Version TJF/6

EGT3
ENGINEERING TRIPOS PART IIB

Friday 7 May 2021   1.30 to 3.10

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 and at the top of each answer sheet.*

STATIONERY REQUIREMENTS
Write on single-sided paper.

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed.
Attachment: 4B19 data sheet (1 page).
You are allowed access to the electronic version of the Engineering Data Books.

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

The time taken for scanning/uploading answers is 15 minutes.

Your script is to be uploaded as a single consolidated pdf containing all answers.

1 (a) An offshore, variable speed, wind turbine generator system is operated at its optimum tip-speed ratio of 8, at which its power coefficient is 0.38, between the cut-in wind speed of 3 m s^{-1} and the rated wind speed of 12 m s^{-1}. The system consists of a turbine of blade diameter 85 m coupled directly to a 40 pole permanent magnet generator with an emf constant of 280 V s rad^{-1} and a synchronous inductance of 3.8 mH. At the wind speed of 10 m s^{-1} find:

(i) the angular speed of the system and the input torque and mechanical power to the generator; [10%]

(ii) the line-line output voltage and excitation emf, the phase current and the load angle assuming that the torque angle is 90°. [15%]

The following may be quoted without proof: $P = 0.5C_p \rho A v^3$, $\lambda = \frac{\omega R}{v}$, $\rho = 1.23$ kg m^{-3}.

(b) The system is controlled so that at wind speeds above the rated wind speed, the turbine angular speed is held constant at its value at the rated wind speed, and the turbine power is held fixed at the rated power of the system. For the wind speed of 14 m s^{-1} find:

(i) the angular speed of the turbine and the torque acting on the shaft of the generator; [10%]

(ii) the generator phase current and excitation voltage assuming that the torque angle of 90° is maintained. [15%]

(c) An offshore wind farm consists of 100 identical wind turbine generators as specified in part (a) above. A platform converter is used to convert the total output power for onward transmission to shore via a 300 kV dc link. The platform converter is 99% efficient, and the dc link has resistance of 5 Ω. Find the required rating for the platform converter, and for the rated wind speed determine:

(i) the input power to the platform converter and its power loss; [10%]

(ii) the dc link current and the dc link power loss; [10%]

(iii) the power that reaches the shore and hence the overall efficiency of the wind farm. [10%]

(d) An engineer is to evaluate the benefit of upgrading the system so that its rated wind speed is 14 m s^{-1}. Outline what costs would be involved, what the benefit would be, and explain the principles of discounted cash flow analysis in quantifying the benefit. [20%]

2 (a) Derive an expression for the output power, P, of a hydroelectric scheme with head of water H, volumetric flow rate Q, and efficiency η. Explain why your expression can be approximated to $P = 10000\eta HQ$. [10%]

(b) Explain the principles of operation of tidal barrage schemes, and show that the theoretical upper limit to the average output power is given by

$$P = \frac{\rho g A R^2}{2T}$$

and define all the terms in this expression. Illustrate your explanation by sketching, on the same axes, graphs of sea level, basin level and output power vs time over a 24 hour period. Explain the difficulties of integrating this form of renewable electricity into the grid, and suggest two ways of mitigating against these difficulties. [25%]

(c) An ebb-flow tidal barrage scheme has a basin area of 140 km^2 and a tidal range and period of 15 m and 12 hours, respectively. It is able to extract 60 % of the theoretical upper limit of the average output power. Assume that the scheme is controlled so that the flow rate through the barrage is constant over the 5 hour period when it is generating. Stating any assumptions, estimate:

(i) the total flow rate through the barrage when generating, and the average electrical output power; [10%]

(ii) the peak electrical output power, the total annual electrical energy supplied by the scheme and its capacity factor. [15%]

(d) The scheme of part (c) is to use 150 propellor turbines which are all directly coupled to identical salient-pole synchronous generators rotating at 150 rpm. The generators are all star-connected directly to the 11 kV, 50 Hz three-phase grid, and may be required to operate with power factors ranging from 0.6 lagging to 0.9 leading.

(i) Find the power and torque rating for the turbines. [10%]

(ii) Specify the salient-pole synchronous generators in terms of their volt-amp rating and pole number. [10%]

(e) The salient-pole generators used in the scheme of part (c) have equivalent circuit parameters $X_d = 1\ \Omega$ and $X_q = 0.75\ \Omega$. When the system is operating at peak output power, and with all the generators operating at a lagging power factor of 0.8, find the phase current, excitation voltage and the load angle of the generators. [20%]

3 A crystalline Si p–n junction solar cell at a temperature of 300 K has the following parameters given in Table 1:

n-region doping N_D	5×10^{24} m^{-3}
p-region doping N_A	5×10^{22} m^{-3}
minority carrier diffusion coefficient in the n-region	2×10^{-6} m^2 s^{-1}
minority carrier diffusion length in the p-region L_e	50×10^{-6} m
minority carrier lifetimes for electrons and holes respectively t_e, t_h	100 μs, 1 μs
Junction area	10^{-2} m^2
Intrinsic carrier concentration	4×10^{16} m^{-3}

Table 1

(a) Under dark conditions:

(i) Calculate the built-in potential for the junction. [10%]

(ii) Find the peak minority carrier concentration on the p-side when a forward voltage of 0.5 V is applied. [10%]

(iii) Derive the current–voltage characteristic of the diode and hence calculate the forward current under the voltage condition in (ii) above. [30%]

(b) 36 identical solar cells are assembled into a panel and connected in series. The panel is exposed to AM 1.5 solar illumination of 1 kW m^{-2}. If the average *generation rate* is taken to be 5×10^{25} m^{-3} s^{-1} within a cell and the panel temperature is maintained at 300 K:

(i) Find the corresponding *short-circuit current* of the cell. [15%]

(ii) Calculate the corresponding *open-circuit voltage* of the cell. [15%]

(iii) The area of the panel is 0.4 m^2. Estimate the efficiency of the solar panel under AM 1.5 insolation. Clearly state any assumptions made. [20%]

4 The absorption coefficient for light in Si at the peak power intensity of the solar spectrum at a light wavelength of 600 nm is 4×10^5 m^{-1}. The wavelength of light present in the solar spectrum which corresponds to having an energy just above the band-gap energy of Si is 1100 nm and has an absorption coefficient of 10^3 m^{-1}.

(a) Sketch the cross section of a Si solar cell showing the doping layers, and choose an appropriate depth for the placement of the junction from the surface which light enters the cell. Give reasons for the choice of junction placement. [10%]

(b) What would the appropriate thickness of the Si solar cell be to maximise absorption of energy from the solar spectrum? Give reasons for your answer. [10%]

(c) Considering the requirement to minimise the cost of a Si solar cell, explain how your choice in (b) above could be modified. [20%]

(d) Derive the expression which links light absorbed at the peak of the solar spectrum to the total electronic charge carriers generated within the Si. [25%]

(e) What are the reasons for all the charge carriers generated in (d) above not contributing to the short-circuit current of a solar cell? [15%]

(f) Design a coating on the Si, made from silicon nitride (Si_3N_4), which has a refractive index of 1.8, to maximise the light coupled into the cell at the peak intensity of the solar spectrum at normal incidence. [20%]

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Short answers

1 (a) (i) 1.88 rad s^{-1}, 705 kNm, 1.33 MW (ii) 934 V, 912 V, 839 A, 12.6°

(b) (i) 2.26 rad s^{-1}, 1000 kNm (ii) 1191 A, 1096 V

(c) (i) 230 MW, 2.3 MW (ii) 759 A, 2.88 MW (iii) 225 MW, 97.7%

2 (c) (i) 116700 m^3 s^{-1}, 2.15 GW (ii) 10.3 GW, 18.8 TW hr, 0.21

(d) (i) 68.7 MW, 4.37 MN m (ii) 114.5 MVA (e) 4.51 kA, 16.8 kV, 17.9°

3 (a) (i) 0.85 V (ii) 7.12×10^{18} m^{-3} (iii) 6.67 mA

(b) (i) 4.1 A (ii) 0.63 V (iii) 19%

4 (b) 0.5 mm