The Solutions

1. Power system in Borduria presented in Figure 1.1, with a 2 GW gas-turbine generator operating at the marginal cost of £30/MWh located in the North and 300 MW of peaking generator operating at the marginal cost of £60/MWh located in the South West. Demand in the North is 200MW, in the South West 750MW and in South East 500MW.

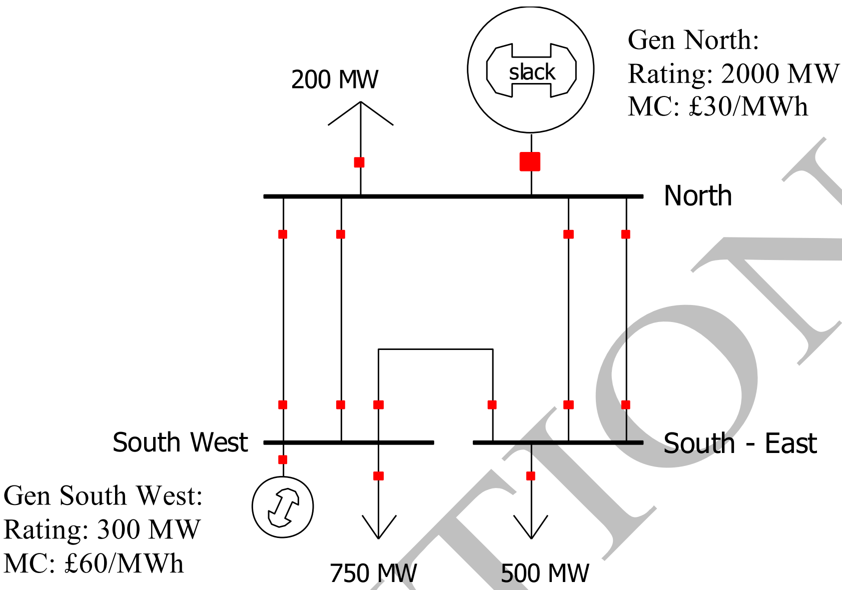


Figure 1.1: A 4-node system

The parameters of the transmission corridors connecting the North and South regions and between the South-East and the South-West region are shown in Table 1.1 below.

Transmission corridor	Number of circuits	X (p.u.)	Capacity per circuit (MW)
North - South East	2	0.50	500
North – South West	2	1.00	375
South East – South West	1	0.25	500

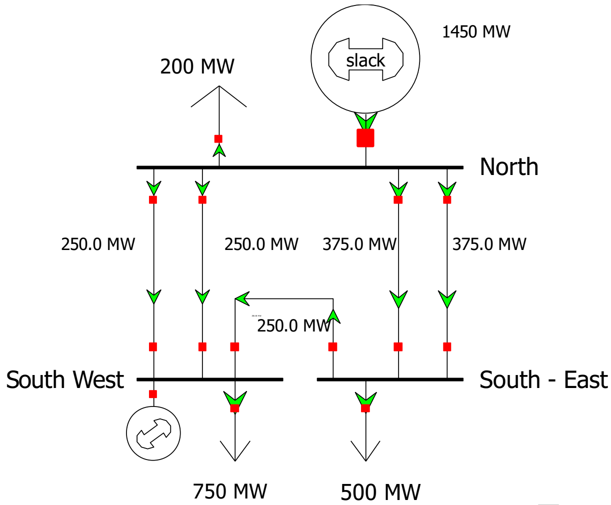
Table 1.1: Parameters of transmission corridors

a) Determine the Economic Dispatch and compute the corresponding power flows in each of the circuits

[3]

Total load is 200 + 500 + 750 = 1450 MW. The ED solution: Gen at North produces 1450 MW and Gen at South East produces 0 MW. Total cost is (1450*30 + 0*60) = £43500/h

The flows can be calculated using superposition or dc load-flow. The flows for the intact system are as follow:



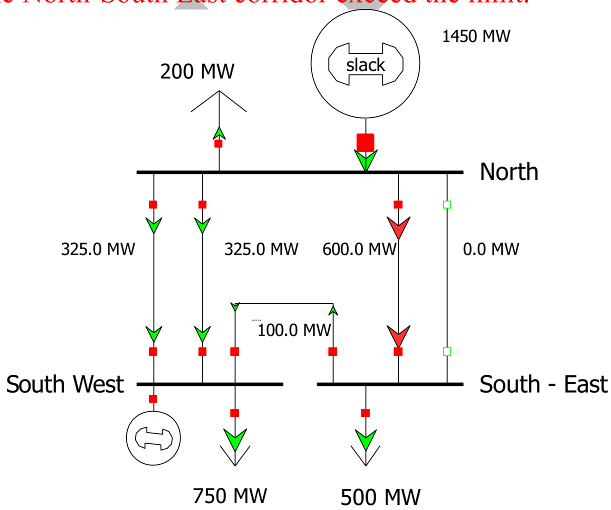
[FEEDBACK]

This question was answered well in general. There was potential ambiguity whether the stated values for X referred to corridors or lines; both were counted as correct.

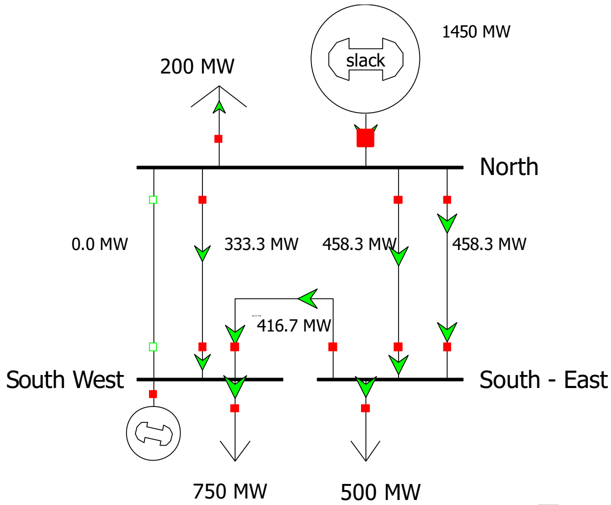
b) Determine the power flows following the outage of single individual circuits and identify conditions in which the power flows during contingency exceed the circuit capacity limit.

[3]

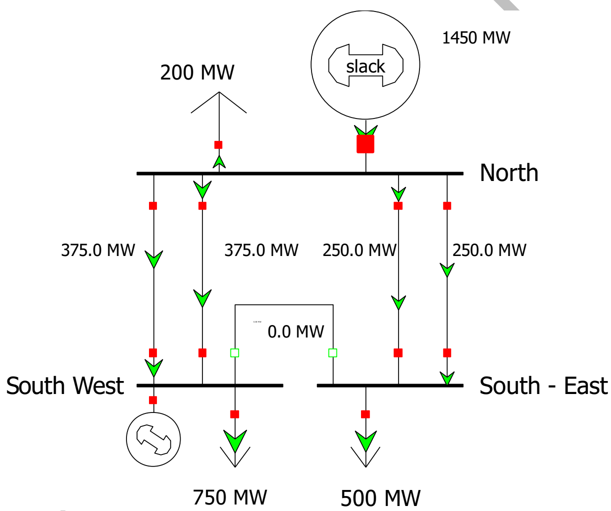
Flows when one circuit of North – South East is out-of-service. Flows at the other circuit of the North-South East corridor exceed the limit.



Flows when one circuit of North – South West is out-of-service. No violation.



Flows when one circuit of South East – South West is out-of-service. No violation.



The critical contingency is the outage at the circuit between the North and South East.

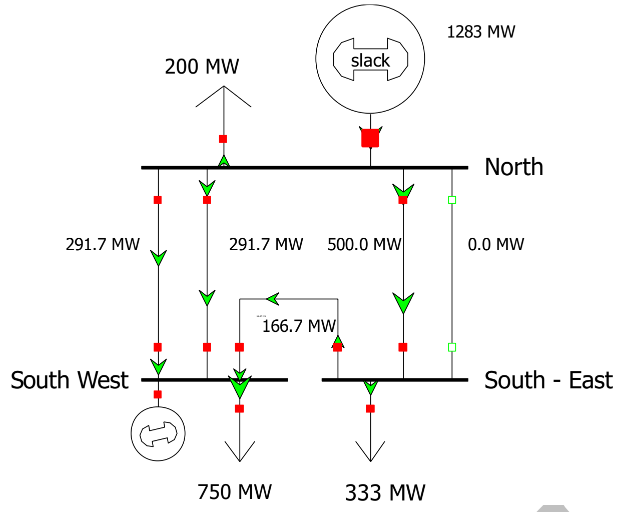
[FEEDBACK]

This question was generally answered well. Occasionally, points were taken off due to omission of steps in the calculation and mathematical/transcription mistakes.

c) In case that Demand Side Response may be available to provide corrective control, determine the minimum amount of Demand Side Response that would be needed to manage the power flows within the limits.

[7]

In order to reduce the flows from North and South East from 600 MW to 500 MW, Demand Side Response of 166.67 MW at South East is required. The remaining demand will be (500-166.67) = 333.33 MW and the flows are as follows:

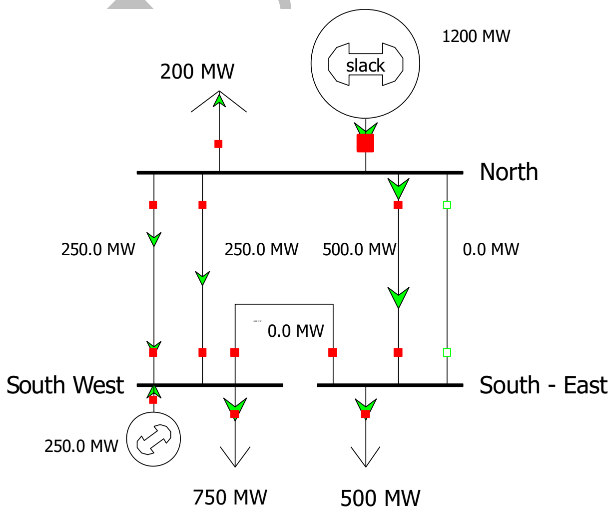


[FEEDBACK]

Occasional mistakes were made in computing the correct ratio of DSR (in MW) and the resulting reduction in post-fault N-SE flows.

d) If the system operator needs to secure the system against one line outage preventively using the South generator, determine the secured dispatch and the corresponding cost. What is the value of Demand Side Response per each MW made available. [7]

In order to operate the system securely in the preventive mode, generator at South West has to increase its production to 250 MW. The flows when one circuit of North-South East is out of service are as follows:



The operating cost is now (1200 x 30 + 250 x 60) = £51000/h. Therefore, the cost of security is 51000 – 43500 = £7500/h. Hence the value of available Demand Side Response, providing post-contingency service in case of the loss of line between North and South-East will be £45/MW/h.

[FEEDBACK]

Common mistakes included:

- Not noticing that due to the rarity of outage events, cost savings are equal to the constraint costs, which are incurred all the time. This is the difference in *pre-fault* costs of the constrained and unconstrained systems.
- Many did not correctly (or not at all) compute the cost per MW *of demand response* (i.e. divide by 167 MW – the answer of question c), instead dividing by MW of generation (250MW) or desired reduction of line overload (100MW).
- Some took a different approach to computing value of DSR, using the marginal cost of generation (SW generator at £60/MWh), the difference in marginal cost between constrained and unconstrained systems (£60/MWh - £30/MWh = £30/MWh) or the VoLL.

2. Flexible appliances and big data

a) Describe operational properties and provide illustrations of flexible appliances with continuously adjustable power levels and appliances with shiftable cycles. Provide example of each type explaining their flexibility characteristics.

[3]

Flexible demand appliances are characterised by flexibility in terms of the specific time period(s) when they consume required energy. The key two types of flexible demand appliances include appliances with continuously adjustable power levels and appliances with shiftable cycles.

Appliances with continuously adjustable power levels are flexible in terms of their power demand at each time period of the scheduling interval; in other words, their power demand can be continuously adjusted up to a maximum power limit. Figure 2.1 illustrates these flexibility characteristics. The solid and the dashed power profile correspond to two different demand patterns. Both of them ensure that the total energy required for the operation of the appliance is acquired within the scheduling interval, but the timing and power level of this energy input is different.

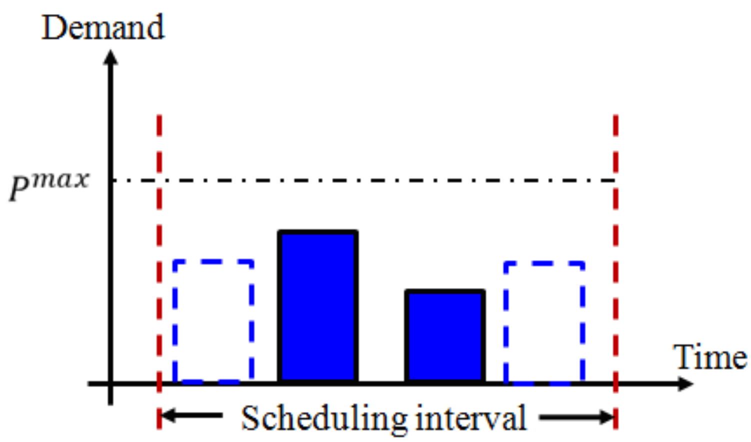


Figure 2.1: Flexibility of appliances with continuously adjustable power levels

Electric vehicles (EV) with smart charging capability constitute a representative example of this type.

Appliances with shiftable cycles are not flexible in terms of their level of power demand at each time period. This is due to the fact that these appliances do not incorporate explicit storage components (such as the battery of EV) and their operation is based on the execution of user-called cycles the power profile of which cannot be altered. As a result, their flexibility is only associated with their ability to shift these cycles in time within the scheduling interval allowed by their users. Figure 2.2 illustrates this flexibility characteristic. The solid and the dashed power profile correspond to two different demand patterns. Both of them ensure that the appliance cycle is executed following the inherent power profile, but the timing that this cycle is executed is different.

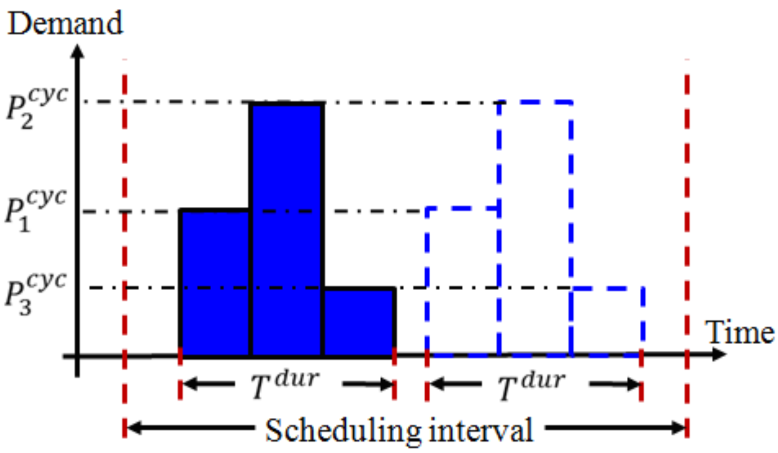


Figure 2.2: Flexibility of appliances with shiftable cycles

Wet appliances e.g. dishwashers and washing machines, with delay functionality constitute a representative example of this type. Their scheduling interval corresponds to the temporal interval between the activation time and the latest desired termination time.

[FEEDBACK]
Common mistakes included:

- Not clearly distinguishing the features of each type of flexibility, including an indication of what is *not* flexible about each load type (e.g. total energy consumption).
- Not providing graphical illustrations, or providing illustrations without explanations.
- Some answers were missing examples.

b) A simple power system, operating over a two-hour time horizon, includes:

- a generator producing power s_t (MW) at hour t with a cost function $C_t(s_t) = 50s_t^2$ (£) and a maximum output limit $s^{max} = 10\text{MW}$
- inflexible demand appliances, consuming power $D_1 = 4\text{MW}$ (at hour 1) and $D_2 = 3\text{MW}$ (at hour 2)
- 1000 identical flexible demand appliances with power d_t (kW), scheduling interval including hours 1 and 2, total energy required $E = 5\text{kWh}$ and maximum power limit $d^{max} = 6\text{kW}$

i) Assuming that price-based scheduling of the flexible demand appliances is employed, what should be the relation between the prices at hour 1 and 2 (denoted by λ_1 and λ_2 respectively)? What is the resulting power demand of each of the flexible demand appliances? What is the total generation cost?

[4]

The price at hour 2 should be lower ($\lambda_1 > \lambda_2$) in order to incentivise flexible demand appliances to move their demand to the off peak-hour 2 and flatten the system demand profile.

Each flexible demand appliance aims at minimising its electricity cost. Therefore, it will obtain as much energy as possible at the hour with the lowest price and the rest at the hour with the highest price:

$d_2 = \min(E, d^{max}) = 5\text{kW}$ and $d_1 = E - d_2 = 0\text{kW}$

The system operator schedules the generator to meet the resulting total demand:

$s_1 = D_1 + 1000 * d_1 = 4\text{MW}$ and $s_2 = D_2 + 1000 * d_2 = 8\text{MW}$

The total generation cost is $50(D_1 + 1000 * d_1)^2 + 50(D_2 + 1000 * d_2)^2 = £4000$

[FEEDBACK]
Most answers were broadly correct. Sometimes points were subtracted due to missing explanations. Some answers reversed the price relation ($\lambda_1 > \lambda_2$), typically without explanation.

ii) Explain how a flexibility limitation approach can be applied to avoid the demand concentration effect in the context of this example. Calculate the most suitable value of the flexibility limit ω minimising the generation cost explaining the rational of your calculation.

[5]

In order to calculate a suitable value of the flexibility limit ω minimising the generation cost in the system, different candidate values of ω are tried out as demonstrated in Table 1 below. For each value of ω, the following quantities are calculated:

- Demand of each flexible demand appliance at each of the two hours: $d_2 = \min(E, \omega * d^{max})$ and $d_1 = E - d_2$
- Total demand (and total production) in the system at each of the two hours: $s_1 = D_1 + 1000 * d_1$ and $s_2 = D_2 + 1000 * d_2$
- Total generation cost: $50(D_1 + 1000 * d_1)^2 + 50(D_2 + 1000 * d_2)^2$

Table 1: Scheduling of flexible demand appliances with different candidate values of ω

ω	d_1 (kW)	d_2 (kW)	s_1 (MW)	s_2 (MW)	Gen. cost (£)
1	0	5	4	8	4000
0.9	0	5	4	8	4000
0.8	0.2	4.8	4.2	7.8	3924
0.7	0.8	4.2	4.8	7.2	3744
0.6	1.4	3.6	5.4	6.6	3636
0.5	**2**	**3**	**6**	**6**	**3600**
0.4 (or lower)	Infeasible (constraint $d_1 + d_2 = E$ cannot be satisfied)				

The most suitable value of the flexibility limit ω minimising the generation cost in the system is $\omega = 0.5$.

[FEEDBACK]
Common mistakes included:

- Not mentioning the definition of ω, or defining it in relation to the maximum power required (5 kW) instead of the maximum power uptake (6 kW).
- Not explaining reasoning or the formulas used, including presenting tables without explanation or units.

c) Give a brief definition for concept of big data and state the primary sources of big data in power systems.

[2]

Answers should state that big data is high-volume, high-velocity and high-variety information made available through increased instrumentation at all system levels.

The primary sources of big data in power systems are:

- Phasor Measurement Units (PMUs)
- Asset monitoring data from various equipment e.g. transformers
- Smart meters
- Electricity market data

[FEEDBACK]
Answers were broadly correct. The most common mistake was not mentioning the "volume, velocity and variety" property of big data.

d) Give an example of how (i) a transmission system operator (ii) an asset owner (iii) an electricity supplier can use big-data analytics to improve their business performance. For each case, identify a specific task, describe how it was carried out in the past and how it can be improved using the concept of big data.

[6]

Two points can be earned for each of the following components:

i. In the case of the Transmission System Operator, one task that can be improved using big data analytics is that of condition awareness (can also be referred to as security assessment/dynamic analysis etc.). Traditionally, security assessment has been carried out at a limited, ad-hoc basis, largely based on empirical rules and conservative estimates. Big data analytics can be applied to data gathered from Phasor Measurement Units (PMUs) to carry out large-scale security assessment and improve situational awareness. In particular, historical PMU data also contain information on what operating points the operator should anticipate in the future. Simulations of faults can be carried out off-line to identify stability characteristics of individual operating points. Machine learning techniques (e.g. Decision Trees) are then used to produce security rules delineating the system's region of stable operation.

ii. In the case of an asset owner, one task that can be improved using big data analytics is that of asset health monitoring (can also be referred to as predictive maintenance etc.). Traditionally, asset maintenance has been scheduled on empirical rules (e.g. replace an asset every 10 years) and has been largely reactive (i.e. replace after a fault occurs). Big data analytics enable the real-time health monitoring of assets to improve efficiency. This can be done by creating a statistical model to characterise the 'basecase' operation. Divergence between measurements and the basecase model indicate need for maintenance.

iii. In the case of an electricity supplier, big data analytics can be used to improve the characterisation of customers and their consumption habits. Traditional energy meters were read once a month. Smart metering data (and meta-data records in terms of household size, appliances etc.) can be instrumental in understanding how customers consume electricity. In addition, data clustering techniques can be used for customer classification in order to design suitable Time-of-Use tariffs and identify suitable profiles for demand-side response schemes.

[FEEDBACK]
This question required clear, coherent answers. In a number of cases, marks were deducted for not explaining how things are currently done, not giving examples of big data methods that can be used (and the problems they solve), or confusing the role of players in the electricity market (e.g. suppliers do not plan network expansions).

3. Reliability models and Monte Carlo simulation

a) A generating unit has failed 20 times in the past 8 years, and repairs have taken 1 week on average. Assuming that this is representative of its overall reliability, what is the mean time to failure (MTTF)? What is the availability of the unit?

[3]

Assumption: The 8 years represents a whole number of failure-repair cycles (i.e. representative).

The mean time between failures (MTBF) is $\frac{8\ years}{20} = 0.4\ years = 20.86\ weeks$. The MTTR is 1 week. Therefore, $MTTF = MTBF - MTTR = 19.86\ weeks$. The availability is $av = \frac{MTTF}{MTBF} = 0.95$.

[FEEDBACK]
Common mistakes included:

- Mixing up MTTF and MTBF (as used in power systems literature and this course in particular: MTBF is the mean time between subsequent failure events; MTTF is the mean time between a repair event and the next failure).

b) Draw the ‘bathtub curve’ associated with component failures, annotating the different sections of the curve. Discuss how it relates to the continuous time Markov model with exponentially distributed times-to-failure. Note: a mathematical derivation is not required.

[3]

Lecture slide [annotated from book]:

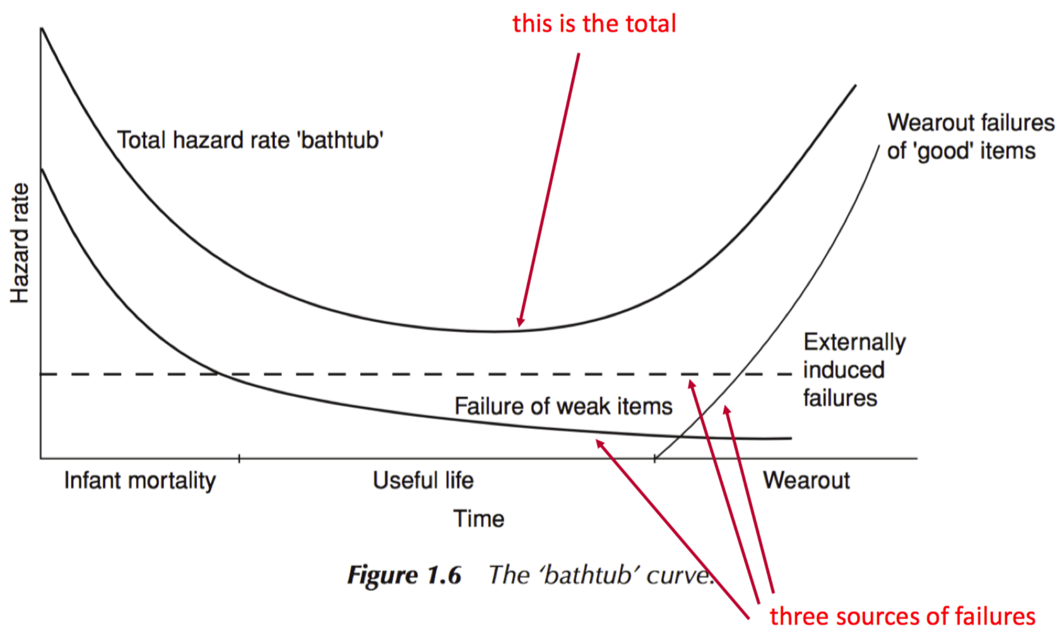


Figure 1.6 The ‘bathtub’ curve.

Practical Reliability Engineering, O’Connnor and Kleyner

The exponentially distributed times-to-failure correspond to the horizontal piece of the curve (approximately constant failure rate) during the ‘useful life’ of the component.

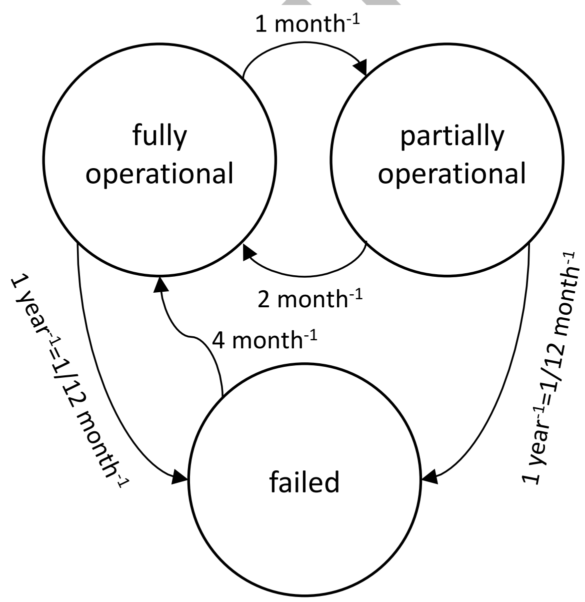
[FEEDBACK]
Common mistakes included:

- Most common: Not addressing the relation between constant failure rate and exponential times to failure, and/or not relating it to the relevant section in the bathtub curve.
- Not listing or describing three stages and the three failure processes.
- Not including units on the axes.

c) Consider a grid-scale storage facility that has three operational states: 'failed', 'fully operational' and 'partially operational'. A Markov model is used to model transitions between states. The transition rates are as follows: (1) from any operational state, complete failures occur at a rate of 1 per year; (2) repairs from the failed state are carried out at a rate of 4 per month and always result in a fully operational unit; (3) fully operational units enter a partially operational state at a rate of 1 per month; (4) partially operational units return to full operation at a rate of 2 per month.

i) Draw the corresponding continuous-time Markov model. [2]

The continuous-time Markov model is the following (or an equivalent representation):



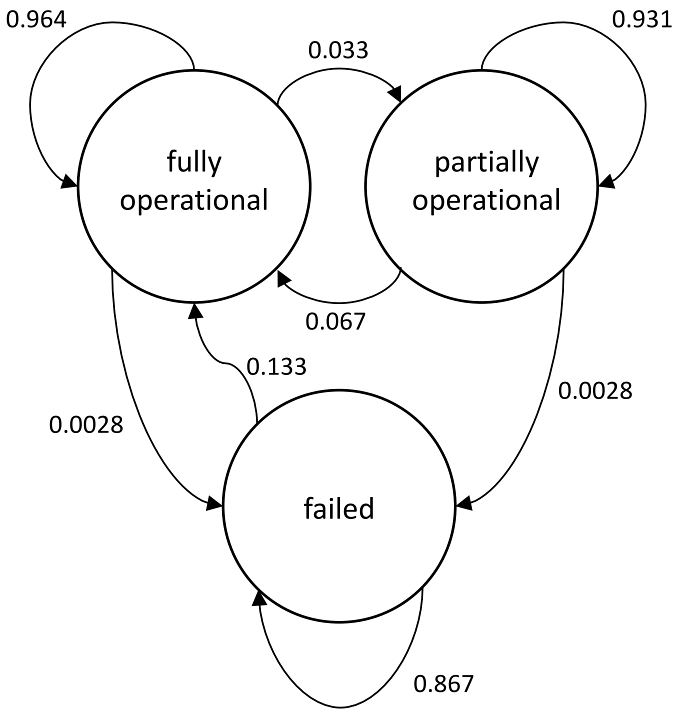
[FEEDBACK]
This question was largely answered correctly, but occasional mistakes included:

- Omitting the transition from the partially operational state to the failed state.
- Numerical issues in converting from units of [1/year] to [1/month]

ii) Draw a discrete time Markov chain for this process, assuming a time step of 1 day. Include all non-zero transition probabilities. [2]

A discrete time Markov chain of the above requires the addition of self-loops for each state and a choice of time step (and units). We use 1 day = 1/30th month.

This results in:



[FEEDBACK]
This question was answered correctly by all, with the exception of the occasional computation error.

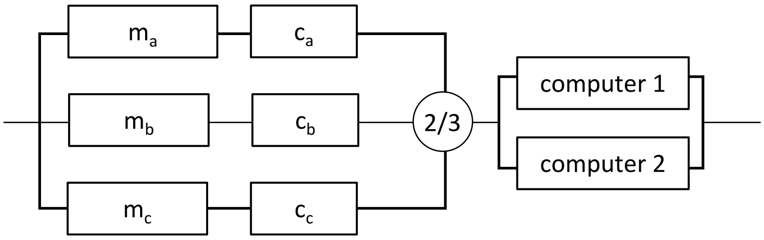
d) A system operator is designing a forced islanding scheme: in case of an acute blackout threat, the scheme preventively splits the power system into separate electrical islands. Such a scheme must have a high degree of dependability, but also be resilient against spurious activations.

The proposed design is as follows. The state of the power system is monitored at three locations (A, B and C), each equipped with a monitoring station (m_a, m_b and m_c). If a monitoring station detects a critical system condition it sends an alert to the control room over a dedicated communication channel (one for each station – c_a, c_b and c_c). The decision to island the system is taken by a computer in the control room when it receives alert signals from *at least two* sites. To provide redundancy, there are two identical computer systems that receive identical signals and that can each activate the islanding signal.

i) Draw a reliability block diagram for the successful activation of the islanding signal in response to a critical system condition. You may assume that the critical condition is observable at each of the three monitoring stations (*if* they are operational).

[2]

Answer:



[FEEDBACK]
Occasionally, the 2-out-of-3 voting element was omitted or incorrectly placed. In some answers, parallel structures were proposed where components appeared in multiple places at the same time. This violates the assumption of independence between availabilities, because both copies of the same component are by definition 100% dependent.

ii) Assuming independence between components and an availability of 95% for monitoring stations, 99% for communication channels and 98% for the computer, quantify the probability that a critical operating condition is successfully detected.

[3]

The probability for the critical condition to be detected is equal to the probability of 'success' in the reliability block diagram. Assuming independence between components, we can compute the average *system availability* as follows.

First, compute the availability of a monitoring – communication pair:

$$av(m_i c_i) = 0.95 \times 0.99 = 0.9405$$

Then, the collective availability of the three monitoring-communication system, including 2-out-of-3 voting is

$$av(MC) = \binom{3}{2} 0.9405^2 \times (1 - 0.9405) + \binom{3}{3} 0.9405^3$$
$$= 3 \times 0.053 + 0.832 = 0.990$$

The availability of the combined computer system is

$$ac(comp) = 1 - (1 - 0.98)^2 = 0.9996$$

The combined availability of the system consists of the availability of both components in series:

$$av(system) = av(MC) * av(comp) = 0.990$$

[FEEDBACK]
The most common mistake involved the correct computation of the availability using 2-out-of-3 voting. Occasionally, numerical errors were made.

e) The reliability of a large distribution network is analysed using time-sequential Monte Carlo simulations. In a 2-hour simulation run, 1,000 independent 'simulated years' were generated. The CML index was computed for each year: the average value was 82.1 minutes, and the sample standard deviation was 63 minutes.

i) What is the (estimated) standard error of the average CML value? What would you expect the standard error to be if we were to run the simulation for 24 hours instead of 2 hours?

[3]

The standard error is defined as $se = \frac{\sigma_{impact}}{\sqrt{n}}$, where n is the number of (independent) samples and σ_{impact} is the standard deviation of samples. The latter is approximated by the sample standard deviation.

$$se \approx \frac{63 minutes}{\sqrt{1000}} = 2.0\ minutes$$

Running for 24 hours would result in 24/2=12 times more samples being generated. Repeating the calculation above with $n = 12000$ results in $se \approx 0.58\ minutes$

[FEEDBACK]
Common mistakes were:

- Not answering the final part of the question (computing the reduced standard error for the 24-hour run). Where only qualitative answers were provided, some answers erroneously stated that the standard error would increase for a longer run time.
- Mixing up the standard deviation of the individual CML values (63 minutes) and the standard error (also known as 'standard error of the mean'; 2.0 minutes).
- Occasionally, answers would unnecessarily normalise the run times to a period of one year. This is apparently due to confusion with the CML measure, which *is* calculated over a period of one year (real time, not simulation time).

ii) State the estimate for the expected CML including its estimated error in three different ways.

[2]

The following three approaches have been used in class. Other valid representations can be acceptable, too.

82.1 $\pm$ 2.0 minutes

[78.2, 86.0] minutes (95% confidence) [*computed using* $\pm$*1.96 SE*]

82.1 minutes (2.4%) [*using the coefficient of variation (SE/mean), i.e. relative standard error*]

[FEEDBACK]
Common mistakes included:

- Missing one or more of the above (all three are needed for full marks).
- Not explaining the meaning of the answers, especially when stating an interval without specifying that it is a 95% confidence interval.
- Some answers involved the standard normal random variable Z. This is acceptable as an alternative answer, but only when it is fully specified (e.g. state that Z ~ N(0,1), etc.).

4. Quantification of distribution network reliability

a) Ofgem specifies CML and CI targets for Distribution Network Operators. Discuss how these targets vary across DNOs and regulatory years. Describe the mechanism by which CML and CI targets are used to incentivise network reliability.

[3]

CML/CI targets vary between DNOs, reflecting properties of their networks and their historical performance. The targets gradually decrease over future regulatory years. Reliability is incentivised through the **interruptions incentive scheme**, which defines a revenue adjustment for deviations from the targets: paying DNOs if targets are exceeded or charging them if targets are missed. This is a capped linear response.

[FEEDBACK]
Common mistakes included:

- Not mentioning the overall decreasing trend in CML and CI statistics (and targets).
- Not mentioning that CML / CI targets vary between DNOs, with some indication why (history, different networks/environments)
- Missing description of the interruptions incentive scheme (name and quantitative details not required).

b) Consider a section of a distribution network that serves 8000 customers. Table 4.1 lists the outage events that occurred on this network in the regulatory year 2015/16.

Customers affected	Duration
50	7 hours
3800	90 minutes
1000	1 minute
30	1 day
700	15 minutes
200	8 minutes
1400	4 minutes

Table 4.1: outage events

Compute the CML and CI values for this section of the network.

[3]

Due to the 3-minute minimum requirement for CML and CI, the recorded event that affected 1000 customers for 1 minute will be excluded from CML/CI calculations.

Taking care to convert hours and days to minutes (for CML), the CML and CI are calculated as

$$\text{CML} = \frac{\sum_{events} N_{affected} T_{minutes}}{N_{customers}} = \frac{50\times420 + 3800\times90 + 30\times1440 + 700\times15 + 200\times8 + 1400\times4}{8000} = 53.0 \text{ minutes}$$

$$\text{CI} = 100\times\frac{\sum_{events} N_{affected\ customers}}{N_{customers}}$$
$$= 100\times\frac{50 + 3800 + 30 + 700 + 200 + 1400}{8000}$$
$$= 77.25$$

[FEEDBACK]

All students answered this question correctly.

c) Consider the distribution network in Figure 4.1.

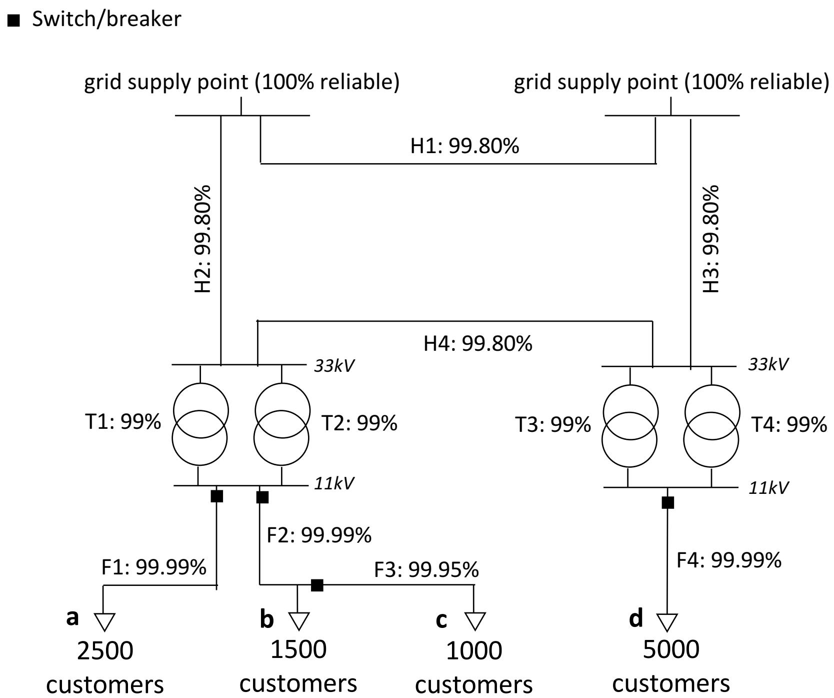


Figure 4.1: network diagram

The network consists of a meshed 33kV network supplied by two grid supply points. There are no constraints on the meshed network; single lines have sufficient capacity to carry all loads. Customer loads are connected to radial 11kV sections that are supplied through 33-11kV transformers T1-T4. The load points (a-d) are labelled with the number of customers connected to each load point. Component failures are assumed to be independent and to last for more than 3 minutes each. Component availabilities are indicated by percentages alongside each component.

Default load level scenario. The 33-11kV transformers are redundant at all times, i.e. either T1 or T2 can fully supply load points **a-c**, and T3 or T4 can fully supply load point **d**.

i) Compute the probabilities that each of the load points is connected to a grid supply point (one expression for each load point). Then compute the expected CML value for this network.

[6]

For all load points, the probability of connection consists of the availability of the 33kV network, the transformers and the (local) 11kV network in series.

The availability of the 33kV network (at the point of transformers T1-T2) is given by the logical statement (H2 or (H3 and H4)). Similarly, the availability at T3-T4 is given by (H3 or (H1 and H4)). Because the availabilities are identical, the availabilities at T1-T2 and T3-T4 are identical. It is computed as

$$av(33kV) = 1 - (1 - 0.998)(1 - 0.998 \times 0.998) = 1 - 8 \times 10^{-6}$$
$$= 0.999992$$

The availability of each transformer pair (assuming full redundancy) is given by

$$av(trans) = 1 - (1 - 0.99)^2 = 1 - 1 \times 10^{-4} = 0.9999$$

The availability of the 11kV distribution network depends on the load point:

$$av(11kV, a) = 0.9999$$
$$av(11kV, b) = 0.9999$$
$$av(11kV, c) = 0.9999 \times 0.9995$$
$$av(11kV, d) = 0.9999$$

The load point availabilities for load point i is the product

$$av(i) = av(33kV) \times av(trans) \times av(11kV, i)$$

The results are

$$av(a) = 0.99979$$
$$av(b) = 0.99979$$
$$av(c) = 0.99929$$
$$av(d) = 0.99979$$

We convert the availabilities to *unavailable minutes per year* using the formula (assuming each interruptions exceeds 3 minutes)

$$m(i) = \left(1 - av(i)\right) \times 8760 \left(\frac{hour}{year}\right) \times 60 \left(\frac{minutes}{hour}\right)$$

This results in

$$m(a) = 109.3\ minutes/year$$
$$m(b) = 109.3\ minutes/year$$
$$m(c) = 372.1\ minutes/year$$
$$m(d) = 109.3\ minutes/year$$

The expected system CML is computed as the customer-weighted average of the above, resulting in

$$expected\ CML = \sum_{i \in load\ points} \frac{cust(i) m(i)}{\sum_j cust(j)} = 135.6\ minutes/year$$

[FEEDBACK]
This question was generally answered well, but things to watch out for are:

- Not correctly identifying redundancy pattern in 33kV network. In particular, H1 is not required to supply load in any case.
- Occasionally, numerical errors accumulated by excessive rounding of results.

Increased load level scenario. Load levels in **d** increase to the point where a single transformer (T3 or T4) is sufficient only 95% of the time. In the remaining 5% of cases, *both* T3 and T4 are required to supply all load. When the available transformer capacity is exceeded, all load in **d** is disconnected.

ii) For the increased load level scenario, compute the probability that loads in **d** are supplied. Compute the updated expected-CML value.

[3]

The first step is to recompute $av(d)$. The transformers remain redundant 95% of the time, but we need to compute a separate availability for the 5% non-redundant cases. The overall availability is a linear combination:

$$av_{new}(d) = 0.95 \times av(d) + 0.05 \times av_{nonredundant}(d)$$

The non-redundant availability is

$$av_{nonredundant}(d) = av(33kV) \times av(11kV, d) \times av(T3) \times av(T4) \\ = 0.9800$$

Therefore

$$av_{new}(d) = 0.95 \times 0.99979 + 0.05 \times 0.9800 = 0.9988$$

and the number of unavailable minutes per year is

$$m_{new}(d) = (1 - av_{new}(d)) \times 8760 \left(\frac{hour}{year}\right) \times 60 \left(\frac{minutes}{hour}\right) \\ = 630.5 \frac{minutes}{year}$$

The expected CML of the system becomes

$$Expected\ CML = 396 \frac{minutes}{year}$$

This is an increase of 260 minutes over the normal load scenario!

[FEEDBACK]
This question was generally answered well by those who provided an answer. Occasionally, the definitions of CML and CI were mixed up, with a factor 100 (for CI) being applied to CML, or the conversion to minutes being omitted.

iii) Propose two reasonable engineering solutions to decrease the expected-CML in the increased load level scenario.

[2]

We know the high load level in the second scenario is associated with peak load situations, because the capacity of a single transformer is only exceeded in 5% of cases. Solutions to decrease the peak load or increase transformer capacity include:

- Installation of third transformer in parallel with T3 and T4
- Replacing T3 and T4 with higher-rated transformers
- Using demand response to shave peak loads
- Installation of electrical storage on the 11kV side of the transformer
- Installation of DG on the 11kV side of the transformer

[FEEDBACK]
Note that solutions must be accompanied by an explanation of their applicability: which problem do they solve and how do they do it?

d) State examples of *physical* threats and *cyber* threats to reliable power system operation. For each category, provide one example of an *accidental/natural* threat and one example of a *malicious* threat (i.e. provide four examples in total).

[3]

Examples (from lecture slides)

	Malicious	**Accidental**
Physical	Terrorism, Vandalism	Weather impacts, mechanical failure
Cyber	Hacking, Jamming of communication	Communication errors, Software bugs

[FEEDBACK]
Common mistakes included:

- Not providing at least four examples – one for each category.
- Not indicating whether examples referred to physical/cyber/malicious/accidental threats.
- Occasionally, misqualifying examples.