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THE NATIONAL UNIVERSITY OF IRELAND, CORK

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

SUMMER EXAMINATIONS, 2003

B.E. DEGREE (ELECTRICAL)

APPLIED POWER ELECTRONICS AND MOTION CONTROL
EE4001

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Time allowed: *3 hours*

Answer *five* 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 and DC Machines

(a) Briefly answer the following ten questions.

- (i) Sketch the flux density profile due to the field flux experienced by an armature conductor rotating in a primitive two-pole dc motor.
- (ii) What are the effects of armature reaction in a dc machine?
- (iii) Derive the torque-speed characteristic equation for a dc machine.
- (iv) A permanent magnet dc motor has the following parameters: R_a = 0.25 Ω, k= 0.5 V/(rad/s), moment of inertia J_m = 0.02 kgm^2. The motor is accelerating a load of inertia 0.08 kg m^2 at 10 rad/s^2. Calculate the armature current and applied voltage instantaneously at 100 rad/s.
- (v) A wound-field dc motor is operating at rated speed, voltage, and current. If the machine is field weakened to double the speed at rated voltage, what happens to the output torque and power if the current remains at the rated value?

(vi) List three disadvantages of switch-mode power electronics amplifiers compared to linear amplifiers?

(vii) Derive an expression for the Pole A duty ratio, d_A, in terms of the control voltage, $v_{c,A}$ and the peak of the triangular voltage, $V_{tri,pk}$.

(viii) Sketch (a) a buck converter, and (b) a boost converter.

(ix) A three-phase sinusoidal PWM inverter is powered by a 400 V dc bus. What is the rated per-phase output voltage of the inverter?

(x) Using a modulation index m = 0.5, what is the per-phase output voltage of the inverter in the above question?

[*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 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 motor is spinning in a reverse direction at a speed of 1000 RPM and supplies a load 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; and (c) 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 $i_a(t)$.

(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*]

2. Induction Motor Steady-State Operation

(a) Briefly answer the following five questions.

- (i) Under rated conditions, does the magnetizing current depend on the mechanical load on the rotor? Typically how large is magnetizing current relative to the rated motor current?
- (ii) Can an induction motor be operated as a generator that feeds into a passive load, for example, a bank of three-phase resistors?
- (iii) Sketch the torque-speed characteristic of the induction motor over the full speed range.
- (iv) Why are star-delta mechanical contactors commonly used to overcome startup problems?
- (v) When conducting a dc resistance test, why should it be modified to account for skin effect?

[*5 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'.

[*8 marks*]

(c) 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.

[*7 marks*]

3. Induction Motor Speed and Torque Control

(a) Briefly answer the following questions on speed control.

(i) Define the power crossing the airgap to the rotor in mechanical and electrical terms.

(ii) Define the power loss in the rotor in mechanical and electrical terms.

(iii) By applying a constant field flux to the motor, what is the relationship between electromagnetic torque and slip?

(iv) What relationship of slip and flux density results in maximum rotor efficiency?

(v) How are the input voltage and frequency controlled in order to apply a constant field flux over the speed range.

(vi) A four-pole motor outputs 40 Nm at 1140 rpm when supplied by a 50 Hz line-line voltage of 400 V and phase current of 10 A lagging at a power factor of 0.88. The series resistance is 1.5 Ω. Neglecting voltage boost and maintaining a constant field flux, what are the approximate slip and electrical frequencies when outputting 20 Nm at 800 rpm.

(vii) Incorporating voltage boost, determine approximate values for the starting frequency and voltage in order to supply 150% of rated torque at startup in the above question. [*3 marks*]

(viii) How can the machine be operated above its base speed.

[*10 marks*]

(b) Torque Control.

(i) Sketch a vector diagram showing the following space vectors: v_s, i_s, i_{ms}, i_r', B_{ms}, B_r, B_{lr}, i_{sd}, and i_{sq}. Use the stator space vector as the reference vector and align the *d*-axis with the rotor flux space vector.

(ii) Derive the transformation matrix *T* used to transform the stator phase currents into the *dq* reference frame.

(iii) Derive an expression for the electromagnetic torque T_{EM} in terms of the direct-axis and quadrature-axis currents i_{sd} and i_{sq}, respectively.

[*10 marks*]

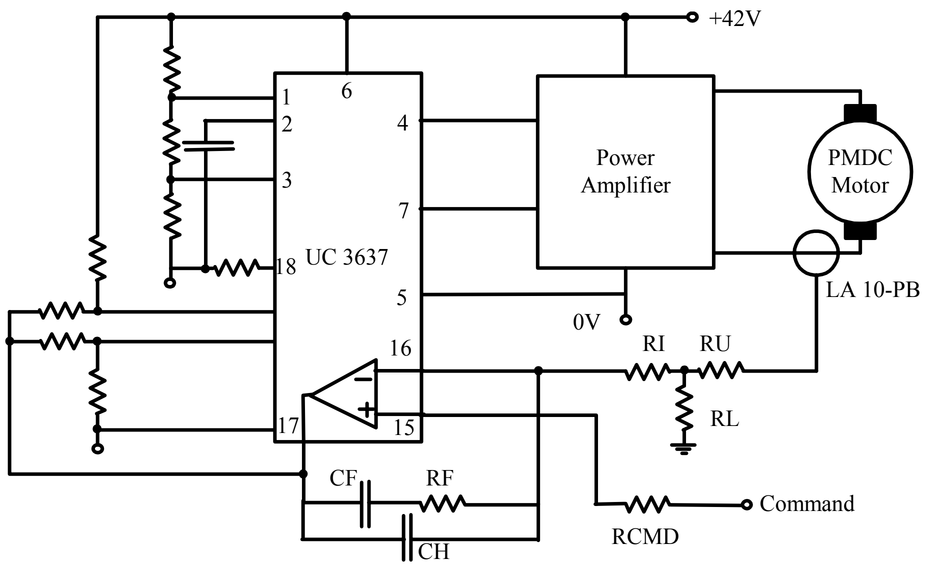

Fig. 1. DC motor control system for Question 4.

4. Controller Design

(a) Briefly answer the following questions.

- (i) A switch-mode power supply has a switching frequency of 50 kHz. What do you think is the upper limit on the crossover frequency of the power supply?
- (ii) How does your answer in the above question compare with the crossover frequency likely achievable in a linear power supply?
- (iii) Define phase margin. What is a typical phase margin in a switch-mode power supply?
- (iv) Define gain margin. What is a typical gain margin in a switch-mode power supply?
- (v) How do we typically model the PWM controller and dc-dc converter in an averaged model?

[*5 marks*]

(b) The system parameters of a permanent-magnet dc motor supplied by a 42 V input switch-mode PWM dc-dc converter, as shown in Fig. 1 on the previous page, are as follows.

DC motor: armature resistance R_a = 1/2 Ω, electrical time constant τ_e=0.8 ms, motor voltage constant k = 0.2 V/(rad/s),

Controller: amplitude of triangular voltage V_{tri} = 2.1 V, switching frequency f_S = 20 kHz, error amplifier open-loop voltage gain of 75 dB. By letting $R_{IN} = R_1 + R_U + \frac{R_1 R_U}{R_L}$ and $C_F >> C_H$, the error amplifier small-signal gain can be approximated by

$$G_{EA}(s) = \frac{1}{R_{IN} C_F} \frac{1}{s} \frac{1 + sR_F C_F}{1 + sR_F C_H}.$$

Armature current transducer: gain of 0.8 V/A into a minimum output resistance of 10 kΩ.

Command: input signal of +/-2.5 V to output an armature current of +/- 5 A.

The feedback effects of the motor-induced back emf and the load torque on the control loop can be neglected.

- (i) Sketch a block diagram of the current-control loop, and derive the small signal open-loop gain function of the current loop.
- (ii) Calculate (a) the gain of the PWM power amplifier, (b) the gain of the feedback stage and values for R_U and R_L, and (c) the low-frequency open-loop gain.
- (iii) Selecting a current loop crossover frequency of 2 kHz, and a phase margin of 60°, sketch the Bode plot showing system gain and phase.
- (iv) Selecting R_I to equal 5 kΩ, calculate the values of the error amplifier compensation components R_{CMD}, R_F, and C_F and C_H.

[*15 marks*]

5. Power Semiconductors

(a) Briefly answer the following ten questions.

(i) In terms of n, n+, n-, p, p+, p-, sketch the four layers of the VDMOSFET going from source to drain?

(ii) What is the principal reason for slower turn off of bipolar devices compared to the MOSFET?

(iii) Why does the MOSFET on resistance increase with temperature?

(iv) What is the purpose of the source-body metallization?

(v) Which layer of the MOSFET largely determines both the maximum drain-source breakdown voltage and the on resistance?

(vi) A MOSFET operates in a boost converter with a 300 V dc bus, and experiences an additional 75 V spike. Using typical derating guidelines, what voltage silicon would you recommend to the nearest 100 V?

(vii) An IGBT has a maximum specified junction temperature of 150 °C. The part is dissipating 50 W and is attached to a heatsink with a total thermal resistance $\theta_{J\text{-}C}$ = 1 °C/W. Under typical derating guidelines, what would you recommend as the maximum heatsink temperature?

(viii) Give two reasons why the reverse recovery of power diode is undesirable?

(ix) In terms of n, n+, n-, p, p+, p-, sketch the five layers of the IGBT going from emitter to collector? Also sketch the electrical symbol of the IGBT.

(x) What characteristics of the IGBT make it the preferred device for high-voltage, high-current operation? What are its disadvantages?

[*10 marks*]

(b) An enhancement-mode n-channel vertically diffused power MOSFET operates in a step-up converter switching at 20 kHz, with a dc link voltage V_d = 400 V, and load current I_o = 20 A. The device characteristics are as follows: threshold voltage $V_{GS(th)}$ = 4 V, drain current I_D = 20 A at gate voltage V_{GS} = 6 V, gate-source capacitance C_{gs} = 4000 pF, gate-drain capacitance C_{gd} = 400 pF, and on-state resistance $R_{DS(on)}$ = 0.25 Ω. The MOSFET is driven by an ideal voltage-source square wave v_{GG}, of amplitude 0 V to 15 V, in series with an external gate resistance R_G = 25 Ω. Assume the diode has a 1 V forward drop and no reverse recovery.

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

(ii) Calculate the following times: (a) turn-on delay time $t_{d(on)}$, (b) current rise time t_{ir}, and (c) voltage fall time t_{fv}. For each of the time durations investigated, sketch the equivalent circuit.

[*10 marks*]

6. Miscellaneous Topics

Answer three sections from the four sections (a) – (d). Each section carries 6 2/3 marks.

(a) An electric vehicle has the following attributes: mass $M = 500$ kg, drag co-efficient $C_W = 0.19$, vehicle cross section $A = 2.4$ m^2, co-efficient of rolling resistance $C_{RR} = 0.0044$, wheel diameter $d_W = 0.6$ m, gear ratio from rotor to drive axle $n = 10.946$, and a nominal gear efficiency of 95%. Neglect internal moment of inertia and use density of air $\rho_{air} = 1.202$ kg m^{-3}.
The vehicle is required to accelerate from 0 to 50 km/hr in 10 s on a flat road surface under calm wind conditions. Instantaneously at 30 km/hr, calculate (i) the aerodynamic drag, (ii) the rolling resistance, (iii) the acceleration force, and (iv) the electromagnetic torque and power required from the rotor.

(b) 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 20 Nm at 6000 rpm, and is powered by a three-phase sinusoidal PWM inverter supplied by a 42 V NiMH battery pack. The motor efficiency and power factor at rated power are 90% and 0.9, 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.

(c) In a balanced three-phase inverter supplied by a dc link voltage $V_d = 300$ V, the phase A average output voltage is $v_{An} = 112.5\cos 283t$. The ac motor internal voltage in phase A can be represented as a pure sinusoid by $e_A(t) = 106.14\cos(283t - 6.6^\circ)$, and the inductance in each phase is 5 mH. The inverter is switching at 20 kHz.
- (i) Calculate the phase A current, $i_A(t)$.
- (ii) Calculate the MOSFET conduction and switching power losses, the diode conduction power losses, and the total inverter power loss.

MOSFET parameters: on-resistance $R_{DS(on)} = 0.5\ \Omega$, turn-on energy $E_{on} = 0.60$ mJ and turn-off energy $E_{off} = 0.20$ mJ at 300V, 10 A. Assume an ideal diode with a forward drop $V_f = 2$ V, and a conduction loss approximated by $P_{C,Diode} = V_f I_{Pk}\left(\frac{1}{2\pi} - \frac{m}{8}\cos\theta\right)$.

Approximate the MOSFET conduction loss by $P_{C,MOS} = R_{DS(on)} I_{Pk}^2\left(\frac{1}{8} + \frac{m}{3\pi}\cos\theta\right)$.

(d) Briefly answer the following questions.
- (i) Sketch a sample common-mode filter on a utility input with live, neutral, and earth.
- (ii) Explain the necessity for and operation of the common-mode filter.
- (iii) What are possible sources of magnetic field radiation?
- (iv) Give a few ways in which EMI from a magnetic source can be reduced?
- (v) Give a few examples of manmade unintentional conducted EMI.
- (vi) What is a ground plane and how does it work?
- (vii) Sketch the equivalent circuit model of an inductor showing its parasitic components from an EMI perspective.