EE9-FPN1-01

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2018

ROLE AND VALUE OF SMART GRID TECHNOLOGIES

Tuesday, 22 May 10:00 am

Time allowed: 3:00 hours

Corrected copy

4C correction at 11:00

There are FOUR questions on this paper.

Answer ALL questions. All questions carry equal marks

Use answer book A to answer Question 1, answer book B to answer questions 2 and answer book C to answer question 3 & 4.

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

Examiners responsible	First Marker(s) :	G. Strbac, A. De Paola, G. Strbac
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The Questions

1. Wind power impact

a) Penetration of wind generation will displace energy produced by large conventional plant, but the ability of this technology to displace capacity of conventional plant will be limited. In a 53GW peak demand system, with installed capacity of wind generation of 15GW, estimate the total amount of conventional plant needed to maintain a 20% capacity margin, assuming that the capacity credit of wind generation is 10%.

[3]

b) An increased penetration of variable and difficult-to-predict wind power will place an additional duty on the remaining generating plant with respect to the task of balancing supply and demand. What will drive the impact on the amount of various forms of generation reserves?

[3]

c) Discuss the cost implications and key drivers that determine the magnitude of these costs and how reserve requirements may reduce the ability of the system to absorb wind.

[3]

d) It is proposed to connect 15GW of wind power to a power system in which demand varies between a minimum of 21GW and a peak of 53GW. The generation mix of the system is composed of inflexible nuclear plant of installed capacity of 8GW and flexible Combined Cycle Gas Turbine (CCGT) plant with characteristics presented in Table 1.1. We will consider hourly cost of balancing this system during minimum and maximum loading conditions, assuming the output of wind generation of 10GW. In order to cover the uncertainty in wind power output, the system operator decides to schedule 3,200MW of reserve to be provided by part loading synchronised CCGTs.

Assume that 8GW of inflexible nuclear plant will be operating at all times and that CCGT plant emits 0.52 tonnes of CO_2 per MWh when operated at full output.

Technology	Rating of the unit [MW]	Minimum stable generation (MSG) [MW]	Marginal cost at full output [£/MWh]	Loss in efficiency when run at MSG [%]
CCGT	480MW	320MW	70	20

Table 1.1: Plant characteristics

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 CO2 emitted (due to the need to provide reserve).

[2]

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

[2]

e) Determine the change in generation costs and CO2 emissions if demand side response can provide 1.8GW of reserve.

[3]

2. Flexible appliances and big data

a) What are the main challenges associated with utilising big data in energy systems? Which are the potential users of big data?

[3]

b) Briefly name three tasks that can be improved by the use of smart-meter data.

[3]

c) Explain how data from Phasor Measurement Units (PMUs) can be used to improve a Transmission System Operator's (TSO's) ability to ensure dynamic system stability in real-time.

[4]

d) Explain how governments aim to decarbonise electricity systems. Which are the resulting challenges for these systems and how can demand flexibility contribute in addressing these challenges?

[4]

e) A simple power system, operating at a three-hour horizon, includes:

- a generator producing power s_t (MW) at hour t with a cost function $C_t(s_t) = 100s_t^2$ (£) and a maximum output limit $s^{max} = 10$MW.
- inflexible demand appliances, consuming power $D_1 = 3$MW (at hour 1), $D_2 = 1$MW (at hour 2) and $D_3 = 2$MW (at hour 3).
- 1000 identical flexible demand appliances with continuously adjustable power d_t (kW), scheduling interval including hours 1, 2 and 3, total energy required $E = 6$kWh and maximum power limit $d^{max} = 4$kW.

i) Under centralised scheduling, what is the optimal power demand of each of the flexible demand appliances at each of the three hours? What is the total generation cost?

[3]

ii) Assuming that price-based scheduling is employed, what should be the relation between the prices at hours 1, 2 and 3 (denoted by λ_1, λ_2 and λ_3 respectively)? What is the resulting power demand of each of the flexible demand appliances? What is the total generation cost? Why is it higher or lower than the total generation cost calculated in i)?

[3]

3. Reliability models and Monte Carlo analysis

a) The overall reliability of a transformer is modelled as a repairable two-state system and it is evaluated according to failures and repairs occurred in the last 30 years. In the first 15 years, the transformer has failed on average every 2 years and its average repair time has been of 10 days. In the last 15 years, its average operational time has been of 3 years and its average repair time has been of 1 week. What is the mean time between failures (MTBF) of the transformer calculated according to the whole time period of 30 years? If the overall availability of the transformer over the last 30 years is 0.995, what is the corresponding mean time to repair (MTTR)?

[4]

b) Consider a control station of an off-shore wind farm. This is subject to two kinds of faults (hardware and software). In case of a hardware fault (which occurs on average every 300 day), the software components are not compromised. Conversely, when the software components malfunction (which occurs once every 1000 day) also the hardware components fail as a result. The repairs of hardware and software are independent and have the following rates: hardware repair: 1 every 6 hours; software repair: 1 every 24 hours.

i) Draw the continuous Markov chain representing the failure/repair model of the control station, clearly indicating for each discrete state whether the hardware and software components are functioning. Calculate the numerical value of the transition rates in consistent units of measurement.

[3]

ii) Derive the corresponding discrete-time Markov chain. Provide an analytical expression of the different transition probabilities as a function of time step and transition rates of the continuous Markov chain in point i).

[3]

c) A distribution network company operates an Active Network Management scheme (ANM). Such scheme curtails distributed generation (in particular photovoltaic generators) when this is above certain limits and is causing overloading of the lines. The monitoring scheme is implemented through the following components: three sensors (S1, S2, S3) that detect power levels throughout the grid, a processing unit (PU) that determines whether the network conditions require generation curtailment and three actuators (A1, A2, A3) that communicate with different groups of generation units.

The components are independent, with the following availability:

Availability S1 = Availability S2 = Availability S3 = r_S = 0.995;
Availability PU = r_{PU} = 0.999;
Availability A1 = Availability A2 = Availability A3 =r_A=0.992;

The ANM scheme intervenes in two distinct cases:

- **OVERLOAD**: distributed generation is slightly above the maximum level. This scenario is only detected if at least two sensors (among S1, S2, S3) are working correctly. In response to the case of **OVERLOAD**, two actuators are activated by the processing unit PU. These actuators activated by PU need to be working properly and reduce the power generation of their associated generation units. Note that PU chooses the actuators randomly and cannot detect in advance their working/failure state.
- **CRITICAL OVERLOAD**: distributed generation is significantly above the maximum level. This scenario requires only one working sensor to be detected. In response to the case of **CRITICAL OVERLOAD**, the processing unit PU will need to activate all actuators, which will then reduce the power generation of their associated generation units.

i) Draw the reliability block diagram for a successful detection and correction of the **OVERLOAD** scenario. Hint: all actuators have the same availability and therefore are indistinguishable from a reliability point of view.

[3]

ii) Draw the reliability block diagram for a successful detection and correction of the **CRITICAL OVERLOAD** scenario.

[1]

iii) Compute the probability of success for the two cases in point i) and ii).

[2]

d) Let $\hat{R}$ denote the outcome of a random Monte Carlo simulation, i.e. the mean of a finite number n of single sampled states Im_i:

$$\hat{R} = \frac{1}{n}\sum_{i=1}^{n} Im_i$$

Characterize the random variable that approximates $\hat{R}$ for large values of n. In addition, specify its mean and variance. How does the variance change if $m=4n$ sampled states are considered instead?

[4]

4. Quantification of network reliability

a) Provide the definition of a metric used by Ofgem to quantify the reliability of distribution networks. Specify typical values of this quantity in the UK. Provide the definition of system availability as a transmission reliability metric, specifying typical values of this quantity for the GB transmission network.

[3]

b) Consider a section of a distribution network serving 10000 customers. The outage events occurred in one year are reported in Table 4.1.

Customers Affected	Duration
4000	30 minutes
300	1 day
6000	2 minutes
200	15 minutes
500	8 minutes
20	12 hours
150	15 minutes

Table 4.1: Outage events

Compute CML and CI for this section of the network.

[3]

c) Consider the distribution network in Figure 4.1.

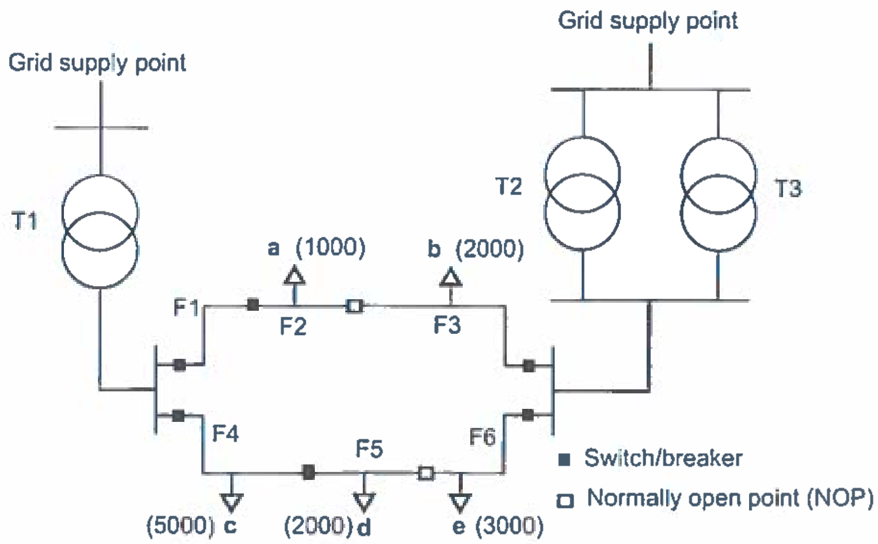

Figure 4.1 Network diagram

The number of customers at each load point (**a**, **b**, **c**, **d**, **e**) is reported between brackets in Fig. 4.1. The customers at load points **a** and **b** are of industrial type. Each customer at load points **a** and **b** has an average power consumption of 3kW and a Value of Lost Load (i.e. interruption cost per unit of lost energy) equal to 25000£/MWh. The customers at load points **c**, **d** and **e** are of residential type. Each customer at these load points has an average power consumption of 0.5kW and a Value of Lost Load (i.e. interruption cost per unit of lost energy) of 8000£/MWh. The availabilities of the transformers (T1, T2, T3) and of the feeders (F1, F2, F3, F4, F5, F6) are reported in Table 4.2. Assume that all components failures are independent and they all last more than three minutes.

Component	T1	T2	T3	F1	F2
Availability	0.9997	0.9995	0.9995	0.9992	0.9995

Component	F3	F4	F5	F6
Availability	0.9998	0.9997	0.9995	0.9994

Table 4.2 Availability parameters

11.00

The capacity of T1 is always sufficient to serve loads at point **a** ~~and~~ **c**, d. Transformers T2 and T3 are redundant, as their individual capacity (of a single transformer) is always sufficient to serve all customers at load points **b**, ~~**d**~~ and **e**. The network is radially operated but the normally open points (NOPs) between F2 and F3 and between F5 and F6 can ensure some redundancy. They can be closed to resupply load points **a** and **d** in case of faults in the left-hand side of the network diagram. This operation is performed only if both transformers T2 and T3 are working. Note that the NOPs are not used to resupply load points other than **a** and **d**.

i) Calculate the probability that each load point is connected to a grid supply point (one expression for each load point).

[5]

ii) Compute the expected CML and the expected annual cost of interruptions for this network.

[4]

iii) Is it possible to quantify the expected annual value of the Normally Open Points on the basis of the results of points i) and ii) or is it necessary to perform additional analyses of a similar kind? If this is the case, provide a general description of the procedure to be followed (actual calculations are not required).

[2]

iv) Customer Interruption Costs represent a crucial concept in the evaluation of network reliability.
- Discuss the main factors that can impact Customer Interruption Costs and provide some examples.
- What are the main methods to measure Customer Interruption Costs?

[3]