°$$

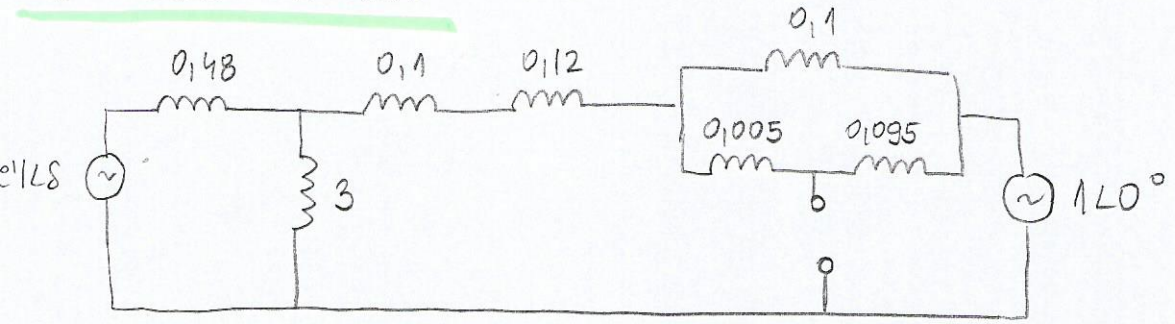
$$1e'1\angle\delta = 1,362\angle 0,552 \text{ rad}$$

$$X_{\Sigma} = X_L + X_D + \frac{X_L \cdot X_D}{X_{DO}} = 0,27 + 0,48 + \frac{0,27 \cdot 0,48}{3} = 0,7932$$

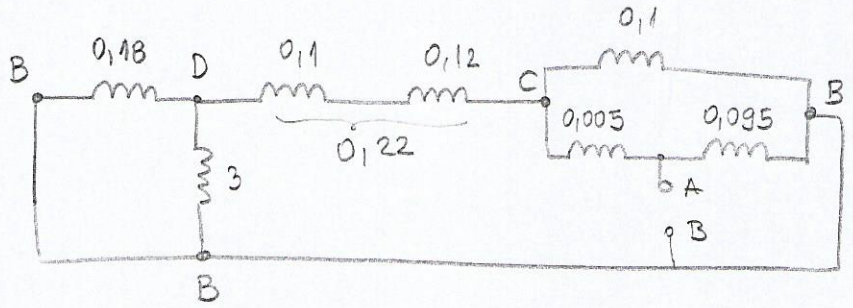
$$P_e^{\alpha} = \frac{|e'1||u_{\infty}|}{X_{\Sigma}} \sin\delta = \frac{1,362 \cdot 1}{0,7932} \cdot \sin\delta = 1,717 \sin\delta$$

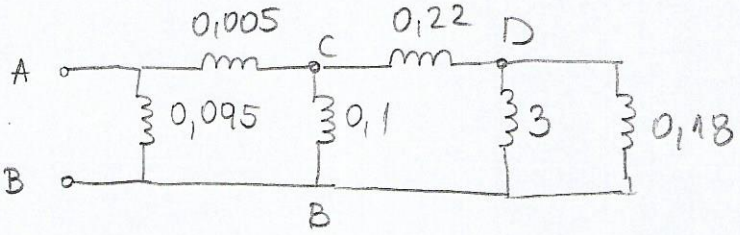
$$P_m = \frac{1,362}{0,7932} \cdot \sin(0,552) = 0,9$$

ZA VRIJEME KVARA



inverzni:

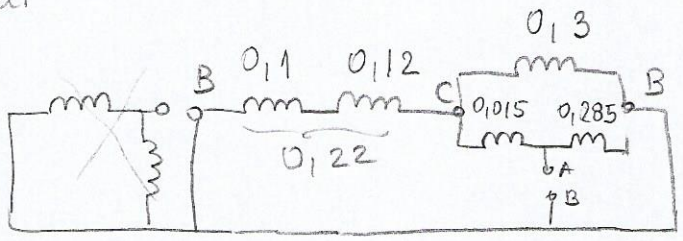


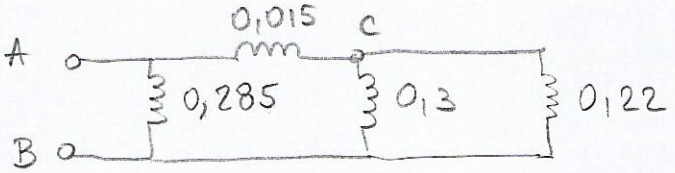


$$X_i = \left[(0,18 \parallel 3 + 0,22) \parallel 0,1 + 0,005\right] \parallel 0,095 = \left[\underbrace{(0,17+0,22)}_{0,39} \parallel 0,1 + 0,005\right] \parallel 0,095 =$$

$$= \underbrace{(0,079+0,005)}_{0,085} \parallel 0,095 = 0,045$$

nulti

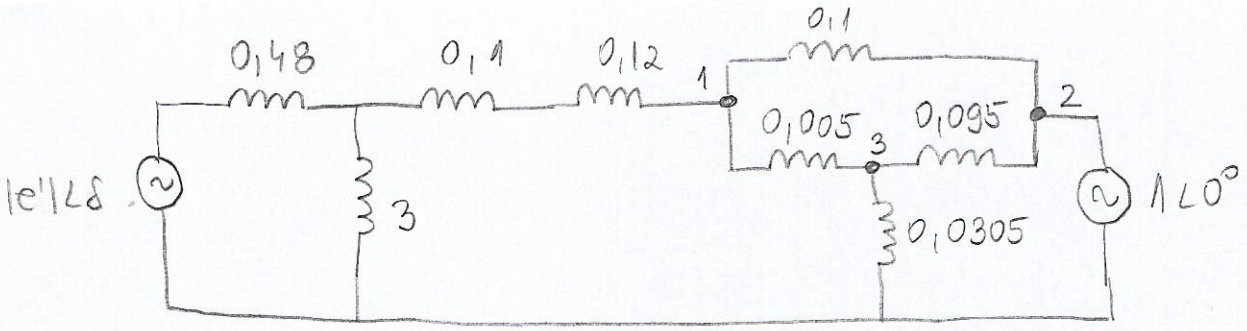


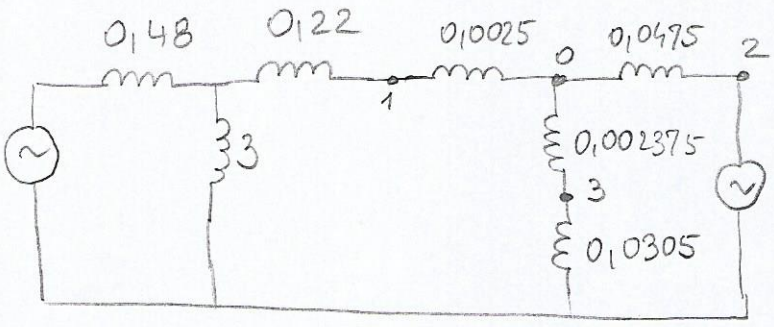


$$X_0 = \left[0,22 \parallel 0,3 + 0,015\right] \parallel 0,285$$

$$X_0 = 0,095$$

$$X_F = X_i \parallel X_0 = 0,0305$$

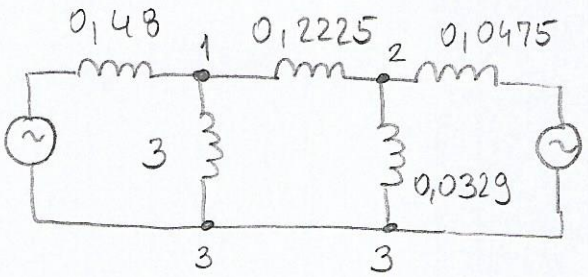




$$X_{10} = \frac{X_{12}X_{13}}{X_{12}+X_{13}+X_{23}} = 0,0025$$

$$X_{20} = \frac{X_{21}X_{23}}{N} = 0,0475$$

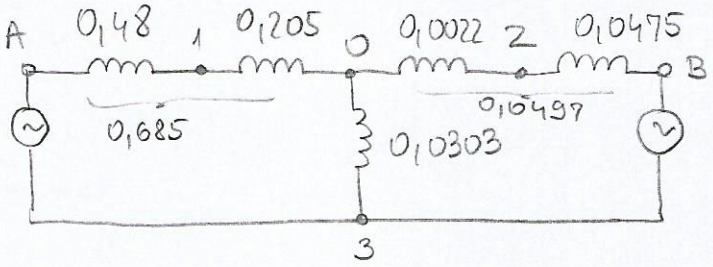
$$X_{30} = \frac{X_{31}X_{32}}{N} = 0,002375$$



$X_{10} = 0,1205$

$X_{20} = 0,0022$

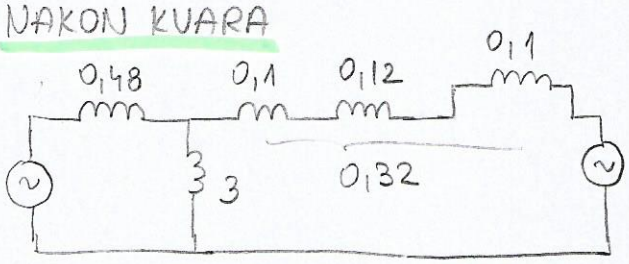
$X_{30} = 0,0303$



$$X_\beta = X_{AB} = X_L + X_D + \frac{X_L X_D}{X_{DO}} = 1,86$$

$$P_{e\beta} = \frac{|e'||U_{00}|}{X_\beta}\sin\delta = \frac{1,362}{1,86}\sin\delta = 0,732\sin\delta$$

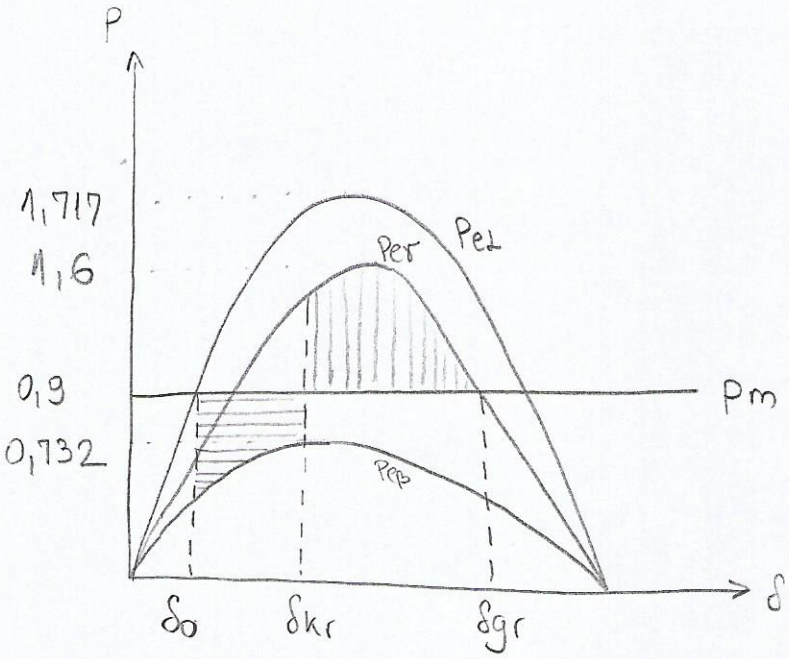
NAKON KVARA



$$X_{AB} = 0,148 + 0,32 + \frac{0,148\cdot 0,32}{3} \Rightarrow$$

$$X_\gamma = 0,2512$$

$$P_{e\gamma} = \frac{1,362}{0,2512}\sin\delta = 1,6\sin\delta$$



$P_{el} = 1,717$

$P_{e\beta} = 0,732$

$P_{er} = 1,6$

$P_m = 0,9$

$\delta_o = 0,552$ rad

δ_{gr} : $P_r = P_m$

$0,9 = 1,6 \sin \delta_{gr} (\pi - \delta)$

$\delta_{gr} = 2,544$ rad

$$A_a = \int_{\delta_o}^{\delta_{kr}} (p_m - P_{e\beta})\, d\delta \qquad A_d = \int_{\delta_{kr}}^{\delta_{gr}} (P_{er} - p_m)\, d\delta$$

$A_a = A_d$

$$p_m (\delta_{kr} - \delta_o) - P_{e\beta} (-\cos\delta_{kr} + \cos\delta_o) = P_{er} (-\cos\delta_{gr} + \cos\delta_{kr}) - p_m (\delta_{gr} - \delta_{kr})$$

$$p_m\delta_{kr} - p_m\delta_o + P_{e\beta}\cos\delta_{kr} - P_{e\beta}\cos\delta_o = P_{er}\cos\delta_{kr} - P_{er}\cos\delta_{gr} - p_m\delta_{gr} + p_m\delta_{kr}$$

$$\cos\delta_{kr} (P_{er} - P_{e\beta}) = p_m (\delta_{gr} - \delta_o) + P_{er}\cos\delta_{gr} - P_{e\beta}\cos\delta_o$$

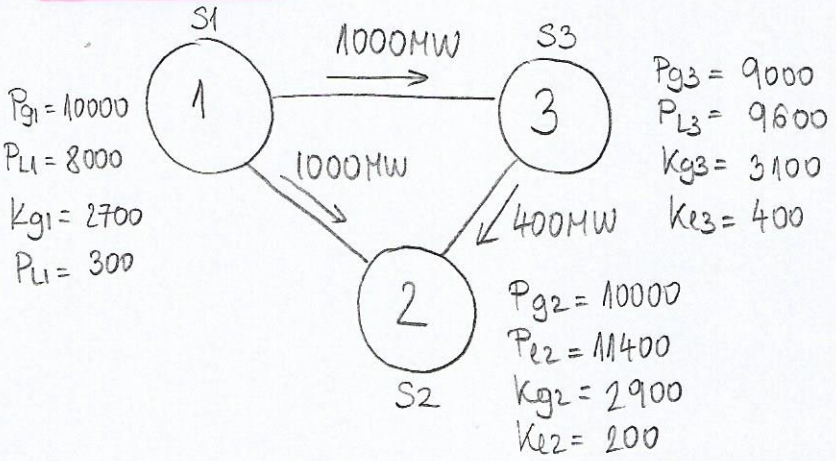
$$\cos\delta_{kr} = \frac{0,9 (2,544 - 0,552) + 1,6 \cdot \cos(2,544) - 0,732 \cos(0,552)}{1,6 - 0,732}$$

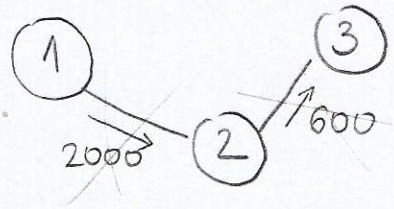
$\delta_{kr} = 1,748$ rad $= 100°$

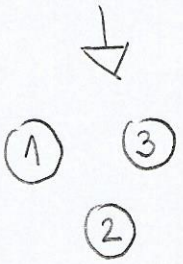
MI 2020./2021.

3. ZADATAK

- isključen vod 1-3
- max opterećenje 1-2 : 1500MW
  1-3 :
  2-3 : 500MW







SUSTAV 1 : gubitak potrošnje 2000 MW
frekvencija će se povećati

$$\Delta f = \frac{2000}{2700+300} = 0{,}667\,Hz$$

$$\Delta P_{g1} = -K_{g1}\cdot\Delta f = -2700\cdot 0{,}667 = -1800{,}9\,MW$$
$$\Delta P_{e1} = K_{e1}\,\Delta f = 300\cdot 0{,}667 = 200{,}1\,MW$$

$$P_{g1}' = P_{g1} + \Delta P_{g1} + \delta P_{g1} = 10000 - 1800{,}9 + 0 = 8199{,}1\,MW$$
$$P_{e1}' = P_{e1} + \Delta P_{e1} + \delta P_{e1} = 8000 + 200{,}1 + 0 = 8200{,}1\,MW$$

$\Sigma P_g = \Sigma P_e$

Sekundarna regulacija : $\Delta f = -0{,}667\,Hz$

$$\delta P = \Delta f\,(K_g + K_e) = -0{,}667\cdot 3000 = -2000\,MW$$

$$P_{g1}'' = 8199{,}1 - 2700\cdot(-0{,}667) - 2000 = 8000\,MW$$
$$P_{e1}'' = 8200{,}1 + 300\cdot(-0{,}667) + 0 = 8000\,MW$$

SUSTAV 2 → gubitak proizvodnje → smanjenje frekvencije

$$\Delta f = \frac{-1400}{2900+200} = -0{,}452\,Hz$$

$$P_{g2}' = 10000 - (-0{,}452)\cdot 2900 + 0 = 11310{,}8\,MW$$
$$P_{e2}' = 11400 + (-0{,}452)\cdot 200 + 0 = 11309{,}6\,MW$$

Sekundarna regulacija : $\Delta f = +0{,}452\,Hz \rightarrow \delta P = 1400\,MW$

$$P_{g2}'' = 11310{,}8 - 0{,}452\cdot 2900 + 1400 = 11400\,MW$$
$$P_{e2}'' = 11309{,}6 + 0{,}452\cdot 200 + 0 = 11400\,MW$$

$\Sigma P_g = \Sigma P_e$

SUSTAV 3 ispad proizvodnje 600MW

$$\Delta f = \frac{-600}{3100+400} = -0,171 \text{ Hz}$$

$$P'_{g3} = 9000 - (-0,171) \cdot 3100 + 0 = 9530,1 \text{ MW}$$
$$P'_{l3} = 9600 + (-0,171) \cdot 400 + 0 = 9531,6 \text{ MW}$$

Sekundarna regulacija: $\Delta f = +0,171$ Hz

$$P''_{g3} = 9530,1 - 0,171 \cdot 3100 + 600 = 9600 \text{MW}$$
$$P''_{l3} = 9531,6 + 0,171 \cdot 400 + 0 = 9600 \text{MW}$$

$\Sigma P_g = \Sigma P_l$

MI 2020/2021.

4. ZADATAK

$$2H\frac{d\Delta\omega}{dt} + D\Delta\omega = \Delta P_m(t) - \Delta P_e(t)$$

$$T_1\frac{d\Delta P_m(t)}{dt} + \Delta P_m(t) = -\frac{1}{R}\Delta\omega$$

T_1, H, D, R konstante

$\Delta P_e(t)$ step poremećaj amplitude A

$$\frac{d\Delta\omega}{dt} = -\frac{D\Delta\omega}{2H} + \frac{1}{2H}\left[\Delta P_m(t) - \Delta P_e(t)\right]$$

$$\frac{d\Delta P_m(t)}{dt} = -\frac{1}{T_1}\Delta P_m(t) - \frac{1}{RT_1}\Delta\omega$$