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.

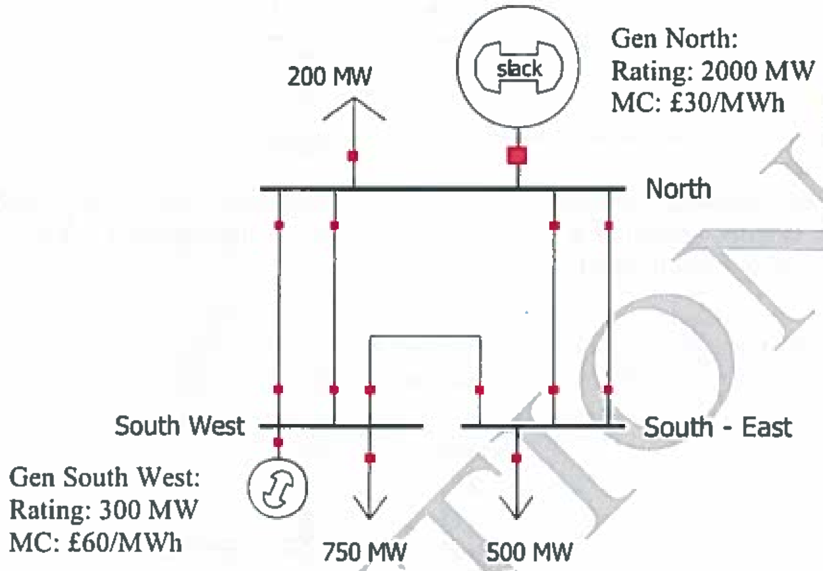


Figure 1.1: A 4-node system

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.

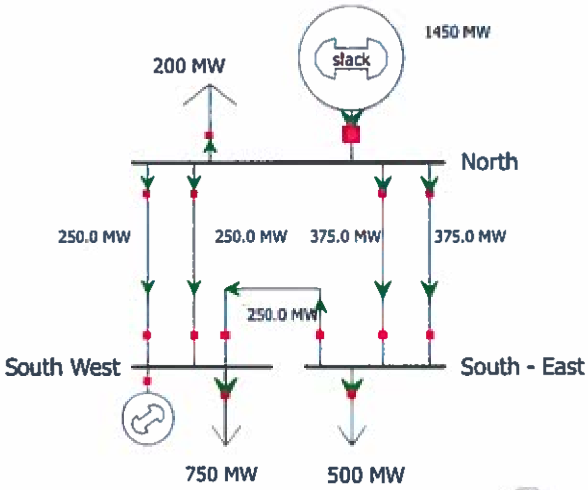
Transmission corridor	Number of circuits	X (p.u.)	Capacity per circuit (MW)
North - South East	2	0.50	500
North – South West	2	1.00	375
South East – South West	1	0.25	500

Table 1.1: Parameters of transmission corridors

a) Determine the Economic Dispatch and compute the corresponding power flows in each of the circuits [3]

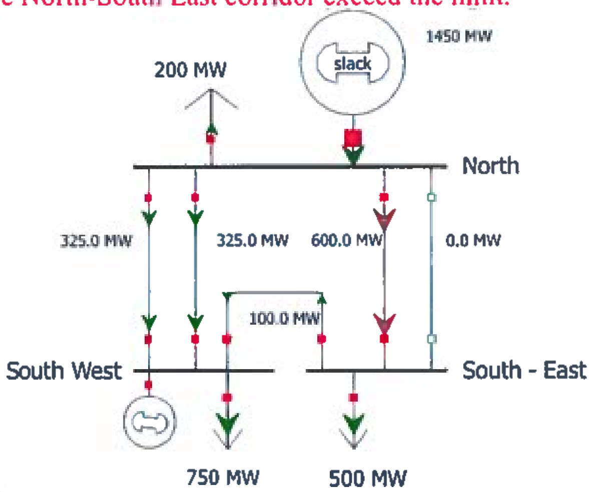
Total load is 200 + 500 + 750 = 1450 MW. The ED solution: Gen at North produces 1450 MW and Gen at South East produces 0 MW. Total cost is (1450*30 + 0*60) = £43500/h

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

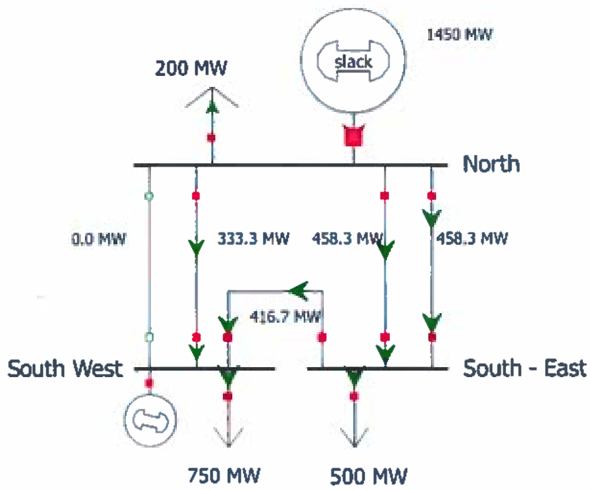


b) Determine the power flows following the outage of single individual circuits and identify conditions in which the power flows during contingency exceed the circuit capacity limit. [3]

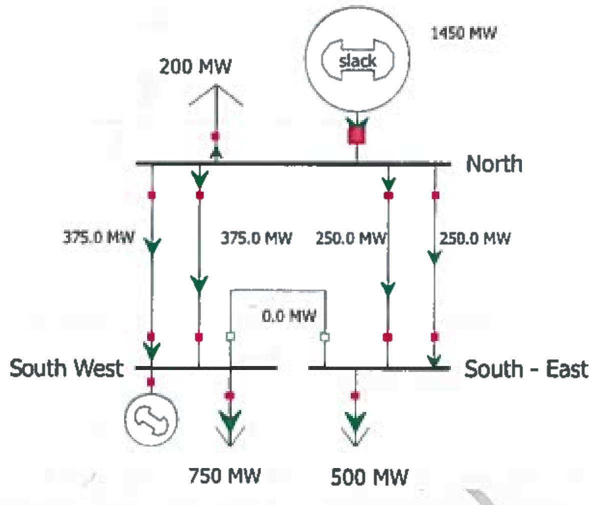
Flows when one circuit of North – South East is out-of-service. Flows at the other circuit of the North-South East corridor exceed the limit.



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



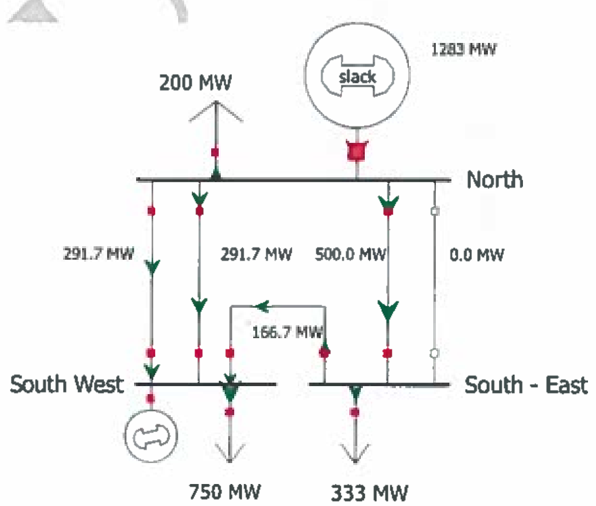
Flows when one circuit of South East – South West is out-of-service. No violation.



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

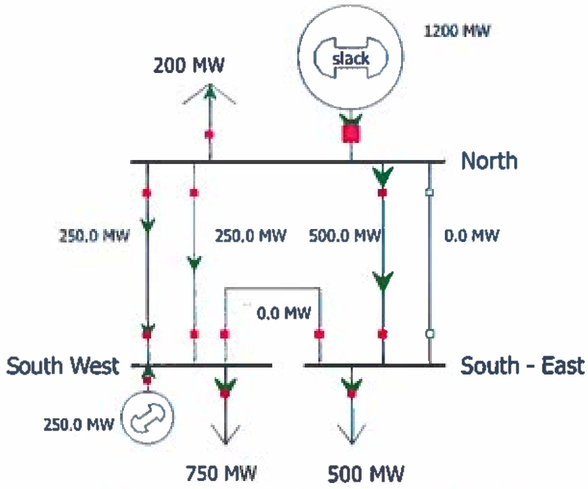
c) In case that Demand Side Response may be available to provide corrective control, determine the minimum amount of Demand Side Response that would be needed to manage the power flows within the limits. [7]

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:



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.

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.

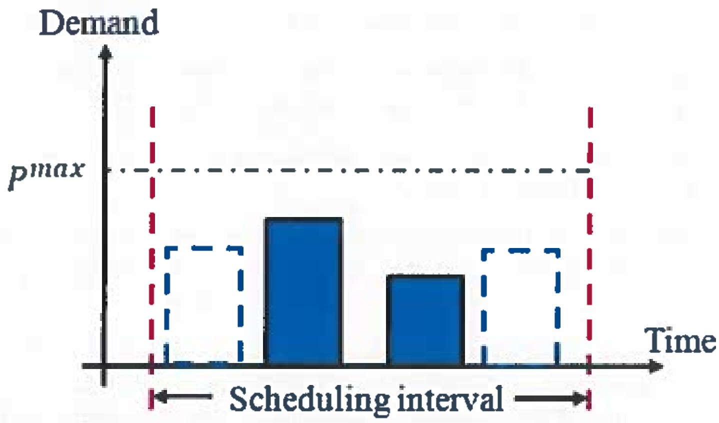


Figure 2.1: Flexibility of appliances with continuously adjustable power levels

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.

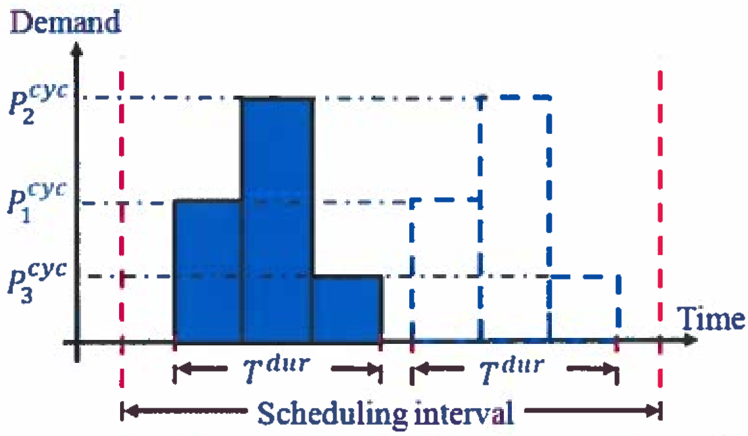


Figure 2.2: Flexibility of appliances with shiftable cycles

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.

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 $s^{max} = 10$MW
- inflexible demand appliances, consuming power $D_1 = 4$MW (at hour 1) and $D_2 = 3$MW (at hour 2)
- 1000 identical flexible demand appliances with power d_t (kW), scheduling interval including hours 1 and 2, total energy required $E = 5$kWh and maximum power limit $d^{max} = 6$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 $50(D_1 + 1000 * d_1)^2 + 50(D_2 + 1000 * d_2)^2 = £4000$

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 $\omega = 0.5$.

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

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.

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 $av = \frac{MTTF}{MTBF} = 0.95$.

Marking:

- 1 point: correct approach to compute MTTF
- 1 point: correct approach to compute availability
- 1 point: correct numbers

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]:

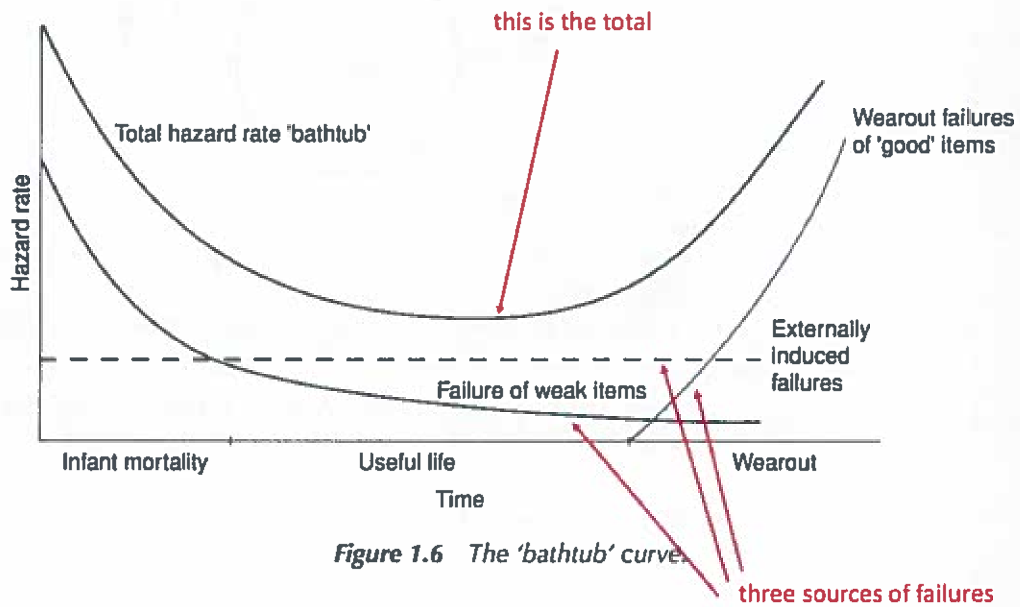


Figure 1.6 The 'bathtub' curve.

Practical Reliability Engineering, O'Connnor and Kleyner

Marking:

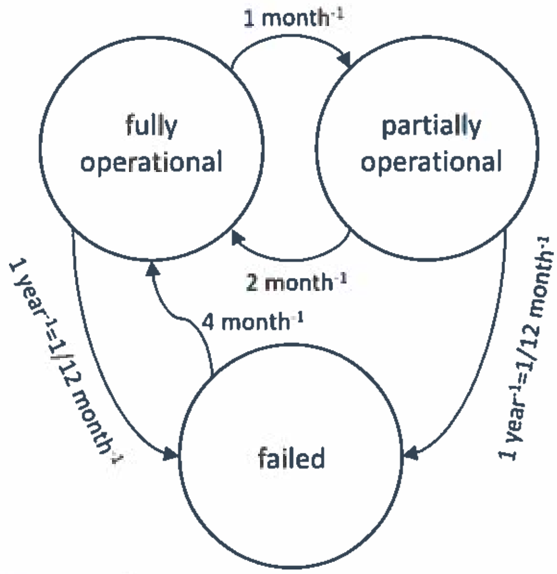
- 1 point: bathtub-shaped graph with time on horizontal access and something akin to failure rate on the vertical axis
- 1 point: identification of early – mid – late component life sections, and/or the associated failure modes.

- 1 point: relation of mid/useful life section with approximately constant failure rate.

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):



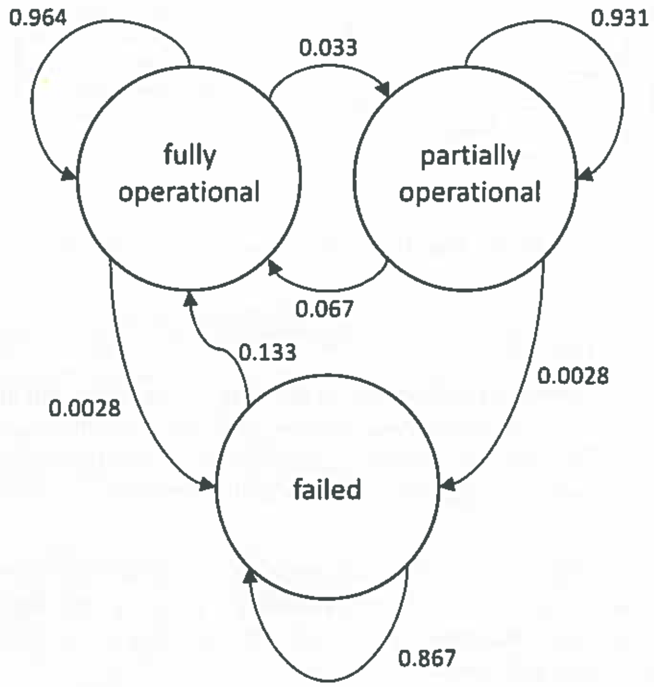
Marking:

- 1 point for drawing the states with the correct connectivity (including directions)
- 1 point for assigning the correct numerical value to the transition rates (including mention of units).

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:



Marking:

- 1 point for identifying the need to include self-loops with a transition probability of (1 - [outgoing probabilities])
- 1 point for computing the correct transition probabilities using a 1-day time step [the use of 28-31 days for a month is correct].

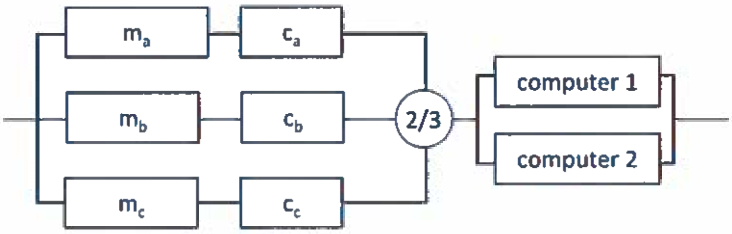
d) A system operator is designing a forced islanding scheme: in case of an acute blackout threat, the scheme preventively splits the power system into separate electrical islands. Such a scheme must have a high degree of dependability, but also be resilient against spurious activations.

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:



Marking:

- 1 point for identifying the structure with two parallel structures in series.
- 1 point for constructing the correct diagram, including 2/3 voting. [note: equivalent diagrams (change of order) are correct as well]

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:

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

Marking:

- 1 point for the correct equation for the redundant computer system
- 1 point for the correct equation for the 2-out-of-3 monitoring-communication system
- 1 point for computing the correct overall probability.

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.

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

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

Marking:

- 1 point: correct formula for the standard error
- 1 point: correct calculation of SE
- 1 point: correct identification of scaling with increased run time, and computation of updated SE.

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 ± 2.0 minutes

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

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

Marking:

- 1 point: 1 or 2 correct
- 2 points (total): 3 correct

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.

Marking:

- 1 point: stating that CML / CI targets vary between DNOs, with some indication why (history, different networks/environments)
- 1 point: stating that CML/CI targets decrease over time.
- 1 point: qualitative description of the interruptions incentive scheme (name or 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

$$\text{CML} = \frac{\sum_{events} N_{affected} T_{minutes}}{N_{customers}} = \frac{50 \times 420 + 3800 \times 90 + 30 \times 1440 + 700 \times 15 + 200 \times 8 + 1400 \times 4}{8000} = 53.0 \text{ minutes}$$

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

Marking:

- 1 point for correctly excluding the 2-minute event
- 1 point for getting the CML/CI formulas right
- 1 point for getting the correct numbers

c) Consider the distribution network in Figure 4.1.

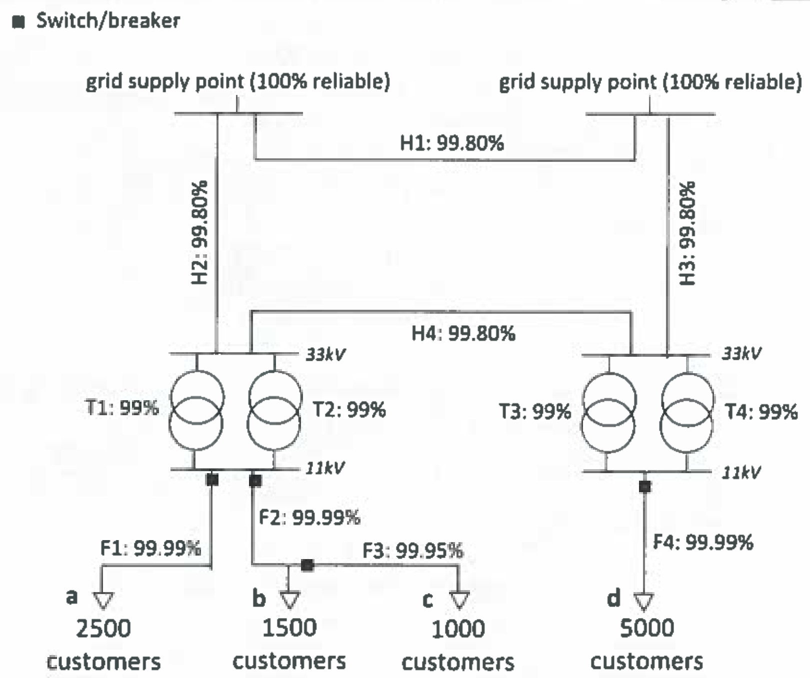


Figure 4.1: network diagram

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

$$av(33kV) = 1 - (1 - 0.998)(1 - 0.998\times0.998) = 1 - 8\times10^{-6}$$
$$= 0.999992$$

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

$$av(trans) = 1 - (1 - 0.99)^2 = 1 - 1\times10^{-4} = 0.9999$$

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

$$av(11kV, a) = 0.9999$$
$$av(11kV, b) = 0.9999$$
$$av(11kV, c) = 0.9999\times0.9995$$
$$av(11kV, d) = 0.9999$$

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

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

Marking:

- 1 point for the correct identification of the redundancy pattern in the 33kV network (parallel combination of 1 line and 2 lines in series)
- 1 point for identifying the redundancy of the transformers
- 1 point for identifying the availability of load points as the product (series) of 33kV, transformers and 11kV availabilities.
- 1 point for correctly computing the availability of load points a-d
- 1 point for stating the correct formula/approach for computing e-CML from the availabilities.
- 1 point for correctly computing the CML (insofar as possible on the basis of previous answers).

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!

Marking:

- 1 point for identifying the correct linear combination of redundant and nonredundant availabilities
- 1 point for correctly computing the updated supply probability $av_{new}(d)$.
- 1 point for correctly computing the updated expected CML value.

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

Marking:

- 1 point for each of the above (or alternative reasonable solutions), with a maximum of two points.

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

Marking:

- 1 point for 2 correct answers (not restricted to above list)
- 2 points (total) for 3 correct answers in 3 different categories, or 4 correct answers in 2 different categories.
- 3 points (total) for four correct answers, one in each category.