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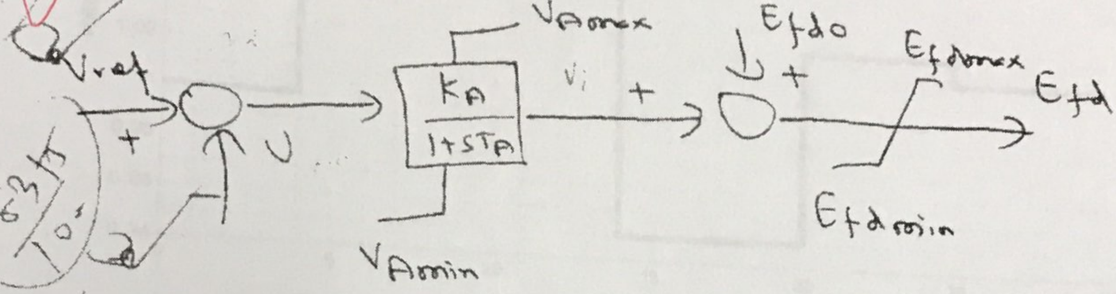
EE581 Power System Stability and Control

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)



$20 < t < 25$ $\quad 4 + E_{fd0} - K_A \times 0.08 = 0$

$E_{fdss} = E_{fd0} + K_A (V_{ref} - V)$

$\Rightarrow E_{fd0} + K_A \times 0 = 0 \Rightarrow \boxed{E_{fd0} = 0}$

$25 < t < 30 \Rightarrow E_{fd0} + K_A \times 0.01 = 1 \Rightarrow \boxed{K_A = \frac{1}{0.01} = 100}$

Zero

$4 < t < 10 \Rightarrow \boxed{T_A = 1.5}$ the time that needs to reach 63% of final value

$V_{Amax} = 4$

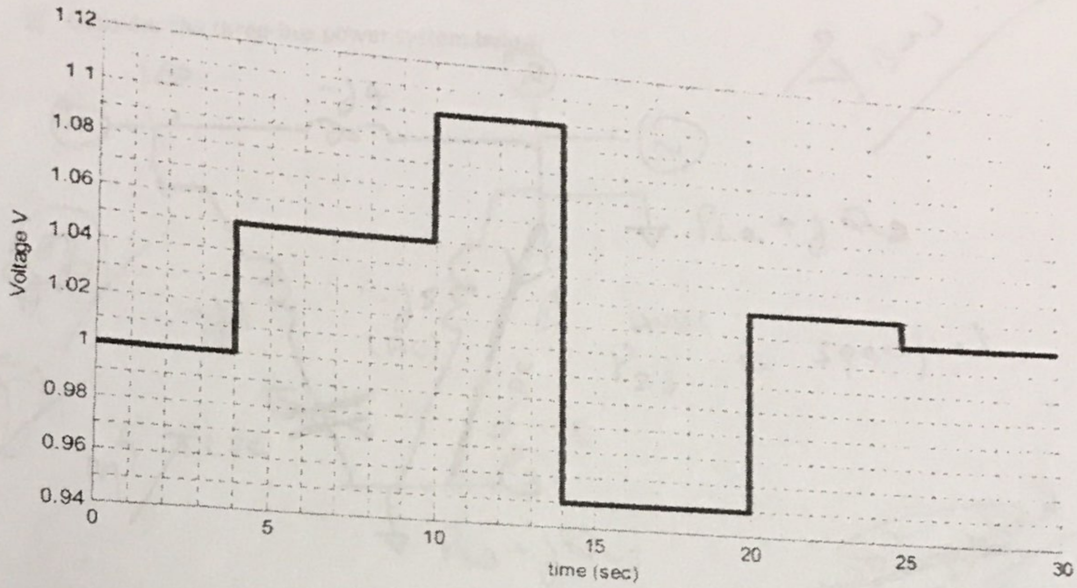
$V_{Amin} = -5$

$E_{fmax} \geq 4$

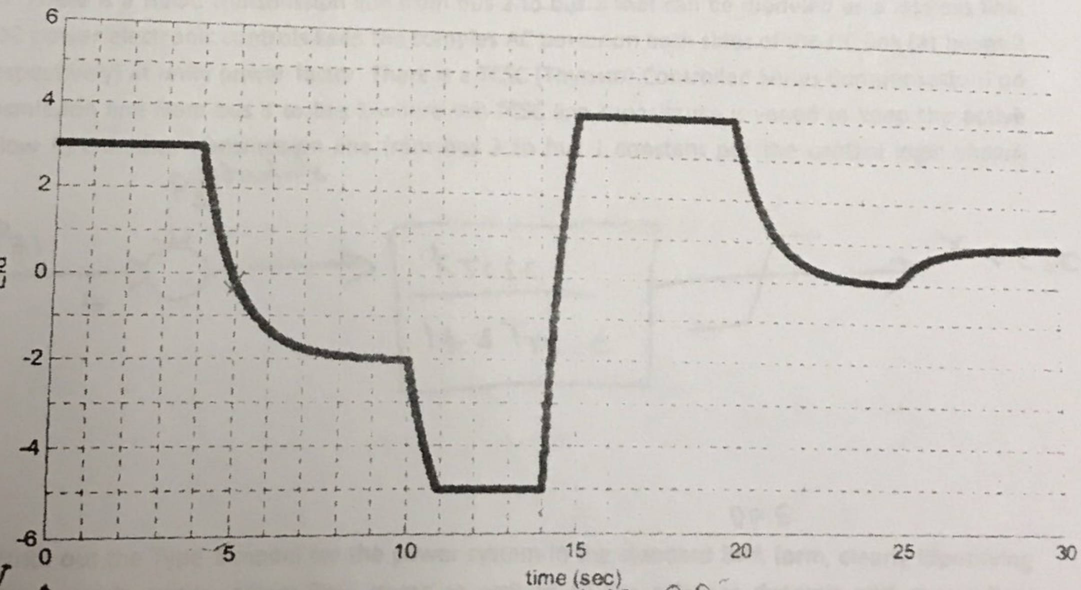
$E_{fmin} \geq -5$

30

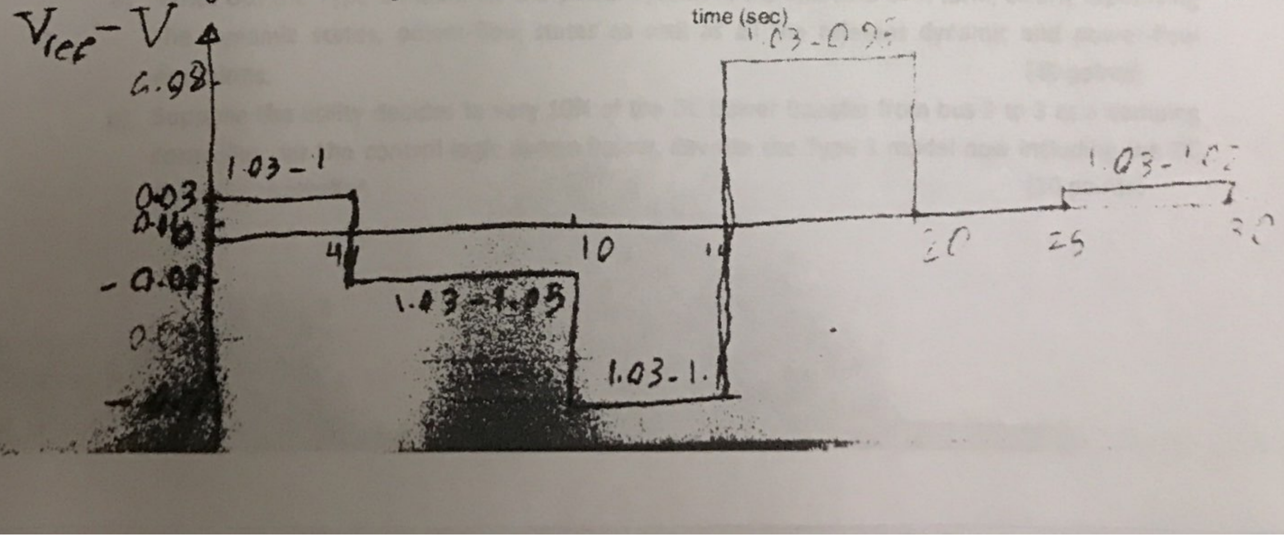
2



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

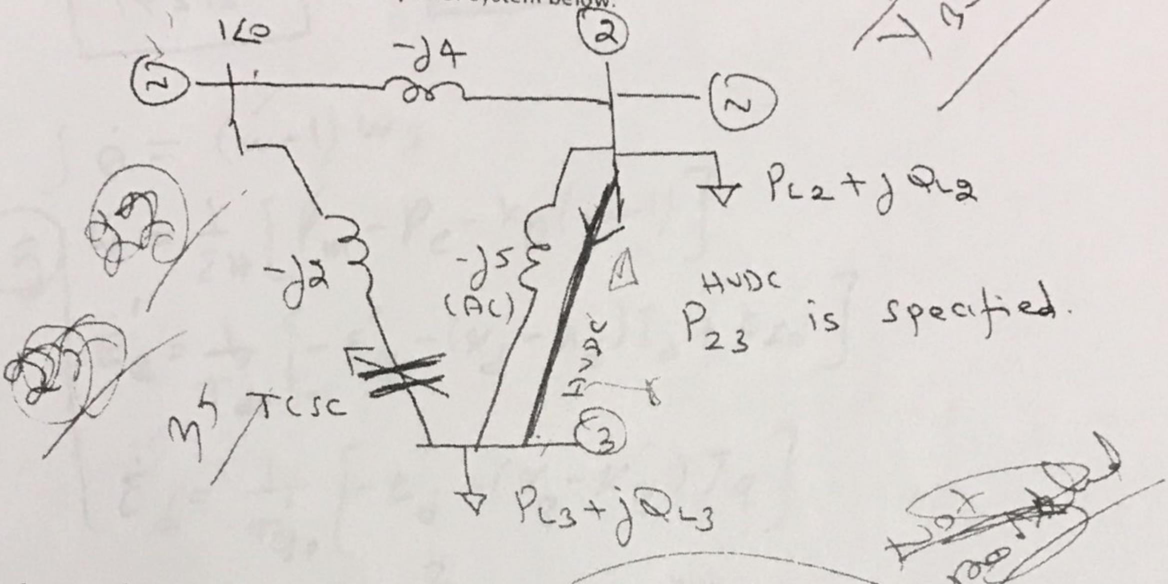


Efd
6
4
2
0
-2
-4
-6
0
5
10
15
20
25
30
time (sec)

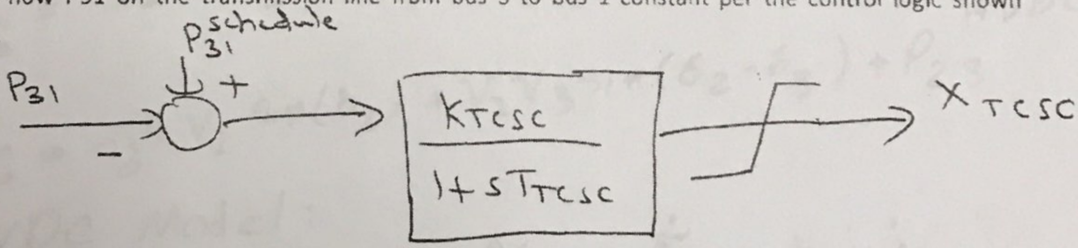


Vref − V
0.08
1.03 − 1
0.03
-0.02
1.03 − 1.05
1.03 − 1.
1.03 − 0.95
4
10
20
25

2) Consider the three-bus power system below.

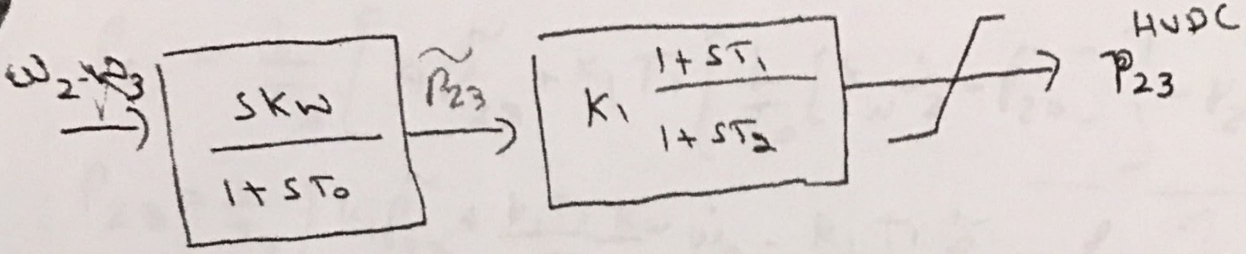


Assume the generator is modeled by a standard first order exciter control with no governor control modeled. There is a HVDC transmission line from bus 2 to bus 3 that can be modeled as a lossless link. The HVDC power electronic controls keep the complex AC power on both sides of the DC link (at buses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



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

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$$P_e = P_G + R_s I_G^2 \to P_{,G}$$

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

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

HVDC Model:

$$\tilde{P}_{23} = \frac{sK_w}{1+sT_0}\,\omega_2 \Rightarrow \tilde{P}_{23} + T_0 \dot{\tilde{P}}_{23} = k_w \dot{\omega}_2$$

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

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

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

$$\Rightarrow T_2 \dot{P}_{23} = K_1 \tilde{P}_{23} + K_1 T_1 \dot{\tilde{P}}_{23} - P_{23} \Rightarrow \dot{P}_{23} = \frac{1}{T_2}\left[K_1 \tilde{P}_{23} + K_1 T_1 \dot{\tilde{P}}_{23} - P_{23}\right.$$

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

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

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

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

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

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

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

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

TCSC: Model

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

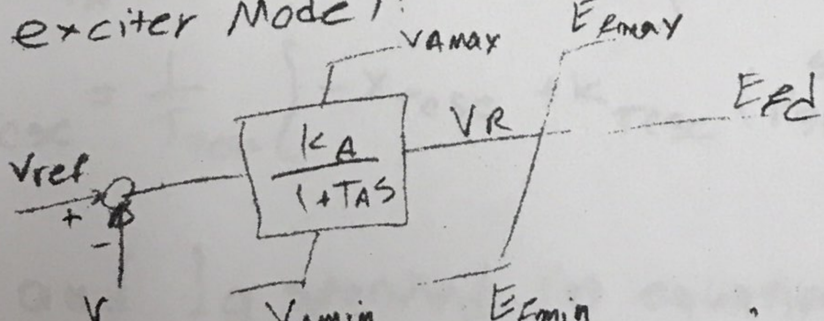
$$\Rightarrow (P_{31}^{schedule} - P_{31}) K_{TCSC} = X_{TCSC}(1+sT_{TCSC})$$

$$T_{TCSC}\dot{X}_{TCSC} = -X_{TCSC} + K_{TCSC}(P_{31}^{schedule} - P_{31})$$

$$P_{31} = V_3 V_1 \times (-j2)\sin(\delta_3 - \delta_1) = -j2V_3\sin(\delta_3)$$

$$\Rightarrow \boxed{\dot{X}_{TCSC} = \frac{1}{T_{TCSC}}\left[-X_{TCSC} + K_{TCSC}\left(P_{31}^{schedule} + j2V_3\sin(\delta_3)\right)\right]}$$

exciter Model:



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

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

P:

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

a) In the first case without HVDC damping controllers state of the system are: θ, W, E'_q, E'_d, V_R, X_{TCSC} and

y variables are V_2, δ_2, V_3, δ_3

The state equations will be:

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

I_d and I_q specified in equation 1 based on x and y in this equations

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

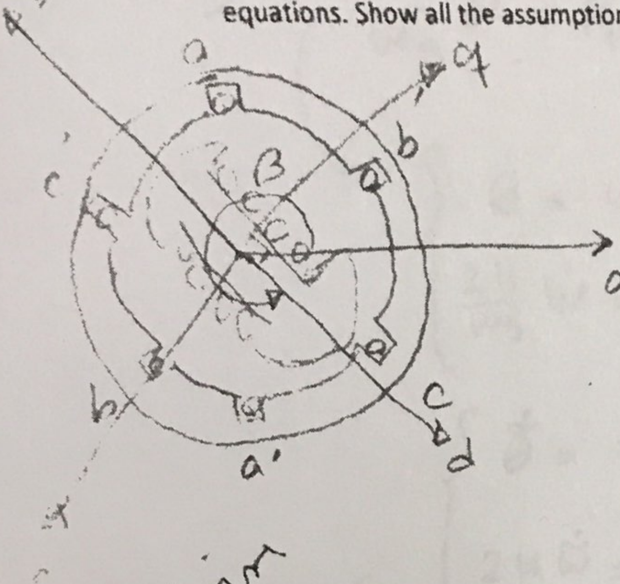
b) with HVDC damping controller states are

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

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 (5)

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)



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

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

$$\dot{\beta} = w_s + \dot{\theta} \Rightarrow \dot{\theta} = w - w_s$$

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

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

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

$w_s \approx w$

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

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

Define

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

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

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

$$P_D = K_D(w - w_s)$$

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

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

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

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