OLLSCOIL NA hÉIREANN, CORCAIGH
THE NATIONAL UNIVERSITY OF IRELAND, CORK

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

SUMMER EXAMINATIONS, 2008

B.E. DEGREE (ELECTRICAL)

POWER ELECTRONICS, DRIVES AND ENERGY CONVERSION
EE4001

Prof. C. Delabie
Prof. P. Murphy
Dr. J.G. Hayes

Time allowed: *3 hours*

Answer *four* out of six questions.
All questions carry an equal weighting of 20 marks.

The use of departmental-approved non-programmable calculators is permitted.

1. Induction Motor Characterization

(a) A symmetrical, four-pole, three-phase, wye-connected induction motor is characterized as follows. The dc phase-to-phase resistance is measured to be 1.1 Ω. A no-load test with an applied voltage of 208 V (line-line), 60 Hz, results in a phase current of 6.5 A, and a three-phase power of 175 W. A locked-rotor test with an applied voltage of 53 V (line-line), 60 Hz, results in a phase current of 18.2 A, and a three-phase power of 900 W.
Estimate the per-phase equivalent circuit parameters: R_S, L_{LS}, L_M, L_{LR}', and R_R'.
[10 *marks*]

(b) The specification table for Westinghouse induction motors is provided as an attachment (see page 6). Consider the 110 kW, four-pole machine with 400 V (line-line), 50 Hz applied in the delta configuration. Assume $R_S = 58.3$ mΩ.
Estimate the per-phase equivalent circuit parameters: L_M, R_R', and P_{CFW}.
[10 *marks*]

2. Induction Motor Inrush and Speed Control

(a) Sketch the wiring diagram for the volts/hertz control of the induction machine.

[4 *marks*]

(b) The specification table for Westinghouse induction motors is provided as an attachment (see page 6). Consider the Westinghouse 75 kW, 4-pole machine with 400 V (line-line), 50 Hz.

(i) What are the initial starting line current and torque for a direct-on-line start?

A volts/hertz controller with voltage boost is integrated into the delta-wired drive. The series resistance is estimated to be 117 mΩ.

(ii) Determine approximate values for the starting frequency, current, and voltage in order to supply the specified starting torque.

(iii) Maintaining rated airgap flux, what are the electrical line voltage, current, frequency, and power factor sourced from the inverter, when operating as a **generator** developing 100 % of the rated torque at 50 % of the rated speed?

Use the formula $slope = \dfrac{V_{ph,rated} - R_S \cdot I'_{R,rated}}{f_{rated}}$ for low-voltage boost.

[16 *marks*]

3. AC Machines Space Vectors and Vector Control of the Induction Motor

(a) A 4-pole, 3-phase induction motor has the following physical dimensions: radius r = 6 cm, length l = 24 cm, airgap length l_g = 0.5 mm, and number of turns per phase per pole N_{sp} = 50. The motor is supplied by a rated voltage of 400 V (line to line) at a frequency of 50 Hz.

(i) Calculate the per-phase magnetizing inductance and the per-phase magnetizing current of the machine.

(ii) Determine the magnitudes of the following rotating stator space vectors: current, voltage and flux density.

(iii) Determine the per-phase current and output torque when a per-phase reflected current I'_r = 5 A flows in the stator.

[6 *marks*]

(b) In a 4-pole induction machine, a per-phase current of 106.1 Arms at an input electrical frequency of 50 Hz is required to establish the rated airgap flux density. A per-phase current of 225 Arms at an input electrical frequency of 51.5 Hz is required to establish rated motoring torque at a mechanical rotor speed of 1500 rpm.

(i) Calculate the magnitudes of the space-vector current $I_{ms,pk}$, the stator direct-axis current i_{sd} and quadrature-axis current i_{sq}, and the three phase currents, i_a, i_b, and i_c, to establish the rated flux at $t = 0^-$, the instant just before injection of a step current to develop rated torque.

(ii) Recalculate the above currents required to establish the rated flux and a re*generative* torque at $t = 0^+$.

(iii) Assuming that the generator speed is constant at 1500 rpm, calculate the input electrical frequency and the per-phase currents at t = 5 ms.

Note that $\vec{i}_s^{\,d} = \sqrt{\dfrac{3}{2}}\left(i_{sd} + j \cdot i_{sq}\right)$

[14 *marks*]

4. Power Electronics Converters

(a) In a regulated flyback converter with a 1:1 turns ratio, $V_O = 12$ V, V_I is 12-24 V, P_{load} is 6-60 W and the switching frequency is 200 kHz.

(i) Calculate the maximum value of the magnetizing inductance L_m that can be used if the converter is always required to operate in a complete demagnetization (equivalent to a discontinuous-conduction) mode. Assume ideal components.

(ii) Sketch to scale the transformer primary and secondary current waveforms at full power and low input voltage.

[6 *marks*]

(b) The system parameters of a permanent-magnet dc machine supplied by a switch-mode PWM dc-dc converter are as follows: armature resistance $R_a = 0.1\Omega$, armature inductance $L_a = 1$ mH, motor moment of inertia $J_m = 0.02$ kg m^2, motor constant $k = 0.2$ V/(rad/s), dc bus voltage $V_d = 42$ V, switching frequency $f_s = 20$ kHz, and amplitude of triangular waveform control voltage $V_{tri} = 3$ V. The machine is acting as a **generator** spinning in a forward direction at a speed of 1000 RPM and demanding a torque of 5 Nm.

(i) Sketch the system.

(ii) Calculate the following: (a) the applied armature voltage V_{AB}; (b) duty ratios for the overall converter, pole A, and pole B; (c) the control voltage; and (d) the peak-to-peak ripple on the armature current.

(iii) Sketch the waveforms for the triangular voltage $v_{tri}(t)$, control voltage $v_c(t)$, pole A voltage $v_A(t)$, pole B voltage $v_B(t)$, armature voltage $v_{AB}(t)$, and armature current $i_{ab}(t)$.

(iv) Sketch the four different switch configurations of the converter sequenced over one switching cycle. Also note these sequences in your timing diagrams in part (iii) above.

[8 *marks*]

(c) The 2005 Lexus RX400h hybrid vehicle uses a bidirectional converter to generate a 650 V dc link voltage from the 288 V NiMH battery. This higher voltage allows the efficiency, range, and emissions of the vehicle to be optimized. The bidirectional converter has an inductance of 245 µH and switches at 10 kHz.

The vehicle is operating in generating mode and the bi-directional converter is required to act as a buck and provide a full power of 30 kW.

(i) Calculate the switch average and rms currents.

(ii) Calculate the rms currents in the input and output capacitors.

[6 *marks*]

5. DC Machines

(a) A wound-field dc motor is driving a load whose torque requirement increases with the **square** of the speed and reaches 5 Nm at a speed of 1400 rpm. The armature terminal voltage is held to its rated value. At the rated flux the no-load speed is 1500 rpm and the full-load speed is 1400 rpm. If the flux is weakened to 80 % of the rated value, calculate the new steady-state speed.

[6 *marks*]

(b) A 100 kW compound generator, of terminal ratings 250 V and 400 A, has an armature resistance (including brushes) of 0.025 Ω and the attached magnetization curve (see page 7). There are 1000 shunt-field turns per pole and 3 series-field turns per pole. Compute the shunt field current required at full load when the generator speed is 1100 rpm. Include the effects of armature reaction.

[6 *marks*]

(c) A four-pole three-phase permanent-magnet ac motor is used for traction in a hybrid-electric vehicle. The vector-controlled motor is rated at 20 Nm at 6000 rpm, and is powered by a three-phase sinusoidal PWM inverter supplied by a 42 V NiMH battery pack. The motor efficiency and power factor at rated power are 90% and 0.9, respectively. Determine the following drive parameters at rated power and speed:
(i) per-phase voltage, V_{ph},
(ii) per-phase back emf, E_{ph},
(iii) per-phase current, I_{ph},
(iv) per-phase synchronous inductance, L_S,
(v) motor constant k_T.
(vi) motor copper loss,
(vii)core, friction and windage losses for the machine, given a per-phase series resistance of R_S = 1.5 mΩ.

[8 *marks*]

6. Power Semiconductors

(a) The IRFPS40N60K power MOSFET (see attached specification sheets on pages 8 to 11) from International Rectifier operates in a boost converter with a dc link voltage V_d = 480 V, and load current I_o = 20 A. The MOSFET is driven by a gate drive IC outputting a square-wave voltage v_{GG}, of amplitude 0 V to +10 V, in series with an external gate resistance R_G = 4.3 Ω. Assume the diode has a 1V forward drop and no reverse recovery.

Useful formula: RC discharge time $t = -RC \ln\left[\dfrac{v_C - (-V_{GG})}{V_{ci} - (-V_{GG})}\right]$

(i) Determine the following parameters from the data sheet at a junction temperature of 100°C: maximum threshold voltage, minimum forward transconductance, gate-source capacitance, gate-drain capacitance, maximum on-state resistance, maximum gate voltage at the 20 A load current, and maximum conduction drop across MOSFET at 20 A.

(ii) Sketch $v_{GG}(t)$, $v_{GS}(t)$, $v_{DS}(t)$, and $i_D(t)$ during turn-off of the MOSFET. Note the approximate voltage levels on waveforms.

(iii) Calculate the following (a) turn-off delay time t_{doff}, (b) voltage rise time t_{vr}, and (c) current fall time t_{fv} at a junction temperature of 100°C. Sketch the basic switching circuit under analysis in each case.

[12 *marks*]

(b) The 2003 Toyota Prius uses a 20 kW bidirectional converter to generate a 500 V dc link voltage from the 200 V NiMH battery. The bidirectional converter has an inductance of 435 uH and switches at 10 kHz.

At full power in generating (buck) mode, the inductor carries 100 Adc with a peak-to-peak ripple of 27.6 A , and the rms/average currents in the IGBT and diode are 63.4 A/40 A and 77 A/60 A, respectively. Determine the typical power loss at 125 C due to conduction and switching in the upper IGBT and lower diode for this full-power condition when using the SEMiX252GB126HDs as the half-bridge module (see attached specification sheets on pages 12 to 14).

[8 *marks*]