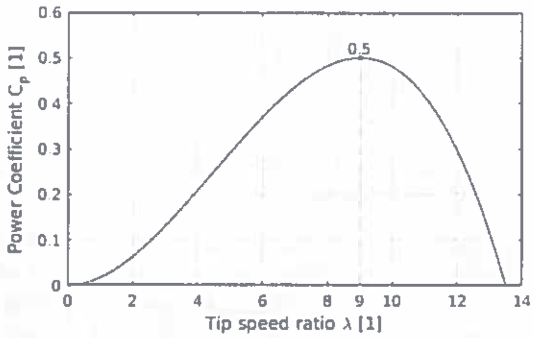
EE4-50 SOLUTIONS

There are five questions; answer four.

1. Wind power

a) The power coefficient of a certain wind turbine of radius R= 35 m is described by the following function of the tip speed ratio:



Answer the following questions:

i) What is the power coefficient? [3]

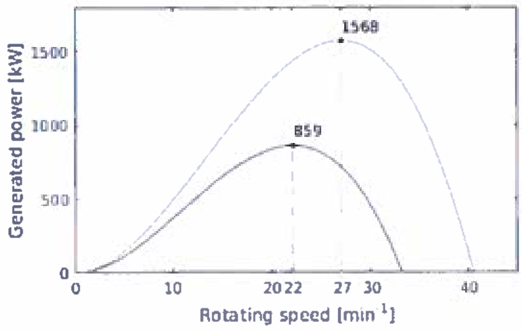
BOOKWORK. The power coefficient, CP, is the ratio between the power extracted by the wind turbine from the airflow and the power that kinetic power of the airflow across the surface swept by the blades of the wind turbine if the wind turbine didn't exert any force over the airflow. An upper bound of the CP can be found by performing a balance of power and mass over a control volume enclosing the airflow that crosses the surface swept by the turbine leading to the so-called Betz limit of 16/27, which is abour 59%. The power extracted by the turbine can be expressed as: $P_T=1/2\cdot\rho\cdot\pi\cdot R^2\cdot v_w^3\cdot C_P$ where ρ is the density of the air, R is the radius of the turbine and v_w is the speed of the wind.

ii) Assuming an air density of ρ=1.225 kg·m^{-3}, what is the maximum power the turbine can generate for a wind speed of v_w=9 m·s^{-1}? What are the rotating speed and the torque of the turbine, T_t and ω_T, for that operating point? [2]

From the plot we see that C_P^{MAX}=0.5; therefore, the turbine can generate up to: $P_T=1/2\cdot\rho\cdot\pi\cdot R^2\cdot v_w^3\cdot C_P^{MAX}$=859 kW. The speed for that operating point can be obtained from the optimal tip speed ratio and $\lambda=\omega_T\cdot R/v_w$, which leads $\omega_T=2.31\ rad/s=22.1\ min^{-1}$. The torque can be obtained by dividing the turbine power by its rotating speed: $T_t=P_T/\omega_T$=372 kN·m.

iii) Sketch the approximate turbine power against the rotating speed for a wind speed of v_w=9 m·s^{-1} and for a wind speed of v_w=11m·s^{-1}. Mark the MPP in the graph. [2]

The curve of power against turbine speed can be obtained precisely from $P_T=1/2\cdot\rho\cdot\pi\cdot R^2\cdot v_w^3\cdot C_P$, however it can be easily sketched as it will have the same shape as the power coefficient curve above with a vertical and horizontal scaling for a given value of the wind speed:

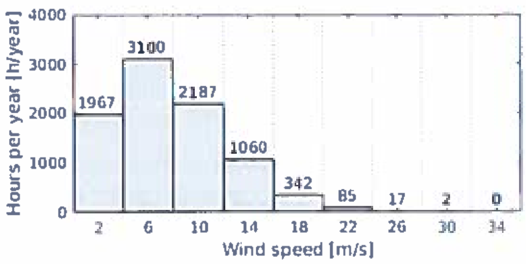


b)

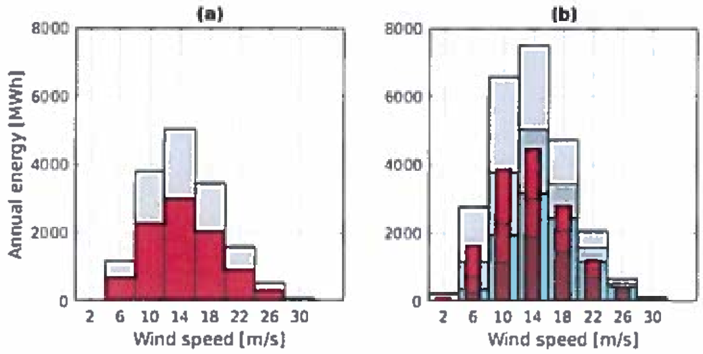
i) **What is the use of the Weibull distribution when calculating the energy yield of a wind turbine?** [2]

The wind speed varies over time due to different phenomena happening at different time scales. When observing the probability of the wind speed over a long period of time, it is found that low wind speeds (~4-5 m/s) are the most frequent; however, the kinetic power available varies with the cube of the wind speed. As a result, most of the energy is found in mid-range wind speeds (~8-10 m/s) above the average. Proper estimates of energy yield of wind turbines must take into account both the kinetic power available and the probability of the wind speed. Experimental wind speed probability plots reveal the underlying probability distribution resembles a Weibull law, which favour the use of this distribution against other distributions such as the Normal law. The two characteristic parameters of the Weibull law can be adjusted from experimental data or be chosen from typical values if no data is available. The equation of the Weibull distribution is used both to derive analytical expressions of the energy yield and to generate simulated wind speed data.

ii) **Which of the frequency ranges (bins in the histogram below) contains more kinetic energy? Justify your answer.** [4]



The energy available for each speed range in the histogram can be obtained by multiplying the average kinetic power that corresponds to each bin by the time the wind speed is within that range. Because we don't know if the probability of the wind speed in each range is uniform, different assumptions can be made to calculate the yield (calculating the average power from the average wind speed, etc). The energy distribution is shown below:



(a) Taking the average wind speed to calculate the average power in each bin. (b) differences between taking the highest, the average or the lowest speed in each bin for the calculation.

Identifying that a speed range above the average wind speed will have greater energy because the kinetic power depends on the cube of the wind speed will give 1 mark even if the exact figure is not calculated. Two marks will be given for those who correctly identify the bin with the highest energy (students are not expected to calculate the energy for all bins). For 3 marks to be given, the student is expected to comment on the issue of calculating the average power without knowing the probability within a bin of the histogram.

c)

i) What were the advantages and the disadvantages of the DFIG (Doubly-Fed Induction Generator) wind turbine when compared to the former SCIG (Squirrel Cage Induction Generator) wind turbine? [3]

BOOKWORK. The SCIG has the advantage of being a simple and robust design. It didn't require a power electronic converter and could use an off-the-shelf squirrel cage machine. On the other hand, being constrained to operate at fixed speed, it would not optimise the use of the turbine at varying wind speeds. It also required reactive power compensation because of the magnetisation of the SCIG.

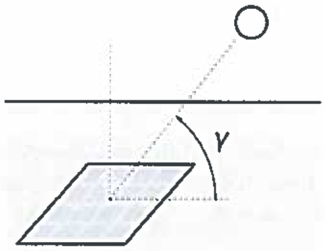
The DFIG enabled variable speed operation by using a power electronic converter connected to the rotor, which makes it possible to improve the power coefficient at varying wind speeds and is also convenient to minimise the stress over the mechanical structure of the wind turbine. The main disadvantage is the cost of the power electronic converter and the wound rotor machine in contrast with the SCIG. This includes not only asset cost but also cost of losses (the converter may conduct around 30% of the power and the current of the stator may be high at sub-synchronous speeds) and the cost of maintenance as well (slip rings of the generator, etc).

ii) Wind turbines have a power limitation (or power reduction) operating region. Explain how they control the power they extract from the wind. [4]

BOOKWORK. The power extracted by the turbine from the airflow depends on the geometry of the turbine, its rotating speed and the wind speed. The methods wind turbine use to reduce the power they extract from the wind at high wind speeds can be classified between active and passive methods. Passive methods were used in early fixed speed wind turbines and they exploited the fact that the power coefficient drops if the wind speed increases but the speed of the turbine is kept constant. Active methods can be based on controlling the speed of the turbine using the torque of the generator to bring it to suboptimal operating conditions with lower CP or they can be based on controlling the blade pitch angle. Two blade pitch angle methods can be used: pitch to feather and pitch to stall. The first is based on decreasing the angle of attack of the blade to produce a smooth reduction of the power extracted, whereas the second is based on increasing the angle of attack to induce stall of the blade, which produces a fast reduction of the power. Full marks will require the students to mention all methods. 3 marks will be given to those who don't mention passive and/or speed-control methods.

2. PV

a) Consider a horizontal PV panel where γ is the elevation angle of the sunrays at a certain time:



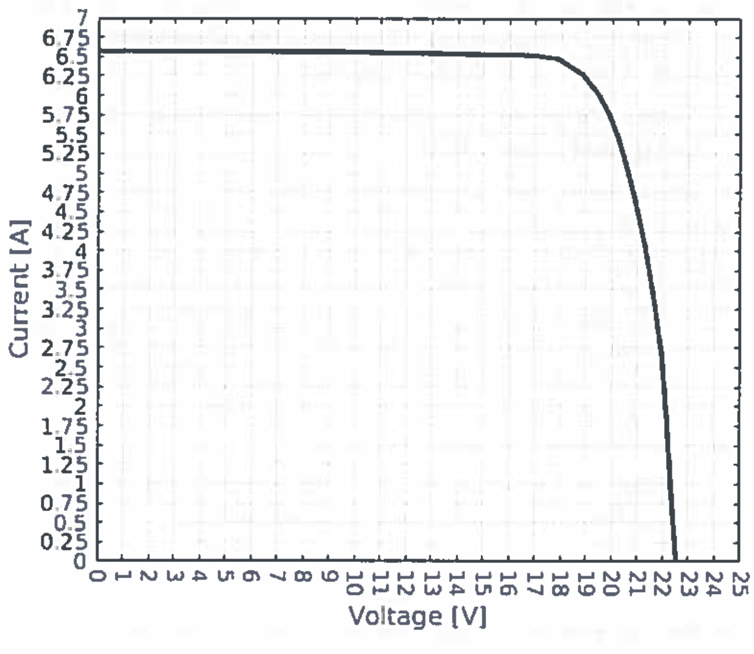
i) Calculate the approximate Air Mass (AM) number if the elevation angle is $\gamma = 62°$ [2]

The AM number is the thickness of air atmosphere that the sunrays have to cross before they reach the surface of the earth in a certain location. A sunray that is perpendicular to the surface of the earth would be received with an AM of 1. The AM can be calculated as: $AM=1/sin(\gamma)$, in this case of $AM=1/sin(62°)=1.13$.

ii) Calculate the total irradiation over the horizontal PV panel (kW) if the surface of the PV panel is S=1.5 m^2, the direct irradiation in the direction of the sunrays is P_{direct}=900 W/m^2, the elevation angle is γ=62° and the diffuse irradiation is $P_{diffuse}$=180 W/m^2. [3]

The direct irradiation is directional, therefore its projection over the horizontal surface must be found as: $P^{surface}_{direct}= P_{direct}\cdot sin(\gamma)$=794.7 W/m^2. The diffuse irradiation is not directional, therefore $P^{surface}_{diffuse}= P_{diffuse}$=180 W/m^2. The total irradiation over the PV panel can be found by adding these two terms together and multiplying by the surface of the panel: $P_{panel}=(P^{surface}_{direct}+P^{surface}_{diffuse})\cdot S$=1462 W.

b) A PV panel with 36 cells and a surface of 0.6 m^2 has the following V-I curve for an irradiation of P= 1,000 W/m^2 and a temperature T=50°C.

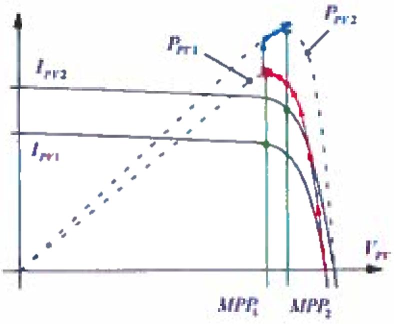


i) Find the coordinates of the MPP of the PV panel: voltage, current and power and calculate the efficiency of the panel at the MPP. [3]

We know that the MPP will be close to the corner in the V-I curve, where both voltage and current are high. Calculating the power for the points in the graph that are close to the corner, we find that the power is maximum for a voltage of 19 V, which gives a current of 6.25 A and therefore 118.25 W. The efficiency can be calculated by dividing the generated power by the total irradiation knowing the surface of the PV panel, the total irradiation is 600 W, therefore the efficiency is 20%.

ii) Describe how a basic perturb-and-observe MPPT algorithm for a PV panel works. Use an illustration of the characteristic curve of the PV panel to explain how the algorithm works. [3]

The characteristic V-I curve of a PV panel changes with the solar irradiation and the temperature of the panel. In order to maximise the generated power, it is necessary to dynamically adapt the current drawn from the PV panel. The perturb-and-observe algorithm, changes the voltage applied by the power electronic converter to trigger changes in the current and therefore the power extracted from the PV panel. The changes are made in small increments and the sign of the increments depends on the previously observed change of the power: if the previous voltage step caused an increase of power. the next step will be done in the same direction. if the power decreased, the direction of the steps will be inverter. This can behaviour is shown in the following V-I plot:



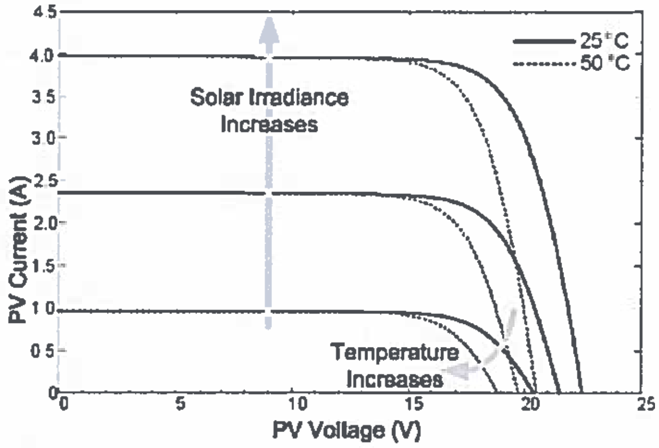
Here the converter starts at the open-circuit voltage of the PV panel and starts decreasing the voltage until a further decrease of the voltage produces a reduction of power. Then the system remains oscillating close to the point of maximum generation. If the irradiation of the panel changes. the system will start "climbing" to the new maximum.

ii) What is the problem of connecting PV cells in series? How would you prevent this problem? [3]

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) Explain how the shape of the V-I curve of a PV cell changes depending on the irradiation and the temperature. [3]

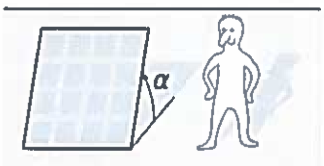
The approximate V-I curve of a PV cell can be obtained from its simplified equivalent circuit. The simplified equivalent circuit of a PV cell has a current source, the magnitude of which is proportional to the irradiation over the PV cell. The current source is connected in parallel with a positive-biased diode, which in turn is connected in parallel with the output leads of the PV cell. When the PV cell is left in open circuit, the diode conducts the current of the current source, when an impedance is connected to the terminals of the PV cell, part of the current is drawn by an external circuit, which can capture energy from the PV cell. If the external impedance is very low (a short-circuit), the voltage across the cell will be close to zero and no current will flow through the internal diode. The V-I curve of the PV panel can be obtained by subtracting the V-I characteristic of the diode from the current of the current source. A change in the temperature of the PV panel causes a change in the V-I curve of the diode, which in turn alters the V-I curve of the PV panel. If the irradiation over the panel is scaled, the V-I curve of the panel is approximately scaled in the I axis. On the contrary, if a change in temperature causes a scaling in the V axis.



Full marks will require justifying the shape of the curve based on the equivalent circuit of the cell.

c)

i) An illuminated traffic sign in London is powered autonomously using a PV panel facing to the South with an inclination angle α of 70º. In contrast, a nearby rooftop PV panel was installed facing to the South with an inclination angle of 20º. Are these angles a reasonable choice? Justify your answer. [3]



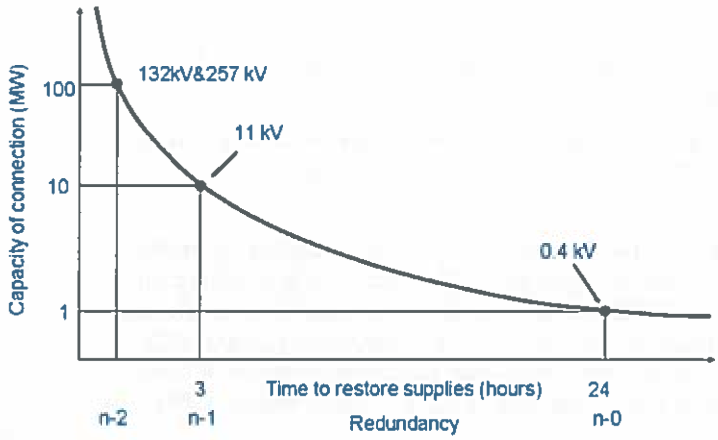
The angle of the sun rays over the surface of the earth varies during the day and across seasons. This is especially noticeable at latitudes far from the equator, such as in the UK. During the summer months, the sun rays are more perpendicular and they become more oblique during the winter months. If a PV panel is to be installed in a fixed position, it would be made to face the South (in the North hemisphere) and its inclination angle would be chosen depending on the latitude and the purpose of the PV panel. In a network-tied application, where the total annual generation is to be maximised, the angle would be chosen to optimise the generation during the months where the irradiation is the strongest. On the contrary, in an autonomous application, the PV panel would not be expected to maximise the energy extracted but to guarantee the minimum required generation during the entire year.

Therefore, special attention would be paid to those months where the irradiation is the lowest. An inclination angle of 70° would maximise the energy extraction during the winter months whereas an angle of 20° would maximise the exposure of the panel during the summer months; therefore the angles described in the question are sensible.

3.

a) Explain the philosophy of the historical distribution network design by considering the relationship between the amount of peak demand that can be disconnected (lost) due to network outages and the allowed time to restore it. Sketch this relationship and indicate how level of redundancy changes with the level of peak demand to be supplied. [4]

For a full mark an appropriate discussion of this diagram is required.



Where:

- n-0 = no redundancy in security (must wait for repair of network); n-1 = one level of network redundancy; and n-2 = two levels of network redundancy.

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. A simplified illustration of this network design philosophy is presented in Figure above. For instance 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.

b) Why is it important to consider the contribution that distributed generation can make to distribution network security? How that may impact the competitiveness of distributed generation against large-scale central generation? [4]

For the full mark a discussion on the commercial integration of DG is required. Only when the impact of DG on network design is established, i.e. benefits and costs that DG brings / imposes, integration can be achieved. The importance of integration (location), at a high level, is illustrated by the value chain from power generation to consumption. Electricity produced by centralised generation is sold in the wholesale market for around 6p/kWh; by the time this electricity reaches the end consumer it is being sold at a retail price of between 8-14p/kWh. This increase in value is driven by the added cost of transmission and distribution services to transport electricity from the point of production to consumption and supplier services. DG however, located close to demand, may be delivering electricity directly to consumers with limited requirement for use of the network. This power may therefore have a higher value than that of conventional generation (e.g. an equivalent value of between 2-8 p/kWh) due to the potential of DG to reduce the demand for distribution and transmission network capacity and corresponding costs. Intermittent generation generally cannot substitute for network assets and hence would not be associated with embedded benefits.

c) Explain the concept of "capacity value" of distributed generation and the method of calculating it. [3]

Capacity value is the ability of generation to displace energy and generation of conventional plant. It is defined as the capacity of 100% reliable network that would deliver the same Expected Energy Not Served.

d) Four distributed generation units are connected to the system via an overhead line as schematically shown in Figure Q3.1. The shape of the load duration curve during winter period (2,200 hours) is shown in Figure Q3.2. Knee point is at duration of 200 hours and power of 0.75 p.u. Minimum power is 0.25 p.u. at 2,200 hours. Calculate the contribution to network capacity of these four identical distributed generation units, each of 2.5 MW and availability of 90%. [9]

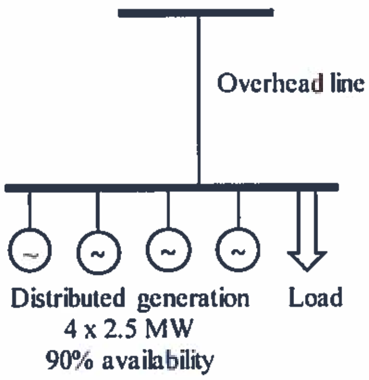


Figure Q3.1

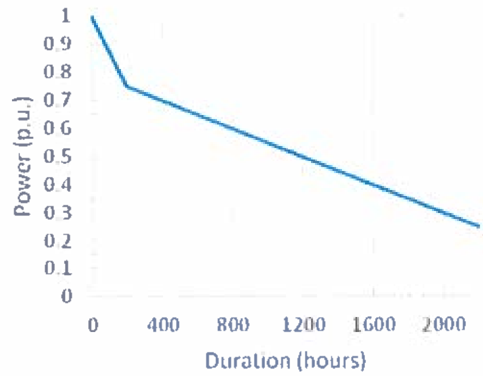


Figure Q3.2

Peak Demand (PD) for calculation of DGs contribution is 4 x 2.5 = 10 MW.

Capacity outage probability table could be created:

Capacity in (MW)	Probability	Lost load (MWh)	EENS (MWh)
10	0.6561	0	0
7.5	0.2916	0.5 x 2.5 x 200 = 250	0.2916 x 250 = 72.9
5	0.0486	250 + 2.5 x 200 + 0.5 x 2.5 x 2000 = 2,000	0.0486 x 2,000 = 97.2
2.5	0.0036	250 + 5 x 200 + 0.5 x 5 x 2000 = 6,250	0.0036 x 6,250 = 22.5

0	0.00 01	6,250 + 2.5 x 2,200 = 11,750	0.0001 x 11,750 = 1.175

Total EENS = 72.9 + 97.2 + 22.5 + 1.175 = 193.775 MWh per winter period.

Given that the EENS is lower than energy in the peak triangle contribution is greater than 75%. The Firm Capacity is then obtained from the following equation:

$$(PD - FC) \cdot 200 \cdot \frac{(PD - FC)}{2.5} = EENS$$

Firm capacity is then 8.4437 MW and contribution 8.4437/10 = 0.84437 i.e. about 84%.

4.

a) What could limit the amount of Distributed Generators that can be connected to urban and rural distribution networks respectively? [4]

Discussion about the following points would suffice for full mark:

- urban distribution networks:
  - fault level limits thermal
  - network thermal limits
- rural distribution networks:
  - voltage rise effect i.e. voltage limits in "weak" network

b) What control strategies and technologies could be applied to enhance the ability of the existing network to accommodate increased capacity of distributed generation? [4]

Discussion about the following points would suffice for full mark:

- Fault current limiters
- generation curtailment
- local reactive power compensation
- area voltage control
- inline voltage regulator
- network reinforcement

c) Wind farm developer "West Sussex Wind" has applied for a connection of a wind farm to local distribution network. In order to facilitate this connection distribution network planning engineers need to investigate voltage rise effect that might occur on the network presented in Figure Q4 below. The On Load Tap Changing (OLTC) transformer is currently set to maintain the voltage at busbar B at 1.03 p.u. The minimum demand at connection point is 10% of the maximum demand.

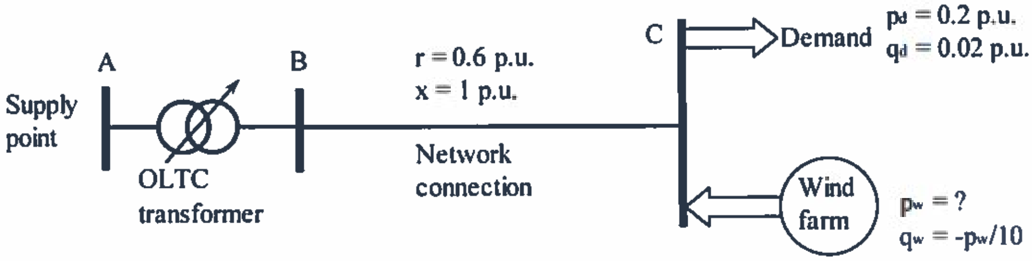


Figure Q4

i) Estimate the amount of wind generation that "West Sussex Wind" could connect to the network if the allowable voltage variation in the network is +/- 6%. [6]

The critical condition, which limits the amount of wind generation that can be connected, is minimum demand condition. Only 0.088 p.u. of wind generation can be connected.

$$v_C = v_B - \left[(p_d - p_w)r + \left(q_d + \frac{p_w}{10}\right)x\right] = 1.06$$

maximum demand condition

$$p_w = \frac{v_C - v_B + p_d r + q_d x}{r - \frac{x}{10}} = \frac{1.06 - 1.03 + 0.2 \times 0.6 + 0.02 \times 1}{0.6 - \frac{1}{10}} = 0.34\, p.u.$$

minimum demand condition

$$p_w = \frac{v_C - v_B + p_d r + q_d x}{r - \frac{x}{10}} = \frac{1.06 - 1.03 + 0.02 \times 0.6 + 0.002 \times 1}{0.6 - \frac{1}{10}} = 0.088\, p.u.$$

ii) What would be the maximum amount of generation that "West Sussex Wind" could connect if a reactive compensation of 0.02 p.u. is also connected to busbar C? [3]

The maximum amount of generation that could be connected if a reactor q_c = -0.02 p.u is also connected to busbar C is

$$\boldsymbol{v_C = v_B - \left[(p_d - p_w)r + \left(q_d + \frac{p_w}{10} - q_c\right)x\right] = 1.06}$$

$$\boldsymbol{p_w = \frac{v_C - v_B + p_d r + (q_d - q_c)x}{r - \frac{x}{10}} =}$$

$$\boldsymbol{= \frac{1.06 - 1.03 + 0.02 \times 0.6 + (0.002 - (-0.02)) \times 1}{0.6 - \frac{1}{10}} = 0.128\, p.u.}$$

iii) In order to increase further the amount of generation that can be connected to the network, distribution planning engineers are considering modifying the control set point of OLTC to 1.01 p.u. How much more generation would be possible to connect? [3]

If control set point of OLTC is set to 1.01 p.u. the maximum generation that can be connected is:

$$p_w = \frac{v_C - v_B + p_d r + q_d x}{r - \frac{x}{10}} = \frac{1.06 - 1.01 + 0.02 \times 0.6 + 0.002 \times 1}{0.6 - \frac{1}{10}} = 0.128\, p.u.$$

therefore the increase if 0.128 – 0.088 = 0.04 p.u.

5.

a) In 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 advantages and disadvantages of providing reserves for managing uncertainty in wind generation production by part-loaded Combined Cycle Gas Turbines (spinning reserve) and 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) Discuss the advantages and disadvantages applying demand side response in providing flexibility and peak demand reduction. [3]

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.

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

- 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) In order to achieve the UK's 2050 CO_2 80% reduction target, heat will need to be decarbonised.

i) Briefly outline the benefits and drawbacks of a district heating system. [4]

- 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.

ii) 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]

Assume: Gas boiler efficiency is 90% and 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

iii) 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]

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