IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2012

EEE PART IV: MEng and ACGI

SUSTAINABLE ELECTRICAL SYSTEMS

Friday, 11 May 10:00 am

Time allowed: 3:00 hours

There are FIVE questions on this paper.

Answer FOUR questions.

All questions carry equal marks.

Any special instructions for invigilators and information for candidates are on page 1.

Examiners responsible First Marker(s) : G. Strbac
Second Marker(s) : T.C. Green

1.

a) Figure 1.1 shows the power produced by a particular turbine blade (with a radius of 35 m) as a function of rotational speed for a variety of wind speed.

i) Define, including appropriate equations, the tip speed ratio, λ and the power coefficient, C_P of a turbine. [3]

ii) Explain why, for each wind speed, there is a peak power production at a particular rotational speed. [3]

iii) Estimate the tip speed ratio required to achieve maximum power for the turbine in figure 1.1. [2]

iv) Estimate the power coefficient of the turbine (assuming air density is 1.25 kg/m^3). [3]

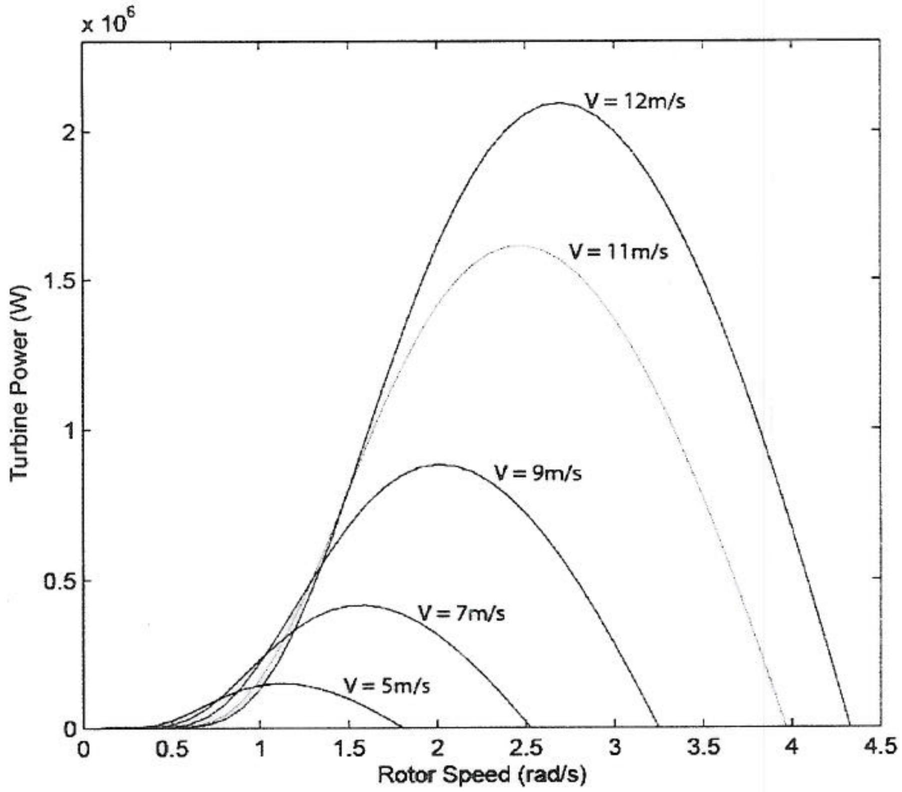

Figure 1.1, Turbine power against rotor speed

b) Figure 1.2 illustrates how various variables of a turbine system change with wind speed under the actions of a typical wind turbine control system.

i) Explain why two different control regions are apparent. [4]

ii) Explain how operation at the optimal tip speed ratio is achieved at low wind speeds. [3]

iii) Explain how the turbine power is controlled at high wind speeds. [2]

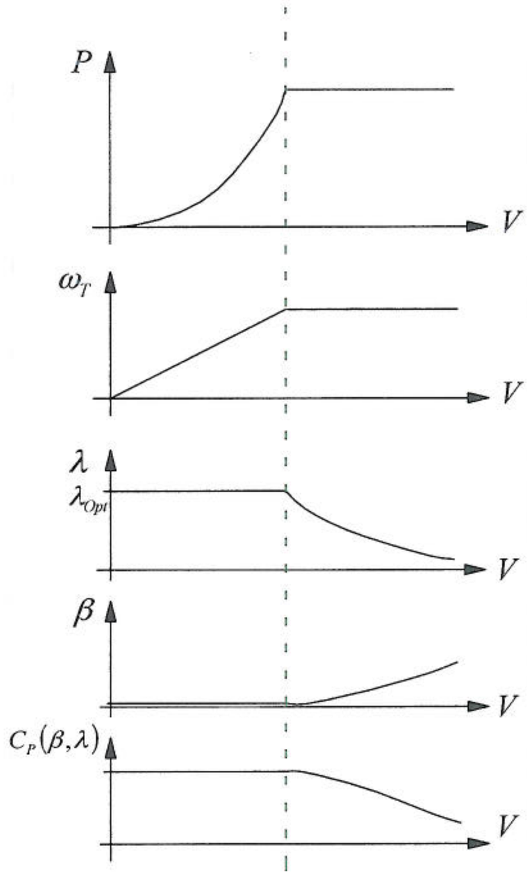

Figure 1.2 Variation under turbine control action of power, rotor speed, tip speed ratio, pitch angle and power coefficient as function of wind speed.

2.

a) The output characteristic for a photovoltaic cell is shown in figure 2. Cells of this type are to be built into an array composed of a number of cells in series to form strings with a number of stings placed in parallel,

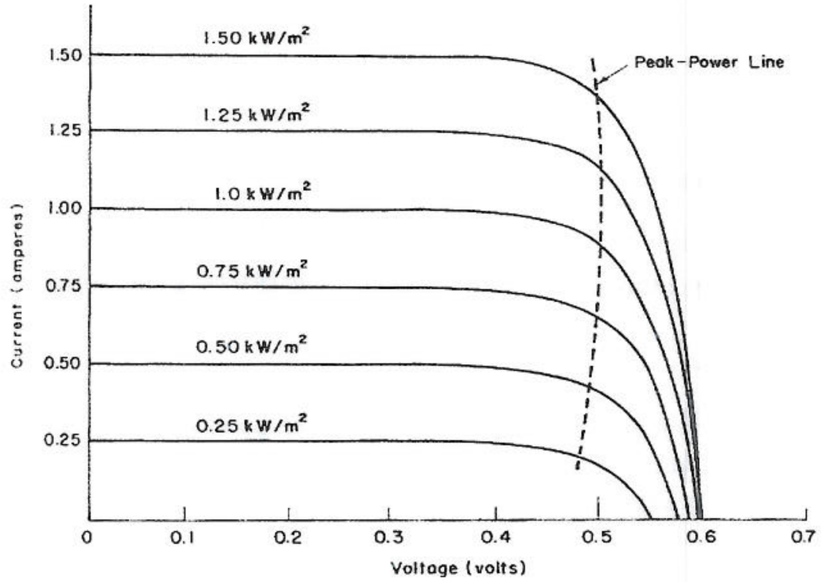

Figure 2, Output characteristic of a PV cell

i) Explain the meaning the term short circuit current and its relationship to the solar irradiance. [2]

ii) Sketch the power output profile of a single cell at 1 kW/m^2 and explain the meaning of the term maximum power point. [2]

iii) Explain how "bypass diodes" can be used to improve the operation of the array. [3]

iv) Explain how "string diodes" can be used to improve the operation of the array. [2]

v) An array is formed of 4 parallel strings of 72 cells in series. Sketch the output characteristic of the array at 1 kW/m^2, assuming no shading of the cells, and estimate the open circuit voltage and short circuit current of the array. [4]

b) Discuss the ways in which the array of part (a) could be interfaced to a 48 V battery. [3]

c) In order to maximise the output of the array, it has been suggested that the panels should be mounted on frames that can be directed towards the sun throughout the day.

i) Explain why this arrangement would improved the output of the panels [2]

ii) Suggest two ways in which the position of the sun could be estimated in order to track the panels. [2]

3.

a) Compare and contrast the variability of energy output of these four renewable energy technologies: solar PV energy; hydroelectric energy; tidal energy and wave energy. [5]

b)

(i) State the advantages of tidal stream turbines over tidal lagoons. [1]

(ii) Describe how pumping is used to augment tidal lagoon operation. [2]

(iii) State the advantages of wave energy converters over offshore wind turbines? [2]

c) In order to achieve the UK's CO_2 reduction target for 2050 of 80%, reductions in the heat sector will need to be significant. List measures that can be taken to reduce CO_2 emissions associated with heat demand. [5]

d) A local housing authority presently provides space and water heating to its properties by natural gas, which has CO_2 emissions of 200g/kWh. It has set itself an aggressive CO_2 reduction target and is investigating other forms of space and water heating. It been advised that the average efficiency of the space and water heating appliances in its properties is 90% whereas electric heat pumps have an average efficiency of 270%.

i) What information is required to determine whether or not the installation of electric heat pumps will lead to a reduction in CO_2 emissions? [2]

ii) Make reasonable assumptions for the data needed and compare the CO_2 emissions for natural gas and the heat pump alternative. [3]

4.

a) Explain how the contribution of distributed generation to network security can be quantified. List the strengths and weaknesses of the method used in the UK. [5]

b) Two generators of capacities 20 MW and 30 MW and fuelled by landfill gas are connected to a 66 kV substation as shown in Figure 4. The figure also shows the load duration curve for winter of the load connected to this network. Quantify the contribution to network security that would be provided by the two generators if the availabilities of the individual generation units are 85% for the 20 MW unit and 90% for the 30 MW unit. [10]

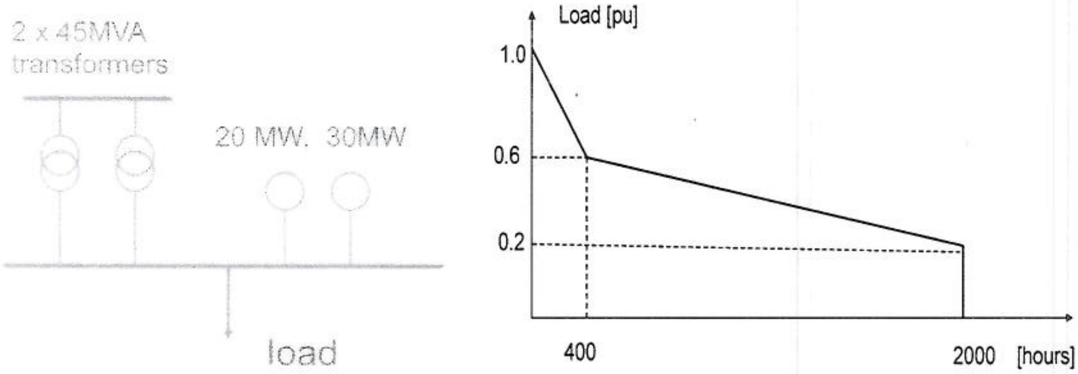

Figure 4, Substation arragnement and load duration curve.

c) Describe how one would quantify the maximum Group Demand that this system would be considered to be able to supply securely and perform the calculation. [5]

5.

a) Describe what limits the amount of Distributed Generators that can be connected to rural and urban distribution networks. [4]

b) Describe how can "active network management" enhance the ability of the existing distribution networks to accommodate increased capacity of distributed generation. [4]

c) A landfill gas plant is to be connected to a weak distribution feeder shown in Figure 5. The demand varies between the maximum indicated in Figure 5 and a minimum that is 10% of the maximum.

i) Estimate the amount of landfill gas generation that could connect to the network if the allowable voltage variation in the network is +/- 5%. The On Load Tap Changing (OLTC) transformer is set to maintain the voltage at busbar B in figure 5 at 1.02 p.u. [6]

ii) Calculate the maximum amount of generation that could connect if the generator absorbs a reactive power of 0.01 p.u. [3]

iii) In order to increase further the amount of generation that can be connected to the feeder, it is proposed to modify the control set point of the OLTC to 1.00 p.u. Calculate how much more generation it would be possible to connect. [3]

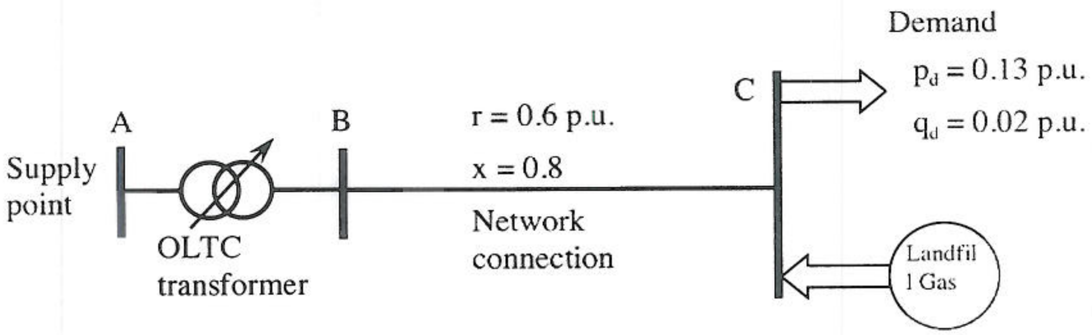

Figure 5, A landfill gas generator on a weak distribution feeder.

1.

a) Figure 1.1 shows the power produced by a particular turbine blade (with a radius of 35 m) as a function of rotational speed for a variety of wind speed.

i) Define, including appropriate equations, the tip speed ratio, λ and the power coefficient, C_P of a turbine. [3]

[Book work]

Tip speed ratio is the ratio of the linear velocity of the tip of the turbine blade (at the tip radius R and rotating at angular speed ω) to the velocity of the wind, V.

$$\lambda = \frac{\omega R}{V}$$

[1 mark]

The power coefficient is defined as the ratio of the power realised by a particular turbine to the power that could be achieved if all the kinetic energy of the air passing over the blades was extracted (which is not possible).

$$C_P = \frac{P}{\frac{1}{2}A\rho V^3}$$

[1 mark for definition; 1 for equation]

ii) Explain why, for each wind speed, there is a peak power production at a particular rotational speed. [3]

[Bookwork]

This is most readily explained in terms of the tip speed ratio which varies as the rotation speed varies (for a given wind speed). Air over the blade has two components of velocity: arising from the wind and one arising from blade cutting the air as it rotates. These are perpendicular components which together define the airspeed over the blade and the angle of attack. The lift forces on the aerofoil, which cause the rotation, depend on the angle of attack. If the blade rotates slowly, the angle of attack increase and the blade stalls. If the blade rotates too quickly, the angle of attack decreases and the lift reduces. There is an optimum angle of attack for producing lift and therefore and optimal tip speed ratio and an optimal rotational speed for each wind speed.

[1 mark for using concept of angle of attack; 1 for link to two flow components and for linking optimal lift to optimal speed]

iii) Estimate the tip speed ratio required to achieve maximum power for the turbine in figure 1.1. [2]

[Interpretation and calculation]

Taking the 12 m/s curve, the peak occurs at approx. 2.75 rad/s

$$\lambda = \frac{\omega R}{V} = \frac{2.75 \times 35}{12} = 8.1$$

[1 mark method; 1 for answer]

iv) Estimate the power coefficient of the turbine (assuming air density is 1.25 kg/m^3). [3]

[Calculation in unusual form]

Taking the 12 m/s curve, the peak of 2.1 MW occurs at approx. 2.75 rad/s

$$C_P = \frac{P}{\frac{1}{2}A\rho V^3} = \frac{2.1\times10^6}{\frac{1}{2}\pi 35^2\times1.25\times12^3} = 0.49$$

[2 marks method; 1 for answer]

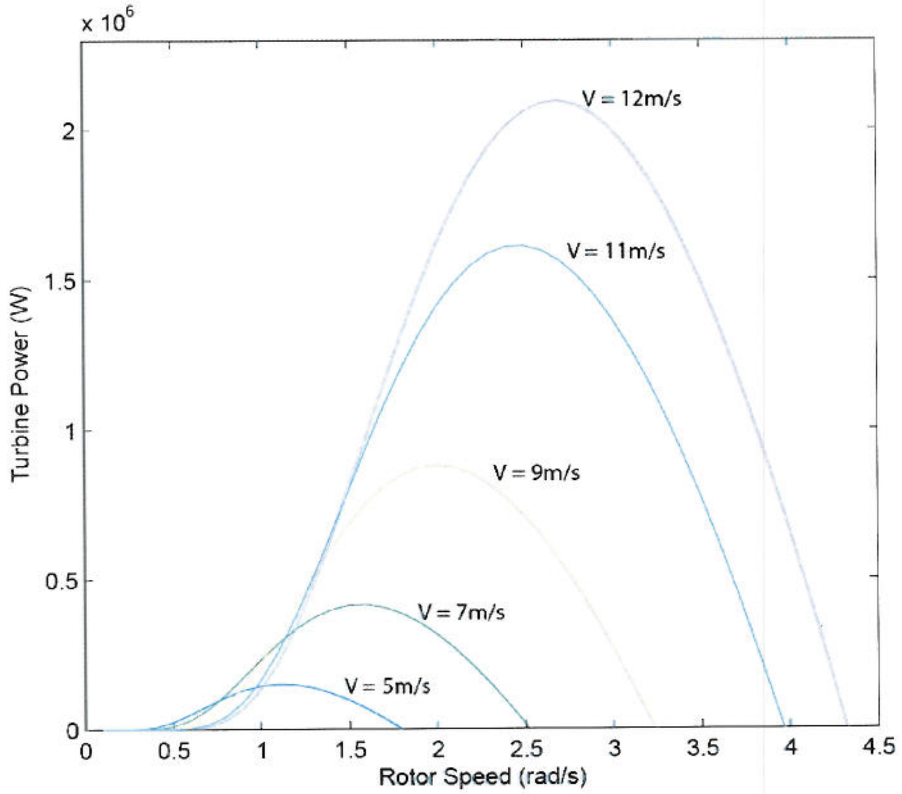

Figure 1.1, Turbine power against rotor speed

b) Figure 1.2 illustrates how various variables of a turbine system change with wind speed under the actions of a typical wind turbine control system.

i) Explain why two different control regions are apparent. [3]

[Summary of principles expressed in notes – 3 marks]

The obvious control objective is to run the turbine at the tip speed ration that optimises the power yield. This is seen in the left hand portion of the diagram. The distribution of wind speeds over a year reveals that high speeds occur rarely and their probability declines rapidly after about 12 m/s. The forces to be withstood to generate from these high speeds means that the turbine (blade and drive train) costs rise steeply. The economic optimisation of the turbine design points to limiting the drive train power and rotational speed above some threshold in the region of 12 m/s. The reduction in energy yield is small.

ii) Explain how operation at the optimal tip speed ratio is achieved at low wind speeds. [3]

[Summary of principles expressed in notes – 3 marks]

In principle one could measure wind speed, calculate the optimal rotational speed and exercise closed lop control of the speed by varying the current (hence reaction torque) of the generator. Instead, the process is reversed. A natural equilibrium point will exist between the torque characteristic of the blades (as a function of wind rotor speed) with torque of the generator if the generator reaction torque is set to the torque expected for optimal conditions (as calculated from power equation at optimal tip speed ratio).

$$T_G = \tfrac{1}{2}\rho A_T C_{Pmax} \frac{\omega_T^2 R^3}{\lambda_{opt}}$$

So long as the generator torque is set to this function of rotational speed, the turbine will settle to the optimal tip speed.

iii) Explain how the turbine power is controlled at high wind speeds. [2]

[Bookwork – 2 marks]

To reduce the power developed by the blades, the blades are pitched into the wind to reduce the angle of attack for a given rotational speed. Pitching requires actuators to rotate the blades around their own axis. Once the maximum power of the turbine drive train is reached, the blade pitch angle is made the subject of a closed loop speed control system operated wit ha constant speed reference.

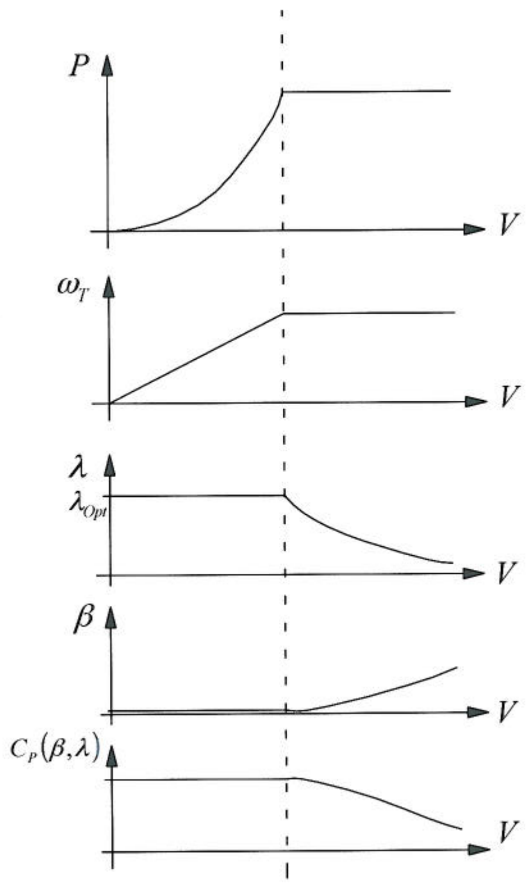

Figure 1.2 Variation under turbine control action of power, rotor speed, tip speed ratio, pitch angle and power coefficient as function of wind speed.

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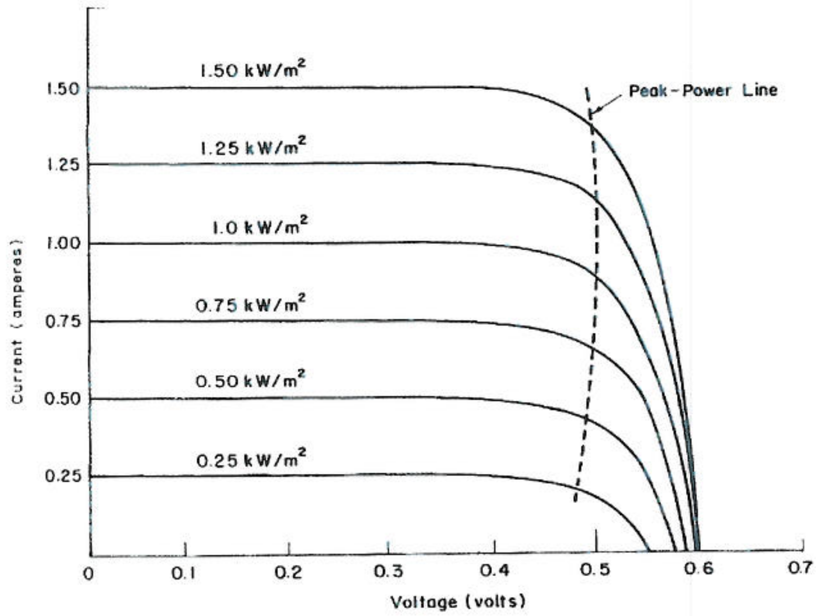


Figure 2, Output characteristic of a PV cell

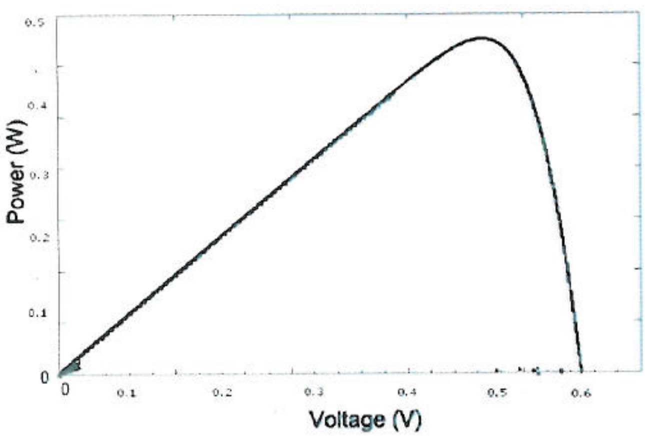
i) Explain the meaning the term short circuit current and its relationship to the solar irradiance. [2]

Short Circuit Current is the current that a solar cell will produce when no load is applied to the terminals (i.e. the cell is short circuited). It is the leftmost point on the cell characteristic. [1 mark]

Short circuit current is directly proportional to the solar irradiance [1 mark]

ii) Sketch the power output profile of a single cell at 1 kW/m^2 and explain the meaning of the term maximum power point. [2]

[1 Mark]

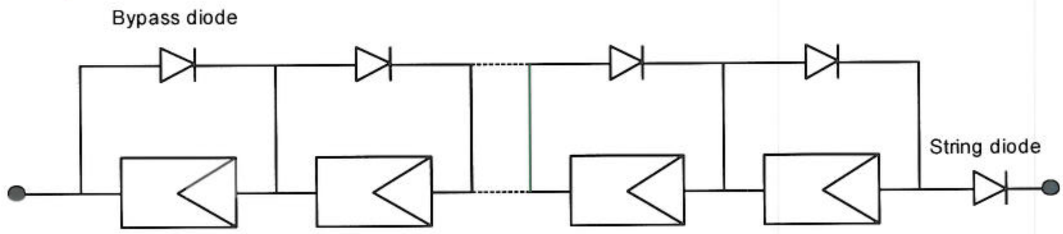


Maximum power point is the point on the cell characteristic that corresponds to the peak of the power curve, i.e. the point at which most solar energy is converted into electrical energy. [1 Mark]

iii) Explain how "bypass diodes" can be used to improve the operation of the array. [3]

When a cell in a series string is shaded, its output falls in proportion to the solar radiation incident on that cell. This limits the maximum current that the cell can conduct in forward bias. If the other cells in the string are still in strong sunlight, they will reverse bias the cell and start to force current through the cell so that it dissipates the excess energy and limits the overall current the string can produce.

Bypass diodes are placed across cells so that if this happens, the diode conducts excess current around the shaded cell. This removes the limitation on the maximum string current imposed by the cell and also reduces the amount of heat that is dissipated by the shaded cell.



iv) Explain how "string diodes" can be used to improve the operation of the array. [2]

If a cell in a string becomes shaded, the maximum voltage that that string can produce is reduced. [1 mark]

Without a string diode, this string would become reverse biased by the other parallel strings, dissipating energy. The string diode stops this reverse current in the shaded string, but it also stops the string from generating any energy. [1 mark]

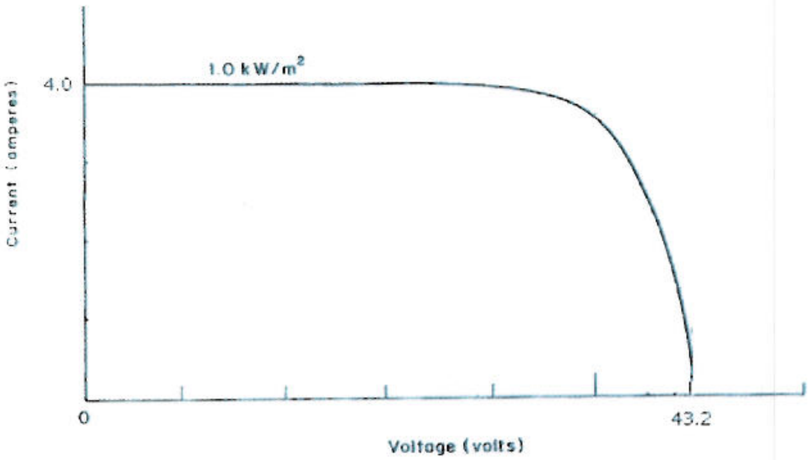
v) An array is formed of 4 parallel strings of 72 cells in series. Sketch the output characteristic of the array at 1 kW/m^2, assuming no shading of the cells, and estimate the open circuit voltage and short circuit current of the array. [4]

Array short circuit current = cell SC current x parallel strings = 1A x 4 = 4 Amps

[1 mark]

Array open circuit voltage = cell OC voltage x series cells = 0.6V x 72 = 43.2 V

[1 mark]



[2 marks]

b) Discuss the ways in which the array of part (a) could be interfaced to a 48 V battery. [3]

The open circuit voltage of the array is too low to assume that it will ever be able to charge the battery directly, even in strong sunlight. Therefore some form of power converter is needed. [1 mark]

In this case, a simple boost DCDC converter would be adequate. [1 mark]

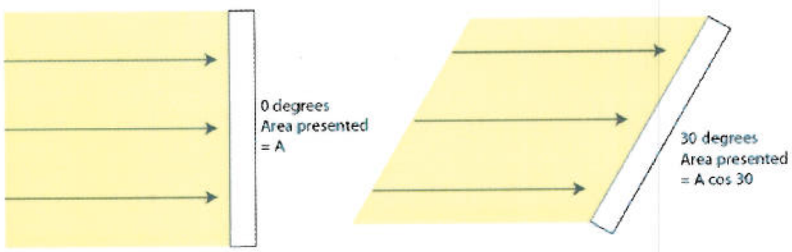
In order maximise the energy collected by the equipment, a maximum power point tracking algorithm should be used to control the output current of the converter.

[1 mark]

c) In order to maximise the output of the array, it has been suggested that the panels should be mounted on frames that can be directed towards the sun throughout the day.

i) Explain why this arrangement would improved the output of the panels [2]

Incident solar radiation is measured in W/m^2. Therefore, the energy collected by a solar panel is related to the area of the array presented to the incoming radiation, in a direction perpendicular to the solar radiation. If the panel is not arranged so that the light hits it in a perpendicular direction, then the area of the panel is not optimised and energy is lost.



ii) Suggest two ways in which the position of the sun could be estimated in order to track the panels. [2]

A semi cube that has an arrangement of photosensitive cells that can determine when a panel is not perpendicular to the sun could be used.

Astronomical calculations could be used that accurately predict the position of the sun based on physical location of the panel on the earth

For low cost installations (in Africa or India) a person can manually adjust the panels using their eye to determine when the panel is aimed at the sun!

[1 mark for each answer provided]

3.

a) Compare and contrast the variability of energy output of these four renewable energy technologies: solar PV energy; hydroelectric energy; tidal energy and wave energy. [5]

[Book work]

Solar PV and wave energy are probably the most variable of these renewable energy types.

PV only produces energy when the sun shines. However, whilst the level of solar radiation at a specific location under perfect conditions is very predictable, the availability of that solar radiation on a specific solar panel is too dependent on unpredictable factors, like cloud cover, to give a guaranteed energy output.

Waves are essentially created by winds out in the deep oceans and share a similar variability with that form of renewable energy. Whilst certain locations have a significant incidence of waves, a stochastic model of this occurrence would be needed to predict annual energy output.

Hydroelectric and tidal energy, by contrast are extremely predictable.

The level and time of tides can be predicted for many years ahead. However, tides do not follow a 24 hour schedule, so the availability of tidal energy is not always well correlated with the demand profile.

Hydroelectric energy is probably the most consistent, as well as the most mature of the renewable technologies. The primary energy source is not so dependent on weather and indeed can be controlled or even stored by the operator and even in times of low water, the change in the availability of the primary energy source is slow and can be factored into future calculations.

b)

(i) State the advantages of tidal stream turbines over tidal lagoons. [1]

[Book work]

Tidal stream and tidal lagoons both utilise the energy from tides but tidal lagoons require massive civil works that affect the wildlife, landscape and shipping in the areas in which they are constructed.

(ii) Describe how pumping is used to augment tidal lagoon operation. [2]

[Book work]

Tidal lagoons can only generate when the tide is flowing and this is not always well correlated with demand. Pumping is used to pump additional water into the high level basin (ebb generation) or out of the low level basin (flood generation) if demand is low. This delays the emptying of the lagoon so that the energy is available at a time more in keeping with the demand peaks.

(iii) State the advantages of wave energy converters over offshore wind turbines? [2]

[Book work]

Wave energy converters utilise an energy resource that is no less predictable than offshore wind turbines. However, wind turbines are often situated hundreds of kilometres from shore necessitating HVDC transmission systems to bring the energy ashore. Wave energy converters are expected to be installed close in to shore. This means that the energy generated needs to be transferred a much shorter distance to the grid requiring simpler connection methods.

c) In order to achieve the UK's CO_2 reduction target for 2050 of 80%, reductions in the heat sector will need to be significant. List measures that can be taken to reduce CO_2 emissions associated with heat demand. [5]

[Bookwork]

Reducing demand for energy in buildings

- Improving building heat efficiency through the introduction of the Green Deal, Energy Company Obligation, building standards.
- Improving the electrical efficiency of lighting and appliances through the introduction of minimum performance standards
- Changing behaviour to reduce demand through the introduction of smart meters, Energy Performance Certificates, Display Energy Certificates, Carbon Reduction Commitment and improved Energy controls.

[2 marks]

Technologies for decarbonising heating include:

- Biomass boilers
- Electrical resistance heating
- Heat pumps.
- Micro-combined heat and power (CHP)
- Solar thermal hot water
- Combined heat and power (CHP) and heating networks

[3 marks]

d) A local housing authority presently provides space and water heating to its properties by natural gas, which has CO_2 emissions of 200g/kWh. It has set itself an aggressive CO_2 reduction target and is investigating other forms of space and water heating. It been advised that the average efficiency of the space and water heating appliances in its properties is 90% whereas electric heat pumps have an average efficiency of 270%.

i) What information is required to determine whether or not the installation of electric heat pumps will lead to a reduction in CO_2 emissions? [2]

[Bookwork]

In order to determine the CO_2 emissions from the electric heat pumps, the CO_2 emissions from grid-supplied electrical energy is required. This can be determined from emissions from figures for generation adjusted for network losses.

[2 marks]

ii) Make reasonable assumptions for the data needed and compare the CO_2 emissions for natural gas and the heat pump alternative. [3]

[Calculation]

Assuming the CO_2 emissions from generation is 500g/kWh and network losses are 10%, then the average CO_2 emissions from an electric heat pump is:

$$\frac{\text{Generation } CO_2 \text{ emissions}}{(\eta \text{ of network} * \eta \text{ of electric heat pumps})} = \frac{500}{(90\% * 270\%)} = 185\text{g/kWh}$$

This compares with the present average CO_2 emissions from natural gas heating which are:

$$\frac{\text{Average natural gas } CO_2 \text{ emissions}}{(\eta \text{ of gas appliances})} = \frac{200}{(90\%)} = 222\text{g/kWh}$$

Hence, electric heat pumps will result in a reduction in CO_2 emissions.

[1 mark for estimated data, 1 for method; 1 for numeric answers]

4.

a) Explain how the contribution of distributed generation to network security can be quantified. List the strengths and weaknesses of the method used in the UK. [5]

[Bookwork]

The method for quantifying the contribution of distributed generation to network security requires the analysis of the ability of generation to substitute for network reinforcement. The process of applying this approach can be summarised as: calculate the expected energy not supplied of a specific distributed generation system with corresponding load duration curve; determine the ideal network line capacity which can give the same EENS as the generation system; the line capacity is the effective capacity of distributed generation system.

[2 marks]

The method used in current UK distribution network explicitly reflects the inherent probabilistic characteristics of distributed generation types present and the expected energy curtailed in outages of studied period. It can be easily understood and computed by DNOs. However, this method cannot deal with the frequency and duration of outages during the time period, is not able to differentiate risk to different customers and hence it is not directly related to customer cost of outage but only system property based method.

[3 marks]

b) Two generators of capacities 20 MW and 30 MW and fuelled by landfill gas are connected to a 66 kV substation as shown in Figure 4. The figure also shows the load duration curve for winter of the load connected to this network. Quantify the contribution to network security that would be provided by the two generators if the availabilities of the individual generation units are 85% for the 20 MW unit and 90% for the 30 MW unit. [10]

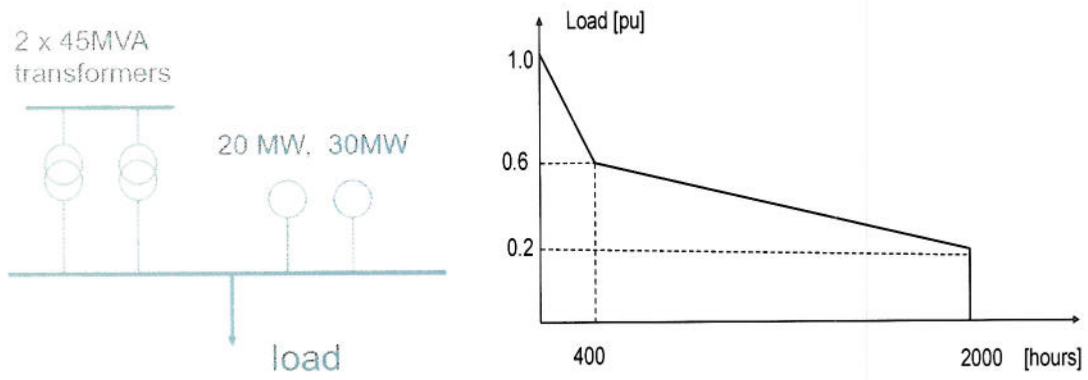


Figure 4, Substation arragnement and load duration curve.

[Calculation]

The function of load duration curve can be derived as

$$y = -0.001x + 1\ (0 \le x \le 400)(30 \le y \le 50)$$
$$y = -0.00025x + 0.7\ (400 \le x \le 2000)(10 \le y \le 30)$$

For the analysis of the capacity value of generation systems, we assume that the peak demand is equal to installed capacity of generation (20MW+30MW)=50MW. Hence, the load duration curve is given by:

$$y = -0.05x + 50 (0 \le x \le 400)$$
$$y = -0.0125x + 35\ (400 \le x \le 2000)$$

y is expressed in MW.

[2 marks]

Capability outage probability table of two generators

Generation(MW)	Probability	ENS(MWh)
50	0.85*0.9=0.765	0
30	0.15*0.9=0.135	4000
20	0.85*0.1=0.085	12000
0	0.15*0.1=0.015	48000
	EENS	2280

[3 marks]

Since EENS=2280MWh<4000MWh, where 4000MWh is the ENS of generation capacity as 30MW. Thus, y is in the range from 30MW to 50MW.

As described in part (i), an ideal distribution circuit with the capability of y_c should deliver the same EENS as the generation system. Clearly 30<y_c<50, and hence we have

$$y_c = -0.05x_c + 50$$
$$(50 - y_c) * x_c/2 = 2280$$

Then, it can be obtained that

$$x_c = 301.99\ (h)$$
$$y_c = 34.90\ (MW)$$

Therefore, the contribution to network security that would be effectively provided by the two generators, if the availability of individual generation unit is 85% (20 MW unit) and 90% (30 MW unit) is **34.90MW**

[5 marks]

c) Describe how one would quantify the maximum Group Demand that this system would be considered to be able to supply securely and perform the calculation. [5]

[Calculation method and interpretation]

The maximum demand that this system would be considered to be able to securely supply is the sum of the effective capacity of the distribution network and the distributed generation, following outage of one of the transformers.

[2 marks]

Thus, the maximum demand is

C = 1*45 * Cyclic_rating * Load_factor + 34.9

= 45*1.3*0.95 + 34.9

= 55.6+34.9

= 90.5 MW

[3 marks]

5.

a) Describe what limits the amount of Distributed Generators that can be connected to rural and urban distribution networks. [4]

[Bookwork]

For full marks, a short statement about the increased fault levels and voltage rise effects being key limiting factors for connecting Distributed Generators in urban and rural networks respectively is needed.

b) Describe how can "active network management" enhance the ability of the existing distribution networks to accommodate increased capacity of distributed generation. [4]

[Book work]

A short statement is expected highlighting the benefits of active flow and voltage management in terms on enhancing the ability of existing network to absorb distributed generation.

c) A landfill gas plant is to be connected to a weak distribution feeder shown in Figure 5. The demand varies between the maximum indicated in Figure 5 and a minimum that is 10% of the maximum.

i) Estimate the amount of landfill gas generation that could connect to the network if the allowable voltage variation in the network is +/- 5%. The On Load Tap Changing (OLTC) transformer is set to maintain the voltage at busbar B in figure 5 at 1.02 p.u.. [6]

[Calculation]

Maximum demand is

$$p_d = 0.13 \text{ p.u.}$$

$$q_d = 0.02 \text{ p.u.}$$

If

$$\mathbf{V} \approx 1 + \text{j}0.0\text{p.u.}$$

$$\mathbf{I}_{PQ} = \mathbf{I}_{BC} = \frac{p_d - \text{j}q}{1} = 0.13 - \text{j}0.02 \text{ p.u.}$$

$$\mathbf{V}_{r+jx} = \left(\frac{p_d - \text{j}q}{1}\right)(r + \text{j}x) = \frac{(p_d r + qx) + \text{j}(\text{p}x - qr)}{1}$$

$$\text{Real}\left\{\mathbf{V}_{r+jx}\right\} = \frac{p_d r + qx}{1}$$

Then

Voltage for maximum condition

$$v_c = v_B - \frac{p_d r + q_d x}{1} = v_B - p_d r + q_d x = 1.02 - (0.13 \times 0.6 + 0.02 \times 0.8) = 0.926 \text{ p.u.}$$

Voltage for minimum condition

$$v_c = v_B - \frac{p_d r + q_d x}{1} = 1.02 - (0.013 \times 0.6 + 0.002 \times 0.8) = 1.0106 \text{ p.u.}$$

[2 mark for method; 1 for numerical answers]

Maximum active power can be calculated from voltage equation. A more onerous criteria is for the minimum demand condition where only 0.0656 p.u. of wind power can be installed is:

$$v_C = v_B - \left[\left(p_d - p_{lf}\right) r + q_d x\right] = 1.05 \text{ p.u.}$$

Maximum demand condition

$$p_{\text{lg}} = \frac{v_C - v_B + p_d r + q_d x}{r} = \frac{1.05 - 1.02 + \left(0.13 \times 0.6 + 0.02 \times 0.8\right)}{0.6} = 0.2066 \text{ p.u.}$$

Minimum demand condition

$$p_{\text{lg}} = \frac{v_C - v_B + p_d r + q_d x}{r} = \frac{1.05 - 1.02 + \left(0.013 \times 0.6 + 0.002 \times 0.8\right)}{0.6} = 0.0656 \text{ p.u.}$$

[1 mark method; 1 for max answer; 1 for min]

ii) Calculate the maximum amount of generation that could connect if the generator absorbs a reactive power of 0.01 p.u. [3]

[Calculation]

Reactive compensation for q_c = -0.01 p.u. which would increase an allowable voltage gap

$$p_{\text{lg}} = \frac{v_C - v_B + p_d r + \left(q_d - q_c\right) x}{r} = 1.05 \text{ p.u.}$$

Maximum demand condition

$$p_{\text{lg}} = \frac{1.05 - 1.02 + \left(0.13 \times 0.6 + \left[0.02 - (-0.01)\right] \times 0.8\right)}{0.6} = 0.22 \text{ p.u.}$$

Then the generated power will increased

$$\Delta p_{\text{lg}} = 0.0134\text{pu}$$

Minimum demand condition

$$p_{\text{lg}} = \frac{1.05 - 1.02 + \left(0.013 \times 0.6 + \left[0.002 - (-0.01)\right] \times 0.8\right)}{0.6} = 0.0790 \text{ p.u.}$$

Then the generated power will increased by

$\Delta p_{\mathrm{lg}} = 0.0134$ p.u.

[2 marks for method; 1 for numerical answer]

iii) In order to increase further the amount of generation that can be connected to the feeder, it is proposed to modify the control set point of the OLTC to 1.00 p.u. Calculate how much more generation it would be possible to connect. [3]

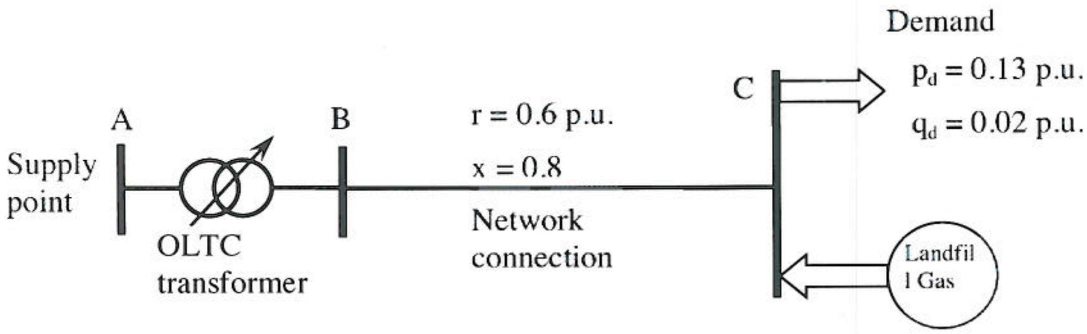


Figure 5, A landfill gas generator on a weak distribution feeder.

[Calculation]

Answer could be calculated with our without the generator drawing reactive power and full marks available for either approach.

[2 marks for method; 1 for numeric answer]

Method 1 (without q_c)

Active power can be calculated from voltage equation.

$$v_C = v_B - \left[\left(p_d - p_{\mathrm{lg}}\right)r + q_d x\right] = 1.05 \text{ p.u.}$$

Maximum demand condition

$$p_{\mathrm{lg}} = \frac{v_C - v_B + p_d r + q_d x}{r} = \frac{1.05 - 1.0 + \left(0.13 \times 0.6 + 0.02 \times 0.8\right)}{0.6} = 0.24 \text{ p.u.}$$

Then the generated power will increased

$\Delta p_{\mathrm{lg}} = 0.02$ p.u.

Minimum demand condition

$$p_{\mathrm{lg}} = \frac{v_C - v_B + p_d r + q_d x}{r} = \frac{1.05 - 1.0 + \left(0.013 \times 0.6 + 0.002 \times 0.8\right)}{0.6} = 0.0990 \text{ p.u.}$$

Then the generated power will increased

$\Delta p_{\mathrm{lg}} = 0.02$ p.u.

Method 2 (with q_c=-0.01)

Active power can be calculated from voltage equation.

$$p_{\lg} = \frac{v_C - v_B + p_d r + (q_d - q_c)x}{r} = 1.05 \text{ p.u.}$$

Maximum demand condition

$$p_{\lg} = \frac{v_C - v_B + p_d r + q_d x}{r} = \frac{1.05 - 1.0 + (0.13 \times 0.6 + 0.03 \times 0.8)}{0.6} = 0.2533 \text{ p.u.}$$

Then the generated power will increased

$$\Delta p_{\lg} = 0.0133 \text{ p.u.}$$

Minimum demand condition

$$p_{\lg} = \frac{v_C - v_B + p_d r + q_d x}{r} = \frac{1.05 - 1.0 + (0.013 \times 0.6 + 0.012 \times 0.8)}{0.6} = 0.1123 \text{ p.u.}$$

Then the generated power will increased

$$\Delta p_{\lg} = 0.0133 \text{ p.u.}$$