Power System Control

Final Exam Example (I)

Problem 1

Figure 1 shows the single line diagram of a π-model of a three-phase transmission line. Assuming per unit quantities, determine:

a. The complete set of equations the define the line dynamics in terms of Park's vectors. Indicate the state variables.

b. Write the transfer function assuming the current in the inductor as output variable and the voltages at the sending and receiving end of the line as input variables.

c. Assuming that the line is a short ditribution line, i.e., $g_{L,h} \approx g_{L,k} \approx 0$, $r_L \approx x_L$ and $b_{L,h} \approx b_{L,k} \ll x_L$, reduce the dynamic order of the equations determined at point 1, preserving only "slow" dynamics.

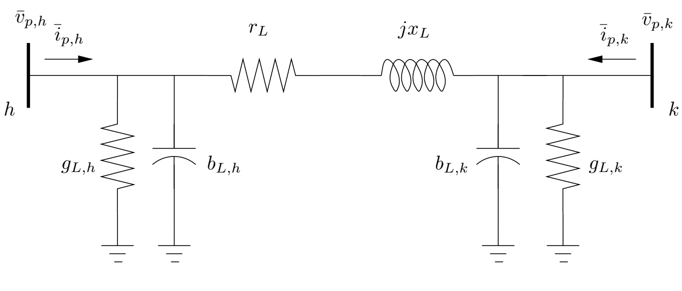

Figure 1 Transmission line lumped π-circuit.

Problem 2

Figure 2 shows a one-machine infinite-bus system. Assume a lossless system and the following values for the system parameters: $x'_d = x_L = x_{\text{Th}} = 0.1$ pu, $p_m = 0.8$ pu, and $v = 1$ pu.

a. Determine the values of the state variables of the system at the operating point obtained for $e = 1.05$ pu. Justify the feasibility of the solution describing the dynamic behaviour of the system for "small" perturbations around the operating point.

b. Find the value of e for which the reactive power produced by the machine is null.

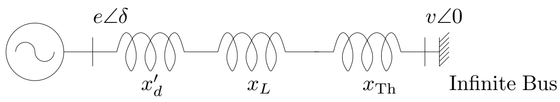

Figure 2 One-machine infinite-bus system.

Problem 3

A power system includes 3 machines with primary frequency regulations. The nominal power as well as droops of the machines are as follows:

$S_{n,i}$ [MVA]	$b_{p,i}$ [%]
167	5
100	5
125	5

where the droops are on machine bases. Assuming a system base of $S_n = 100$ MVA, determine the steady-state frequency error and the power variation of each machine of the system after a load increase of 5 MW.

Questions

a. Describe advantages and disadvantages of ac systems versus dc ones. Focus on control and protection aspects.

b. Describe the need and the purpose of primary controls of a synchronous machine. Draw a simple AVR control scheme and its connections with the synchronous machine.

c. Identify the number and the physical meaning of the state variables of a synchronous generator characterized by the following parameters: $T'_{d0} \neq 0$, $T'_{q0} \neq 0$, $T''_{d0} = 0$, $T''_{q0} = 0$.

d. Sketch the qualitative transient behavior of the voltage at the terminal bus of a synchronous machine following a line outage. Consider two scenarios: with AVR and without AVR.

e. Sketch and properly justify the dynamic response of the tap of an ULTC following the disconnection of a load on the secondary winding of the transformer. Assume that the voltage magnitude on the primary winding is constant.

f. Describe two series FACTS devices, draw their most common control schemes and indicate their main effects on the electric power system.

g. Describe the rationale behind the pitch control of a wind turbine and draw a qualitative control scheme. Discuss whether the pitch control can be effective to regulate the system frequency.

Power System Control

Final Exam Example (II)

Problem 1

Figure 3 shows a single-line equivalent circuit of a balanced compensated line. Using Park vectors and assuming as input variables v_1 ans v_2, write the differential equations that describe the dynamic of the line. Assume that a synchronous machine is connected at bus 1 and the its fluxes and currents are described by the following equations:

$$
\begin{aligned}
\dot{\psi}_d &= \Omega_b(r_a i_d + \omega\psi_q + v_{1d}) \\
\dot{\psi}_q &= \Omega_b(r_a i_q - \omega\psi_d + v_{1q}) \\
\psi_d &= (x_d - x_\ell)i_f - x_d i_d \\
\psi_q &= -x_q i_q
\end{aligned}
$$

where i_d and i_q are the currents injected at node 1. Rewrite the line equations determined above as a function of the machine field current, line inductance current and capacitance voltage and the voltage at bus 2 (e.g., eliminate the dependence on the voltage at bus 1 and machine fluxes).

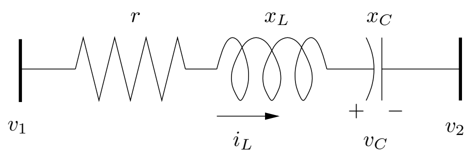

Figure 3 Compensated line.

Problem 2

Consider the following 8$^{\text{th}}$ order model (expressed in pu) of the synchronous machine:

$$
\begin{aligned}
\dot{\delta} &= \omega_n(\omega - \omega_s) \\
\dot{\omega} &= \frac{1}{2H}(\tau_m - \tau_e - D(\omega - \omega_s)) \\
\dot{\psi}_d &= \omega_n(r_a i_d + \omega\psi_q + v_d) \\
\dot{\psi}_q &= \omega_n(r_a i_q - \omega\psi_d + v_q)
\end{aligned}
$$

$$
\begin{aligned}
\dot{e_q}' &= (-e_q' - (x_d - x_d')i_d + v_f)/T_{do}' \\
\dot{e}_d' &= (-e_d' + (x_q - x_q')i_q)/T_{qo}' \\
\dot{e}_q'' &= (-e_q'' + e_q' - (x_d' - x_d'')i_d)/T_{do}'' \\
\dot{e}_d'' &= (-e_d'' + e_d' + (x_q' - x_q'')i_q)/T_{qo}'' \\
0 &= \psi_d + x_d'' i_d - e_q'' \\
0 &= \psi_q + x_q'' i_q + e_d'' \\
\tau_e &= \psi_d i_q - \psi_q i_d
\end{aligned}
$$

a. Simplify the model above to a 4^{th} order DAE model neglecting fastest dynamics. Justify the choice of "fast" variables.

b. Simplify the model above to a 4^{th} order DAE model neglecting slowest dynamics. Justify the choice of "slow" variables.

c. Write the expression of active and reactive powers of the machine injected at the terminal bus in terms *only* of *d*-*q* axis stator voltages (e.g., v_d and v_q) and machine state variables. Hint: assume $\omega \approx 1$ pu = constant.

Problem 3

Figure 4 shows an integral-proportional speed controller of an induction motor. Define the modifications to apply to the control scheme of Figure 4 to obtain a blending control.

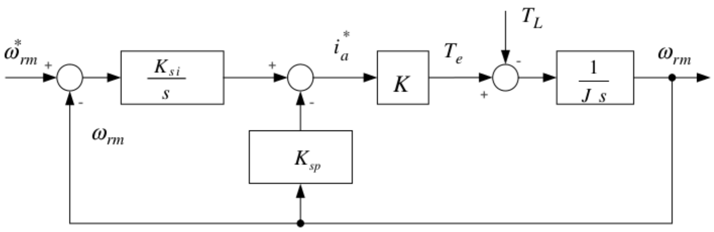

Figure 4 Integral-proportional speed regulator of an induction motor.

Questions

a. Provide and discuss an expression for the conventional efficiency of electrical machines.

b. Describe the effect of assuming a round rotor on the equations of the Park-Concordia synchronous generator model.

c. Sketch the qualitative transient behavior of the system frequency driven by the primary frequency control of synchronous machines following the connection of a load consumption.

d. Discuss the need for the over-excitation limiter and its effects on the primary voltage control of synchronous machines.

e. Illustrate the discrete model of the ULTC voltage control and discuss its dynamic interaction, if any, with the following controllers:

- Turbine governors of synchronous machines.
- Voltage control of FACTS devices.

f. Describe the StatCom device and sketch its steady-state control characteristics.

g. Describe and draw the scheme two wind turbine concepts. Discuss some advantages and drawbacks of the usage of power electronics for wind power generation.

Power System Control

Final Exam Example (III)

Problem 1

Consider the following model of a wind turbine with pitch control. The mechanical power p_w can be approximated as:

$$p_w = \frac{\rho}{2} c_p(\lambda, \theta_p) A_r v_w^3$$

where efficiency $c_p(\lambda, \theta_p)$ can be approximated as follows:

$$c_p = 0.22 \left(\frac{116}{\lambda_i} - 0.4\theta_p - 5 \right) e^{-\frac{12.5}{\lambda_i}}$$

with

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\theta_p} - \frac{0.035}{\theta_p^3 + 1}$$

where θ_p is in degrees. Assuming a tip speed ratio $\lambda = 5$, determine an approximated value of the pitch angle θ_p that reduces the efficiency of the turbine by 10%.

Problem 2

Using the following exciter model:

$$T_e \frac{dE_{fd}}{dt} = -(K_E + S_E(E_{fd}))E_{fd} + V_R$$

with $K_E = 1.0$, $S_E = 0$ and $T_E = 0.5$ s, compute the response of E_{fd} for a step variation of the input with amplitude $V_R = 1.0$ pu. Use as initial value $E_{fd}(0) = 0$.

Problem 3

Figure 5 shows a PI speed controller of an induction motor. Define the closed loop transfer functions of the controller, namely $\omega_{rm}/\omega_{rm}^*$, as well as a set of ordinary differential equations that represent the control scheme.

Questions

a. Discuss advantages and drawbacks of a power system fed by generators that impose the voltage (i.e., independent voltage sources).

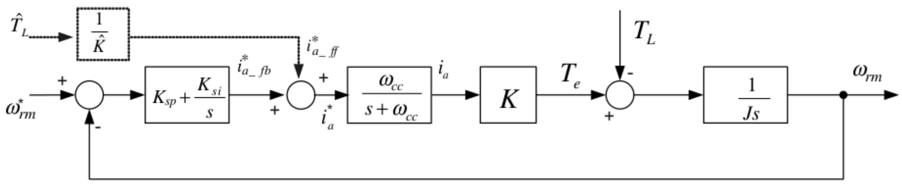

Figure 5 PI speed controller of an induction motor.

b. List three auxiliary controllers of a synchronous generator and describe their purpose and operating principle. Sketch a synoptic control scheme of a synchronous generator including the three controllers previously described.

c. Sketch the trajectory of the frequency of a power system following the connection of a load considering both primary and secondary frequency control (AGC). Illustrate the effect of increasing the gain of the AGC.

d. Sketch and properly justify the dynamic response of the tap of an ULTC controlling the voltage on the secondary winding following a sudden voltage drop on the primary winding. Assume a continuous model if the tap ratio and that the model of the load connected on the secondary winding is a constant impedance.

e. Describe the main features and drawbacks of TCR-based FACTS devices. Indicate a typical simplified control scheme of the SVC device and discuss its main purpose for power system control.

f. Discuss the principles on which the direct vectorial control of an asynchronous machine is based.

g. Describe the physical principle, the purpose and the effects of the stall control of a wind turbine.

Remarks and Hints on Exam Questions

- Answer each question properly justifying the statements and, whenever possible, provide theoretical and/or practical considerations.
- Whenever adequate, sketch typical transient trajectories of relevant variables and provide a detailed description of the behavior of the device and/or control system involved.
- Provide concise and clear answers. Each answer can take up to a maximum of 100 words.
- Base your answers on lecture notes, suggested bibliography and on the experience achieved while preparing assignment reports.
- Be aware that computers, books and lecture notes are **not** allowed during the exam.
- Use your best handwriting and, preferably, print your answers. Illegible text will be considered incorrect.