Distribution System Reliability Evaluation

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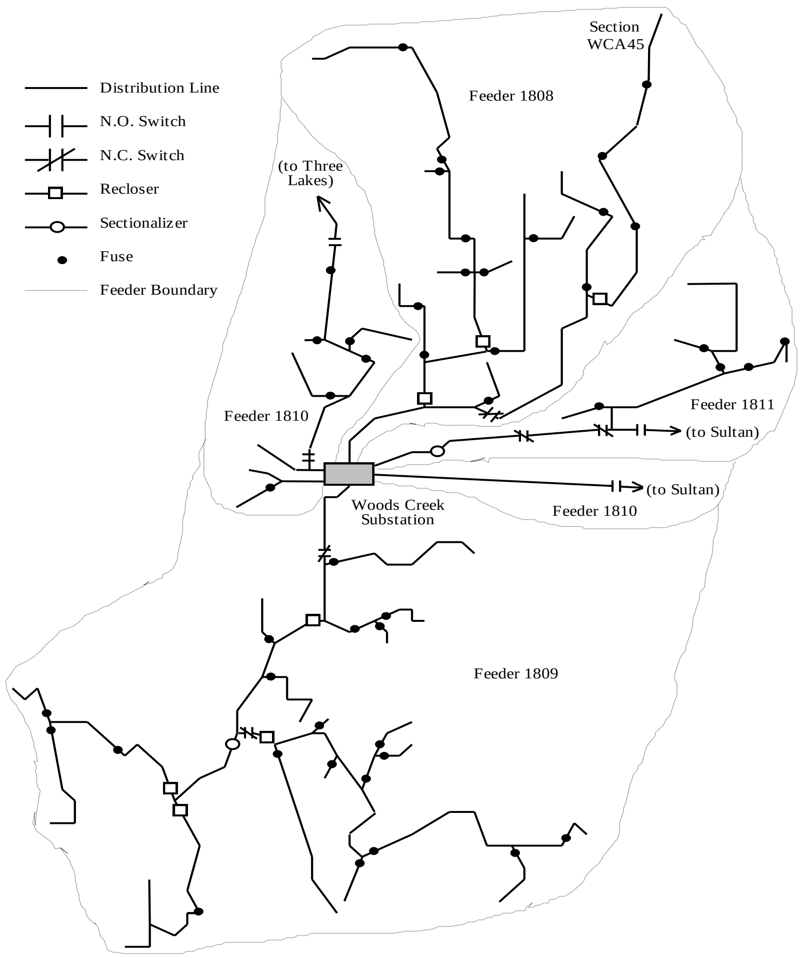
Overview

- Introduction to Distribution systems
- Distribution Reliability
- Standard Reliability Metrics
- Information Required for Reliability Evaluation
- Predictive Reliability Evaluation
  - Analytical Methods
  - Simulation Based Methods
- Methods to improve reliability

Introduction to Distribution Systems

- 5kV- 69kV system class
- Layout
  - Substations
  - Primary distribution system
  - Secondary distribution system
- Largely a radial system with single, two and three phase lines.
- Responsible for the majority (about 80%) of customer interruptions that are either momentary or sustained.



Distribution Reliability

- Motivation/Objective
  - Determine the system reliability and customer satisfaction:
    - Number of momentary and sustained interruptions
    - Duration of interruptions
    - Number of customers interrupted
  - Improve system performance
  - Basis for new or expanded system planning
  - Satisfy regulatory requirements
  - Determine performance based rate making
  - Maintenance scheduling and Resource allocation

Standard Reliability Metrics

- Load point indices
  - Determine for each customer
    - The Number of outages (per year)
    - The Duration of outages (per year)
    - Unavailability / Availability of service
- System wide indices
  - SAIFI (System Average Interruption Frequency Index)

$$SAIFI = \frac{Total\,Number\,of\,Customer\,Interruptions}{Total\,Number\,of\,Customers\,Served} = \frac{\sum N_i}{N_T}$$

  - SAIDI (System Average Interruption Duration Index)

$$SAIDI = \frac{Total\,Duration\,of\,Customer\,Interruptions}{Total\,Number\,of\,Customers\,Served} = \frac{\sum r_i N_i}{N_T}$$

Standard Reliability Metrics Contd.

- CAIDI (Customer Average Interruption Duration Index)

$$CAIDI = \frac{Total\ Duration of\ Customer Interruptions}{Total\ Number of\ Customer Interruptions} = \frac{\sum r_i N_i}{\sum N_i} = \frac{SAIDI}{SAIFI}$$

- CTAIDI (Customer Total Average Interruption Duration Index)

$$CTAIDI = \frac{Total\ Duration of\ Customer Interruptions}{Total\ Number of\ Customers Interrupted} = \frac{\sum r_i N_i}{CN}$$

- CAIFI (Customer Average Interruption Frequency Index)

$$CAIFI = \frac{Total\ Number of\ Customer Interruptions}{Total\ Number of\ Customers Interrupted} = \frac{\sum N_i}{CN}$$

- MAIFI (Momentary Average Interruption Frequency Index)

$$\text{MAIFI} = \frac{\text{Total Number of Momentary Customer Interruptions}}{\text{Total Number of Customers Served}} = \frac{\sum ID_i N_i}{N_T}$$

Standard Reliability Metrics Contd.

– ASAI (Average Service Availability Index)

$$ASAI = \frac{Customer\,Hours\,Service\,Availabilty}{Customer\,Hours\,Service\,Demand} = \frac{N_T \cdot 8760 - \sum r_i N_i}{N_T \cdot 8760}$$

– ASIFI (Average Service Interruption Frequency Index)

$$ASIFI = \frac{Connected\ kVA\ Interrupted}{Total\ Connected\ kVA\ Served} = \frac{\sum L_i}{L_T}$$

– ASIDI (Average Service Interruption Duration Index)

$$ASIDI = \frac{Connected\ kVA\ Duration\ Interrupted}{Total\ Connected\ kVA\ Served} = \frac{\sum r_i L_i}{L_T}$$

Historical Vs Predictive Analysis

- Historical Analysis
  - Use system outage histories to compute indices that reflect past performance of the system
  - Basis for most short term decision making
  - Used in the computation of failure rates and repair times required as input to predictive analysis
- Predictive Analysis
  - Combine system topology with a set of techniques to estimate load-point and system indices
  - Basis for most long term as well as short term decision making

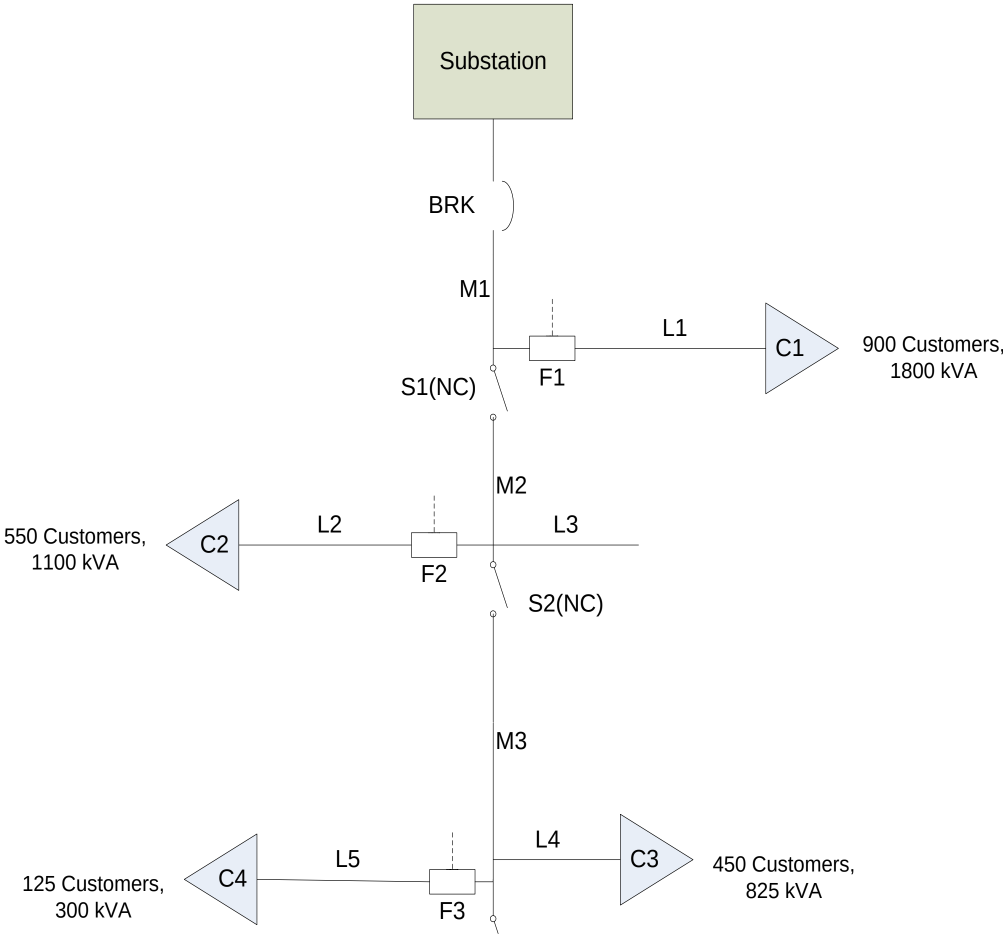
Information Required for Predictive Reliability Evaluation

- System topology
- Reliability parameters
  - Over-head and underground line segments
    - Permanent Failure Rate (λ_p)
    - Temporary Failure Rate (λ_t)
    - Mean Time to Repair (MTTR)
  - Protective and Switching Devices (Reclosers, Switches, Fuses, Breakers, etc.)
    - Probability of Failure (POF)
    - Protection Reliability (PR)
    - Reclose Reliability (RR)
    - Mean Time to Repair (MTTR)
    - Switching Reliability (SR)
    - Mean Time to Switch (MTTS)
- Customer and Load Information

How to Compute Reliability?

- Analytical Methods
  - Use system topology along with mathematical expressions to determine reliability indices
- Simulation Based Methods
  - Compute indices by simulating the conditions on the system by generating system states of failure and repair randomly
- Assumptions made in Analytical Methods
  - Temporary and Permanent fault processes are independent and mutually exclusive
  - Occurrence of a fault excludes the occurrence of another until the system is restored to normalcy. Can be a reasonable assumption if the system spends a majority of the time in its normal working state
  - The failure time and the repair time of components are exponentially distributed.

An example feeder



Component	Failure Rate (λ)	MTTR (Hours)
M1	0.10	4
M2	0.25	4
M3	0.30	4
L1	0.20	3
L2	0.40	3
L3	0.10	1
L4	0.10	2
L5	0.25	2

Enumerative Analysis (FMEA)

Failure mode	Load Point C1 (f/y)			Load Point C2 (f/y)			Load Point C3 (f/y)			Load Point C4 (f/y)		
	λ (f/y)	r (hr)	U=$\lambda.r$ (hr/y)	λ (f/y)	r (hr)	U=$\lambda.r$ (hr/y)	λ (f/y)	r (hr)	U =$\lambda.r$ (hr/y)	λ (f/y)	r (hr)	U =$\lambda.r$ (hr/y)
M1	0.10	4	0.40	0.10	4	0.40	0.10	4	0.40	0.10	4	0.40
M2	0.25	0.50	0.125	0.25	4	1.00	0.25	4	1.00	0.25	4	1.00
M3	0.30	0.50	0.15	0.30	0.50	0.15	0.30	4	1.20	0.30	4	1.20
L1	0.2	3	0.60									
L2				0.40	3	1.20						
L3	0.10	0.50	0.05	0.10	1	0.10	0.10	1	0.10	0.10	1	0.10
L4	0.10	0.5	0.05	0.10	0.5	0.05	0.10	2	0.20	0.10	2	0.20
L5										0.25	2	0.50
Total	$\Sigma\lambda$	$\frac{\sum U}{\sum \lambda}$	ΣU	$\Sigma\lambda$	$\frac{\sum U}{\sum \lambda}$	ΣU	$\Sigma\lambda$	$\frac{\sum U}{\sum \lambda}$	ΣU	$\Sigma\lambda$	$\frac{\sum U}{\sum \lambda}$	ΣU
	1.05	1.31	1.375	1.25	2.32	2.90	0.85	3.4	2.9	1.1	3.10	3.40

FMEA contd.

$$SAIFI = \frac{\sum N_i}{N_T}$$

$$= \frac{1.05*900 + 1.25*550 + 0.85*450 + 1.1*125}{900 + 550 + 450 + 125} = \frac{2152.5}{2025} = 1.06 \text{ Interruptions/Customer}$$

$$SAIDI = \frac{\sum r_i N_i}{N_T}$$

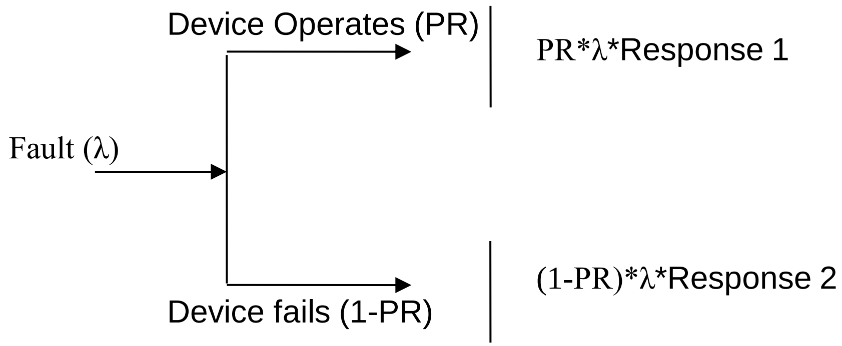
$$= \frac{1.375*900 + 2.90*550 + 2.90*450 + 3.40*125}{900 + 550 + 450 + 125} = \frac{4562.5}{2025} = 2.253 \text{ Hrs/Customer Interruption}$$

$$CAIDI = \frac{SAIDI}{SAIFI} = \frac{2.253}{1.06} = 2.12 \quad \text{Hrs/Customer}$$

$$ASAI = \frac{N_T \cdot 8760 - \sum r_i N_i}{N_T \cdot 8760} = \frac{2925*8760 - 4562.5}{2925*8760} = 0.999821$$

Accounting for Protection and Switching Failures

- When a protective device fails to operate after a fault occurs downstream of it, the backup protective device operates and clears it causing more number of customers to be interrupted for a longer period of time.



- When a switch fails to operate, customers are not restored and experience a duration equal to the MTTR of the fault.
  - Equivalent outage duration experienced:

$$SR * MTTS_{eq} + (1 - SR) * MTTR$$

where $MTTS_{eq} = Min(MTTS_{swi}, MTTS_{device}) + \left| MTTS_{swi} - MTTS_{device} \right|$

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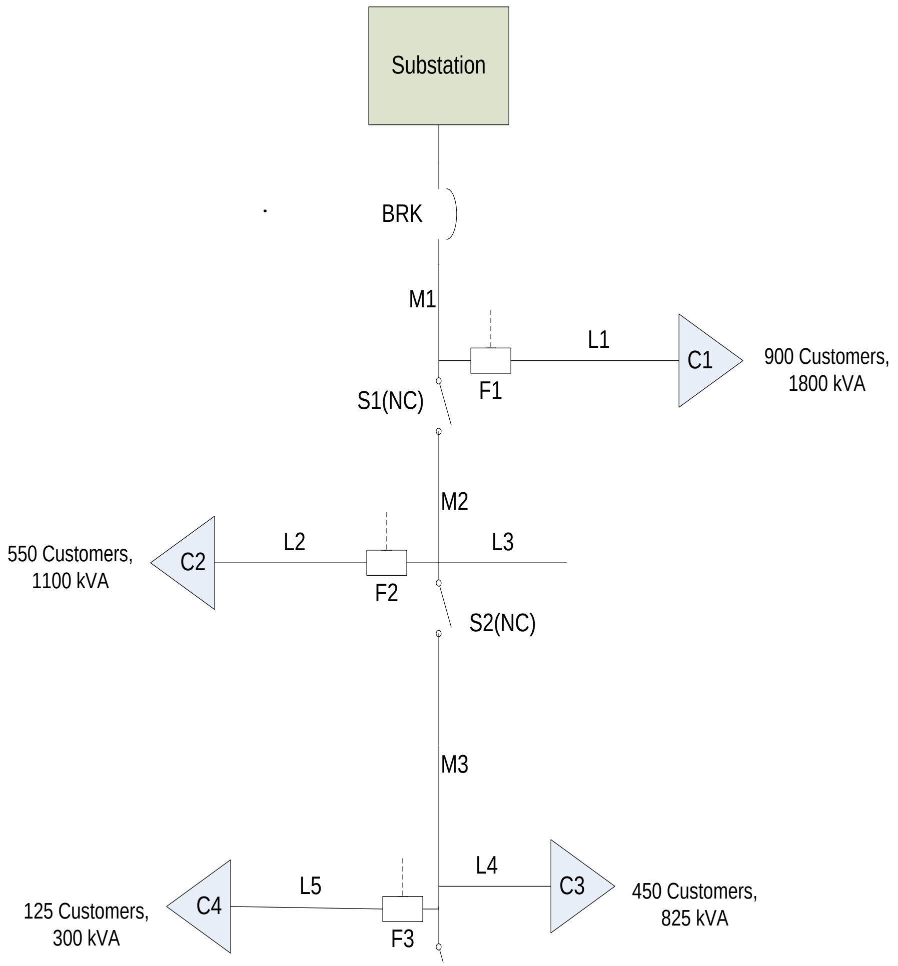
Zone-Branch Reduction

Zone Number	Device Name	Branches in the zone	
		Branch 1	Branch 2
1	BRK	M1	
2	F1	L1	
2	S1	M2	L3
3	F2	L2	
3	S2	M3	L4
4	F3	L5	



Zone Branch Reduction Method contd.

$$RIA = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R(z,k) = \begin{bmatrix} 4 & 4 & 4 & 4 & 4 & 4 & 4 & 4 \\ 0 & 3 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.5 & 0.5 & 4 & 4 & 4 & 4 & 4 & 4 \\ 0.5 & 0.5 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 3 & 0 & 0 & 0 \\ 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 4 & 4 & 4 \\ 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 2 & 2 & 2 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 \end{bmatrix}$$

$$FZB = \begin{bmatrix} \lambda_{M1} \\ \lambda_{L1} \\ \lambda_{M2} \\ \lambda_{L3} \\ \lambda_{L2} \\ \lambda_{M3} \\ \lambda_{L4} \\ \lambda_{L5} \end{bmatrix} = \begin{bmatrix} 0.10 \\ 0.2 \\ 0.25 \\ 0.1 \\ 0.4 \\ 0.3 \\ 0.1 \\ 0.25 \end{bmatrix}$$

$$\lambda T(i,j) = \sum RIA(z,k) * FZB(k)^T \ \ failures/year$$

$$\lambda r(i,j) = \sum RIA(z,k) * FZB(k)^T * R(z,k) \ hours/year$$

Analytical Methods Contd.

- Markov Modeling
  - Divide the entire feeder into zones and branches
  - List the possible contingencies in the feeder
  - For each contingency, determine the frequency and outage duration at each of the zones.
  - Apply the zone reliability indices to all the branches in the zone
- Network Reduction
  - Use of series- parallel combinations to reduce the network
  - Determine load point indices and aggregate them to get the system wide indices
- Fault Tree Analysis
  - For each load point, determine the components that cause interruptions to it.
  - Combine the load point indices to get the system indices
- Cut-set Analysis
  - Determine First and second order minimal cutsets that cause outages at each load point
  - Determine load point and system indices

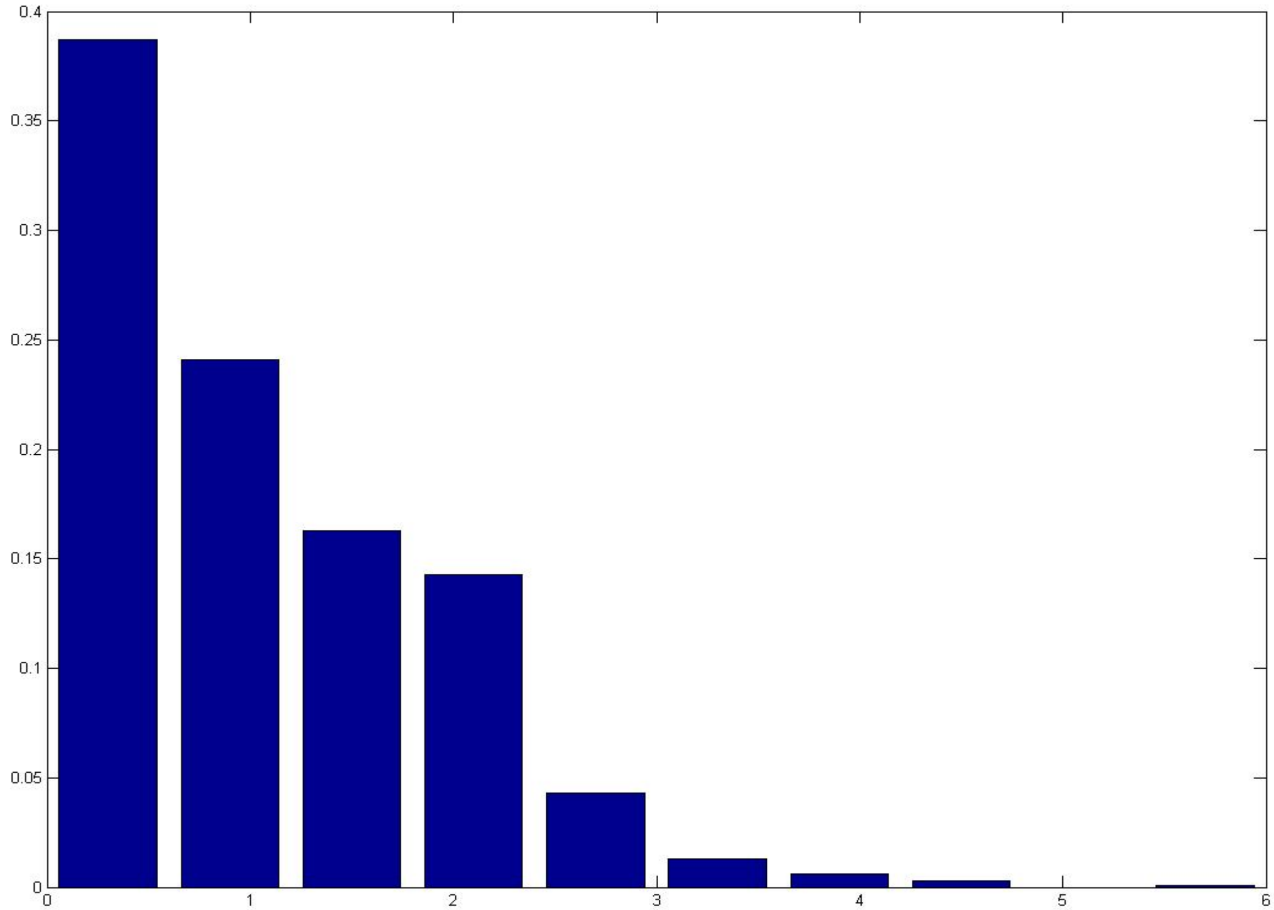
Simulation Based Methods

- Drawbacks of the analytical methods
  - System and load point indices determined as average values with no information on the variability in the indices
  - Analytical methods use the simplifying assumption that failure and repair times in a distribution system are exponentially distributed
- Types of simulation based methods
  - Sequential Monte Carlo: Simulate the systems operation by generating an artificial history of failure and repair events in time sequence
  - Non-sequential Monte Carlo: Determine the systems response to a set of events whose order have no influence or significance

Sequential Monte Carlo

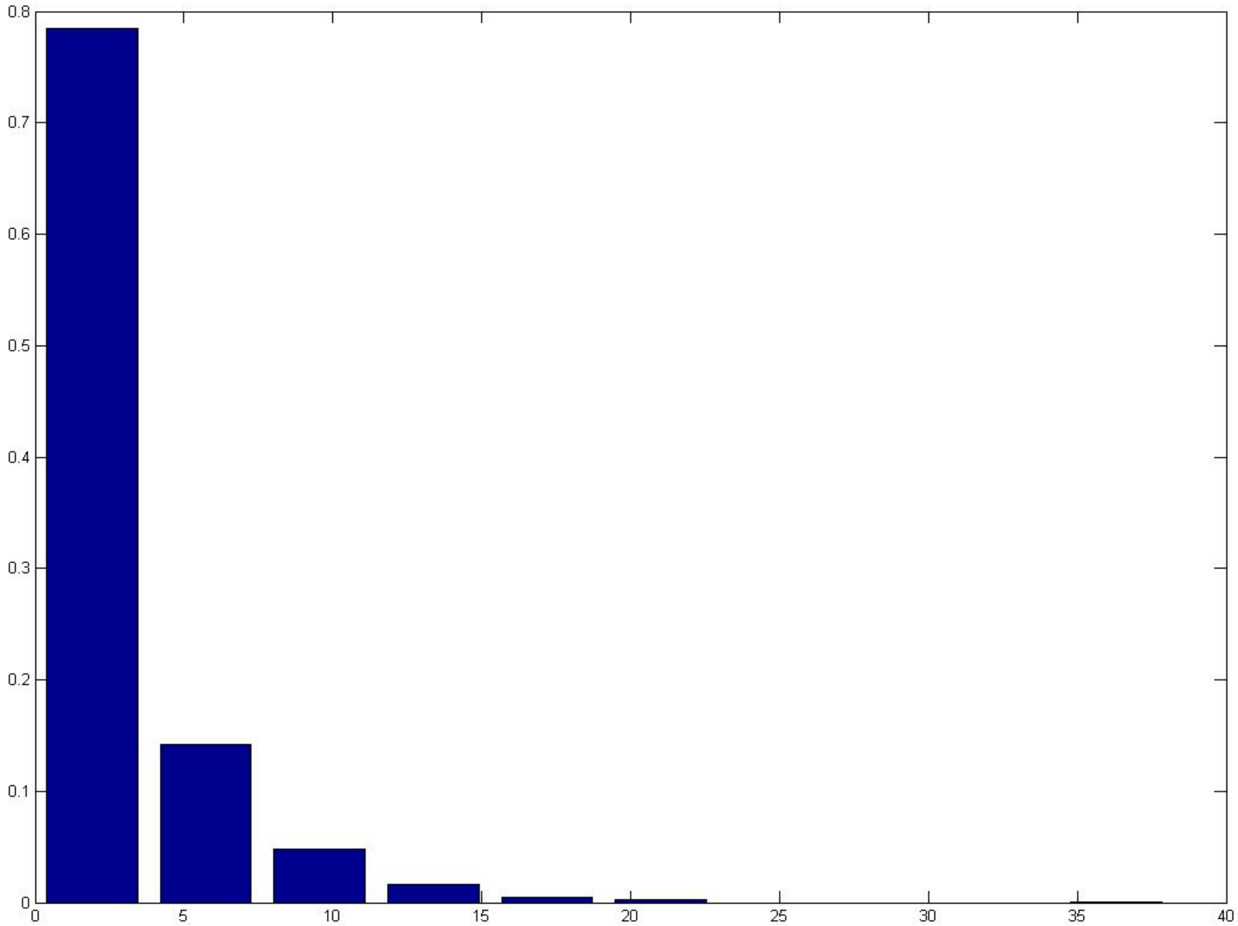
1. Generate a random number for each element in the system and convert it to TTF (Time to failure) corresponding to the probability distribution of the element parameter.
2. Determine the element with minimum TTF.
3. Generate a random number and convert this number into the repair time (RT) of the element with minimum TTF.
4. Generate another random number and convert this number into the switching time (ST) according to the probability distribution of the switching time if this action is possible.
5. Determine the load points that fail and record the outage duration for each failed load point.
6. Generate a new random number for the failed element and convert it into a new TTF, and return to step 2 if the simulation time is less than one year. If the simulation time (i.e. TTF+RT of the failed component) is greater than one year, go to step 9.
7. Calculate the number and duration of failures for each load point for each year.
8. Calculate the average value to the load point failure rate and failure duration for the sample years.
9. Calculate the system indices and record these indices for each year.
10. Calculate the average values of these system indices.
11. Return to step 2. If the simulation time is less than the specified total simulation years, otherwise output the results.

PDF of SAIFI



A histogram of SAIFI obtained by sequential Monte-Carlo simulation for the example system. The x-axis represents the range of values SAIFI can take while the y-axis is the frequency. The mean value of SAIFI is found to be: 1.03447

PDF of SAIDI



A histogram of SAIDI obtained by sequential Monte-Carlo simulation for the example system. The x-axis represents the range of values SAIFI can take while the y-axis is the frequency. The mean value of SAIFI is found to be: 2.475

Methods to Improve Reliability

- Maintenance
  - Corrective Maintenance
  - Preventive Maintenance
    - Time based or periodic maintenance
    - Condition based preventive maintenance
    - Reliability centered maintenance

Reduces both the momentary and sustained outage frequency

- Installing reclosers and breakers

Reduces both the outage frequency and duration

- Fuse saving and Fuse clearing methods

Reduces both the outage frequency and duration

Methods to Improve Reliability Contd.

- Switching
  - Upstream switching
  - Downstream switching or back feeding

Reduces the outage duration experienced by customers

- Use of automation

Reduces the outage duration

- Crew management

Reduce the outage duration

- System reconfiguration

Reduces both the outage frequency and duration

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QUESTIONS