ENGINEERING TRIPOS PART IIB

Wednesday 22 April 2009 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

1 (a) How is electricity generated from the combustion of biomass? Name two sources of fuel and comment on their availability? [15%]

(b) Describe one way in each case of generating electricity from (i) tidal currents (ii) waves at the shoreline (iii) waves offshore? Comment on the extent of the resource, the power take off method, any energy conversion steps and any environmental concerns. [75%]

(c) There is an number of proposals for large offshore wind farms. What are the technical issues to be addressed in moving from land based farms? [10%]

2 (a) Why is the brushless doubly fed machine (BDFM) an attractive alternative to the slip ring induction machine as a variable speed generator for marine current turbine (MCT) applications? [10%]

(b) An MCT uses a 4 pole/8 pole BDFM with a natural speed of 500 rpm. The operating speed range is 300 to 750 rpm with an output of 200 kW at 500 rpm. The BDFM's control winding is fed via a bi-directional converter.

(i) Sketch a system diagram of the above arrangement.

(ii) Determine the net output to the grid at 300 and 750 rpm, ignoring losses.

(iii) Determine minimum ratings for the line and machine side converters assuming that the line side converter operates at unity power factor and the machine side 0.9 lagging.

(Cont.

(iv) Assuming that a three-phase full bridge converter is used to supply the control winding, show that the output line voltage, V_L, is given by

$$V_L = \frac{\sqrt{3}\ V_{DC}}{2\sqrt{2}} . m$$

where V_{DC} is the DC link voltage and m is the modulation index.

(v) Find the voltages and frequencies to be applied to the control winding at speeds of 750, 500 and 200 rpm on the basis of minimum winding current. Take the DC link voltage to be 1200 V and the maximum value of m to be 0.95. Comment on the values for the 500 rpm case. [80%]

(c) Design calculations to suggest that the voltage drop between generator and the shore is excessive based on transmission at 690 V. How could this problem be mitigated? [10%]

Note: The rotational speed N of a BDFM is given by $N = \frac{f_p + f_c}{p_p + p_c}$

where f_p and f_c are the frequencies of the power and control windings respectively and p_p and p_c are the respective pole pair numbers.

(iv) Assuming that a three-phase full bridge converter is used to supply the control winding, show that the output line voltage, V_L, is given by

$$V_L = \frac{\sqrt{3}\ V_{DC}}{2\sqrt{2}}.\,m$$

where V_{DC} is the DC link voltage and m is the modulation index.

(v) Find the voltages and frequencies to be applied to the control winding at speeds of 750, 500 and 200 rpm on the basis of minimum winding current. Take the DC link voltage to be 1200 V and the maximum value of m to be 0.95. Comment on the values for the 500 rpm case. [80%]

(c) Design calculations suggest that the voltage drop between generator and the shore is excessive based on transmission at 690 V. How could this problem be mitigated? [10%]

Note: The rotational speed N of a BDFM is given by $N = \dfrac{f_p + f_c}{p_p + p_c}$

where f_p and f_c are the frequencies of the power and control windings respectively and p_p and p_c are the respective pole pair numbers.

3 (a) Show that the power extracted from a hydroelectric scheme in which the head of water is maintained constant is given by

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

and define all the terms in this expression. Explain how hydroelectric schemes are categorised by the head of water available and outline the turbine technologies associated with each category. Also explain how pumped storage schemes are used to stabilise power systems against sudden changes in demand for electrical power. [25%]

(b) Explain the principles of tidal barrage schemes for renewable electrical power generation and show that the theoretical upper limit to the average output power is given by

$$P = \rho g A R^2 / 2T$$

and define all the terms in this expression. Sketch, on the same axes, graphs of sea level, basin level and output power vs time over a 24 hour period. Use your graph to explain the difficulties of integrating such schemes into the National Grid. Give two means of mitigating against these difficulties. [25%]

(c) A 3-phase star-connected salient pole synchronous generator is to be used in a tidal barrage scheme. It is to be directly coupled to a turbine which produces a maximum mechanical output power of 40 MW at a rotational speed of 300 rpm. The generator has its stator windings connected directly to the 11 kV, 50 Hz three-phase grid. It has direct and quadrature synchronous reactances of 1.75 Ω and 1 Ω respectively. With the turbine operating at maximum output power, and with the generator excited so that it generates 30 MVAr of reactive power:

(i) Find the number of poles of the generator, its input torque and determine the generator output current and power factor.

(ii) Draw a phasor diagram for this operating point and use your diagram to determine the generator line-line excitation emf and load angle. [50%]

4 (a) Briefly explain the benefits of variable speed compared to fixed speed operation of wind turbines. With reference to speed control of induction generators using rotor resistance control, explain the underlying ideas of slip energy recovery. Give two reasons why slip energy recovery is preferred to rotor resistance control. [30%]

(b) A 3-phase star-connected 10-pole induction generator is mechanically coupled to a wind turbine which has an optimal rotational speed of 15 rpm when the wind speed is 8 ms^{-1}. At this wind speed the turbine produces an output torque of 320 kNm. The stator of the generator is connected directly to the 6.6 kV, 50 Hz grid. Slip energy recovery is used to implement variable speed operation. The generator has equivalent circuit parameters: $R_1 = 0.6\ \Omega$, $R_2' = 0.5\ \Omega$, $X_1 = 1.2\ \Omega$, $X_2' = 1.0\ \Omega$, R_0 and X_m are large enough to be ignored. Determine:

(i) The gearbox ratio required so that the injected rotor voltage is zero when the generator rotational speed is 15 rpm.

(ii) Find the values of the referred rotor injected voltage at wind speeds of 6 ms^{-1} and 12 ms^{-1} assuming variable speed operation at the optimum tip-speed ratio.

(iii) Find the real and reactive output power of the generator at the wind speed of 12 ms^{-1}. Assume that the turbine output torque varies with wind speed squared. [50%]

(c) From a power systems point of view explain why it is undesirable to have a generator which consumes a significant amount of reactive power. With the aid of a phasor diagram (no calculations necessary) show how phase control of the injected rotor voltage enables an induction generator to operate at unity power factor. [20%]

END OF PAPER

4B19 Renewable Electrical Power 2009 Short Answers

1. -

2. (b) (ii) At 300 rpm net output is 120 kW, at 750 rpm net output is 300 kW.

(iii) Line side converter rating is 100 kVA , machine side converter rating is 111 kVA.

(v) At 750 rpm: +25 Hz , 698 V. At 300 rpm: -20 Hz, 558 V. At 500 rpm: 0 Hz, 0 V.

3. (c) (i) 20 poles; 1273 kNm; 2.62 kA; 0.8 lagging.

(ii) $\delta=14.8^0$; 16.7 kV line – line.

4. (b) (i) 40 (ii) At 6 ms^{-1} $V_3' = 1.65$ kV line; At 12 ms^{-1} $V_3' = -3.3$ kV line

(iii) P = 1.1 MW; Q = -61.3 kVAr

Dr T J Flack

Dr R A McMahon

May 2009