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

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

SUMMER EXAMINATIONS, 2009

B.E. DEGREE (ELECTRICAL)

POWER ELECTRONICS, DRIVES AND ENERGY CONVERSION
EE4001

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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) The specification table for Westinghouse induction motors is provided as an attachment (see page 6). Consider the 22 kW, **eight**-pole machine with 400 V (line-line), 50 Hz applied in the delta configuration.
Estimate the per-phase equivalent circuit parameters:, R_R', P_{CFW}, L_{LS}, L_{LR}', and L_M.
Assume $R_S = 0.432\ \Omega$ and L_{LS} equals L_{LR}' for this class of machine.

[10 *marks*]

(b) A four-pole star-connected induction motor has the following per-phase equivalent circuit parameters:
$R_S = 0.55\ \Omega$, $L_{LS} = 1.5$ mH, $L_M = 47.3$ mH, $L_{LR}' = 2.25$ mH, and $R_R' = 0.356\ \Omega$.
When supplied by a current-controlled inverter at 60 Hz (electrical), the motor generates an output torque of 50 Nm at 1746 rpm. Friction and windage losses are estimated at 105 W at this speed.
Determine approximate values for the per-phase input voltage, current and power factor at this operating point.
Assuming a core loss of 100 W, determine the machine efficiency at this operating point.

[10 *marks*]

2. Induction Motor Inrush and Speed Control

(a) Sketch the wiring diagram of the star-delta starter for inrush control of the induction machine.

[4 *marks*]

(b) A four-pole star-connected induction motor interfaces a mechanical load to the 400 V (line-line) 50 Hz power grid (via gearing, contactor and breaker). The machine has the following per-phase equivalent circuit parameters:
R_S = 20 mΩ, L_{LS} = 0.2 mH, L_M = 7.2 mH, L_{LR}' = 0.3 mH, and R_R' = 35 mΩ.
(i) Calculate the value of startup current when star configured?
(ii) How much greater would the startup current be if the machine was started in a delta configuration.

A power electronics inverter is now integrated into the system and the motor is connected in star. The motor develops an electromagnetic torque (including friction and windage) of 865 Nm at 1453.5 rpm when supplied by a voltage-source PWM inverter supplying a 50 Hz line-line voltage of 400 V and line current of 225 A lagging at a power factor of 0.89.
(iii) By maintaining a constant airgap flux, what are the electrical line voltage, current, and frequency, and power factor sourced from the inverter, when developing 25 % of the rated torque at 25 % of the rated speed?
(iv) Determine approximate values for the starting electrical line voltage, current, and frequency in order to supply 150% of rated torque at startup.

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 2-pole, 3-phase induction motor has the following physical dimensions: radius r = 6 cm, length l = 24 cm, airgap length l_g = 1.5 mm, and number of turns per phase per pole N_{sp} = 50. The star-connected motor is supplied by a rated voltage of 208 V (line to line) at a frequency of 60 Hz.
(i) Calculate the per-phase magnetizing inductance and the per-phase magnetizing current of the machine.
(ii) Determine the peak magnitudes of the rotating space vector flux density.
(iii) Determine the rms per-phase current and output torque when a per-phase reflected current I_r' = 10 A flows in the stator.
(iv) Roughly sketch a space vector diagram showing the approximate phase angles and magnitudes of the space vector voltage, the magnetizing space vector current, the reflected rotor current, and the stator current.

[6 marks]

(b) The specification table for the Westinghouse 22 kW, four-pole induction motor, with 400 V (line-line), 50 Hz applied in the delta configuration, is provided as an attachment (see page 6). Consider the machine running as a motor with a power electronics interface.

(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 motoring torque at $t = 0^+$.

(iii) Assuming rated rotor speed calculate the per-phase currents at $t = 2.5$ ms.

Note that $$\vec{i}_s(t) = \sqrt{\frac{3}{2}}\left(i_{sd}(t) + j \cdot i_{sq}(t)\right)$$

[14 marks]

4. Power Electronics Converters

(a) Design a continuous-conduction flyback converter for the following conditions: V_I = 400 V, V_O = 12 V, P_O = 20-60 W and the switching frequency is 40 kHz. Maintain the maximum duty cycle at no greater than 0.45. Calculate the minimum magnetizing inductance required. Assume ideal components.

[8 *marks*]

(b) The system parameters of a permanent-magnet dc motor supplied by a switch-mode PWM dc-dc converter are as follows: armature resistance R_a = 0.1 Ω, armature inductance L_a = 1 mH, motor constant k = 0.07 V/(rad/s), dc bus voltage V_d = 12 V, switching frequency f_s = 20 kHz, and amplitude of triangular waveform control voltage V_{tri} = 5 V. The motor is spinning forward at a speed of 750 rpm and acts as a *generator* supplied by a full-load torque of -0.7 Nm.

(i) 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.

(i) Calculate the rms currents in the upper and lower MOSFET switches of pole A.

[6 *marks*]

(c) The 2004 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.

The above vehicle is operating in motoring mode and the bi-directional converter is required to act as a boost and provide full power.

(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) The specification sheet for the Maxon 250 W, 24 V, 5300 rpm, EC dc motor is provided as an attachment (see page 7).

(i) Compute the armature current, the applied voltage, and the machine efficiency for the condition shown in line 10 of motor data.

[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 50 Nm at 5000 rpm, and is powered by a three-phase sinusoidal PWM inverter supplied by a 300 V NiMH battery pack. The motor efficiency and power factor at rated power are 90% and 0.95, 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 $R_S = 30\ \mathrm{m\Omega}$.

[8 *marks*]

6. Power Semiconductors

(a) An enhancement-mode n-channel vertically diffused power MOSFET operates in a step-up converter switching at 50 kHz, with a dc link voltage V_d = 300 V, and load current I_o = 10 A. The device characteristics are as follows: threshold voltage $V_{GS(th)}$ = 4 V, drain current I_D = 10 A at gate voltage V_{GS} = 7 V, gate-source capacitance C_{gs} = 1000 pF, gate-drain capacitance C_{gd} = 150 pF, and on-state resistance $R_{DS(on)}$ = 0.5 Ω. The MOSFET is driven by a voltage-source square wave v_{GG}, of amplitude –15 V to +15 V, in series with an external gate resistance R_G = 50 Ω. Assume the diode has a 1V forward drop and neglect the reverse recovery.

Useful formulae: RC charge time $t = -RC \ln\left[1 - \frac{v_c - V_{ci}}{V_{GG} - V_{ci}}\right]$

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

(ii) Calculate the following (i) turn-on delay time t_{don}, (ii) current rise time t_{ir}, (iii) voltage fall time t_{fv}.

(iii) Calculate the turn-on energy losses.

[12 *marks*]

(b) The 2005 Lexus RX400h hybrid vehicle uses a 30 kW bidirectional converter to generate a 650 V dc link voltage from the 288 V NiMH battery. The bidirectional converter has an inductance of 245 uH and switches at 10 kHz.

At full power in motoring (boost) mode, the inductor carries 104.2 Adc with a peak-to-peak ripple of 65.5 A , and the rms/average currents in the IGBT and diode are 79 A/58 A and 70.5 A/46.2 A, respectively. Determine the typical power loss at 125 C due to conduction and switching in the lower IGBT and upper diode for this full-power condition when using the SEMiX252GB126HDs as the half-bridge module. (see attached specification sheets on pages 8 to 10).

[8 *marks*]