PART IIB 2010

4B19 Renewable Electrical Power 2010 Crib **Dr T J Flack**

1. (a) For the wind speeds of 2 ms-1 and 22 ms-1 no power is produced since these speeds are below cut-in and above stall, respectively. For the 14 ms^{-1} and 18 ms^{-1} wind speeds the output power is capped at the rated power of 1.6 MW. For all other wind speeds the power is scaled according to the wind speed cubed eg at 6 ms^{-1} wind speed the output power is:

$(6/12)^3 \times 1.6 = 1.6/8 = 0.2$ MW = 200 kW.

By determining the number of hours for each wind speed, and then multiplying the output power in MW by this figure the total energy produced in one year may be found:

Wind speed (ms^{-1})	Days	Hours	Power(MW)	Energy (MWhr)
6	170	4080	0.2	816
10	110	2640	0.926	2445
14	35	840	1.6	1344
18	15	360	1.6	576

giving a total annual energy output of 5181 MWhr.
Capacity factor = $5181/(365 \times 24 \times 1.6) = 0.370$

(b) Synchronous generator: Well-known technology. Can generate or absorb reactive power. But in a variable speed system the output frequency goes up and down with the speed of the turbine, hence the whole of the output volt-amps must be processed to match the grid voltage and frequency. Can avoid use of a gearbox, but this does require a very large diameter generator.

Doubly-fed induction generator (DFIG): Needs only slip-frequency power converter, connected to wound rotor via slip-rings. Typically the converter has only 25% - 30% of the system total volt-amp rating. With slip-energy recovery the system is very efficient, and can generate/absorb reactive power as needed. Wound rotor induction generators are more expensive and less reliable than their cage rotor counterparts. Slip-rings are a maintenance issue.

(c) 2.5 MW at 14 ms^{-1} produces (12/14)3×2.5 MW = 1.57 MW and so this is essentially the same turbine but with a larger generator, blade and power train designed to handle more torque. Same method as first part of (a) used to find energy produced:

Wind speed (ms^{-1})	Days	Hours	Power(MW)	Energy (MWhr)
6	170	4080	0.196	800
10	110	2640	0.911	2405
14	35	840	2.5	2100
18	15	360	2.5	900

giving a total annual energy output of 6205 MWhr.
Capacity factor = 6205/(365×24×2.5) = 0.283

(d) For proposal (a) 1.6 MW = 1600 kW and so £1.6M must be borrowed.
The real discount rate is 8% - 3% = 5% and from the annuitisation table it is seen that discounted to present this costs £71 per £1000 borrowed (5% rate, 25 year period) giving present annual repayments of £113.6k.

Assume that the annual maintenance costs remain fixed in real terms at 3% of £1.6M=£48k giving total annual costs of £161.6k. Therefore the present cost per kWhr of the electricity produced is £161.6k/5181000 = 3.1p/kWhr.

For proposal (b) 2.5 MW = 2500 kW and so £2.5M must be borrowed.
Thus the present annual repayment is £71×2500 = £177.5k, maintenance costs are 3% of £2.5M = £75k giving a total annual £252.5k giving a cost per kWhr of £252.5k/6205000 = 4.1p/kWhr.

Clearly proposal (b) is substantially less attractive than proposal (a). Despite being able to produce more energy, the far worse capacity factor means that the extra borrowing to achieve the 2.5MW cannot be justified, since the higher winds needed to produce this power don't occur frequently enough.

Assessor's comments:

A very popular question attempted by all candidates. Most candidates did well at determining the total annual energy output of the two proposed turbines. The discussion of the merits of the two technologies was less well answered. The economic comparison was done well by a substantial number of candidates, but a good number also demonstrated that they hadn't grasped the underlying ideas.

2 (a) The best locations for renewable are often remote from load centres. To deal with this the transmission and distribution systems can be upgraded to connect such locations more robustly into the grid.

The output power from renewable energy sources varies with time of day and seasonally, depending on the prevailing weather conditions. Availability of power is not necessarily well-matched to demand. Solutions: increased interconnection of the grid (diversity of supply); energy storage such as pumped storage schemes, batteries.

Real power is controlled by varying the load angle of the generators with respect to the load bus angle. In practice this equates to varying the generated power in such a way to keep the grid frequency fixed. Reactive power is controlled by varying the magnitude of the voltage at the generator bus with respect to the load bus. In practice this equates to varying the excitation emfs of the generators.

(b) With a 100 MVA base the pu reactances of the step-up and step-down transformers become, respectively:

$X_{T1} = 100\times0.25/200 = 0.125$ pu and $X_{T2} = 100\times0.3/300 = 0.1$ pu

The base impedance for the transmission line is V_b^2/VA_b ie $275^2/100 = 756\ \Omega$ giving a pu reactance of $1\times200/756 = 0.264$ pu. Thus, the total pu series reactance impedance is j0.489.

(i) Working in the pu system,$P_L=0.8$, $Q_L=0.2$, $S_L=(0.8^2+0.2^2)^{1/2} = 0.824 = VI$ giving the per-unit load current as 0.824 since $V = 1$ pu at the load bus. Using conservation of P and Q

$P_S = P_L = 0.8$ pu and $Q_S = Q_L+I^2X = 0.2 + 0.824^2\times0.489 = 0.532$ pu and so $S_S=(P_S^2+Q_S^2)^{1/2}$ giving $S_S=0.961$ pu so $V_S = 0.961/0.824 = 1.166$ pu $= 12.83$ kV

Using $P=V_SV_L\sin\delta/X = 1\times1.166\sin\delta/0.489 = 0.8$ gives $\delta=19.6^0$

(ii) Solution carried out in exactly the same way as (i) except now $Q_L = -0.2$ pu giving $Q_S=0.132$ pu, and so $S_S = 0.811$ pu giving $V_S = 0.984$ pu $= 10.82$ kV

Load angle found by same method as in (i) and is 23.4^0.

(c) FACTS stands for flexible ac transmission systems and these devices facilitate the control of the flow of real and reactive power in electrical power systems.

It is assumed that the shunt-connected FACTS devices ensure that the voltage at the wind farm bus remains within 10% of its nominal value of 11 kV, whereas the voltage at the load bus is known to be 33 kV ie 1 pu. The problem with the increased power from the wind farm is that an excessively large load angle is needed to transmit the power at the given transmission voltage, and so the solution using a FACTS device is three-phase series-connected capacitance in order to bring down the line impedance. The pu real power to be transmitted is 1.6 and the maximum load angle is 40^0, and in the worst case V_S=0.9 pu. Therefore the total reactance between source and load is given by:

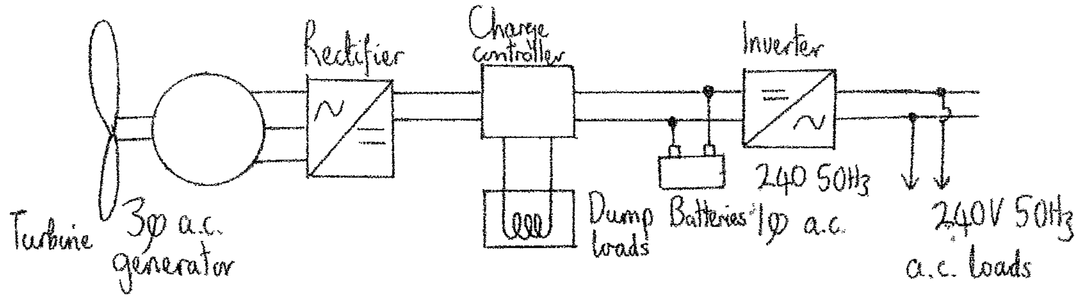
$1.6 = (0.9\times1\times\sin40^0)/X$ so X=0.362 pu. At present it is 0.489 pu and so the series-connected capacitances must remove 0.127 pu = 96Ω. Therefore the per-phase series capacitance needed is given by $96 = 1/\omega C = 1/(2\pi\times50C)$ giving $C = 33\mu F$.

(d) Another possibility is to increase the transmission link voltage up to say 400 kV by replacing the transformers and upgrading the cable insulation. For a given maximum load angle this would increase the power transmission capability by $(400/275)^2 = 2.1$. An advantage of this approach is that for the same power being transmitted the current is lower by the factor (275/400) and the power losses are proportional to I^2 so they would be reduced to 0.473 of the original power losses.

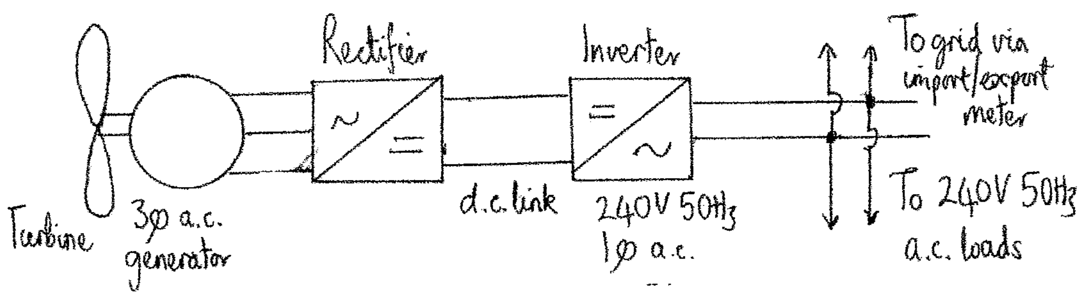
Assessor's comments:

An unpopular question. Those who attempted this question showed a good understanding of the problems of integrating more renewable energy sources into the existing grid infrastructure. Only a few succeeded at quantifying the magnitude and angle needed for the voltage at the wind farm to transfer a given amount of real and reactive. The principles of FACTS devices were well understood, and many candidates realized that increasing the transmission voltage as a means of transmitting more power had merits as an alternative to using a series FACTS device.

3 (a)



Off-grid system. The **turbine-generator** combination extract energy from the wind and convert it into electrical energy. The output from the generator will be variable frequency, variable amplitude 3 phase ac and so this needs to be converted into a useable form. The **rectifier** is the first step in this process. The output from the rectifier feeds a **charge controller** which charges **batteries** used to store surplus electrical power. If the batteries become fully charged then surplus power must be diverted to **dump loads** (often water heaters). Finally the **inverter** converts dc into single phase 240V, 50 Hz ac used for standard domestic loads.



On-grid system: Same as off-grid system except that there is no issue of dealing with excess power – the **inverter** is a grid-tie inverter, capable of exporting power to the grid when excess power is available and importing it from the grid when demand exceeds supply from the wind turbine. An **import/export electricity meter** is also needed to measure net consumption of energy.

(b) Since tip-speed ratio is given by $\lambda=\omega_m R/v$ inserting figures gives $10=\omega_m\times 1/v$ so $\omega_m=10v$. Thus lower and upper angular speeds are 50 rads^{-1} and 150 rads^{-1} respectively.

$E=k_e\omega_m$ where k_e is the emf constant, giving line-line rms output voltages of $1.2\times 50=60$V and $1.2\times 150=180$V at the lower and upper wind speeds, respectively.

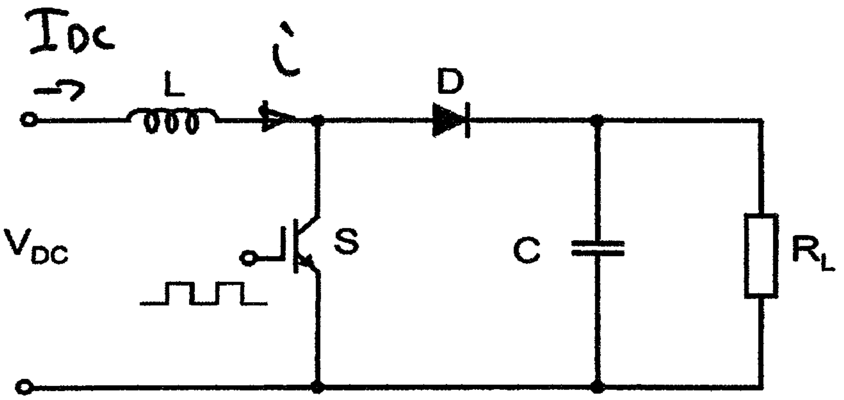
Frequency is given by $p\omega_m/2\pi$ where p is the number of pole-pairs of the generator, 4. This gives 31.8 Hz and 95.5 Hz at the lower and upper wind speeds, respectively.

From $P=0.5C_p\rho Av^3$ with $\rho=1.23\ \mathrm{kgm^{-3}}$, $A=\pi R^2=\pi\ \mathrm{m}^2$ and $C_p=0.3$ the output power ignoring power losses in the system is 72.5 W at $v=5\ \mathrm{ms^{-1}}$ and 1.96 kW at $v=15\ \mathrm{ms^{-1}}$.

(c) $V_{DC}=1.35V_L$ and so at $v=5\ \mathrm{ms^{-1}}$ V_L is 60V giving 81V. This expression ignores voltage drops owing to the inductance of the PMG and the diodes in the rectifier. Ignoring power losses the dc link current I_D is given by $P=V_{DC}I_D$ so $I_D=72.5/169 = 0.895$ A.

At $v=15\mathrm{ms^{-1}}$ $V_{DC}=1.35\times180=243$V and so $I_D=1960/506=8.06$A.

(d)



IGBT is on for time ρT and off for $(1-\rho)T$ where T is the switching period.
With IGBT ON current builds up in L according to $V_{DC}=Ldi/dt$. Integrating both sides of this and letting I vary between I_1 (minimum) and I_2 (maximum) gives $I_2-I_1=V_{DC}\rho T/L$ (1).

With IGBT OFF inductor current discharges into load, whose time constant is large and so the load voltage is sensibly constant at V0. Therefore $V_{DC}-V_0=Ldi/dt$ and integrating gives

$I_1-I_2=(V_{DC}-V_0)(1-\rho)T$ (2). Adding (1) and (2) and rearranging gives $V_0=V_{DC}/(1-\rho)$.

A single phase full bridge converter will produce a maximum ac output voltage of $2V_{DC}$ and therefore a maximum rms ac output voltage of $\sqrt{2}V_{DC}$ and so for a 240V output V_{DC} must be at least $240/\sqrt{2}=170$ V. At the lower wind speed $V_{DC}=81$V and so one possibility it to choose $m_A=1$ for the inverter and $81/(1-\rho)=170$ giving $\rho=0.523$.

At the upper wind speed $V_{DC}=243$V so no boost action is required ie $\rho=0$ and so the input DC voltage to the inverter is 243V, and so the modulation index required is $170/243 = 0.70$.

Assessor's comments:

A popular question in which most candidates showed that they understood the system components required for on-grid and off-grid small wind installations. They were also able to quantify the speed, output voltage, frequency and output power of the permanent magnet generator. Most candidates made a good attempt at quantifying the dc link voltage and current, but very few were successful on the final part in which they needed to specify the power electronic converter parameters in order to achieve a fixed 240V, 50Hz ac output at all wind speeds.

4 (a) Wave power offers a substantial resource, estimated at 25% of the UK's electrical power demand being economically recoverable. It is also relatively predictable compared to wind power. Another motivating factor is the need to reduce dependence on fossil fuels owing to the need to reduce greenhouse gas emissions.

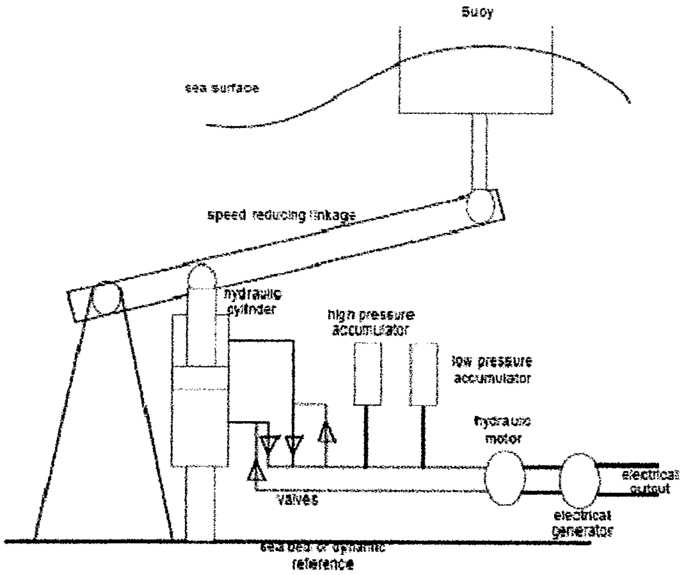
Challenges: Very hostile environment; immature technology, no clear preferred solution so harder to attract investment; cost of generation when compared to alternative forms; power take-off ie getting power from device to land and thence to load centres.

A point absorber moves with the incident wave producing an up and down reciprocating motion. They are small compared to the wavelength of the wave. An example is the IPS buoy.

A terminator has its principal axis parallel to the incident wavefront. An example is Salter's duck.

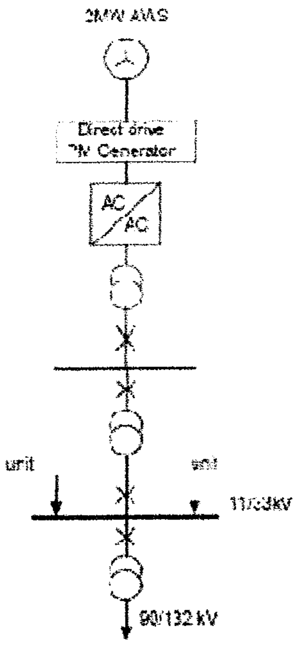
An absorber has its principal axis normal to the incident wavefront. An example is Pelamis.

(b) (i)



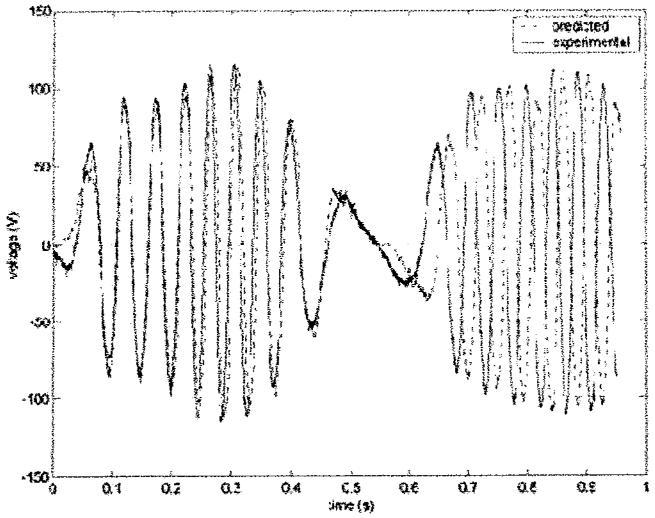
An advantage of this method of power take-off is that the power flow is smoothed out by the hydraulics and can be used to drive an efficient high-speed generator such as a DFIG, which can be directly connected to the 11 kV grid. A disadvantage is the complexity and hence cost, and also reliability issues owing to the complexity.

(ii)



(Courtesy of Markus Mueller)

Power take-off via a hybrid vernier direct drive generator has the advantage of simplicity, avoiding a complex hydraulic system. A disadvantage is the need to convert all of the output power to dc before converting back to ac, owing to its variable amplitude, variable frequency nature, sketched below.



(c) The equation gives the theoretical maximum power that can be extracted from waves of a given height H and period T per meter length of wavefront. Putting in the numbers gives:

(i) $P=(10000\times1030\times9.81^2/32\pi)\times TH^2=9.86\times10^6TH^2$. For $H=1$ m, $T=6$s this gives 59.2 MW and for $H=5$ m, $T=12$s it gives 2958 MW.

(ii) For devices spaced at 4 m intervals there will be 10000/4 = 2500 such devices. Assuming that they are rated for the maximum power available of 2958 MW then each vernier hybrid machine has a 2958/2500 = 1.2 MW rating.

(iii) The height H means the trough to crest height of the wave, and so assuming that the buoy moves up and down with the instantaneous amplitude of the wave then its position, $y(t)$, can be written:

$y(t)=(H/2)\sin(\omega t)$ and so its velocity is $dy/dt=\omega(H/2)\cos(\omega t)$ and so peak velocity is $2\pi H/2T$. This will be largest for $H=5$m, $T=12$s giving 1.3 ms^{-1}.

Let thrust acting on the translator be $F\cos(\omega t)$ and velocity be $V\cos(\omega t)$ then instantaneous power available is $FV\cos^2(\omega t)$ which has a mean value of $FV/2$. Equating with the 1.2 MW mean power developed gives $F=1.83$MN.

Assessor's comments:

A very popular questions, with many candidates demonstrating a good understanding of the technologies used and their relative merits. Most candidates were able to determine the available power from the proposed scheme and there were good attempts at working out the rating for the vernier hybrid machine. No one was able to