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THE NATIONAL UNIVERSITY OF IRELAND, CORK

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

SUMMER EXAMINATIONS, 2005

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 6). Consider the 110 kW, four-pole machine with 400 V (line-line), 50 Hz applied in the delta configuration. Assume $R_S = 58.3\ m\Omega$.
(i) Determine the slope of the torque/speed (Nm/Hz) curve in its linear region?
(ii) Estimate the per-phase equivalent circuit parameters: L_M, R_R', and P_{CFW}.

[12 *marks*]

(b) The four-pole, 22 kW induction motor in the tables is missing the power factor for the 50 % load point. Calculate an approximate value for the power factor based on the information provided at the 100 % load point.

[4 *marks*]

(c) Given that the four-pole, 22kW motor has $R_R' = 0.44\ \Omega$ and $R_S = 0.58\ \Omega$, determine the leakage inductances L_{LS} and L_{LR}'. Assume that $L'_{LR} = \frac{3}{2} L_{LS}$ for this class of machine.

[4 *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.

[3 *marks*]

(b) The specification table for Westinghouse induction motors is provided as an attachment (see page 6). Consider the 22 kW, four-pole machine with 400 V (line-line), 50 Hz applied. What is the direct-on-line starting current when a star-delta starter is used?

[3 *marks*]

(c) A four-pole star-connected motor outputs 40 Nm at 1746 RPM when supplied by a 60 Hz line-line voltage of 440 V and a phase current of 10.39 A lagging at a power factor of 0.866. The series resistance is 1.5 Ω.
(i) By maintaining a constant field flux, what are the electrical line voltage, current, frequency, and power factor sourced from the inverter, when developing 50% of the rated torque at 50% of the rated speed?
(ii) Determine values for the slip frequency, line current and power factor required to ensure constant-power operation of the machine at twice the rated speed.

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

[14 *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.

[14 *marks*]

4. Power Electronics Converters

(a) The Toyota Prius uses a 20 kW bidirectional converter to generate a 500 V dc link voltage from the 200 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 435 uH 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 half power level of 10 kW. For this 10 kW condition:

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

(ii) Calculate the switch average and rms currents and the resulting conduction losses in (a) the IGBT with $V_{CE(knee)} = 2.5$ V and $R_{CE} = 0.01\ \Omega$, and (b) the diode with $V_{F(knee)} = 1.5$ V and $R_F = 0.005\ \Omega$.

[12 *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 $R_a = 0.1\,\Omega$, 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.

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

[8 *marks*]

5. Power Semiconductors

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

[5 *marks*]

(b) The IRFPS40N60K power MOSFET (see attached specification sheets on pages 7 to 10) 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 $t = -RC \ln\left[\frac{v_c - (-V_{GG})}{V_{ci} - (-V_{GG})}\right]$

(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.

(iv) Calculate the turn-on off energy loss.

[15 *marks*]

6. DC Machines

(a) A motor/generator with a pure inertial load is often used as a flywheel to store energy. A motor has a machine constant of 0.5 Nm/A, an armature resistance of 0.35 Ω, and an inertia J = 0.06 kg m^2. Calculate the electrical energy recovered when the machine slows from 1500 rpm to 750 rpm. The braking current is clamped at 10 A during the energy recovery period.

[8 *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 11). 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 magnetic circuit consists of a high permeability core, an airgap of length l_g = 1 mm and cross-sectional area A_g = 100 cm^2, and a rare-earth Nd-Fe-B permanent magnet with the attached magnetization curve (see page 11).

(i) Determine the point of maximum energy density for the magnet.

(ii) Find the minimum magnet volume required to achieve an airgap flux density of 0.8 T.

[6 *marks*]