Version TJF/3

EGT3
ENGINEERING TRIPOS PART IIB

Wednesday 2 May 2018 2 to 3.40

Module 4B19

RENEWABLE ELECTRICAL POWER

Answer not more than ***three*** *questions.*

All questions carry the same number of marks.

The ***approximate*** *percentage of marks allocated to each part of a question is indicated in the right margin.*

Write your candidate number ***not*** *your name on the cover sheet.*

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed
Attachment: 4B19 data sheet (1 page).
Engineering Data Book

10 minutes reading time is allowed for this paper at the start of the exam.

You may not start to read the questions printed on the subsequent pages of this question paper until instructed to do so.

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1 (a) Give three advantages and three disadvantages of siting wind farms offshore. [15%]

(b) Explain why offshore wind farms frequently utilise a DC link to transmit power ashore. Hence explain why permanent magnet generators are increasingly used in offshore wind farms. [20%]

(c) A direct-drive variable speed wind turbine generator system consists of a turbine and a permanent magnet generator. The turbine has a blade diameter of 90 m and it is operated at its optimum tip-speed ratio of 9, at which the power coefficient is 0.42 over its variable speed range. Its variable speed range is from the cut-in wind speed of 2.5 ms^{-1} up to the rated wind speed of 12 ms^{-1}. The generator is a 48 pole star-connected permanent magnet generator with an emf constant of 320 $Vsrad^{-1}$ and a synchronous inductance of 1 mH. For rated wind speed find:

(i) the input torque and mechanical power to the generator, and its angular speed; [15%]

(ii) the line-line excitation emf, line-line output voltage, phase current and load angle assuming that the generator is controlled so that its torque angle is 90^0. [30%]

(d) An offshore wind farm consists of 80 wind turbines as specified in part (c) above. A series of power conversions which are 95% efficient takes the power from the wind farm to a bi-polar +/- 180 kV DC link to bring the power ashore. Stating any assumptions made, estimate the DC link current for wind speeds of 6 ms^{-1}, 10 ms^{-1} and 14 ms^{-1}. [20%]

The following may be quoted without proof: $P = \frac{1}{2} C_p \rho A v^3$, $\lambda = \frac{\omega R}{v}$ and take ρ to be 1.23 kgm^{-3}.

2 (a) Derive an expression for the output power available from a hydroelectric scheme, defining the terms in your expression. Explain why salient-pole synchronous generators are used in hydroelectric schemes. [15%]

(b) Explain the role of pumped storage schemes in helping to stabilise the electrical power network at times of peak power demand. Also explain how this sort of scheme enables the greater integration of renewable electrical power sources into the grid. Explain how *Discounted Cash Flow analysis* is used to evaluate the economic viability of renewable energy schemes, and the limitations of this type of analysis in the case of a pumped storage scheme. [25%]

(c) A pumped storage scheme operates with a head of water of 300 m and is capable of providing a peak output power of 200 MW. The scheme is 75% efficient when generating, and utilises 8 identical turbine-generator sets. Explain why impulse turbines would be used in this application and find the volumetric flow rate of the water coming out of the reservoir when the scheme is generating at peak output power. [20%]

(d) The scheme utilises 8 three-phase, star-connected, 10 pole salient-pole synchronous generators which are connected directly to the three-phase 6.6 kV, 50 Hz grid. The generators have direct and quadrature synchronous reactances of 0.8 Ω and 0.6 Ω respectively. Assume that the system is generating at peak power, with the input power shared equally by the 8 turbine-generator sets, and that all generators are generating at a power factor of 0.6 lagging.

(i) Find the speed, input torque and phase current of the generators. [10%]

(ii) Draw a phasor diagram for the generators and derive an expression for the load angle. [15%]

(iii) Hence find the load angle, the direct and quadrature components of the stator phase current and the excitation voltage. [15%]

3 A Si p–n junction solar cell has the following parameters given in Table 1.

n-region doping - N_D	10^{24} m^{-3}
p-region doping - N_A	5×10^{22} m^{-3}
minority carrier diffusion length in n-region - L_h	1 µm
minority carrier diffusion length in p-region - L_e	50 µm
Minority carrier lifetimes t_e, t_h	10 µs, 1 µs
intrinsic carrier concentration at 300 K - n_i	5×10^{16} m^{-3}
Junction area - A	10^{-2} m^2

Table 1

(a) Assuming the junction temperature is kept at 300 K, calculate the expected:

(i) built in potential for the junction under dark conditions; [15%]

(ii) reverse saturation current of the junction. [15%]

(b) The solar cell is exposed to AM 1.5 solar insolation of 1 kW m^{-2}. Under these conditions the measured open circuit voltage of the cell (V_{OC}) is 0.6 V. Assume the temperature remains at 300 K.

(i) Estimate the corresponding short circuit current of the cell. [20%]

(ii) What is the corresponding solar power conversion efficiency of the cell (fill factor must be taken into account). [30%]

(iii) Comment on the limitation posed by assuming the temperature remains at 300 K in the accuracy of the efficiency calculation. [20%

4 (a) Sketch the cross section of a typical Si p-n junction solar cell. Indicate clearly the positions of the junction, electrical contacts and anti-reflection coating.

(b) What are the main considerations in deciding the position of the junction in (a) above? [20%]

(c) The anti-reflection coating is chosen to minimise reflection at the peak of the solar spectrum at 550 nm.

(i) What is the optimum thickness of the anti-reflective coating for a material having a refractive index of 2.0 ? [15%]

(ii) What would the ideal refractive index be? [10%]

(iii) What is the coating thickness for the ideal case in (ii)? [10%]

(d) On the equivalent circuit of a solar cell indicate the parameter which is enhanced by having an anti-reflection coating. Give reasons for your answer. [25%]

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Short answers

1 (c) (i) 1.18 M Nm; 2.83 MW; 2.4 rad s^{-1} (ii) 1.330 kV; 1.336 kV; 1228 A; 5.26^0
(d) 74.7 A; 346 A; 597 A

2 (c) 90.6 m^3 s^{-1} (d) (i) 62.8 rad s^{-1}; 398 kNm; 3645 A (iii) 13.3^0; I_d = 3340 A;
I_q = 1460 A; E = 11.05 kV line.

3 (a) (i) 0.80 V (ii) 400 pA (b) (i) 4.2 A (ii) 20.9%

4 (c) (i) 60 nm (ii) 1.86 (iii) 44 nm

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4B19 Data sheet

Reflection coefficient from the third layer of a 3 layer system, comprising a thin film sandwiched between two bulk materials, extending away from their interfaces with the thin film, is given as:

$$R = \frac{n_2^2 (n_1 - n_3)^2 Cos^2 \vartheta + \left(n_1 n_3 - n_2^2\right)^2 Sin^2 \vartheta}{n_2^2 (n_1 + n_3)^2 Cos^2 \vartheta + \left(n_1 n_3 + n_2^2\right)^2 Sin^2 \vartheta} \quad \text{where} \quad \vartheta = \frac{2\pi\, n_2\, d}{\lambda}$$

n_1, n_2 and n_3 are the refractive indices of 3 materials m_1, m_2 and m_3 respectively: d is the thickness of the thin film m_2 sandwiched between materials m_1 and m_3. Direction of light flow is taken to be from m_1 to m_3.

Fill Factor for a solar cell

$$FF_o = \frac{\frac{qV_{oc}}{kT} - ln\left(\frac{qV_{oc}}{kT} + 0.72\right)}{\frac{qV_{oc}}{kT} + 1}$$

where V_{oc} is the open circuit voltage for the cell. This is an empirical relation.

Constants

Electronic charge unit **q: 1.602×10^{-19} C**

Boltzmann's constant **k: 1.38×10^{-23} J K^{-1}**

Speed of light **c: 3×10^{8} m s^{-1}**

Planck's constant **h: 6.626×10^{-34} J s**

Dielectric permittivity free space ε_0**: 8.85×10^{-12} F m^{-1}**

Relative permittivity of Si ε_r**: 11.9**

Refractive index (for weakly and non-absorbing wavelengths) **n** = $\varepsilon_r^{0.5}$

Band-gap energy of Si**: 1.12 eV**