PART IIB 2011  4B19
RENEWABLE ELECTRICAL
POWER

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## 4B19 2011 Crib

1 (a) (i) The British Isles have the highest wind speeds in Europe, especially on the western coast of Scotland and Ireland. The amount available on land could provide a substantial fraction of the UK's need for electricity, and more is available offshore. The target is around 20 GW of installed wind power by 2020.

The British Isles are also well favoured in terms of marine power, with the highest powers per unit length of wave front in Europe, again the Atlantic facing coast being particularly attractive.

(ii) On land there are concerns about the visual impact of wind turbines, their acoustic output and "industrialisation" of the landscape. More specifically there are concerns about the impact on birds. Offshore the objections centre on the effect on birds.

In the case of marine devices, the environmental impact can be considerable, especially in the cases of barrages and shoreline devices. At sea, the effect is on sea life. [10%]

(b) Key components are the tower, the nacelle, the blades, the hub, the yaw mechanism, the main bearing, gearbox if used, the generator and power conversion electronics if used. The control and supervisory system is also a key part.

(i) In a direct drive wind turbine the input shaft is directly coupled to the generator. The generator speed is say 10 to 20 rpm, with very high torque. This necessitates a large diameter machine which is heavy. All direct drive generators use power conversion.

With a gearbox the generator speed can be chosen so that a relatively light and cheap 4 pole or 6 pole generator can be used. This gives a gearbox ratio of say 1500:15 = 100:1 ratio. This is likely to be in three stages.

(ii) In full conversion, all the output power from the generator goes through AC-DC and DC-AC conversion to produce a fixed voltage fixed frequency output from the variable voltage, variable frequency generator output. The converter rating must be at least as great as the maximum generator output.

In the double feed arrangement, most of the power goes directly to the grid. A fraction, depending on the speed range but typically up to 1/3, goes through AC to AC conversion (via DC). This significantly reduces the rating of the converter, and hence its cost. [35%]

(c) Capacity factor = (Actual turbine output energy in a year)/(Maximum possible output energy in a year)

The denominator is the power rating times one year. The top line is the actual energy delivered.

A developer should look at the wind statistics for a site to ensure that there is enough wind. The blading of the turbine should be matched to the wind conditions. Finally turbine reliability should be considered. [15%]

(d) (i) There are many examples - these will be defined for the shoreline (Limpet), near shore or further offshore (Pelamis, Trident).

(ii) Devices are terminators, attenuators (Pelamis), point absorbers (buoy systems).

(iii) Power take-off can be via hydraulics, pneumatics, rotating generators or linear generators. All have or are being tried.

Marine renewable have been slow to develop for several reasons: technologies are still at an early stage; marine environment is hostile are two of them. [40%]

Examiner's comment:

This was a general question on wind power and marine renewables. Most candidates could describe at least the principal features of a wind turbine but some candidates were not clear, for example, about the important differences between direct drive and coupling via a gearbox. Again, in the marine generation part most candidates could recall ways of generating power from the sea but some were unclear about details. The relatively small number of good answers was a little disappointing.

2. (a) Consider wind passing a wind turbine of swept area A at wind speed v. Kinetic energy in the wind which passes in time T is $0.5mv^2$ and $m = \rho AvT$ where $\rho$ is the density of air. If all this energy is extracted in time T then the power is $0.5\rho AvTv^2/T = 0.5\ \rho Av^3$. It is impossible to extract all the energy, and the fraction that is extracted is the power coefficient, $C_p$. Thus:

$P=0.5C_p\ \rho Av^3$ [15%]

(b) Let the rated power of the system be $P_{max}$ at the wind speed of 13 $ms^{-1}$. The table below is filled in remembering that for wind speeds between cut-in and rated the turbine output is proportional to wind speed cubed.

| Wind speed (m/s) | Days | Hours | Power (MW) | Energy (MWhr) |
|---|---|---|---|---|
| 2 | 25 | 600 | 0 | 0 |
| 6 | 160 | 3840 | $0.0983P_{max}$ | $378P_{max}$ |
| 10 | 120 | 2880 | $0.455P_{max}$ | $1310P_{max}$ |
| 14 | 40 | 960 | $P_{max}$ | $960P_{max}$ |
| 18 | 16 | 384 | $P_{max}$ | $384P_{max}$ |
| 22 | 4 | 96 | 0 | 0 |

(i) Summing the energies and equating with the required energy of 8 GWhr = 8000 MWhr gives:

$3032P_{max} = 8000$ and so $P_{max} = 2.64$ MW [15%]

The turbine generates 2.64 MW with a power coefficient of 0.36 at the wind speed of 13 $ms^{-1}$. Using the equation derived in part (a) gives a swept area A of 5427 $m^2$. Equating this with $\pi R^2$ gives a blade radius R = 41.6 m and so the blade diameter is 83.2 m. [15%]

(ii) The tip-speed ratio is 9 and using $\lambda = \omega R/v$ gives $\omega = 1.30$ $rads^{-1}$ at $v = 6$ $ms^{-1}$and $\omega = 2.16$ $rads^{-1}$ at $v = 10$ $ms^{-1}$. [5%]

(c) (i) Synchronous speed $\omega_s = 2\pi f/p = 100\pi/6 = 52.4$ $rads^{-1}$. The optimum turbine speed at the wind speed of 6 $ms^{-1}$ is 1.30 $rads^{-1}$ so the required gearbox ratio is 52.4/1.30 = 40. [10%]

(ii) At $v = 10$ $ms^{-1}$ the slip $s = (52.4 - 86.4)/52.4 = -0.649$. For the no-load slip to be -0.649 the referred injected rotor voltage $V_3$ (phase voltage) is given by:

$V_3/s = 11\ kV/\sqrt{3}$ giving $V_3 = -4.12$ kV phase (= 7.14 kV line) [10%]

(iii) For $v = 10$ $ms^{-1}$ the turbine power is 1.2 MW and the induction generator speed is 86.4 $rads^{-1}$. Assuming no gearbox losses the generator torque is given by $P=T\omega$ giving T=13900 Nm. Using $T = 3(I_2'^2R_2' + V_3'I_2')/s\ \omega_s$

$-13900 = 3(0.6I_2'^2 - 4120I_2')/(-0.649 \times 52.4)$ giving $I_2' = -38.0$ A

The converter power is $3V_3\ I_2' = 470$ kW [20%]

iv) Generator losses $= 3I_2'^2R_2' + 3I_2'^2R_1 = 5.63$ kW

$P_{elec} = P_{mech} - P_{loss} = 1.2\times10^6 - 5.63\times10^3 = 1.194$ MW

Efficiency = 1.194/1.2 = 99.5% [10%]

## Q2 Examiner's comments:

There were many good attempts to this question, especially in the first two parts on the derivation of the theoretical power available from the wind, and basic sizing calculations of wind turbines. The third part of the question was more mixed: most candidates were able to calculate the gearbox ratio needed, some got the injected rotor voltage but very few were successful in determining the converter power and the generator output power, losses, input power and efficiency.

3. (a) Less environmental impact. More reasonable costs relative to expected output as civil works are much reduced. [10%]

(b) (i) Using the formula:

$10^6 = 0.5\times0.5\times10^3 A\times5.1^3$ and so $A = 30.15$ m$^2$ giving a diameter of 6.2 m (quite modest).

(ii) 10% of full output is 100 kW and again using the formula;

$10^5 = 0.5\times0.5\times10^3\times30.15\times v^3$

and solving for v gives 2.37 ms$^{-1}$.

(iii) At maximum output, the generator speed is maximum. Blade speed at the periphery is

$12\times5.1 = 61.2$ ms$^{-1}$. This gives $\omega = 19.74$ rads$^{-1}$ using $\lambda v = \omega R$ and so N = 186 rpm.

Ratio is 1250/186 = 6.72:1 (quite reasonable).

(iv) Minimum generator speed corresponds to v = 2.37 ms$^{-1}$ and assuming operation at optimum $\lambda$, the turbine speed must be kept proportional to the flow speed. Hence:

$N_{min} = 186\times2.37/5.1 = 86.4$ rpm. [40%]

(c) (i) Consider a half bridge and split DC voltage into $\pm V_{DC}/2$. Amplitude of AC output is $V_{DC}/2$ maximum and so rms value is $V_{DC}/(2\sqrt{2})$. With a modulation index m the rms phase voltage is $mV_{DC}/(2\sqrt{2})$ and so the line-line rms ac output voltage is $\sqrt{3}\, mV_{DC}/(2\sqrt{2})$.

(ii) Nominal grid voltage is 690 V but it can be 10% higher than this ie 759 V. Using the expression derived above with m = 0.95 gives $V_{DC} = 1305$ V.

(iii) Maximum generator volts from DC link is 759 V. This applies at 1250 rpm, corresponding to 67.5 Hz for a 6-pole machine assuming slip is small. Therefore, on a constant V/f basis, the machine should be wound for 607 V (0.8x759) at 50 Hz.
[50%]

## Q3 Examiner's Comments

Most candidates were able to obtain the range of generator speeds for the marine current turbine in the first part of the question. The second part concerned power conversion. Whilst most candidates were able to derive the relationship between the DC link voltage and AC output, very few candidates realized that the worst case was high grid voltage.

4 (a) As the sea level rises water becomes trapped behind a barrage. Thus, potential energy is acquired. When the sea level has fallen to close to its low tide level, the water behind the barrage is released via turbines coupled to electrical generators, thereby converting the potential energy to electrical power.

Basin area is A, tidal range is R, at high tide centre of gravity of water is at R/2 and so potential energy = $MgR/2 = \rho ARgR/2 = \rho gAR^2/2$. If this is converted to power in period T between high tides then the average power is energy/T = $\rho gAR^2/2T$. This is an upper limit - in reality there will be power losses etc. [15%]

(b) Tidal barrage schemes resemble low-head hydroelectric schemes. Propeller turbines are best suited to low head but large flow rate hydroelectric schemes, and so these are the type of turbines used in tidal barrage schemes. Since the water speed through the turbine blades is low, the rotational speed of the generators is correspondingly low and this favours the use of synchronous generators with a large number of pole-pairs. Thus, salient-pole synchronous generators are the generator technology of choice. [10%]

The specific speed of a turbine is an empirical expression enabling suitable system angular speeds to be determined for the turbine-generator combination. In the expression, n is the system speed in rpm, P is the power in kW and H is the head of water in m. [5%]

(c) (i) The total volume of water trapped is AR = $16\times160\times106\ \text{m}^3 = 2.56\times10^9\ \text{m}^3$

The time taken for this volume of water to drain out of the barrage is 6 hours = $6\times60\times60$ s = 21600 s.

The flow rate is then $2.56\times10^9/21600 = 118.5\times10^3\ \text{m}^3\text{s}^{-1}$. [15%]

(ii) The upper limit to the power available is given by

$P = \rho gAR^2/2T = 1000\times9.81\times16^2\times160\times10^6/(2\times12\times60\times60) = 4.65$ GW. 40% of this is extracted giving 1.86 GW as the average output power. [5%]

Total annual energy is $365\times24\times1.86 = 16.3$ TWhr. [5%]

(iii) Peak output power is when the scheme first starts generating and so the head of water is 16 m giving

$P_{max} = \eta\rho gHQ = 0.4\times1000\times9.81\times16\times118.5\times103 = 7.44$ GW [5%]

Capacity factor = Average power/Peak power = 1.86/7.44 = 0.25 [5%]

(d) (i) The average power when the scheme is generating is when the head of water H is 8 m, and is 7.44/2 GW. For 200 turbines, the power per turbine is 18.6 MW. Using the expression for specific speed leads to:

Q4 examiner's comments:

An unpopular question, and one which received many competent attempts, but no outstandingly good ones and no very poor ones. Virtually all candidates did well at the first two parts of the question, which were largely bookwork. The second two parts were more searching, requiring candidates to make assumptions to estimate the mean output power of the scheme, total annual energy, capacity factor, and then determine ratings for the generators used, and their rotational speeds and number of pole pairs. Very few candidates provided good answers to these parts, which explains the small spread of marks achieved.

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2. (b) (i) Rated power = 2.64 MW Diameter = 83.2 m (ii) 1.30 $\text{rads}^{-1}$ at v = 6 $\text{ms}^{-1}$ and 2.16 $\text{rads}^{-1}$ at v = 10 $\text{ms}^{-1}$. (c) (i) Ratio = 40 (ii) Referred injected rotor voltage = 7.14 kV (line) (iii) Converter power = 470 kW (iv) Losses = 5.63 kW; Output power = 1.2 MW; $\eta$ = 99.5%.

3. (b) (i) Diameter = 6.2 m (ii) v = 2.37 ms-1 (iii) Ratio = 6.72:1 (iv) Min speed = 84.4 rpm. (c) (ii) $V_{DC}$ = 1305 V (iii) V = 607 V.

4. (c) (i) Flow rate = 118500 $m^3s^{-1}$ (ii) Average power = 1.86 GW Total energy = 16.3 TWhr (iii) Peak power = 7.44 GW Capacity factor = 0.25 (d) (i) Speed range = 34.5 rpm – 98.6 rpm Pole number from 174 – 60 (ii) VA rating = 31 MVA.