Massachusetts Institute of Technology
Department of Electrical Engineering and Computer Science
6.061/6.690 Introduction to Power Systems

Problem Set 10

<div align="right">Issued April 19, 2011
Due April 27, 2011</div>

Problem 1: From Chapter 13, Problems 2, 3 and 4
NOTE: This problem is a holdover from Problem Set 9

Problem 2: This problem deals with an induction motor with the following parameters. Note that all of the impedance parameters are per phase, assuming the machine is connected in wye:

Rated Output	25 Horsepower	18,650 W	
Terminal Voltage	V_{ll}	600 V,	RMS, line-line
Number of Poles Pairs	p	2	(4-pole machine)
Supply frequency		60 Hz	
Armature Resistance	R_1	0.3 Ω	
Rotor Resistance	R_2	0.375 Ω	
Armature Leakage Inductance	X_1	1.6 Ω	
Rotor Leakage Inductance	X_2	1.9 Ω	
Magnetizing Inductance	X_ϕ	75 Ω	
Core Loss at rated voltage		400 W	
Friction and windage loss at rated speed		75 W	

1. Calculate and plot a torque-speed curve for this machine as a motor running with a power supply of rated voltage and frequency. This is 60 Hz, 600 Volts, RMS, line-line or 346 volts, RMS per phase. In this part you should neglect windage but approximate the effects of core loss as a linear resistance.

2. Calculate and plot the magnitude of terminal current drawn as a function of speed.

3. What is 'breakdown' or maximum running torque for this motor with rated terminal voltage? What are the current and power factor when the motor is at breakdown?

4. In a test of this motor, the thing is run 'light', (without a mechanical load aside from friction and windage). If this test is carried out at rated terminal voltage, what are the real and reactive power drawn?

5. A similar test is called 'blocked rotor': the rotor of the machine is prevented from turning and the stator driven with a reduced voltage. What voltage should be used to result in a terminal current of 22.4 A, RMS? What are the real and reactive power drawn during such a test? What torque is produced?

6. Calculate and plot curves for efficiency and power factor vs. load power, from five to 100 percent of rated output power (933 W to 18,650 W). Assume that friction and windage are roughly constant.

7. A common strategy for operating induction motors with adjustable speed drives is to use 'constant volts per Hz', or to make terminal voltage proportional to drive frequency, for frequencies less than *base* or rated frequency. Above rated frequency voltage is held constant. To see how this would work, plot a family of torque-speed curves for this motor operating with terminal frequencies of 20, 40, 60, 80 and 100 Hz. Use voltage proportional to frequency below 60 Hz and uniform voltage for 60 Hz and above.

Problem 3 For 6.690 Continuing with the volts/Hz operation of the previous problem, assume the machine is driving a load that has a constant torque characteristic (unusual, but there it is...) The load torque is 100 N-m. Find and plot against motor speed:

1. Input Power
2. Output Power
3. Power Factor
4. Efficiency

You will probably find it appropriate to calculate, using a relatively large number of frequencies, and cross-plotting to generate the curves asked for in this problem. How fast can you make this motor go, using constant voltage? You will also find operation is awful squirrely at low speed, but don't bother with really low speeds (below a few hundred RPM).
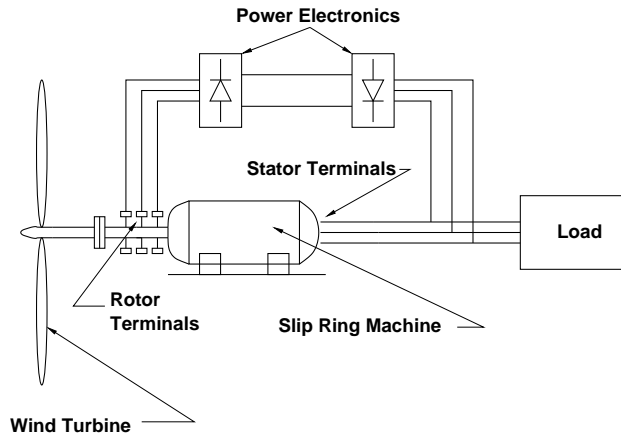

Figure 1: Wind Turbine Generator Setup

Problem 4: This is about a three-phase wound-rotor induction generator that might be used as a wind turbine generator. The setup is shown in Figure 1. The stator and rotor windings are identical, except for the numbers of turns. It has characteristics as shown here:

Number of Poles	2p	4
Armature Phase Self Inductance	L_a	3.5 mHy
Armature Phase-to-Phase Mutual Inductance	L_{ab}	-1.75 mHy
Rotor Phase Self Inductance	L_A	31.5 mHy
Rotor Phase-to-Phase Mutual Inductance	L_{AB}	-15.75 mHy
Rotor to Stator (Peak) Mutual Inductance	L_{aA}	10.4 mHy
Effective Transformer Turns Ratio	$\frac{N_r}{N_s}$	3
Rotational Speed		1800 RPM
Terminal Voltage (RMS, Line-Line)	V_a	690 v
Rated Power		2400 kVA
Frequency		60 Hz

The rotor windings are connected to a set of slip rings and so can be driven by an inverter. Machines such as these are used for adjustable speed drives as well as windmill generators.

Suppose this machine is operating as a generator at some speed other than synchronous. This will cause the rotor to have an electrical frequency different from the stator. The stator is supplying rated volt-amperes at a power factor of 0.8 (so that the stator is supplying VARs). What is the complex power required into the rotor terminals if the machine speed is:

1. 70% of synchronous?
2. 130% of synchronous?

Problem 5: for 6.690 Now the wind turbine machine is to be operated over a speed range, with (improbably) constant wind power. The slip rings are fed through a bidirectional converter which can provide both real and reactive power to the rotor windings. Assume that the power electronics interacts with the power bus terminals at unity power factor (that is, the reactive power either drawn or supplied by the right-hand end of the converter is zero). The converter connected to the slip rings, however, may be required to supply or absorb reactive power.

Assume that the wind turbine is supplying P=2400 kW, and the machine is to be injecting power into the system, assumed to be a voltage source, with unity power factor (Q=0). Ignoring losses in the system, find and plot the following quantities over a speed range of between 70% and 130% of synchronous:

1. Power *out of* the stator winding
2. Power *in to* the slip rings (and rotor winding)

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Spring 2011