Power System Control

Exam 2013 - Questions

Question 1

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

Question 2

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.

Question 3

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.

Question 4

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.

Question 5

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.

Question 6

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

Question 7

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

Power System Control

Exam 2013 - Solutions

Question 1

The main advantages of imposing the voltage through the generators are the following:

- Load are connected in parallel. Hence, the connection or the disconnection of a load does not create any particular protection issue.
- The disconnection fo a load does not affect the energy supply to other loads.
- Most common and efficient electrical machines (e.g., synchronous generators) impose the voltage. Hence imosing the voltage is the most adequate scheme to operate a power system.

Main drawbacks are:

- A shortcirucit can cause high overcurrents. The protections have to brake the system quickly if a short circuti occurs.
- As the load consumption increases, the voltage decreases. A voltage support and/or control can be required.
- Lines have to be properly designed to avoid overloading and, hence, overheating.
- The start-up of induction motors can lead to severe voltage drops.

Question 2

The most relevant auxiliary controllers of a synchronous generator are:

- Power system stabilizer (PSS). The objective of the PSS is to damp electromechanical oscillations following a disturbance in the power systems that affects the active power balance. The operating principle of the PSS is to emulate a damping on the mechanical shaft through the regulation of the rotor field voltage of the synchronous machine.
- Overexcitation Limiter (OEL). The objective of the OEL is to limit the rotor field current below a given thermal limit. The operating principle is to reduce the rotor field voltage in order to increase the field current (direct application of the Ohm's law). Since the OEL reduces the production fo reactive power of the generator, the OEL has to be delayed to avoid a destabilizing effect on the system.

- Underexcitation Limiter (UEL). The objective of the UEL is to avoid low current values of the rotor field current that can lead to overheating of the stator end-core. The operating principle is to increase the rotor field voltage in order to decrease the field current (direct application of the Ohm's law). Similarly to the OEL, the effect of the UEL can be destabilizing. It has been observed that a proper coordination of high-initial-response AVR and PSS can be more effective than the UEL.

The synoptic control scheme of the generator including the three controllers discussed above is shown in Figure 1.

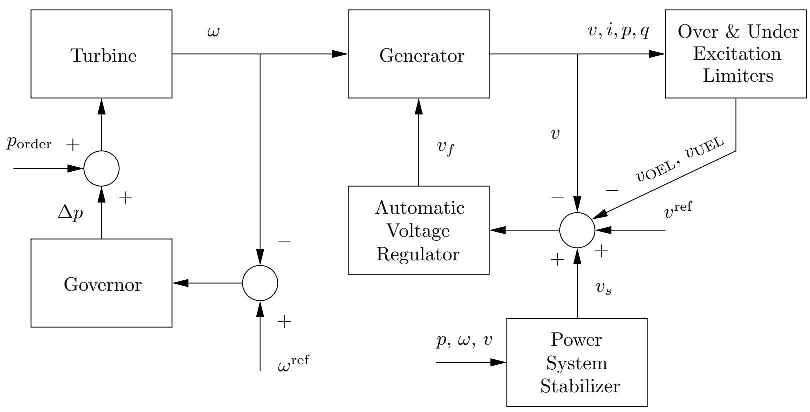


Figure 1 Synoptic scheme of synchronous machine regulators.

Question 3

Figure 2 shows the typical trajectory of the system frequency following a load connection. We assume that the power requested by the load can be supplied by the generators and that the system does not show transient instability. After connecting the load the frequency decreases. The primary frequency regulator is able to recover the frequency even though with a non-zero error after about 50 seconds. The AGC recovers the frequency to its synchronous valuein about ten times the primary frequency regulation response.

Figures 3 and 4 show the trajectories of the frequency for high and very high values of the AGC gain, respectively. The higher the value of the AGC gain, the less damped the oscillations of the frequency. For extremely high values of the AGC gain, the system can be unstable.

Question 4

Figures 5 and 6 shows the typical trajectories of the voltage at both sides of the regulating transformer and of the tap ratio, respectively. We assume that the

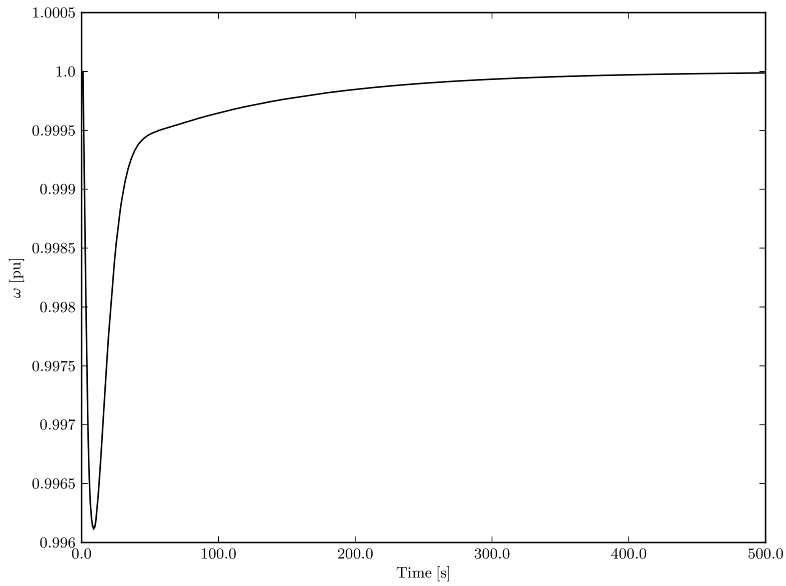


Figure 2 Typical frequency response following a line disconnection.

transformer regulates the voltage on the secondary winding and that the tap ratio has a continuous model. After the sudden voltage drop on the primary winding, also the voltage on the secondary winding drops. Then the ULTC regulator decreases the tap ratio to recover the voltage on the secondary winding to the reference value. The voltage recovery is possible as long as the tap ratio does not reach its minimum value. Observe that, in this case, the load model is immaterial.

Question 5

Thyristor controlled reactor (TCR) devices are the first generation of FACTS devices and are characterized by a thyristor-based bridge in series with a reactor. In parallel with the bridge and the reactor there can be one or more static condensers. The firing angle of the thyristor bridge allows varying the current flowing in the reactor and, in turn, results in a variable reactance at the fundamental frequency (see Figure 7). Depending on the firing angle, the overall system can behave like a reactor or like a condensers. There are two kinds of TCR-based FACTS: the static var compensator (SVC), which is a shunt device, and the thyristor controlled series compensator (TCSC). The main advantages

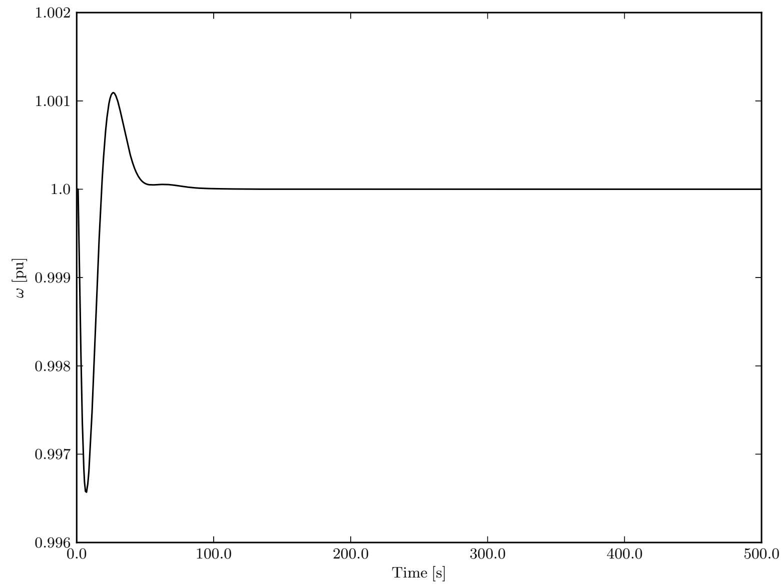


Figure 3 Frequency response following a line disconnection with high AGC gain.

of these devices are the relatively low cost of the overall device and simplicity of control. The main drawbacks are the high harmonic distorsion that require proper filters and the possibility of resonances.

The Static Var Compensator (SVC) is a variable shunt capacitor that is varied to maintain a constant voltage at the bus to which it is connected (see Figure 7). A typical simplified control scheme used in transient stability analysis is depicted in Figure 8. More complex models have to take into account the firing angle of the thyristor-based bridge.

Question 6

Vector control, also called field-oriented control (FOC), is a variable frequency drive (VFD) control method which controls three-phase AC electric motor output by means of two controllable inverter output variables: (i) voltage magnitude; and (ii) frequency.

In vector control, an AC induction or synchronous motor is controlled under all operating conditions like a separately excited DC motor. That is, the AC motor behaves like a DC motor in which the field flux linkage and armature

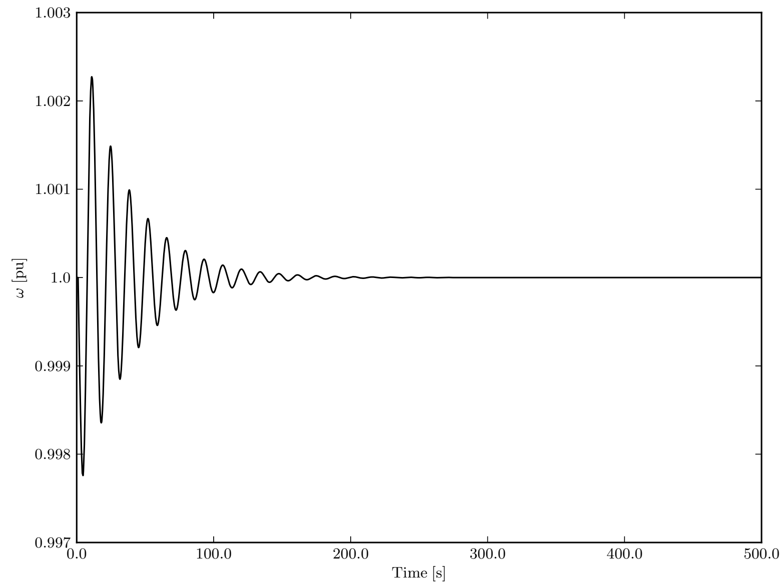


Figure 4 Frequency response following a line disconnection with very high AGC gain.

flux linkage created by the respective field and armature (or torque component) currents are orthogonally aligned such that, when torque is controlled, the field flux linkage is not affected, hence enabling dynamic torque response.

Vector control accordingly generates a three-phase PWM motor voltage output derived from a complex voltage vector to control a complex current vector derived from motor's three-phase motor stator current input through projections or rotations back and forth between the three-phase speed and time dependent system and these vectors' rotating reference-frame two-coordinate time invariant system. Decoupled torque and field currents can thus be derived from raw stator current inputs for control algorithm development.

Whereas magnetic field and torque components in DC motors can be operated relatively simply by separately controlling the respective field and armature currents, economical control of AC motors in variable speed application has required development of microprocessor-based controls with all AC drives now using powerful DSP (digital signal processing) technology.

There are two vector control methods, direct or feedback vector control (DFOC) and indirect or feedforward vector control (IFOC), IFOC being more commonly used because in closed-loop mode such drives more easily operate

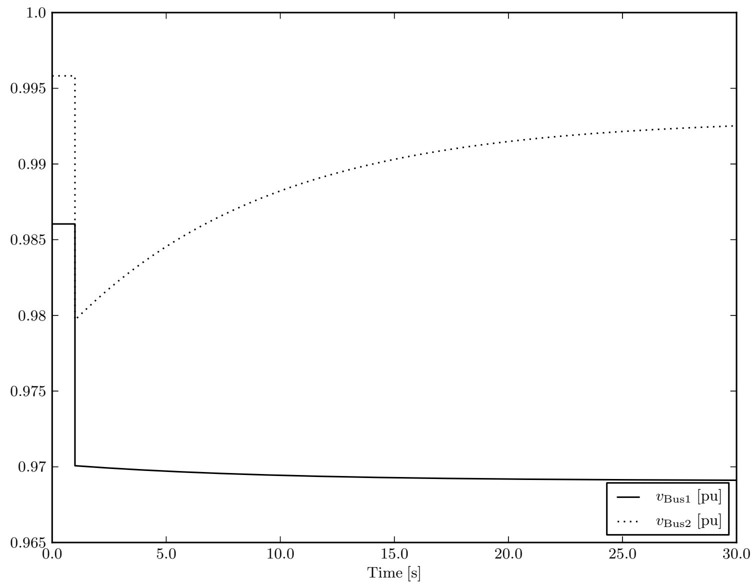


Figure 5 Trajectories of the voltage on the primary and secondary winding of the transformer.

throughout the speed range from zero speed to high-speed field-weakening. In DFOC, flux magnitude and angle feedback signals are directly calculated using so-called voltage or current models (see Figure 9).

Question 7

The stall control is one of the "braking" (i.e., safety) systems of modern wind turbines. Braking systems are triggered by above-threshold wind speeds. These setups use a power-control system that essentially hits the brakes when wind speeds get too high and then "release the brakes" when the wind is back below the speed threshold. Modern large-turbine designs use several different types of braking systems. These include the pitch control; passive stall control; and active stall control. The functioning of the two kinds of stall controls is described below:

- Passive stall control - The blades are mounted to the rotor at a fixed angle but are designed so that the twists in the blades themselves will apply the brakes once the wind becomes too fast. The blades are angled so that winds above a certain speed will cause turbulence on the upwind side of

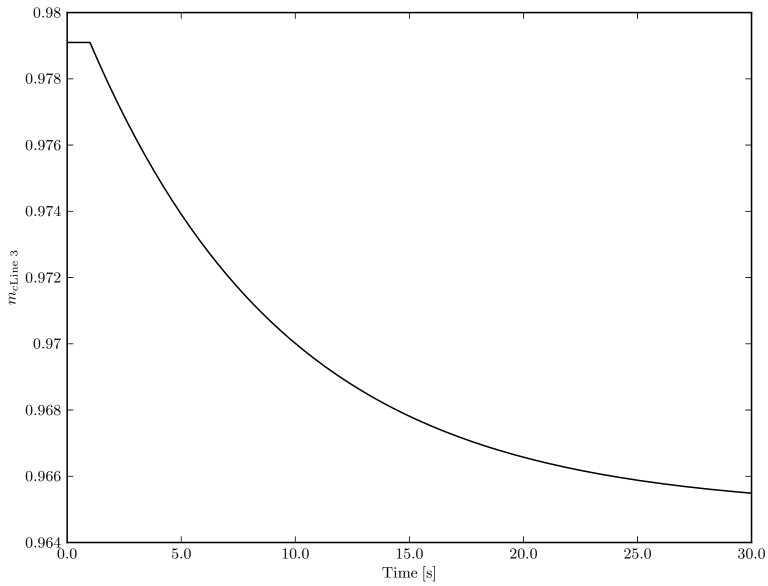


Figure 6 Trajectory of the tap ratio of the transformer.

the blade, inducing stall. Simply stated, aerodynamic stall occurs when the blade's angle facing the oncoming wind becomes so steep that it starts to eliminate the force of lift, decreasing the speed of the blades.

- Active stall control - The blades in this type of power-control system are pitchable, like the blades in a pitch-controlled system. An active stall system reads the power output the way a pitch-controlled system does, but instead of pitching the blades out of alignment with the wind, it pitches them to produce stall.

The by-product of the stall control is a wind spillage and, as a consequence, a limit on the power that can be injected into the system by each wind turbine.

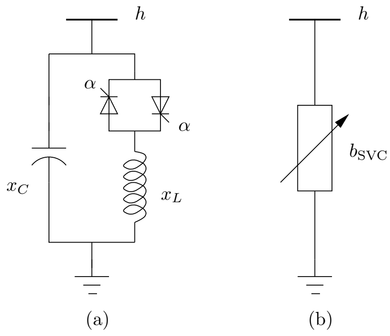


Figure 7 SVC schemes: (a) firing angle model and (b) equivalent susceptance model.

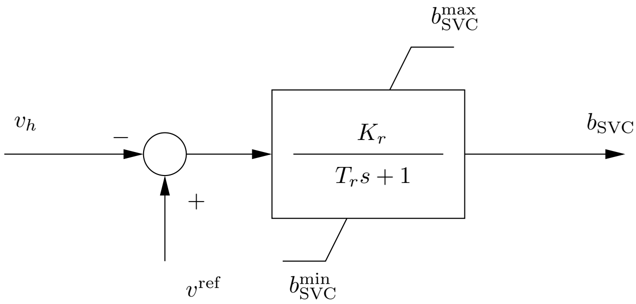


Figure 8 Simplified SVC control diagram.

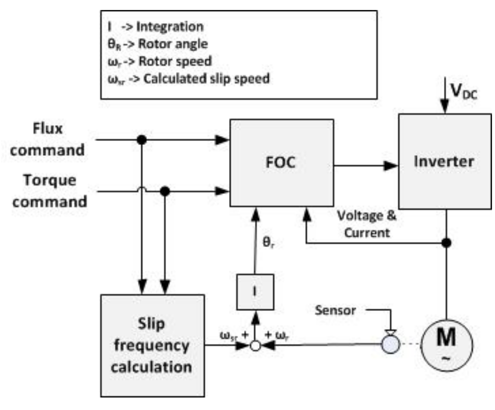


Figure 9 Simplified direct FOC block diagram.

Power System Dynamics and Control

Exam 2014 – Problems and Questions

Problem 1

Neglect saturation and derive an expression for $\bar{E}'$ in the alternative steady-state equivalent circuit shown of Fig. 1. Write $\bar{E}'$ as a function of E'_q, I_d, I_q, δ and machine parameters.
Hint: in steady-state, one has:

$$\begin{aligned} E'_d &= (X_q - X'_q)I_q \\ V_d &= -R_sI_d + E'_d + X'_qI_q \\ V_q &= -R_sI_q + E'_q - X'_dI_d \end{aligned}$$

100%

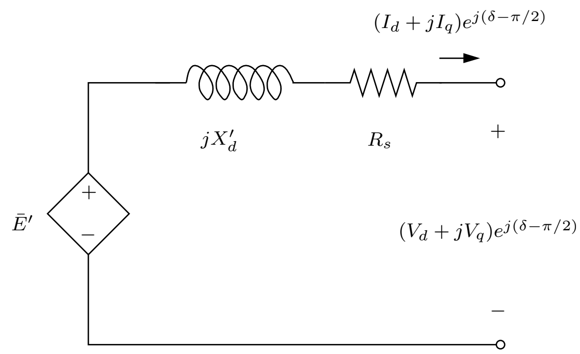


Figure 1

Problem 2

The exciter of a synchronous machine has the following steady-state model:

$$\begin{aligned} V_R &= (K_E + S_E(E_{fd}))E_{fd} \\ S_E(E_{fd}) &= A_x e^{B_x E_{fd}} \end{aligned}$$

100%

Assuming $K_E = 1.0$, $V_{R\,\max} = 8.0$, $S_{E\,\max} = 0.9$, $S_{E\;0.75\,\max} = 0.5$ (all in pu), find $E_{fd\,\max}$, A_x and B_x.

Problem 3

Consider the following model of the magnetic fluxes of a synchronous machine as it is defined in the book "Power system dynamics and stability" by P. W. Sauer and M. A. Pai:

$$\begin{aligned} \dot{e}'_q &= (-e'_q - (x_d - x'_d)(i_d + \gamma_{d2}\dot{\psi}''_d) + v_f)/T'_{d0} \\ \dot{e}'_d &= (-e'_d + (x_q - x'_q)(i_q + \gamma_{q2}\dot{\psi}''_q))/T'_{q0} \\ \dot{\psi}''_d &= (-\psi''_d + e'_q - (x'_d - x_\ell)i_d)/T''_{d0} \\ \dot{\psi}''_q &= (-\psi''_q - e'_d - (x'_q - x_\ell)i_q)/T''_{q0} \end{aligned}$$

where the coefficients γ_{d2} and γ_{q2} are defined as follows:

$$\begin{aligned} \gamma_{d1} &= \frac{x''_d - x_\ell}{x'_d - x_\ell} \\ \gamma_{q1} &= \frac{x''_q - x_\ell}{x'_q - x_\ell} \\ \gamma_{d2} &= \frac{x'_d - x''_d}{(x'_d - x_\ell)^2} = \frac{1 - \gamma_{d1}}{x'_d - x_\ell} \\ \gamma_{q2} &= \frac{x'_q - x''_q}{(x'_q - x_\ell)^2} = \frac{1 - \gamma_{q1}}{x'_q - x_\ell} \end{aligned}$$

100%

Determine the approximations that allow rewriting the Sauer-Pai's model as the well-known machine model below:

$$\begin{aligned} \dot{e}'_q &= (-e'_q - (x_d - x'_d)i_d + v_f)/T'_{d0} \\ \dot{e}'_d &= (-e'_d + (x_q - x'_q)i_q)/T'_{q0} \\ \dot{e}''_q &= (-e''_q + e'_q - (x'_d - x''_d)i_d)/T''_{d0} \\ \dot{e}''_d &= (-e''_d + e'_d + (x'_q - x''_q)i_q)/T''_{q0} \end{aligned}$$

Questions

Answer the following questions.

a. Describe the differences between the voltage control obtained by means of a ULTC transformer and that obtained using a thyristor-based shunt FACTS device (e.g., SVC). In particular, discuss the time scales of regulator response, possible harmonic injections and risk of resonances, as well as the effectiveness of the control to damp oscillations and/or increase power transfer capability of the transmission system. 25%

b. Describe the features of the constant V/f control of the induction motor. Sketch the family of torque/speed curves reulting from this kind of control. Indicate also the expected behavior of the control for speeds higher than the nominal one. 25%

c. Sketch the Bode diagram and the root locus for the primary frequency control shown in Fig. 2. Assume $G_f(s) = K_I/s$ and the following linearized model of the synchronous machine:

$$\Delta\dot{\omega} = (\Delta p_m - \Delta p_e - D\Delta\omega)/M$$ 25%

Assume also reasonable values for machine and control parameters. Discuss whether the control above is acceptable for an interconnected system with several machines.

d. Describe the rationale and the control scheme of the frequency control based on the synthetic inertia of variable-speed wind turbines. 25%

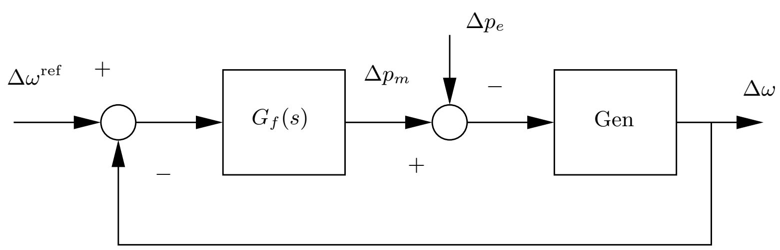


Figure 2

Power System Dynamics and Control

Exam 2014 – Solutions

Problem 1

Using the notation given in Figure 1, we can write the KVL as follows:

$$\bar{E}' - (R_s + jX_d')(I_d + jI_q)e^{j(\delta-\pi/2)} = (V_d + jV_q)e^{j(\delta-\pi/2)}$$

which, can be rewritten as:

$$\bar{E}' = [(V_d + R_sI_d - X_d'I_q) + j(V_q + R_sI_q + X_d'I_d)]e^{j(\delta-\pi/2)}$$

From the electrical equations of the machine we obtain:

$$\begin{aligned} V_d + R_sI_d &= E_d' + X_q'I_q \\ V_q + R_sI_q &= E_q' - X_d'I_d \end{aligned}$$

which substituted in the expression of $\bar{E}$ leads to:

$$\bar{E}' = [(E_d' + (X_q' - X_d')I_q) + jE_q']e^{j(\delta-\pi/2)}$$

Finally, $E_d' = (X_q - X_q')I_q$, hence:

$$\bar{E}' = [(X_q - X_d')I_q + jE_q']e^{j(\delta-\pi/2)}$$

Problem 2

To determine the three unknowns, namely $E_{fd\,\max}$, A_x and B_x, we need three independent equations. The first equations is obtained by imposing $V_{R\,\max}$:

$$8.0 = (1.0 + 0.9)E_{fd\,\max}$$

which leads to $E_{fd\,\max} = 4.2$ pu. Similarly, we obtain $E_{fd0.75\,\max}$ as:

$$0.75 \cdot 8.0 = (1.0 + 0.5)E_{fd0.75\,\max}$$

which provides $E_{fd0.75\,\max} = 4.0$ pu.

Then, we can write two independent equations using the ceiling function computed at $E_{fd\,\max}$ and at $E_{fd0.75\,\max}$:

$$\begin{aligned} 0.9 &= A_x e^{B_x 4.2} \\ 0.5 &= A_x e^{B_x 4.0} \end{aligned}$$

The ratio of the two equations above gives:

$$1.8 = e^{B_x 0.2}$$

and, hence, $B_x = 2.939$.

Finally:

$$0.9 = A_x e^{2.939 \cdot 4.2}$$

from where, we obtain $A_x = 3.922 \cdot 10^{-6}$.

Problem 3

The required approximations are:

$$e''_q = \psi''_d, \qquad e''_d = -\psi''_q$$

and:

- $\gamma_{d1} \approx \gamma_{q1} \approx 0$.
- $\gamma_{d2}\dot{\psi}''_d \approx 0$ in the differential equations of $\dot{e}'_q$.
- $\gamma_{q2}\dot{\psi}''_q \approx 0$ in the differential equations of $\dot{e}'_d$.

Questions

a. Both controller allows regulating the voltage at a given bus. However, the ULTC is a series device, while the SVC is a shunt device. Hence, the ULTC allows regulating the voltage only if there is a power flow through the transformer, while the SVC is able to provide reactive power in any loading conditions. Another relevant difference is the time response of the two controllers. The ULTC is *slow* as each tap position may reuire several seconds (the first variation even tens of seconds). The SVC is much faster as its dynamic response depends on power electronic switches. The SVC time reposnse is of the order of few ten of seconds. Finally, from hormonic distortion view point, the ULTC can cause ferromagnetic resonances and current distortions due to saturation of the magnetic core. The SVC can lead to resonances for certain operation points due to the mode of the parallel connection of the internal reactor and capacitor and introduces high frequency current harmonics due to the power electronic switching logic.

   Due to its relatively fast response, the SVC is able to damp electromechanical and/or voltage oscillations, while the ULTC is too slow for this purpose. The SVC is also capable of increasing the power transfer capability of the system by reducing the reactive power flows in the transmission lines. On the contrary, the ULTC can reduce the transfer capability of the system as its effect is to keep constant the power load consumption.

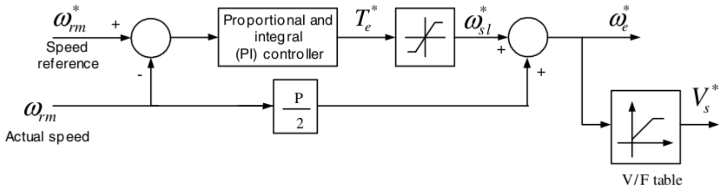


Figure 3 Typical constant V/f control scheme.

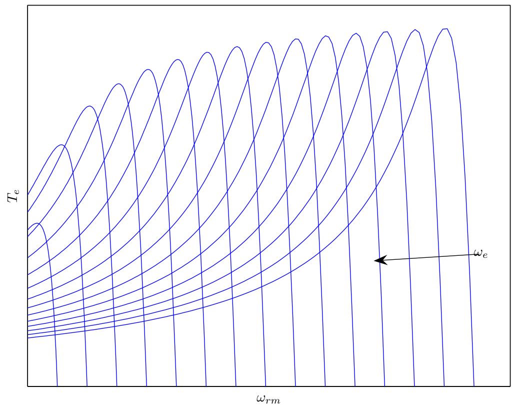


Figure 4 Torque/speed curves obtained through a constant V/f control.

b. Figure 3 shows a simple scheme of constant V/f control of induction motors. The resulting family of torque/speed curves are depicted in Figure 4.

   For rotor speed higher than the nominal one, the voltage is maintained at its nominal value and, hence, the flux in the air gap decreases.

c. The Bode diagram and the root locus are shown in Figure 5 assuming $K_I = 1$, $M = 2$ s and $D = 0.001$. The control is integral and thus is not acceptable for an interconnected system as it would force the machine to regulate the frequency *alone* or, if other machine were equipped with the same controller, the power variations of each machine due to the primary frequency control would be undetermined.

d. This method is based on the idea to use the kinetic energy available at the wind turbine shaft. We add an "additional" torque signal to the machine torque control, based on the measure of the system frequency, as shown in Figure 6. The dummy speed (ω_m^{ad}) cancels out the reduction in speed caused by the additional torque (τ_m^{ad}).

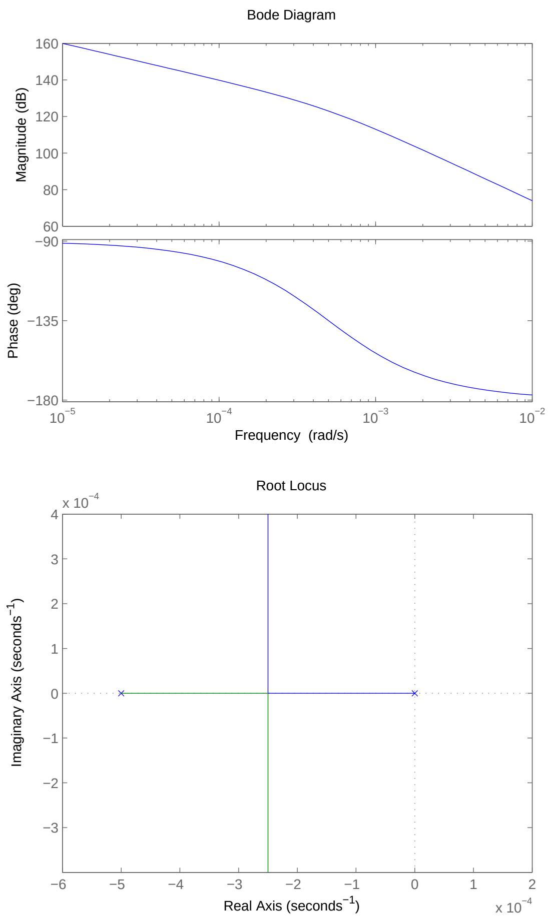


Figure 5 Bode diagram and root locus.

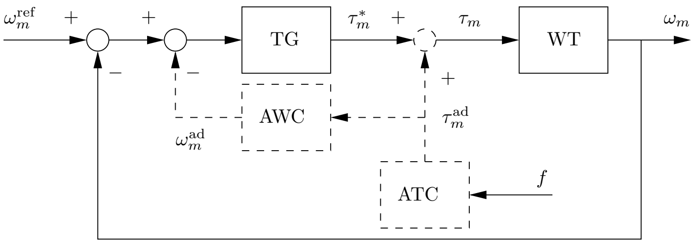


Figure 6 Synthetic inertia.

Power System Dynamics & Control

Exam 2015 – Problems & Questions

Section A

Given a synchronous generator with a two-axis model:

$$
\begin{aligned}
T'_{d0}\dot{e}'_q &= -e'_q - (x_d - x'_d)i_d + v_f \\
T'_{q0}\dot{e}'_d &= -e'_d + (x_q - x'_q)i_q \\
\dot{\delta} &= \Omega_n(\omega - \omega_s) \\
2H\dot{\omega} &= \tau_m - e'_d i_d - e'_q i_q - (x'_q - x'_d)i_d i_q - D(\omega - \omega_s) \\
0 &= r_a i_d - x'_q i_q - e'_d + v_d \\
0 &= r_a i_q + x'_d i_d - e'_q + v_q
\end{aligned}
$$

operating point:

$$
\begin{aligned}
(v_d + jv_q)e^{j(\delta - \pi/2)} &= \bar{v} = 1\angle 0 \text{ pu} \\
(i_d + ji_q)e^{j(\delta - \pi/2)} &= \bar{i} = 0.5\angle 30^\circ \text{ pu}
\end{aligned}
$$

and parameters: $r_a = 0$ pu, $x_d = 1.2$ pu, $x_q = 1.0$ pu, $x'_d = 0.2$ pu, $x'_q = 0.2$ pu

1. Find the steady-state values of δ, e'_q and e'_d. 40%
2. Find the inputs v_f and τ_m. 30%
3. Find e' and δ for the classical model. 30%

Section B

Consider a d-axis model of the synchronous machine with inclusion of the automatic voltage regulator shown in Figure 1. The relevant equation of the machine is as follows:

$$
\dot{e}'_q = (-e'_q - (x_d - x'_d)i_d + v_f)/T'_{d0}
$$

4. Assume $\Delta i_d = \Delta v = 0$. Determine the open loop transfer functions $G(s) = \Delta e'_q(s)/\Delta v^{\text{ref}}(s)$. 60%

5. Assume $\Delta i_d = 0$ and $\Delta v/\Delta e'_q = \text{const}$. Discuss whether it is possible to obtain an oscillatory response of the voltage controller. Indicate also whether the regulator of Figure 1 provides a perfect tracking of the voltage reference v^{ref}. 40%

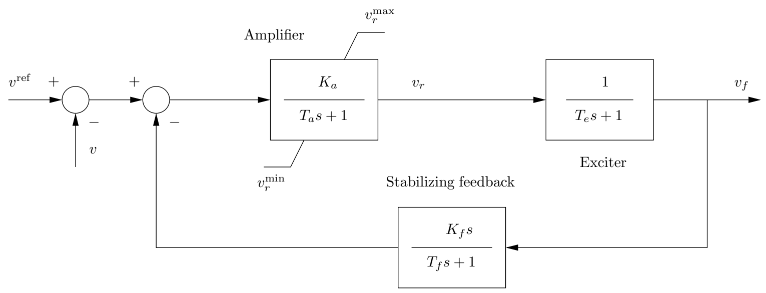


Figure 1

Section C

Consider the primary frequency control shown in Figure 2 where $G_f(s) = (1 + sT_2)/[(1 + sT_1)(1 + sT_3)]$ and the following machine model:

$$\Delta\dot{\omega} = (\Delta p_m - \Delta p_e)/M$$

6. Sketch the Bode diagram and the root locus of the system assuming $T_1 > T_2 \gg T_3$. 50%

7. Sketch the Bode diagram and the root locus of the system assuming $T_3 \gg T_1 > T_2$. 50%

Note: assume standard values for T_1, T_2 and M.

Section D

Answer the following questions.

8. Discuss the effect of the deadband on the primary frequency regulation of synchronous machines and sketch a qualitative trajectory of the frequency considering the transient following a loss of load. Compare the case with and without deadband in the primary frequency controllers (assume the same deadband for all controllers). Discuss also the expected effect of having different deadband values for different power plants in the system. 25%

9. In practical applications, the first variation of the tap ratio of ULTCs regulating the voltage in transmission systems is often delayed by a few tens of seconds. Following variations of the tap ratio are not delayed. Discuss advantages and drawbacks of this practice. 25%

10. Determine the maximum active power transfer from bus S to bus R of the system shown in Figure 3. Assume $v_S = v_M = v_R$ and $\angle \bar{v}_M = 0$. 25%

11. Discuss similarities and differences of the following controllers: (i) induction machine speed control with acceleration feedback; and (ii) wind turbine frequency control. 25%

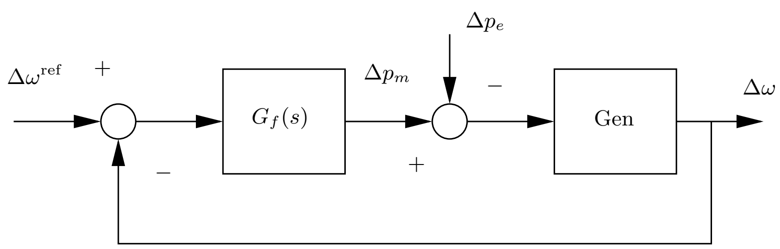


Figure 2

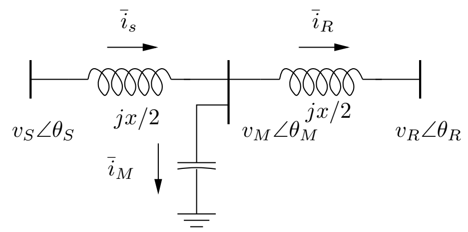


Figure 3

Power System Dynamics and Control

Exam 2015 – Solutions

Section A

1. The fmm $\bar{e}$ behind the reactance is given by:

$$\bar{e} = \bar{v} + (r_a + jx_q)\bar{i} = 1\angle 0 + j0.5\angle 30^\circ = 0.75 + j0.433 \text{ pu} \tag{1}$$

where $\delta = \angle \bar{e}$. Hence:

$$\delta = \Im(\log(\bar{e}/e)) = 0.5236 \text{ rad} = 30^\circ \tag{2}$$

Note that same result can be obtained by imposing the steady-state conditions to the machine equations. Then, the d- and q-axis components of the voltage and the current at the machine terminal bus are:

$$v_d + jv_q = \bar{v} \cdot \mathrm{e}^{j(\pi/2-\delta)} = 0.5 + j0.866 \text{ pu} \tag{3}$$

$$i_d + ji_q = \bar{i} \cdot \mathrm{e}^{j(\pi/2-\delta)} = 0 + j0.5 \text{ pu} \tag{4}$$

From the electrical equations of the machine, one has:

$$e'_d = v_d - x'_q i_q = 0.4 \text{ pu} \tag{5}$$

$$e'_q = v_q + x'_d i_d = 0.866 \text{ pu} \tag{6}$$

2. The rotor field voltage can be obtained from the differential equations of the flux e'_q, the steady-state conditions, i.e., $\dot{e}'_q = 0$, and the results above, as follows:

$$v_f = e'_q + (x_d - x'_d)i_d = 0.866 \text{ pu} \tag{7}$$

The mechanical torque can be obtained from the mechanical differential equations:

$$\tau_m = e'_d i_d + e'_q i_q = 0.433 \text{ pu} \tag{8}$$

where it is imposed that $\dot{\omega} = 0$; $\omega = \omega_s$ to satisfy $\dot{\delta} = 0$; and $x'_d = x'_q$.

3. The classical model define a fmm $\bar{e}' = e'\angle\delta$ behind the transient reactance x'_d, hence one has:

$$\bar{e}' = \bar{v} + (r_a + jx'_d)\bar{i} = 1\angle 0 + j0.2 \cdot 0.5\angle 30^\circ = 0.95 + j0.0866 \text{ pu} \tag{9}$$

From where one obtains:

$$e' = |\bar{e}'| = 0.954 \text{ pu} \tag{10}$$

$$\delta = \Im(\log(\bar{e}/e)) = 0.091 \text{ rad} = 5.2^\circ \tag{11}$$

Section B

4. Let's define:

$$G_1(s) = \frac{K_a}{(1 + T_a s)(1 + T_e s)} \tag{12}$$

$$H_1(s) = \frac{K_f s}{1 + T_f s} \tag{13}$$

The resulting transfer function of the voltage regulator is:

$$\begin{aligned} \frac{\Delta v_f}{\Delta v^{\mathrm{ref}}}(s) &= \frac{G_1(s)}{1 + G_1(s)H_1(s)} \\ &= \frac{K_a(1 + T_f s)}{(1 + T_a s)(1 + T_e s)(1 + T_f s) + K_a K_f s} \end{aligned} \tag{14}$$

From the differential equation of the d-axis transient flux, one obtains:

$$\frac{\Delta e'_q}{\Delta v_f}(s) = \frac{1}{1 + T'_{d0} s} \tag{15}$$

Hence, the total transfer function $\Delta e'_q / \Delta v^{\mathrm{ref}}$ is:

$$\frac{\Delta e'_q}{\Delta v^{\mathrm{ref}}}(s) = \frac{K_a(1 + T_f s)}{[(1 + T_a s)(1 + T_e s)(1 + T_f s) + K_a K_f s](1 + T'_{d0} s)} \tag{16}$$

5. The open-loop transfer function includes 4 poles and 1 zero. Three poles are the solutions of the polynomial function:

$$\begin{aligned} 0 &= (1 + T_a s)(1 + T_e s)(1 + T_f s) + K_a K_f s \\ &= 1 + c_1 s + c_2 s^2 + c_3 s^3 \end{aligned} \tag{17}$$

Depending on the gains K_a and K_f, the open-loop transfer function can thus have complex eigenvalues. Moreover, the poles of the closed-loop transfer function includes the gain $\Delta v / \Delta e'_q$, which, for simplicity, can be assumed constant. The total gain of the closed control loop can lead to an oscillatory response of the voltage regulator. Moreover, for high loading conditions, oscillations can be unstable.

The voltage error $\epsilon_v = v^{\mathrm{ref}} - v$ enters into a control block that does not have any null pole, e.g., no integral behaviour. Hence the scheme of Figure 1 does not provide a perfect tracking and $\epsilon_v \neq 0$ in steady-state after a step variation of the input signal v^{ref}.

Section C

6. The Bode diagram and the root locus for the case $T_3 = 0.1$ s, $T_2 = 5$ s, $T_1 = 15$ s and $M = 10$ s are shown in Figure 4.

7. The Bode diagram and the root locus for the case $T_3 = 100$ s, $T_2 = 5$ s, $T_1 = 15$ s and $M = 10$ s are shown in Figure 5.

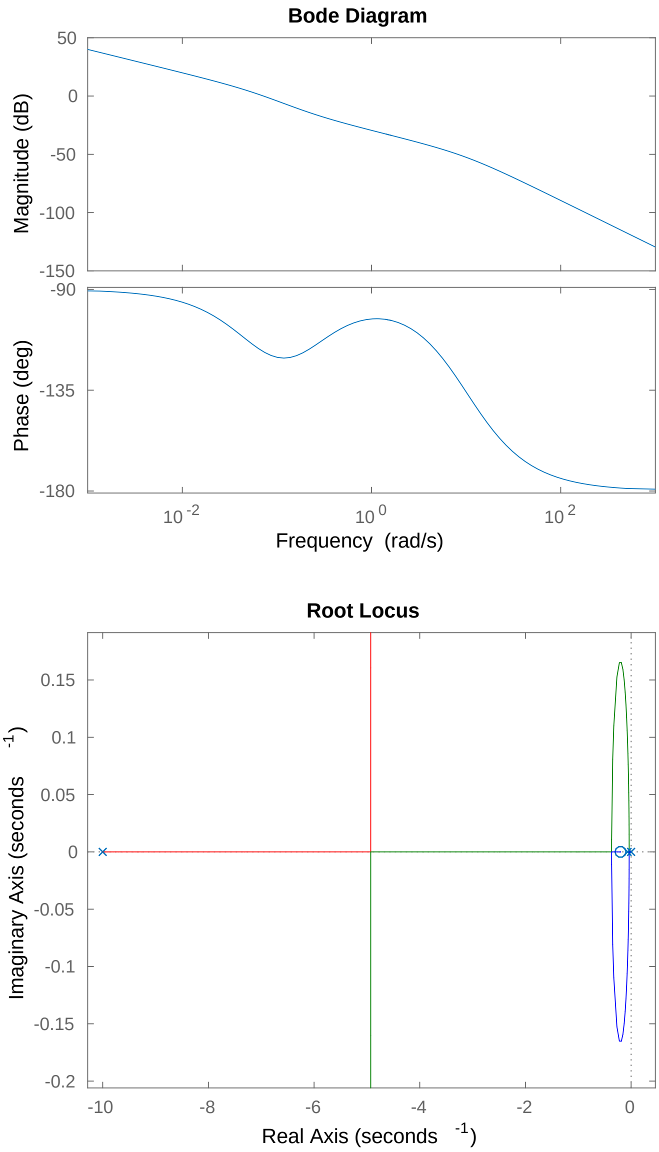
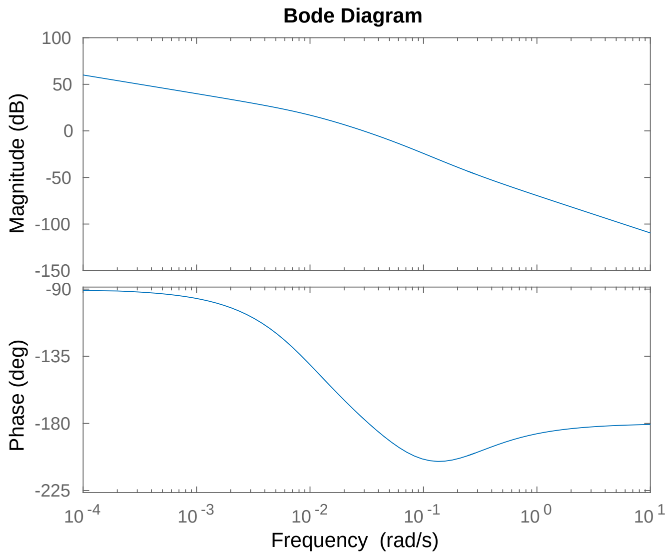

Bode Diagram
Magnitude (dB)
50
0
-50
-100
-150
Phase (deg)
-90
-135
-180
10 -2
10 0
10 2
Frequency (rad/s)
Root Locus
Imaginary Axis (seconds -1)
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-10
-8
-6
-4
-2
0
Real Axis (seconds -1)

Figure 4


Bode Diagram
Magnitude (dB)
Phase (deg)
Frequency (rad/s)

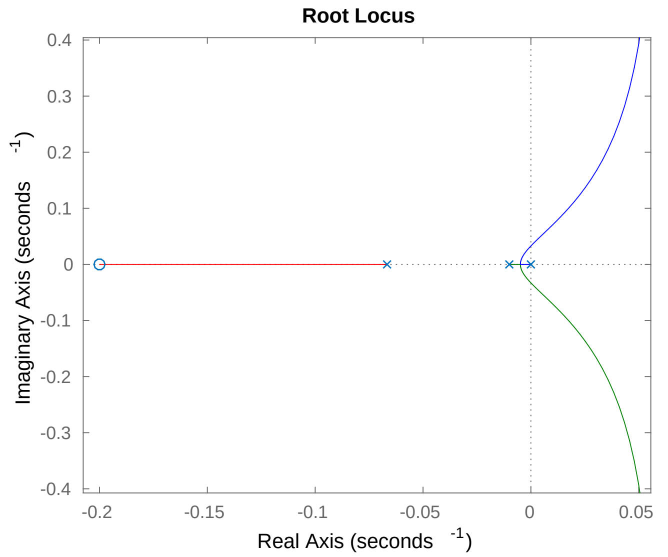

Root Locus
Imaginary Axis (seconds -1)
Real Axis (seconds -1)

Figure 5

Section D

8. It is a generalized industry practice to add a small deadband (db) to the calibration of the governor speed error bias to reduce the movement for very small speed deviations. The selection of the db affects the fidelity of the regulation. Figure 6 shows the trajectory of the frequency of the COI of a sample system after the loss of a load. In Figure 6, $db = 0.0006$ pu(Hz) for all turbine governors. No secondary frequency regulation is considered. The main effect of the deadband is to increase the overall steady-state frequency error of the system with respect to the case without deadband.

   The effect of using different deadbands leads to a intermediate results between the case with no deadband and with same deadband. Figure 6 also shows the frequency of the COI as obtained using deadband values distributed in the range $db \in [0.0001, 0.0006]$ pu(Hz).

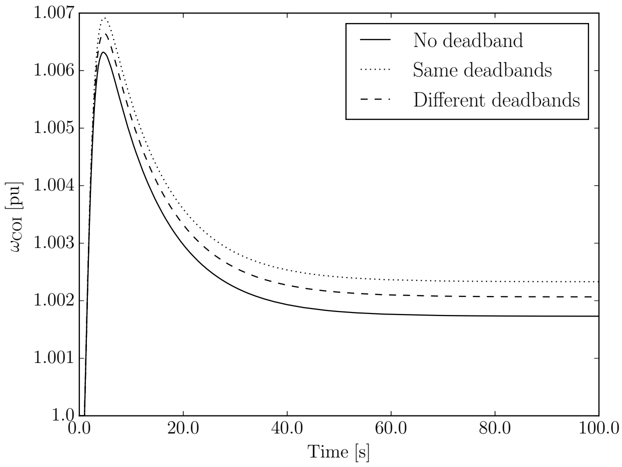


Figure 6

9. Typical regulators of ULTC consists of mechanically-moved brushes that slip on the primary winding turns. Such brushes are shortcircuited for a short time whenever the tap ratio is varied. To delay the operation of the controller after a period of inactivity can prevent unnecessary operations and reduce the need of maintanance of the device. Moreover, introducing an intentional delay in the regulator can help prevent the congestion of the system in case of load ramps on the low voltage side of the ULTCs. The main drawback of delaying the first tap variation of the ULTC is clearly a transient degradation of the voltage profile on the low voltage level of the

ULTC.

10. Assuming $\bar{v}_M = v_M \angle 0$, $\bar{v}_S = v_S \angle \theta_S$, and $\bar{v}_R = v_R \angle \theta_R$, one has:

$$\bar{i}_S = \frac{2v_S \sin\theta_S}{x} + j\frac{2(v_M - v_S\cos\theta_S)}{x} \tag{18}$$

Power flows are:

$$p_S + jq_S = \bar{v}_S \bar{i}_S^* = \frac{2v_S v_M \sin\theta_S}{x} + j\frac{2v_S^2 - 2v_S v_M \cos\theta_S}{x} \tag{19}$$

For the special case $v_S \equiv v_R \equiv v$, one has:

$$\bar{i}_S = \frac{2v\sin(\delta/2)}{x} + j\frac{2(v_M - v\cos(\delta/2))}{x} \tag{20}$$

$$p_S + jq_S = \frac{2vv_M \sin(\delta/2)}{x} + j\frac{2v^2 - 2vv_M\cos(\delta/2)}{x} \tag{21}$$

where $\theta_S = -\theta_R = \delta/2$. Hence the maximum power transfer is achieved for $\delta = \pi$:

$$p_S^{\max} = \frac{2vv_M}{x} \tag{22}$$

Finally, if $v_M \equiv v_R \equiv v_S$, one has:

$$p_S^{\max} = \frac{2v^2}{x} \tag{23}$$

11. A simple scheme that implements the acceleration feedback used to improve the speed control of induction motors is shown in Figure 7. The main purpose of such feedback is to "virtually" increase the inertia, i.e., the *dynamic stiffness*, of the motor so that the system responds slower to fast varying disturbances. The physical inertia is not increased though, thus the start-up transient of the motor is not affected. This control strategy assumes that it is possible to measure the rate of change of the frequency, i.e., the acceleration of the rotor of the motor.

    The control technique based on the emulated inertia of wind power plants is depicted in Figure 8. This method takes advantage of the kinetic energy available at the wind turbine shaft. It adds an "additional" torque signal to the machine torque control, based on the measure of the system frequency. In order to prevent that the MPPT counteracts the effect of the additional torque signal ($\tau_m^{\rm ad}$), a speed input is required. Such a speed signal ($\omega_m^{\rm ad}$) cancels out the reduction in speed caused by the additional torque ($\tau_m^{\rm ad}$).

    The main difference of the emulated inertia control with respect to the acceleration feedback control is that the feedback signal is the frequency of the system, not the rate of change of frequency. Both controllers, however, emulate an inertia. If the additional torque $\tau_m^{\rm ad}$ is computed based on the rate of change of the system frequency $f_{\rm sys}$ then the two controllers are equivalent.

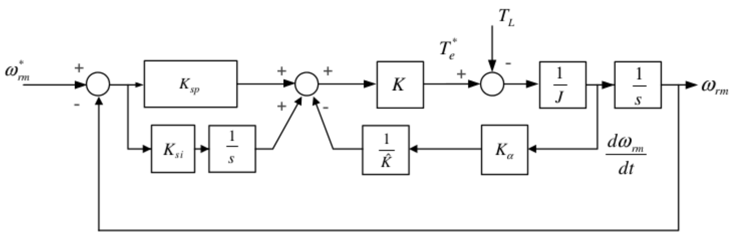


Figure 7

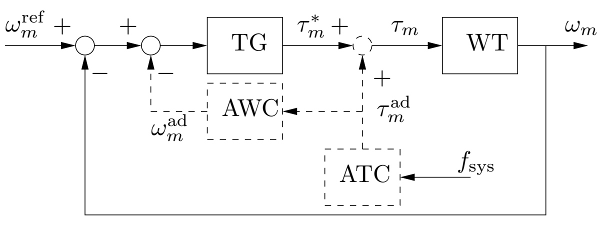


Figure 8

Power System Dynamics & Control

Exam 2016 – Problems & Questions

Section A

Consider the circuit given in Figure 1.

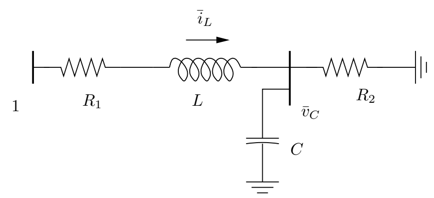


Figure 1

1. Using dq-axis frame and pu quantities, write the expression of the voltage at bus 1 as a function of the state variables of the circuit. What is the dynamic order of the circuit? 50%
2. Rewrite the expression obtained in the question above assuming stationary conditions. 30%
3. Neglecting losses and assuming stationary conditions, determine the value of the frequency for which the circuit behaves as a short circuit at node 1. 20%

Section B

Consider the following dynamic model of a synchronous generator:

$$
\begin{aligned}
\dot{\delta} &= \omega_n(\omega - \omega_s) \\
\dot{\omega} &= \frac{1}{2H}(\tau_m - \tau_e - D(\omega - \omega_s)) \\
\dot{e_q}' &= (-e'_q - (x_d - x'_d)i_d + v_f)/T'_{do} \\
\dot{e}'_d &= (-e'_d + (x_q - x'_q)i_q)/T'_{qo} \\
\dot{e}''_q &= (-e''_q + e'_q - (x'_d - x''_d)i_d)/T''_{do} \\
\dot{e}''_d &= (-e''_d + e'_d + (x'_q - x''_q)i_q)/T''_{qo} \\
\dot{\psi}_d &= \omega_n(r_a i_d + \omega\psi_q + v_d) \\
\dot{\psi}_q &= \omega_n(r_a i_q - \omega\psi_d + v_q)
\end{aligned}
$$

and algebraic constraints:

$$
\begin{aligned}
0 &= \psi_d + x''_d i_d - e''_q \\
0 &= \psi_q + x''_q i_q + e''_d \\
0 &= \psi_d i_q - \psi_q i_d - \tau_e
\end{aligned}
$$

4. Deduce a reduced order model adequate for studying the first instants after a short circuit at the terminal bus of the machine. 50%
5. Deduce a model with the minimum dynamic order able to study the coupling between primary voltage regulation to machine dynamics. 50%

Section C

A power system includes 3 machines with primary frequency regulation. The nominal powers and droops of the machines are:

Machine	S_n [MVA]	b_p [%]
1	150	5
2	200	5
3	50	5

where the droop values are given on machine bases.

6. 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 decrease of 10 MW. 50%

7. Solve again the problem assuming that machine 3 has $b_p = 0$. 30%

8. Solve again the problem assuming that machine 3 has $b_p \to \infty$. 20%

Section D

Answer the following questions.

9. Discuss the purpose of the power system stabilizer (PSS) and illustrate how it works using the classical model of the synchronous machine. 25%

10. Sketch the steady-state characteristic tap ratio vs. secondary voltage of the ULTC transformer as a function of different load models and discuss the effect of such load models on the stability of the ULTC controller (for simplicity assume that the tap ratio is a continuous variable). 25%

11. Indicate the maximum active power that can be delivered to the load shown in Figure 2. Indicate two compensation approaches to increase the power transfer limit and the corresponding FACTS devices that can be used to achieve such compensation. 25%

12. Discuss advantages, drawbacks and technical differences of wind turbines type C and D. Sketch a schematic diagram of both wind turbine types. 25%

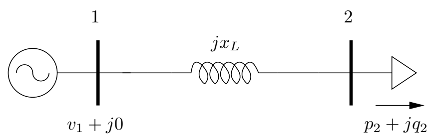


Figure 2

Power System Dynamics and Control

Exam 2016 – Solutions

Section A

1. Using Park notation and pu quantities, circuit equations are:

$$\bar{v}_{p1} = \bar{i}_{pL}(r_1 + p x_L) + \bar{v}_{pC}$$
$$\bar{i}_{pL} = \bar{v}_{pC}(r_2 + p b_C)$$

where $p = \frac{1}{\Omega_n}\frac{d(\cdot)}{dt} + j\omega$ is the time derivative in the dq-axis reference frame and ω is the angular speed, in pu, of the Park transformation.

Expanding Park's vectors, one has:

$$v_{d1} = i_{dL} r_1 + \frac{1}{\Omega_n} x_L \frac{d i_{dL}}{dt} - \omega x_L i_{q1}$$
$$v_{q1} = i_{qL} r_1 + \frac{1}{\Omega_n} x_L \frac{d i_{qL}}{dt} + \omega x_L i_{d1}$$
$$i_{dL} = v_{dC} g_2 + \frac{1}{\Omega_n} b_C \frac{d v_{dC}}{dt} - \omega b_C v_{qC}$$
$$i_{qL} = v_{qC} g_2 + \frac{1}{\Omega_n} b_C \frac{d v_{qC}}{dt} + \omega b_C c_{dC}$$

where:

$$\bar{v}_{p1} = v_{d1} + j v_{q1}$$
$$\bar{v}_{pC} = v_{dC} + j v_{qC}$$
$$\bar{i}_{pL} = v_{dL} + j v_{qL}$$

and r_1, g_2, x_L and b_C are pu values of R_1, $1/R_2$, L and C, respectively.

2. In stationary conditions $\frac{d(\cdot)}{dt} = 0$ and $\omega = \text{const.} = 1$ pu. Hence:

$$v_{d1} = i_{dL} r_1 - x_L i_{q1}$$
$$v_{q1} = i_{qL} r_1 + x_L i_{d1}$$
$$i_{dL} = v_{dC} r_2 - b_C v_{qC}$$
$$i_{qL} = v_{qC} r_2 + b_C c_{dC}$$

which corresponds to the phasor notation:

$$\bar{v}_1 = \bar{i}_L(r_1 + j x_L) + \bar{v}_C$$
$$\bar{i}_L = \bar{v}_C(g_2 + j b_C)$$

3. The resonant condition is:

$$\begin{aligned} 0 &= j\omega x_L + \frac{1}{j\omega b_C} \\ \Rightarrow \quad \omega &= \frac{1}{\sqrt{x_L b_C}} = \frac{1}{\sqrt{LC}} \end{aligned}$$

Section B

4. Fast dynamics are ψ_d, ψ_q, e''_d and e''_q. Other dynamics can be asusmed "slow" and thus constant during the very first instants of the transient. The resulting model is:

$$\begin{aligned} \dot{e}''_q &= (-e''_q + e'_q - (x'_d - x''_d)i_d)/T''_{do} \\ \dot{e}''_d &= (-e''_d + e'_d + (x'_q - x''_q)i_q)/T''_{qo} \\ \dot{\psi}_d &= \omega_n(r_a i_d + \omega\psi_q + v_d) \\ \dot{\psi}_q &= \omega_n(r_a i_q - \omega\psi_d + v_q) \\ 0 &= \psi_d + x''_d i_d - e''_q \\ 0 &= \psi_q + x''_q i_q + e''_d \end{aligned}$$

where e'_d and e'_q are constant and $v_d = v_q = 0$ (short-circuit conditions). Note that the due to the fast variation of the fluxes, the torque τ_e varies consistently in the first instants and thus, the variations of the rotor speed cannot be neglected even if its dynamic is slow. So the mechanical equation

$$\dot{\omega} = \frac{1}{2H}(\tau_m - \tau_e - D(\omega - \omega_s))$$

can be considered in the model. However one can approximate $\omega \approx$ const. in the equations of the fluxes ψ_d, ψ_q. Finally, the equation of the rotor angle can be neglected as the machine is not delivering power to the network and, thus, the rotor angle position is immaterial. The resulting full model is thus:

$$\begin{aligned} \dot{\omega} &= \frac{1}{2H}(\tau_m - \tau_e) \\ \dot{e}''_q &= (-e''_q + e'_q - (x'_d - x''_d)i_d)/T''_{do} \\ \dot{e}''_d &= (-e''_d + e'_d + (x'_q - x''_q)i_q)/T''_{qo} \\ \dot{\psi}_d &= \omega_n(r_a i_d + \psi_q) \\ \dot{\psi}_q &= \omega_n(r_a i_q - \psi_d) \\ 0 &= \psi_d + x''_d i_d - e''_q \\ 0 &= \psi_q + x''_q i_q + e''_d \\ 0 &= \psi_d i_q - \psi_q i_d - \tau_e \end{aligned}$$

5. The minimum machine model that can be coupled with an AVR must include explicitly the field voltage v_f. The resulting model is thus the so-called one d-axis model which include mechanical equations and the dynamic of e'_q:

$$\begin{aligned}
\dot{\delta} &= \omega_n(\omega - \omega_s) \\
\dot{\omega} &= \frac{1}{2H}(\tau_m - \tau_e - D(\omega - \omega_s)) \\
\dot{e}'_q &= (-e'_q - (x_d - x'_d)i_d + v_f)/T'_{do} \\
0 &= r_a i_q - e'_q + x'_d i_d + v_q \\
0 &= r_a i_d - x_q i_q + v_d \\
0 &= (e'_q + (x_q - x'_d)i_d)i_q + \tau_e
\end{aligned}$$

where it has been assumed $T'_{q0} = T''_{q0} = T''_{d0} = 0$ and $\dot{\psi}_d \approx 0$ and $\dot{\psi}_q \approx 0$ and $\omega \approx 1$ pu in the flux equations.

Section C

6. Droop coefficients on system base:

$$\begin{aligned}
b_{p1} &= 0.05\frac{100}{150} = 0.0333 \\
b_{p2} &= 0.05\frac{100}{200} = 0.025 \\
b_{p3} &= 0.05\frac{100}{50} = 0.1
\end{aligned}$$

The load variation in pu is $\Delta p_L = -0.1$ pu.

In steady state, the power balance has to be satisfied:

$$\Delta p_{m1} + \Delta p_{m2} + \Delta p_{m3} = \Delta p_L$$

Moreover, the freqeuncy is the same for all machines:

$$\begin{aligned}
\Delta p_{m1} &= -\frac{1}{b_{p1}}\Delta\omega \\
\Delta p_{m2} &= -\frac{1}{b_{p2}}\Delta\omega \\
\Delta p_{m3} &= -\frac{1}{b_{p3}}\Delta\omega
\end{aligned}$$

Hence:

$$-\left(\frac{1}{b_{p1}} + \frac{1}{b_{p2}} + \frac{1}{b_{p3}}\right)\Delta\omega = \Delta p_L$$

which leads to:

$$\begin{aligned}\Delta\omega &= -\frac{\Delta p_L}{\frac{1}{b_{p1}} + \frac{1}{b_{p2}} + \frac{1}{b_{p3}}} \\ &= \frac{0.1}{30+40+10} = 1.25 \cdot 10^{-3} \text{ pu(Hz)}\end{aligned}$$

and, finally:

$$\begin{aligned}\Delta p_{m1} &= 0.0375 \text{ pu(MW)} \\ \Delta p_{m2} &= 0.05 \text{ pu(MW)} \\ \Delta p_{m3} &= 0.0125 \text{ pu(MW)}\end{aligned}$$

7. If $b_{p3} = 0$, machine 3 takes the whole load variation (isochronous control). Hence:

$$\begin{aligned}\Delta p_{m1} &= 0 \\ \Delta p_{m2} &= 0 \\ \Delta p_{m3} &= 0.1 \text{ pu(MW)}\end{aligned}$$

8. If $b_{p3} \to \infty$, machine 3 does not regulate the frequency (constant active power control). Hence $\Delta p_{m3} = 0$. The other machines have to compensate the load variation:

$$\Delta p_{m1} + \Delta p_{m2} = \Delta p_L$$

and:

$$-\left(\frac{1}{b_{p1}} + \frac{1}{b_{p2}}\right)\Delta\omega = \Delta p_L$$

which leads to:

$$\begin{aligned}\Delta\omega &= -\frac{\Delta p_L}{\frac{1}{b_{p1}} + \frac{1}{b_{p2}} + \frac{1}{b_{p3}}} \\ &= \frac{0.1}{30+40} = 1.43 \cdot 10^{-3} \text{ pu(Hz)}\end{aligned}$$

and, finally:

$$\begin{aligned}\Delta p_{m1} &= 0.043 \text{ pu(MW)} \\ \Delta p_{m2} &= 0.057 \text{ pu(MW)}\end{aligned}$$

Section D

9. The objective of the PSS is to damp the electromechanical oscillations of a synchronous machine by using a measure of the rotor speed (or active

power) and using such a signal to properly modify the reference voltage of the AVR of the machine.

Let's consider the electro-mechanical model of the machine:

$$2H \frac{\mathrm{d}\omega}{\mathrm{d}t} = p_m - p_e(\delta)$$

where

$$p_e(\delta) = \frac{e'_q v_h}{x'_d} \sin(\delta - \theta_h)$$

and differentiating:

$$2Hs\Delta\omega = -\frac{\partial p_e}{\partial \delta}\Delta\delta - \frac{\partial p_e}{\partial e'_q}\Delta e'_q - \frac{\partial p_e}{\partial v_h}\Delta v_h$$

if e'_q and v_h are constant, we have:

$$2Hs\Delta\omega = -\frac{\partial p_e}{\partial \delta}\Delta\delta = -K\Delta\delta$$

where

$$K = \frac{e'_q v_h}{x'_d} \cos(\delta_0 - \theta_0)$$

Since $\Delta\omega = s\Delta\delta$, we have:

$$2Hs^2\Delta\delta + K\Delta\delta = 0$$

which has a pair of pure complex eigenvalues (if there is no damping):

$$\lambda_{1,2} = \pm j\sqrt{\frac{K}{2H}}$$

The PSS allows imposing:

$$\Delta e'_q = K_1 s\Delta\delta$$

Hence, we have:

$$2Hs\Delta\omega = -K\Delta\delta - K_\omega s\Delta\delta$$

where:

$$K_\omega = K_1 \frac{\partial p_e}{\partial e'_q}$$

so:

$$2Hs^2\Delta\delta + K_\omega s\Delta\delta + K\Delta\delta = 0 \quad \Rightarrow \quad \lambda_{1,2} = -\frac{K_\omega}{4H} \pm j\frac{\sqrt{8KH - K_\omega^2}}{4H}$$

10. Figure 5 shows the requested steady-state characteristic of the ULTC assuming a continuous model of the tap ratio for three kind of loads: constant power, constant current and constant impedance. The feasibility region of the ULTC (in grey in the figure) indicates that the ULTC is stable regardless the load model.

11. If the voltage at the load is constant, the maximum active power that can be transferred is:

$$p^{\max} = \frac{v_1 v_2}{x_L}$$

If load voltage is not controlled, this limit cannot be matched. Assuming a constant power factor $\cos(\phi_2)$, the active power delivered to load is a function of the voltage magnitude v_2:

$$p_2 = \frac{v_2^2}{x_L}\left(\frac{-\tan(\phi_2) + \sqrt{\tan^2(\phi_2) - \left(1 - \frac{v_1^2}{v_2^2}\right)}}{1 + \tan^2(\phi_2)}\right)$$

which has a maximum as indicated in Figure 4.

In both cases, it is straightforward to observe that the power that can be delivered to the load can be increased either reducing x_L or increasing the voltage v_2 at the load bus. In the first case, this can be achieved using a series compensation (series capacitor, TCSC or SSSC) and in the second case, using a shunt compensation at bus 2 (bank of shunt capacitors, SVC or Statcom).

12. Wind turbines type C and B are sketched in Figure 5. Both types are able to regulate the speed and thus can maximize the power extracted from the wind by means of a MPPT device. Pitch angle regulation is also possible for both technologies. Moreover, thanks to the grid-side converter, both wind turbine types can regulate the voltage at the point of connection with the grid. The main advantages of Type C is that the converters do not need to be designed for the full capacity of the wind turbine, which allows reducing costs. On the other hand, Type C is limited to wound-rotor induction generators which do not have the best capacity/weigth ratio. Type D requires full-size converters, but can be connected to any type of generator, including induction machines, and synchronous machines. The latter has the advantage to have an excellent capacity/weight ratio. Finally, the full-size converter of Type C is effectively a VSC-based solid-state transformer, which allows a high level of flexibility in terms of control and fault-ride through capability of the wind turbine.

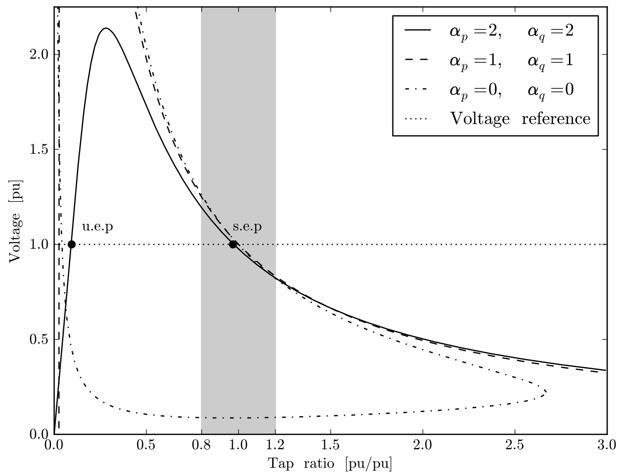


Figure 3

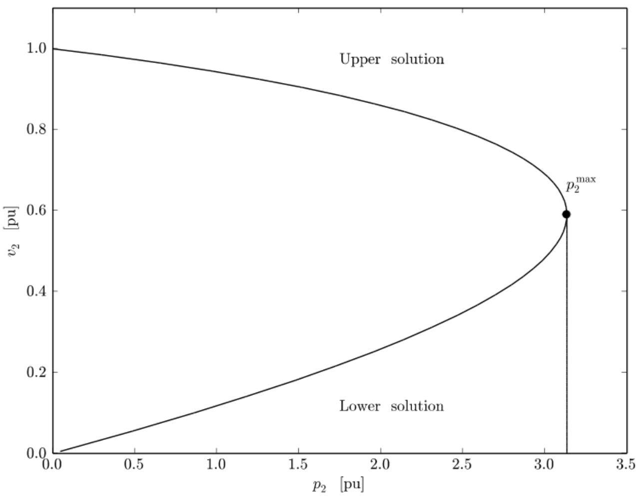


Figure 4

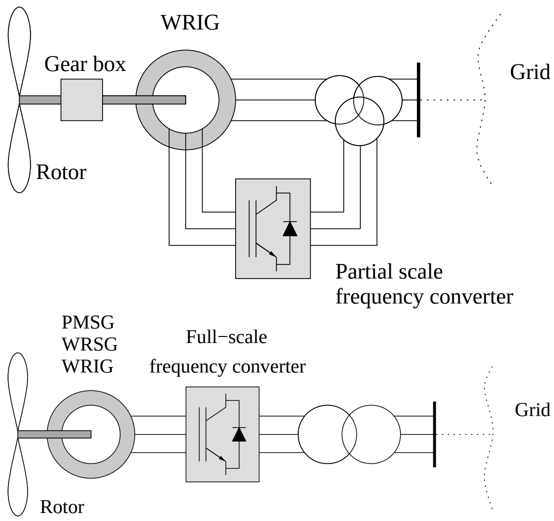

WRIG
Gear box
Grid
Rotor
Partial scale
frequency converter
PMSG
WRSG
WRIG
Full−scale
frequency converter
Grid
Rotor

Figure 5

Power System Dynamics & Control

Exam 2017 – Problems & Questions

Section A

The circuit shown in Figure 1 is a single-line diagram of a symmetrical three-phase system.

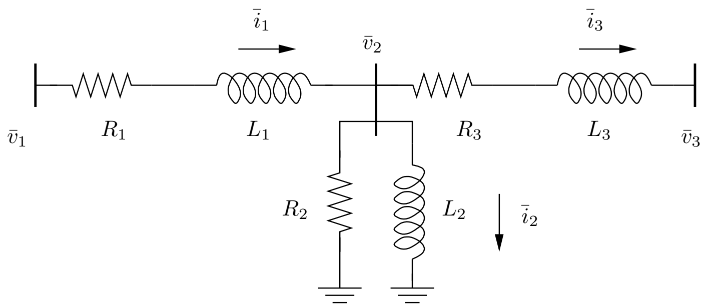


Figure 1

1. Using dq-axis frame and pu quantities and assuming that $\bar{v}_1$ and $\bar{v}_3$ are assigned, write the set of differential-algebraic equations that model the circuit. Indicate state and algebraic variables and the dynamic order of the resulting set of equations. 50%
2. Rewrite the expression obtained in the question above in phasor domain assuming stationary conditions. 30%
3. Assuming that the circuit models a transmission system transformer, define a simplified reduced-order model of the circuit suitable for transient stability analysis. Duly justify the answer. 20%

Section B

Consider the following one-axis model of a synchronous generator with inclusion of stator flux dynamics. This model is formed by the field voltage differential equation:

$$\dot{\psi}_f = (v_f - e'_q)/T'_{d0} \tag{1}$$

where the field flux ψ_f is:

$$\psi_f = e'_q - (x_d - x'_d)i_d$$

which leads to rewrite (1) as:

$$\dot{e}'_q = \frac{x_d}{x'_d}\left(\frac{1}{T'_{d0}}(v_f - e'_q) - \frac{x_d - x'_d}{x_d}\dot{\psi}_d\right)$$

Stator electrical equations link the voltages to currents and stator magnetic fluxes, as follows:

$$\begin{aligned}\dot{\psi}_d &= \omega_n(r_a i_d + \omega\psi_q + v_d)\\ \dot{\psi}_q &= \omega_n(r_a i_q - \omega\psi_d + v_q)\end{aligned}$$

Finally, mechanical equations are:

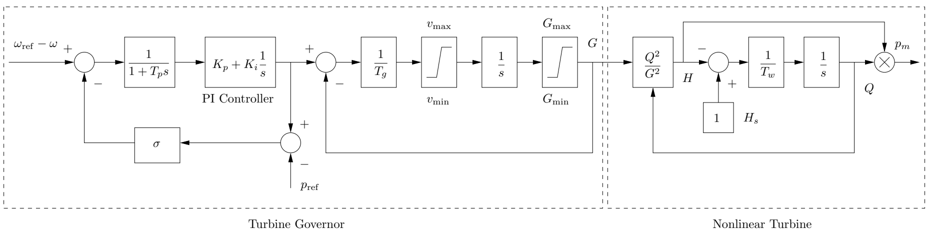
$$\begin{aligned}\dot{\delta} &= \omega_n(\omega - \omega_s)\\ \dot{\omega} &= \frac{1}{2H}(\tau_m - \tau_e - D(\omega - \omega_s))\end{aligned}$$

where:

$$\tau_e = \psi_d i_q - \psi_q i_d$$

4. Rewrite the equations of the machine as a set of explicit ordinary differential equations (ODEs). 30%
5. Assuming as reference time scale the transient stability analysis, group the state variables of the model into *fast*, *of interest*, and *slow* and discuss whether the proposed machine model is adequate for detailed transient stability analysis. 40%
6. Deduce a model with the minimum dynamic order able to study the coupling between primary voltage regulation and machine dynamics. 30%

Figure 2



$\omega_{\text{ref}} - \omega$
$\frac{1}{1+T_p s}$
$K_p + K_i \frac{1}{s}$
PI Controller
σ
p_{ref}
$\frac{1}{T_g}$
$v_{\max}$
$v_{\min}$
$\frac{1}{s}$
$G_{\max}$
$G_{\min}$
G
$\frac{Q^2}{G^2}$
H
$\frac{1}{T_w}$
$\frac{1}{s}$
1
H_s
Q
p_m
Turbine Governor
Nonlinear Turbine

Section C

Consider the block diagram of Figure 2, which represents the turbine governor and the turbine of a typical hydro power plant.

7. Write the differential-algebraic equations modelling the control scheme of Figure 2. 50%

8. Indicate whether the controller is perfectly tracking the frequency and the expression of the static droop of this regulator. 30%

9. Assuming $p_m = \omega = 1$ pu and that all quantitites are within limits, determine the initial value of all variables and input quantities of the turbine governor. 20%

Section D

Answer the following questions.

10. Discuss the purpose of the over excitation limiter (OEL) and its impact on the transient stability of the system. Sketch also the effect of the OEL on the steady-state capability curve of the synchronous machine. 25%

11. Discuss the purpose of phase-shifting transformers and the main differences in terms of control capability and transient response with respect to series FACTS devices, such as the TCSC and SSSC. 25%

12. Discuss the effect of load models on the transient response of transmission systems. 25%

13. Discuss advantages and drawbacks of controlling the frequency with non-synchronous devices, such as wind power plants, controlled loads and VSC-based energy storage systems. 25%

Power System Dynamics and Control

Exam 2017 – Solutions

Section A

1. Using Park notation and pu quantities, circuit equations are:

$$\begin{aligned}
\bar{v}_{p1} &= \bar{i}_{p1}(r_1 + px_{L1}) + \bar{v}_{p2} \\
\bar{v}_{p2} &= \bar{i}_{p3}(r_3 + px_{L3}) + \bar{v}_{p3} \\
\bar{v}_{p2} &= \bar{i}_{p2}(r_2 + px_{L2}) \\
\bar{i}_{p1} &= \bar{i}_{p2} + \bar{i}_{p3}
\end{aligned}$$

where $p = \frac{1}{\Omega_n}\frac{d(\cdot)}{dt} + j\omega$ is the time derivative in the dq-axis reference frame and ω is the angular speed, in pu, of the Park transformation.

Expanding Park's vectors, one has:

$$\begin{aligned}
v_{d1} &= i_{d1}r_1 + \frac{1}{\omega_n}x_{L1}\frac{di_{d1}}{dt} - \omega x_{L1}i_{q1} + v_{d2} \\
v_{q1} &= i_{q1}r_1 + \frac{1}{\omega_n}x_{L1}\frac{di_{q1}}{dt} + \omega x_{L1}i_{d1} + v_{q2} \\
v_{d2} &= i_{d3}r_3 + \frac{1}{\omega_n}x_{L3}\frac{di_{d3}}{dt} - \omega x_{L3}i_{q3} + v_{d3} \\
v_{q2} &= i_{q3}r_3 + \frac{1}{\omega_n}x_{L3}\frac{di_{q3}}{dt} + \omega x_{L3}i_{d3} + v_{q3} \\
v_{d2} &= i_{d2}r_2 + \frac{1}{\omega_n}x_{L2}\frac{di_{d2}}{dt} - \omega x_{L2}i_{q2} \\
v_{q2} &= i_{q2}r_2 + \frac{1}{\omega_n}x_{L2}\frac{di_{q2}}{dt} + \omega x_{L2}i_{d2} \\
i_{d1} &= i_{d2} + i_{d3} \\
i_{q1} &= i_{q2} + i_{q3}
\end{aligned}$$

where:

$$\begin{aligned}
\bar{v}_{ph} &= v_{dh} + jv_{qh}, \qquad & h &= \{1,2,3\} \\
\bar{i}_{ph} &= i_{dh} + ji_{qh}, \qquad & h &= \{1,2,3\}
\end{aligned}$$

and r_h, x_{Lh} are pu values of R_h, L_h, with $h = \{1,2,3\}$, respectively.

All current are state variables, and all voltage are algebraic variables. The dynamic order of the system is 6.

2. In stationary conditions $\frac{d(\cdot)}{dt} = 0$ and $\omega = \text{const.} = 1$ pu. Hence:

$$
\begin{aligned}
v_{d1} &= i_{d1}r_1 - x_{L1}i_{q1} + v_{d2} \\
v_{q1} &= i_{q1}r_1 + x_{L1}i_{d1} + v_{q2} \\
v_{d2} &= i_{d3}r_3 - x_{L3}i_{q3} + v_{d3} \\
v_{q2} &= i_{q3}r_3 + x_{L3}i_{d3} + v_{q3} \\
v_{d2} &= i_{d2}r_2 - x_{L2}i_{q2} \\
v_{q2} &= i_{q2}r_2 + x_{L2}i_{d2} \\
i_{d1} &= i_{d2} + i_{d3} \\
i_{q1} &= i_{q2} + i_{q3}
\end{aligned}
$$

which corresponds to the phasor notation:

$$
\begin{aligned}
\bar{v}_1 &= \bar{i}_1(r_1 + jx_{L1}) + \bar{v}_2 \\
\bar{v}_2 &= \bar{i}_3(r_3 + jx_{L3}) + \bar{v}_3 \\
\bar{v}_2 &= \bar{i}_2(r_2 + jx_{L2}) \\
\bar{i}_1 &= \bar{i}_2 + \bar{i}_3
\end{aligned}
$$

3. In transformers, the shunt impedance represents the magntization and iron losses. These can be neglected in standard transient stability analysis. The resulting trasformer model is thus a series impedance that consists of the series of $r_1 + r_3$ and $x_{L1} + x_{L3}$. The resultimg model has only two state variables, i_{d1} and i_{q1}:

$$\bar{v}_{p1} = \bar{i}_{p1}(r_1 + r_3 + p(x_{L1} + x_{L3})) + \bar{v}_{p3}$$

or, equivalently:

$$
\begin{aligned}
v_{d1} &= i_{d1}(r_1 + r_3) + \frac{1}{\omega_n}(x_{L1} + x_{L3})\frac{di_{d1}}{dt} - \omega(x_{L1} + x_{L3})i_{q1} + v_{d3} \\
v_{q1} &= i_{q1}(r_1 + r_3) + \frac{1}{\omega_n}(x_{L1} + x_{L3})\frac{di_{q1}}{dt} + \omega(x_{L1} + X_{L3})i_{d1} + v_{q2}\ .
\end{aligned}
$$

Section B

4. Explicit DAEs have the time derivative of state variables on the right hand side. The expression of $\dot{\psi}_d$ must thus be substituted in the equation of $\dot{e}'_q$. The final set differential equations is as follows:

$$
\begin{aligned}
\dot{\delta} &= \omega_n(\omega - \omega_s) \\
\dot{\omega} &= \frac{1}{2H}(\tau_m - \tau_e - D(\omega - \omega_s)) \\
\dot{\psi}_d &= \omega_n(r_a i_d + \omega\psi_q + v_d) \\
\dot{\psi}_q &= \omega_n(r_a i_q - \omega\psi_d + v_q) \\
\dot{e}'_q &= \frac{x_d}{x'_d}\left(\frac{1}{T'_{d0}}(v_f - e'_q) - \omega_n\frac{x_d - x'_d}{x_d}(r_a i_d + \omega\psi_q + v_d)\right)
\end{aligned}
$$

where e'_q, i_d, i_q, ψ_d and ψ_q are linked by proper algebraic equations.

5. Fast dynamics are ψ_d, ψ_q, while the dynamics of interest are e'_q and δ and ω. There are no slow dynamics in the model if the time scale of interest is that of transient stability.

   The model is not adequate for a detailed transient stability analysis as it lacks, at least, of the transient dynamic on the q-axis (e'_d). A detailed transient-stability model would also include d- and q-axis sub-transient dynamics (e''_q and e''_d).

6. The minimum machine model that can be coupled with an AVR must include explicitly the field voltage v_f. The resulting model is thus the so-called one d-axis model which include mechanical equations and the dynamic of e'_q:

$$\begin{aligned}
\dot{\delta} &= \omega_n(\omega - \omega_s) \\
\dot{\omega} &= \frac{1}{2H}(\tau_m - \tau_e - D(\omega - \omega_s)) \\
0 &= r_a i_d + \psi_q + v_d \\
0 &= r_a i_q - \psi_d + v_q \\
\dot{e}'_q &= \frac{x_d}{x'_d}\frac{1}{T'_{d0}}(v_f - e'_q)
\end{aligned}$$

   where e'_q, i_d, i_q, ψ_d and ψ_q are linked by proper algebraic equations and where it has been assumed $\dot{\psi}_d \approx 0$ and $\dot{\psi}_q \approx 0$ and $\omega \approx 1$ pu in the flux equations.

Section C

7. The block diagram shown in Fig. 2 is described by the following equations:

$$\begin{aligned}
\dot{x}_{g1} &= \frac{1}{T_p}[(\omega_{\text{ref}} - \omega) + (\sigma K_p - 1)x_{g1} - \sigma x_{g2} + \sigma p_{\text{ref}}] \\
\dot{x}_{g2} &= K_i x_{g1} \\
\dot{x}_{g3} = v &= \begin{cases} \frac{1}{T_g}(-K_p x_{g1} + x_{g2} - x_{g3}) & \text{if } v_{\max} \geq \frac{1}{T_g}(-K_p x_{g1} + x_{g2} - G) \geq v_{\min} \\ v_{\max} & \text{if } v_{\max} < \frac{1}{T_g}(-K_p x_{g1} + x_{g2} - G) \\ v_{\min} & \text{if } v_{\min} > \frac{1}{T_g}(-K_p x_{g1} + x_{g2} - G) \end{cases} \\
\dot{x}_{g4} &= \frac{1}{T_w}[1 - (\frac{x_{g4}}{G})^2] \\
G &= \begin{cases} x_{g3} & \text{if } G_{\max} \geq x_{g3} \geq G_{\min} \\ G_{\max} & \text{if } G_{\max} < x_{g3} \\ G_{\min} & \text{if } G_{\min} > x_{g3} \end{cases} \\
p_m &= x_{g4}(\frac{x_{g4}}{G})^2
\end{aligned}$$

8. The turbine governor is not perfect tracking unless $\sigma = 0$. σ is the static (permanent) droop of the turbine governor.

9. If the system is in steady state, $\omega = \omega_{\text{ref}}$, and $G = p_{\text{ref}}$. Initial values are:

$$G = x_{g2} = x_{g3} = x_{g4} = p_m = p_{\text{ref}}$$
$$x_{g1} = 0$$

Section D

10. The OEL is a limiter that prevents the field current of synchornous machines to be above its maximum limit and thus prevent the field winding to overheat. Since its effect is to reduce the availability of reactive power of synchronous machines, the effect of the OEL can lead to voltage instability.

    In steady-state, the OEL implements the rotor current thermal limit, as shown in Figure 3.

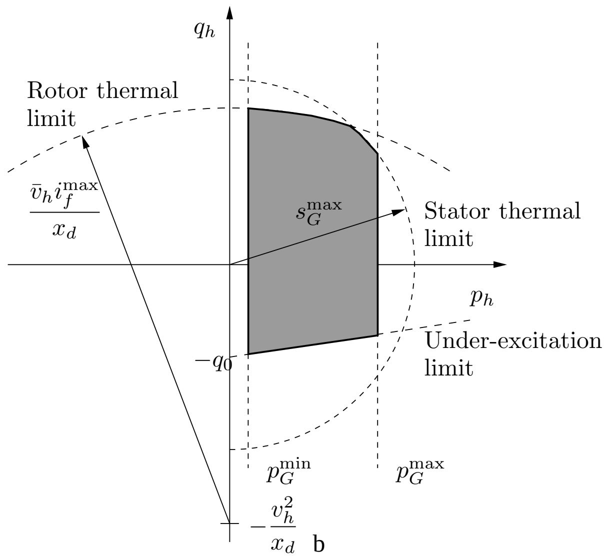


Figure 3

11. Phase-shifting transformers (PhSs) are utilized for regulating the active power flow in meshed HV networks. As ULTCs, PhSs are based on an electromechanical control system, which is relatively slow and delicate. TCSC and SSSC are based on power electronics converters and can be thus much faster and more robust than PhSs.

12. Load model greatly impacts on power system dynamics. In general, impedance load models tend to increase the system stability margin, while constant power load model to decrease it. Since load models are not easy to define, considering constant power loads is a conservative approach. Due to the slow response of ULTCs, constant impedance models are more appropriate for short term dynamic analysis (up to few tens of seconds), while constant power load models are more adequate for long term analysis (fomr minutes to several tens of minutes).

13. Non-synchronous devices do not, in general, provide inertia. Their response is thus subject to a precise measure of local frequency deviations and cannot be instantaneous as that of the inertia of synchronous machines. However, the primary frequency control of wind turbine and other VSC-based DERs and/or ESS systems tends to be faster than the primary frequency control of synchronous machines. This can help reducing the ROCOF and the nadir/zenith of frequency deviations. A drawback of non-synchronous devices is also a limited reserve/capacity which results, thus, in a limited capability ot provide frequency control.