EE4-50 Sustainable Electrical Systems
SOLUTIONS

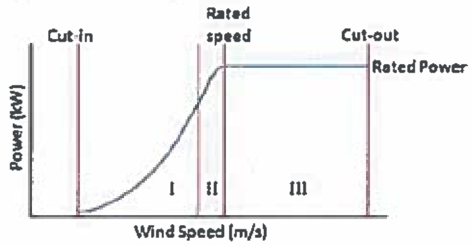
There are five questions; answer four.

1. Wind power

a)

i) Sketch and describe the characteristic curve of a wind turbine (power yield against wind speed). [3]

The characteristic curve of a wind turbine is divided into different operating regions that correspond to different wind speed ranges (see figure below). The cut-in speed is the lowest wind speed at which the wind turbine can produce power. The cut-out speed is the highest wind speed at which the wind turbine can operate. In between these boundaries, there are two main regions of operation (I and III in the graph). In region I, the wind turbine operates under maximum power point tracking to maximise the power yield. In region III, the wind turbine uses power reduction mechanisms (mainly pitch angle control) to keep the extracted power, the speed of the turbine and the torque below the maximum rated values. A transition region (II) between I and III is sometimes included in the description. In this region the pitch angle may be kept constant and generator speed control may be used instead to reduce the power extracted from the wind.



ii) Explain what mechanisms wind turbines use to control (or to limit) the power they extract from the wind. [4]

Different methods can be used to control the power yield of the turbine, these can be classified as:

- Constant pitch angle methods:

Passive regulation in fixed speed turbines: a higher wind speed results in a lower tip-speed ratio causing a reduction of the power coefficient.

Variable speed generator control: the torque of the generator is controlled to change the tip-speed ratio causing a reduction of the power coefficient.

- Variable pitch angle methods:

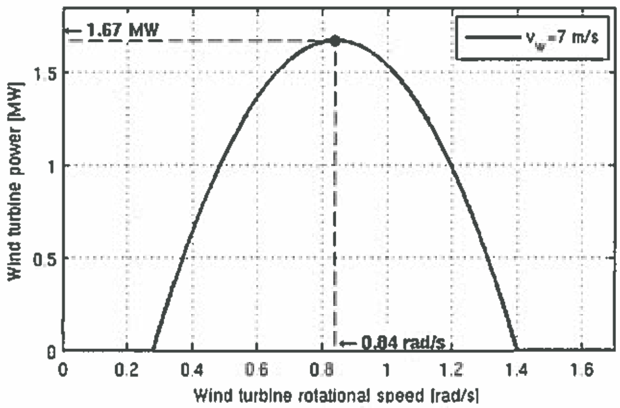
Pitch-to-feather: the angle of attack is reduced by increasing the pitch angle through a servo actuator. This causes a smooth reduction of the power coefficient that enables precise control of the power but requires great displacements of the blade angle to produce significant reduction of the power yield.

Pitch-to-stall: the angle of attack is increased using the pitch mechanism. This leads to flow separation, with a great reduction of the lift force and the resulting power yield. This method enables a sudden reduction of the power yield but generates mechanical stress due to the turbulence generated by the blade.

iii) Wind turbines have a power-limitation operating region. Explain the reasons in favour of having a power-limitation region. [2]

The kinetic energy of an airflow depends on the cube of the wind speed. Therefore, high wind speed leads to high kinetic power available. However, high wind speeds are rare and the energy available over long term due to high wind speeds is small. Being able to obtain optimal power at high wind speeds requires sizing the turbine to withstand high torque and high rotational speed. This proves uneconomical and wind turbines are designed to limit the power they extract from the wind above a certain wind speed threshold. A trade-off between the cost of the turbine and its efficiency to generate power at high wind speeds must be found. Most wind turbine manufacturers offer different types of wind turbines optimised for sites with different wind speed characteristics.

b) The following graph shows the power extracted by a wind turbine against its rotational speed for a wind speed of 7 m s^{-1}. To answer the following questions, take 75 m as the radius of the blades and assume the density of the air is 1.225 kg m^{-3}.

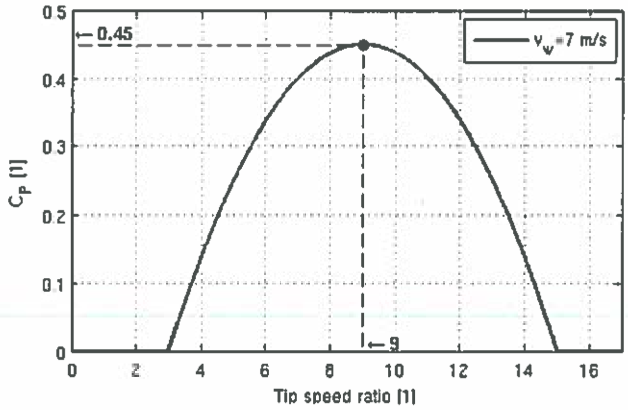


i) Calculate the power coefficient, the tip speed ratio (TSR) and the turbine torque at the maximum power point (MPP) for a wind speed of 7 m s^{-1}. [3]

The power coefficient can be found by dividing the power yield at the MPP (1.67 MW) by the kinetic power available (1/2*rho*A*vw3). This gives CP=0.45. The tip speed ratio can be calculated by dividing the blade tip speed (wr*R) by the wind speed (7), which gives TSR=9. The torque can be found by dividing the power by the rotational speed, which gives T=2 MNm.

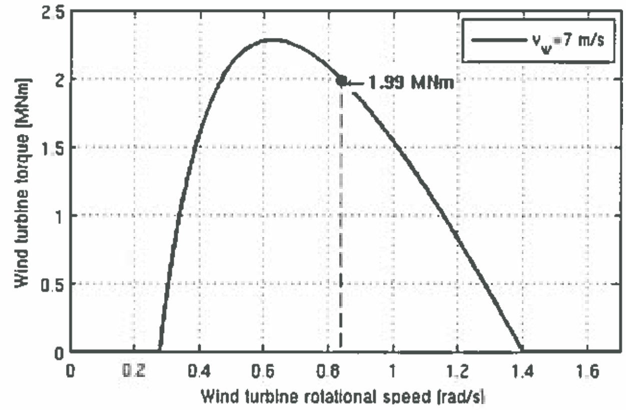
ii) Sketch the power coefficient against the TSR. Mark on the graph the MPP. Confirm that the maximum power coefficient is consistent with maximum value predicted by the Betz limit. [3]

The graph of the power coefficient against the TSR can be obtained by scaling both axis of the original plot using the aforementioned equations. The maximum power coefficient is 0.45 which is less than the maximum predicted by Betz using the actuator disk model, which gives CpMAX<16/27~=0.59.



iii) Sketch the wind turbine torque against the rotational speed for a wind speed of 7 m s^{-1}. Mark on the graph the operating point that corresponds to the MPP. [2]

The torque can be obtained by dividing the plot of the power by the rotational speed:



c)

i) Describe the differences and potential pros and cons of a wind turbine with direct-drive permanent magnet synchronous generator (PMSG) against a wind turbine with doubly-fed induction generator (DFIG). [3]

The DFIG consists of a wound-rotor induction generator connected to the turbine shaft through a gearbox with a large transformation ratio. The stator of the machine is connected to the collection grid through a step-up transformer whereas the rotor is connected to a back-to-back converter that is used to control the torque of the generator. The converter is rated ~30% of the rated power of the turbine and the direction of its power flow depends on whether the DFIG operates at sub-synchronous or super-synchronous speed.

The direct-drive PMSG uses a synchronous generator with permanent magnets as the source of excitation. The generator is designed to have a large number of pairs of poles to reduce its operating speed and enable its connection to the turbine shaft without a gearbox. The stator of the machine is connected to the network through a fully-rated back-to-back converter.

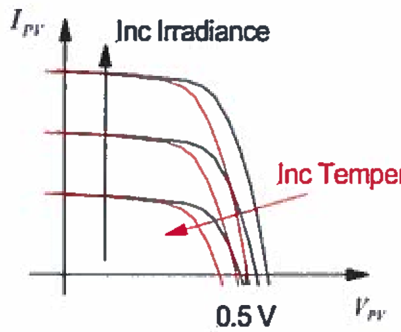
The DFIG enables variable speed operation using a power converter that handles only a fraction of the power. This reduces the cost of the converter and its energy losses. On the other hand it makes the machine more vulnerable to disturbances in the network (voltage unbalance, voltage dips, etc). The PMSG enables a generator without gearbox, which has been identified as a concern in terms of maintenance cost and availability (the gearbox is hard to replace in situ). Synchronous machines can have higher efficiency than induction machines and by using magnets rather than a wound rotor configuration with slip rings, maintenance can be reduced. Also, a full-rated power converter gives greater freedom to provide services to the network to mitigate grid-integration issues caused by renewables.

2. PV, hydro and marine

a)

i) Sketch and describe the characteristic curve (current against voltage) of a PV panel and explain how temperature and irradiation affect its shape. [5]

The equivalent circuit of a PV panel contains a current source, which varies linearly with the irradiation over the cell, and a diode with its anode connected to the positive terminal of the current source and the cathode connected to the negative terminal. If the voltage set by an external impedance is low enough, all current will pass through the external impedance rather than the diode; however, if the external impedance is large (or open circuit), all current will flow through the diode. Therefore, the characteristic curve can be obtained by subtracting the characteristic curve of a diode from a constant current source. The characteristic curve of the diode depends on the temperature, making it more conductive at higher temperatures; this causes the open circuit of the cell to decrease at higher temperatures:



ii) What is the problem of connecting PV cells in series? How would you prevent this problem? [2]

When PV cells are connected in series, the current passing through all of them is constrained to be the same. The short-circuit current of a PV cell varies linearly with the irradiation over the cell. If one cell receives significantly lower irradiation than the rest, it will limit the current passing through the whole string. If the total voltage of the string is reduced enough (for example if the PV panel is connected to a power converter doing MPPT), the voltage of the shaded cell can become negative, which causes the cell to absorb power rather than producing. This causes the cell to warm up and may damage it. To avoid this problem, a bypass diode can be connected in parallel with the cell to provide a low impedance path for current in case the voltage of the cell drops below zero.

iii) What is the meaning of the watt-peak rating of a PV panel? [2]

The watt-peak rating or nominal power rating, describes how much power the PV panel would produce under the so-called Standard Test Conditions. These conditions can be summarised as having a total irradiation of 1,000 W/m^2 at 20^{o}C of ambient temperature.

iv) What is the meaning of the Air Mass (AM) number? [2]

Atmospheric path that sunlight beams follow until they reach the surface of the earth affects the absorption at certain wavelengths of the spectrum by gasses and particles in the air (oxygen, water, CO2, dust, etc). Path length depends on angle of light through the atmosphere which in turn depends on the time of day, season and location. This is often summarised as an air mass number, AM1.5 indicating the spectrum after a path 1.5 times longer than a radial path.

v) Explain why is it beneficial to adjust the position of a PV panel to track the position of the sun. [2]

The energy collected by a PV panel from direct irradiation from the sun is proportional to the projection of the panel's surface in the direction of the sun. The direction of the sun changes following the day-night cycles due to the rotation of the earth over its axis but it also changes over the year due to the orbit of the earth around the sun. Therefore, two degrees of freedom of orientation would be required to precisely track the direction of the sun following both cycles.

b)

i) Two hydroelectric power plants are planned to be built in two different locations: one with 30 m of head and another with 600 m of head. Which location would be adequate for a Kaplan-type turbine and which would be adequate for a Pelton-type turbine? List the basic characteristics of these turbines. [3]

Kaplan turbines would be the choice for the first location (30 m) as they are suitable for low-head applications (5-70 m), whereas Pelton turbines would be the choice for the second location (600 m) as they are meant for high-head applications 400-1500 m.

Kaplan turbines are reaction turbines (energy extraction is based on a combination of kinetic and pressure energy) with axial flow. They can have adjustable blades together with wicket gates for regulation purposes.

Pelton turbines are impulse turbines (energy extraction is based on kinetic energy) with radial flow and they adjust their needle injectors to regulate the flow.

ii) Describe two different types of wave energy generators. [2]

A number of different types of mechanisms have been proposed to extract energy from waves. Some of these devices include:

- Attenuators (floats or pitching devices)

- Point absorbers

- Oscillating wave surge converters

- Oscillating water columns

- Overtopping devices (or focusing devices)

- Submerged pressure differential devices

- A basic description of any of these would be acceptable.

iii) Compare the advantages and disadvantages of tidal barrage generation versus tidal stream generation. [2]

Tidal barrages require major civil engineering work to build the barrage to keep the water from the tide until enough head is available. The barrage interferes with marine traffic and requires locks to be built to allow ships to pass. It also creates a significant impact on marine life. On the other hand, the ability to control the flow and to store water enables a certain degree of flexible operation similar to hydro.

In contrast, stream generators are less flexible as they have little control over the resource but they don't require barrages to be built, with significantly lower impact.

3. Offshore power transmission

a)

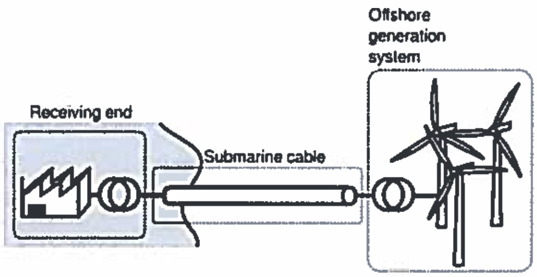
i) Explain why the space required to build an LCC-HVDC substation is greater than the space required for a VSC-HVDC substation. [2]

LCC-HVDC uses thyristors, hence the name "line-commutated". This causes the output current waveforms of the converter to have low frequency harmonic content. Given the size of the converter, these harmonics would cause great voltage distortions and heating of transformers in the network and therefore they have to be suppressed. This is normally done by combining several mechanisms: first, series connection of valves with different transformer arrangements to produce phase shifting is used to increase the frequency of the harmonics. These transformers have to be designed to have high DC voltage insulation, which makes them large. Also, a series of passive filters tuned at the frequencies of multiple harmonics need to be installed to reduce the remaining distortion below a desired threshold. Both mechanisms imply increasing the number of elements in the converter and a greater use of space. In contrast, VSC-HVDC uses high frequency switching devices, which enables creating harmonic distortion at higher frequencies, with minimal requirement of filtering and smaller filter size.

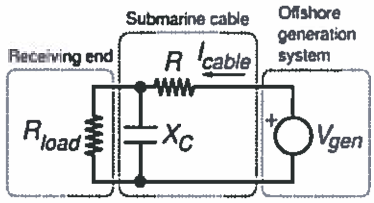
ii) List the advantages and disadvantages of XLPE cables compared to MI. [1]

XLPE cables are less expensive than MI for a number of reasons: the weight of the cable is lower and the bending angle of the cable is higher, this enables cable-laying ships to carry longer lengths of cable. Also, cable joints in XLPE take less time to make than MI. Both features enable speeding up the process of building an offshore transmission system. On the other hand, even though recent developments have brought voltage ratings in XLPE cables close to those of MI, insulation in MI cables has greater dielectric strength, which enables them to reach higher voltage. In LCC-HVDC, reversing the direction of the power flow requires reversing the voltage of the link. This is possible in MI cables but it is a known cause of aging of XLPE insulation.

b) An offshore transmission system feeds an onshore load from an offshore generator through a submarine HVAC cable (see diagram below). The generator can be modelled as a voltage source with V_{gen}= 220 kV and the load can be modelled as a resistor R_{load}= 440 Ω. According to the manufacturer, the submarine cable has a maximum rated current of 600 A and its equivalent circuit can be modelled using a resistor, R, and a capacitor X_c. The impedances of the resistor and the capacitor are: R=0.034·L Ω and X_c=23,000·$(1/L)$ Ω, where L is the length of the cable in kilometres (see equivalent circuit below).



Equivalent circuit:



i) Calculate the current flowing through the cable, I_{cable}, for a cable length of L=1 km and L=50 km. Which case causes the cable current rating to be exceeded? [2]

The current of the cable can be obtained once the equivalent impedance of the cable plus the load is known. The resistance of the load and the capacitance of the cable are connected in parallel and both are connected in series with the effective series resistance of the cable. In both cases, the series resistance of the cable is small compared to the combined impedance of the load and the cable capacitance. If neglected, the calculation leads to similar results.

The equivalent impedance can be calculated as:

$$Z_{eq}=(R+R_{load}\cdot X_c^2/(R_{load}^2+X_c^2))-j\cdot(X_c\cdot R_{load}^2/(R_{load}^2+X_c^2))$$

For L=1 km, the equivalent impedance is:

Z_{eq}=440 Ω with an angle of -1.1°

The cable current is I_{cable}=500 A (the current limit is NOT exceeded).

For L=50 km, the equivalent impedance is:

Z_{eq}=319 Ω with an angle of -44°

The cable current is I_{cable}=689 A (the current limit IS exceeded).

ii) Explain why the cable current rating is exceeded in one case only even though load and generation are the same. [3]

Long conductors have a noticeable stray capacitance caused by having the cable conductor laid in parallel with another conductor (the cable sheath or simply the surrounding soil) separated by a relatively short layer of dielectric material. The capacity of the cable increases with its length, therefore its capacitance ($1/(\omega_e\cdot C)^{-1}$) decreases. This causes the charging current to increase as the length of the cable increases. In the case above, when L=1 km the capacitance is very high when compared to the resistance of the load (R_{load}=440 Ω, X_c=23,000 Ω); therefore, the charging current is almost negligible. In contrast, when L=50 km, the capacitance is of the same order of magnitude as the load (R_{load}=440 Ω, X_c=460 Ω); therefore, the charging current becomes large and the current rating is exceeded.

This question can be answered qualitatively from the theory learnt in the module without solving the previous question as long as the case with the longest cable is identified as the case that has the largest charging current. To get full marks, a quantitative answer connected to the previous question is expected.

iii) Explain how would you modify the design of the transmission system to avoid this problem in a real application. [2]

This question is open to multiple possible answers.

If an HVAC transmission system was used, the voltage of the link could be changed: a higher voltage would require less current to supply the load but would cause the charging current to increase. On the other hand, reducing the voltage would reduce the charging current but would increase the current required to feed the load. Answering how the voltage would need to be changed requires solving a 4th order polynomial, and it is not required as an answer. Alternatively (or additionally), reactors could be added in both ends of the cable (or at different intermediate points) to provide the reactive power required by the cable capacitance.

A different option would be to replace the HVAC transmission system by an HVDC system or even a low-frequency HVAC transmission system. However, in both cases a larger offshore substation would need to be built to fit the AC-DC or AC-AC power converters. This would imply a great expenditure cost and this should be pointed out in the answer.

c) It is expected that variable and difficult to predict wind generation will make a significant contribution to reducing carbon emissions in future UK electricity systems. List and briefly describe the key challenges associated with integration of wind generation in the future UK system, considering both short term operation and long term planning time horizons. [5]

The availability of wind resource varies over time following yearly and daily cycles that are hard to predict. Generation of windfarms is correlated due to similar seasonal weather conditions but this is seen at longer time scales rather than short term thanks to location diversity. Precise forecasting is not easy and prediction error increases with the prediction horizon. Introducing a large amount of wind generation in the power system makes the problem of balancing demand and generation no longer a matter of adjusting generation to a variable demand but matching a variable generation and a variable demand. At very short term, a potential loss of a large conventional power plant poses a bigger concern than the potential drop of wind power. However, wind generation does not contribute to inertial response, thus in case of sudden loss of a power plant the frequency of the grid will drift faster in a scenario with high penetration of wind. At longer time scale, from minutes to hours, forecasting uncertainty affects planning of reserves and poses a big challenge as classic solutions may result in poor asset utilisation and poor efficiency due to plants operating at low loading.

d) Briefly describe how and why the level of redundancy in electricity network design changes with the level of connected load. Explain why it is important to consider the contribution that distributed generation can make to distribution network security. [5]

The level of security in distribution networks is defined in terms of the time taken to restore power supplies following a predefined set of outages. Consistent with this concept, security levels on distribution systems are graded according to the total amount of peak power that can be lost.Small demand groups, less than 1MW peak, are provided with the lowest level of security, and have no redundancy (N-0 security). This means that any fault will cause an interruption and the supply will be restored only after the faulty circuit is repaired. It is expected that this could take up to 24 hours. For demand groups between 1MW and 100 MW, although a single fault may lead to an interruption, the bulk of the lost load should be restored within 3 hours. This requires presence of redundancy, as 3 hours is insufficient to implement repairs, but it does allow network reconfiguration activities. Such networks designs are often described as providing n-1 security. For demand groups larger than 100MW, the networks should be able to provide supply continuity to customers following a single circuit outage (with no loss of supply) but also provide significant redundancy to enable supply restoration following a fault on another circuit superimposed on the existing outage, i.e. n-2 security.

Distributed generation, unlike large scale generation, is installed close to the demand, which implies it does not require to make use of the whole transmission system to get the energy from the generator to the load. Therefore, distributed generation has an impact to network security because of its ability to substitute for network reinforcement.

4. Heat

a)

i) In order to achieve the UK's 2050 CO_2 80% reduction target, heat will need to be decarbonised. Heat can be categorised as high grade heat and low grade heat. Briefly outline the difference between each category. [1]

High grade heat is typically used for industrial process applications and is provided at temperatures well in excess of 100°C. Low grade heat is typically used for space and water heating and is provided at temperatures below 100°C.

b) 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. [3]

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

ii) List the heat sources that can be connected to a district heating system. [2]

Heat sources include:

- Combined heat and power units
- Heat pumps (air/ ground/ water)
- Waste heat recovery
- Solar thermal
- Geothermal

iii) What are the benefits and drawbacks of a district heating system? [3]

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.

iv) List the key challenges for the large scale deployment of district heating systems in GB. [3]

Key challenges include:

- Design, planning and construction of the heat network
- Engineering skills and expertise
- Regulatory policy (infrastructure, performance, investment, operations and maintenance, supply competition and customer service)
- Consumer behaviour and acceptance
- Impact on gas system

c) Heat pumps are generally seen as key technology for decarbonising heat.

i) Briefly explain how a heat pump works. [1]

A heat pump recovers heat from sources such as air, ground or water and then by using energy upgrades the heat to a higher temperature.

ii) Briefly explain how a heat pump produces renewable heat and what factor influences the proportion of heat deemed to be renewable. [1]

Heat recovered from ground, water and air is a form of solar energy. The factor influencing the proportion of renewable heat produced is the source of energy to drive the heat pump. If this is from non-renewable sources then it must be offset against the heat produced by the heat pump.

d)

i) 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 13p/kWh whereas the gas tariff is 5p/kWh. Stating any assumptions, calculate her expected annual cost or saving from installing a heat pump. [3]

Assume:

- Gas boiler efficiency is 90%.
- Heat pump efficiency is 270%.

Then annual savings are:

10 MWh x (5p/kWh / 90% - 13p/kWh/270%) = £10000 x (5.556 - 4.815)/100 = £74.1/a

ii) The householder has been advised that the heat pump will result in lower CO_2 emissions. Her gas boiler is 90% efficient whereas she expects her new heat pump to have an average efficiency of 270%. What information is required to determine whether or not the installation of electric heat pumps will lead to a reduction in CO_2 emissions? Assuming the CO_2 emissions from gas combustion is 190g/kWh and from grid electricity is 500 g/kWh, calculate the annual CO_2 savings she can expect from her heat pump. [3]

The information required is the CO_2 emissions from:

- gas combustion
- grid electricity

The 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

5. Active network management

a) A wind farm is connected to the electrical system via 11kV overhead line as shown in Figure 5.1. The 33kV/11kV transformer is equipped with automatic voltage regulator and keeps the voltage at busbars 1 at 11 kV. Overhead line length, unit resistance and reactance are shown in Figure 5.1.

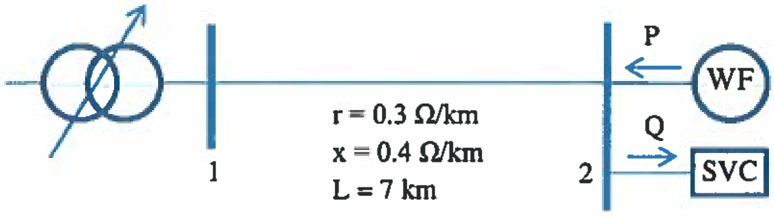


Figure 5.1: Wind farm connection.

i) Determine the maximum rating of the wind farm that can be connected without curtailment and without any active network management measure being applied, if maximum allowed voltage rise at the connection point is limited to 3%. Wind farm operates at the unity power factor. [5]

The relationship between voltages is

$$V_2 \approx V_1 + \frac{RP - XQ}{V_2}$$

Assuming that the voltage at busbar 2 is close to the rated voltage, the relationships between voltages becomes

$$(V_2 - V_1)V_2 = \Delta V \cdot V_{rated} \approx RP - XQ = (R - tg(\varphi)X)P$$

where $Q = tg(\varphi)P$.

Hence the maximum rating of the wind farm is

$$P^m \approx \frac{\Delta V \cdot V_{rated}}{R - tg(\varphi)X} = \frac{\left(\frac{3}{100}11\right) \cdot 11}{0.3 \cdot 7 - tg(\cos^{-1}1)0.4 \cdot 7} = 1.73MW$$

Hint: $tg(\varphi) = 0$ for unity power factor.

b) Energy production of the wind farm is variable and changes in time. The relative annual wind farm production duration curve is given in Figure 5.2.

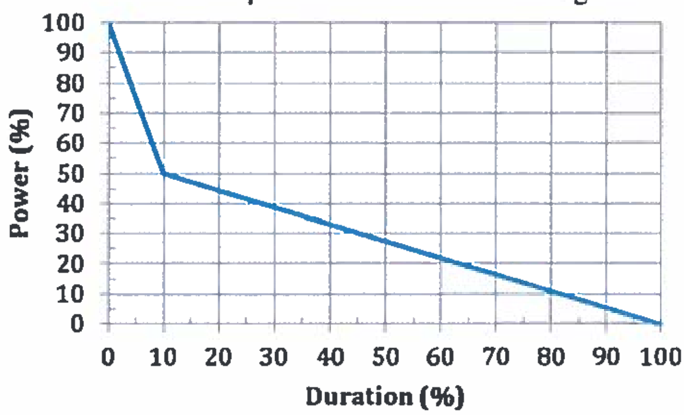


Figure 5.2: Wind farm production duration curve duration (100% = 8760h).

If the wind farm rating is 5 MW (power 100% in Figure 5.2) estimate the annual curtailment of wind energy for different active management techniques:

i) When only active power management is used for voltage control. [5]

For a wind farm of 5 MW, if only active power management is used then, a power above 2.38 MW has to be curtailed. Duration of curtailed energy is therefore:

$$d_a = \frac{10}{100} + \frac{100-10}{0-50}\left(\frac{1.73}{5} - \frac{50}{100}\right) = \frac{37.8}{100} = 37.8\%$$

which is $D_a = \frac{37.8}{100}8760 = 3309h$ per year.

And curtailed energy is:

$$e_a = 0.5\left(\frac{100}{100} - \frac{50}{100}\right)\left(\frac{10}{100} - \frac{0}{100}\right) + \left(\frac{50}{100} - \frac{2.38}{5}\right)\left[\left(\frac{10}{100} - \frac{0}{100}\right) + 0.5\left(\frac{37.8}{100} - \frac{10}{100}\right)\right] = \frac{6.19}{100} = 6.19\%$$

This equates to:

$$E_a = e_a \cdot 5 \cdot 8760 = 2{,}709MWh$$

Energy wind farm could potentially produce is:

$$e_W = 0.5\left(\frac{10}{100} - \frac{0}{100}\right)\left(\frac{100}{100} - \frac{50}{100}\right) + \left(\frac{10}{100} - \frac{0}{100}\right)\left(\frac{50}{100} - \frac{0}{100}\right) + 0.5\left(\frac{100}{100} - \frac{10}{100}\right)\left(\frac{50}{100} - \frac{0}{100}\right) = \frac{30}{100} = 30\%$$

i.e.

$$E_W = e_W \cdot 5 \cdot 8760 = 13{,}140MWh$$

Curtailed energy is $\frac{6.19}{30} = \frac{20.62}{100} = 20.62\%$ of possible wind farm generation.

Hint: to save on the above calculation time calculate the energy in the peak triangle

$$e_p = 0.5\left(\frac{100}{100} - \frac{50}{100}\right)\left(\frac{10}{100} - \frac{0}{100}\right) = \frac{2.50}{100} = 2.50\%$$

ii) If a reactive compensation is applied in the busbar 2 and reactive power can be absorbed to compensate for voltage rise effect, so that the wind farm can operate at power factor of 0.95. [5]

If a reactive compensation is added and overall wind farm power factor is 0.95 (cap) then the maximum rating of the wind farm without need for curtailment is

$$pm \approx \frac{\Delta V \cdot V_{rated}}{R - tg(\varphi)X} = \frac{\left(\frac{3}{100}11\right) \cdot 11}{0.3 \cdot 7 - tg(\cos^{-1}0.95)0.4 \cdot 7} = 3.08MW$$

Duration of curtailed energy is therefore:

$$d_b = \frac{0}{100} + \frac{10-0}{50-100}\left(\frac{3.08}{5} - \frac{100}{100}\right) = \frac{7.7}{100} = 7.7\%$$

which equates to $D_b = \frac{7.7}{100}8760 = 674h$ per year.

And curtailed energy is:

$$e_b = 0.5\left(\frac{7.7}{100} - \frac{0}{100}\right)\left(\frac{100}{100} - \frac{3.03}{5}\right) = \frac{1.48}{100} = 1.48\%$$

This equates to:

$$E_b = e_b \cdot 2000 \cdot 8760 = 648MWh$$

Curtailed energy is $\frac{1.48}{30} = \frac{4.93}{100} = 4.93\%$ of possible wind farm generation.

iii) If a coordinated voltage control can be used, which would reduce the voltage at the busbar 1 for 2% (and hence allow additional voltage rise at the wind farm connection point of approximately 2%) combined with the active and reactive power management. [5]

If in addition to the active and reactive power management a coordinated voltage control is added then the maximum rating of the wind farm without curtailment is

$$p_m \approx \frac{\Delta V \cdot V_{rated}}{R - tg(\varphi)X} = \frac{\left(\frac{3+2}{100}11\right) \cdot 11}{0.3 \cdot 7 - tg(\cos^{-1} 0.95)0.4 \cdot 7} = 5.13MW$$

Hence there is no curtailed energy expected i.e. an active power management is not needed.