ENGINEERING TRIPOS PART IIB

Wednesday 21 April 2010 9 to 10.30

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.*

There are no attachments.

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS
Engineering Data Book
CUED approved calculator allowed

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

tjf02

1 (a) A proposal for a large wind turbine is that it should be rated at 1.6 MW and it is to produce this output power at a wind speed of 12 ms^{-1}. The cut-in and stall wind speeds are to be 3 ms^{-1} and 20 ms^{-1} respectively. It is to operate at its optimal tip-speed ratio between cut-in and rated wind speeds. A table with simplified wind speed data is below.

Wind speed (ms^{-1})	2	6	10	14	18	22
Number of days	30	170	110	35	15	5

Determine the output electrical power at each of the wind speeds given, and hence find the annual output electrical energy and capacity factor of the system. [30%]

(b) Two possibilities for the generator are the synchronous generator and the doubly-fed induction generator utilising slip-energy recovery. Given that this is a variable speed system, discuss the relative merits of these two proposals. [20%]

(c) In order to exploit some of the higher wind speeds more fully it is proposed instead to rate the system at 2.5 MW at a wind speed of 14 ms^{-1}. The cut-in and stall wind speed remain the same as in part (a). Using the wind speed data of part (a) determine the annual output electrical energy and capacity factor of the system. [15%]

(d) Using the method of discounted cash flow analysis, find the current cost per kWhr of electricity produced by the two proposals. Assume that the capital cost for the systems is £1000 per kW of rated output, that annual maintenance is 3% 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 below. Comment on your answers. [35%]

Real discount rate

Capital repayment/£1000	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

2 (a) Give three difficulties of integrating renewable electrical power sources into the existing UK grid infrastructure, and two methods for overcoming these difficulties. Also explain how the flows of real and reactive power are controlled in electrical power systems. [25%]

(b) Under optimum wind conditions a large wind farm produces 80 MW of real power and can produce up to ±60 MVAr of reactive power. All the generators of the wind farm are connected to the three-phase 50 Hz power system at an 11 kV bus. The 11 kV bus is connected to a 275 kV transmission line of j1 Ω/km via an 11 kV/275 kV, 200 MVA transformer of 0.25 pu reactance. The transmission line is 200 km long. The other end of the transmission line is connected to the 33 kV load bus via a 275 kV/33 kV, 300 MVA transformer of 0.3 pu reactance. The voltage at the 33 kV load bus is maintained at exactly 33 kV. Find the magnitude and the angle of the voltage at the wind farm bus when the load real and reactive powers are, respectively:

(i) 80 MW, +20 MVAr;

(ii) 80 MW, -20 MVAr. [35%]

(c) It is proposed to use FACTS devices to facilitate an upgrade of the wind farm in part (a) to a maximum real power of 160 MW and reactive power of up to ±120 MVAr. A series-connected FACTS device is to be used, connected in series with the transmission line. The voltage at the 33 kV load bus is maintained constant at 33 kV. The angle of the voltage at the wind farm bus must not exceed 40^0, and the magnitude of the wind farm bus voltage must be within 10% of its nominal 11 kV value. Specify the FACTS device required to achieve the upgrade assuming that the maximum real power taken from the load bus is 160 MW, and that shunt-connected FACTS devices are used to ensure that the magnitude of the wind farm bus voltage complies with the limits given above. [30%]

(d) Give another way of upgrading the transmission link to achieve the same objective as part (c), and state one advantage of your proposal. [10%]

3 (a) Draw schematic diagrams for off-grid and on-grid small wind power systems, and explain the role of the various components in your diagrams. [20%]

(b) A 3-phase, 8 pole, star-connected permanent magnet generator (PMG) has an emf constant of 1.2 $Vsrad^{-1}$ and negligible synchronous inductance. It is driven directly by a wind turbine of blade radius 1 m, optimum tip-speed ratio 10, at which the power coefficient is 30%. The system is controlled so that the wind turbine always operates at its optimum tip–speed ratio. For wind speeds between 5 ms^{-1} (cut-in) and 15 ms^{-1} (rated) find the upper and lower limits for: the generator angular speed; the line-line rms output voltage; the frequency of the output voltage; the output power. [30%]

(c) The three-phase output from the generator is connected to an uncontrolled three-phase full-wave bridge rectifier. Estimate the dc link average voltage and current for the upper and lower wind speeds, stating any assumptions. You may use the following result for the rectifier: $V_0 = 1.35\ V_L$ where V_0 is the average open-circuit dc link voltage and V_L is the line-line input voltage from the three-phase supply. [15%]

(d) It is proposed to utilise a boost converter between the uncontrolled rectifier of part (c) and an inverter which is to be used to provide 240 V, 50 Hz ac power to single-phase loads. Draw a circuit for such a boost converter and explain its principles of operation. Show that

$$V_0 = \frac{V_{DC}}{1-\rho}$$

and define the symbols in this expression. Assuming that the inverter is a single phase full bridge converter, find the minimum dc input voltage needed to produce 240V rms ac at the output. Hence suggest values for the modulation index of the inverter and the switching ratio ρ of the boost converter at the lower and upper wind speeds of part (b). [35%]

4. (a) Give two reasons for the current interest in wave and tidal flow electrical power generation, and three challenges facing the development of this resource. In the context of power generation from waves, explain what is meant by the terms 'point absorber', 'attenuator' and 'terminator'. [20%]

(b) Consider a buoy system in which a buoy that moves up and down with the waves produces a reciprocating motion. Draw schematic diagrams showing how power take-off is achieved via:

(i) a hydraulic system consisting of a hydraulic cylinder, valves, hydraulic motor and an electrical generator;

(ii) a direct drive system utilising a vernier hybrid machine.

Give one advantage and one disadvantage of the above methods of power take-off. Also sketch a graph of the output voltage vs time of the vernier hybrid machine and hence explain why a fully-rated converter is required to connect its output to the grid. [40%]

(c) The mean power per unit width of wave front, P, is given by

$$P = \frac{\rho g^2 T H^2}{32\pi}$$

where ρ is the density of sea water, 1030 kgm^{-3}. It is proposed to populate a 10 km length of coastline with buoy-type devices. The devices are spaced 4 m apart, and every device drives a vernier hybrid machine. It is known that the wave height, H, can vary between 1 m and 5 m, and the corresponding wave periods, T, are 6 s and 12 s, respectively. Estimate:

(i) the minimum and maximum available total power;

(ii) the rating of the vernier hybrid machines;

(iii) the peak velocity and thrust of the translators of the vernier machines. [40%]

END OF PAPER

Short answers for 4B19 Renewable Electrical Power 2010 **Dr T J Flack**

1. (a) Total annual energy output = 5181 MWhr, capacity factor = 0.37
(c) Total annual energy output = 6205 MWhr, capacity factor = 0.283.
(d) For proposal (a) cost of electricity is 3.1p/kWhr, for (b) it is 4.1p/kWhr.

2 (b) (i) Voltage is 12.83 kV, angle is 19.6^0 (ii) Voltage is 10.82 kV, angle is 23.4^0.(c) C = 33μF.

3 (b) Angular speeds are 50 $rads^{-1}$ and 150 $rads^{-1}$; voltages are 60 V and 180 V; frequencies are 31.8 Hz and 95.5 Hz; powers are 72.5 W and 1.96 kW. (c) DC link voltages are 81 V and 243 V; currents are 0.895 A and 8.06 A. (d) At the lower wind speed m_A=1 and ρ=0.523. At higher wind speed ρ=0 and m_A = 0.7.

4 (c) (i) Minimum power = 59.2 MW, maximum power = 2958 MW.(ii) Power rating = 1.2 MW. (iii) Peak velocity = 1.3 ms^{-1}. Peak thrust = 1.83 MN.