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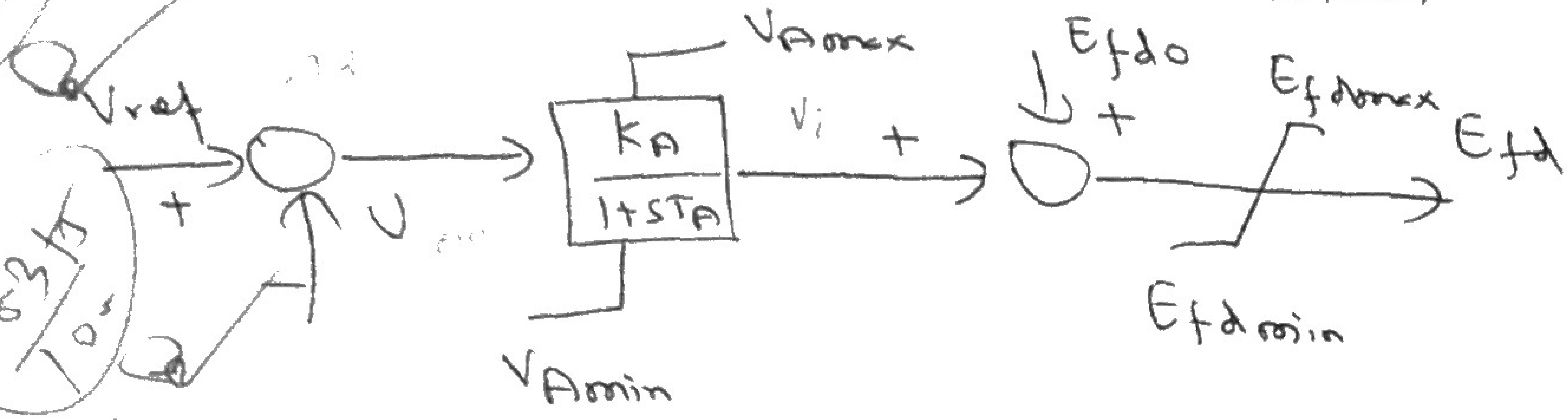
EE581 Power System Stability and Control

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. (30 points)



$20 < t < 25 \qquad 4 + E_{fdo} - K_A \times 0.08 = 0$

$E_{fd\,ss} = E_{fdo} + K_A (V_{ref} - V)$

$\Rightarrow E_{fdo} + K_A \times 0 = 0 \Rightarrow \boxed{E_{fdo} = 0}$

zero

$25 < t < 30 \Rightarrow \cancel{E_{fdo}} + K_A \times 0.01 = 1 \Rightarrow \boxed{K_A = \frac{1}{0.01} = 100}$

$4 < t < 10 \Rightarrow \boxed{T_A = 1}$ the time that needs to reach 63% of final value

$V_{Amax} = 4$

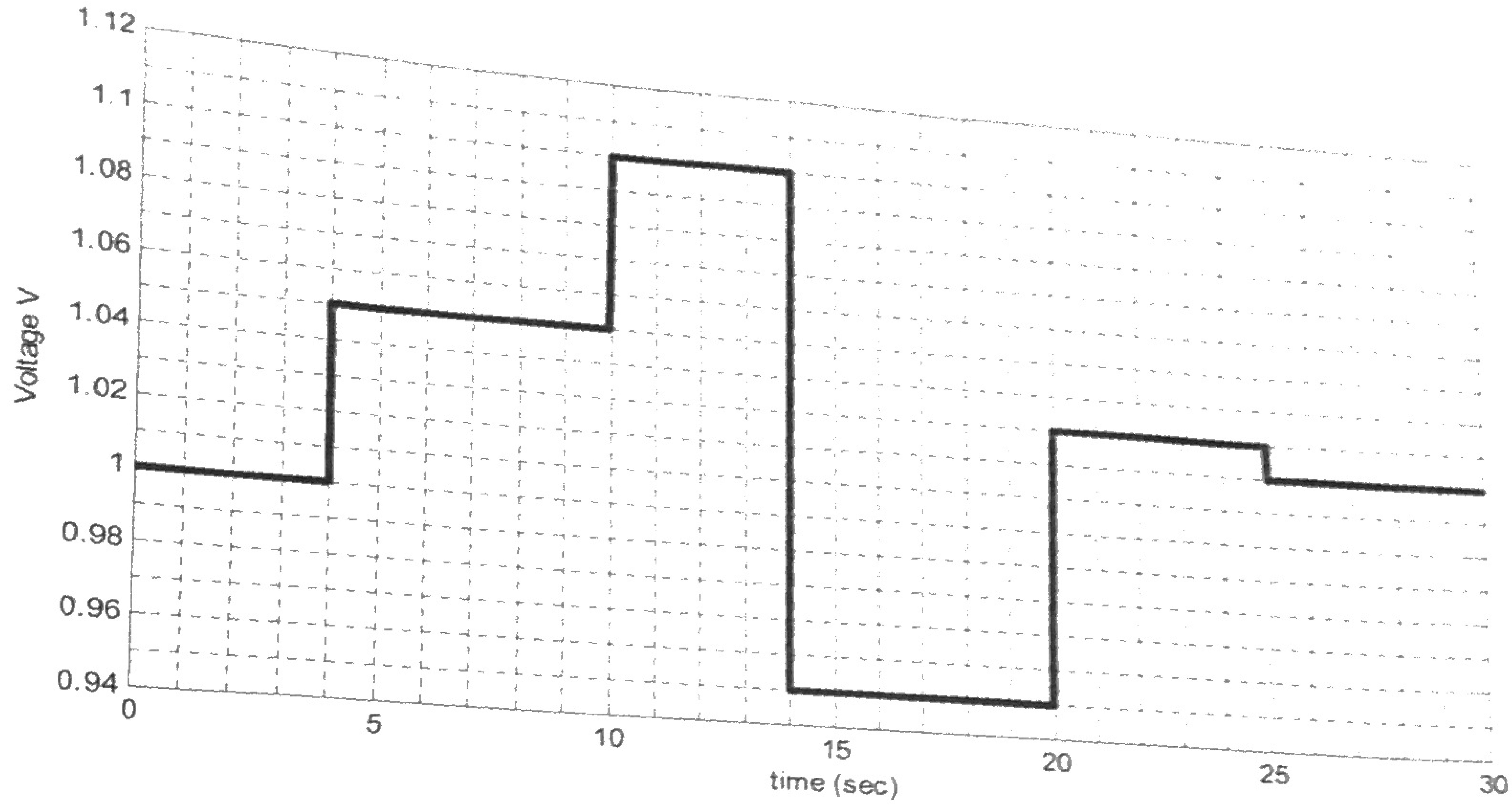
$V_{Amin} = -5$

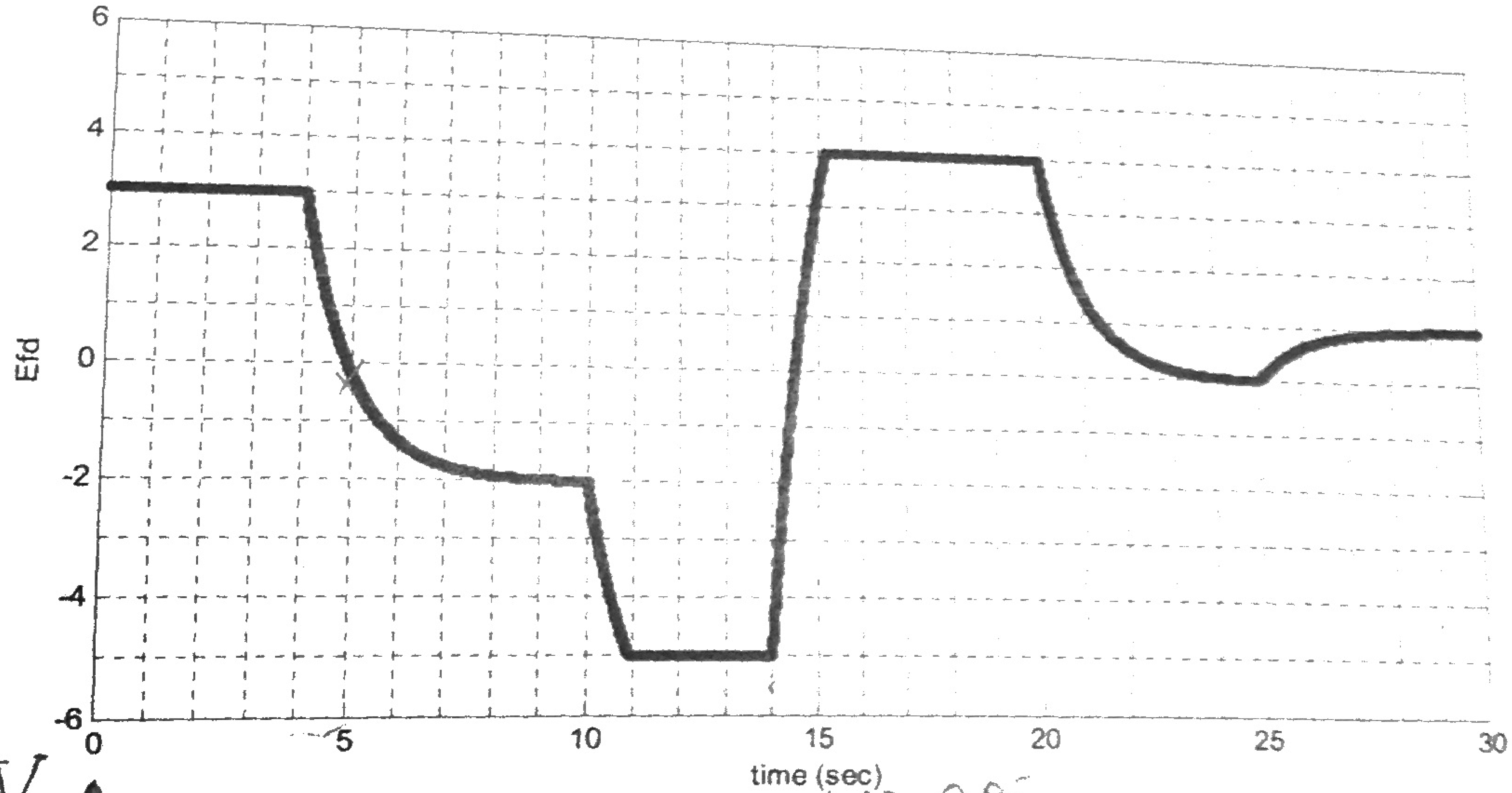
$E_{fmax} \geq 4$

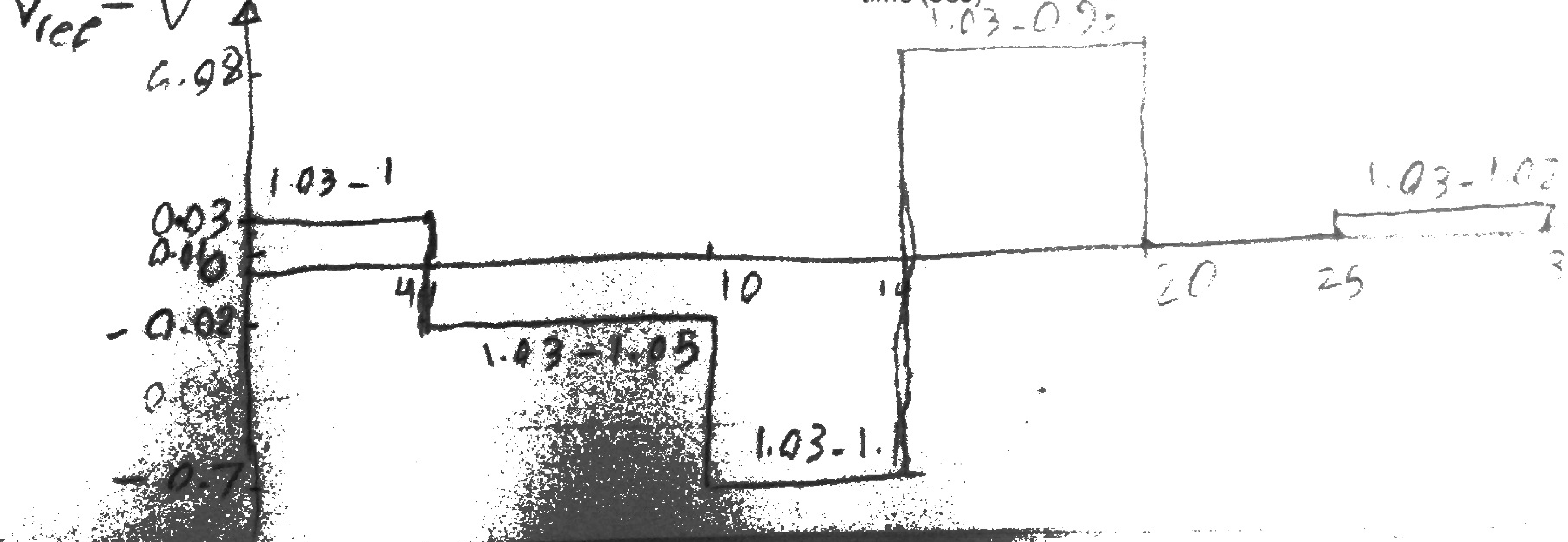
$E_{fmin} \leq -5$

30

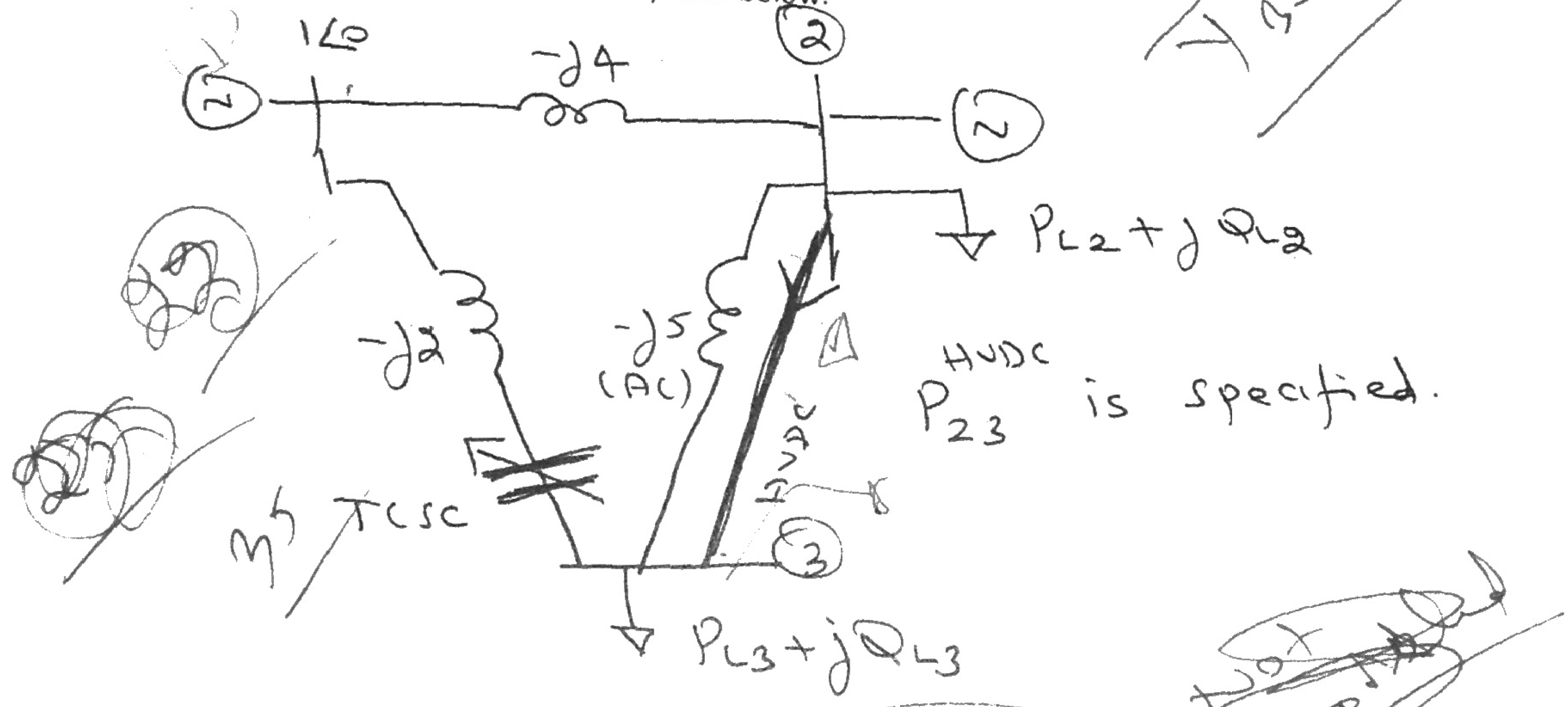
2


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)

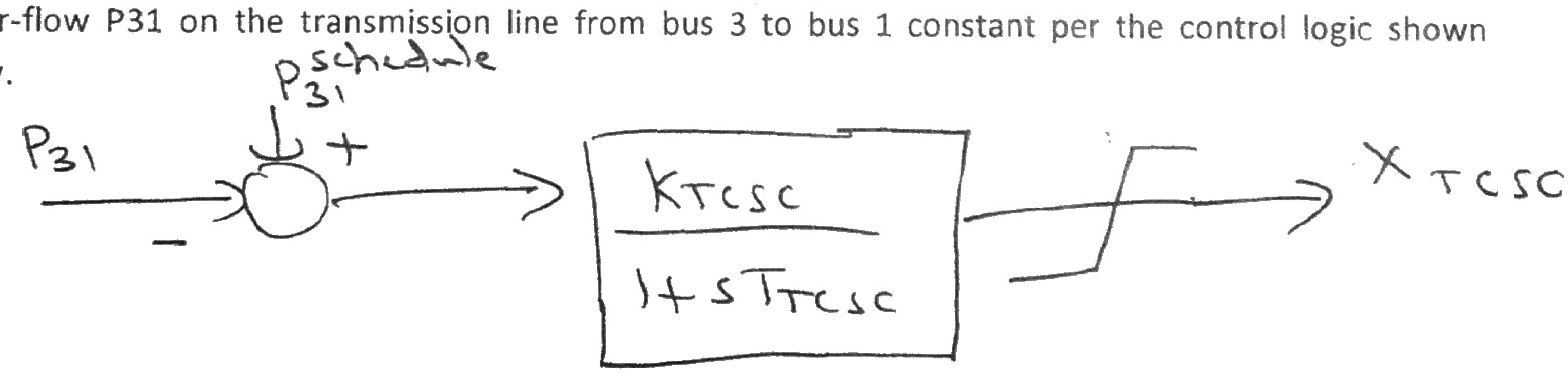

6
4
2
0
-2
-4
-6
Efd
0
5
10
15
20
25
30
time (sec)


Vref−V
0.08
0.03
0
-0.02
-0.7
1.03-1
1.03-1.05
1.03-1.
1.03-0.95
1.03-1.02
4
10
14
20
25
30

2) Consider the three-bus power system below.

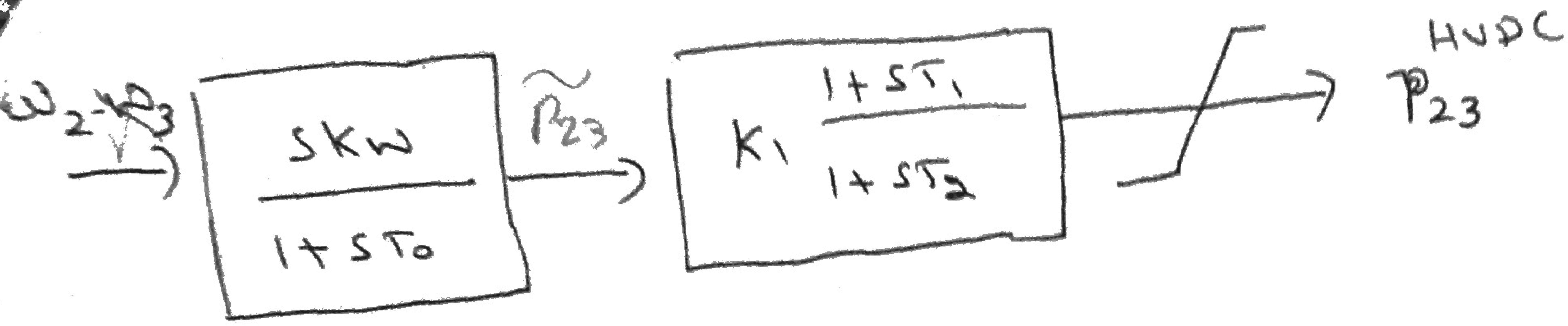


Assume the generator is modeled by a standard first order exciter control with no governor control modeled. There is a HVDC transmission line from ~~bus 2 to bus 3 that can~~ be modeled as a lossless link. The HVDC power electronic controls keep the complex AC power on both sides of the DC link (at buses 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 ~~DAR~~ 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)



$$\begin{cases} \dot{\theta} = (w-1)\,w_s \\ \dot{w} = \frac{1}{2H}\left[P_m - P_e - k_D(w-1)\right] \\ \dot{E}'_q = \frac{1}{T'_{do}}\left[-E'_q - (x_d - x'_d)I_d + E_{fd}\right] \\ \dot{E}'_d = \frac{1}{T'_{qo}}\left[-E'_d + (x_q - x'_q)I_q\right] \end{cases} \quad (5)$$

$$P_e = P_G + R_s I_G^2 \rightarrow P_G$$

$$P_G = V_2 V_1 Y_{21} \sin(\delta_2 - \delta_1) + V_2 V_3 \sin(\delta_2 - \delta_3) + P_{23}^{HVDC}$$

2 $$P_G = -j4\, V_2 \sin(\delta_2) + V_2 V_3 \sin(\delta_2 - \delta_3) + P_{23}^{HVDC}$$

HVDC Model:

$$\tilde{P}_{23} = \frac{sK_w}{1+sT_0} w_2 \Rightarrow \tilde{P}_{23} + T_0 \dot{\tilde{P}}_{23} = k_w \dot{w}_2$$

$$T_0 \dot{\tilde{P}}_{23} = k_w \dot{w}_2 - \tilde{P}_{23}$$

$$(3) \quad \boxed{\dot{\tilde{P}}_{23} = \frac{1}{T_0}\left[k_w \dot{w}_2 - \tilde{P}_{23}\right]}$$

$$P_{23} = K_1 \frac{1+sT_1}{1+sT_2} \tilde{P}_{23} \Rightarrow P_{23} + T_2 \dot{P}_{23} = K_1 \tilde{P}_{23} + K_1 T_1 \dot{\tilde{P}}_{23}$$

$$\Rightarrow T_2 \dot{P}_{23} = k_1 \tilde{P}_{23} + k_1 T_1 \dot{\tilde{P}}_{23} - P_{23} \Rightarrow \dot{P}_{23} = \frac{1}{T_2}\left[k_1 \tilde{P}_{23} + k_1 T_1 \dot{\tilde{P}}_{23} - P_{23}\right.$$

$$\dot{P}_{23} = \frac{1}{T_2}\left[k_1 \tilde{P}_{23} + k_1 T_1 \left[\frac{1}{T_0}\left[k_w \dot{w}_2 - \tilde{P}_{23} \right] \right] - P_{23} \right]$$

$$\dot{P}_{23} = \frac{1}{T_2}\left[k_1 \tilde{P}_{23} + \frac{k_1 T_1 k_w}{T_0} \dot{w}_2 - \frac{k_1 T_1}{T_0} \tilde{P}_{23} - P_{23} \right] \quad (4)$$

$$E'_d = V_d + R_a I_d - X'_q I_q \qquad \Rightarrow \qquad E'_d - V_d = R_a I_d - X'_q I_q$$

$$E'_q = V_q + R_a I_q + X'_d I_d \qquad\qquad E'_q - V_q = R_a I_q + X'_d I_d$$

$$\Rightarrow \begin{bmatrix} E'_d - V_d \\ E'_q - V_q \end{bmatrix} = \begin{bmatrix} R_a & -X'_q \\ X'_d & R_a \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix}$$

$$\Rightarrow \begin{bmatrix} I_d \\ I_q \end{bmatrix} = \frac{1}{R_a^2 + X'_d X'_q} \begin{bmatrix} R_a & X'_q \\ -X'_d & R_a \end{bmatrix} \begin{bmatrix} E'_d - V_d \\ E'_q - V_q \end{bmatrix}$$

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \underbrace{\frac{R_a}{R_a^2 + X'_d X'_q}}_{Y_{11}} & \underbrace{\frac{X'_q}{R_a^2 + X'_d X'_q}}_{Y_{12}} \\ \underbrace{\frac{-X'_d}{R_a^2 + X'_d X'_q}}_{Y_{21}} & \underbrace{\frac{R_a}{R_a^2 + X'_d X'_q}}_{Y_{22}} \end{bmatrix} \begin{bmatrix} E'_d - V_d \\ E'_q - V_q \end{bmatrix}$$

$$\overset{(1)}{\Longrightarrow} \begin{cases} I_d = Y_{11}(E'_d - V_d) + Y_{12}(E'_q - V_q) \\ I_q = Y_{21}(E'_d - V_d) + Y_{22}(E'_q - V_q) \end{cases}$$

TCSC: Model

$$\left(P_{31}^{schedule} - P_{31}\right)\frac{k_{TCSC}}{1+sT_{TCSC}} = X_{TCSC}$$

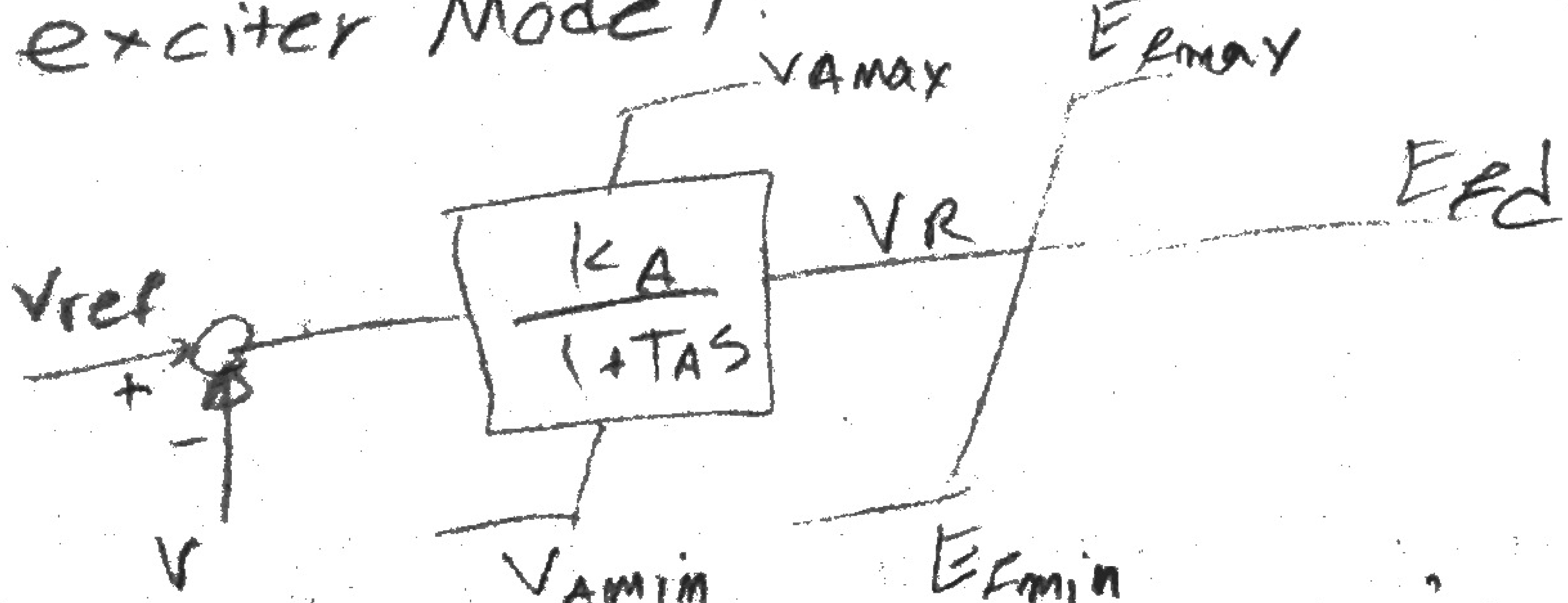
$$\Rightarrow \left(P_{31}^{schedule} - P_{31}\right)k_{TCSC} = X_{TCSC}\left(1 + sT_{TCSC}\right)$$

$$\cancel{T_{TCSC}\dot{X}_{TCSC} = -X_{TCSC} + k_{TCSC}\left(P_{31}^{schedule} - P_{31}\right)}$$

$$P_{31} = V_3 V_1 \times \underline{(-j2)} \sin(\delta_3 - \delta_1) = \underline{-j2 V_3 \sin(\delta_3)}$$

$$\Rightarrow \boxed{\dot{X}_{TCSC} = \frac{1}{T_{TCSC}}\left[-X_{TCSC} + k_{TCSC}\left(P_{31}^{schedule} + \underline{j}2V_3\sin(\delta_3)\right)\right]}$$

exciter Model:



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$$k_A(V_{ref} - V) = (1+T_A s)V_R \Rightarrow T_A\dot{V}_R = -V_R + k_A(V_{ref} - V)$$

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

P1

$$\Rightarrow \dot{V}_R = \begin{cases} 0 & V_R = V_{Amax},\ \dot{V}_R > 0 \\ 0 & V_R = V_{Amin},\ \dot{V}_R < 0 \\ V_R^{dot} & O.W \end{cases}, \quad E_{fd} = \begin{cases} E_{fmax} & V_R > E_{fmax} \\ E_{fmin} & V_R < E_{fmin} \\ V_R & O.W \end{cases}$$

a) In The first Case without HVDC damping controllers state of the system are: $\theta, W, E'_q, E'_d, V_R, X_{TCSC}$ and

y variables are $V_2, \delta_2, V_3, \delta_3$

The state equations will be:

$$\begin{cases} \dot{\theta} = (w-1)w_s \\ \dot{w} = \frac{1}{2H}\left\{P_m - \left[(-j^4 V_2 \sin(\delta_2) + V_2 V_3 \sin(\delta_2-\delta_3) + P_{23}) + R_s(I_q^2 + I_d^2)\right] - k_D(w-1)\right\} \\ \dot{E}'_q = \frac{1}{T'_{do}}\left[-E'_q - (x_d - x'_d) I_d + E_{fd}\right] \\ \dot{E}'_d = \frac{1}{T'_{qo}}\left[-E'_d + (x_q - x'_q) I_q\right] \\ \dot{V}_R = \frac{1}{T_A}\left[-V_R + k_A(V_{ref} - V)\right] \\ \dot{X}_{TCSC} = \frac{1}{T_{TCSC}}\left\{-X_{TCSC} + k_{TCSC}\left(P_{31}^{schdule} + j^2 V_3 \sin(\delta_3)\right)\right\} \end{cases}$$

I_d and I_q specified in equation 1 based on x and y in this equations $V_d = V\cos(\theta - \delta)$

$V_q = V\sin(\theta - \delta)$

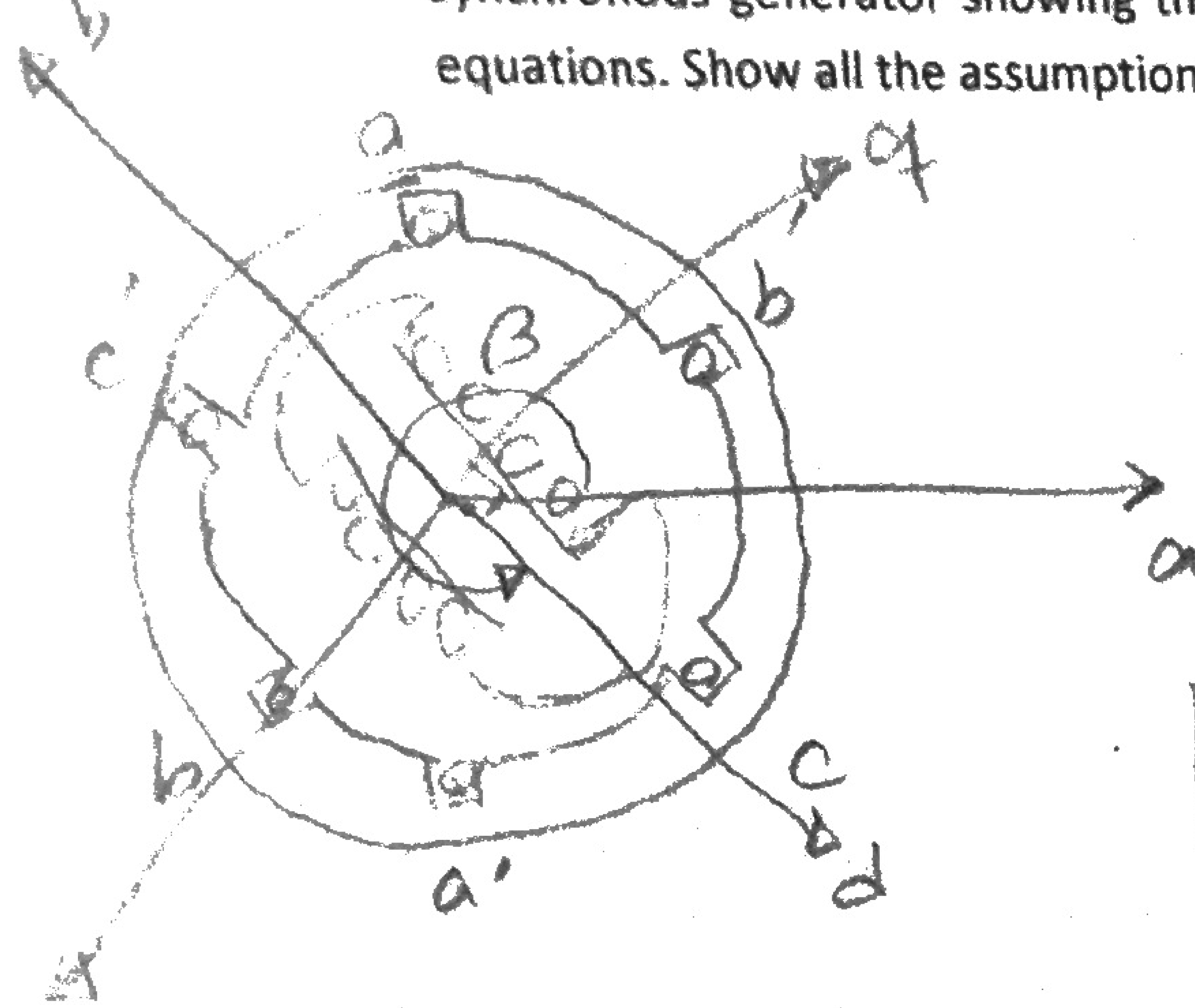
b) with HVDC damping controller states are

$\delta, \omega, E'_q, E'_d, V_R, X_{TCSC}, \tilde{P}_{23}, \tilde{P}_{23}$

and two equations 3 and 4 will be added to the state equations at part a in the equation 4 $\dot{\omega}_2$ is based on equation 6

3) Derive the standard swing equations that describe the electromechanical angle dynamics of the generator starting from Newton's equations. Draw a cross-section of a typical synchronous generator showing the windings and define the angles involved in the swing equations. Show all the assumptions and definitions needed in deriving the swing equations.

(20 points)



$$J\ddot{\beta} = T_m - T_e - T_D$$

$$\beta = \omega_s t + \theta - \frac{\pi}{2}$$

$$\dot{\beta} = \omega_s + \dot{\theta} \Rightarrow \dot{\theta} = \omega - \omega_s$$

$$\ddot{\beta} = \ddot{\theta}$$

$$J\ddot{\theta} = T_m - T_e - T_D$$

$$J\ddot{\theta}\omega_s = T_m\omega_s - T_e\omega_s - T_D\omega_s$$

$\omega_s \approx \omega$

$$J\ddot{\theta}\omega_s = P_m - P_e - P_D$$

$$\frac{J\ddot{\theta}\omega_s}{S_{rating}} = \frac{P_m}{S_{rating}} - \frac{P_e}{S_{rating}} - \frac{P_D}{S_{rating}}$$

Define

We define $H = \frac{\text{Energy in rotor}}{S_{rating}} = \frac{\frac{1}{2}J\omega_s^2}{S_{rating}}$

$$\Rightarrow \boxed{\frac{J\ddot{\theta}\omega_s}{S_{rating}} = \frac{2H}{\omega_s}\ddot{\theta}}$$

$$\Rightarrow \frac{2H}{\omega_s}\ddot{\theta} = P_m(pu) - P_e(pu) - P_D(pu)$$

$$P_D = K_D(\omega - \omega_s)$$

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$$\Longrightarrow \quad \frac{2H}{\omega_s}\ddot{\theta} = P_m(pu) - P_e(pu) - K_D(\omega - \omega_s)$$

$$\begin{cases} \dot{\theta} = \omega - \omega_s \\ \dfrac{2H}{\omega_s}\dot{\omega} = P_m(pu) - P_e(pu) - K_D(\omega - \omega_s) \end{cases}$$

$$\begin{cases} \dot{\tilde{\theta}} = (\tilde{\omega} - 1)\,\omega_s \\ 2H\dot{\tilde{\omega}} = P_m(pu) - P_e(pu) - \underbrace{K_D\,\omega_s}_{\tilde{K}_D}(\tilde{\omega} - 1) \end{cases}$$

$$\begin{cases} \dot{\tilde{\theta}} = (\tilde{\omega} - 1)\,\omega_s \\ 2H\dot{\tilde{\omega}} = P_m(pu) - P_e(pu) - \tilde{K}_D(\tilde{\omega} - 1) \end{cases}$$

Bonus Questions:

(5 points)

1) Who is the Secretary of Energy in President Obama's cabinet?

2) Who is regarded as the father of AC power grid?

3) Identify the two main HVDC links in the western power grid by naming the states that host the two ends of each HVDC link.

4) Why have the governors of WA and OR states resisted deregulation of electricity markets in our states?

5) Name the top two countries that are largest producers of hydroelectric power in the world today.