1(a) The principal interest is related to reducing emissions of CO_2 in response to concerns about climate change. Renewable sources are either "low carbon" (wind, wave, solar) or carbon neutral (biomass). Other reasons relate to energy security, generation in remote locations, and for some sources, e.g. conventional hydropower, low cost.

(b) Wind power: (i) This resource is widely distributed but some areas such as the British Isles, especially western coasts, are particularly favoured. The resource has a relatively low energy density so high power wind turbines are large. Output depends on wind conditions and actual output may be ~25% of potential maximum output.

(ii) Wind power is relatively mature – many turbines are in operation. The three blade, horizontal axis machine is ~~with~~ the standard configuration; in most cases a step up gearbox is used in conjunction with a high speed generator.

~~The environmental impact is~~

(i) This resource is obviously restricted to coastal regions. North-western Europe is favoured; the British Isles especially so. The resource has a relatively high energy density and, although subject to fluctuations, is less variable than wind.

(ii) The technology is immature. Many

prototype systems have been described and some have been tested but the marine environment is harsh. There is no commercial production of power.

(2) Burning biomass.

i) Sources of biomass for firing essentially otherwise conventional power stations include crops such as willow, surplus materials such as straw or wood chips and waste, e.g. chicken litter or animal carcasses. However, the sources are often limited in availability. Growing crops such as willow could be extended but would be in competition with other land uses, e.g. for growing food.

(ii) The technology is mature, at least on the generation side. Depending on the fuel, special care may be needed to limit emissions of certain pollutants.

(c) A point absorber is a device, such as a float, whose dimensions are small compared to the wavelength of the sea waves. They move with the wave. A terminator has its principal axis parallel to the incident wave front. Salter's duck is an example. An attenuator has its long axis perpendicular to the wave front. Pelamis (the sea snake) is an example.

(d) The linear generator solution involves coupling the movement of the buoy directly to the generator. This arrangement is very simple mechanically but the output of the linear generator is variable voltage, variable frequency ac which has to be converted, via ac, to a fixed voltage and frequency output for grid feed. Also, velocities are low in linear generators and the resistive drop in the coils can be large relative to the generated voltage

The solution with a hydraulic allows the use of a conventional fixed speed generator but involves a relatively complex hydraulic system, which may include an accumulator to even up the power output. Hydraulic motors are not particulaly efficient, especcially at part load. There are issues of reliability and the leakage of hydraulic fluid. The generator can feed ac directly to the grid.

2(a) The main reason is that the power converter need only be a fraction of the total power output. For example if an induction generator is rated at 100 kW and the range of speeds is nominal ± 33%, the converter need, in principle, only handle 33⅓ kW of slip power. This represents a significant saving relative to converting the whole of a generator's output.

(b) (i) The maximum power is at 1000 rpm.

The fractional speed deviation is ~~1000~~ 250/750 = 1/

So total output = $P_{\text{power wdg}} + P_{\text{control wdg}}$

$$100\,\text{kW} = P_p + \tfrac{1}{3} P_p$$

$$\therefore\ P_p = 75\ \text{kW} \ \& \ P_c = 25\ \text{kW}.$$

Control is ~~Both~~ ~~are~~ at 0.75 pF so ratings in VA are 75 ~~100~~ kVA & 33⅓ kVA respectively.

(ii) The minimum rating of the machine side converter is $33\frac{1}{3}$ kVA. In practice it would be made larger to give some headroom and to accommodate machine non-idealities. The range of frequencies is obtained from:

$$N = 60 \cdot \frac{f_p + f_c}{p_1 + p_2}$$

which gives $+\ 50/3$ Hz (1000 rpm)

and $-\ 50/5$ Hz ~~50Hz~~ (600 rpm)

That is $+\ 16\frac{2}{3}$ Hz, $-\ 10$ Hz.

14:10

(iii) The line side converter has to process 25 kW. The VArs for the machine side are dealt with by the machine side converter. ~~However the grid side converter needs to supply the VArs associated~~ ~~with~~ the power winding ~~supplying 100kW.~~ ~~and~~

The VA rating of the converter is then

~~$S = \sqrt{([25k]^2 + [10k]^2)}$~~ =

~~$\approx$ 26.9 kVA~~. 25 KVA

(iv) The output from one leg of the inverter can be written as $M \cdot \frac{V_{DC}}{2\sqrt{2}}$ (rms). The maximum amplitude is $V_{DC}/2$ as the peak to peak cannot exceed V_{DC}.

Three voltages are produced, $V_{AO} = \frac{mV_{DC}}{2\sqrt{2}}$ with $V_{BO} = \frac{V_{DC}}{2\sqrt{2}} \cdot m \cdot \angle -120$ and

$$V_{CO} = \frac{V_{DC}}{2\sqrt{2}} m \angle -240.$$

The line voltages is obtained by taking the difference, eg.

$$V_{AB} = \frac{V_{DC}}{2\sqrt{2}} \cdot m \angle 0 - \frac{V_{DC}}{2\sqrt{2}} m \cdot \angle -120$$

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

(v) dc link must be such that V_{AB} out is $\geq$ V_{line} on the grid. Maximum output is when $m = 1$.

$$690 = \frac{\sqrt{3}\, V_{DC}}{2\sqrt{2}}$$

$$V_{DC} = 1127\,V$$

(vi) At 600 rpm, $f = -10\,Hz$. With a V/f of 20, this is 200 V phase. Line volts is $200\sqrt{3} = 346\,V$.

m is then ~~690 ← ma~~

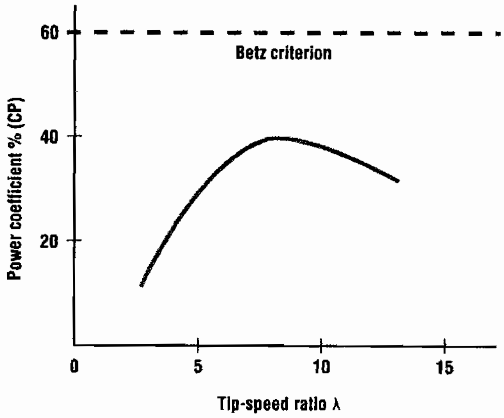
$$\frac{346 \leftarrow \text{desired}}{690 \leftarrow \text{max poss}} = 0.50$$

At 1000 rpm
$M = \frac{333\sqrt{3}}{690} = 0.84$

(c) IGBTs are available in suitable ratings - 100s A / few kV - and in convenient modules. Gate drive is relatively straightforward (MOS input requires voltage drive) but charging i/p capacitance is an issue. On state losses are moderate, as are switching losses at reasonable switching frequencies.

Module 4B19 2008 Crib

3 (a) The power coefficient, C_p, is the fraction of the available power in the wind that the wind turbine is physically able to extract. It has a maximum theoretical value of about 0.6, and modern wind turbines have power coefficients of the order of 0.4. Tip-speed ratio, λ, is the ratio of the speed that the tip of a turbine blade moves at to the wind speed. A typical sketch of C_p vs λ is shown below.



It shows that there is an optimum tip-speed ratio for which C_p is a maximum. Thus it is advantageous to maintain λ at this optimum value, and since $\lambda = \omega R/v$, constant λ implies that the turbine rotational speed must be kept in proportion to the wind speed. Thus variable speed operation is better at extracting maximum power from the wind.

(b) 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 ρ 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:

$$P = 0.5C_p\,\rho Av^3$$

(c) (i) Using the power equation and putting in the numbers:

$1.5\times10^6 = 0.5\times0.37\times1.23\times A\times12^3$ from which A may be found as 3815 m^2. Equating swept area with $\pi d^2/4$ gives d = 69.7 m.

(ii) Using $\lambda = \omega R/v$ and putting in the numbers:

$9 = \omega\times34.8/12$ gives $\omega = 3.10$ rads^{-1} .

$P = T\omega = T\times3.1 = 1.5\times10^6$ gives T = 484 kNm

(d) The induction generator needs to operate on the steep part of its torque-speed curve such that the slip is negative. Thus its speed will be just greater than the synchronous speed of a 6 pole 50 Hz induction generator which is $2\pi f/p = 2\pi\times50/3 = 104.7$ rads^{-1}. At a wind speed of 12 ms^{-1} the turbine rotates at 3.1 rads^{-1}. Denoting the gearbox ratio n_g gives:

$n_g\times3.1 \geq 104.7$ giving $n_g = 34$.

At rated wind speed the turbine output power is 1.5 MW, and assuming no power losses in the transmission (eg gearbox losses) 1.5 MW is also the input power to the induction generator.

Assuming operation on the steep part of the torque-speed curve means that the rotational speed of the generator is very close to its synchronous speed of 104.7 rads-1. Thus the generator torque is given by

$T\times 104.7 = 1.5\times 10^6$ giving T = 14.3 kNm. The Electrical data book torque expression may be simplified for operation on the steep part of the torque speed curve by approximating the generator impedance as R_2'/s, giving

$$T = \frac{3sV^2}{\omega_s R'_2}$$

in which V is the phase voltage of 6.6 kV/√3 = 3.81 kV (star-connected). Rearranging and putting in the numbers gives the slip as -0.012. At this slip the generator phase current may be found as:

$$I'_2 = \frac{V}{\sqrt{(R_1 + R'_2/s)^2 + (X_1 + X'_2)^2}} = \frac{3810}{\sqrt{(0.4 + 0.35/(-0.012))^2 + 1.1^2}} = 132\,A$$

The generator power loss is $3\times 132^2\times(0.4 + 0.35) = 39.4$ kW and so its output power is 1.5 MW – 39.4 kW = 1.46 MW. The generator consumes reactive power of $3\times 132^2\times(0.6 + 0.5) = 57.5$ kVAr.

4 (a) (i) One of the main problems of renewable electrical energy sources is that their power outputs vary widely and sometimes unpredictably. This is especially so in the case of wind power. Furthermore, the times of peak output may not be well-matched to times of peak demand. Diversity of supply means that by connecting many such sources into a large interconnected grid, the variability of the power output of the sources is 'smoothed out'. This helps to ensure that supply and demand are better matched.

(ii) Even with maximum integration of the power supply network, above a certain threshold of energy being sourced from renewable there will be periods of time when total supply and demand are not well matched. Energy storage helps overcome this problem by storing excess energy when supply exceeds demand, and the recovering that energy when demand exceeds supply. Pumped storage schemes are one example of how excess electrical energy can be 'stored' in the potential energy of water, to be released when needed. Other examples are batteries (chemical energy), compressed air energy storage, flywheel storage, hydrogen.

(b) The phase current is:

$I = (V_1 - V_2)/jX = (|V_1|(\cos\delta + j\sin\delta) - |V_2|)/jX = (|V_1|(-j\cos\delta + \sin\delta) + j|V_2|)/X$

$S_1 = 3V_1I^* = 3|V_1|e^{j\delta}I^* = 3|V_1|(\cos\delta + j\sin\delta)(|V_1|\sin\delta - j(|V_2| - |V_1|\cos\delta))/X$

$S_2 = 3V_2I^* = 3|V_2|I^* = 3|V_2|(|V_1|\sin\delta - j(|V_2| - |V_1|\cos\delta))/X$

Multiplying out:

$S_1 = P_1 + jQ_1 = 3((|V_1||V_2|\sin\delta)/X + j(|V_1|^2 - |V_1||V_2|\cos\delta)/X)$

$S_2 = P_2 + jQ_2 = 3((|V_1||V_2|\sin\delta)/X - j(|V_2|^2 - |V_1||V_2|\cos\delta)/X)$

P_1 and P_2 are the same – this is expected since the line is lossless. Q_2 and Q_1 differ by the amount equal to the reactive power consumed by the line. The average value of Q_1 and Q_2 is $(Q_1+Q_2)/2 = 3(|V_2|^2-|V_1|^2)/2X)$. Thus the average complex power transmitted along the line is

$S = 3(|V_1||V_2|\sin\delta)/X + j3(|V_2|^2-|V_1|^2)/2X$

(c) (i) $P = \sqrt{3}V_2I\cos\varphi$ and $\cos\varphi = 1$, $V_2 = 11$ kV and $P = 10$ MW. Solving for I gives 525 A.

(ii) Line resistance << line reactance so the lossless line equation derived in (b) may be used. Average Q is $3I^2X/2$ (factor of 2 because $Q = 0$ at load, $Q = 3I^2X$ at wind farm to supply line reactive power and the average is therefore $3I^2X/2$).

$Q_{ave} = 3\times525^2\times2/2 = 827$ kVAr $= 3(V_1^2 - V_2^2)/2X$. Putting in the numbers and solving for V_1 gives $V_1 = 11.15$ kV.

$P = 10$ MW $= 3V_1V_2\sin\delta/X$. Putting in the numbers and solving for δ gives 9.4^0.

(iii) Line power loss is $3I^2R = 3\times525^2\times0.4 = 331$ kW.

(d) Increasing transmission voltage to 33 kV means that for the same power transmitted the current will be reduced to one third of its original value. Since line power loss scales with I^2, the new power loss will be one ninth of the original loss ie 36.8 kW.

(e) If the capital cost of the upgrade is known, as well as the real interest rate and the borrowing period for financing the upgrade then the annual repayment based to year 0 may be found using annuitisation tables.

The benefit of the upgrade is that for a given output from the wind farm, following the transmission upgrade the power loss is far less and so there is more electrical power available to sell to customers. Knowing the typical wind variation at the site enables the annual saving in electrical energy to be calculated, and knowing the cost per kWhr of electricity would mean that the annual saving following the upgrade could be found. Providing this income exceeds the annual borrowing cost of financing the upgrade then the upgrade will pay in the long run. The greater the extra revenue the shorter the payback period.