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THE NATIONAL UNIVERSITY OF IRELAND, CORK

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

SUMMER EXAMINATIONS, 2007

B.E. DEGREE (ELECTRICAL)

APPLIED POWER ELECTRONICS AND MOTION CONTROL
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 a Casio fx570w or fx570ms calculator is permitted.

1. Induction Motor Characterization

(a) The specification table for Westinghouse induction motors is provided as an attachment (see page 5). Consider the 75 kW, **four**-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 = 117 mΩ and L_{LS} equals L_{LR}' for this class of machine.

[10 *marks*]

(b) A symmetrical, four-pole, three-phase, star-connected induction motor is characterized as follows. The dc phase-to-phase resistance is measured to be 3.54 Ω. A no-load test with an applied voltage of 400 V (line-line), 50 Hz, results in a phase current of 1.8 A, and a three-phase power of 120 W. A locked-rotor test with an applied voltage of 71 V (line-line), 50 Hz, results in a phase current of 4 A, and a three-phase power of 150 W. Estimate the per-phase equivalent circuit parameters: R_S, L_{LS}, L_M, L_{LR}', and R_R'. Assume that $L'_{LR} = \frac{3}{2} L_{LS}$ for this Class B machine.

[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 the Westinghouse 22 kW, 8-pole induction motor, with 400 V (line-line), 50 Hz applied in the delta configuration, is provided as an attachment (see page 5).

(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 0.43 Ω.

(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 developing 50 % of the rated torque at 75 % 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 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 5). 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 $\vec{i}_s(t) = \sqrt{\dfrac{3}{2}}\left(i_{sd}(t) + j \cdot i_{sq}(t)\right)$

[14 marks]

4. Power Electronics Converters

(a) 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 motoring mode and the bi-directional converter is required to act as a boost and provide a full power of 30 kW.

- (i) Calculate the switch average and rms currents and the resulting conduction losses in (a) the IGBT with $V_{CE(knee)}$ = 2.5 V and R_{CE} = 0.01 Ω, and (b) the diode with $V_{F(knee)}$ = 1.5 V and R_{CE} = 0.005 Ω.
- (ii) Calculate the rms currents in the input and output capacitors.
- (iii) What voltage rating would be suitable for the IGBTs in this converter?

[10 *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.

[10 *marks*]

5. DC Machines

(a) The specification sheet for the Maxon 250 W, 48 V, 6500 rpm, EC dc motor is provided as an attachment (see page 6).

- (i) Compute the armature current, the applied voltage, and the machine efficiency for the condition shown in line 10 of motor data.
- (i) What are the amplitude of per-phase back emf and the rms per-phase current?

[10 *marks*]

(b) A 100 kW, 250 V dc shunt motor has the attached magnetization curves (including armature-reaction effects) given on page 7. The armature circuit resistance, including brushes is 0.025 Ω. The field rheostat is adjusted for a no-load speed of 1100 rpm.

- (i) Determine the field current set point at no load.
- (ii) Determine the speed in rpm corresponding to an armature current of 600 A.
- (iii) Because the speed-load characteristic referred to in (ii) above is considered undesirable, a stabilizing winding of 1.5 cumulative series turns per pole is to be added. The resistance of this winding is negligible. There are 1000 turns per pole in the shunt field. Compute the speed corresponding to an armature current of 600 A.

[10 *marks*]

6. Power Semiconductors

(a) Sketch the vertical structure of the power diode. What is the purpose of the drift region? Sketch $v_{GS}(t)$, $v_{DS}(t)$, and $i_D(t)$ during turn-on of the power MOSFET showing the effect of diode reverse recovery.

[6 *marks*]

(b) The IRFP460 power MOSFET (see attached specification sheets on pages 8 and 9) from International Rectifier operates in a boost converter switching at 20 kHz with a dc link voltage V_d = 300 V, and load current I_o = 13 A. The MOSFET is driven by a gate drive IC outputting a square wave voltage v_{GG}, of amplitude –5 V to +15 V, in series with an external gate resistance R_G = 25 Ω. Assume the diode has a 1V forward drop and no reverse recovery.

Useful formulae: 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 80°C: maximum threshold voltage, minimum forward transconductance, gate-source capacitance, gate-drain capacitance, and on-state resistance.

(ii) Sketch $v_{GG}(t)$, $v_{GS}(t)$, $v_{DS}(t)$, and $i_D(t)$ during turn-off of the MOSFET.

(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 80°C. Sketch the switching circuit under analysis in each case.

[14 *marks*]