Professional Engineers Ontario

Electromagnetic Energy Conversion Exam

98-Elec-A6

Spring 2003

Notes:

1. There are 7 questions. Attempt ***ONLY*** question 1 and FOUR (4) other questions (FIVE (5) questions in all). Unless you indicate otherwise, the first five questions in the answer book will be the only ones marked. All questions are of equal value.
2. You may use one of the approved Casio or Sharp calculators.
3. This is a closed book exam. Formulae sheets are attached.
4. Marks will be lost if answers do not include appropriate units
5. All ac voltages and currents are rms values unless noted otherwise. For three-phase circuits, all voltages are line-to-line voltages unless noted otherwise.
6. You may use pencil.
7. Parts of questions may or may not be related - read carefully!

If doubt exists as to the interpretation of any question, you should submit with your answer paper a clear statement of any assumptions made.

Question 1 - General Knowledge

a. A synchronous generator connected to an infinite grid has its frequency and terminal voltage fixed. What is the effect of increasing the excitation current in this case?

b. Why would a 20 hp motor be a poor choice to supply a 2 hp load?

c. The winding on a typical machine rotor runs length-wise along the rotor. No force is produced in the portion of the winding that loops around either end of the rotor. Why?

d. How can the direction of a three-phase induction motor be reversed?

e. Can a dc shunt motor be started across the line (i.e., by connecting it directly to a source)? Why or why not?

f. Can a 3-phase synchronous motor be started across the line? Why or why not?

g. Can a 3-phase a.c. induction motor be started across the line? Why or why not?

h. Given the rotating field in the stator of a three-phase induction motor, explain why the rotor turns.

i. The OCC of a synchronous generator has a "knee," while the SCC is a straight line. Why is that?

j. What is armature reaction? How can it be reduced?

k. IEEE Standard 519 (*Recommended Practice and Requirements for Harmonic Control in Electric Power Systems*) is a standard that specifies the levels of harmonics that are acceptable in ac power systems (harmonics are voltage and current components whose frequencies are integral multiples of the fundamental frequency; e.g. in a 60 Hz system, the third harmonic is 180 Hz). The standard does not allow *any* DC component. Why is that?

Question 2 - DC Machines

A 10 hp, 230 V, 500 rpm DC shunt motor has a full-load current of 37 A. The armature resistance is 0.39 ohms. A starter is used, with step resistances of 1.56, 0.78 and 0.39 Ω, in the order that they are successively cut out, i.e., when the armature current has dropped to its rated value, the starting box is switched to the next point, thus eliminating a step at a time in the starting resistance.

a. Find the initial and final values of the armature current, as well as the motor speed, at each step.

b. Determine the steady-state efficiency if rotational losses are 500 W and the field current is 0.8 A.

Question 3 - Induction Motors

A 6-pole, 208 V, 3ϕ, 60 Hz, 10 hp, Y-connected squirrel cage induction motor has the following characteristics (all values referred to the stator):

$R_1 = 0.3\ \Omega$ $X_1 = 0.5\ \Omega$

$R_2' = 0.15\ \Omega$ $X_2' = 0.2\ \Omega$ $X_m = 165\Omega$

Rotational and core losses are 400 W (independent of the load). If the slip is 3%, and the supply voltage provides rated voltage and frequency, sketch the per-phase equivalent circuit for the motor, and determine the following:

a. motor input current;
b. motor power factor;
c. rotor speed;
d. output power (may be different than the rated value for the slip given);
e. output torque;
f. motor efficiency; and,
g. the starting torque.

Question 4 - Synchronous Machines

Two three-phase, 6.6 kV, Y-connected synchronous generators are operating in parallel to supply a load of 3000 kW at 0.8 power factor lagging. The synchronous reactance per phase of machine *A* is $j10\ \Omega$, while that of machine *B* is $j12\ \Omega$ (winding resistance and losses are negligible). The excitation of machine *A* is adjusted so that it delivers 150 A at a lagging power factor, and the governors that control the input torque of the generator prime movers are set such that the load is shared equally between the two machines.

a. Determine the following for each machine:
   - i. the armature current;
   - ii. the power factor;
   - iii. the excitation voltage, Ef; and,
   - iv. the power angle.

b. Neatly sketch a phasor diagram for machine *A*, taking the terminal voltage as the reference. Ensure all phasors are labelled, and all angles indicated.

Question 5 - Transformers

A 150 kVA, 2400/240 V, 60 Hz, single-phase transformer has the following equivalent circuit parameters:

$R_1 = 0.3\ \Omega$ $X_1 = 0.65\ \Omega$

$R_2 = 0.003\ \Omega$ $X_2 = 0.0065\ \Omega$

$R_C = 4.5\ \text{k}\Omega$ $X_m = 1.0\ \text{k}\ \Omega$ (R_c and X_m referred to the HV winding)

a. Sketch the approximate equivalent circuit for this transformer, with all values referred to the high-voltage winding.

b. Determine the voltage regulation if the transformer supplies a 100 kVA load at 240 V and a leading power factor of 0.83.

c. Suppose the transformer is used in a power system, and, on a typical day, operates on the following cycle:

12 hours - full load, 0.8 power factory lagging
4 hours - no load
8 hours - one-half full load, unity power factor.

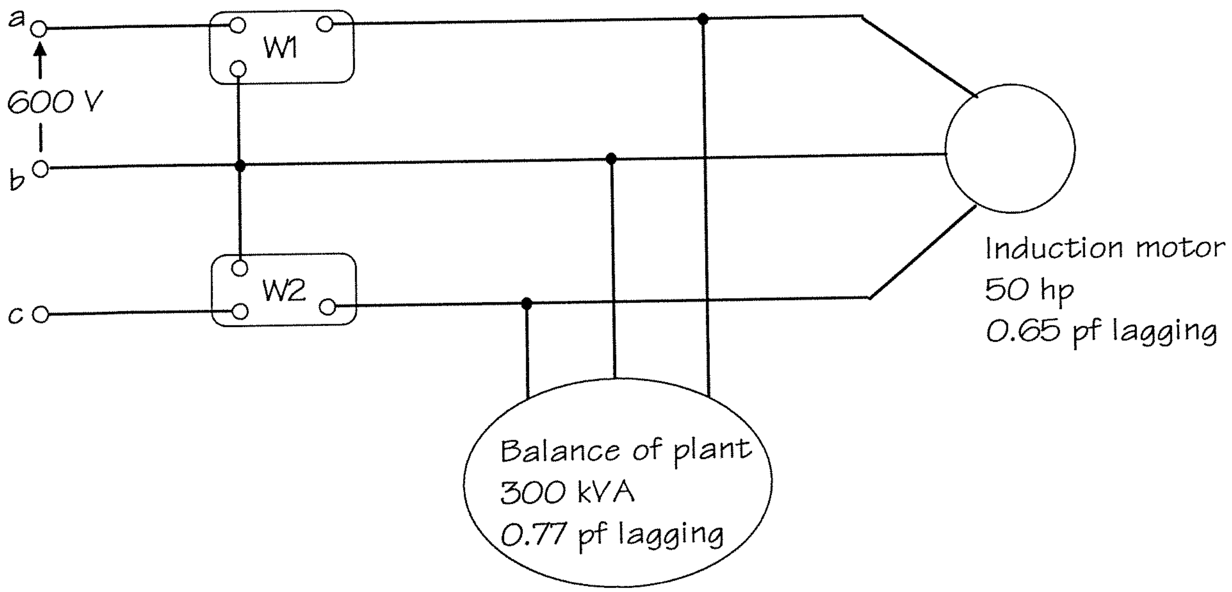
Determine the energy efficiency over 24 hours.

Question 6 - Three-phase power

a. The figure below represents a small factory supplied by a balanced 60 Hz, 600 V, 3ϕ source. Determine the wattmeter readings, W1 and W2, for the system as shown. What is the power factor?

b. If the induction motor is replaced by a synchronous motor that can operate at 0.8 pf leading while supplying the same power as the induction motor, determine the new wattmeter readings. What is the new power factor?

c. With the synchronous motor in place, it is determined that the power factor is below 0.9, and the factory will be penalized. How many kVARs of capacitor are needed to improve the pf to 0.9?



Question 7 -Magnetic Circuits

a. For the magnetic circuit shown below in Figure 2, the core material is silicon steel, for which the magnetization curve is given in Figure 3. Each coil has 500 turns. What current is needed if we wish to establish a flux of 3.6 mWb in the air-gap by applying the same current to both windings? Fringing can be neglected, but the effect of the core must be considered.

b. Many aircraft and ship power systems use 400 Hz. Can a transformer designed for use in a 60 Hz system be used in a 400 Hz system, assuming the voltages are the same? Why or why not?

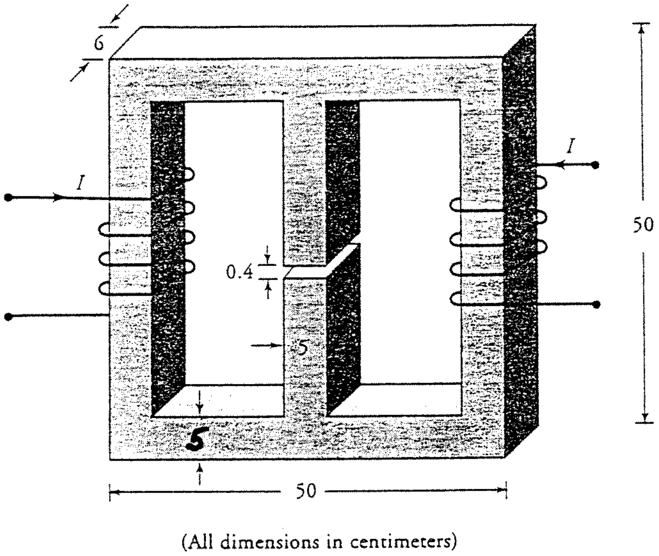


Figure 2

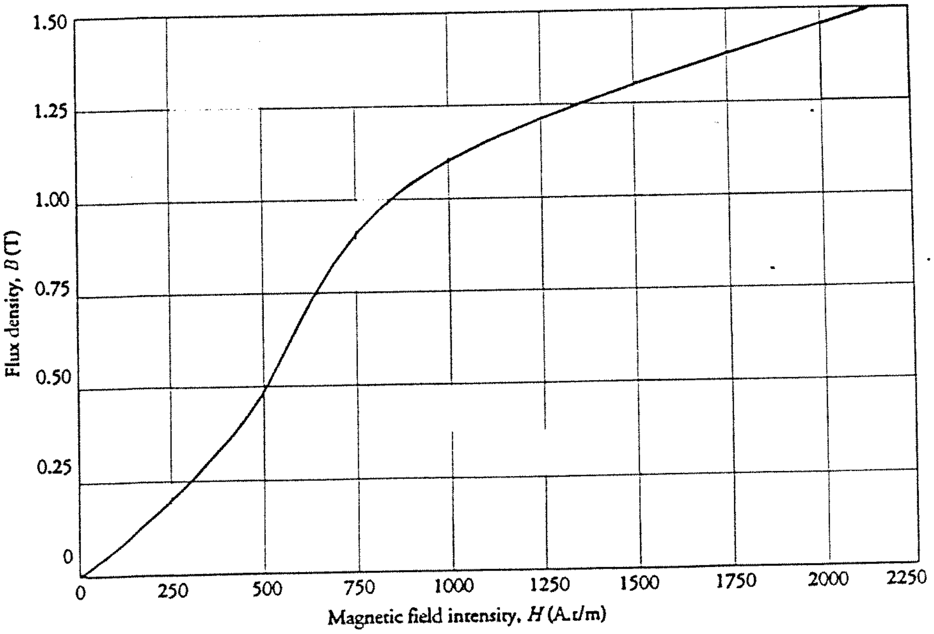


Figure 3

Potentially useful formulae

$$P = VI\cos\theta = \frac{V_R^{\,2}}{R} = I^2 R = Re\left[\mathbf{V}\mathbf{I}^*\right]$$

$$Q = VI\sin\theta = \frac{V_X^{\,2}}{X} = I^2 X = Im\left[\mathbf{V}\mathbf{I}^*\right]$$

$$\mathbf{S} = \mathbf{V}\mathbf{I}^*$$

$$|\mathbf{S}| = \sqrt{P^2 + Q^2} = VI = I^2 Z = \frac{V^2}{Z}$$

$$p.f. = \cos\theta = \frac{R}{Z} = \frac{P}{S}$$

$$P_T = \sqrt{3}\,V_L I_L \cos\theta = 3P_P \qquad P_P = V_P I_P \cos\theta$$

$$Q_T = \sqrt{3}\,V_L I_L \sin\theta = 3Q_P \qquad Q_P = V_P I_P \sin\theta$$

$$S_T = \sqrt{3}\,V_L I_L \qquad S_P = V_P I_P$$

$$B = \frac{\Phi}{A} = \mu H = \mu\frac{\mathscr{F}}{l} = \mu\frac{Ni}{l} \qquad \left[\frac{Wb}{m^2} = T\right]$$

$$H = \frac{NI}{l} = \frac{B}{\mu} = \frac{\Phi/A}{\mu} \qquad \left[\frac{A-t}{m}\right]$$

$$\mathscr{F} = Ni = \Phi\frac{l}{\mu A} = \Re\Phi \qquad [A-t]$$

$$\Re = \frac{l}{\mu A} \qquad \left[\frac{A-t}{Wb}\right]$$

$$\mu_0 = 4\pi\ x\ 10^{-7}\ \frac{Wb}{A-t-m} \qquad \mu = \mu_0\mu_r$$

$$P_e = K_e f^2 B^2_{\max} V_{vol} \qquad P_h = K_h f B^x_{\max} V_{vol}$$

$$L = \frac{N^2}{\Re}$$

$$I_L = I_f + I_a$$

$$V_t = E_a + I_a R_a$$

$$E_a = K_a \Phi \omega$$

$$T = K_a \Phi I_a$$

$$P_{input} = V_t I_L$$

$$P_{dev} = E_a I_a = T_{dev} \omega_m$$

$$P_{out} = P_{dev} - P_{rot} = T_{out} \omega_m$$

$$P_{rot} = \text{No load } P_{dev}$$

$$n_s = 120 \frac{f}{p}$$

$$s = \frac{n_s - n_m}{n_s}$$

$$P_{input} = 3 V_1 I_1 \cos\theta$$

$$P_{gap} = P_{input} - 3 I_1^2 R_1 = 3 I_2'^2 \frac{R_2'}{s} = T_{dev} \omega_s$$

$$3 I_2'^2 R_2' = s P_{gap}$$

$$P_{dev} = P_{gap} - 3 I_2'^2 R_2' = (1 - s) P_{gap}$$

$$P_{out} = P_{dev} - P_{rot} = T_{out} \omega_m$$

$$\mathbf{E_f} = \mathbf{V_t} + \mathbf{I_a}(R_a + jX_s)$$

$$P = \frac{3 V_t E_f}{X_s} \sin\delta$$