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THE NATIONAL UNIVERSITY OF IRELAND, CORK

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

SUMMER EXAMINATIONS, 2004

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. Power Electronics Converters and Modulation Schemes

(a) 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 supplies a full-load torque of 0.7 Nm.

(i) Sketch the electrical circuit.

(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) 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 $i_a(t)$.

(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*]

(b) A three-phase inverter has a dc bus voltage $V_D = 654$ V and a switching frequency of 10 kHz. Calculate the space-vector modulation time intervals *x*, *y*, and *z* to synthesize an average stator space vector voltage $\vec{v}_s = 417.9 e^{j2.62} V$. What is the optimum switching pattern to minimize the switching loss?

[10 *marks*]

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

(a) Derive an expression for the self inductance for a single phase of a three-phase machine with sinusoidally-distributed windings. Ignore machine parasitics, and assume energy storage in the airgap only.

[5 *marks*]

(b) 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.

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

[5 *marks*]

(c) In a 4-pole induction machine, a per-phase current of 46 Arms at an input electrical frequency of 200 Hz is required to establish the rated airgap flux density. A per-phase current of 93 Arms at an input electrical frequency of 202 Hz is required to establish rated motoring torque at a mechanical rotor speed of 6000 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 6000 rpm, calculate the input electrical frequency and the per-phase currents at $t = 1.25$ ms.

[10 *marks*]

3. Induction Motor Steady-State Operation

(a) A symmetrical, four-pole, three-phase, star-connected 70 hp induction motor is characterized as follows. The dc phase-to-phase resistance is measured to be 23.6 mΩ. A no-load test with an applied voltage of 195 V (line-line), 200 Hz, results in a phase current of 64.7 A, and a three-phase power of 1.093 kW. A locked-rotor test with an applied voltage of 35.6 V (line-line), 200 Hz, results in a phase current of 93 A, and a three-phase power of 641 W. Estimate the per-phase equivalent circuit parameters: R_S, L_{LS}, L_M, L_{LR}', and R_R'. Assume that $L_{LR}' = 0.8 \cdot L_{LS}$ for this class of machine.

[8 *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.

At full power, the induction motor requires a per-phase current of 225 A at a power factor of 0.89 and an overall system efficiency of 89.7 %. Calculate approximate values for the following: (i) the electrical input power, (ii) the airgap power, (iii) the per-phase magnetizing current, (iv) the per-phase rotor current, (v) the slip, and (vi) the core, friction and windage losses.

Calculate approximate values for the following when the mechanical load drops to 25 % of its value at full load: (i) the slip, (ii) the per-phase rotor current, (iii) the per-phase current, and (iv) the power factor.

[12 *marks*]

4. 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) Which motor parameters limit the startup current and what value of peak startup current do you expect?

(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) Calculate the minimum dc link voltage for the voltage-source inverter.

(iv) 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? Also calculate the modulation index for this operating point.

(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*]

5. Power Semiconductors

(a) Briefly explain reverse recovery in power diodes and sketch the effects of reverse recovery on the turn-on waveforms of the complementary IGBT or MOSFET.

[6 *marks*]

(b) The IRFP460 power MOSFET (see attached specification sheets on pages 6 and 7) 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.

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

(ii) 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.

[14 *marks*]

6. DC Machines

(a) Briefly answer the following four questions.

( ) What is the structure of the trapezoidal-waveform electronically-commutated motor?

( ) Sketch the phase currents in the above brushless dc machine.

( ) How can armature reaction be compensated to minimize its effects in dc machines?

(i) A generator develops a back emf of 100 V at 1000 rpm. Under full-load current draw of 10 A, the field flux is weakened by 5 % due to armature reaction. Calculate the full-load terminal voltage when the armature resistance is 0.5 Ω.

[4 *marks*]

(b) A wound-field dc motor is driving a load whose torque requirement increases linearly with 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 reduced to 80 % of the rated value, calculate th enew steady-state speed.

[8 *marks*]

(c) A 100 kW, 250 V dc shunt motor has the attached magnetization curves (including armature-reaction effects) given on page 8. 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.

[8 *marks*]