Module 8
Composite System Reliability Evaluation

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Composite System Reliability

- Concerned with the total problem of assessing the ability of the generation and transmission system to supply adequate and suitable electrical energy to major system load points.

Motivation

- ✓ Need to consider internal transmission limitations in generating capacity reliability evaluation.
- ✓ Optimize relative investments in generation and transmission systems.
- ✓ Increased trends in resource sharing.
- ✓ Need for better representation of generation effects in transmission system reliability analysis.
- ✓ Dispersed generation - battery storage, co-generation, etc.

Multi-area v.s. Composite System Reliability

- Similar in many ways
- The major difference is in the transmission network modeling
- Because of more detailed network model, the composite system reliability model has many more nodes than the multi-area model
- Network flow model(transportation type) and DC flow methods are considered adequate for multi-area reliability evaluation
- Dc flow or AC flow methods are considered adequate for composite system reliability evaluation

Methods

Deterministic

- The main principle is to maintain adequate service under most likely outages but to accept some degradation of performance under low probability outages involving multiple generation and transmission facilities.

Probabilistic

- Direct Analytical
- Monte Carlo Simulation
- Hybrid

Reliability Indices

- System Problem Indices:

These indices are calculated without remedial actions and thus represent an upper bound on unreliability.

- Severity Indices:

These are computed after remedial actions and are thus a lower bound.

Component Models

- Modeling of component failures

For performing the reliability analysis of any system, the component models need to be properly defined. The components considered in composite system reliability evaluation are:

- Generating units.
- Transmission lines.
- Transformers.
- Buses.
- Circuit Breakers.

- In addition, weather is an important component of this analysis and common mode failures of groups of components need to be specified.

Component Models

- Generating unit models

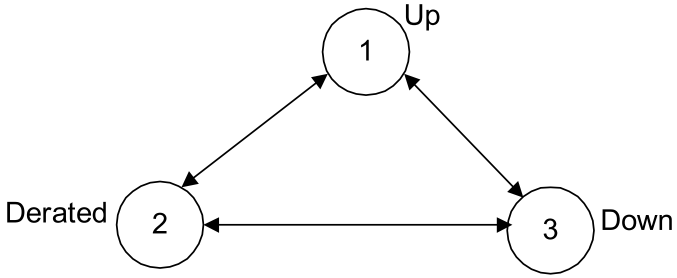
- Generators are modeled as three state devices. The state transition diagram is shown in the figure below. Here the various states are as follows.

State 1: Up state with full capacity.

State 3: Down state with zero capacity.

State 2: Derated state.

- A two state model is a special case of this model where there is no transition to state 2.



Three state model of a generator

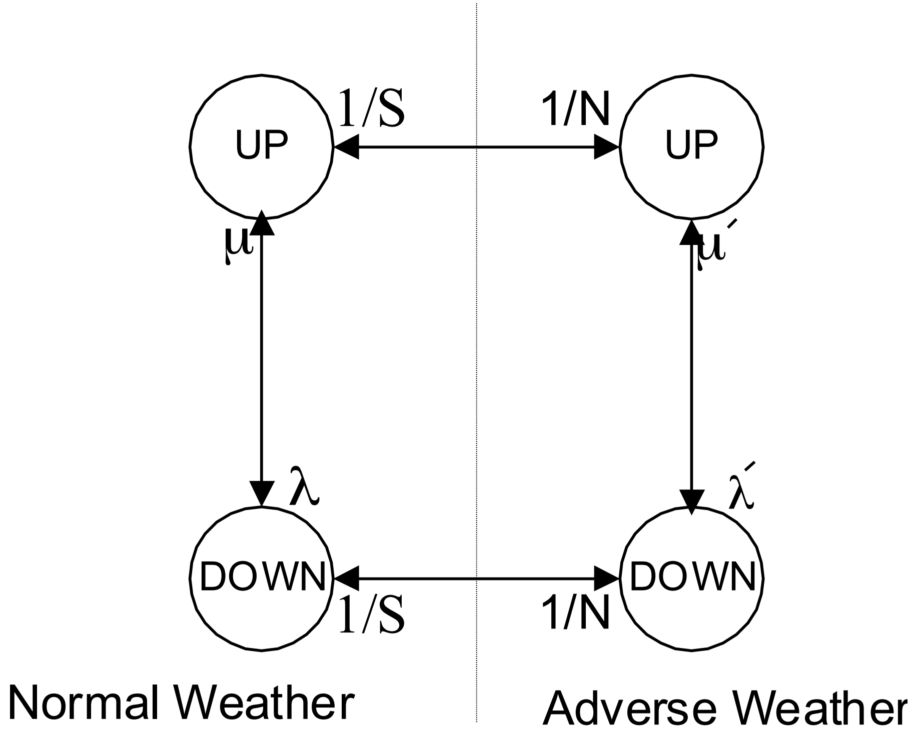
Component Models

- Transmission lines

- Transmission lines are assumed to be either in the up state or failed state. The failure and repair rates are further assumed to be dependent on weather. The state transition diagram of a transmission line is shown in figure in next page, where

- λ = Failure rate in the normal weather.
- λ' = Failure rate in adverse weather.
- μ = Repair rate in the normal weather.
- μ' = Repair rate in the adverse weather.
- N, S = Mean durations of normal and adverse weather.

Component Models



Model of Transmission line

Component Models

- Weather is assumed to exist either in the normal or adverse state. An important issue concerning weather is its extent of coverage. When the system is spread over a large area, at any given time, different regions may have different states of weather. An exact treatment of this effect is not possible and some simplifications are needed.
- One approach divides the whole area into regions. The weather in each region is characterized by mean duration of normal and adverse states. The weather changes in different regions are assumed independent. Every line is assigned to a particular region which really means that this line is predominantly effected by the weather in this region.
- It should be noted that for parallel transmission lines just using failure rate that is average of normal and adverse weather rates can lead to error.

Component Models

- Transformers and buses

Like the transmission lines, transformers and buses are treated as two state devices but the failure rate and repair rates are assumed independent of the weather.

Component Models

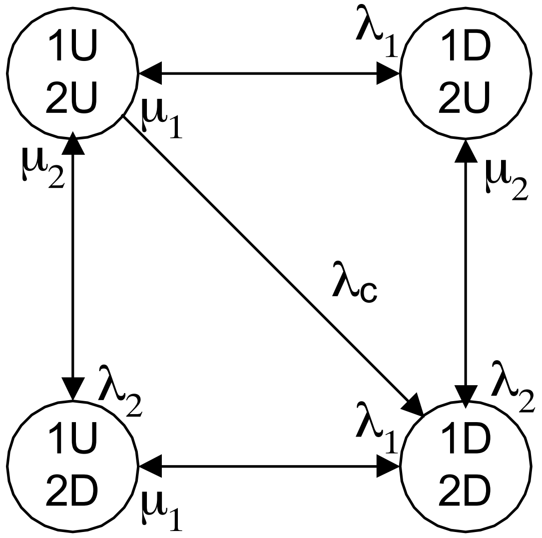
- Circuit breakers

A circuit breaker can have several failure modes as described below.

1. Ground faults: This refers to the fault in the circuit breaker itself. For this type of fault, the circuit breaker is treated in the same fashion as a transformer or a bus.
2. Failure to open: The objective of a circuit breaker is to isolate the faulted component. Because of latent faults in the breaker or the associated protection system, the breaker may not open when needed. This may result in healthy components being isolated due to the operation of secondary zone protection. This failure mode is characterized by a probability p. This means that when this breaker receives a command to open, there is a probability p that it may not respond. This could be either due to a problem in the breaker or the associated protection system.
3. Undesired tripping: It is also possible that a breaker may open without a command or fault. This can be characterized as a rate and its effect will be an open line. This is generally considered not to have a significant effect on the related outages.

Common mode failures

- The common mode outage is an event when multiple outages occur because of one external cause. An example of common mode outage is the failure of a transmission tower supporting two circuits. A simple common mode outage model for two components is as follows.



- where λ_i, μ_i are the failure and repair rates of components i and λ_c is the common mode failure rate.

Analytical Methods

- These methods are based on some kind of contingency enumeration approach. A direct enumeration approach is described on the next page. The exhaustive enumeration is, however, not possible except for very small number of components as the number of contingencies increases exponentially with the number of components.

Analytical Methods

- Several improvements have been made to this basic enumeration approach to improve its efficiency. Examples are:

1. Contingency ranking and selection:

This procedure consists of the following two steps:

a. Ranking of branch and/or generator outages for overload conditions and voltage problems using a performance index. This procedure will be briefly discussed later.

b. Selection of contingencies from the ranked list using event probability or event depth cut off.

2. State space truncation:

In this approach contingencies of only a certain order are considered. For example only upto second order contingencies may be considered.

3. Implicit enumeration based on system reliability coherence:

If a state is identified as a failure state, it is assumed that all states resulting from this state by degradation of components are also failure states.S^2

Analytical Methods

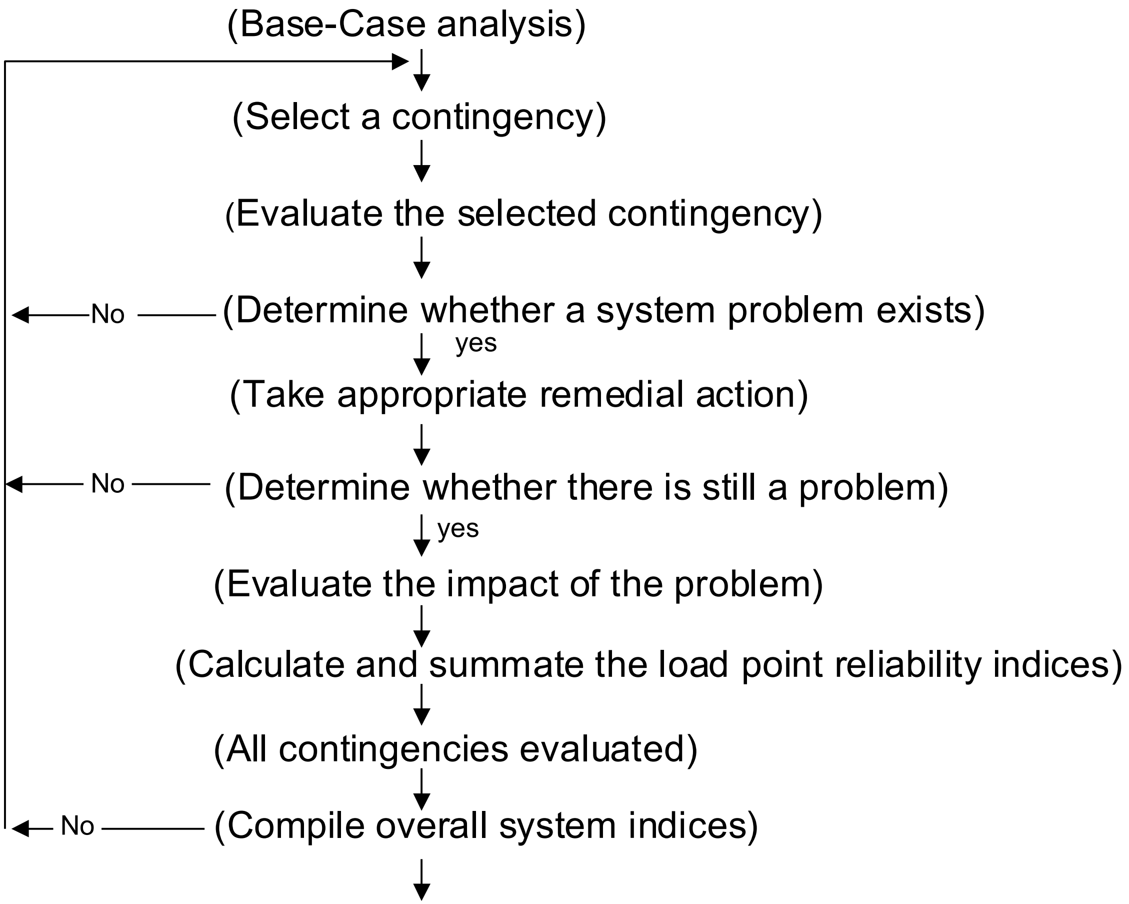
4. State Space Pruning Using State Space Decomposition.

5. Non-overlapping failure regions:

Higher order outages are restricted to circuits in the same electrical neighborhood, drastically decreasing the number of contingencies to be examined.

Analytical Methods

Contigency Enumeration Approach



(Base-Case analysis)

(Select a contingency)

(Evaluate the selected contingency)

(Determine whether a system problem exists)

(Take appropriate remedial action)

(Determine whether there is still a problem)

(Evaluate the impact of the problem)

(Calculate and summate the load point reliability indices)

(All contingencies evaluated)

(Compile overall system indices)

Basic Structure of Contingency Enumeration Approximate

Network Solution Methods

- Network solution methods are needed for state evaluation. The three types of solution methods used are:

1. Linear network flow model
2. DC load flow or linearized power flow model
3. AC power flow model

Network Solution Methods

1. Linear network flow model:

- Also called transportation model is based on only on Kirchoff’s first law. Here the sum of active power flows entering or leaving each bus is equal to the net injection at that bus.

Network Solution Methods

$$\bar{A}F + G = D$$

where

$\bar{A}$ = node-branch incidence matrix

F = circuit flow vector

G = generation vector

D = demand vector

Network Solution Methods

The constraints here are

$$G \leq G_{max}$$
$$F \leq F^{f}$$
$$-F \leq F^{r}$$

where

G = vector of generation

F= vector of flows

G_{max} = vector of max available generation

F^{f}, F^{r} = forward and reverse tie capacities

Network Solution Methods

- Although this model is generally considered adequate for multi-area reliability analysis, for composite system reliability this model is not considered accurate enough.

Network Solution Methods

2. DC load flow or linearized power flow model:

- This model has also been described in multi-area reliability section. This model is usually expressed by the equation

Network Solution Methods

$$B\theta = M$$

where B matrix is such that

b_{ij} = ijth element of B

=-(susceptance between nodes i and j)

if $\mathrm{i} \neq j$

b_{ii} = sum of susceptances connected to node i.

= node voltage angle vector

and

M = bus injection vector

The line flow from node i to node j is given by

$$f_{ij} = (\theta_j - \theta_i)b_{ij}$$

Network Solution Methods

The constraints here are

$$G \leq G_{max}$$
$$F \leq F^f$$
$$-F \leq F^r$$

where

G = vector of generation

F= vector of flows

G_{max} = vector of max available generation

F^f, F^r = forward and reverse tie capacities

Network Solution Methods

- The DC power flow model is generally felt to be a reasonable compromise between computational cost and accuracy for planning studies. This is often used in regions where systems are strongly meshed and do not have voltage problems.

Network Solution Methods

3. AC power flow model

- The AC flow model handles both active and reactive power flow model aspects. In addition to the bounds on generator active power generation there are bounds to reactive power, and constraints on voltage at buses.

Remedial Actions

- Invoked after all the automatic controls as part of network solution exhausted.

Steps:

- Identification of failed operating constraints: line overloads, low/high bus voltages, generator reactive power output violations, area net MW export violations.
- Use of linear programming to determine optimal remedial actions.

Remedial Actions

DC Mode:

- Phase shifter adjustment
- Generation re-dispatch
- Interruptible load curtailment
- Critical load shedding

AC Mode:

- MW & MVAR generation adjustment
- Gen bus voltage adjustment
- Phase shifter adjustment
- Transformer tap adjustment
- Switched cap/reactor
- Load curtailment

Contingency Ranking and Selection

- The goal of contingency selection techniques: From the set of all possible contingencies, determine the subset that will cause system failure.
- Perhaps no contingency selection method can attain this goal perfectly – perhaps at best to provide a subset that contains most contingencies causing system failure.
- One possible approach would be to rank contingency by first solving each contingency using DC load flow but it would be very time consuming.
- In a faster but less accurate method contingencies are ranked approximately by severity based on a performance index.

Contingency Ranking and Selection

- The scalar function, called performance index (PI) is first defined to provide a measure of system stress.
- Then some technique is used for predicting ΔPI - the change in PI when a component is outaged.
- The ΔPI for contingencies are then used to rank them in order of severity.
- Then ac or dc load flows are used to determine which of these ranked contingencies actually do cause problems.
- When a certain specified number of consecutive contingencies do not lead to system failure, the process is stopped. The assumption here is that remaining lower ranked contingencies will also not cause system failure.

Contingency Ranking and Selection

- This is not a foolproof method of ranking contingencies. It is possible that some severe contingencies may be left out and also some not so severe contingencies may be ranked.
- Contingency ranking may be done either based on overload or voltage problems. A brief discussion is provided here. For further details refer to EPRI report EL-2526 “Transmission System Reliability Methods” Vol 1: Mathematical Models, Computing Methods, and Results, July 1982.

Contingency ranking based on overloads

- Performance index for circuit overloads:

A performance index used for this purpose is:

$$PI = \sum_{I} W_I (P_I - \overline{P}_I)^n$$

where

W_I = weighting factor for circuit I

PI = real power flow on circuit I

$\overline{P}_I$= power rating of circuit I

n = an even integer, generally two

Contingency ranking based on overloads

- Several approaches for finding ΔPI have been proposed.
- PI can generally provide a good measure of system stress.
- In cases where load in one branch increases but in others decreases, the PI may fail to recognize overloads – masking
- Masking can be reduced by increasing the exponent n but it becomes difficult to solve ΔPI for n> 2.

Contingency ranking based on overloads

PI for Generator outages:

- Generator outages are ranked based on the prediction of overloads resulting from outages.
- The PI used is the same as that for lines. The change in PI as power injection at the bus i, Pi changes is estimated by

$$PI = \frac{\partial PI}{\partial P_i} \quad \Delta P_i$$

- This linear predictor has been found to produce reasonably good rankings for unit outages.

Contingency ranking based on overloads

$$\frac{\partial PI}{\partial P_i} = n\overline{\theta}_i$$

$\overline{\theta}_i$ = ith component of vector

N = number of buses

$$\theta = x\,\overline{P}$$

x = B^{-1}

B = NxN system susceptance matrix

$\overline{P}$ = Nx1 vector built by adding for each circuit l, an injection of PI on the from bus and -PI on the to bus of circuit l where

Contingency ranking based on overloads

$$P_I = \frac{W_I B_I^n \theta_I^{n-1}}{P_I^n}$$

- After the base case DC flow calculation elements of B are available. One additional calculation is required to find .

Contingency selection based on voltage deviations

- When a circuit is outaged, two factors contribute to voltage drop – loss of charging of the outaged circuit and increased var consumption on circuits that have increased loading as a result of this outage.

- One of the simplest PI is

$$PI = \sum_i X_i P_i^2$$

X_i = reactance of circuit I

Contingency selection based on voltage deviations

- A performance index that has shown more success is:

$$PI = \sum X_I \left(\frac{1}{P_{oi}^2} + \frac{1}{P_{oj}^2}\right)^{0.25} P_I^2$$

where

X_I = reactance of circuit I

P_I = power flow on circuit I

i,j = from and to buses of circuit I

P_{oi}, P_{oj} = terms recognizing line charging and/or reactive sources and loads on buses i and j.

Contingency selection

- The contingencies are evaluated in the decreasing order of severity. For each single order contingency, secondary contingencies are also ranked and evaluated. Evaluation is stopped either if a prespecified number of successes are encountered or if the contingency probability is lower than a threshold.
- This can be explained using the so called wind-chime scheme which is based on the concept of implicit enumeration.

Contingency selection

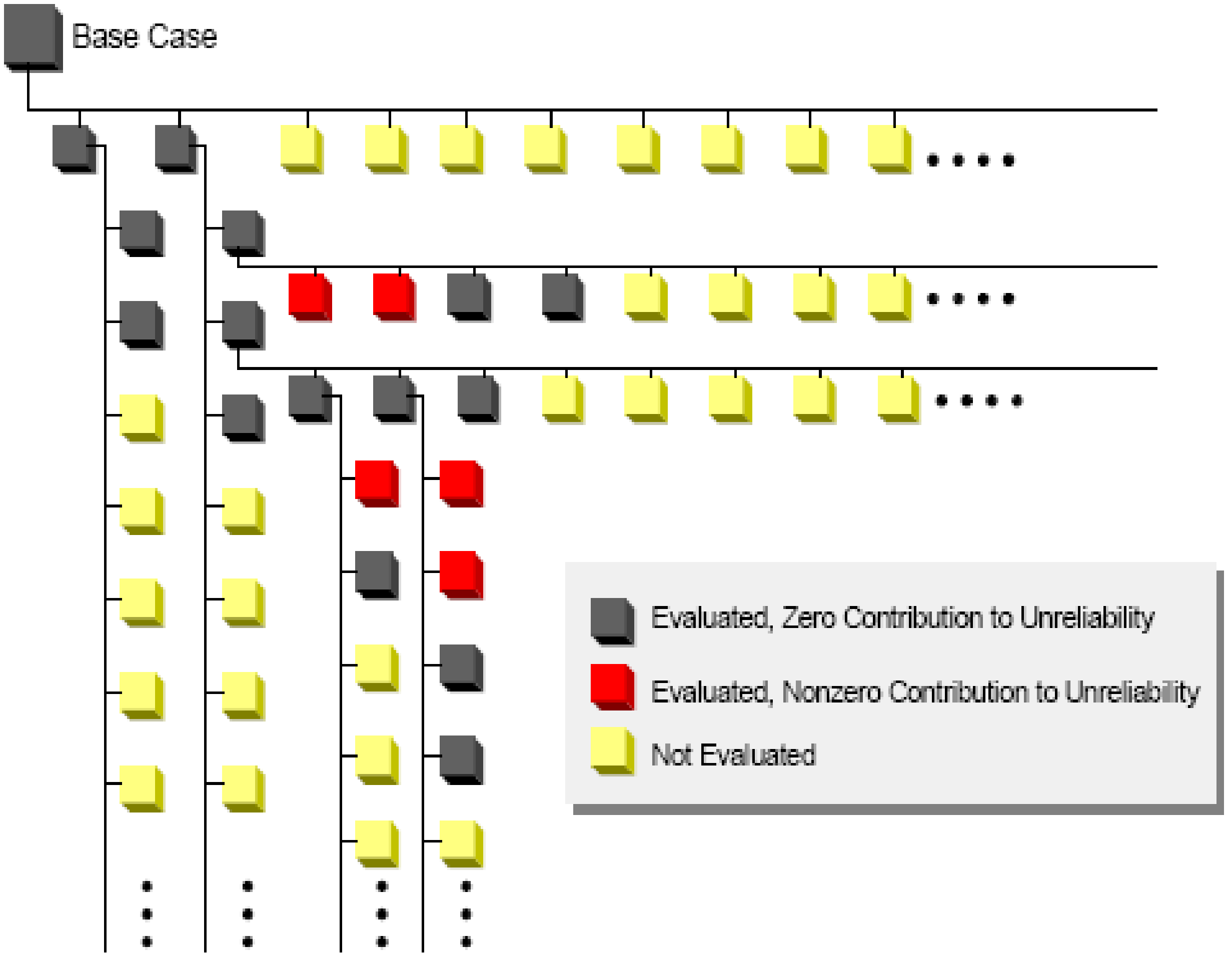


Figure 2. A Wind-Chime enumeration scheme.

Ref: http://www.pserc.wisc.edu/ecow/get/publicatio/2006public/yang_securityconstrained.pdf

Monte Carlo Simulation

- Estimates the reliability indices by simulating the actual process and random behavior of the system.
- Two Broad Categories:

1. Random sampling or non-sequential simulation.
2. Sequential simulation
   - Sequential simulation is generally slower to converge than random sampling.
   - For non-F&D indices random sampling requires less data than sequential simulation.
   - Sequential simulation very suitable for considering time correlated events.

Basic Ideas of Random Sampling of States

- Let

$x = (x_1, x_2, \ldots\ldots.., x_m)$

be the state of power system where

x_i = State of i^{th} component

X = Set of all possible states

$P(x)$ = Probability of state x

- Let

$F(x)$ = Test applied to verify state x is able to satisfy the load.

Basic Ideas of Random Sampling of States

The expected value of F(x)

$$E(F)=\sum_{x \in X} F(x)P(x)$$

For E(F) to be LOLP

$$F(x) = \begin{cases} 1 & \text{if load curtailment in state } x \\ 0 & \text{otherwise} \end{cases}$$

In random sampling, x∈X are sampled from their joint distributions. Then estimate of E(F).

$$E(F) = \frac{1}{NS}\sum_{i=1}^{NS} F(x^i)$$

where

NS = number of samplings

x^i = i^{th} sampled value

$F(x^i)$ = test result for i^{th} sampled value

Basic Ideas of Random Sampling of States

$$V(\hat{E}(F)) = \frac{V(F)}{NS}$$

Since V(F) is not known, its estimate can be used,

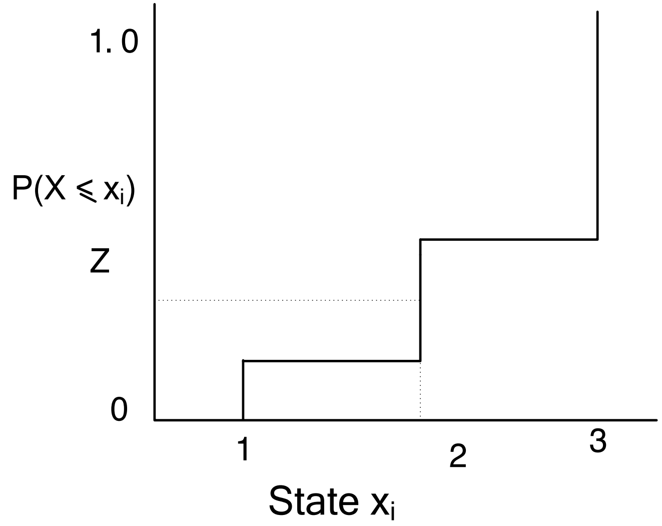
$$\hat{V}(F) = \frac{1}{NS}\sum_{i=1}^{NS}(F(x^{i} - \hat{E}(F))^{2}$$

Algorithm

1. NS = 0
2. NS = NS + 1, select state $x^i \in X$ by sampling from the probability distribution of $P(x)$.
3. Calculate $F(x^i)$.
4. Estimate .
5. Calculate uncertainty of the estimate.
6. If uncertainty is acceptable, stop, otherwise return to step 2.

System State Selection

- System state is sampled by sampling states of equipment.
- Principle of proportionate allocation is used.
- Sample a value z from a uniform [0,1] pseudo random number generator. The state can be found from the cumulative probably distribution.



Convergence

COV = Coefficient of variation

$$= \frac{S(\hat{E}(F))}{\hat{E}(F)}$$

$S(\hat{E}(F))$ = Standard deviation of the estimator of E(F)

$$COV = (V(\hat{E}(F)))^{\frac{1}{2}} \Big/ \hat{E}(F)$$

$$= \frac{[V(F)]^{1/2}}{NS^{1/2}\,\hat{E}(F)}$$

$$= \frac{V(F)}{(cov.\hat{E}(F))^{2}}$$

Convergence

- Sample size not effected by system size or complexity.
- Accuracy required and the probability being estimated effect the sample size.
- Computational effort depends on NS and CPU time/sample.

Variance Reduction for Computational Efficiency

- Control Variable Method

Let Z be a rv that is strongly correlated with F.

Define

$Y = F - \alpha (Z - E(Z))$

Then

$$E(Y) = E(F)$$

$$V(Y) = V(F) + \alpha^2 V(Z) - 2\alpha C(F,Z)$$

If

$$2\alpha C(F,Z) > \alpha^2 V(Z)$$

then

$$V(Y) < V(F)$$

Example: Z can be LOLP due to generation alone. E(Z) can be computed by a generation reliability program.

Antithetic Variable Method

Let

$F_\alpha = 1/2(F' + F'')$

If

$E(F') = E(F'') = E(F)$

Then

$E(F_\alpha) = E(F)$

$V(F_\alpha) = 1/4[V(F') + V(F'')] + 2C(F',F'')$

If F' and F'' are negatively correlated, $C(F',F'') < 0$, then

$V(F_\alpha) < V(F)$

To obtain negative correlation, use random numbers Z_i to compute $E(F')$ and $(1 - Z_i)$ to compute $E(F'')$.

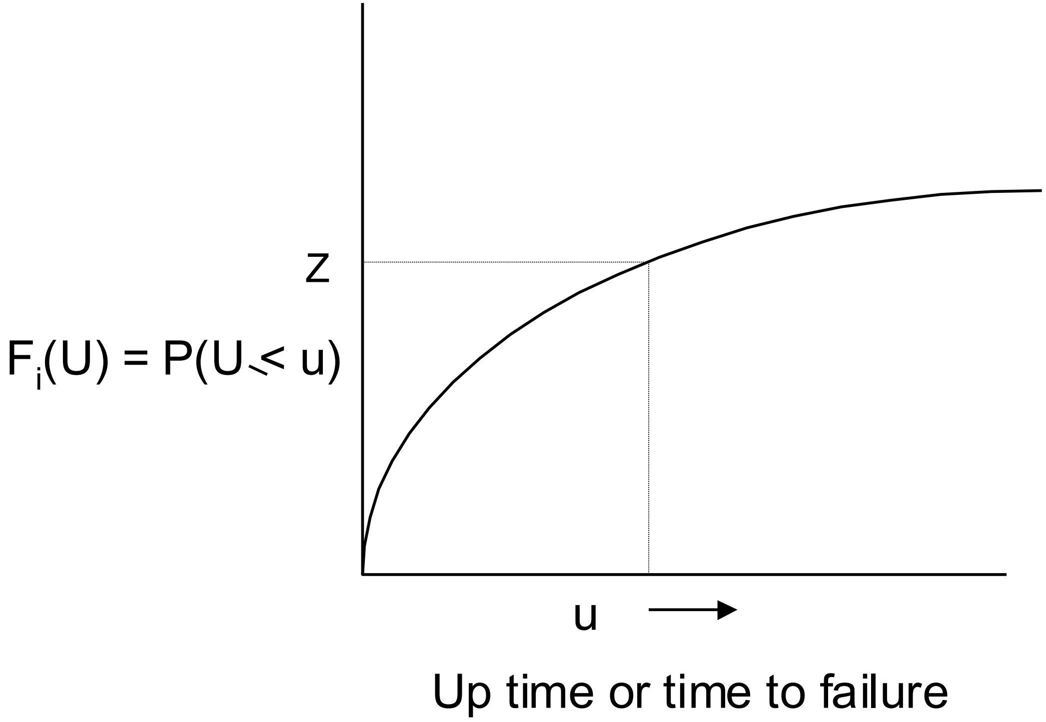
Sequential Simulation

- States of the system are generated sequentially by transition from one state to the next using probability distributions of component state durations and random numbers from [0,1].
- Take a component *i*. Assume that this component is up and its duration is given by U_i(rv). If *Z* is a random number then the observation of up time can be drawn by using

$$\begin{aligned} z &= P(U_i \leq U) \\ &= F_i(U) \end{aligned}$$

Sequential Simulation

- Component with minimum time makes a transition and causes system transition.
- State evaluation is done in a fashion similar to random sampling.



Sequential Simulation

The algorithm can be described in the following steps:

Let us assume that the nth transition has just taken place at time tn and the time to next transition of component i is is given by Ti . Thus the vector of times to component transitions is given by { Ti } and the simulation proceeds in the following steps.

Step 1. The time to next system transition is given by

$T = \min \{T_i\}$

If this T corresponds to T_p ,that is, the pth component, then next transition takes place by the change of state of this component.

Sequential Simulation

Step 2. The simulation time is now advanced :

$t_{n+1} = t_n + T$

Step 3. The residual times to component transitions are calculated by

$T^r_i = T_i - T$

where T^r_i is the residual time to transition of component i.

Step 4. The residual time for component p causing transition becomes zero and time to its next transition T_p is determined by drawing a random number.

Sequential Simulation

Step 5. The time T_i is set where

$T_{i, i \neq p} = T^r_i$

and

$T_{i, i=p} = T_p$

Step 6. From t_n to t_{n+1} ,the status of equipment stays fixed and the following steps are performed:

a. The load for each node is updated to the current hour.

b. If no node has loss of load, the simulation proceeds to the next hour otherwise state evaluation module is called.

c. If after remedial action all loads are satisfied, then simulation proceeds to next hour. Otherwise, this is counted as loss of load hour for those nodes and the system. Also if in the previous hour there was no loss of load, then this is counted as one event of loss of load.

d. Steps (a) - (c) are performed till t_{n+1} .

Sequential Simulation

Step 7. The statistics are updated and the process moves to step 2.

Step 8. The simulation is continued till convergence criterion is satisfied.