

University of North Carolina-Charlotte  
Department of Electrical and Computer Engineering  
ECGR 4143/5195      Electrical Machinery      Fall 2009

Problem Set 5  
Due: Thursday October 29

Problem 1: Steady-State Operation of Synchronous Generators

A 60Hz three-phase synchronous generator with sinusoidally-distributed windings has the following parameters:

$$L_d = 4.1484\text{mH}$$
$$M = 31.695\text{mH}$$

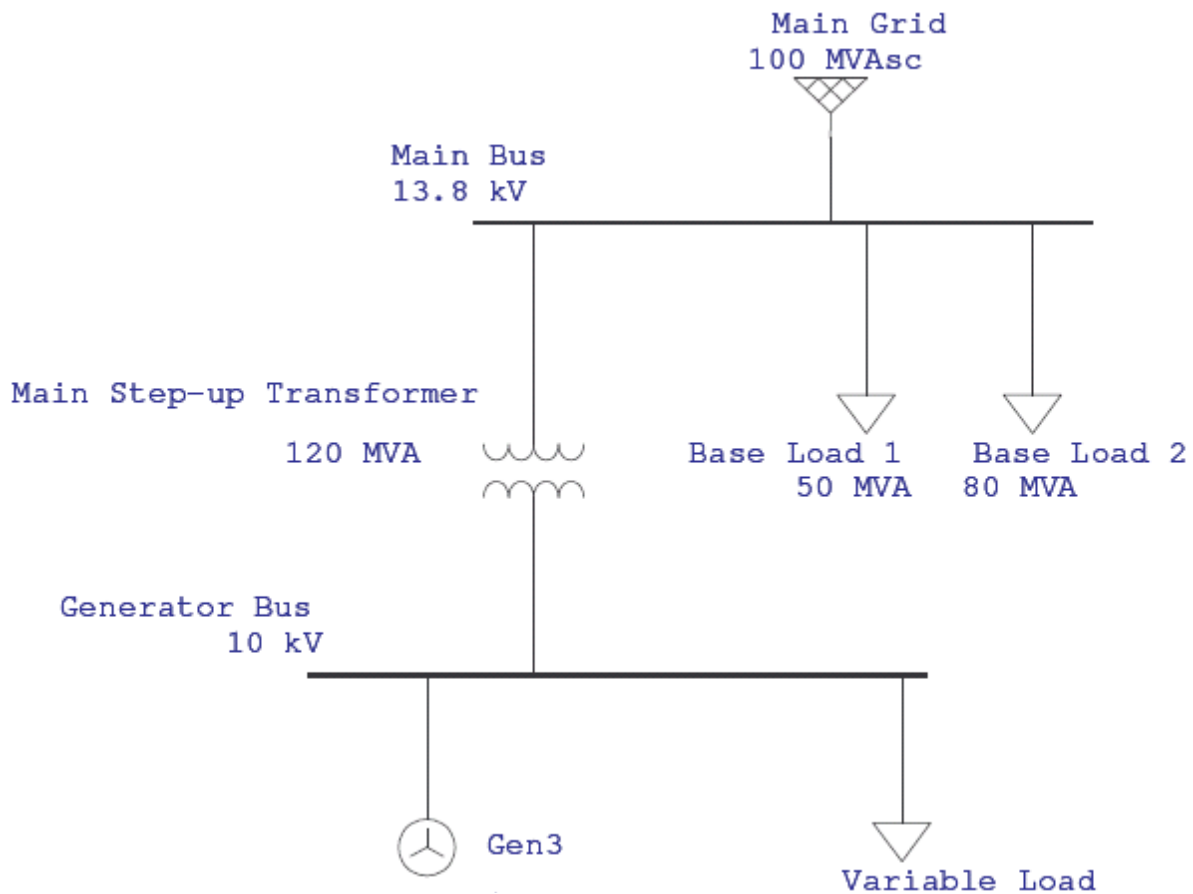
This machine is rated to operate at 635MVA, with a power factor of 0.9 lagging. It is also rated to operate with a line-to-line voltage of 24kV RMS. It is a two-pole machine, and it is connected to a very large system that has a constant voltage. Throughout this problem, assume that the system is operating at rated voltage.

- a) Provide time-domain expressions for the three line-to-neutral voltages present at the machine terminals. You are given that  $v_a(t) = V\cos(\omega t)$ , and you have enough information to determine numeric values for  $V$  and  $\omega$ . Provide time-domain expressions for the three line-to-line voltages present at the machine terminals. What are the peak values of the line-to-neutral voltages? What are the RMS values?
- b) This machine is operating at its rated power factor and it's currently supplying an apparent power of approximately 550MVA. How much power  $P$  and reactive power  $Q$  are being supplied by the machine? Is it under-excited or over-excited during these conditions? What is the RMS value of the current being drawn out of phase A? Please provide a time-domain expression for the phase A current.
- c) What is the power angle  $\delta$  of the machine under the operating conditions specified in part b? What is the field current  $I_F$  at this time? On the same set of axes, plot the voltage  $e_{af}(t)$  for phase A and plot the voltage  $v_a(t)$ .
- d) Operators at the plant where this machine is located are instructed by the dispatcher to lower  $Q$  by 20%. As a result, the operators change one variable. Which is it, and what will be its new value? What will be the new value of the power angle  $\delta$ ? Does the real power output  $P$  of the machine change?
- e) The dispatcher now instructs the plant to decrease the reactive power to -10MVAR. Which variable did the operators change, and what is its new value? What is the power angle under these conditions? Is this machine supplying or absorbing  $Q$ ? Does the real power change?
- f) The dispatcher now instructs the plant to increase real power and reactive power to the rated limit. At that point, the machine is providing 635MVA at a power factor of 0.9 lagging. What is the value of the field current? What is the value of the power angle? How much total RMS current is being supplied?

- g) What is the maximum RMS current that can be provided by phase b of this machine?
- h) Before the machine is connected to the grid, the operators spin it up to synchronous speed and make sure that the open-circuit voltage is approximately 24kV RMS line-to-line. What value of field current must the operators provide in order for the open-circuit voltage to be at this value? The field current value here is sometimes referred to as AFNL (amps field, no-load).
- i) Based on what you've seen here, how do operators control the reactive power provided by a generator?

**Problem 2: Generator Reactive Power Flow in a Small System (ETAP)**

In this problem, you are going to construct a system that looks like the following:



You should place all of the elements in just the same way that you did last time. Here are the specs that you should use (NB: All voltages are line-to-line RMS, which is standard):

- Main Grid:
  - Mode: Swing
  - Rated kV: 13.8kV (Remember this is line-to-line, RMS)
  - 3-Phase MVA<sub>sc</sub>: 100

- 3-Phase X/R ratio: 40
- Main Bus:
  - Voltage: 13.8kV
- Base Load 1 (Use a static load):
  - MVA: 50
  - PF: 80%
- Base Load 2 (Use a static load):
  - MVA: 80
  - PF: 90%
- Main Step-Up Transformer
  - When you place this transformer, you will need to change its orientation so that the secondary is connected to the Main Bus (13.8kV) and its primary is connected to the Generator Bus (10kV). You can change the orientation by right-clicking on the transformer once it's been placed on the diagram. You should right-click and change the orientation before you actually connect the primary or secondary, however, so that wires don't cross.
  - Primary Rated kV: 10kV
  - Secondary Rated kV: 13.8kV
  - MVA: 120
  - Select Typical Z & X/R
- Generator Bus:
  - Voltage: 10kV
- Variable Load (Use a static load):
  - MVA: 200
  - PF: 100%
- Main Generator:
  - You will also have to right-click and change the orientation of this element
  - Operation Mode: Voltage Control (on the Info Tab)
  - Rated kV:10
  - Rated MVA: 200
  - Rated PF: 85%
  - Rated Efficiency: 98%
  - # of Poles: 4
  - Design MW: 150 (This is located in the table on the Rating Tab)
  - MVar Limits: Choose Capability Curve (This located on the Rating Tab)
  - On the Impedance/Model Tab, enter  $X_d = 1.2$  pu and  $X_q = 1.2$  pu. We won't worry about any other parameters. They don't really affect us just yet. We'll get to them later.  $X_q$  is also a parameter that we'll discuss later in the semester. For now, suffice it to say that  $X_d = X_q$  for a round rotor machine. ***These two values are per-unit!***

At this point, you're ready to start answering some questions:

- a) The per-unit value for  $X_d$  must be converted into ohms. Calculate the base impedance and use this to determine a value for  $X_d$  in Ohms.
- b) Before running any simulations, we need to determine a capability curve for the machine. Open up the generator and go to the Capability Tab. Select "User-Defined  $Q_a$ " Notice that there are several points defined on the capability curve.
  - 1) The point  $Q_b$  is where the machine is producing maximum apparent power at rated power factor. Use the apparent power and power factor rating to compute  $Q_b$ . Your calculation should match the value displayed by ETAP. If it does not, figure out why.
  - 2) Calculate the value of the power angle  $\delta$  and the excitation voltage  $E_{af}$  when the machine is delivering the maximum apparent power at rated power factor. Make sure to use  $X_d$  in Ohms, not in pu. Remember that the machine has a line-to-line voltage of 10kV RMS. You'll have to compute the line-to-neutral voltage in order to compute the power angle  $\delta$  and the excitation voltage  $E_{af}$ .
  - 3) The excitation voltage that you calculated previously is the maximum possible  $E_{af}$  for the machine. At that value, the maximum rated field current is passing through the field coil. Use this value to compute the reactive power at  $Q_a$ . Note that the power angle at that point is 0 degrees. Enter this value into the  $Q_a$  box.
  - 4) The other theoretical limit for the machine is the stability limit. This is the point at which  $\delta = 90$  degrees. Compute  $Q$  when  $\delta = 90$  degrees. This value should be used for  $Q_c$  and  $Q_d$ .
  - 5) Select "Print" on the capability tab. Before you do so, go into "Print Setup" in the file menu and make sure that you know where the file will print. Print the file and submit it.
- c) Since we have selected the generator bus as a "Voltage Control" bus, we have told ETAP that we would like the voltage at that bus to remain at 100% of its rated value. This is typically what the utility desires to have happen at a generator bus. In order for this to happen, the "Variable Load" must not draw any  $Q$  from the Main Bus. If it does draw  $Q$  from the Main Bus, then some  $Q$  will be "lost" in the leakage inductance of the transformer and the voltage at the generator bus will fall below 100% of its rated value.

In order to maintain rated voltage at the generator bus, we need to make sure that our generator can provide the proper amount of  $Q$ . Let's try it:

- 1) Run a load flow with the current setup. Record the magnitude of the voltage at the generator bus and the  $P$  and  $Q$  delivered by the generator. Perhaps this is the situation in our power plant during the middle of the night when most of the motors in the nearby area are turned off.
- 2) Now it's morning and more motors turn on. To accommodate this, we increase the reactive power output of the generator. To simulate this, change the power factor of the variable load to 95%. Record the magnitude of the voltage at the generator bus (in kV) and the  $P$  and  $Q$  delivered by the generator. Note that the generator's  $Q$  should have gone up but that its  $P$  did not change. Why didn't  $P$

change? In the real world, which variable would the operators have changed in order for Q to increase without a change in P.

- 3) Now suppose that the power factor of the variable load begins to get very low, let's say 80%. Set the power factor of the variable load to 80% and run another load flow. Record the magnitude of the voltage at the generator bus (in kV) and the P and Q delivered by the generator. Click on the red bell on the right side of the screen. This bell displays a warning. What does the warning tell you?
- d) For part c.1 and part c.2, compute the excitation voltage  $E_{af}$  and the power angle  $\delta$ . You should find that  $E_{af}$  was larger in part c.2 when the reactive power output was higher. If  $E_{af}$  had not been increased by increasing the field current in the generator, the voltage on the generator bus would have decreased. Use the single phase circuit model of the generator to explain why  $E_{af}$  must increase if the line voltage is to remain constant as reactive power output increases.
- e) When Q is positive, the machine is said to be over-excited. Why? When answering, consider your answers to part d.
- f) In part c.3, the output voltage on the generator bus decreased from 10kV. In this case,  $E_{af}$  cannot be increased to a value that will allow the bus to remain at 10kV. Why? What causes the reduction in voltage at the generator bus? To answer consider the fact that some of the reactive power supplied to the variable load is now coming from the "stiff" 13.8kV bus. As reactive power flows from the 13.8kV bus to the generator bus, where is voltage "lost"?