1.

a)

i) Explain why a wind turbine cannot capture all of the kinetic energy in an air flow. Describe the Betz limit and explain its importance. [4]

BOOKWORK: By extracting kinetic energy, the wind turbine changes the speed of the air flow. Extracting all the kinetic energy would imply unlimitted accumulation of air in the wake of the turbine. Moreover, Betz showed that reducing the speed of the air flow also reduces the massic flow passing through the wind turbine, thus it does not necessarily lead to higher power yield. The optimum occurs when the flow velocity over the turbine is 2/3 of the up-stream velocity and the power yield is 16/27 ~ 60% of the available power.

ii) Explain why is it important for a wind turbine to be able to operate at different rotational speeds. [3]

BOOKWORK: Wind turbine blades are based on the same principles as the wings of the aircrafts. The profile of the blade generates a lift force that is perpendicular to the relative speed between the profile and the airflow; the projection of this force in the direction of rotation of the blade produces useful torque. For a given wind speed, different turbine rotational speeds result in different torque and different mechanical power. There is a certain ratio between the wind speed and the rotational speed that maximises the power extraction; thus, if the wind speed increases, the rotational speed of the turbine should increase proportionally. This is usually expressed as maintaining the optimal tip-speed ratio or the optimal angle of attack. Students might sketch Cp against the tip-speed ratio or the generated power against the rotational speed for different wind speeds to illustrate.

iii) Describe what is meant by the fault ride-through capability of a wind turbine. [2]

BOOKWORK: When a fault occurs in the AC grid, it takes a certain time for circuit breakers to isolate the faulty equipment. During this time, the voltage of the grid is depressed. This causes a sudden drop of the capacity of nearby wind turbines to inject power into the grid. In such situation, early wind turbines would do an emergency stop. Once the fault had been cleared, the wind turbine would not be ready to generate power. This created a power imbalance in the grid which could potentially escalate to a major stability problem. Nowadays, most transport system operators require wind turbines to have fault ride-through capabilities. The basic fault ride-through requirement is to remain connected to the grid during the normal clearance time of faults in order to be ready to inject power to the grid once the fault is cleared. During the fault, wind farms are also required to generate reactive power to minimise the voltage depression.

b) A particular variable speed wind turbine has a blade radius of 45 m, a cut-in wind speed of 3.5 m s^{-1}, a rated wind speed of 12 m s^{-1}, a cut-out wind speed of 26 m s^{-1}, a rated turbine power of 3.23 MW and a rated turbine speed of 18 min^{-1}.

i) Calculate the maximum power coefficient the wind turbine achieves and the optimal tip speed ratio assuming perfect maximum power point tracking below the rated wind speed and an air density of 1.225 kg m^{-3}. [2]

These parameters can be calculated using the information available about the nominal operating point.

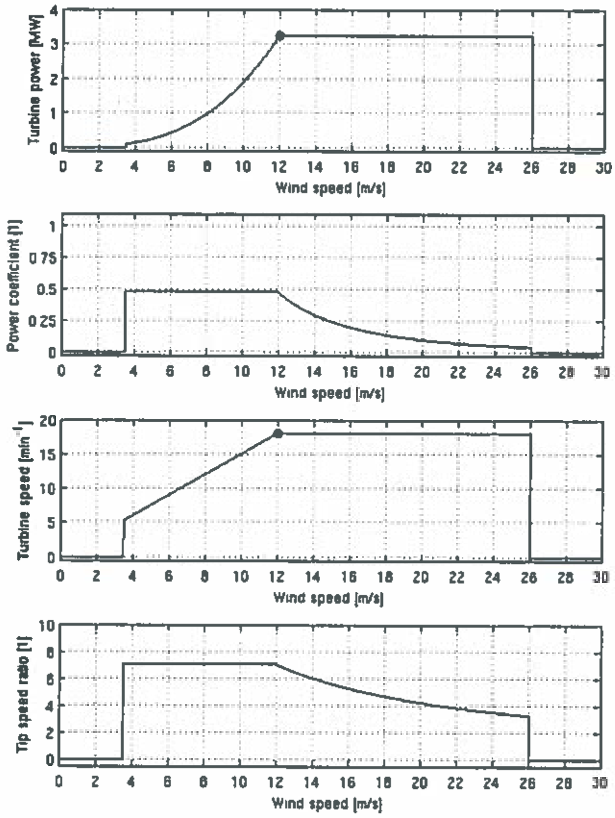
Maximum power coefficient: P=3.23 MW; $P_0=1/2\cdot\rho\cdot A\cdot v_w^3=6.73$ MW; $C_P=P/P_0=0.479$

Optimal tip speed ratio: $\lambda=\omega\cdot R/v_w=((18\cdot\pi/30)\cdot 45)/12 = 7.07$

ii) Sketch the turbine power, the power coefficient, the turbine speed and the operating tip-speed ratio for a range of wind speeds from 0 to 30 m/s using the supplied graph paper. Assume the power reduction above the rated wind speed is achieved through blade pitch angle control only. Make sure you include a short description of the curves and any calculation required to plot them. [5]

According to the description, there are 3 different wind speed ranges in which the wind turbine behaves differently:

- The turbine does not operate below the cut-in wind speed (3.5 m s^{-1}) nor over the cut-out speed (26 m s^{-1}); therefore, in this range of wind speeds, the turbine speed is zero and so is the extracted power, the power coefficient and the tip-speed ratio.
- For wind speeds between the cut-in speed and the rated wind speed (12 m s^{-1}) the wind turbine is doing perfect MPPT. Therefore, the power coefficient is the maximum power coefficient obtained in the previous question (0.48). This can be used to calculate the generated power. Also, the tip-speed ratio is optimal and this can be used to calculate the speed of the wind turbine.
- For wind speeds between the rated wind speed and the cut-out speed, the wind turbine is doing power reduction, hence the generated power is equal to the rated power. This can be used to calculate the power coefficient for each wind speed. In this operating region, the wind turbine speed is kept constant at the rated speed; this can be used to calculate the tip-speed ratio for each wind speed.



c)

i) Compare the pitch-to-stall versus the pitch-to-feather power reduction methods for wind turbines equipped with variable pitch. [2]

BOOKWORK: The pitch-to-feather method allows to reduce the power extracted from the wind by reducing the angle of attack of the blade. This is achieved by increasing the blade pitch angle. This method allows to control the power extracted from the wind precisely but it requires a long displacement of the blade angle to achieve high reduction. In contrast, the pitch-to-stall method allows to reduce the power extracted from the wind by increasing the angle of attack causing the blade to stall. This is done by reducing the blade pitch angle. This method allows to reduce the power extracted quickly because the stall regime causes a sudden drop of the torque. The downside of this method is that the stall regime induces strong vibrations in the blade. Also, precise control of the power reduction is hard to achieve.

ii) Discuss the benefits and drawbacks of a wind turbine designed to operate at a high tip-speed ratio versus one designed for a low tip-speed ratio. [2]

BOOKWORK: The tip-speed ratio measures the ratio between the turbine speed and the wind speed. For a given wind speed, a turbine that is designed to operate at a high tip-speed ratio will rotate at a higher speed than one that is designed to operate at a lower tip-speed ratio. Most wind turbines achieve optimal power extraction at rotational speeds that are much lower than the operational speeds that are convenient for most electrical generators. Thus, most wind turbines require gearboxes to multiply the speed of their shaft. Wind turbines with higher tip-speed ratio have the advantage of requiring a gearbox with a lower multiplication ratio. On the other hand, for a given generated power, wind turbines with lower rotational speed produce higher torque; this is convenient to counteract the dry friction and helps the turbine operate at low speeds and do black-start. Wind turbines designed for high tip-speed ratios, such as the one-bladed wind turbine, may be unable to do black-start and require the generator to behave as a motor and speed up the turbine so that it can start generating power. Students may also refer to the graph that compares the maximum power coefficient against the tip-speed ratio for different types of wind turbines. Examples of wind turbines with low tip-speed ratio include the American wind turbine, the European windmill and the drag-based wind turbines, these wind turbines have comparatively lower power coefficient than the three-bladed wind turbine.

2.

BOOKWORK: This section is about the similarities and differences between tidal and hydro power.

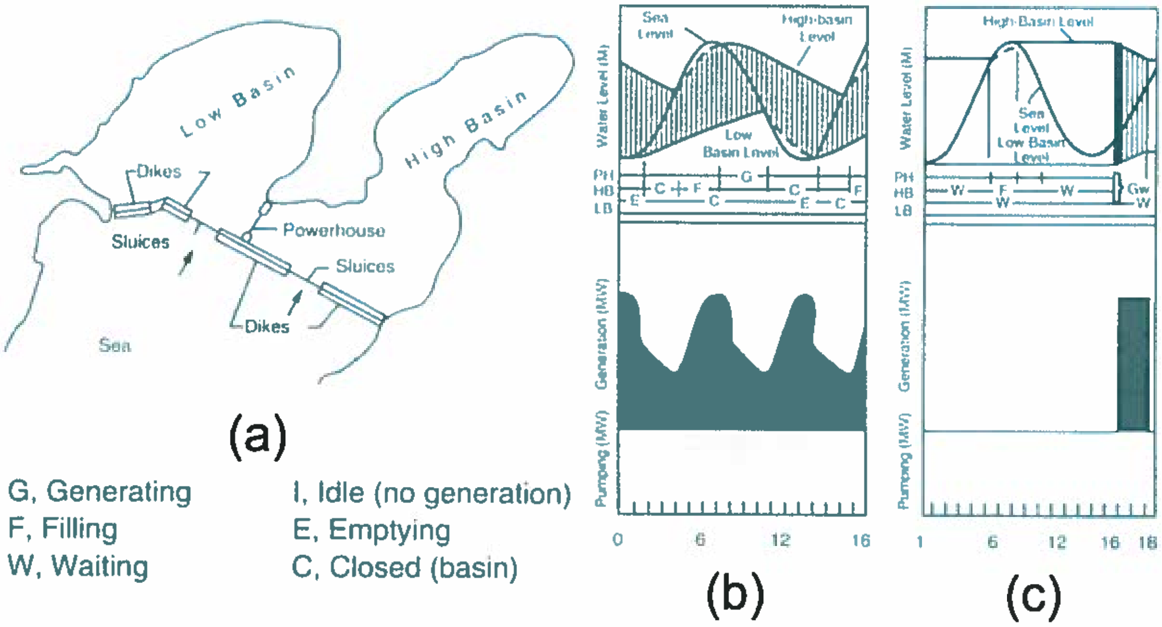
a)

i) Describe the problems associated with integrating tidal electricity generation into an electricity network compared with hydroelectric electricity generation. [3]

BOOKWORK: This is intended to ellicit a discussion of tides not being synchronised with the peak demands but hydroelectric power is available all the time and can be used to provide energy at all times.

ii) Describe the way in which both of these generation technologies can be used to provide on demand electricity. [4]

BOOKWORK: Pumped storage. Tidal barrages and lagoons can be created to produce on demand but this needs to be much more complicated system where one basin is always used as a high basin and one is the low basin.



b)

i) Discuss why technology of both hydroelectric generation schemes and tidal generation schemes could lead to objections from the public. [4]

BOOKWORK: This question is challenging the student to realise that hydro and tidal lagoons are similar in the need for large civil constructions that lead to massive ecological and social upheaval.

ii) Explain the way in which both generation technologies have produced a similar solution to overcome many of these objections. [3]

BOOKWORK: This is hopefully going to get the students to think about how tidal stream converters and run of river hydro turbines can be used to capture kinetic energy from the flowing water without the need for large civil constructions that and hence limit the effect on the river/estuary traffic and the ecology of the local area.

c)

BOOKWORK: this section is on wave energy converters

i) **Compare the variability in energy available from wave energy converters with the variability of energy available from wind turbines.** [2]

BOOKWORK: Although waves are created by the wind, they tend to exhibit less variation in energy because waves can travel a great distance without losing any energy and therefore are a less susceptible to localised variations in wind.

ii) **Explain the way in which wave energy converters, tidal generation schemes and offshore wind turbines are connected to the grid. What advantages are there to tidal generation schemes and wave energy converters.** [4]

Due to the distances involved, offshore wind turbines usually need HVDC connections and converters out at the wind farm. By contrast, tidal generation schemes and WECs are close in to shore and so they can use the local civil infrastructure to house the generation equipment close to shore allowing simpler grid connections. In the case of WECs, some do not even house the generation equipment out at sea, instead they place it on shore and pump high pressure air or fluid from the wave device itself.

3.

a) Explain why it is important to quantify the ability of distributed generation to substitute for distribution network assets and incorporate this contribution in distribution network design standards? [3]

b) What are the key weaknesses of the method used in the UK for assessing contribution of DG to network security? [3]

c) Consider the network in which two embedded CHP generators of capacities of 2 MW and 3 MW are connected to a 33/11kV substation as shown on Figure 3. For the winter demand profile of the load connected to this network shown below, quantify the contribution to network security that would be effectively provided by the two generators, if the availability of individual generation unit is 85% (3 MW unit) and 90% (2 MW unit). [10]

d) If the peak demand is 15.8 MW, assess if this network is compliant with the UK network security standards. [4]

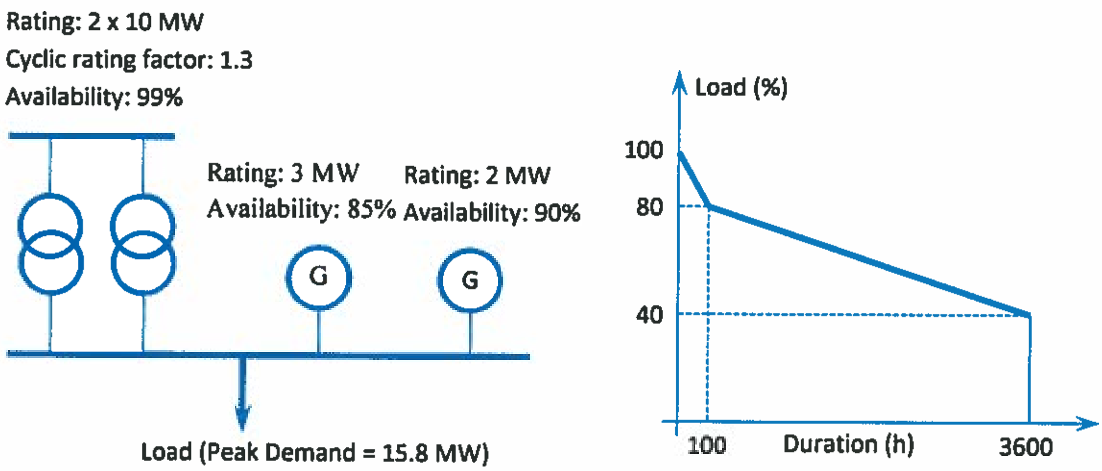


Figure 3

Q3. Solution

Statements covering the key points below would be sufficient for the full mark

(i) Assessing the ability of distributed generation is critical for establishing level playing field for the competitiveness between centralised and distributed generation.

(ii) The method used in current UK distribution network design cannot deal the frequency and duration of outages during the time period, not able to differentiate risk of customers and hence it is not directly related to customer cost of outage but only system property based method.

(iii)

- Estimation of generation capability:

Capacity outage probability table

Capacity (MW)	Probability
5	$0.85 \cdot 0.9 = 0.765$
3	$0.85 \cdot (1 - 0.9) = 0.085$
2	$(1 - 0.85) \cdot 0.9 = 0.135$
0	$(1 - 0.85) \cdot (1 - 0.9) = 0.015$

Sum of probabilities is $0.765 + 0.085 + 0.135 + 0.015 = 1$

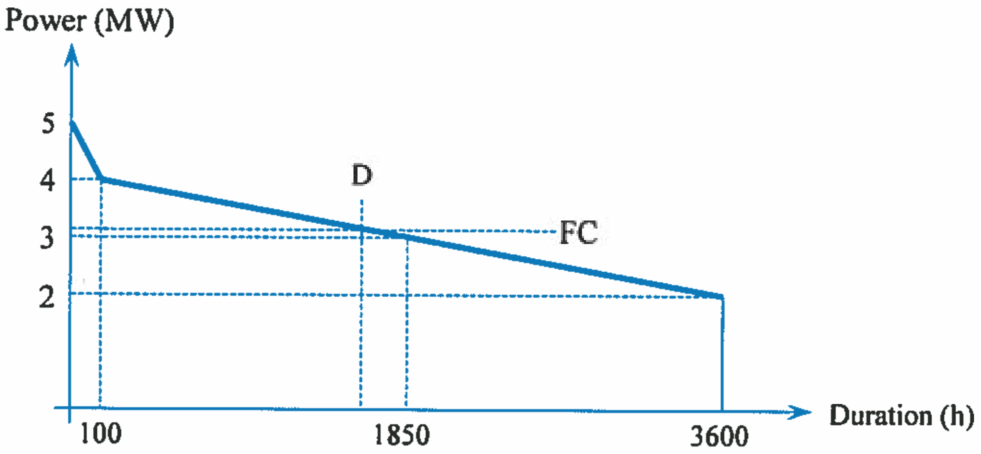


Figure: Winter load duration curve for generation capability estimation

Duration of 3MW is $100 + \frac{3600-100}{2} = 1850h$

Energy not supplied for generation state 3MW is:

$$ENS_{3MW} = \frac{1}{2}\big((5-4)\cdot 100\big) + \big((4-3)\cdot 100\big) + \frac{1}{2}\big((4-3)\cdot(1850-100)\big) = 1025MWh$$

Energy not supplied for generation state 2MW is:

$$ENS_{2MW} = 1025 + \big((3-2)\cdot 1850\big) + \frac{1}{2}\big((3-2)\cdot(3600-1850)\big) = 3750MWh$$

Energy not supplied for generation state 0MW is:

$$S_{0MW} = 3750 + (2\cdot 3600) = 10950MWh$$

Expected energy not supplied due to generation is:

$$EENS = 1025\cdot 0.085 + 3750\cdot 0.135 + 10950\cdot 0.015 = \frac{6061}{8} = 757.625MWh$$

Estimation of equivalent firm capacity for which EENS is the same:

$$S_{4MW} = \frac{1}{2}\big((5-4)\cdot 100\big) = 50MWh$$

$$EENS = 50 + \big((4-FC)\cdot 100\big) + \frac{1}{2}\big((4-FC)\cdot(D-100)\big) = 757.625MWh$$

$$D = \frac{100-3600}{4-2}\cdot(FC-4) + 100$$

$$50 + \big((4-FC)\cdot 100\big) + \frac{1}{2}\left((4-FC)\cdot\left(\frac{100-3600}{4-2}\cdot(FC-4) + 100 - 100\right)\right) = 757.625$$

$$FC = 3.156MW$$

$$D = \frac{100-3600}{4-2}\cdot(3.156-4) + 100 = 1577h$$

Contribution to security of supply (capability) of both generations is 3.156MW i.e. $\frac{3.156}{5}\cdot 100 = 63.12\%$

(iv)

Maximum group demand which can be supplied under the first circuit outage is:

$$GD_{Max} = (2-1)\cdot 10\cdot 1.3 + 3.156 = 16.156MW > 15.8MW$$

The second circuit outage condition is not relevant.

It can be concluded that the network is compliant with the UK network security standards.

4.

a) In order to achieve the UK's 2050 CO_2 80% reduction target, heat will need to be decarbonised. In March 2013 the UK Government published "The future of heating: Meeting the challenge". Amongst a number of proposals it announced the establishment of a Heat Networks Delivery Unit to support the longer-term development of heat networks.

i) Briefly outline the features of a district heating system and list the main components and their function. [4]

ii) What are the benefits and drawbacks of a district heating system? [4]

iii) A householder is considering installing a heat pump to replace her gas boiler. The heat pump is subsidised by the Government so that the cost is the same as the gas boiler. Her annual heat demand averages 10 MWh and the electricity tariff 12p/kWh whereas the gas tariff is 5.5p/kWh. Stating any assumptions, calculate her expected annual cost or saving from installing a heat pump. [3]

iv) Assuming the CO_2 emissions from gas combustion is 190g/kWh and from grid electricity is 500 g/kWh, estimate the annual CO_2 savings from replacing the gas boiler with the heat pump. [3]

b) There has been growing interest in the application of energy efficiency and demand side management / response in supporting cost effective operation of future electricity systems.

i) List 3 measures introduced by the government to facilitate uptake of energy efficiency measures and demand side management / response. [3]

ii) Describe the effects of load reduction and load recovery when demand side management / response is used to provide peak demand reduction. [3]

Q4 - Answer

(i)

(a) A district heating system provides heat for building space and water heating. The main components are:

- Heat sources (see below)
- Heat storage - to provide additional capacity, to provide backup and to improve infrastructure utilisation, i.e. "smoothing out the peaks and the troughs in heat demand"
- Pipe heat network – connecting heat sources, heat storage, etc with buildings using supply and return pipework.
- Pumps – to circulate the hot water (normally) or steam
- Heat substations – for pressure and temperature changes
- Heat metering – to monitor production and consumption
- Heat exchangers/ heat interface units - for connection of the heat network to buildings

(b) Benefits include:

- Provides an option to connect multiple forms of heat sources including renewable and low carbon heat sources
- Low cost of heat production
- Low cost of heat storage which can be used to augment heat capacity as well as providing backup
- Can use existing heat emitters (radiators) thereby avoiding the need for building upgrades
- Can be integrated with the electricity system to provide grid services, energy storage and better utilisation of assets.

The main drawback is the need to construct a heat network and develop the heat load. The investment cost is substantial and the time taken to recover the investment can be lengthy.

(c) Assume: Gas boiler efficiency is 90% and Heat pump efficiency is 270%, then annual savings are: 10 MWh x (5.5p/kWh / 90% - 12p/kWh/270%) = £10000 x (6.11 - 4.44)/100 = £166.67/a.

(d) heat pump will deliver annual CO_2 savings of: 10 MWh x (190 g/kWh/90% - 500g/kWh / 270%) = 10000 x (211.11 – 185.19)/1000 kg/a = 259.2 kg/a

(II)

(a) Any of the following

- Climate Change Levy (CLL), an energy tax for commercial and industrial consumers who do not fall within the ETS.
- The Carbon Reduction Commitment (CRC), a mandatory demand side emission trading scheme for large business.

- Energy Companies Obligation 2013, in parallel to 'Green deal' (superseded 'The Carbon Emission Reduction Order' (CERT) which replaced 'Efficiency Commitment (EEC) in 2008').
- Energy efficiency labelling, a Europe wide scheme intended to promote energy efficiency technologies through mandatory labelling (EST 2008).
- Energy efficiency minimum standards, prohibition of appliances with the lowest efficiency.
- National targets and rebate schemes for the adoption of micro-generation.
- Building standards.
- Feed In Tariffs
- Smart meters

(b) Demand side response generally re-distributes demand across time. Hence energy overall energy consumption is unchanged. Hence load reduction periods are preceded by or followed by load recovery / increase periods. Managing these is a key to effective demand side control.

5.

a) In the future UK electricity system, it is expected that inflexible nuclear generation and variable and difficult to predict wind generation, will make the key contribution to reducing carbon emissions in electricity production.

i) What are the advantages and disadvantages of providing reserves for managing uncertainty in wind generation production by part-loaded Combined Cycle Gas Turbines (spinning reserve) and by Open Cycle Gas Turbines (standing reserve)? [4]

Statements along the following lines would be sufficient for the full mark:

Reserve provided by OCGT running part loaded (spinning reserves)

- Advantage: CCGT more efficient than OCGT (hence less costly to run and lower carbon emission when operating)
- Disadvantage: less flexible and provision of reserve reduces the efficiency of generation, Increased emissions, Provision of reserve accompanied with energy production which limits the amount of wind that can accommodated, particularly during low demand condition

Reserve provided by standing plant, OCGT

- Advantage: more flexible, provision of reserve can be decoupled from provision of energy
- Disadvantage: higher fuel cost when exercise of reserve is needed

ii) What are the advantages and disadvantages of using pumped-storage hydro generation to provide flexibility in systems with significant penetration of wind generation? [3]

Statements along the following lines would be sufficient for the full mark:

Advantage: pump hydro plant is generally very flexible output can modulated at virtually no impact on efficiency

Disadvantage: cycle efficiency is about 70%, it wastes 30% of energy used to fill in the reservoir

iii) What are the advantages and disadvantages of enhancing the flexibility of nuclear generation to provide reserve in systems with intermittent renewables? [3]

Statements along the following lines would be sufficient for the full mark:

Advantage: Flexible nuclear plant could be used to provide reserve through being part loaded and enhance the ability of the system to absorb nuclear

Disadvantage: cost, reduced load factor of zero carbon generation, effect of part-loading nuclear is similar effect to curtailing wind b)

i) Which HVDC technology is preferred for offshore wind power transmission, VSC-HVDC or LCC-HVDC? Justify your answer. [3]

BOOKWORK: VSC-HVDC is the preferred technology for offshore wind power transmission. LCC-HVDC uses line-commutated converters which require a strong AC grid to operate and cannot do black-start (generate the voltage of the AC grid itself). In contrast, VSC-HVDC can be connected to weak isolated AC grids and do black-start. Moreover, the footprint of the VSC-HVDC substations is comparatively smaller than the footprint of LCC-HVDC, this is convenient for offshore as the substation has to be installed on an offshore platform which has a high cost with a strong dependency on the volume and the weight of the substation.

ii) Explain what transmission technology, HVAC or HVDC, would be most cost effective in the following cases: [2]

(1) An offshore wind farm located 150 km far from the shore.

BOOKWORK: The technology of choice would be HVDC. Submarine cables have very high capacitance which is hard to compensate in submarine cables and makes HVAC impractical for such long distances. The break even distance when comparing the costs of HVAC and HVDC for offshore power transmission is somewhere between 50 to 100 km. Most wind farms using HVAC power transmission are located within 40 km from the coastline.

(2) A wind farm located in a remote inland location connected to the main grid through a 200 km overhead line.

BOOKWORK: The technology of choice would be HVAC. Unlike the previous case, overhead lines have low capacitance compared to cables; thus they are suitable for longer distances using HVAC. HVDC has high fixed costs due to the power converters. The variable costs in HVDC are slightly lower than HVAC, however the break even distance is around 800 km.

c)

i) Discuss the advantages and disadvantages of building multi-terminal HVDC grids compared to individual point-to-point HVDC links. [3]

BOOKWORK: Some possible advantages and disadvantages are summarised below:

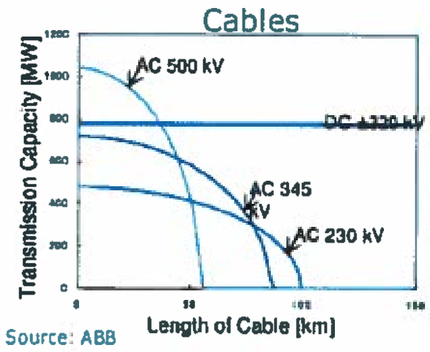
- Advantages of building individual HVDC links:
  - HVDC voltage levels are still evolving. New HVDC links can use higher voltage levels to reduce losses without having to worry about being compatible with older systems.
  - Point to point links can be easily protected from short circuits using AC circuit breakers installed on the AC side of the converters.
  - Operating a point-to-point link is relatively easy, LCC-HVDC has been in used for more than 50 years and some experience gained from it can also be applied to point-to-point VSC-HVDC links.
- Disadvantages of building point-to-point HVDC links:

- The power yield of an offshore wind farm fluctuates as weather conditions change; however, HVDC links have to be sized for the maximum expected power generation. This causes underutilisation of the transmission system.
- Having an offshore wind farm connected to a single HVDC link makes it totally dependent of the state of the HVDC link as the wind farm can not export power during HVDC link outages and maintenance operations.

- Advantages of building multi-terminal HVDC grids:
  - Underutilisation could be reduced. For example, the same power converter could import power from another AC grid when the offshore wind farms had low power production.
  - The reliability of the system could be improved. Maintenance can be done to one HVDC converter station without losing all the generation from a wind farm as the power can be exported through a different route.
- Disadvantages of building multi-terminal HVDC grids:
  - Protecting a multi-terminal HVDC grid from short circuits is not straightforward. Protecting the grid from the AC side is only practical when the number of terminals is very small. DC circuit breakers are still under development and have a high cost.
  - VSC-HVDC voltage levels are still evolving. Building a multi-terminal HVDC grid gradually by building a series of single point-to-point links and connecting them together in the future creates a problem of voltage compatibility: newer HVDC links would need to adopt lower voltage levels used in the older links.

ii) **Sketch approximate graphs of maximum power transmission capacity against transmission distance for AC cables and DC cables. Explain why they are different.** [2]

BOOKWORK: Cables have a high parasitic capacitance that increases with length. When using a cable for DC transmission, this capacitance is charged when starting the system causing a certain inrush current. Once the initial transient is over, the capacitance remains charged and no current flows through it. The power losses of the cable at high loading depend mainly on its current and increase linearly with the resistance of the cable which increases with its length. The losses cause the maximum power transmission capacity to decrease slightly in a linear way with distance. When using cables for AC, the parasitic capacitance is continuosly charged and discharged; this causes a reactive current flowing through the cable. There's a certain cable length at which the capacitance is so high that the maximum rated current of the cable is spent entirely on charging and discharging it. The leakage current increases at higher voltage levels, thus rising the voltage level of the cable makes the maximum transmission distance shorter.


Cables
Transmission Capacity [MW]
AC 500 kV
AC 345
kV
AC 230 kV
Length of Cable [km]
Source: ABB