IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2013

EEE PART IV: MEng and ACGI

SUSTAINABLE ELECTRICAL SYSTEMS

Thursday, 8 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) :	T.C. Green, R. Silversides, G. Strbac
	Second Marker(s) :	G. Strbac, T.C. Green, T.C. Green

1.

a) The "angle of attack" of an airflow over a turbine blade and the "tip speed ratio" of a turbine are key concepts in determining the power yield of a wind turbine.

i) Explain the relationship between angle of attack and tip speed ratio. [3]

ii) Explain why there is an optimal tip speed ratio operation at a constant tip speed that gives maximum power extraction as wind speed varies. [3]

iii) Explain why the profile of a blade changes along its length [2]

[Book work and interpretation]

(i) Angle of attack is the angle of the airflow with respect to the chord line of the blade and defines the lift and drag forces. There are two components of airflow: one is airflow due to wind and one is due to blade cutting the air as it rotates. The two flows are perpendicular and their ratio sets the angle of attack. The 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.

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

Thus the numerator and denominator are the two components of airflow over the blade that define also the angle of attack.

(ii) There is an optimal angle of attack, and therefore an optimal tip speed ratio, because too high an angle causes the blades to stall and too low an angle produces little lift force. The power is optimal for one particular angle and one tip speed ratio.

(iii) The linear velocity of airflow due to blade rotation depends on the distance along the blade. The airflow due to the wind does not. Therefore the chord line of the blade must depend on the distance from the root in order to maintain the angle of attack.

b) A wind turbine has a blade diameter of 105 m and is designed to operate with a tip speed of 6.1. In an air density of 1.21 kg/m^3 and a wind speed of 11.5 m/s the turbine produces 4.0 MW. Calculate the power coefficient of the turbine and comment on the value in comparison to the Betz limit. [4]

[Standard calculation and interpretation.]

Power coefficient is ratio of realised power to power represented by kinetic energy of upstream wind.

$$C_P = \frac{P}{\frac{1}{2}\rho\pi R^2 V^3} = \frac{4\times10^6}{\frac{1}{2}\times1.21\times\pi\times52.5^2\times11.5^3} = 0.502$$

A value of 0.502 presents a good turbine design given that the Betz limit is 0.59.

c) The turbine in (b) is designed to cut-in at 3 m/s and transition from optimal power mode to constant power control at 12.5 m/s.

i) Calculate the range of rotational speeds that will be needed for optimal power operation. [2]

ii) The optimal power mode will require variable speed operation. The "full converter" form has been chosen. Sketch a block diagram of the turbine drive train and explain what is meant by "full converter". [3]

iii) In the constant power mode, the turbine will be operated at constant rotational speed. Explain how the turbine control is configured to achieve this. [3]

(i)

[Standard calculation]

At cut-in speed, rotational speed will be

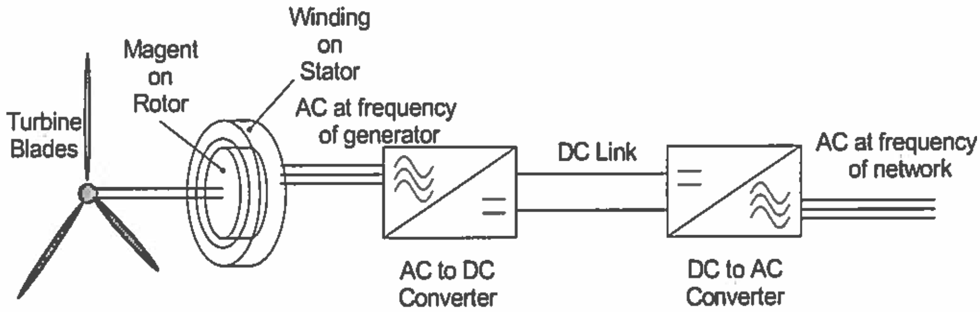
$$\omega_{cutin} = \lambda_{opt} V_{cutin} \frac{2}{d} = 6.1 \times 3 \times \frac{2}{105} = 0.349 \quad rad/s$$

$$= 0.055 rev/s = 3.32 rpm$$

$$\omega_{base} = \omega_{cutin} \frac{12.5}{3} = 13.7 rpm$$

(ii)

[Book work]



Full converter describes a system in which the variable speed shaft creates variable frequency AC and that all of the electrical power is passed through a AC/DC converter and then a DC/AC converter to effect a change from variable frequency to (almost constant) grid frequency. The contrast is with the DFIG in which only a fraction of the electrical power is process in power converters (and frequency changed) with a larger fraction being generated directly at grid frequency.

iii) [Book work and interpretation] The key means of control is the pitching of the blades that can be used to control the power (or torque) applied the blades by the air flow. The generator can be set to draw constant current using the AC/DC converter. This is equivalent to operation at constant torque. Speed feedback is applied to form a speed error which via a control gain set the blade pitch angle to maintain constant speed. Constant speed and constant torque result in constant power.

2.

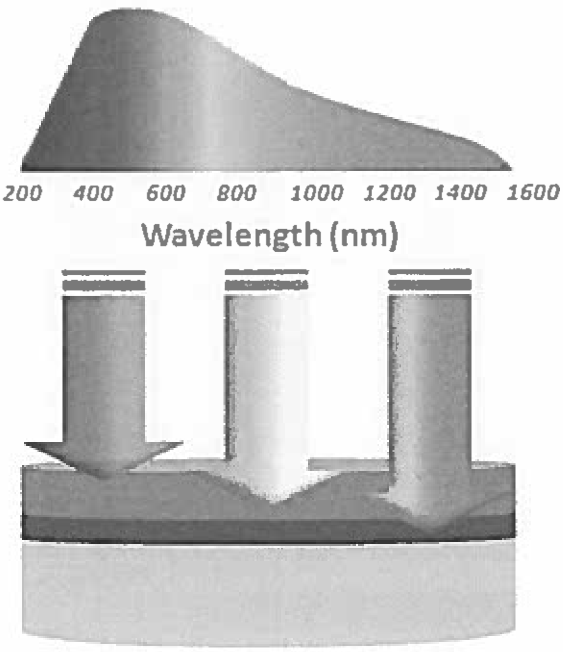
a) **Solar cells are available in a range of technologies, efficiencies and costs.**

i) **In 2012, the highest efficiency recorded for a solar cell was 44%. Describe the key features of this cell that allowed it to achieve such high efficiency.** **[3]**

[Book work]

Very efficient materials (e.g. GaAs).

Multilayer so absorbs a greater amount of the colour spectrum. Must arrange the colour spectrum so that high frequency (blue light) is absorbed first.



ii) **Describe the measures that may be taken to make best use of a sophisticated high efficiency cell and how this compares in an economic sense with using a low efficiency cell.** **[5]**

[Book work]

Concentrating allows a small but very expensive cell to be installed. But must avoid over temperature.

Must track the sun as only direct radiation can be concentrated effectively.

Because a large lens concentrates onto a small area, the PV cell itself can be very small. This means that a very small high quality cell can be used which reduces the overall cost of the panel but with some additional expense in the concentration system.

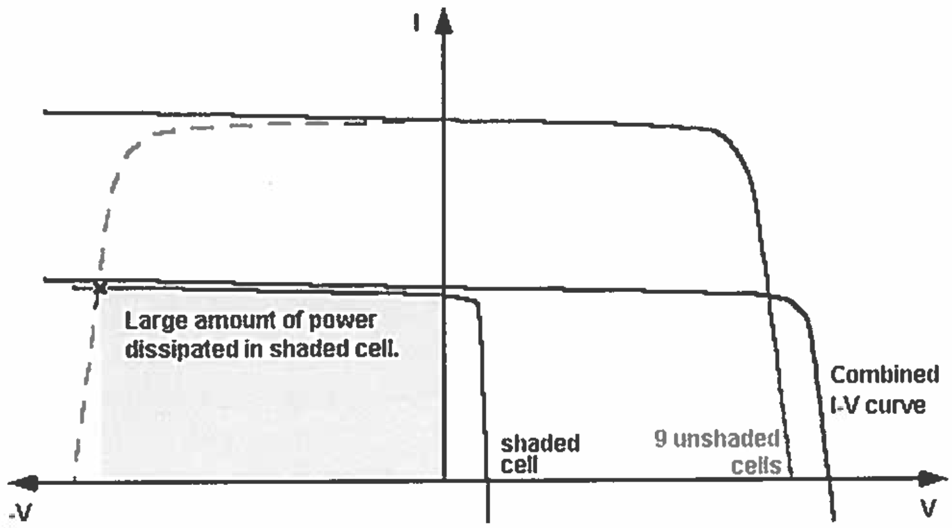
iii) **Explain what disadvantage one might find when applying the techniques in (ii) in a country like the UK.** [2]

Only direct/beam radiation can be concentrated effectively. There is roughly 50:50 split between beam and direct radiation in the UK, so a non-concentrated monocrystaline cell will gather approaching twice as much energy and may be significantly less costly.

b)

i) **Explain how shading can cause physical damage to a solar panel.** [4]

A string of cells must have the same current flowing in all cells. If one cell becomes shaded, its operating characteristic is changed but the current flowing through it causes it to become reverse biased. Hence, power is absorbed by the cell rather than generated. This causes the cell to heat up. Excess heat can damage the PN junction and in extreme cases cause the panel to crack.



ii) **Suggest a simple solution to this problem and explain why it works.** [2]

Bypass diode – shunts excess current around the shaded cell so that the power dissipated in it is less

c) **Describe the main functions that need to be performed in a PV inverter for a simple domestic installation.** [4]

Maximum power point tracking is needed in order to draw power from the solar panel at the most effective operating point and obtain the most electrical energy from the available sunlight.

DC output voltage of the PV panels is boosted to a suitable voltage to invert to mains voltage.

The DC output of the boost stage is converted to AC current synchronised to the mains.

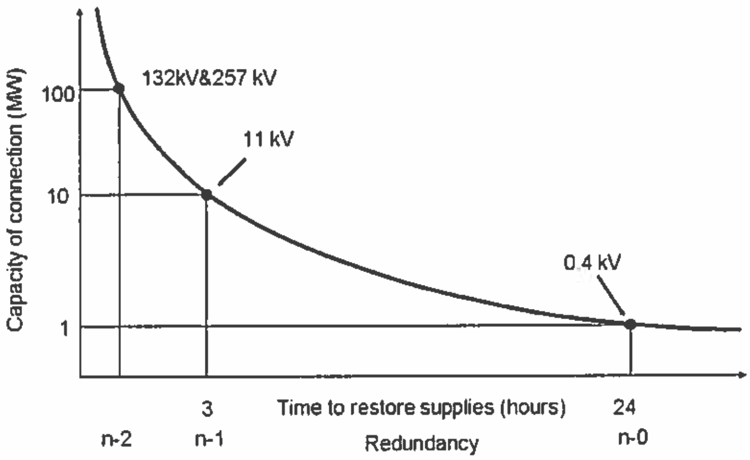
3.

a)

i) Sketch the relationship between the level of peak demand that may be lost (disconnected) due to a network outage and the specified for its restoration. [2]

ii) Explain the principle behind the historical design of a distribution network with reference to the sketch in (i) and describe how the level of redundancy changes with the level of peak demand to be supplied. [3]

[Book work]



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) **Consider the integration of distributed generation. Discuss why it is important to consider the contribution that distributed generation can make to distribution network security and explain the impact this has on the competitiveness of distributed generation. Describe how this position is changed if the distributed generation is an intermittent renewable source.** **[5]**

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, can integration 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) **The availability of a landfill-gas based distributed generator is 90%.**

i) **Calculate the effective contribution to network security of a single landfill-gas generator considering the shape of the winter load duration curve in Figure Q3.1.** **[5]**

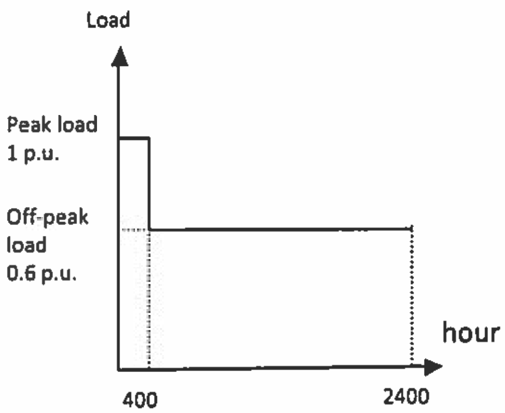


Figure Q3.1, Winter load duration curve

Contribution of a single DG unit to security

Outage (no of DG units)	**Probability**	**Loss of load – peak load**	**Loss of load – off peak load**	**EENS p.u.**
0	0.9	0	0	0
1	0.1	1	0.6	0.1 x (1 x 400 + 0.6 x 2000) = 160

EENS = 160p.u.

Contribution (1-NC) x 400 = 160

NC = 0.6

Effective contribution to network security is 60%.

ii) **Calculate the maximum group demand that the system in Figure Q3.2 can securely supply, if the capacity of each transformer is 10 MW and the capacity of each landfill-gas generator is 3 MW.** **[5]**

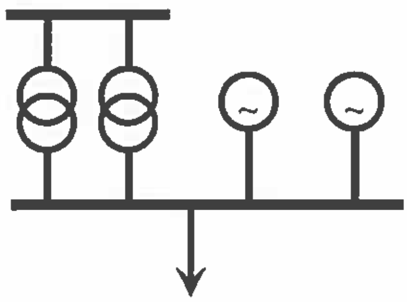


Figure Q3.2. Example System for Group Demand

Contribution of DGs to security

Outage (no of DG units)	**Probability**	**Loss of load – peak load(MW)**	**Loss of load – off peak load(MW)**	**EENS (MWh)**
0	0.9 x 0.9 = 0.81	0	0	0
1	2 x 0.9 x 0.1 = 0.18	3	0.6	0.18 x (3 x 400 + 0.6x 2000) = 432
2	0.1 x 0.1 = 0.01	6	3.6	0.01 x (6 x 400 + 3.6 x 2000) = 96

The EENS is $432 + 96 = 528$ MWh

The capacity of the network (y) to achieve the same level of EENS:

$(6-y) \times 400 = 528$

$\Leftrightarrow 2400 - 400y = 528$

$\Leftrightarrow y = 4.68$

Effective capacity value of DG1 and DG2 is 4.68 => 4.68/6 = 78%

The maximum demand that this network can secure is:

$1.3 \times 8 \times 0.95 + 4.68 = 14.45$ MW

4.

a) Although penetration of wind generation will displace energy produced by large conventional plant, the ability of this technology to displace capacity of conventional plant will be limited. For a system with a peak demand of 58 GW with an installed capacity of wind generation of 25 GW, estimate the total amount conventional plant needed to maintain levels the level generation capacity margin at historical levels, assuming that the capacity credit of wind generation is 10%. [4]

Using the wind capacity credit of 10%, 25 GW of wind capacity is equivalent to 2.5GW of capacity of conventional plant. A suitable assumption for historical capacity margin is 20% (other values in this region can be used). Under this assumption, the total installed generation capacity should be 58 x 1.2 = 69.6 GW. Hence the required capacity of conventional plant is 69.6-2.5 = 67.1GW.

b) An increased penetration of variable and unpredictable wind power will place an additional duty on the remaining generating plant with respect to balancing supply and demand.

i) Discuss the changes expected in amount of various forms of generation reserve that are need. [4]

Uncertainty in wind forecast becomes a source of additional balancing requirement which can be fairly substantial in magnitude. Wind forecast time scales are important for determining reserve requirements. For time scales from several seconds to a few minutes, the fluctuation of the overall output of wind generation will be small given that there is considerable diversity in outputs of individual wind farms. In these very short time scales (response time scales), the dominant factor is the potential loss of conventional plant and not fluctuations in wind power. Reserve requirements are concerned with the wind forecast uncertainty over longer time scales of minutes to hours. Wind forecast techniques vary for different time scales. For longer horizons beyond several hours, forecasts based on meteorological information are preferred. For short-term forecasts, up to several hours ahead, such methods are out-performed by various statistical techniques.

ii) Discuss the types of generation reserve that are available, the nature of the costs they incur and how choice of reserve is made. Explain how provision of reserve may reduce the ability of a system to absorb wind generation. [4]

In deciding the composition of system reserve, technical and economic considerations need to be made in selecting reserve options. Options include spinning and standing reserve. Combined cycle gas turbines (CCGT) or coal fired plant synchronized but running part loaded will provide spinning reserve. Generating plant that is not synchronized but that can start within the time scale required is classified as standing reserve. Standing reserve is often provided by open cycle gas turbines (OCGT) or pump storage. Costs of holding spinning reserve include fixed fuel losses associated with start-up and no-load costs during running hours whilst utilisation costs are generally the same as system marginal costs. For storage, the holding costs are negligible but utilisation costs are based on pumping costs which consist generally of marginal plant costs, plus losses incurred during the pumping/generation cycle.

For gas turbines that provide standing reserve, the holding costs are negligible but utilisation costs may be very high. Synchronised reserve is used to accommodate relatively frequent but comparatively small imbalances between generation and demand while standing reserve will be used for absorbing less frequent but relatively large imbalances.

Reserve is allocated in order to meet imbalances between predicted and actual demand and it is beneficial to determine the optimal split between the allocation of spinning and standing reserve for achieving the lowest fuel costs. Fuel costs involve a trade off between the more expensive nature of standing reserve plant and the higher costs involved in running spinning reserve plant part loaded. Furthermore, in a generation system with wind, the allocation of reserve affects the ability of the system to absorb wind generation. A high allocation of spinning reserve requires a large number of generators to run part loaded, therefore delivery of energy accompanies provision of reserve. This "must run" generation leaves less room for utilisation of wind generation.

d) It is proposed to connect 25 GW of wind generation capacity to a power system in which demand varies between a minimum of 18 GW and a peak of 58 GW. The generation mix of the system comprises inflexible nuclear plant with an installed capacity of 5 GW and flexible Combined Cycle Gas Turbine (CCGT) plant with characteristics presented in Table Q4. Assume that all of the inflexible nuclear plant will be running at all times.

Table Q4, Characteristics of CCGT plant

Rating of the unit [MW]	Minimum stable generation (MSG) [MW]	Marginal cost at full output [£/MWh]	Loss in efficiency when run at MSG [%]
500MW	300MW	60	20

When the wind plant is producing 12 GW, the system operator decides to schedule 3,600 MW of reserve which is to be provided by part loading synchronised CCGTs. Consider the **hourly** cost of balancing this system during minimum and maximum loading conditions.

i) Determine the minimum number of flexible generators that need to run to provide the reserve required and their power output. [2]

ii) Determine the cost associated with this reserve. [2]

iii) Determine the additional CO_2 emitted (due to the need to provide reserve) given that CCGT plant emits 0.42 tonnes of CO_2 per MWh produced when operated at full output. [2]

iv) Calculate the amount of wind power that may need to be curtailed in both the minimum and maximum system loading conditions. [2]

(i) [Standard calculation]

Each CCGT set can provide reserve of 200 MW when at MSG. Eighteen generators are required to provide reserve of 3,600 MW. Those 18 generators will produce 5,400 MW at MSG.

(ii) The cost is the additional cost of running at reduced efficiency which for this generator is an additional 20% fuel burn and a 20% increase in marginal cost.

Cost per hour = 3,600 MW x 60 £/MWh x 20% = £43,200 /h

(iii) The additional CO_2 is the CO_2 arising from the 20% additional fuel burn.

CO_2 per hour = 3,600 MW x 0.42 t/MWh x 20% = 302.4 t/h

(iv)

"Must run" CCGT for reserve produces 5.4 GW

"Must run" nuclear is 5 GW

Minimum demand of 18 GW less must run generation of 10.4 GW leaves 7.6 GW of other generation required.

12 GW if wind is available but only 7.6 GW required leaving 4.4 GW of wind to be curtailed off.

At peak demand of 58 GW, 47.6 GW of generation is required so no wind curtailment is needed.

5.

a) Many wind farms are now large installations of several hundred megawatt.

i) Explain why "fault ride through" is an important feature of a wind turbine. [3]

For a power system to be transiently stable, sufficient generation must remain connected through a disturbance such as a fault to ensure that all demand can continue to be served after the disturbance has settled (the fault has been cleared). When wind turbines were in small installations it was not necessary for them to contribute post-fault. Now that they are significant in size, they must ride through the fault (i.e., stay connected) and be ready to supply power when the voltage recovers.

ii) Describe the control actions taken within a wind turbine to achieve fault ride through. [3]

The turbine's inverter will enter current limit during a severe voltage dip and so the power export will be small. The important task is to manage the drive train so that the incoming wind energy does not cause problems while it is not being exported to the grid. It is possible to start pitching the blades to reduce the energy capture but this process is too slow for most faults. A small increase in turbine speed might be tolerated but most of the incoming power must be taken off the shaft as electrical power to prevent an over-speed. The electrical power can be dumped into a resistor switched in when the fault is detected.

iii) Explain why DC connection is preferred over AC connection for large wind farms a long distance off-shore. [3]

Cables, by virtue of the think plastic insulation layer between the conductors, has a large capacitance per unit length. When excited with an AC voltage, a capacitive reactive current will flow. The longer the cable and the higher the voltage (the higher the cable rating), the higher the current. This current uses fraction of the cables current rating and reduces the utilisation of the cable pushing up the cost of installation. If operated on DC, this would not happened but there would be capital and running costs in performing DC/AC and AC/DC conversions. If the distance is long enough and the power transfer high enough, the DC solution is cheaper overall.

b) In contrast to the present electricity system that is dominated by conventional generation, a future power system may be characterised by high penetration of renewable and low carbon distributed generation.

i) Explain how a distributed energy system may achieve higher energy efficiency levels when compared to a centralised one. [4]

In the process of generating electricity, significant amount of heat energy is produced that is wasted. The overall thermal efficiency of modern type gas fired technologies (CCGT) is approaching 60%, while the coal-based generation operates at less than 35%. An alternative policy (adopted by some European countries) has been to build smaller power stations nearer to load centres and use these to supply both electricity and heat to consumers (such as district heating) which allows greater use of the available heat and achieves overall efficiency for the supply of heat and electricity loads together of around 80% of the fuel burnt. However heat networks are required for this more distributed system.

ii) Explain why the present "fit and forget" approach to distribution network management may limit the amount of distributed generation that can be accommodated by the existing networks. **[3]**

The limitation is a consequence of the paradigm of distribution network operation and planning. Constraints on the network would appear in the form of voltage, thermal or fault level constraints violation. Inability to control generation and demand will limit the options for network control and hence limit the amount of generation that may be connected.

iii) Give a list of active network management techniques and briefly state how these can enhance the ability of a network to accommodate increased amounts of distributed generation. **[4]**

By changing the network operation philosophy from passive to active a number of control options may be used to release the latent network capacity through

- generation curtailment, local reactive power compensation, area voltage control, inline voltage regulators to resolve voltage rise effect (rural areas)
- fault current limiters, to limit the fault contribution from distributed generation and hence avoid replacement of circuit breakers (urban networks)