EE5200 "STAB" SOLUTION

KEY
Name & ID Number

1) [10 pts] A 3ϕ 60-Hz 400-MVA 13.8-kV 4-pole turbine-generator unit has an H constant of 5.0 s.

   a) Calculate the energy stored in the rotating mass at synchronous speed.
   b) If the unit is operating at synchronous speed and suddenly experiences an accelerating power of 400 MW, calculate the mechanical angular acceleration in rad/sec and the speed in RPM after 0.5 seconds.

a) $W = \frac{1}{2} J\omega^2$ $\quad H = \frac{\text{STORED ENERGY}}{\text{Machine MVA}} = 5 = \frac{W}{400\times10^6}$

(4) $\quad \Rightarrow \boxed{W = 2000 \text{ MJ}}$

b) From a) $J = \frac{2(2\times10^9)}{\omega^2_{s,mech}} = \frac{2(2\times10^9)}{\left[\frac{2\pi}{60}(1800)\right]^2} = \cancel{21.22\times10^6}$ $\underline{112,580 \text{ kg-m}^2}$

$\omega_s = \frac{2\pi}{60}(1800) = \underline{188.5 \text{ rad/s}}$

(6)

400 MW over 0.5 sec increases stored energy to $\underline{2200}$ MJ

$\omega = \sqrt{\frac{2 \times 2.2\times10^9}{112,580}} = 197.7 \text{ rad/sec} \Rightarrow \boxed{1887.8 \text{ RPM}}$ ($\omega = 197.7$)

2) [10 pts] A power system is represented by two **non-coherent** synchronous generators which are connected by a short 13.8-kV line whose impedance is j0.40 p.u. on a 100 MVA base. The specifications for the generators, on the respective bases of the two generators, are given as:

Generator 1: 13.6 kV	Generator 2: 13.8 kV
80 MVA	50 MVA
X_d' = j0.15 p.u.	X_d' = j0.15 p.u.
H = 4.0 s	H = 5.0 s

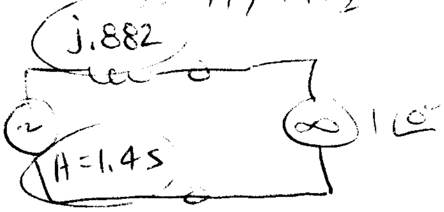
Calculate the equivalent H value and the transfer impedance if this 2-machine equivalent is converted to a single machine connected to an infinite bus. State the values on the 100-MVA system base.

$H_1 = 4.0 \frac{80}{100} = 3.2 \text{ s}$

(5)

$H_2 = 5.0 \frac{50}{100} = 2.5 \text{ s}$

$H_{12} = \frac{H_1 H_2}{H_1 + H_2} = \boxed{1.40 \text{ s}}$



$jX_1 = j.15 \left(\frac{13.6^2}{80}\right)\left(\frac{100}{13.8^2}\right)$

$= j.182 \text{ p.u.}$

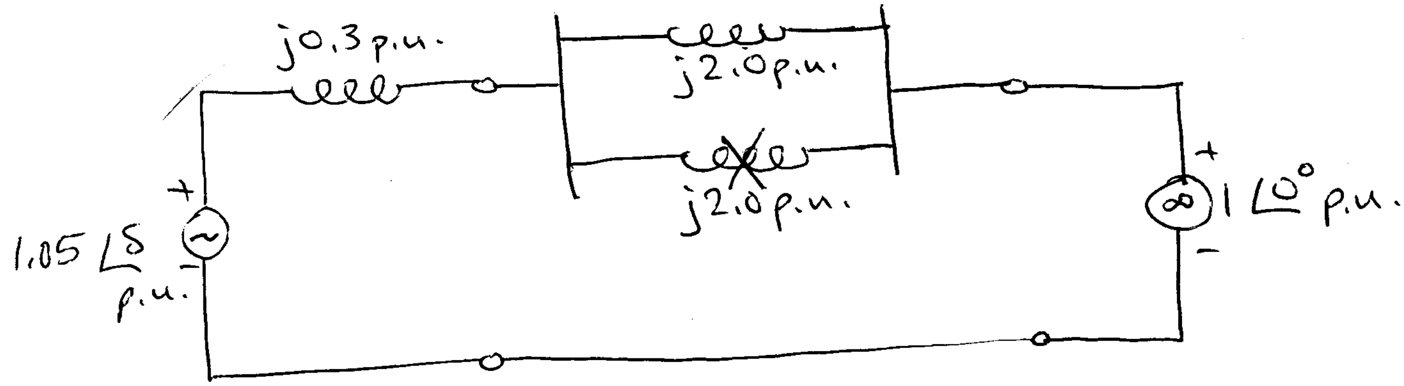
(5)

$jX_2 = j.15\left(\frac{100}{50}\right) = j.30$

$jX_{TRANSFER} = j.182 + j.30 + j.40$

$\boxed{= j\,0.882 \text{ p.u.}}$

3) [20 pts] The per phase equivalent of a 3ϕ system is shown below. A fault occurs midway along the indicated line.



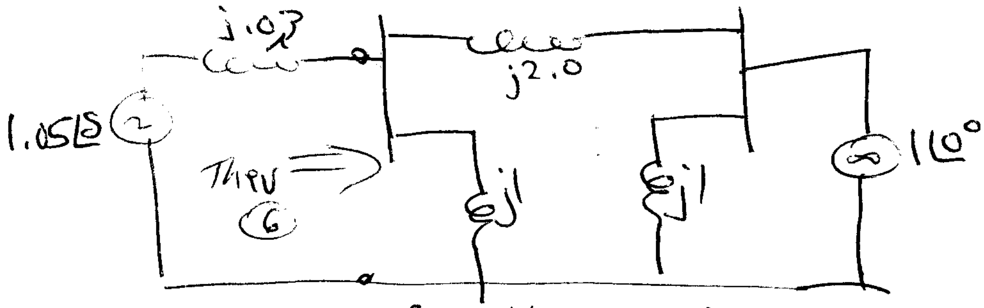
a) Calculate the transfer impedance, Thevenin voltage of the infinite bus, and $P_{MAX,E}$ for prefault conditions.

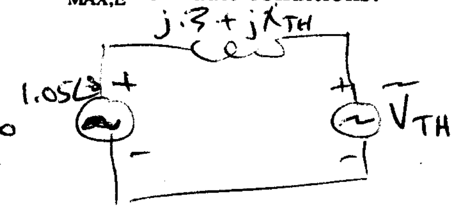
(2) $X = j.3 + j2 // j2 = j1.3 \text{ pu}$

(1) $V_{TH} = 1\angle 0°$

(2) $P_{MAX} = \frac{E_q' V}{X} = \frac{(1.05)(1)}{1.3} = 0.808 \text{ p.u.}$

b) Calculate the transfer impedance, Thevenin voltage of the infinite bus, and $P_{MAX,E}$ for fault conditions.





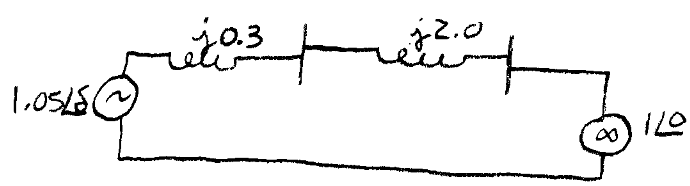
$V_{TH} = 0.333\angle 0°$ $\quad X_{TH} = j0.667$

$I_{TH} = 0.5\angle 90°$

(2) $P_{MAX} = \frac{E_q' V}{X} = \frac{(1.05)(.333)}{0.967}$ (2)

$P_{MAX} = 0.3615 \text{ p.u.}$

c) Calculate the transfer impedance, Thevenin voltage of the infinite bus, and $P_{MAX,E}$ after the line section has been cleared.



(2) $X = j.3 + j2 = j2.3$

(1) $V_{TH} = 1\angle 0°$

(2) $P_{MAX} = \frac{E_q' V}{X} = \frac{(1.05)(1)}{2.3} = 0.4565 \text{ p.u.}$

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4) [20 pts] Answer **any four of the** of the following short concept/essay questions. Be sure to clearly indicate which one you do not want graded, or the first four will be graded. **Explain in your own words and/or diagrams - explanations copied word-for-word from your textbook or notes will not be given credit.**

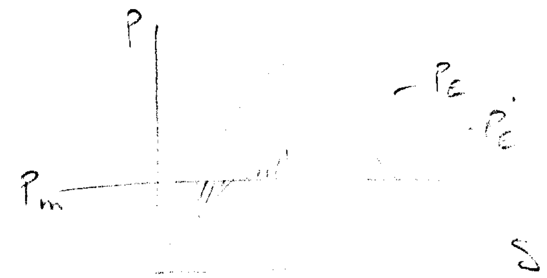
a) [5 pts] What is the main assumption made that allows us, for the purpose of transient stability studies, to approximate a salient rotor machine as a Thevenin equivalent of voltage E_q' and impedance X_d'?

Assume $X_d' \approx X_q$, which makes $\bar{E}_q' \approx \bar{E}_q$

Essentially, this implies that the "round rotor" model is also appropriate for a salient machine in the case of stability studies.

b) [5 pts] Consider the equal-area criterion as applied to a synchronous generator. What significance do the area above and the area below the P_M line have in terms of the speed of the synchronous machine?

The area below the line represents acceleration, that above represents deceleration.
(Areas are proportional to K.E. & ω^2)



c) [5 pts] Explain what reclosing is and whether or not reclosing can improve the stability of a system.

After a fault has been cleared and the fault is extinguished, the line is "closed in" again. This is called reclosing. This can greatly improve the liklihood of maintaining stability, since $P_{E\,max}$ can be increased back to its original prefault value.

d) [5 pts] Why is solution of the swing equation complicated if the reference speed of the system is not chosen to be synchronous speed?

$$\left(P_m - \frac{E_q' V}{X}\sin\delta\right) = \frac{H}{\pi f}\left(\underbrace{\frac{d\omega_{ref}}{dt}}_{0,\ \text{if } \omega_{ref} = \omega_s} + \frac{d^2\delta}{dt}\right)$$

An additional first order term is introduced into the swing equation.
This term goes to zero if ω_{ref} chosen to be at an infinite bus.

e) [5 pts] For a given machine, what steady-state torque angle would result in the highest natural frequency oscillations for load fluctuations? Answer in terms of the synchronizing power coefficient or with reference to the terms in the natural frequency equation.

$S_p = P_{max}\cos\delta$ ← (Slope of P_E characteristic).

$$\omega_n = \sqrt{\frac{\omega_s P_{max}\cos\delta}{2H}}$$

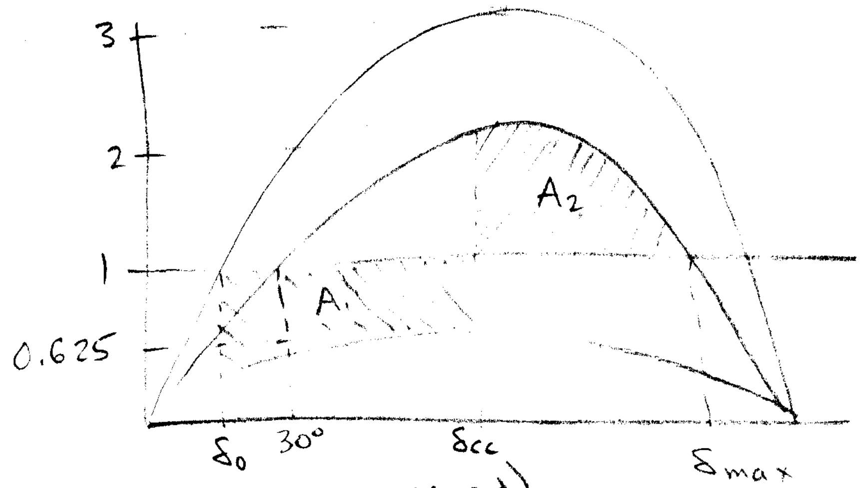
∴ Freq is largest for unloaded machine, $\delta = 0$. ω_n decreases with load.

5) [20 pts] For a given fault, $P_{MAX,E}$ before, during, and after a fault is 3.125, 0.625 and 2.0 p.u. respectively. P_M is 1.0 p.u. and can be considered constant.

a) Sketch out P_E and P_M for the three cases given above.
b) Calculate the pre-fault torque angle, the critical clearing angle, and the post-fault torque angle.
c) Is stability possible? Can you say at this point if transient stability will be achieved?

a)

(6)



b) $\delta_0 = \sin^{-1}\frac{1}{3.125} = \boxed{18.66^\circ}$ (0.326 rad) (2) $\delta_{max} = 180 - \sin^{-1}\frac{1}{2}$

$= 150^\circ$ (2.618 rad)

$$\int_{\delta_0}^{\delta_{cc}} (1 - .625 \sin\delta)\, d\delta = \int_{\delta_{max}}^{\delta_{cc}} (1 - 2\sin\delta)\, d\delta$$ (4)

$$\delta + .625\cos\delta \Big|_{.326}^{\delta_{cc}} = \delta + 2\cos\delta \Big|_{2.62}^{\delta_{cc}}$$

$$\cancel{\delta_{cc}} - .326 + .625\cos\delta_{cc} - .625\cos .326 = \cancel{\delta_{cc}} - 2.62 + 2\cos\delta_{cc} - 2\cos 2.62$$

$$-0.0321 = 1.375\cos\delta_{cc}$$ (2)

$\Rightarrow \boxed{\delta_{cc} = 91.34^\circ}$ (1.59 rad)

$\boxed{\delta_{\text{post fault}} = 30^\circ}$ (2)

c) Stability is possible, provided $\delta_c \leq 91.34^\circ$

(4)

Transient may or may not damp out,
so numerical method must be used to solve swing eqn.
Equal area method cannot tell us.

11.