1.(a) (i) The main difficulty is that many sites are not usable. There is a general view that wind farms should not be sited too close to habitation and there are areas such as National Parks where development is not considered acceptable (even though wind conditions are generally good in these upland regions!). Some objectors even argue that wind farms should not be visible from protected areas – an example is the proposed siting of turbines off the Dorset Coast which would be visible from the cliffs. There are issues with wildlife, such as bird flight paths. There can also be difficulties in terms of site conditions, distance to a grid connection point and grid congestion, though all these points can be overcome. [10%]

(ii) The Limpet in Islay is perhaps the best known example of this kind of generation but the massive construction means that these devices are going to be ruled out on grounds of visual and environmental intrusiveness along the great majority of the coastline. [10%]

(iii) There are fewer restrictions on sites for marine current devices (likely to be marine current turbines but other devices have been proposed) but these include obstruction to shipping, worse if there is structure just below or above the waterline, and possible adverse effects on marine life. [10%]

b) (i) The construction of barrages is a mature technology and suitable turbines exist. Experience dates from the scheme on the Rance in the 1960s to more recent schemes such as those in Korea. In contrast operating experience to date with marine current turbines (MCTs) is limited and there are still reliability issues. [10%]

(ii) A barrage is a major civil engineering undertaking involving large quantities of material but the construction industry understands how to build them. Installing MCTs is more dependent on the techniques developed for offshore wind such as jack up barges, assuming the MCTs are seabed mounted. [10%]

(iii) A barrage will have a major environmental impact by altering the normal tides, affecting wildlife. There are also issues with shipping. Installing MCTs will be less of an issue but the energy extracted is likely to be significantly less. [10%]

c) Direct drive is when the wave energy is coupled directly to a generator – rotary motion relies on a turbine but many devices exploit some kind of oscillatory motion. One example is the point absorber which produces an oscillating linear motion which can be used to drive a linear generator. Direct drive is mechanically simpler but high reaction force generators have to be physically large. The electrical output will vary both in amplitude and frequency.

A hydraulic system can convert oscillatory into rotary motion for driving a conventional generator. Movement can be used to pump hydraulic fluid and unidirectional flow can be achieved by using non-return valves. The hydraulic fluid can then drive a hydraulic motor and the flow can be made more even by employing an accumulator. The low efficiency of these systems, especially at part load, is a major drawback. Complexity and concerns about the leakage of fluid are other issues. Pelamis uses a hydraulic system. www.pelamiswave.com [30%]

d) Mounting MCTs and other devices on the seabed involves expensive construction methods and becomes increasingingly difficult, and expensive, as the depth of water increases although from a power extraction point of view locations further offshore can be attractive. Seabed geological conditions can be poor, requiring more extensive foundations. Mooring with anchors and ropes offers a potentially cheap alternative but it is not straightforward to devise schemes that are satisfactory. Controlling the orientation of the marine power device is difficult. [10%]

This was generally well answered but marks were lost in the first two parts through imprecision in answers. Again, in the third part marks were lost by candidates' not describing their chosen approaches clearly.

2. a) It is desirable to operate MCTs at the optimum tip-speed ratio and this implies variable speed operation. The doubly-fed induction generator has the benefit of only needing a fractionally rated converter, making it an economical system. The system power factor can also be adjusted through the excitation applied to the rotor. Against this, the slip-ring generator is an expensive machine because of the wound rotor and the brushgear and the brushes need regular changing and can be a source of failure. [20%]

b) (i) With a 100:1 gear ratio this is 15x100 = 1500 rpm. This is the synchronous speed (N_{sync}) of a 4-pole induction generator on 50 Hz. [5%]

(ii) The speed of a doubly fed machine is given by

$$N = 60\ (1 + f_r/50) \text{ x } N_{sync}$$

Shaft speeds of 10 and 20 rpm correspond to generator speeds of 1000 and 2000 rpm respectively, and these correspond to rotor frequencies of -16 2/3 Hz and +16 2/3 Hz respectively. Negative frequency reflects a reversal of phase sequence. [10%]

(iii) The turbine achieves its maximum output at a generator speed of 1500 rpm. The rotor power is related to the speed deviation and the rotor power Pr is

$$P_r = (\ N/N_{sync}) \text{ x } P_s$$

Where Ps is the stator power. At 1500 rpm the rotor is supplied with DC and the power is zero (ignoring any losses). At 2000 rpm the total output power is still 600 kW but both the rotor and stator contribute.

$$P_s + P_r = (1 + f_r/50)P_s = 600 \text{ kW.}$$

Hence $P_s = 450$ kW and $P_r = 150$ kW

At 1000 rpm, the power output follows the cube law so is 600 x (2/3)*3 = 177.8 kW

Again using $P_s + P_r = (1 + f_r/50)P_s = 177.8$ kW. However, f_r is negative so P_s is 266.7 kW and P_r is – 88.9 kW i.e. power is being fed into the rotor.

(iv) For the machine side converter the maximum power is 150 kW (at 2000 rpm) so with a power factor of 0.9 this is 166.7 kVA. This is of course the minimum rating. For the grid side converter, 150 kVA is enough as the power factor is unity. [10%]

(v) Using the formula provided and assuming a maximum modulation index of unity the minimum DC link voltage V_{dcmin} is

$$V_{dcmin} = \frac{2\sqrt{2}}{\sqrt{3}}.V_{ac}$$

Putting in numbers gives V_{dcmin} = 1470 V. The figure given is 9% higher giving some margin for variations in the grid voltage and for ripple on the DC link. Also, modern modulation schemes allow increased AC output from the DC link, giving a further margin. [10%]

(vi) The machine side converter will produce a maximum of 900 V from the DC link adopted so this would be a good figure. This voltage would be applied at the maximum rotor frequencies of +/- 16 2/3 Hz. [10%]

(vii) The distance to shore is modest so an AC link is acceptable (long AC cables have unacceptably high charging currents so DC has to be used). The power levels are modest so 33 kV is reasonable and cables of this voltage are available at modest cost. A transformer will be needed at the MCT to step up from 900 V to 33 kV. On land another transformer will step the voltage up to the 275 kV of the grid. A higher voltage could be used for the sub-sea connection but would be more costly; a lower voltage (11 kV) could be used but losses would be higher. [10%]

Some candidates did not take into account the fact that the power obtained from the marine current turbine falls below 15 rpm. Most candidates did not offer good answers to the last part, namely grid connection of a relatively near-shore turbine. An AC connection at 33 kV is the obvious choice but most candidates suggested conversion to DC or even transmission at 275 kV, both of which would be significantly more expensive.

3 (a)

CONNECTION TO GRID

Large wind power connected into high voltage grid – always a demand for the power; supplements grid. Small wind power can be ‘off-grid,’ which requires energy storage (batteries) and dump loads. Small wind can also be 'on-grid' – power is imported from grid when demand exceeds supply and exported to grid when supply exceeds demand. Electricity supplier may pay for electricity exported to grid.

MAINTENANCE, POWER RATING, TYPE OF MACHINE

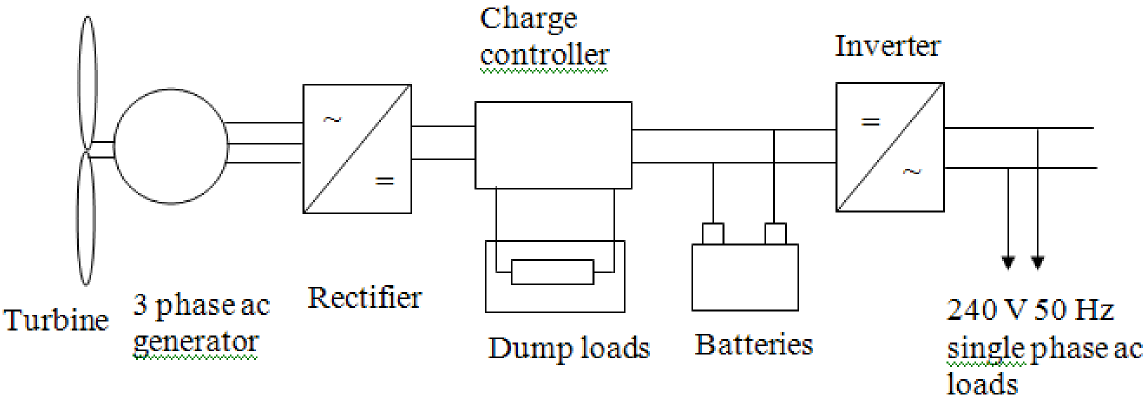
Large wind installations are owned and operated by power generation companies. Small wind often operated and maintained by owner – must be easy to maintain and fail-safe. The need to keep maintenance to a minimum means that generators with brushes and slip-rings are not preferred. Cage rotor induction generators not favoured owing to difficulties of supplying VARs and their control. Permanent magnet generators (PMG) have no brushes or slip-rings and can produce substantial power at low rotational speeds. Modern PM materials result in high power densities.

Small wind power systems produce far less power. Power conditioning equipment used to match output power to load.

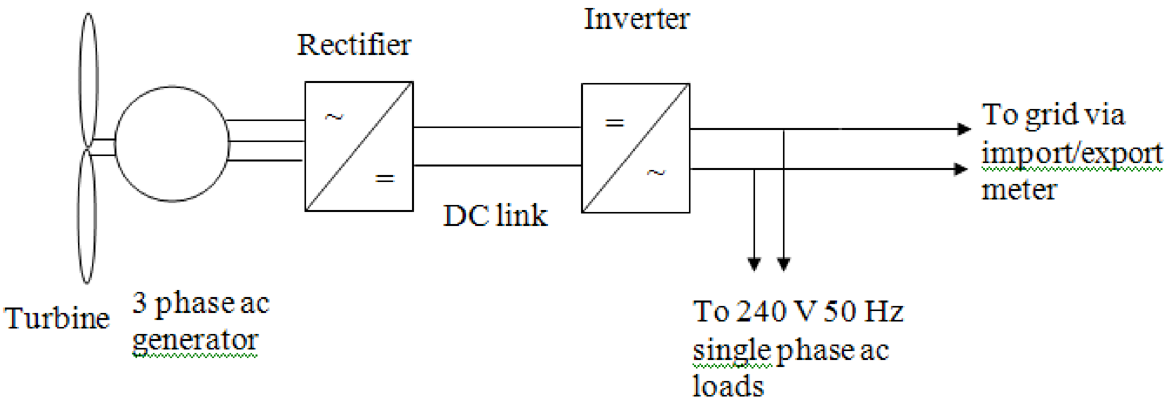
COMMON COMPONENTS: Turbine, 3 phase AC generator, rectifier, inverter

DIFFERENCES: Charge controller, dump loads and batteries for storage (off-grid), connection to either (commonly) single phase AC loads (off-grid) or the grid via import/export meter (on-grid)

Off-grid system typically rectifies generator output and uses it to charge batteries via charge controller. Inverter connected to batteries to produce 240V, 50 Hz single phase supply.



On-grid system takes rectified generator output and inverts it, matching it to the mains supply in magnitude, frequency and phase.



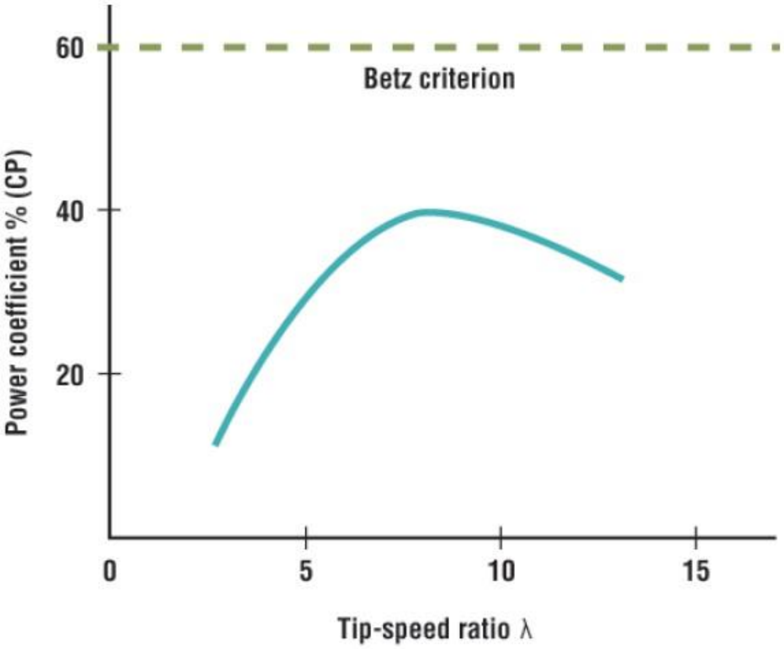
[30%]

(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, Cp. Thus: $P = 0.5C_p\rho Av^3$

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.

There is an optimum tip-speed ratio where C_p is a maximum, so it is advantageous to maintain λ at this optimum value. $\lambda = \omega R/v$, so a constant λ implies that the rotational speed of the turbine must be kept in proportion to the wind speed. Therefore, variable speed operation is better at extracting maximum power from the wind.



Variable speed operation allows the maximum power to be extracted at all wind speeds (within the limits of the turbine and generator). The problem with variable speed operation is that synchronous generators cannot be connected directly to the grid, since they only produce power at their synchronous speed. 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 does not make the best use of the wind power available because the turbine speed will, in general, not give the optimum tip-speed ratio. A gear box is generally required. It does have an advantage, however, in that synchronous machines can be used to generate power – synchronous machines are well understood by decades of experience by industry, they can contribute to demands for reactive power by controlling field current, and are fairly reliable.

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. [35%]

(c) Let the rated power be P_{max} kW. We know that this occurs at a wind speed of 12 ms^{-1}, and we also know that at constant tip-speed ratio the output power varies as the wind speed cubed. Therefore, we can find the output power of the system at the 6, 8 and 10 ms^{-1} wind speeds by scaling:

At 6 ms^{-1} wind speed $P = (6/12)^3 P_{max} = P_{max}/8$
At 8 ms^{-1} wind speed $P = (8/12)^3 P_{max} = 0.3P_{max}$
At 10 ms^{-1} wind speed $P = (10/12)^3 P_{max} = 0.58P_{max}$

There is no power produced at the 2 ms^{-1} wind speed since it is below the cut-in wind speed, and the power produced when the wind speed is in excess of 12 ms^{-1} will be P_{max}, i.e., at the 14 ms^{-1} wind speed. Complete the table below:

Wind speed	kW	Days	Hours	kWhr
2 ms^{-1}	0	30	720	0
6 ms^{-1}	$P_{max}/8$	150	3600	$450P_{max}$
8 ms^{-1}	$0.3P_{max}$	100	2400	$720P_{max}$
10 ms^{-1}	$0.58P_{max}$	60	1440	$835.2P_{max}$
14 ms^{-1}	P_{max}	25	600	$600P_{max}$

Summing the total power, we have $2605.2P_{max}$ and we require 10000 kWhr, so P_{max} = 3.84 kW.

Wind speed	kW	Days	Hours	kWhr	Power
2 ms^{-1}	0	30	720	0	0
6 ms^{-1}	$P_{max}/8$	150	3600	$450P_{max}$	480
8 ms^{-1}	$0.3P_{max}$	100	2400	$720P_{max}$	1152
10 ms^{-1}	$0.58P_{max}$	60	1440	$835.2P_{max}$	2227.2
14 ms^{-1}	P_{max}	25	600	$600P_{max}$	3840

If the generator produced its rated output power all of the time, then over one year it would produce 365 x 24 x 3.84 kW = 33638 kWhr, but here it produces 10000 kWhr, so the capacity factor is 0.297 (close to 0.3).

Using the equation from part (c), and the fact that rated power 3.84 kW occurs at the rated wind speed of 12 ms^{-1}, the area can be calculated as A = 3840/0.5/0.4/1.23/12^3 = 9.03 m^3, giving a diameter of 3.39 m. [35%]

This question was generally well answered but many candidates missed the key point when discussing rotor resistance and slip energy recovery control techniques in so far as the rotor circuit is at slip frequency.

4 (a)

LOCATION: The best locations for renewables are often far from load centres.

AVAILABILITY OF SOURCE: The output power from renewable energy sources varies with the time of day and seasonally, depending on the prevailing weather conditions. The availability of this power is not necessarily well-matched to demand.

SOLUTIONS:

(1) Upgrade transmission and distribution systems to connect remote renewable locations more robustly into the grid;

(2) Greater integration, increased interconnection of the grid (diversity of demand/supply), which has a smoothing effect on the power system;

(3) Energy storage systems, such as hydroelectric/pumped storage schemes, heat storage, compressed air energy storage (CAES), batteries, hydrogen (future?);

(4) Flexible AC transmission systems (FACTS). Defined by the IEEE as “power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability.” Series FACTS compensation increases transmission line capability (real and reactive), shunt compensation allows for variable power factor correction to respond to reactive power demand/supply at load bus-bars.

[10%]

(b) The phase current is given by

$I = (V_1 - V_2)/jX = (|V_1|(\cos\delta + j\sin\delta) - |V_2|)/jX = (|V_1|(-j\cos\delta + \sin\delta)+j|V_2|)/X$
$S_1 = 3V_1I^* = 3|V_1|e^{j\delta}I^* = 3|V_1|(\cos\delta + j\sin\delta)(|V_1|\sin\delta - j(|V_2| - |V_1|\cos\delta))/X$
$S_2 = 3V_2I^* = 3|V_2|I^* = 3|V_2|(|V_1|\sin\delta - j(|V_2| - |V_1|\cos\delta))/X$

Therefore, we have

$S_1 = P_1+jQ_1 = 3((|V_1||V_2|\sin\delta)/X + j(|V_1|^2 - |V_1||V_2|\cos\delta)/X)$
$S_2 = P_2+jQ_2 = 3((|V_1||V_2|\sin\delta)/X - j(|V_2|^2 - |V_1||V_2|\cos\delta)/X)$
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 $(Q_1+Q_2)/2 = 3(|V_2|^2 - |V_1|^2)/2X)$.

So the average complex power transmitted along the line is
$S = 3(|V_1||V_2|\sin\delta)/X + j3(|V_2|^2 - |V_1|^2)/2X$

Under normal operating conditions (i.e., there are no system faults) two things have to occur:

1. The supply must be matched to the demand for real electrical power – this is equivalent to keeping the system frequency constant.

2. The supply must be matched to the demand for reactive power – this is equivalent to keeping the system voltage profile constant.
Since the transmission line is assumed to be lossless, then $P_1 = P_2$. Furthermore, assuming that V_1 and V_2 are roughly equivalent to 1 pu, then this shows that the flow of power is controlled by controlling the angle between the voltages at either end of the transmission line. Therefore, to increase the power flow, δ must be increased. This corresponds to increasing the load angle of the synchronous generators, which in turn requires more torque to be provided at the generator shaft. If this torque is not supplied then the load angle does increase, but by the generator slowing down, and the grid

frequency starts to fall. Therefore, real power is controlled by monitoring the grid frequency and adjusting the load angles of the generators by supplying more input torque as required to bring the frequency back up to nominal.
The average value of Q_1 and Q_2 is the average reactive power flowing between the two ends of the line, and this is given by $3(V_1^2 - V_2^2)/2X$. This shows that the flow of reactive power is controlled by controlling the magnitudes of the voltages at the source and load ends of the transmission line. In practice, these are controlled by the excitation voltage of the generators. [40%]

(c) Choosing a 600 MVA base (lowest common multiple, but other base values are possible) the pu reactances of the step-up and step-down transformers become, respectively:

$X_{T1} = 600\times0.2/200 = 0.6$ pu and $X_{T2} = 600\times0.35/300 = 0.7$ pu

The base impedance for the transmission line is $V_b^2/VA_b = 275^2/600 = 126\ \Omega$ giving a pu reactance of 0.5x300/126 = 1.19 pu. Thus, the total pu series reactance impedance is j(1.19+0.6+0.7) = j2.49.

Working in the pu system, $P_L = 0.2$, $Q_L = 0.05$, and $S_L = \text{sqrt}(0.2^2+0.05^2) = 0.206 = VI$ giving the per-unit load current as 0.206 since V = 1 pu at the load bus. Using the conservation of P and Q $P_S = P_L = 0.2$ pu (lossless line) and $Q_S = Q_L + I^2X = 0.05 + 0.206^2\text{x}2.49 = 0.156$ pu and so

$S_S = \text{sqrt}(P_S^2+Q_S^2)$ giving $Ss = 0.254$ pu so $V_S = 0.254/0.206 = 1.23$ pu = 13.5 kV

Using $P = V_SV_L\sin\delta/X = 1\text{x}1.23\sin\delta/2.49 = 0.2$ gives $\delta = 23.9°$

Same procedure, but with 400 kV transmission line

$Z_b = 400^2/600 = 266.67\ \Omega$ so pu reactance is 0.5*300/266.67 = 0.5625 pu
Series impedance = j(0.5625+0.6+0.7) = j1.8625

$P_S = P_L = 0.2$ pu (lossless line) and $Q_S = Q_L + I^2X = 0.05 + 0.206^2\text{x}1.8625 = 0.129$ pu and so

$S_S = \text{sqrt}(P_S^2+Q_S^2)$ giving $Ss = 0.238$ pu so $V_S = 0.238/0.206 = 1.155$ pu = 12.7 kV

Using $P = V_SV_L\sin\delta/X = 1\text{x}1.155\sin\delta/1.8625 = 0.2$ gives $\delta = 18.8°$

With the higher, 400 kV transmission line, the voltage at the wind farm bus is lower and the load angle is smaller. [50%]

Many candidates struggled with the per-unit question, partly because they didn't choose the easiest base VA rating for the calculations (lowest common multiple of the rated devices). A few candidates confused three phase analysis and the per-unit assumptions, resulting in incorrect answers.