IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2018

EEE PART II: MEng, BEng and ACGI

POWER ENGINEERING

Corrected copy

Monday, 4 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.

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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

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

Photovoltaic Systems

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

Power Flow in Lines and Cables

Cable Parameters

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

OHL Parameters (approximate form)

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

Power Flow (full form)

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

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 national-scale AC electricity system.

i) For an example country, the UK for instance, outline the changes in proportions of generation from various sources in the last decade and the reasons for the change. [4]

ii) Explain why very high voltages are used for national-scale transmission but lower voltages for local distribution. [4]

iii) Explain why a three-phase system is used. [4]

iv) Explain why DC is used in place of AC for some parts of a transmission system. [4]

b) Consider a typical photovoltaic panel.

i) Describe, with the aid of a sketch, the structure of a photovoltaic panel. [4]

ii) Explain why a maximum power point tracking algorithm is needed for a photovoltaic panel and briefly explain how it operates. [4]

c) Consider a Boost SMPS.

i) Describe the operating principle of the Boost SMPS [4]

ii) The commonly used expression for output voltage in continuous conduction mode is $\frac{V_O}{V_I} = \frac{1}{1-\delta}$. Explain why the voltage observed in practice would be less than this. [4]

iii) The graph of efficiency against output power normally exhibits a central plateau with efficiency reducing at low and high output powers. Explain why this is so. [4]

d) For the equivalent circuit of an induction machine shown in figure Q1, identify which components give rise to power loss and what physical process or feature of the machine they represent. [4]

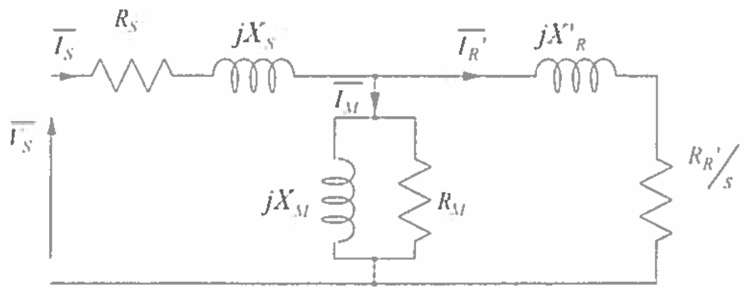

Figure Q1

2.

A **buck** switch-mode power supply (SMPS) is to be used to provide a 5 V output from an 18 V input. The SMPS is intended to operate at a maximum output current of 10 A.

The MOSFET to be used has an on-state resistance of $R_{DS(on)} = 35\ \text{m}\Omega$ and turn-on and turn-off energy losses of $E_{Sw\text{-}on} = 9\ \mu\text{J}$ and $E_{Sw\text{-}off} = 7\ \mu\text{J}$. The diode to be used is a Schottky device with an on-state voltage of $V_{AK(on)} = 0.45$ V.

The capacitor to be used has a capacitance of 330 µF and has an effective series resistance (ESR) of $R_{ESR} = 70\ \text{m}\Omega$.

You may assume that the SMPS operates in continuous conduction mode for the calculations that follow.

a)

i) Calculate the duty-cycle with which the SMPS should operate. [2]

ii) Sketch the shape of the current through the inductor, MOSFET and capacitor at this duty-cycle. [4]

b)

i) Calculate the average power loss in the diode at maximum output current. [4]

ii) Calculate the maximum switching frequency allowed if the total power loss in the MOSFET and diode are to be limited to 5 W at maximum output current. [6]

iii) State an equation for the sum of the voltage ripples across the output capacitance and its ESR and hence find the inductor current ripple allowed if the output voltage ripple is to be limited to 40 mV. Assume that the frequency found in (ii) is used. [7]

iv) Calculate the inductor value that should be used in this design. [3]

v) If the input voltage rose to 20 V (and duty-cycle adjusted to maintain output voltage), would this SMPS become more of less efficient? (You only need consider the power losses in the semiconductors.) [4]

3. This question addresses several aspects of AC systems.

a) A three-phase induction machine with 2 pole-pairs has the following equivalent circuit parameters:

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

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

Magnetising resistance, $R_M = 200\ \Omega$;

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.

When used to drive a particular mechanical load, the machine runs at 1,445 rpm.

i) Give an expression for the total input impedance of the machine and calculate its value in complex form for the conditions given. [8]

ii) Calculate the mechanical power being developed and the electro-magnetic torque. [10]

b) An overhead line is found to have an inductive reactance per unit length of 0.1 Ω/km and negligible resistance. The line is 300 km long and is operated with sending and receiving end voltages of 400 kV and 390 kV respectively.

i) Calculate the angle difference between sending and receiving end voltages that will exist if the line transfers 1,200 MW. [4]

ii) If the line current has to be limited to 1,000 A, what is the maximum angle that can be allowed and what power flow does this allow. [4]

iii) Calculate the reactive power flows at the sending and receiving ends under the conditions in (ii) and compare with the reactive power of the reactance of the line itself. [4]

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