IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2016

EEE PART II: MEng, BEng and ACGI

POWER ENGINEERING

Corrected Copy

Wednesday, 1 June 2:00 pm

Time allowed: 2:00 hours

There are THREE questions on this paper.

Answer ALL questions.

Q1 carries 40% of the marks. Questions 2 and 3 carry equal marks (30% each).

Any special instructions for invigilators and information for candidates are on page 1.

Examiners responsible First Marker(s) : T.C. Green
Second Marker(s) : B. Chaudhuri

Information for Candidates

Switch-Mode Power Supplies

Voltage ratio equations for buck SMPS $\frac{V_o}{V_i} = \delta$ or $\frac{V_O}{V_I} = \frac{1}{1 + \frac{2fLI_O}{V_I \delta^2}}$

Voltage ratio equations for boost SMPS $\frac{V_o}{V_i} = \frac{1}{1-\delta}$ or $\frac{V_o}{V_i} = \frac{1}{1 - \frac{V_i \delta^2}{2fLI_i}}$

Three-Phase Systems

Line Voltages and Current

Star $V_L = \sqrt{3} V_P \quad I_L = I_P$ Delta $V_L = V_P \quad I_L = \sqrt{3} I_P$

Power
$$P_{3\Phi} = 3 V_P I_P \cos(\phi) = \sqrt{3} V_L I_L \cos(\phi)$$

Induction Machines

$$\omega_S = \frac{\omega_E}{P} \qquad s = \frac{\omega_S - \omega_R}{\omega_S} \qquad T_{em} = \frac{3 I_R'^2 R_R'}{\omega_R}\left(\frac{1-s}{s}\right)$$

Photovoltaic Systems

$$I_{PV} = I_{Ph} - I_{AK} - I_{Sh} \qquad I_{AK} = I_0\left[e^{\frac{V_{PV} + I_{PV} R_S}{K_I v_T}} - 1\right]$$

Power Flow in Lines and Cables

Cable Parameters

$$R'_{LF} = \frac{1}{\sigma_C \pi r_C^2} + \frac{1}{\sigma_C 2\pi r_O t_O} \quad L' = \frac{\mu_0}{2\pi}\ln\left(r_O/r_C\right) \quad C' = \frac{2\pi\varepsilon_0\varepsilon_{RI}}{\ln\left(r_O/r_C\right)} \quad G' = \frac{2\pi\sigma_I}{\ln\left(r_O/r_C\right)}$$

OHL Parameters (approximate form)

$$R'_{LF} = \frac{2}{\sigma_C \pi r_C^2} \quad L' = \frac{\mu_0}{\pi}\ln\left(d/r_C\right) \quad C' = \frac{\pi\varepsilon_0\varepsilon_{RI}}{\ln\left(d/r_C\right)} \quad G' = \frac{\pi\sigma_I}{\ln\left(d/r_C\right)}$$

Power Flow (full form)

$$P_S = \frac{V_S^2}{Z_{SR}}\cos(\theta) - \frac{V_S V_R}{Z_{SR}}\cos(\theta + \delta)$$

$$Q_S = \frac{V_S^2}{Z_{SR}}\sin(\theta) - \frac{V_S V_R}{Z_{SR}}\sin(\theta + \delta)$$

Voltage Drop (approximate form)

$$\Delta V = |V_S| - |V_R| \approx \frac{RP_S + XQ_S}{|V_S|}$$

1. This question covers several topics and all parts should be attempted.

a) Consider a national-scale electricity system based on AC.

i) Describe the principal difference between the transmission and distribution networks and explain why transmission networks use higher voltages than distribution networks. [6]

ii) Most countries of the world operate their electricity networks at a nominal frequency of 50 or 60 Hz, however, in practice the frequency is not strictly constant. Explain why the frequency varies a little around its nominal value. [4]

b) Consider power transfer in AC networks.

i) A single-phase cable operated at 50 Hz and 120 kV has a capacitance per unit length of 0.25 μF/km. Calculate the capacitive charging current for a 75 km length of cable. [2]

ii) A single-phase overhead line has a series impedance which is purely reactive with a value of 18 Ω and is operated at a voltage of 400 kV. Calculate the phase angle that would exist between sending and receiving end voltages when transferring 1,000 MW. [4]

iii) A three-phase load is composed of impedances of 10 + j2 Ω connected in star. It is connected to a supply with a line voltage of 400 V. Calculate the real and reactive power drawn. [4]

c) Compare buck and boost switch mode power supplies (SMPSs) through the following steps.

i) For a fixed input voltage, sketch the shape of the output voltage as a function of the duty-cycle of the switch (assuming continuous conduction) for each SMPS. [3]

ii) Sketch the shape of the currents as a function of time for the currents that flow in the inductor, diode and capacitor for each type of SMPS. [5]

iii) For similar magnitudes of output current and the same choice of capacitor, compare the amplitudes of output voltage ripple. [2]

d) Consider a typical photovoltaic panel.

i) Describe the operating principle of a photovoltaic cell and the role of the band-gap energy in determining the efficiency of the cell. [5]

ii) A PV cell was tested at 25°C. It produced a short-circuit current of 0.8 A under an irradiance of 250 W/m^2. The reverse saturation current of the cell was measured as $I_0 = 1\times10^{-10}$ A. You may assume that the cell has a very small series resistance, a very large shunt resistance and an ideality factor of 1. Boltzmann's constant is $k = 1.380\times10^{-23}$ J/K and the electronic charge is $q = 1.602\times10^{-19}$ C. Calculate the open-circuit voltage at irradiances of 250 and 1,000 W/m^2. [5]

2.

A **buck** switch-mode power supply, SMPS, is to be designed to provide a 5 V output voltage from a 24 V input. The output current will be in the range 0.1 A to 2.0 A and it is intended that the SMPS operates in continuous conduction mode across this range. It has been decided to design for a switching frequency of 150 kHz.

A suitable MOSFET has been identified for the SMPS with the following properties:

On resistance $R_{DS(on)} = 0.25\ \Omega$
Turn-on loss $E_{on} = 13\ \mu J$ when switched on at 2.0 A
Turn-off loss $E_{off} = 7\ \mu J$ when switched off at 2.0 A

The diode to be used has an on-state voltage of 1.0 V.

i) Calculate the duty-cycle at which the switch will operate. [2]

ii) Calculate the power losses in the semiconductors and the efficiency (ignoring other losses) when operating at maximum output power. [8]

iii) Choose an inductor to ensure continuous conduction. [4]

iv) Choose a capacitor to ensure that the output voltage ripple is less than 40 mV. You may work on the basis that 80% of the ripple will arise from the effective series resistance of the capacitor (ESR) and 20% from the capacitance. [6]

v) Calculate the switching frequency that would be needed to improve the efficiency to 80%. [6]

vi) What design changes would be needed (trends rather than numerical values are sufficient) as a consequence of the change of frequency determined in Part (v)? [4]

3.

A 2 pole-pair, 3-phase induction machine is star-connected and supplied at 50 Hz. The equivalent circuit of the machine is shown in Figure Q3 for which the parameters, referred to the stator, are:

stator resistance	0.04 Ω,
stator leakage reactance	0.4 Ω,
referred rotor resistance	0.055 Ω,
referred rotor leakage reactance	0.4 Ω,
magnetising resistance	20 Ω,
magnetising reactance	8 Ω.

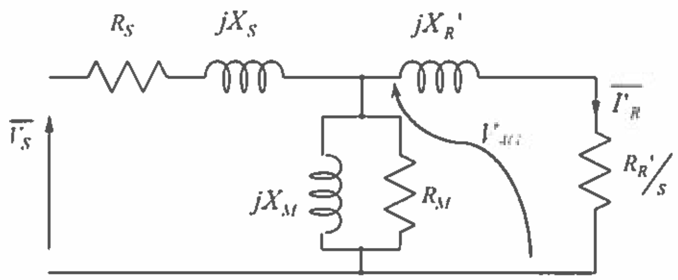

Figure Q3

The machine is rated to develop a torque of 500 Nm at a slip of 0.03. Calculate the following for operation at rated torque:

i) the rotor speed in rad/s [2]

ii) the mechanical output power [3]

iii) the referred rotor current required to develop this power [5]

iv) the voltage appearing across the rotor branch (denoted V_{AG} in the equivalent circuit) in the magnitude and angle form [5]

v) the magnetising current and stator current (in any convenient form) [5]

vi) the magnitude of the required stator voltage [5]

vii) the efficiency at the rated torque [5]