UNIVERSITY OF ESWATINI

MAIN EXAMINATION

2021

FACULTY OF SCIENCE AND ENGINEERING

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING

TITLE OF PAPER: POWER ELECTRONICS AND ELECTRIC DRIVES

COURSE CODE : EEE554

TIME ALLOWED: THREE HOURS

INSTRUCTIONS:

1. There are four questions in this paper. Answer ALL questions. Each question carries 25 marks.

2. If you think that not enough data has been given in any question you may assume any reasonable values.

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Question 1. [25]

(a) The safe T_m–ω_m operating area of a separately excited DC motor can be divided into a constant torque region and the constant power region.

i. Sketch the T_m–ω_m operating area of the constant torque region and indicate and explain the values (symbolically) that define the operating boundary. [3]

ii. Sketch the T_m–ω_m operating area of the constant power region on sketch (i) above, and indicate and explain the values (symbolically) that define the operating boundary. [3]

iii. With the field terminal voltage constant, derive an equation for the developed torque as a function of speed (ω_m) of the separately excited DC-motor and plot the typical characteristic curves of the developed torque for (say) three different **armature terminal voltage values** on the safe operating area of (i) and/or (ii) above. [6]

(b) The safe P_m–ω_m operating area of a separately excited DC motor can also be divided into a constant torque region and the constant power region.

i. Sketch the P_m–ω_m operating area of the constant torque region and indicate and explain the values (symbolically) that define the operating boundary. [3]

ii. Sketch the P_m–ω_m operating area of the constant power region on (i) above, and indicate and explain the values (symbolically) that define the operating boundary. [2]

(c) What four conditions are required in order to connect a synchronous machine to an infinite bus? [4]

(d) If we ignore the armature resistance of a synchronous machine, prove from a phasor diagram during generator operation, that the developed power of the synchronous machine can be given by the following equation: [4]

$$P_{\text{conv}} = \frac{3V_\phi E_A}{X_S}\sin\delta$$

Question 2. [25]

(a) A 12 kW, 100 V, 1000 r/min separately excited dc motor has the following parameters, $R_f = 80\ \Omega$, $V_{f0} = 100$ V, $R_a = 0.1\ \Omega$ and $K_f = 0.7$ V/(A.rad/sec). Assuming the field voltage to be held constant at 100 V and the motor to be operating at rated torque, calculate the variation in motor speed as a function of terminal voltage as the armature voltage is varied from 60 V to 100 V. [8]

(b) A 575 V, 50 kW, 50 Hz three phase synchronous motor has a synchronous reactance of $X_s = 4.65\Omega$ and an armature to field mutual inductance, $L_{af} = 105$ mH. The motor is supplied from a 575 V source and it is operating at rated speed and terminal voltage and at an output power of 40 kW. Ignore losses in the motor. If the motor is operating at 0.95 power factor lagging as measured at the source:

   i. Calculate the generated voltage E_{af}. [4]

   ii. Calculate the field current I_f. [3]

(c) A 2.5 kW, 3600 r/min, 230 V, 2-pole, 3-phase permanent magnet synchronous motor produces rated open-circuit voltage at a rotational speed of 3530 r/min and has a synchronous inductance of 15.6 mH. Assume that the motor is to be operated under field-oriented control at 3000 r/min and 80 % of rated torque. Neglect any effects of saliency.

   i. Calculate the required quadrature-axis current. [5]

   ii. If the motor is operated with quadrature-axis current only ($i_d = 0$), calculate the resultant armature flux linkage. [5]

Question 3. [25]

An 11 kW, 400 V three-phase, wye-connected, 50 Hz, 1440 r/min squirrel-cage induction machine's equivalent circuit parameters are shown in the table below.

R_1	X_1	R_2	X_2	X_M
0,52 Ω	0,95 Ω	0,45 Ω	0,95 Ω	35,0 Ω

(a) Draw the equivalent circuit of the induction motor and show clearly the sign conventions of all currents and voltages on the circuit. [3]

(b) Make use of the above equivalent circuit of the three-phase induction motor, and:

i. calculate the rated supply current and power factor. [6]

ii. if we can assume that the rated shaft-output power is *exactly* 11 kW, calculate the rated windage-and-friction- / rotational losses. [3]

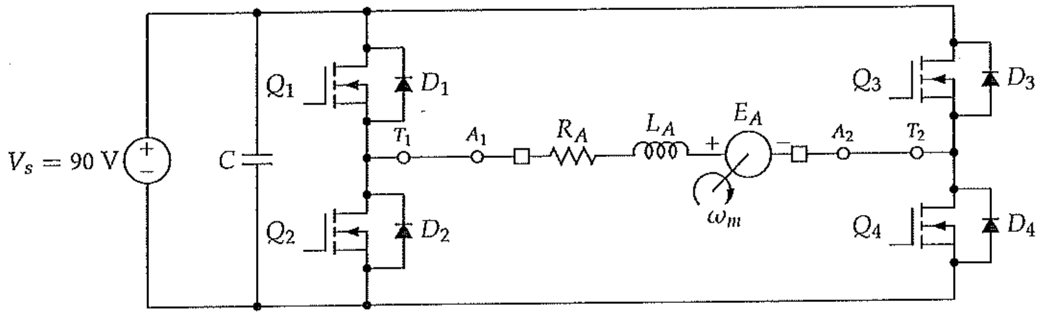
(c) The speed of the three-phase induction machine is controlled using a Variable Speed Drive (VSD) whose control is based on the Volt-per-Hertz principle. If we were to ignore the core – and rotational losses of the induction machine, *make use of the equivalent circuit* of the induction machine, and:

i. Calculate the theoretical value, according to the Volt-per-Hertz principle, of the speed at which the induction machine will deliver its rated torque when it is driven by the VSD at 40 Hz. [3]

ii. If the induction machine is driven by the VSD at 40 Hz and the speed of the motor is measured as 1150 r/min, calculate the torque developed by the induction machine. [10]

Question 4. [25]

A 359 W, 90 V, 5 A permanent magnet DC motor has a motor constant, K_m=0.481 (Nm/A or V/rad/s), an armature resistance, R_A=1.45 Ω, an armature inductance, L_A=5.4 mH and is connected to a four-quadrant DC-DC converter with a DC bus voltage of 90 V as shown below.



(a) If the "switches" and diodes of the four-quadrant converter are considered to be ideal, prove that the output voltage, V_T, of the four-quadrant converter as measured between terminals T_1 and T_2, can be given by [4]

$$V_T = V_s(2D - 1),$$

where D is the duty cycle of switch Q_1.

(b) If the "switches" and diodes of the four-quadrant converter are considered to be ideal and the voltage drop over the brushes of the DC motor can be ignored, calculate the duty-cycle required so that the motor will be able to develop a torque of 2.0 Nm at standstill. [4]

(c) If the IRF543 MOSFETs of the four-quadrant converter have an "ON"-resistance of $r_{DS|_{on}}$=0.077 Ω, the parasitic diodes in anti-parallel with each MOSFET have an "ON"-voltage of 2.5 V, the MOSFETs are switched at 20 kHz with a duty-cycle of 80 %, whilst the shaft of the motor is rotating clock wise at 1000 r/min and if the voltage drop over each brush of the DC motor can be taken as 1.0 V:

N.B.Assume that the polarity of the induced armature voltage is as indicated on the figure for a motor rotating clockwise.

i. Calculate the average armature current. [5]
ii. Calculate the ripple current caused by the converter. [4]
iii. Sketch the approximate voltage waveform over the equivalent armature inductance of the DC motor for one switching cycle, and show the values of the voltage for the D and the $1-D$ periods clearly on the sketch. [4]
iv. Sketch the approximate current waveform through the equivalent armature inductance of the DC motor for one switching cycle, and show the values of the current for the D and the $1-D$ periods clearly on the sketch. [4]

Formulas

$$\sin(\alpha+\beta) = \sin\alpha\cos\beta + \cos\alpha\sin\beta$$
$$\sin(\alpha-\beta) = \sin\alpha\cos\beta - \cos\alpha\sin\beta$$
$$\cos(\alpha+\beta) = \cos\alpha\cos\beta - \sin\alpha\sin\beta$$
$$\cos(\alpha-\beta) = \cos\alpha\cos\beta + \sin\alpha\sin\beta$$
$$\oint_S \mathbf{B}\cdot d\mathbf{a} = 0$$
$$\int_S \mathbf{B}\cdot d\mathbf{a} = \phi$$
$$\oint_C \mathbf{H}\cdot d\mathbf{l} = Ni = \mathcal{F}$$
$$\mathbf{B} = \mu\mathbf{H}$$

$$\mathcal{F} = \phi\mathcal{R}$$
$$\mathcal{R} = \frac{\ell}{\mu A}$$

$$\mu = \mu_0\mu_r$$
$$\mu_0 = 4\pi\times10^{-7}\ \text{H/m}$$

$$\phi = \frac{2lrB_{peak}}{p}$$
$$\mu_R = \frac{B_r}{H_c'}$$
$$(Ni)_{equiv} = -H_c'd$$
$$\mathcal{R}_{equiv} = \frac{d}{\mu_R A_m}$$

$$L = \frac{N^2}{\mathcal{R}}$$

$$\lambda = N\phi$$

$$L = \frac{\lambda}{i}$$
$$e = \frac{d\lambda}{dt}$$

$$\begin{bmatrix}\lambda_1\\ \lambda_2\end{bmatrix} = \begin{bmatrix}L_{11} & L_{12}\\ L_{21} & L_{22}\end{bmatrix}\begin{bmatrix}i_1\\ i_2\end{bmatrix}$$

$$T = -\frac{\pi}{2}p^2\Phi_{sr}F_r sin\delta_r$$
$$\theta_{me} = p\theta_m$$
$$\omega_e = p\omega_m$$
$$\omega_m = \frac{2\pi}{60}n_m$$
$$p = \frac{\text{poles}}{2}$$
$$n_s = \frac{60f_e}{p}$$
$$s = \frac{n_s - n_m}{n_s}$$
$$P_m = \omega_m T_m$$

$$E_a = K_f i_F \omega_m$$
$$T_m = K_f i_F I_a$$
$$T_b = b_m\omega_m$$
$$T_J = J_m\frac{d\omega_m}{dt}$$

$$I_{base_{1\phi}} = \frac{S_{base_{3\phi}}}{3V_{base_{1\phi}}}$$
$$Z_{base} = \frac{V_{base_{1\phi}}}{I_{base_{1\phi}}}$$

Formulas

$$P_m = \frac{3V_\phi E_a}{X_s} sin\delta$$

$$I_a = \sqrt{\frac{i_d^2 + i_q^2}{2}}$$

$$T_{mech} = \frac{3pL_{af}i_Fi_q}{2}$$

$$\lambda_{a(rms)} = \frac{V_a}{\omega_e} = \sqrt{\frac{\lambda_d^2 + \lambda_q^2}{2}}$$

$$\lambda_d = L_di_d + L_{af}i_F$$

$$\lambda_q = L_qi_q$$

$$\sqrt{2}E_{af} = \omega_eL_{af}i_F$$

$$P_{gap} = 3\frac{R_2}{s}I_2^2$$

$$P_{rotor} = 3R_2I_2^2$$

$$P_{mech} = P_{gap} - P_{rotor}$$

$$T_{mech} = 3\frac{poles}{2\omega_e}I_2^2R_2/s$$

$$P_{shaft} = P_{mech} - P_{rot}$$