Version TJF/3

EGT3
ENGINEERING TRIPOS PART IIB

Thursday 2 May 2019 2 to 3.40

Module 4B19

RENEWABLE ELECTICAL 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.

1 (a) Describe five factors involved in site selection for wind turbines. [10%]

(b) Give three advantages of slip energy recovery for the generation of electricity by wind turbines using induction machines. Draw a schematic diagram of an induction machine with a slip energy recovery scheme, connected to the three-phase grid, and explain its principles of operation. [25%]

(c) Wind speed data for a wind turbine site is given in Table 1 below.

Wind Speed (m s^{-1})	3	8	10	14	18	21	24
Days	25	45	90	120	50	25	10

Table 1

A fixed speed 2.5 MW wind turbine is to be installed at the site, and the turbine is to produce rated power at the most probable wind speed at which it operates at its optimum tip-speed ratio. The power coefficient (C_p) is given as a function of tip speed ratio (λ) as:

$C_p = -0.005\lambda^2 + 0.08\lambda + 0.08$ for $\lambda < 16$; $C_p = 0$ otherwise.

(i) Determine the maximum power coefficient and the corresponding optimal tip-speed ratio. [10%]

(ii) Find the turbine radius. [5%]

(iii) The cut-in wind speed is 4 m s^{-1} and the stall wind speed is 20 m s^{-1}. Determine the output electrical power for each of the given wind speeds in Table 1, and hence find the total annual energy supplied by the turbine, ignoring generator losses. [15%]

(iv) Determine the capacity factor of this wind turbine installation. [5%]

Assume $P = 0.5C_p\rho Av^3$, $\lambda = \frac{\omega R}{v}$, and $\rho = 1.14$ kg m^{-3}.

(d) Using the method of discounted cash flow analysis, find the current cost per kWhr of electricity produced by the wind turbine of part (c). Assume that the capital cost for the turbine-generator system is £1500 per kW of rated output, that annual maintenance is 4% of the capital cost and that the initial capital investment is paid back over the assumed lifetime of the project, which is 25 years. The average interest rate over the period is 8%, and the average inflation rate is 3%. An annuitisation table is provided in Table 2. Also calculate the annual profit assuming a current electricity market price of 10.6p per kWhr. [30%]

Capital Repayment in £ per £1000	Real discount rate			
	2%	5%	8%	10%
5 years	212	231	250	264
10 years	111	130	149	163
15 years	78	96	117	131
20 years	61	80	102	117
25 years	51	71	94	110
30 years	45	65	89	106

Table 2

2 (a) Explain why High Voltage Direct Current (HVDC) is used for connection of far-offshore wind farms to land. [10%]

(b) Give three advantages and three disadvantages of large scale hydroelectric power schemes as a source of renewable electrical power. [15%]

(c) Show that the power generated by a hydroelectric scheme in which the head of water is maintained constant is given by $P = \eta g H \rho Q$ and define all the terms in this expression. Describe how hydroelectric schemes are categorized by the head of water available and outline the turbine technologies associated with each turbine. [25%]

(d) A 3-phase, 33 kV, 50 Hz, star-connected, salient pole synchronous generator is to be directly coupled to a turbine which is used in a 100 MW hydroelectric plant. The turbine efficiency is 80% and it operates at a speed of 300 rpm. The generator has equivalent circuit parameters $X_d = 4\ \Omega$ and $X_q = 3\ \Omega$. The turbine is operating at maximum output power, and the generator is excited to supply 60 MVAr of reactive power. The generator power losses can be neglected.

(i) Find the number of generator poles, input torque, generator output current and power factor. [15%]

(ii) Draw a phasor diagram for the generator and hence calculate its load angle and line-line excitation voltage. [35%]

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

n-region doping N_D	10^{25} m^{-3}
p-region doping N_A	10^{23} m^{-3}
minority carrier diffusion coefficient in the n-region	10^{-6} m^2 s^{-1}
minority carrier diffusion coefficient in the p-region	16×10^{-6} m^2 s^{-1}
Minority carrier lifetimes for electrons and holes respectively t_e, t_h	100 μs, 1 μs
Junction area	10^{-2} m^2

Table 3

The intrinsic carrier concentration n_i as a function of temperature T is given by the expression:

$n_i = n_0 \exp\left(\frac{-T_0}{T}\right)$, where $n_0 = 3.1 \times 10^{26}$ m^{-3} and $T_0 = 6.9 \times 10^3$ K.

(a) Assume that the junction temperature is 300 K under dark conditions.

(i) Determine the built-in potential for the junction under dark conditions. [10%]

(ii) Find the reverse saturation current of the junction. [10%]

(iii) If the threshold for turn-on of the p-n junction under dark conditions is taken to be 1 A m^{-2} estimate the turn-on voltage of the junction. [10%]

(b) The solar cell is assembled in a panel and exposed to AM 1.5 solar illumination of 1 kW m^{-2}. Under these conditions the temperature of the cell rises to 340K. The average generation rate is then 6×10^{25} m^{-3} s^{-1}.

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

(ii) Calculate the corresponding open-circuit voltage of the cell. [30%]

(iii) Why is the built-in potential of the junction different from the open-circuit voltage obtained under solar illumination? [20%]

4 (a) Sketch the equivalent circuit for an ideal p-n junction solar cell. Explain what the circuit elements represent. [10%]

(b) What is the significance of the $fill\ factor$ for a solar cell? [10%]

(c) How does the equivalent circuit for the ideal cell need to be modified for a practical cell? Give reasons for your modifications. [15%]

(d) When a solar cell having area 1.0×10^{-2} m^2 is exposed to AM 1.5 (1 kW m^{-2}) solar radiation, an open-circuit voltage of 0.6 V is measured. The cell temperature is 340 K.

(i) Assuming the solar cell to be ideal estimate its fill factor. [10%]

(ii) When the cell is connected to a load of 200 mΩ under AM 1.5 illumination a current of 2.5 A is measured. What is the efficiency of the cell under this load condition? [20%]

(iii) The fill factor is modified to 0.65 based on the measurements in (ii) to take into account the effect of contact resistance. Determine the corresponding short-circuit current for the cell. [25%]

(iv) Find the maximum power conversion efficiency expected from the cell. [10%]

END OF PAPER