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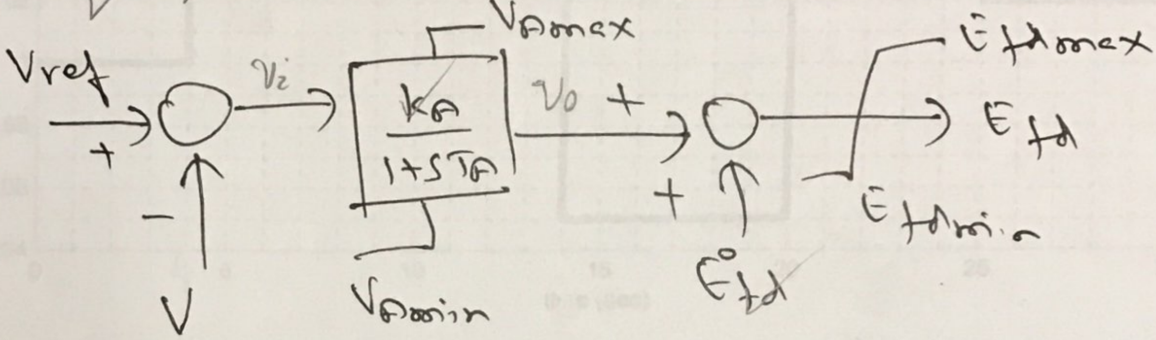
# EE523 Power System Stability and Control

## Midterm Examination

1) Consider the exciter model below. Exciter response from a step response test is shown in the plot below. Assume Vref=1.03. Estimate the exciter parameters KA, TA, Efd0, and VAmin, VAmax, Efdmin and Efdmax. (25 points)




$$v_i = v_{ref} - v$$
$$v_0 = \frac{k_A}{1+sT_A} v_i$$
$$E_{fd} = v_0 + E^0_{fd}$$

$$E_{fd} = E^0_{fd} + \frac{k_A}{1+sT_A}(\overset{1.03}{V_{ref}} - V)$$

Let's look at steady state response:

$t=0 \rightarrow V=1, E_{fd}=3 \Rightarrow 3 = E^0_{fd} + k_A(0.03)$ (I)

$t=25 \rightarrow V=1.03, E_{fd}=0 = E^0_{fd} + k_A(0) \Rightarrow \boxed{E^0_{fd}=0}$

Put in (I)

$3 = 0 + k_A(0.03)$

$\Downarrow$

$\boxed{k_A = 100}$

In order to find $T_A$ we look at the response of the system in time $4 \sim 10$.

$t=4 \rightarrow E_{fd}=3$
$t=10 \rightarrow E_{fd}=-2$
$5 \times 0.634 = 3.17$

in $t = 4 + T_A \rightarrow E_{fd} = -0.17$

Now we look at figure

$t \cong 5$ sec

$\boxed{T_A \cong 1}$

Again Based on the figure:

$\boxed{\begin{matrix} V_{Amax} = +4 \\ V_{Amin} = -5 \end{matrix}}$

we dont have enough information to find exact Efdmin, Efdmax but $E_{fdmin} \geq 4$ and $E_{fdmin} \geq -5$

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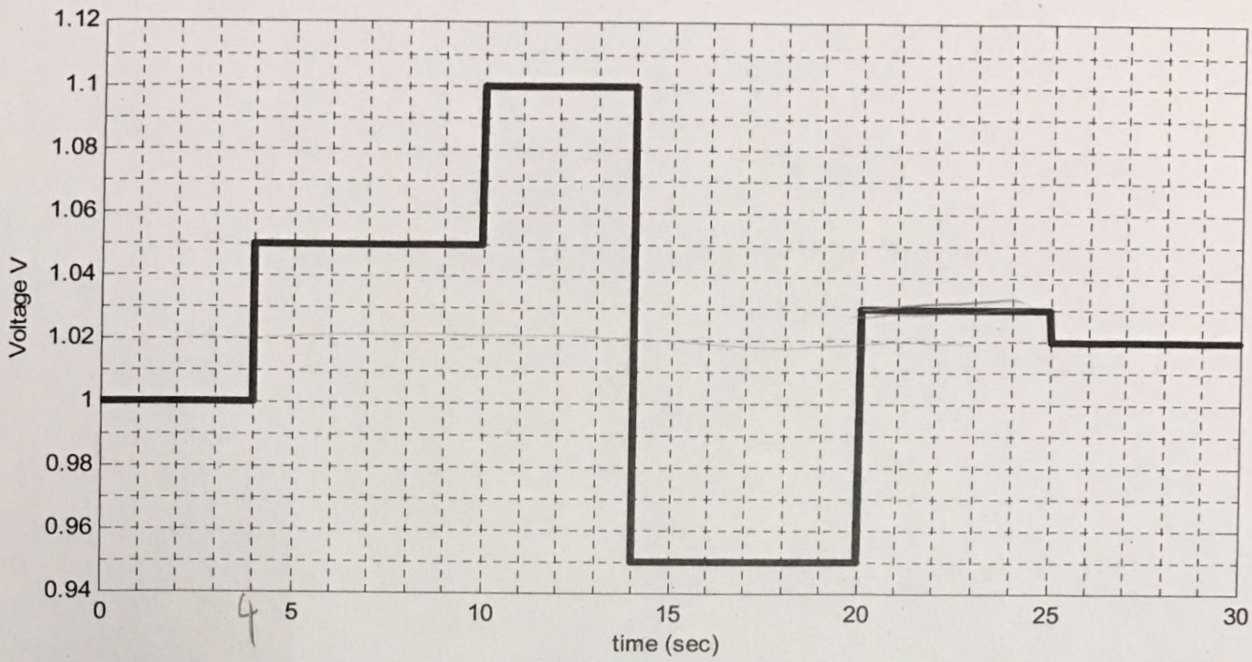
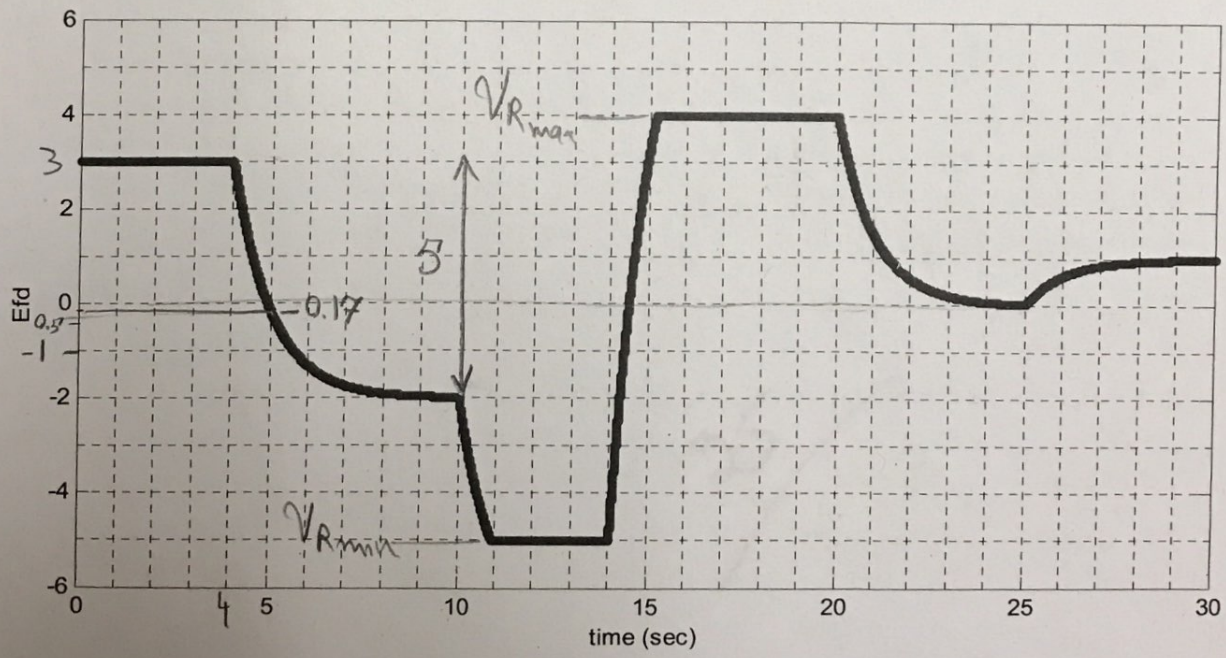
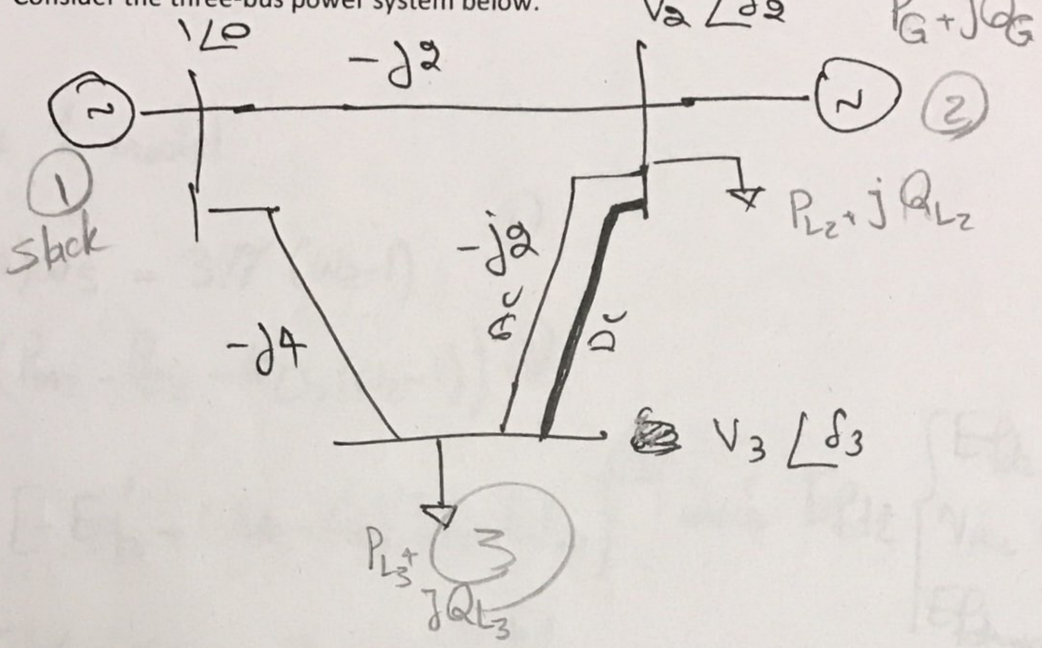


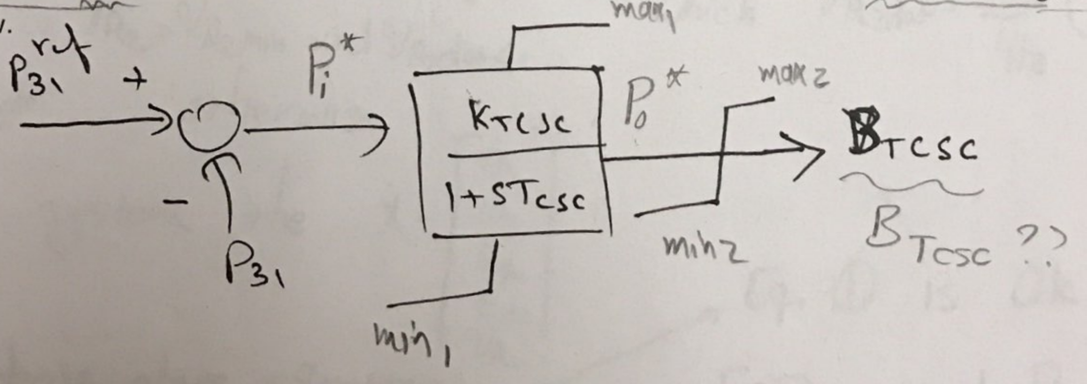




$$Efd_2 = \begin{cases} Efd_{2\,max} & V_{R_2} > Efd_{2\,max} \\ V_{R_2} & Efd_{min} < V_{R_2} < Efd_{2\,max} \\ Efd_{min} & V_{R_2} < Efd_{min} \end{cases}$$

2) Consider the three-bus power system below.

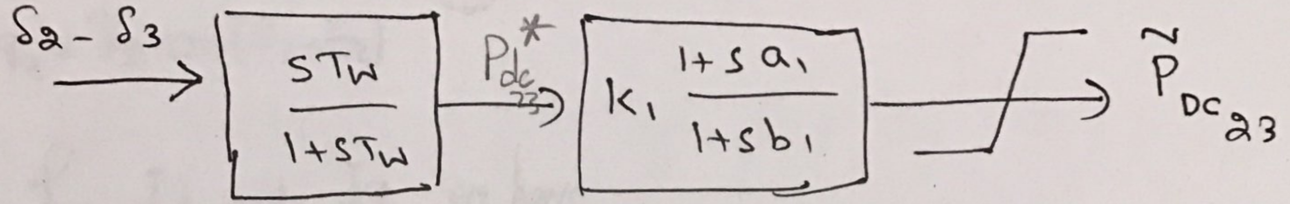



Assume the generator is modeled by a standard first order exciter control with no governor control modeled. There is a HVDC transmission line from bus 2 to bus 3 that can be modeled as a lossless link. The HVDC power electronic controls keep the complex AC power on both sides of the DC link (at buses 2 and 3 respectively) at unity power-factor. There is a TCSC (Thyristor Controlled Series Compensation) on the transmission line from bus 3 to bus 1 where the TCSC line capacitance is varied to keep the active power-flow P31 on the transmission line from bus 3 to bus 1 constant per the control logic shown below.




a) Write out the Type 1 model for the power system in the standard DAE form, clearly identifying the dynamic states, power-flow states as well as all the relevant dynamic and power-flow equations. (40 points)

b) Suppose the utility decides to vary 10% of the DC power transfer from bus 2 to 3 as a damping controller per the control logic shown below. Rewrite the Type 1 model now including the DC damping controller. (10 points)




a) Type 1 model

$$\dot{\theta}_2 = (\omega_2 - 1)\omega_s = 377(\omega_2 - 1) \quad ①$$

$$\dot{\omega}_2 = \frac{1}{2H_2}\left(P_{m2} - P_{e2} - k_{D2}(\omega_2 - 1)\right) \quad ②$$

$$\dot{E}'_{q2} = \frac{1}{T'_{do2}}\left[-E'_{q2} - (X_{d2} - X'_{d2}) I_{d2} + E_{fd2}\right] \quad ③$$

which $E_{fd2} = \begin{cases} E_{fd2max} & V_{R2} > E_{fd2max} \\ V_{R2} & E_{fdmin} < V_{R2} < E_{fdmax} \\ E_{fdmin} & V_{R2} < E_{fdmin} \end{cases}$

$$\dot{E}'_{d2} = \frac{1}{T'_{qo2}}\left[-E'_{d2} + (X_{q2} - X'_{q2}) I_{q2}\right] \quad ④$$

$$\dot{V}_{R2} = \begin{cases} 0, & V_{R2} = V_{R2max} \text{ and } V_{Rdot_2} > 0 \\ 0, & V_{R2} = V_{R2min} \text{ and } V_{R2dot} < 0 \\ V_{R_2dot} & \text{otherwise} \end{cases} \quad ⑤$$

which $V_{R2dot} = \frac{1}{T_{A2}}\left(-V_{R2} + V_{A2}(V_{ref2} - V_2)\right)$

for this system the $\dot{X} = \begin{bmatrix} \dot{\theta}_2 \\ \dot{\omega}_2 \\ \dot{E}'_{q2} \\ \dot{E}_{d2} \\ \dot{V}_{R2} \end{bmatrix}$

By considering above equations:
- Eq. ① is Ok ✓
- Eq. ② we need $P_{e2}$
- Eq. ③, Eq. ④ we need $I_{d2}$ and $I_{q2}$

for $P_{e2}$ we have:

$$P_{e2} = P_{G2} + I_{G2}^2 R_s \quad \text{and} \quad P_{G2} = V_{d2} I_{d2} + V_{q2} I_{q2}$$

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$$\begin{cases} V_{d2} = V_2 \sin(\theta_2 - \delta_2) \\ V_{q2} = V_2 \cos(\theta_2 - \delta_2) \end{cases} \quad (6)$$

and for $I_{d2}$ and $I_{q2}$ we have:

$$\begin{bmatrix} I_{d2} \\ I_{q2} \end{bmatrix} = \frac{1}{R_{s2}^2 + X'_d X'_q} \begin{bmatrix} R_{s2} & X'_q \\ -X'_d & R_{s2} \end{bmatrix} \begin{bmatrix} E'_d - V_d \\ E'_q - V_q \end{bmatrix}$$

if we consider $R_s = 0 \implies \begin{cases} I_{d2} = \dfrac{1}{X'_{d2}} (E'_{q2} - V_{q2}) \\ I_{q2} = \dfrac{-1}{X'_{q2}} (E'_{d2} - V_{d2}) \end{cases} \quad (7)$ and $P_{e2} = P_{G2} = V_{d2} I_{d2} + V_{q2} I_{q2} \quad (8)$

Now if we put (6) in (7) and also plug in (6) and (7) in (8)

all the eq. (1), (2), (3), (4) become ready.

for type 1 we have: $\dot{x} = f(x, y)$

and $0 = g(x, y) \longrightarrow$ for this part we should write the power flow for the Network.

for this aim we have:

$$Y_{bus} = \begin{bmatrix} -j6 & j2 & j4 \\ j2 & -j4 & j2 \\ j4 & j2 & -j6 \end{bmatrix}$$

and $y$ here is $y = \begin{bmatrix} \delta_2 \\ \delta_3 \\ V_2 \\ V_3 \end{bmatrix}$

$P_G = P_i + P_L$

$$\begin{cases} P_{G2} - P_{L2} - P_{2j} = 0 \\ 0 - P_{L3} - P_{3j} = 0 \\ Q_{G2} - Q_{L2} - Q_{2j} = 0 \\ 0 - Q_{L3} - Q_{3j} = 0 \end{cases}$$

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$$P_{2j} = \sum_{j=1}^{3} Y_{2j} V_2 V_j \cos(\delta_2 - \delta_j - \theta_{2j}) = Y_{21} V_2 V_1 \cos(\delta_2 - \delta_1 - \theta_{21})$$

$$+ Y_{22} V_2^2 \cos(-\theta_{22}) + Y_{23} V_2 V_3 \cos(\delta_2 - \delta_3 - \theta_{23}) + P_{DC}$$

$$P_{3j} = P_{31} + \sum_{j=2}^{3} Y_{3i} V_3 V_j \cos(\delta_3 - \delta_j - \theta_{3j}) + P_{DC}$$

and for $P_{31}$ we have:

$$(P_{31}^{ref} - P_{31}) \times \frac{k_{TCSC}}{1 + sT_{csc}} = B_{TCSC} \Longrightarrow (P_{31}^{ref} - P_{31}) k_{TCSC} =$$

$$= B_{TCSC} + \dot{B}_{TCSC} T_{csc} \Longrightarrow$$

$$B_{TCSC}^{dot} = \frac{1}{T_{csc}} \left[ - B_{TCSC} + k_{TCSC} (P_{31}^{ref} - P_{31}) \right] \longrightarrow$$ without windup and non windu limiter:

Base on figure:

$$B_{TCSC} = \begin{cases} max_2 & \text{if } B_{TCSC} > max_2 \\ B_{TCS} & min_2 < B_{TCSC} < max_2 \\ min_2 & B_{TCSC} < min_2 \end{cases}$$

$$Q_{2j} = \sum_{j=1}^{3} Y_{2j} V_2 V_j \sin(\delta_2 - \delta_j - \theta_{2j})$$

the same equation for $Q_{3j}$

(due to time limit I did not mentioned here)

Then for this system:

$P_{31} = ?$

$$\dot{X} = \begin{pmatrix} \dot{\theta}_2 \\ \dot{\omega}_2 \\ \dot{E}'_{q_2} \\ \dot{E}'_{d_2} \\ \dot{B}_{TCSC} \end{pmatrix} \quad y = \begin{pmatrix} \delta_2 \\ \delta_3 \\ V_2 \\ V_3 \end{pmatrix}$$

and for nonwindup limit

$$\dot{B}_{TCSC} = \begin{cases} 0 & P_0^* = max_1 \text{ and } B_{TCSC}^{dot} > 0 \\ 0 & P_0^* = min_1 \text{ and } B_{TCSC}^{dot} < 0 \\ B_{TCSC}dot & \text{otherwise} \end{cases}$$

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Part b) Now by considering the DC damping controller we have:

$$P^*_{dc_{23}} = (\delta_2-\delta_3)\frac{sT_\omega}{1+sT_\omega} \Rightarrow P^*_{dc_{23}} + T_\omega \dot{P}_{dc_{23}} = (\dot{\delta}_2-\dot{\delta}_3)T_\omega$$

and $$\tilde{P}_{DC_{23}} = P^*_{dc_{23}} k_1 \frac{1+sa_1}{1+sb_1} \Rightarrow \tilde{P}_{DC_{23}} + b_1 \dot{\tilde{P}}_{DC_{23}} = k_1 P^*_{dc_{23}} + a_1 k_1 \dot{P}^*_{dc_{23}}$$

$$\Longrightarrow \dot{\tilde{P}}_{DC_{23}} = \frac{1}{b_1}\left[-\tilde{P}_{DC_{23}} + k_1\left(-T_\omega \dot{P}_{dc_{23}} - (\dot{\delta}_2-\dot{\delta}_3)T_\omega\right) + \frac{a_1 k_1}{T_\omega}\left[-P^*_{dc_{23}} + (\dot{\delta}_2-\dot{\delta}_3)T_\omega\right]\right]$$

Then we should add $\dot{P}_{DC_{23}}$ to our states from Part (a).

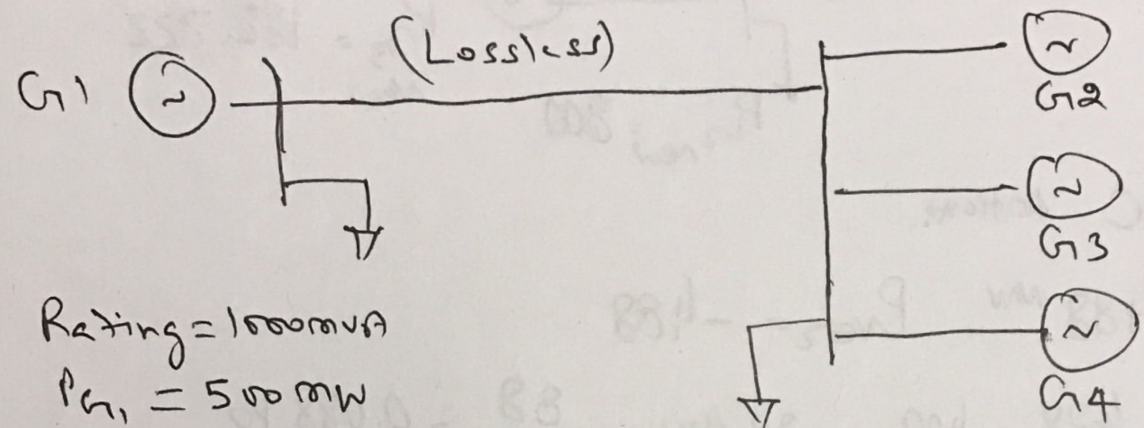
how?

$P_{DC}$ (?) $P_{DC}$ ~>

3) Consider the two area system below. Suppose there is a sudden loss of generator 4 in Area 2. Compute the governor responses before and after AGC actions. Assume generator 2 to be the slack bus for Area 2.

(25 points)

Area 1 | Area 2




Rating = 1000 MVA
$P_{G_1} = 500$ MW
$P_{L_1} = 100$ MW
$R = 5\%$

$P_{L_2} = 800$ MW

Rating = 1000 MVA
$P_{G_2} = 100$ MW
$R_2 = 5\%$

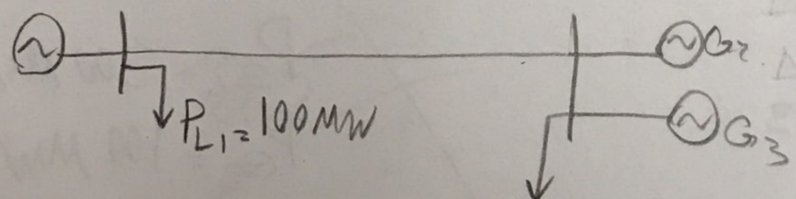
Rating = 500 MVA
$P_{G_3} = 100$ MW
$R_3 = 10\%$

Rating = 500 MVA
$P_{G_4} = 200$ MW
$R_4 = 5\%$

~~$\Delta P_{G4} = 200$ MW · 0.4~~

~~$\Delta P_{G4} = + \frac{\Delta f}{R_4} \Rightarrow \Delta f = 0.4 \times 0.05 = 0.02$ pu $\times 60 = 1.2$ Hz, $f_{new} = 58.8$ Hz~~

We assume The loss of generator 4 is equivalent to as a sudden Increase in $P_{L2}$ then we have:




$$\Delta P_L^{pu} = \frac{900 - 1100}{\underbrace{1000}_{Rating1} + \underbrace{1000}_{Rating2} + \underbrace{500}_{Rating3}} = 0.08 \text{ pu} \qquad P_{L_3} = 800$$

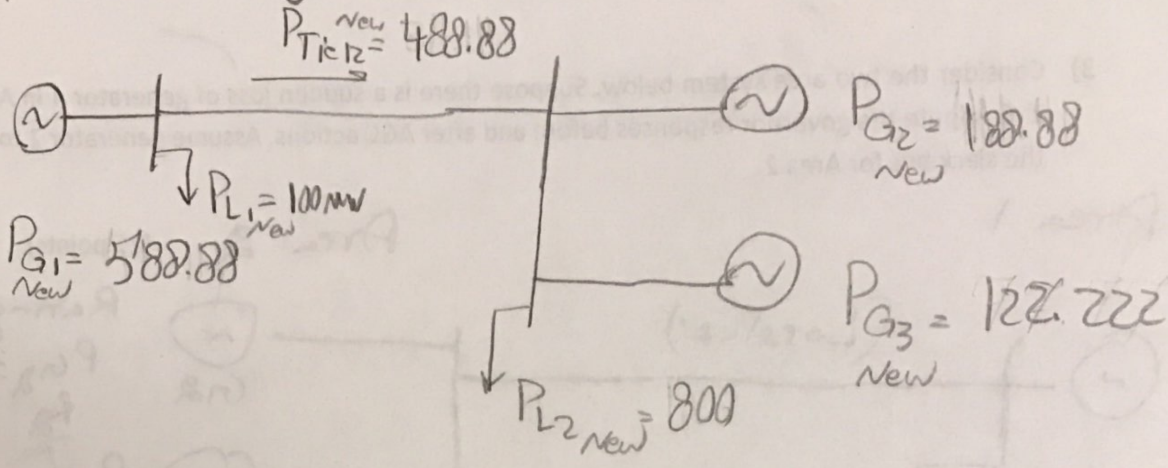
$$\Delta f = \frac{+200}{\frac{1000}{0.05} + \frac{100}{0.05} + \frac{500}{0.1}} = 4.44 \times 10^{-3} \text{ pu} = 0.2666 \text{ Hz} \rightarrow \text{New } f = 59.733 \text{ Hz}$$

$$\Delta P_{G_1} = \frac{-4.44 \times 10^{-3}}{0.05} = +0.0888 \text{ pu} \times 1000 = +88.88$$

$$\Delta P_{G_2} = \frac{-4.44 \times 10^{-3}}{0.05} = +0.0888 \text{ pu} \times 1000 = +88.88$$

$$\Delta P_{G_3} = \frac{+4.44 \times 10^{-3}}{0.1} = 0.0444 \times 500 = +22.22$$

Then after governor action we have:




Now AGC actions:

$P_{Net_1} = 488^{MW} \quad P_{Net_2} = -488$

$\Delta P_{Net_1} = 488 - 400 = +88^{MW} = \frac{88}{1000} = 0.088 \text{ pu}$

$\Delta f_1 = -4.44 \times 10^{-3} \text{ pu}$

$ACE_1 = \Delta P_{Net1} + B_1 + \Delta f_1$

$ACE_1 = \frac{-88}{1500} + \frac{1}{0.03} \times (-4.44 \times 10^{-3}) = 0 \implies$ Then $P_{G_1} = 500$

$ACE_2 = 0.088 + 3.33(-4.44 \times 10^{-3}) = -200 \implies$ Because Gen. 2 is slack

$1/R_{eq} = \frac{1}{R_2} + \frac{1}{R_3}$

$P_{G_2} = 300 \text{ MW}$

$P_{G_3} = 100 \text{ MW}$

**Bonus Questions:**

(5 points)

1) Who is the Secretary of Energy?

2) What are the two main basic principles from Physics in the design of synchronous generators? Name and state them.

Newton law

Farady law

[illegible]

3) Name two South American countries where the AC frequency is 60 Hz and 50 Hz respectively.

Argentina Brazil

2

4) Which is the second largest hydroelectric power generation facility in US next to Grand Coulee?

5) Which is the largest solar power plant (or farm) in the world? Germany

2

2

$$Y_{Net} = \left[\begin{array}{cc|c} -j2 & 0 & j2 \\ 0 & -j4 & j4 \\ \hline j2 & j4 & 0.277-j5.9849 \end{array}\right]$$

$$\vec{Y}_{Gen} = \vec{Y}_{11} - \vec{Y}_{12}\,\vec{Y}_{22}^{-1}\,\vec{Y}_{21} = \begin{bmatrix} -j2 & 0 \\ 0 & -j4 \end{bmatrix} - \begin{bmatrix} j2 \\ j4 \end{bmatrix} \frac{1}{0.277-j5.9849} [j2 \;\; j4]$$

$$= \begin{bmatrix} 1.3334\angle -1.5476 & 1.3353\angle +1.5245 \\ 1.3353\angle 1.5245 & 1.3380\angle -1.4784 \end{bmatrix}$$

$$P_{e_2} = Y_{Gen_{21}} E_2' E_1' \cos(\theta_2 - \theta_1 - \theta_{21}) + Y_{Gen_{22}} E_{22}'^{2} \cos(-\theta_{22}) =$$

$$= 1.3353 \times 1.111 \times 1 \cos(\theta_2 - 0 - (+1.5245)) + 1.3380 \times 1.111^2 \cos(1.4784)$$

$$P_{e_2} = 1.4836 \cos(\theta_2 - 1.5245) + 0.1523$$

$$\dot{\omega}_2 = \frac{1}{2 \times 5}\left[P_{m_2} - (1.4836 \cos(\theta_2 - 1.5245) + 0.1523) - (\omega_2 - 1)\right]$$

$$\dot{\omega}_2 = 0.1 P_{m_2} - 0.14836 \cos(\theta_2 - 1.5245) + 0.08477 - 0.1\,\omega_2$$

$$J = \begin{bmatrix} \frac{\partial \dot{\theta}_2}{\partial \theta_2} & \frac{\partial \dot{\theta}_2}{\partial \omega_2} \\ \frac{\partial \dot{\omega}_2}{\partial \theta_2} & \frac{\partial \dot{\omega}_2}{\partial \omega_2} \end{bmatrix} = \begin{bmatrix} 0 & 377 \\ 0.14836 \sin(\theta_2 - 1.5245) & -0.1 \end{bmatrix}$$

$$J\Big|_{\begin{pmatrix}0.5812^{rad}\\1\end{pmatrix}} = \begin{bmatrix}0 & 377\\ -0.12182 & -0.1\end{bmatrix}$$

$$\det(\lambda I - J) \overset{\det}{=} \begin{bmatrix}\lambda & -377\\ +0.12182 & \lambda+0.1\end{bmatrix} = (\lambda^2 + 0.1\lambda) + 45.92 = 0$$

$$\Longrightarrow \lambda^2 + 0.1\lambda + 45.92 = 0 \Longrightarrow \lambda_1 = -0.05 + j6.77$$

$$\lambda_2 = -0.05 - j6.77$$

Then system is S.S Stable

$$\vec{v}_1 = \begin{bmatrix}0.9998\\ -0.0001 + j0.018\end{bmatrix} \quad \vec{v}_2 = \begin{bmatrix}0.9998\\ -0.0001 - j0.08\end{bmatrix}$$

$$\vec{w}_1 = \begin{bmatrix}0.0001 - j0.018 & 0.9998\end{bmatrix} \qquad \vec{w}_2 = \begin{bmatrix}0.0001 + j0.018 & 0.9998\end{bmatrix}$$

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