Name: TUSHAR.

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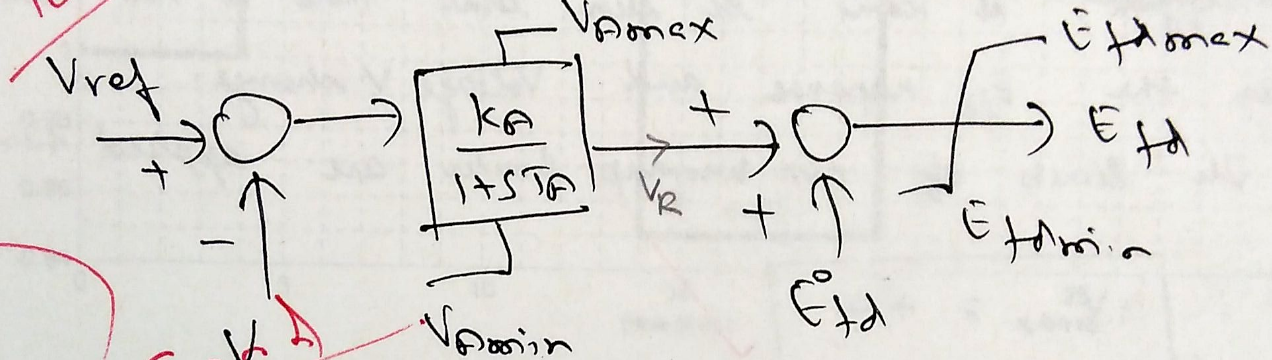
EE523 Power System Stability and Control

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)



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$$V_R(s) = \left(\frac{K_A}{1+sT_A}\right)(V_{ref} - V)$$

$$V_R + T_A \dot{V}_R = K_A(V_{ref} - V)$$

$$\dot{V}_R = \frac{1}{T_A}\left[K_A(V_{ref} - V) - V_R\right]$$

At steady state

$$\dot{V}_R = 0$$

$$V_R = K_A(V_{ref} - V)$$

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$$V_R + E_{fd_0} = E_{fd} \quad ; \quad E_{fd} = K_A(V_{ref} - V) + E_{fd0}$$

At time $t = 25$

$E_{fd} = 0$; $V = 1.03$ $V_{ref} = 1.03$

$$\boxed{0 = E_{fd0}}$$

At time $t = 30$

$V = 1.02$

$$1 = K_A(1.03 - 1.02) \Rightarrow \boxed{K_A = 100}$$

For time between $t = 4$ and $t = 10$

Change in $E_{fd} = -2 - (3) = -5$

63.2% of $(-5) = -3.16$

From figure $\therefore$ Time constant $= T_A = 1$ Second.

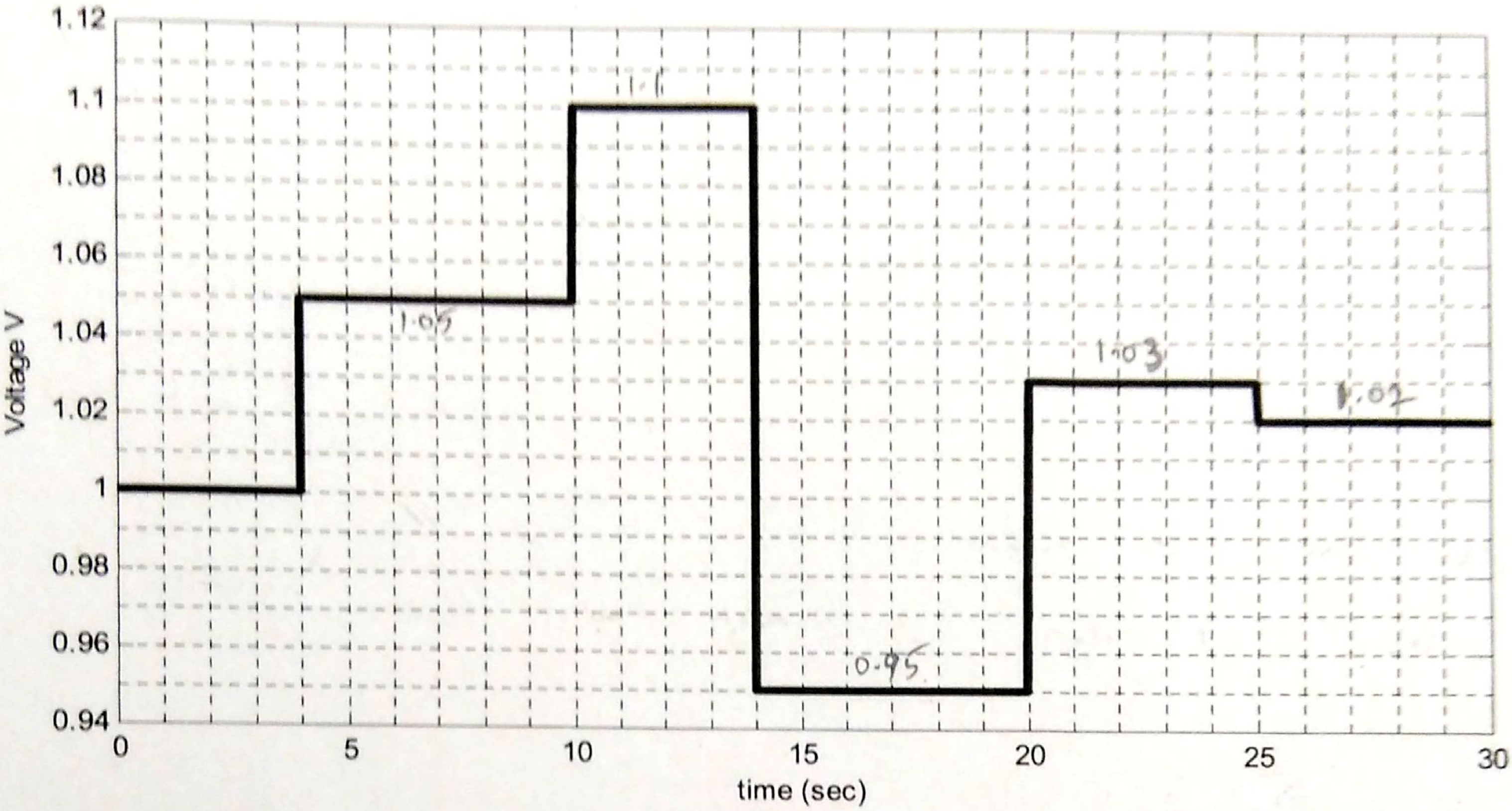
From figure, it can be seen that there is no delay between the E_{fd} response and Voltage V change.

$\therefore$ The limits of non windup limiter are applied here.

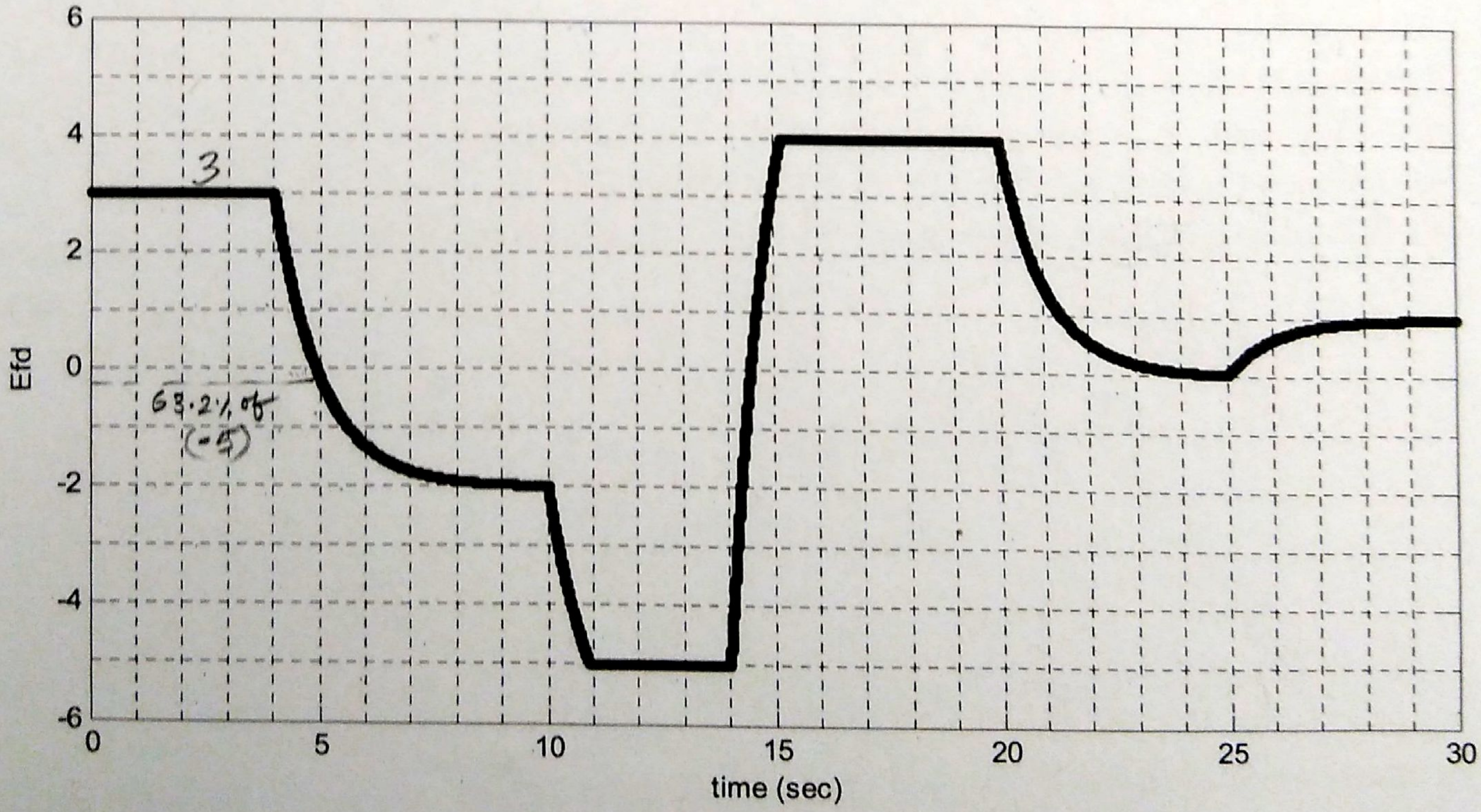
$\therefore$ $\boxed{\begin{aligned} V_{Amax} &= +4 \\ V_{Amin} &= -5 \end{aligned}}$

The wind-up limits can be greater or equal to non windup limits

$\therefore$ $\boxed{\begin{aligned} E_{fdmax} &\geq +4 \\ E_{fdmin} &\leq -5 \end{aligned}}$

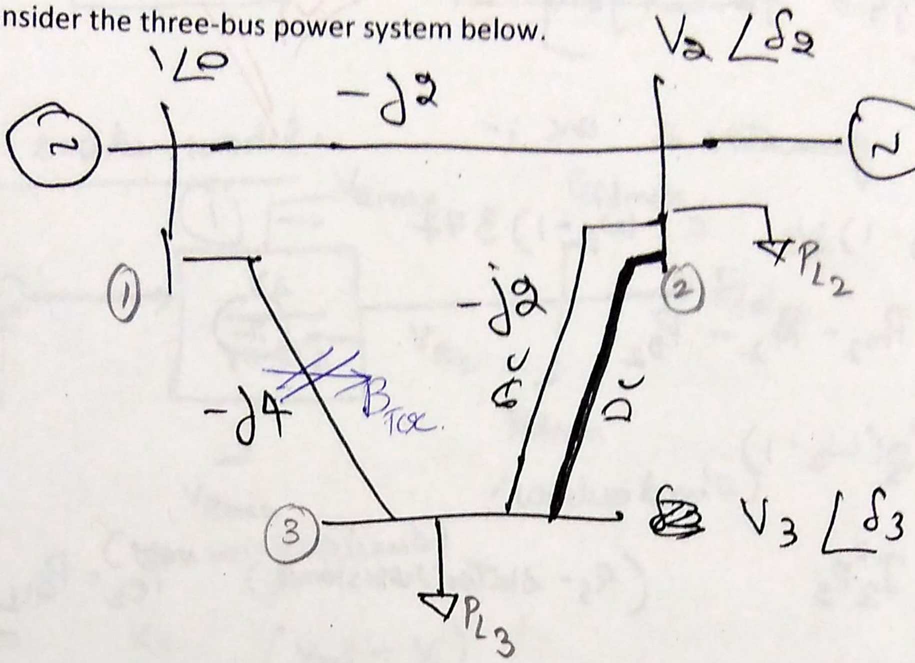


1.12
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
Voltage V
0
5
10
15
20
25
30
time (sec)
1.1
1.05
1.03
1.02
0.95

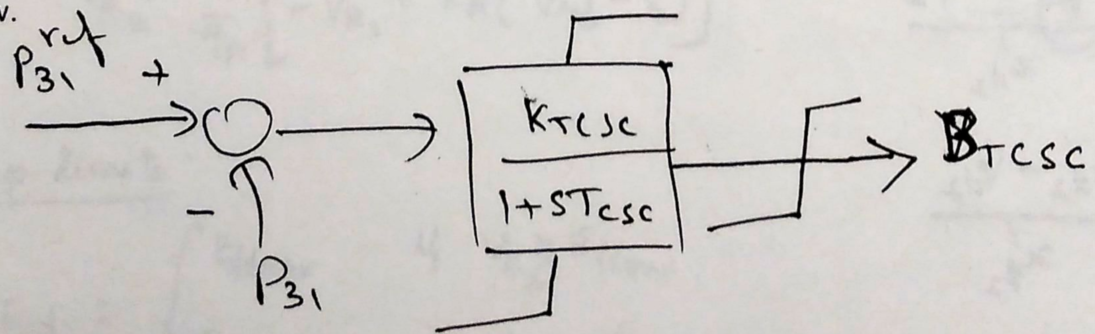


6
4
2
0
-2
-4
-6
Efd
0
5
10
15
20
25
30
time (sec)
3
63.2% of
(-5)

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) $$Y_{bus} = \begin{array}{c} \\ 1 \\ 2 \\ 3 \end{array} \begin{array}{c} \begin{array}{ccc} 1 & 2 & 3 \end{array} \\ \begin{bmatrix} -j6+B_{TCSC} & j2 & j4-B \\ j2 & -j4 & j2 \\ j4-B & j2 & -j6+B \end{bmatrix} \end{array}$$

B_{TCSC}

DAE equations for generator 2 are :-

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

$$2H_2\dot{\omega}_2 = P_{m_2} - P_{e_2} - P_{D_2} \quad \text{— (2)}$$

$$P_{D_2} = K_{D_2}(\omega_2 - 1)$$

$$P_{e_2} = P_{G_2} + I_2^2 R_s$$

(R_s - stator resistance) $P_{e_2} = P_{G_2}$ (neglecting stator resistance)

$$P_{G_2} = V_{d_2} I_{d_2} + V_{q_2} I_{q_2}$$

$$V_{d_2} = V_2 \cos(\delta_2 + \pi/2 - \theta_2)$$

$$V_{q_2} = V_2 \sin(\delta_2 + \pi/2 - \theta_2)$$

$$I_{d_2} = \frac{E'_{q_2} - V_{q_2}}{x'_{d_2}}$$

$$I_{q_2} = \frac{E'_{d_2} - V_{d_2}}{x'_{q_2}}$$

$$T'_{do_2}\dot{E}'_{q_2} = -E'_{q_2} - (x_{d_2} - x'_{d_2})I_{d_2} + E_{fd_2} \quad \text{— (3)}$$

$$T'_{do_2}\dot{E}'_{q_2} = -E'_{q_2} - (x_{d_2} - x'_{d_2})\left(\frac{E'_{q_2} - V_{q_2}}{x'_{d_2}}\right) + E_{fd2}$$

$$T'_{qo_2}\dot{E}'_{d_2} = -E'_{d_2} + (x_{q_2} - x'_{q_2})I_{q_2} \quad \text{— (4)}$$

$$= -E'_{d_2} + (x_{q_2} - x'_{q_2})\left(\frac{E'_{d_2} - V_{d_2}}{x'_{q_2}}\right)$$

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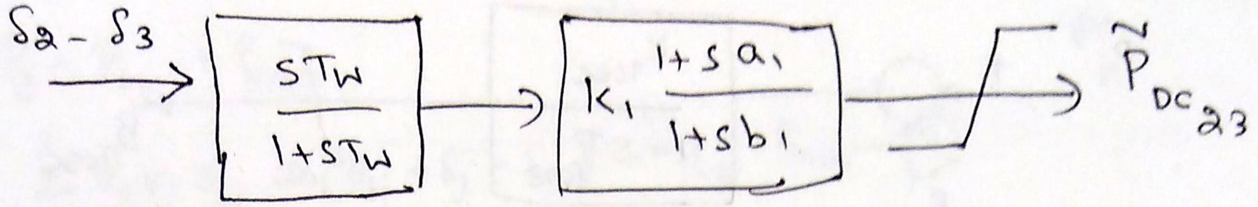
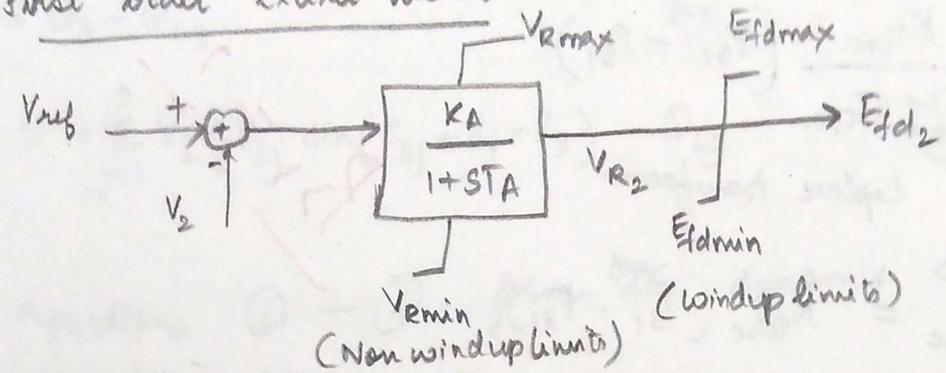


First order exciter model.



$$V_{R_2}(s) = \frac{K_A}{1+sT_A}\left(V_{ref} - V_2\right)$$

Taking Inverse Laplace Transform

$$V_{R_2} + T_A \dot{V}_{R_2} = K_A\left(V_{ref} - V_2\right)$$

$$\dot{V}_{R_2} = \frac{1}{T_A}\left[-V_{R_2} + K_A\left(V_{ref} - V_2\right)\right] \quad \text{— (5)}$$

Windup limits:

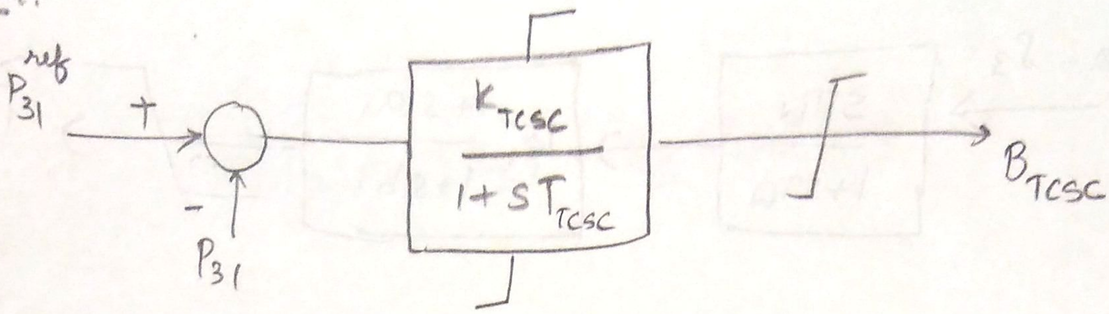
$$E_{fd_2} = \begin{cases} E_{fdmax} & \text{if } V_{R_2} \geq E_{fdmax} \\ E_{fdmin} & \text{if } V_{R_2} \leq E_{fdmin} \\ V_R & \text{otherwise.} \end{cases}$$

4.0

Non windup limits:-

$$\dot{V}_{R_2} = \begin{cases} 0 & \text{if } V_{R_2} = V_{Rmax} \text{ and } \dot{V}_{R_2} > 0 \\ 0 & \text{if } V_{R_2} = V_{Rmin} \text{ and } \dot{V}_{R_2} < 0 \\ \dot{V}_{R_2} & \text{otherwise.} \end{cases}$$

TCSC model:



$$B_{TCSC}(s) = \frac{K_{TCSC}}{1+sT_{TCSC}}\left(P_{31}^{ref} - P_{31}\right)$$

Taking inverse Laplace transform.

$$B_{TCSC} + T_{TCSC}\dot{B}_{TCSC} = K_{TCSC}\left(P_{31}^{ref} - P_{31}\right)$$

$$\dot{B}_{TCSC} = \frac{1}{T_{TCSC}}\left[-B_{TCSC} + K_{TCSC}\left(P_{31}^{ref} - P_{31}\right)\right] \quad — (6)$$

with windup and non-windup limits similar to exciter model.

∴ The dynamic states include, $\theta_2, \omega_2, E_{q_2}', E_{d_2}', V_{R_2}, B_{TCSC}$

Assuming power is flowing from Bus 2 to Bus 3 in the HVDC line. HVDC line flow power is modeled as load at bus 2 and generator at Bus 3.

$$P_2 = P_{G_2} - P_{L_2} - P_{HVDC}$$ where P_{HVDC} is load due to HVDC line model.

$$0 = P_2 - P_{G_2} - P_{L_2} - P_{HVDC} \quad — (7)$$

where $P_2 = \sum_{j=1}^{3} V_2 V_j Y_{2j} \cos(\theta_{2j} + \delta_j - \delta_2)$

$$Q_2 = Q_{G_2} - Q_{L_2}$$

$$0 = Q_2 - Q_{G_2} - Q_{L_2} \quad — (8)$$

where $Q_2 = -\sum_{j=1}^{3} V_2 V_j Y_{2j} \sin(\theta_{2j} + \delta_j - \delta_2)$

∴ The power flow states include $\delta_2, V_2, \delta_3, V_3$.

$$0 = P_3 - P_{L_3} + P_{HVDC}$$

$$0 = \sum_{j=1}^{3} V_3 V_j Y_{3j} \cos(\theta_{3j} + \delta_j - \delta_3) - P_{L_3} + P_{HVDC} \quad — (9)$$

$$0 = Q_3 - Q_{L3}$$

$$0 = -\sum_{j=1}^{3} V_3 V_j Y_{3j} \sin(\theta_{3j} + \delta_j - \delta_3) - Q_{L3} \quad — (10).$$

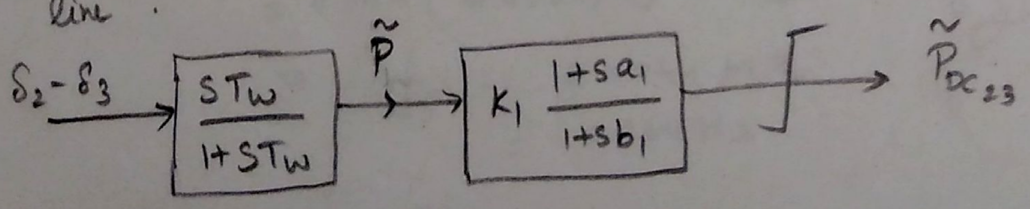
Equations (1) – (6) form the dynamic state equations of the form $\dot{x} = f(x, y)$

the powerflow state equations of equations (7) – (10) form the power flow ~~Gi~~ the form $0 = g(x, y)$

where $x \rightarrow$ dynamic states

$y \rightarrow$ power flow states.

(b) Here we are going to control the power flow in the HVDC line.



From the block diagram,

$$\tilde{P}(s) = \left(\frac{sT_w}{1+sT_w}\right)(\delta_2 - \delta_3)$$

Need two states

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Taking Inverse laplace transform,

$$\tilde{P} + T_w \dot{\tilde{P}} = T_w(\dot{\delta}_2 - \dot{\delta}_3) \quad — (11)$$

$$\dot{\tilde{P}} = \frac{1}{T_w}\left[-\tilde{P} + T_w(\dot{\delta}_2 - \dot{\delta}_3)\right]$$

$$\tilde{P}_{DC_{23}}(s) = K_1 \frac{1+sa_1}{1+sa_2} \tilde{P}(s)$$

Taking inverse laplace transform

$$\tilde{P}_{DC_{23}} + a_2 \dot{\tilde{P}}_{DC_{23}} = K_1 \tilde{P} + K_1 a_1 \dot{\tilde{P}}$$
$$= K_1 \left[\tilde{P} + a_1 \dot{\tilde{P}} \right]$$

Using equation (11) we get

$$\dot{\tilde{P}}_{DC_{23}} = \frac{1}{a_2}\left[-\tilde{P}_{DC_{23}} + K_1 \left[\tilde{P} + a_1 \times \frac{1}{T_W}\left\{ -\tilde{P} + T_W(\dot{\delta}_2 - \dot{\delta}_3) \right\} \right] \right] \quad -(12).$$

with windup limits.

∴ In case (b) the dynamic states are

$$\theta_2,\ \omega_2,\ E'_{q_2},\ E'_{d_2},\ V_{R_2},\ B_{TCSC},\ \tilde{P}_{DC_{23}} \quad (A)$$

Equations (1) - (6) and (12) are the dynamic state equations.

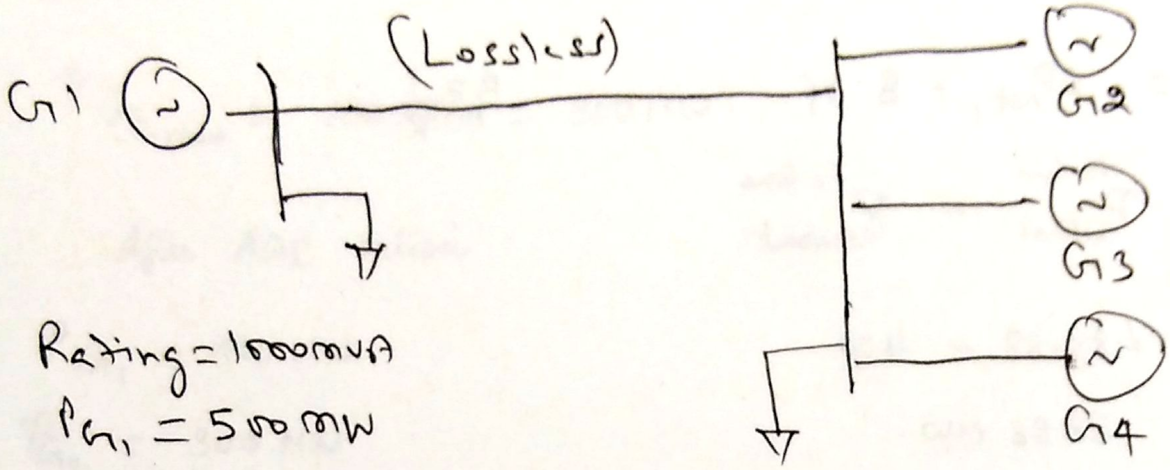
Power flow states are

$$\delta_2,\ V_2,\ \delta_3,\ V_3.$$

Equations (7) - (10) are the power flow state equations.

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.

Area 1 Area 2 (25 points)



Area 2:

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

Rating = 500 MVA, $P_{G_3} = 100$ MW, $R_2 = 10\%$

Rating = 500 MVA, $P_{G_4} = 200$ MW, $R_2 = 5\%$

$P_{L_2} = 800$ MW

Area 1:

Rating = 1000 MVA

$P_{G_1} = 500$ MW

$P_{L_1} = 100$ MW

$R = 5\%$

Governor Response:

$$\Delta P = \frac{200}{2250} = 0.0889 \text{ pu}$$

for generator 3 ; $R_3 = 10\%$ @ 500 MVA.
$R_3 = 5\%$ @ 250 MVA.

$$P_{\text{Tie line contract}} = 500 - 100 = 400 \text{ MW}.$$

$$R = \frac{\Delta f}{\Delta P} \qquad \Delta f = R \cdot \Delta P$$

$$= 0.05 \times (0.0889)$$

$$= \frac{1}{225} = 0.0044 \text{ pu}.$$

$$= 0.264 \text{ Hz}$$

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$$f_{new} = 59.736 \text{ Hz}$$

$$\Delta P_{G_1} = \frac{\Delta f}{R_1} = \frac{0.0044}{0.05} = 0.0888 \text{ pu} = 88.88 \text{ MW}.$$

$$\therefore P_{G_1} = 588.88 \text{ MW}$$

$$\Delta P_{G_2} = \frac{\Delta f}{R_2} = \frac{0.0044}{0.05} = 0.0888 \text{ pu} = 88.88 \text{ MW}$$

$$\therefore P_{G_2} = 188.88 \text{ MW}$$

$$\Delta P_{G_3} = \frac{\Delta f}{R_3} = \frac{0.0044}{0.10} = 22.22 \text{ MW} \qquad \therefore P_{G_3} = 122.22 \text{ MW}$$

$$P^{actual}_{Tie\ line} = 500 + 88.88 - 100 = 488.88\ MW.$$

These values are not in accordance with the contract and hence AGC action will take place.

AGC action:

$$ACE_1 = \Delta P_{net_1} + B\,\Delta f \qquad B = \frac{1}{R}$$

$$\Delta P_{net_1} = P^{tie\ line}_{actual} - P^{tie\ line}_{contract}$$

$$= 488.88 - 400$$

$$= 88.88\ MW.$$

$$= \frac{88.88}{1000} = 0.0888\ pu.$$

$$\Delta f = f_{actual} - f_{contract}$$

$$= 59.736 - 60 = -0.264\ Hz = -0.0044\ pu$$

$$ACE_1 = 0.0888 + \frac{1}{0.05} \times (-0.0044)$$

$$= 0$$ (Area 1 shouldnot increase or decrease the generation)

$$ACE_2 = \Delta P_{net_2} + B\,\Delta f$$

$$\Delta P_{net_2} = -488.88 - (-400)$$

$$= -88.88\ MW$$

$$= \frac{-88.88}{1250} = -0.0711\ pu$$

$$ACE_2 = -0.0711 + \frac{1}{0.05}(-0.0044) = -0.1591\ pu \approx -200\ MW$$

$\therefore$ Area 2 should increase the generation by 200 MW.

Assuming generator 2 is the slack bus for area 2.

Generator 2 will increase its generation by 200 MW.

$P_{G_{2new}} = 100 + 200 = 300$ MW.

After AGC action

$P_{G_1} = 500$ MW

$P_{G_2} = 300$ MW

$P_{G_3} = 100$ MW

$P_{L_1} = 100$ MW

$P_{L_2} = 800$ MW.

$f = 60$ Hz

$P_{Tie\ line} = 400$ MW.

Bonus Questions:

(5 points)

1) Who is the Secretary of Energy?

Ernest Moniz

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

Newton's second law – Rate of change of ~~[illegible]~~ velocity is directly proportional to the applied force.

Faraday's law – The emf induced in a circuit is directly proportional to the rate of change of flux in the circuit.

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

Argentina – 60Hz

Brazil – 50Hz

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

Chief Joseph

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

Texas.

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