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THE NATIONAL UNIVERSITY OF IRELAND, CORK

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

SUMMER EXAMINATIONS, 2006

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 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 Ω and L_{LS} equals L_{LR}' for this class of machine.

[10 *marks*]

(b) A four-pole star-connected induction motor used in an electric vehicle application has the following per-phase equivalent circuit parameters:
R_S = 11.8 mΩ, L_{LS} = 0.0972 mH, L_M = 2.0 mH, L_{LR}' = 0.0772 mH, and R_R' = 12.9 mΩ.
When supplied by a current-controlled inverter outputting 93 A at 200 Hz, the motor generates an output torque of 40 Nm at 5945 rpm. Core, friction and windage losses are estimated at 2.3 kW at this speed. Determine approximate values for the input per-phase voltage, power factor, and efficiency at this operating point.

[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 75 kW, 4-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 stator series resistance is estimated to be 117 mΩ.

(ii) Determine approximate values for the starting frequency, current, and voltage in order to match the specified starting torque determined above for a direct-on-line start.

(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 2-pole, 3-phase induction **generator** has the following physical dimensions: radius r = 6 cm, length l = 24 cm, airgap length l_g = 1 mm, and number of turns per phase per pole N_{sp} = 50. The star-connected generator is connected to a rated voltage of 400 V (line to line) at a frequency of 50 Hz.

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

(ii) Determine the peak of the space vector flux density.

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

(iv) Sketch a space vector diagram showing the approximate phase angles and magnitudes of the space vector voltage, the magnetizing current, the reflected rotor current, and the stator current.

[6 marks]

(b) The specification table for the Westinghouse 30 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 an induction generator 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 generating torque at $t = 0^+$.

(iii) The generator speed is dropped to 1400 rpm, calculate the input electrical frequency and the per-phase currents at t = 1 ms when operating at rated torque and rated flux.

[14 marks]

4. Power Electronics Converters

(a) Design a Voltage Regulator Module (VRM) for local power regulation of a microprocessor on a mobile phone. The VRM is powered from a 3.3 V lithium ion battery and uses a **synchronous** buck converter. The microprocessor specifications call for a 1 V supply with a +/- 1 % allowable fluctuation while consuming 50 mA. The switching frequency is 1 MHz. Neglect the parasitic effects of the controlled MOSFETs.

(i) Sketch the synchronous buck converter.
(ii) Choose an inductor that limits the current ripple to +/- 10 %.
(iii) Choose a capacitor to limit the voltage ripple to +/ 1 %.
(iv) Determine the rms currents in the inductor, and output and input capacitors.
(v) Calculate the total conduction losses in the MOSFETs for $R_{ds(on)}$ of 0.5 ohm.

[10 *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 = 0.1Ω, 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.

[10 *marks*]

5. Power Semiconductors

(a) Sketch the symbol and the vertical structure of the MOSFET. Briefly state the advantages of the MOSFET over the MOSFET for high-frequency, low-voltage operation.

[4 *marks*]

(b) 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_{ds} = 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 $t = -RC\ln\left[1 - \frac{v_c - V_{ci}}{V_{GG} - V_{ci}}\right]$

RC discharge time $t = -RC\ln\left[\frac{v_c - (-V_{GG})}{V_{ci} - (-V_{GG})}\right]$

(i) 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.
(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.
(iv) Estimate the MOSFET junction temperature if the MOSFET is bonded to a 70 °C heatsink. The thermal impedance from the heatsink to the junction is $\theta_{J\text{-}C}$ = 0.5 °C/W. Assume turn-off energy loss equals the turn-on energy loss, and the conduction loss equals the combined switching loss.

[16 *marks*]

6. 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 50 % of the rated value, calculate the new steady-state speed.

[10 *marks*]

(b) The specification sheet for the Maxon 250 W, 24 V, 5300 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*]