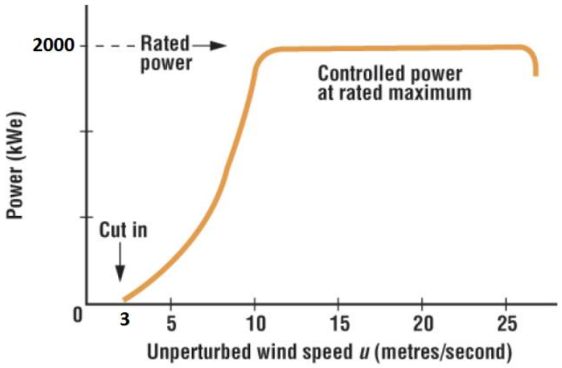
Wind, Induction Generator, Power Systems – Solutions

1 (a) Energy potential – wind data is gathered, usually measured over a year or more, to make an accurate assessment of the site
Engineering considerations – suitability of the site for structure; ease of connecting to the grid, particularly offshore; strength of the grid
Logistics – transporting and constructing the wind turbine
Social – planning; noise; distraction of road users
Environmental – visual impairment of landscape; bird strike; damage to other flora/fauna/ecosystems
Risk to aviation and shipping (offshore)
Economic – payback time; cost of electricity generated
Ease and cost of ongoing maintenance

Offshore advantages: Avoids some of the social and environmental issues that onshore wind turbines suffer from; energy potential tends to be higher due to stronger winds

Offshore disadvantages: Higher cost and difficulty of construction; requires improved/strengthened grid/infrastructure to connect to grid; routine inspection and maintenance more difficult; conditions are often more severe/harsh (especially storms); installation more difficult and requires a foundation in or on the sea bed. [20%]

(b)



Cut-in = wind speed above which producing power is worthwhile
Rated = wind speed at which turbine-generator produces rated output power
Stall = wind speed above which turbine operation is unsafe, so turbine is stalled

Two ways to control wind turbine power: 1) furling blades (twisting them at hub to make turbine less efficient), 2) active yaw turbines drive the nacelle to reduce wind normal to blades. [20%]

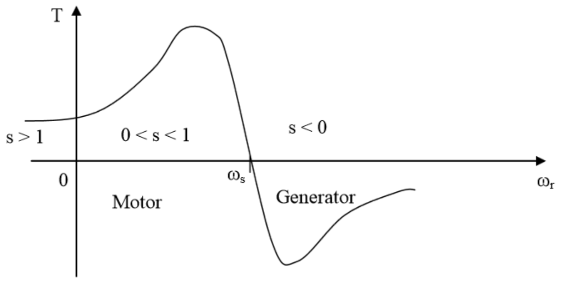
(c) No power is produced at wind speeds of 2 ms^{-1} and 22 ms^{-1} (below cut-in speed and above stall speed). At 14 ms^{-1} and 18 ms^{-1}, the turbine produces 2 MW. At 6 ms^{-1} and 10 ms^{-1}, the power scales with the wind speed cubed (at optimum/constant tip ratio), and the system produces 2 MW at 12 ms^{-1}. At 6 ms^{-1}, $P = (6/12)^3 * 2$ MW = 0.25 MW, and at 10 ms^{-1}, $P = (10/12)^3 * 2$ MW = 1.16 MW.

Wind speed [ms^{-1}]	Power [MW]	Days	Hours	Energy [MWh]
6	0.25	150	3600	900
10	1.16	85	1920	2222
14	2	50	1200	2400
18	2	30	720	1440

Annual total energy supplied = 6962 MWh = 6.96 GWh (approx. 7 GWh)

Capacity factor = 6962 / (365 x 24 x 2) = 39.7% (approx. 40%) [30%]

(d)



Using $\lambda = \omega_t R/v$ gives $\omega_t = 2.74$ rads^{-1}

$P = T\omega_t = 2.74T = 2$ MW gives $T = 730$ kNm

The induction generator operates on the steep part of the torque-speed curve, with a negative slip, at a speed just greater than the synchronous speed, $\omega_s = 2\pi f/p = 2\pi*50/4 = 78.5$ rads^{-1}. At the rated speed (12 ms^{-1}), the turbine rotates at 2.74 rads^{-1}, so the gearbox ratio n_g is

$n_g * 2.74 \geq 78.5$, giving $n_g = 29$.

With the gearbox, the torque at the generator shaft is 730 kNm / 29 = 25.2 kNm.

Using simplified torque equation: -25.2 kNm = $3V^2 s/(\omega_s R_2')$ where $V = 6.6\text{kV}/\sqrt{3} = 3.81$ kV (star-connected), $\omega_s = 78.5$ rads^{-1} and $R_2' = 0.4\ \Omega$. Rearranging gives $s = -0.018$. $\omega_r = (1-s)\omega_s = 79.9$ rads^{-1}.

[30%]

2 Hydro – Solutions

(a)

a. Advantages:
    i. Hydroelectric power is clean and renewable, and does not involve the burning of fossil fuels. The process of generating power does not produce greenhouse gases that contribute to climate change.
    ii. Hydroelectric schemes are powered by the hydrological cycle and as such does not rely on a resource that is limited (on an engineering time scale anyway).
    iii. Hydroelectric schemes have existed since ancient times and it is a well-understood and well-developed process.
    iv. The cost of power generated by hydroelectric schemes is very cheap once the infrastructure is installed.
    v. Hydroelectric power plants often have long lifetimes, and operating costs are usually low with automated processes and a minimal human presence required during normal operation.

b. Disadvantages:
    i. Most good (and economical) sites have already been developed in developed countries, particularly the UK
    ii. Environmental issues such as ecosystem damage and loss of land. Hydroelectric schemes can affect ecosystems and wildlife both up- and down-stream of the plant.

iii. Social issues such as displacement/relocation of the people living nearby the planned reservoir/dam site. A dammed river, for example, can adversely affect those people relying on the natural flow of the river in their daily lives.
iv. Hydroelectric scheme proposals are often financially unattractive at the start and require a large upfront capital cost, which is not paid back for several years while the scheme is constructed.
v. Often the sites most suitable for hydroelectric schemes are not located near load centres and the power is required to be transmitted over large distances. [15%]

(b) Water of mass M stored at a height H with respect to the point where the energy is extracted has potential energy, $PE = MgH$

When water is released the rate at which energy is extracted (i.e., the power) is given by
$P = d(MgH)/dt = gHdM/dt = gH\rho dV/dt = \rho gHQ$
where ρ is the density of water, g is the acceleration due to gravity, H is the height of the water (or the 'head') and Q is the volumetric flow rate in m^3s^{-1}.

However, losses mean that not all of this power is extracted, and this is accounted for by the efficiency term η giving $P = \eta\rho gHQ$

Hydroelectric schemes are either high head ($H > 100$ m), low head ($H < 10$ m) or medium head ($10 \text{ m} < H < 100$ m). Low head = Propeller turbine, medium head = Francis turbine, high head = Impulse turbine. [25%]

(c) Assuming $\rho = 1000$ kgm^{-3} and $g \sim 10$ms^{-2}, $P = \eta gH\rho Q \sim 10000\eta HQ$.

Therefore, site A is a 24 MW scheme and site B is a 1.6 MW scheme (note these values are approximate and answers will vary slightly if 9.8 or 9.81 is used).

The maximum head values, maximum flow rates and power ratings (using answers from part (b) and (c)) suggest that site A would use a Francis turbine (high head, medium flow) and site B would use a propeller turbine (low head, medium flow); impulse turbines would be acceptable in both cases.

Site A = 24 MW, Francis (N_S = 70–500 rpm), $N_S = 0.39n$,
so n = 179–1282 rpm and n = 4 pole (1500 rpm) – 32 pole (187.5 rpm)

Site B = 1.6 MW, Propeller (N_S = 136–390 rpm), $N_S = 2.57n$,
so n = 136–390 rpm and n = 16 pole (375 rpm) – 44 pole (~136 rpm)

The rotational speeds in the hydroelectric schemes are lower than conventional fossil fuel/nuclear power systems, and hence a larger number of poles need to be accommodated. Therefore, the rotor needs to be of the salient pole type. [30%]

(d) Payback period = time required for the net income generated by the project to equal the fixed, or capital costs. A short payback time is more attractive to investors.
Unit cost of electricity generated = Assuming a certain lifetime for the scheme, the unit cost of generating electricity over the project lifetime can be calculated. In this way, the costs can be

directly compared with other forms of generation.

kWh produced per year = 0.2 x 365 x 24 x 0.5 x 10^6 = 8.76 x 10^8 kWh
Annual income per year = 8.76 x 10^8 x 0.1 = £87.6 million
Capital costs = £672 + 87 million = £759 million
O&M = £0.1 million per year
759 + 0.1 T = 87.6 T
T = 8.67 years

Electrical energy produced over lifetime = 100 x 8.76 x 10^8 kWh = 8.76 x 10^{10} kWh
Total income = 8.76 x 10^{10} x 0.1 = £8.76 billion
Total costs over lifetime = £672 + 2 x £87 + £10 million = £856 million
Cost per kWh = £856 million / 8.76 x 10^{10} = 1 p / kWh

The assumptions rather simplistically ignore two important economic factors: the cost of borrowing (interest) and the tendency of money to lose value over time (inflation). For a large scale hydro scheme, construction in fact takes several years, during which there would be no income stream, and the capital borrowing would need to be phased. This borrowing would need to be financed by borrowing at some interest rate.

The basic principle of discounted cash flow analysis is that all costs and income must be discounted to account for the fact that a sum of money representing a cost/income at some point in the future is equivalent to a smaller sum of money today. All cash flow is rebased to a common point in time, which is the start of the project. Real interest rate = monetary rate – inflation. [30%]

3 (a) (i) The advantage of generating at a higher voltage is reduced current, reducing Ohmic losses, enabling the use of small section cables or both. For example at 690 V and 1.5 MW, the line current is 1,255 A assuming unity power factor. At 900 V the current is 962 A, reducing Ohmic losses by over 40% if the same cables are used. Increasing the voltage to 900 V does not create undue difficulty in terms of choosing appropriate IGBTs for the converter. [10%]

(ii) Applying the fomula for a 900 V output at a modulation index m = 1 suggests a DC link of

$$V_{DC} = 900 \frac{2\sqrt{2}}{\sqrt{3}} 1 = 1470 \text{ V}$$

However, this is a minimum value and a margin is necessary to accommodate, for example, the normally expected variations in grid-side voltage. A margin of +10% i.e. 1600 V is a guide. On the other hand, the use of a modem PWM scheme effectively allows a degree of extra output so 1500 V would be satisfactory. Higher voltages would require higher rated components, which is unattractive. [15%]

(b) (i) The power from the rotor via the slip rings, P_R, is related to the stator power, P_S, by

$$P_R = \left(\frac{N_R}{N_{SYNC}} - 1 \right) P_S$$

Where N_R is the rotor speed and N_{SYNC} is the synchronous speed. Putting in numbers gives

$$P_R = [(1000/750) - 1] P_S = {}^{P_S}\!\!/_{3}$$

So the power from the stator is 1.2 MW and that from the rotor is 0.4 MW (total 1.6 MW). [15%]

(ii) The rotor frequency fr is related to the supply frequency fs as

$$fr = \left({N_R}/{N_{SYNC}} - 1 \right) fs$$

Hence: at $N_R = 500,\ fr = -16\,{}^2/_3$ Hz

at $N_R = 1000,\ fr = +16\,{}^2/_3$ Hz

The negative frequency is equivalent to a reversal of phase sequence. [10%]

(iii) The power from the slip rings is 0.4 MW

$P = S\cos\phi$ here $\cos\phi = 0.9$

So $S = {0.4}/{0.9} = 0.44$ MVA [10%]

(c) (i) Full output will be achieved at a lower wind speed and the cut-in speed of the turbine will be reduced. The effect will be to increase capacity factor, hence earnings will be greater. Against this, the spacings of turbines may need to be increased. [10%]

(ii) Full power is achieved at a speed of 750 rpm but no power is exported via the slip rings at this speed. The full output of 1.6 MW will come from the stator. At 1000 rpm the power splits 3:1 stator to rotor as before, so they are 1.2 MW and 0.4 MW respectively. It would be sensible to arrange that the generator speed is constant at its highest value over the constant power range of wind speeds, avoiding the need to increase the generator's rating. [15%]

(iii) The stator of the generator needs to be uprated to 1.6 MW. The converter rating remains the same. A bigger generator is heavier and more costly, and increases the weight of the naceller. However, this needs to be set against the high earnings of the turbine. [15%]

4 (a) (i) The power available from both wind is given by $P = {}^1/_2 C_p \rho A v^3$ where C_p is the power coefficient, A is the turbine's swept area, ρ is the fluid density and v is the velocity. The density of sea water is just over 1000 times greater than that of air, but currents are slower, say 2 to 6 m/s, as opposed to 6 m/s upwards for wind. Putting these together means that for a given output power the swept area is smaller and the turbine diameter might be 5 to 10 times smaller.

[10%]

(ii) The output of a wind turbine depends on the weather – a well sited on-shore turbine might have a capacity factor of 25% - an offshore turbine might achieve 50% or greater.

Tidal currents are relatively predictable – a 50% capacity factor is achievable. [10%]

(iii) Wind turbines are an established technology with many suppliers, although there are still improvements to be had, especially in reducing off-shore costs. Tidal current turbines are still at an early stage of development with few installations to-date. [10%]

(iv) With all devices proximity to a suitable point to feed into the grid is helpful. In the case of offshore wind farms and marine turbines, undersea connections are needed and above a certain distance DC is preferred over AC. [10%]

(b) There are many examples of devices for generating power from sea waves. The Limpet is a shoreline device; the Trident TE5 and Pelamis could be used either near-shore or in deeper water. Considering the first and last:

(i) The near-shore resource is greater than the shore-line, notwithstanding the acceptability of a significant number of shore-based devices. [5%]

(ii) The Limpet has a large opening to the sea and uses ‘pneumatic gearing’ to achieve a high speed air flow from the waves. Pelamis is an attenuator device with its axis at right angles to the wavefront. It has several jointed sections and they rotate relative to each other in response to incoming waves. [15%]

(iii) The Limpet uses a Wells turbine, an air turbine which rotates in the same sense irrespective of the direction of air flow to drive an induction generator.

The flexing joints in Pelamis pump hydraulic fluid which drives a hydraulic motor, in turn driving a generator (induction or synchronous). An accumulator can be used to smooth power flow. [15%]

(iv) The Limpet has a considerable environmental impact in that it needs substantial shoreline structures. The direct impact is the displacement of shoreline habitat.

Pelamis type devices may affect some forms of sea life. Perhaps a greater risk is spillage of hydraulic fluid. [5%]

(c) The grid operator needs to match supply and demand. The output from many renewable sources is variable and so may not be available at a particular time – “non-despatchable”. With a higher percentage of renewable generation, conventional forms of generation experience greater variations in demanded output. Mitigation measures include

(a) more interconnection between grids
(b) demand side control to adjust load
(c) more energy storage (i.e. pumped storage)
(d) curtailment of renewable output as needed.

Generally, the variability of renewable generation, which is predictable reasonably far ahead, has not proved particularly difficult to manage, but problems may develop as the proportion of renewable power rises. [20%]