ENGINEERING TRIPOS PART IIB

Monday 7 May 2012 2.30 to 4

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

TJF03

1 (a) Land-based wind turbines, tidal currents and the combustion of biomass are three means of generating power from renewable sources. Compare these, in the context of the British Isles, in terms of:

(i) extent of the resource;

(ii) the state of the technology;

(iii) electrical equipment needed for generation;

(iv) possible environmental impact. [60%]

(b) Currently wind turbines are being installed at both onshore and offshore sites. Compare these locations in terms of:

(i) reliability issues;

(ii) maintenance;

(iii) expected capacity factor;

(iv) choice of turbine type. [20%]

(c) As part of the move towards generating an increasing fraction of power by renewable means, especially wind power, DC transmission lines are being increasingly considered. What is the rationale for:

(i) DC links to offshore wind turbine clusters;

(ii) long-distance undersea DC links. [20%]

2 (a) Explain why it is advantageous for wind turbines to operate at variable speed, making reference to the ideas of tip-speed ratio and power coefficient. [15%]

(b) A wind turbine has a 40 m blade radius, a cut-in wind speed of 2.5 ms^{-1}, rated wind speed of 12 ms^{-1} and stall wind speed of 20 ms^{-1}. Power coefficient vs tip-speed ratio data, and wind speed data at its site are given in the tables below. Determine, stating any assumptions made:

(i) the rated power of the wind turbine;

(ii) the annual electrical energy output and capacity factor assuming continuously-variable speed operation at the optimum tip-speed ratio;

(iii) the annual electrical energy output and capacity factor assuming fixed speed operation such that the turbine operates at its optimum tip-speed ratio at the most common wind speed. [35%]

The output power of a wind turbine is given by $P = 0.5\ C_p \rho A v^3$ and ρ should be taken as 1.23 kgm^{-3}.

Wind speed (ms^{-1})	< 2	3.5	7	10	14	22
Number of days	25	65	180	55	30	10

λ	4	8	12	16
C_p	0.22	0.4	0.35	0.25

(c) Explain the principles of discounted cash flow analysis in assessing the economic viability of renewable electricity projects. [15%]

(d) A wind farm developer has to choose between the variable speed and fixed speed schemes of part (b). The fixed-speed scheme has capital costs of £2 million and annual maintenance costs of 1% of the capital cost, whereas the variable speed scheme has capital costs of £2.2 million and has annual maintenance costs of 1.5% of its capital costs. Both schemes will sell their electricity to the grid operator at 7p/kWhr. Both schemes have an expected lifetime of 25 years and the capital costs will be financed by borrowings to be paid back over this period. Estimate the annual profit made by both schemes assuming real interest rates of 0% and 5%, for which annual repayments per £1000 borrowed over 25 years are £40 and £71 respectively. State any assumptions made, and comment on the significance of your answers. [35%]

3 (a) Show that the output power of a hydroelectric power scheme is given by

$$P = \eta\rho g H Q$$

and define all the terms in this expression. Explain how the choice of turbine type is made. Also outline the use of specific speed in determining the choice of system rotational speed. Give two reasons for the use of salient-pole synchronous generators in hydroelectric schemes. [25%]

(b) A hydroelectric scheme is to be developed at a site with an available head of 30 m and flow rate of 10 m^3s^{-1}. The overall system efficiency is estimated to be 75%. A Francis turbine coupled to a salient-pole synchronous generator is proposed for this application. The ideal specific speed of the turbine is 200.7. The generator is to be connected directly to the 50 Hz grid and is required to operate over a range of power factors from 0.6 lagging to 0.8 leading. Take g to be 9.81 ms^{-2} and ρ to be 1000 kgm^{-3}.

Determine:

(i) the maximum power produced by the scheme;

(ii) the turbine rotational speed assuming that the turbine operates at its ideal specific speed, and hence the turbine torque;

(iii) the number of pole-pairs and the VA rating of the generator. [25%]

The specific speed of a turbine, N_S, is given by $N_S = nP^{1/2}H^{-5/4}$ in which n is the rotational speed in rpm, P is the power in kW and H is the head in m.

(c) An 11 kV, 50 Hz, star-connected salient-pole synchronous generator of the same number of pole-pairs and rating determined in (b) part (iii) above has direct and quadrature synchronous reactances of 15 Ω and 10 Ω respectively. It is to be used in the hydroelectric scheme of part (b). Determine its line-line excitation voltage and its load angle when delivering rated power to the 11 kV 50 Hz bus at power factors of:

(i) 0.6 lagging;

(ii) 0.8 leading. [50%]

4 (a) Why do doubly-fed systems remain widely used for variable speed generation in wind turbines? [10%]

(b) Draw a system diagram of a slip-ring induction generator configured for double feed. Explain the functions of:

(i) the machine side converter;

(ii) the grid or line side converter;

(iii) the line reactor. [40%]

(c) A particular 1.5 MW wind turbine uses a 6-pole slip-ring induction generator supplied at 690 V to generate over a speed range of 640 to 1360 rpm.

(i) Find the minimum rating for machine and grid side converters, assuming that the power factors are 0.9 and unity respectively;

(ii) Calculate the range of frequencies required from the machine-side converter;

(iii) Find a suitable DC link voltage, stating any assumptions made;

(iv) Specify a voltage for the feed to the rotor when operating at 1360 rpm, giving reasons for your choice. [40%]

The DC link voltage is related to the AC output by

$$V_{ac} = \frac{\sqrt{3}}{2\sqrt{2}} . V_{dc} . m$$

where m is the modulation index.

(d) Give two reasons why a brushless doubly-fed generator could be preferred over a slip-ring induction generator. [10%]

END OF PAPER