IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2017

EEE PART II: MEng, BEng and ACGI

POWER ENGINEERING

Corrected copy

Wednesday, 7 June 10:00 am

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 $\frac{V_O}{V_I} = \frac{1}{1+\frac{2fL\,I_O}{V_I\delta^2}}$

Voltage ratio equations for boost SMPS $\frac{V_O}{V_I} = \frac{1}{1-\delta}$ or $\frac{V_O}{V_I} = \frac{1}{1-\frac{V_I\delta^2}{2fL\,I_I}}$

Three-Phase Systems

Line Voltages and Current

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

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

Induction Machines

$\omega_S = {}^{\omega_E}/_{p}\;;\qquad s = \frac{\omega_S-\omega_R}{\omega_S}\;;\qquad T_{EM} = \frac{3\,I'^2_R\,R'_R}{\omega_R}\left(\frac{1-s}{s}\right)$

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) $\Delta V = |V_S| - |V_R| \approx \frac{R\,P_S + Z\,Q_S}{|V_S|}$

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

a) Consider a typical photovoltaic panel.

i) With the aid of a sketch (showing clearly the intended direction of incident light), describe the construction of a photovoltaic panel. [5]

ii) The choice of width of the metallisation tracks on the top surface of a panel affects the efficiency of the panel. Describe why this is so. [3]

iii) List the factors that affect the intensity of light that is incident on a panel. [4]

b) An impedance connected to a single-phase supply of 230 V draws a current of 12 A that leads the voltage by 15°.

i) Calculate the resistance and reactance of the impedance. [2]

ii) Calculate the real and reactive powers consumed by the impedance [2]

c) Three impedances, each of $10 + j3\ \Omega$, are connected to a 400 V three-phase supply in delta configuration. Calculate the real and reactive powers consumed. [4]

d) Consider a national-scale AC electricity system.

i) Describe the principal differences between the transmission and distribution networks and include an explanation of why distribution networks use lower voltages than transmission networks. [4]

ii) Explain the disadvantages and advantages of using a frequency higher than 60 Hz and suggest why 400 Hz is the standard for aircraft power systems system. [4]

e) Consider the characteristics of overhead lines and cables.

i) Explain why the $X{:}R$ ratio of an overhead line is different for different voltage ratings. [2]

ii) Explain why an underground cable has a higher capacitance per unit length than an overhead line. [2]

iii) An overhead line is found to have an inductance per unit length of 125 μH/km and is operated at 132 kV and 50 Hz. What is the longest length of line that could be operated with a power transfer of 1,500 MW if the load angle is not to exceed 30°. [4]

iv) An overhead line has a series impedance of $0.35 + j\,0.40\ \Omega$. Measurements at the sending end are that the voltage is 11.0 kV and real power of +8.0 MW with zero reactive power flows from sending end. Estimate the voltage magnitude change across the line. Then estimate the reactive power that would be needed (as seen at the sending end) to bring the voltage change to zero. [4]

2.

A boost switch-mode power supply (SMPS) is to be used to provide a 20 V output from a 4 V input. The inductor has a value of 80 μH and the capacitor has a capacitance of 100 μF and a series resistance of 20 mΩ.

a) Describe the operating principle of the boost SMPS including an explanation of how an output voltage higher than the input voltage is achieved. [5]

b)

i) Calculate the value of duty-cycle required assuming continuous conduction. [2]

ii) Calculate the minimum switching frequency for which the SMPS will stay in continuous conduction for an input power of 2 W. [6]

iii) Sketch the shape of the current through the capacitor during continuous operation and label the sketch with scales for an input power of 12 W and the switching frequency found in (ii). [5]

iv) Calculate the output voltage ripple under the conditions used in (iii). [5]

v) The MOSFET used in the SMPS has a channel resistance of $R_{DS(on)}$) = 20 mΩ and turn-on and turn-off energy losses, E_{on} and E_{off} of 5 and 7 μJ respectively, and diode on-state voltage is $V_{AK(on)}$ = 0.6 V. Calculate the total power lost in the semiconductors when the SMPS operates at 15 W. [3]

vi) One way to reduce the output voltage ripple would be to increase the switching frequency. Without detailed calculation, comment on how effective a doubling of switching frequency would be and the impact on efficiency. [4]

3.

a) Explain in outline the operating principle of a three-phase induction machine. [7]

b) A three-phase induction machine with one pole-pair has the following equivalent circuit parameters:

Stator resistance, $R_S = 0.8\ \Omega$.

Stator leakage reactance, $X_S = 2\ \Omega$;

Iron loss resistance, $R_I = 200\ \Omega$;

Magnetising reactance, $X_M = 60\ \Omega$;

Referred rotor leakage reactance, $X_R = 2\ \Omega$;

Referred rotor resistance, $R_R = 0.8\ \Omega$;

The machine is supplied at a phase voltage of 200 V and a frequency of 50 Hz.

i) Initially, the machine runs at 2,930 r.p.m. Calculate the stator current and the real power drawn from the stator supply. [8]

ii) For the conditions in (i), calculate the rotor current and power converted to mechanical form. [8]

iii) Consider now that the mechanical load speeds up to 3,050 r.p.m and recalculate the power exchanged with the supply and comment on this value. [7]