2009 PART IIB 4B19 RENEWABLE ELECTRICAL POWER
Dr T J Flack and Dr RA McMahon

1 (a) The generation of electricity from biomass normally uses conventional steam plant with a turbine-driven alternator. The plant can be configured for combined heat and power if desired. There are many sources of fuel - straw, willow, wood in general, miscanthus grass. A second group of fuels includes wastes such as chipboard chippings, left over ready meals, old tyres etc.

The first group of fuels often compete for land area with food crops and even feedstocks for liquid biofuels - so the supply, ultimately limited by land area is further constrained. Whilst it may well be sensible to burn fuels in the second group, supply is obviously limited.

(ii) Shoreline devices - the limpet type in which air is forced though a Wells (air turbine) is a possible approach. Power conversion can generally be avoided as the generator can be a synchronous machine but variable speed generation could be advantageous. Tidal devices can be deployed along coastlines - the resource is modest compared to the offshore potential but it is relatively easy to exploit.

Environmental concern centres on the intrusive nature of the edifices on the shoreline (massive concrete structures). They are unsightly and there is loss of habitat.

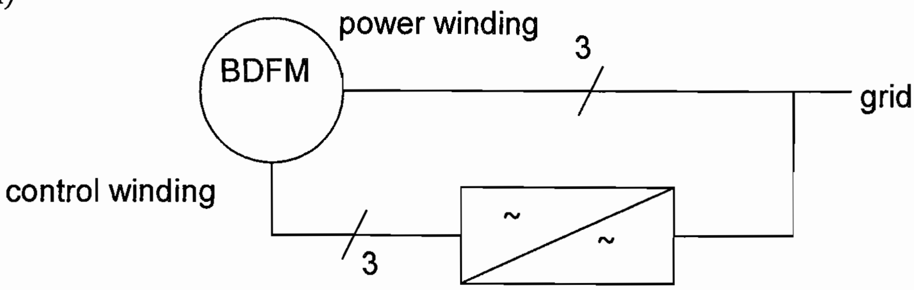
(b) (i) Tidal currents - a marine current turbine is perhaps the most obvious but hydroplane devices have been proposed. A turbine is similar to a wind turbine but with a smaller swept area, reflecting the greater power density with a tidal current. Variable speed generation is likely to be used - so the generator output will be fully converted, or partially converted if a doubly fed generator is employed. Power conversion will be involved if dc transmission to shore is adopted. There is only a limited number of good sites - Strongford Lough, Severn Estuary etc. Environmental concerns are presently limited to the effects on sea creatures hitting the blades.

(ii) Off shore waves - many devices have been proposed - such as the Pelamis, the Archimedes wave swing, various bouy based devices. One class of device uses linear generators, the output of which must be converted to ac, or dc, depending on final transmission method. As devices may be some way offshore, dc may be preferred, Another class of devices use hydraulic methods ultimately driving a fixed or variable speed generator with a hydraulic motor. Power conversion will be needed if variable speed generation is adopted. The earlier remarks about dc and ac transmission apply. The resource is extensive, in principle comparable with the UK's electricity consumption. However, there are many difficulties in realising the potential - devices are expensive, the marine environment is hostile, power transmission to shore is difficult and costly. Environmental concerns have not been widely voiced though there will be effects on sea life.

(c) Moving offshore presents difficulties of installation and subsequent maintenance, so reliability is critical. Power transmission to land is difficult - dc may have to be used with consequent power conversion costs, Power transmission infrastructure is vulnerable.

2. (a) The brushless doubly-fed machine's key benefit is the absence of brushes. Brushed generators ie doubly fed induction machines, need regular brush changes. Whilst this can be considered a nuisance, say in land-based wind turbines, itis highly unattractive in submerged marine systems.

(b) (i)



Key features in diagram are direct connection of power winding to the grid, and the connection of the control winding via a bi-directional converter giving a variable voltage, variable frequency feed.

(ii) Power on the control winding is give by $P_c = P_p(N - N_{nat})/N_{nat}$ where N_{nat} is the natural speed and N is the actual speed.

At 300 rpm $P_c = 200(300 - 500)/500 = -80$ kW.

So net output is 120 kW.

At 750 rpm $P_c = 200(750 - 500)/500 = +100$ kW. So net output is 300 kW.

(iii) The maximum power flow through the line side converter is 100 kW. There is no reactive power so a minimum rating of 100 kVA is needed - in practice a sizeable margin is advisable!

On the machine side there is reactive power so $S = P/\cos\varphi = 100k/0.9 = 111$ kVA.

Again this is the minimum rating.

(iv) Assuming a full bridge inverter the line voltage output V_L is

$V_L = \sqrt{3}V_{DC}m/(2\sqrt{2})$ m is the modulation index.

The output from any individual bridge, relative to the mid-point of the dc link is

$\hat{V}_{AO} = V_{DC}m/2$ The rms line voltage VAB is then

$\hat{V}_{AO} - \hat{V}_{BO} = \sqrt{3}V_{DC}m/(2\sqrt{2})$

(v) At 750 rpm, the control winding frequency is +25 Hz and this will be the highest voltage on a constant V/Hz basis.

$V_L = \sqrt{3}\times1200\times0.95/(2\sqrt{2}) = 698$ V

At 300 rpm, f = -20 Hz and so the voltage will be 20×698/25 = 558 V

At natural speed, $V_L = 0$ ie dc. However, as the machine windings have resistance, a finite voltage will need to be applied to keep the current at the correct value. This is so-called "voltage boost".

(c) The simplest way is to step up the voltage using a transformer say to 22 kV. However, ac transmission by cable over significant distances poses reactance issues so transmission by dc can be considered although this requires extra converters.

3. (a) Variable speed operation means that the tip-speed ratio of the turbine can be kept constant at the value that optimises the power coefficient. This means that the turbine always extracts the greatest possible power from the prevailing wind conditions. Fixed speed operation, whilst simpler to implement, means that the turbine speed will in general not give the optimum tip-speed ratio and so will not extract the greatest possible power.

Rotor resistance control of the torque-speed curve of an induction generator is simple to implement - it enables the peak torque to remain fixed, merely altering the slip, and hence speed at which the peak torque occurs. By considering the extra rotor resistance as causing a rotor voltage to appear at the slip-rings of slip frequency, the idea of slip energy recovery can be explained: instead of generating the voltage by external resistance it is generated using a four-quadrant power converter, which produces an ac voltage at slip frequency. Thus, instead of dissipating the power in an externally-connected resistor, power is either transferred to the generator, or extracted from the generator, and apart from the losses in the converter, this power is not wasted. Thus, the main advantage of slip energy recovery is that it is far more efficient than rotor resistance control. Furthermore, the converter may be controlled so that the induction generator operates at unity power factor, or even generates reactive power.

(b) (i) Synchronous speed of a 10 pole generator connected to 50 Hz grid is 60f/p = 60.50/5 = 600 rpm. Turbine rotates at 15 rpm giving a gearbox ratio of 600:15 = 40.

The generator torque will be reduced by this factor ie T = 320/40 = 8 kNm.

(ii) Simplified torque equation is valid for generator on the steep part of the torque speed curve:

$\omega_s = 2\pi f/p = 2\pi.50/5 = 62.8$ rads^{-1}

$T = 3V^2 s/(\omega_s R_2')$ so $8000 = 3\times(6600/\sqrt{3})^2 s/(62.8\times 0.5)$ giving s = 0.00577 or 0.577%

(ii) Assuming that the torque speed curve is very steep then the referred rotor injected voltage can be estimated because the no-load slip and actual slip will be virtually the same. The no-load slip is the slip that results in zero input current ie

$V_3'/s_{nl} = V$ so $V_3' = s_{nl}V$ For wind speed v = 6 ms^{-1} $\omega_r = 6\omega_s/8$ and so $s_{nl} = (\omega_s - 6\omega_s/8)/\omega_s = 0.25$. Therefore $V_3' = 0.25 \times 6.6 = 1.65$ kV line.

For v = 12 ms^{-1} $\omega_r = 12\omega_s/8$ and = $(\omega_s - 12\omega_s/8)/\omega_s$ = -0.5 so V_3' = -0.5 × 6.6 = -3.3 kV line.

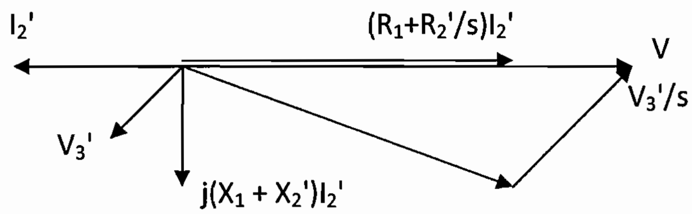
(iii) $T = 3(I_2'^2R_2' + V_3'I_2')/s\,\omega_s$ For v = 12 ms^{-1} T = -8 × (12/8)2 = -18 kNm (since turbine torque varies with wind speed squared).

$-18000 = 3(0.5I_2'^2 - 3300I_2'/\sqrt{3})/(-0.5 \times 62.8)$ giving I_2' = -96.4 A

$P_{elec} = P_{mech} - P_{loss} = 18000\times62.8 - 3\times96.4^2\times(0.6 + 0.5) = 1.1$ MW

$Q_{out} = -3I_2'^2(X_1 + X_2') = 3\times96.4^2\times(1.2 + 1) = -61.3$ kVAr

(c) The induction generator absorbs substantial reactive power from the grid. This means that unless there is a means of injecting reactive power at the point where the generator is connected it will cause the voltage to sag. Power factor correction capacitors could be employed to solve this problem. However, if slip energy recovery is used to enable variable speed operation, a quadrature component of V_3' may be injected to enable the generator to operate at unity power factor, as shown below.



4. (a) Potential energy = MgH When water is released rate at which energy is extracted is

$P = d(MgH)/dt = gHd(\rho V)/dt = \rho gHQ$. However, losses mean that not all of this power is extracted, and this is accounted for by the efficiency term η giving $P = \eta\rho gHQ$ in which ρ is the density of water, g is the acceleration due to gravity, H is the head of water and Q is the volumetric flow rate.

Hydroelectric schemes are either high head (H > 100 m), low head (H < 10 m) or medium head (10 m < H < 100 m).

Low head - propeller turbine

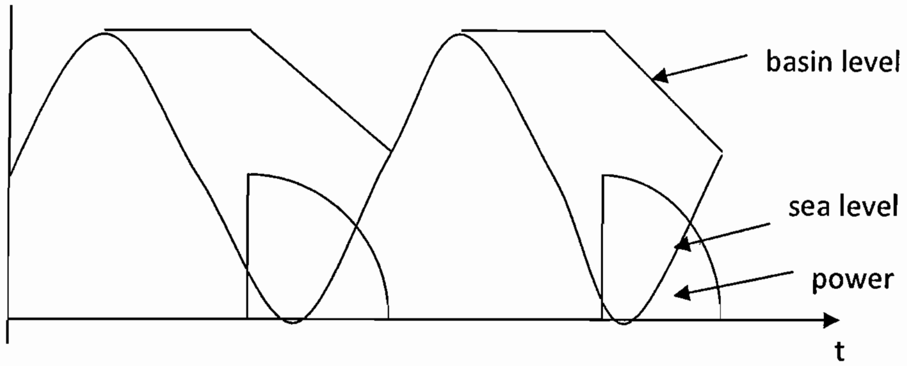
Medium head - Francis turbine

High head - impulse turbine.

Pumped storage schemes utilise off-peak electricity to pump water from a low potential to a high potential, and then release the energy at times of sudden demand for electrical power.

(b) Tidal barrage schemes utilise the tidal range by trapping water at high tide behind a barrage and then releasing it at low tide thereby extracting its potential energy typically by using a propeller turbine. Thus they are very similar to low head hydroelectricity.

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



Graph shows how these schemes produce bursts of large amounts of power but for relatively short periods, say 6 hours. By increasing the diversity of supply eg by connecting in a similar scheme which has high tides at opposite times this effect is reduced. By strengthening the grid at the location of the scheme the power can be exported to where it is needed.

(c) (i) Synchronous speed in rpm is 60f/p where f is frequency, p is pole pairs. With f = 50 Hz this gives $300 = 60\times50/p$ and so p = 10 and number of poles is 20.

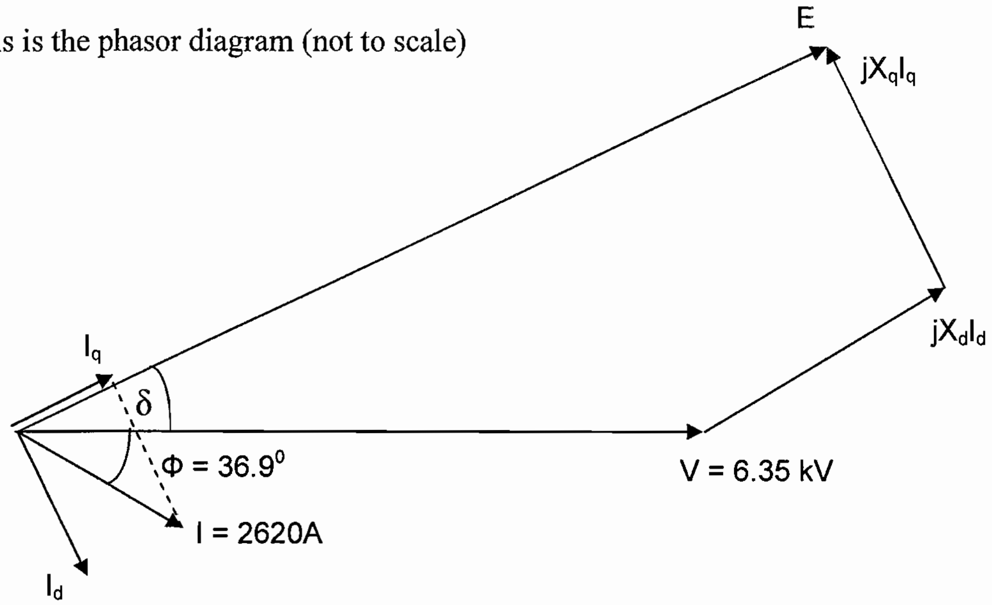
$40\times10^6 = T\omega_s$ and so T = 1273 kNm.

(ii) P = 40 MW, Q = 30 MVAr $S = (P^2+Q^2)^{1/2} = 50$ MVA

$\cos\varphi = P/S = 40/50 = 0.8$ lagging.

$50\times10^6 = \sqrt{3}V_lI_l$ and with $V_l = 11$ kV this gives I = 2.62 kA.

This is the phasor diagram (not to scale)



$I_q = I\cos(\varphi+\delta) = I(\cos\varphi\cos\delta - \sin\varphi\sin\delta)$

$V\sin\delta = X_q I_q = X_q I(\cos\varphi\cos\delta - \sin\varphi\sin\delta)$

Divide through by cosδ and make tanδ the subject of the equation:

$\tan\delta = X_q I\cos\varphi/(V+X_q I\sin\varphi) = (1\times2620\times0.8)/(6350+1\times2620\times0.6) = 0.265$ giving $\delta=14.8^0$.

$I_d = I\sin(\varphi+\delta) = 2057$ A

$E = V\cos\delta + X_d I_d = 6350\times\cos(14.8^0) + 1.75\times2057 = 9739$ V = 16.7 kV line – line.

Dr T J Flack

Dr R A McMahon

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