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# **Reliability Evaluation in Electric Power Systems**

Presentation for Academic Forum

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- He has worked as a research scholar and visiting professor at
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  - Power system reliability,
  - Probabilistic methods in power system,
  - Electric power quality,
  - Electric power system deregulation and electricity market.
- He is a member of IEEE and CIGRE



# Outline

- Reliability basics overview
- Power system reliability
  - Definition
  - Reliability Assessment: Objectives
  - Reliability Assessment Problems
  - Reliability-related decisions
  - Functional Zones and Hierarchical Levels
  - Generating Capacity Reliability
  - Composite System Reliability
  - Distribution System Reliability
  - System Reliability Indices
  - Power Systems Reliability Indices
  - Application

# Concept of Reliability



# What is Reliability?

- The ability of an item to perform a required function, under given environmental and operational conditions and for a stated period of time [ISO 8402].
- Reliability is the ability of an item to perform a required function under stated conditions for a stated period of time (IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms)
- Reliability is the probability that a product or service will operate properly for a specified period of time (design life) under the design operating conditions (such as temperature or voltage) without failure (E. Elsayed).
- Reliability is the probability of a device or system performing its function adequately, for the period of time intended, under the operating conditions intended (J. Endrenyi).

# What is Reliability?

- Ability of a component/system to perform its intended function
- Within a specified period of time
- Under stated condition

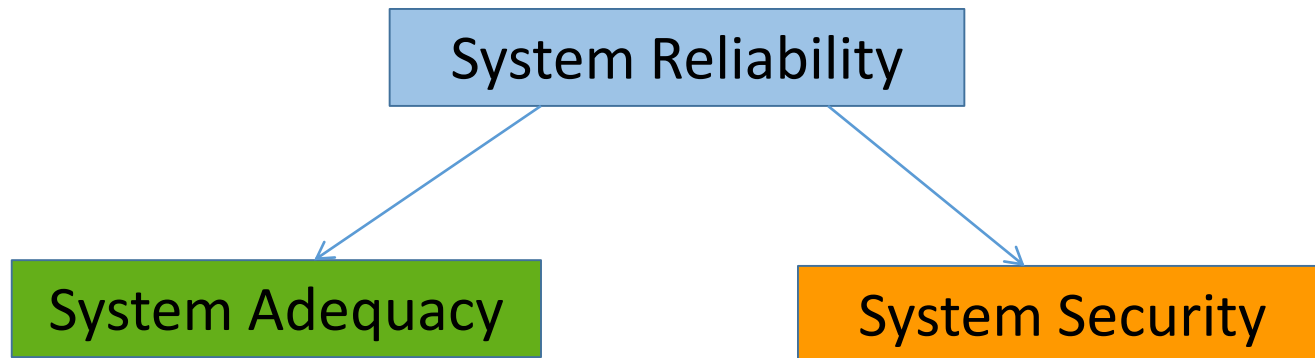
→ Qualitative sense in terms of performance function, time, and surrounding conditions

# What is Reliability?

- The concept of power system reliability, however, is extremely broad and covers all aspects of the ability of the system to satisfy the consumer requirements.
- The term reliability has a very wide range of meanings and cannot be associated with a single specific definition such as that often used in the mission-oriented sense.
- It is therefore necessary to recognize its extreme generality and to use it to indicate, in a general rather than specific sense, the overall ability of the system to perform its function.

# Power system reliability

- Electrical power system reliability assessment power system reliability assessment is divided into two basic aspects;



# Power system reliability

## Adequacy:

The ability of the electric systems to supply the aggregate electrical demand and energy requirements of their customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements; and

## Security:

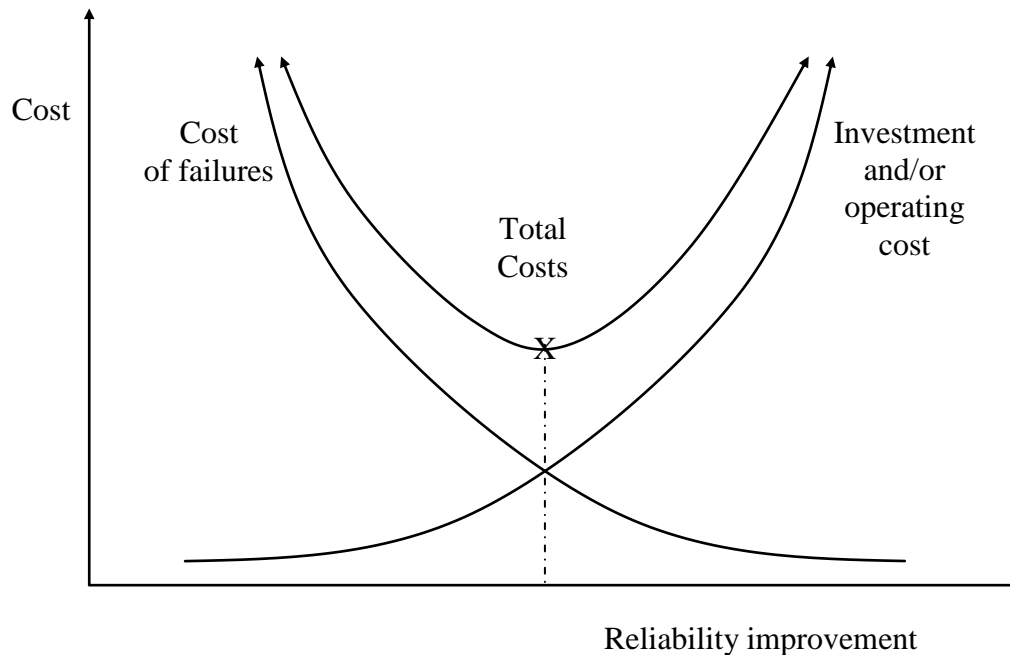
The ability of the electric systems to withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements.”

# Reliability Assessment Problems

- Generation System Reliability
- Bulk System Reliability
- Distribution System Reliability
- “Active” Distribution System Reliability

# Reliability-related decisions

- The relationship motivating almost all reliability-related decisions, and that is that reliability improvements, which result in fewer failures and therefore lower cost of failures, typically occurs only with increased investment or operating costs.



- Cost of failures
- Investment costs
- Operating costs
- “X” in Fig. as being *optimal in the least-cost sense*.

# Reliability-related decisions

Reliability-related decisions may be classified by problem type,

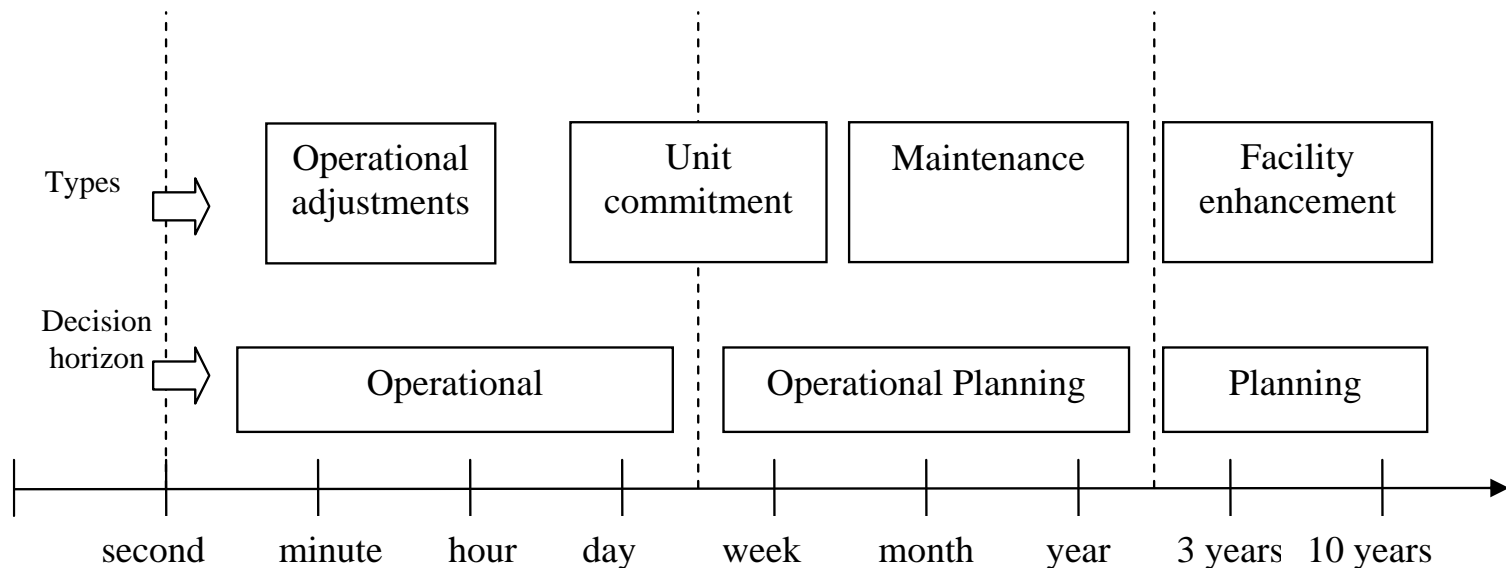
- **Operational adjustments:**
  - Identify the tradeoff between system reliability and operational adjustments such as unit commitment, redispatch, switching, or load curtailment.
- **Unit commitment:**
  - Identify the tradeoff between system reliability and unit commitment.
- **Maintenance:**
  - Maintain equipment so as to maximize the improvement in overall reliability.
- **Facility enhancement:**
  - Reinforce the system through installing new equipment.

# Reliability-related decisions

- Reliability-related decisions may also be classified by decision-horizon.
- The decision-horizon is the amount of time between the present and the time at which the decision is to be implemented.
- Traditional power system terminology use
  - “operational” and
  - “planning”
- **Operational**: short-term decision horizon (minutes to days or weeks)
- **Operational planning**: mid-term decision horizon (days to 1 or 2 years)
- **Planning**: long-term decision horizon (exceeding 1-2 years, typically in the range of 3-10 years).

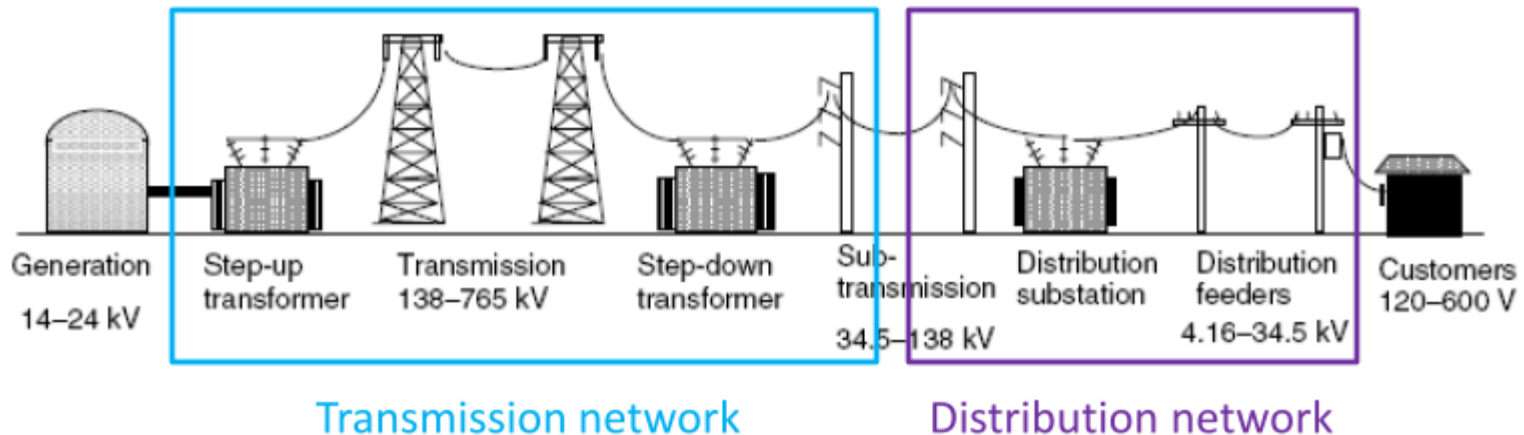
# Reliability-related decisions

## Reliability-related decisions: type & decision-horizon



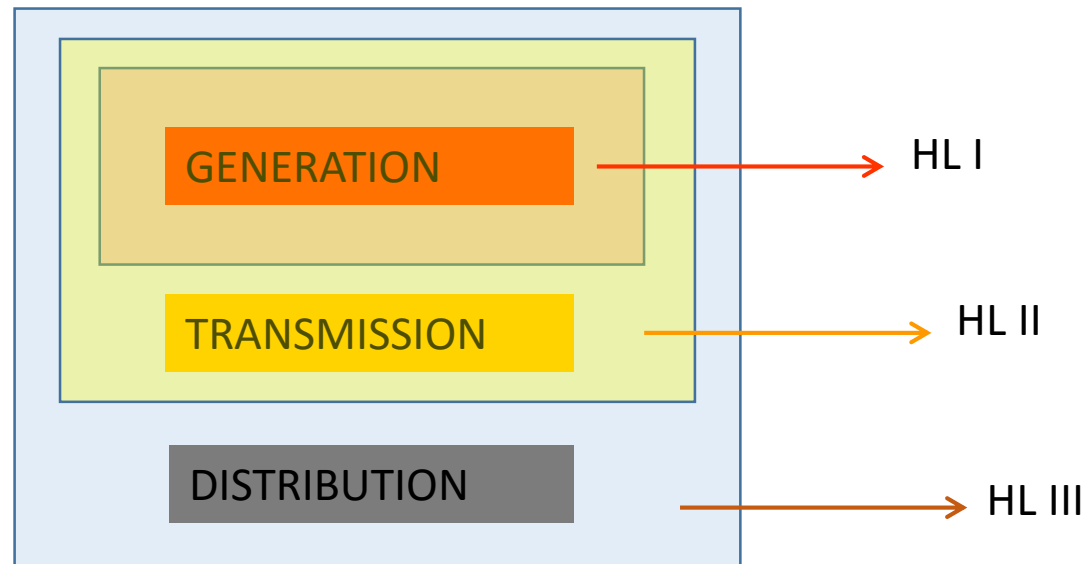
# Power system reliability

The adequacy studies of power supply system are conducted individually in three functional zones: generation, transmission, and distribution.



# Functional Zones and Hierarchical Levels

The reliability studies of power supply system are conducted individually in three functional zones: generation, transmission, and distribution.



# Functional Zones and Hierarchical Levels

## 1. **Generating capacity reliability**

- Concern with generation adequacy

## 2. **Composite system reliability**

- Consider both generation and transmission lines

## 3. **Distribution system reliability**

- Local network connected to end-users

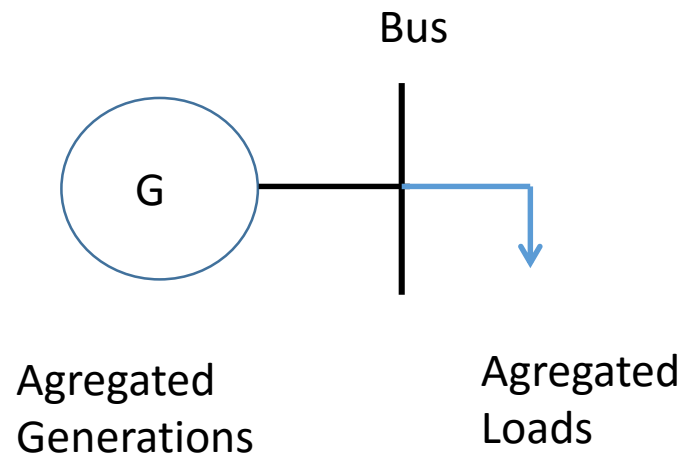
# Functional Zones and Hierarchical Levels

## *Hierarchical level I (HL-I)*

- This was the earliest power system reliability problem addressed.
- In HL-I evaluation, the reliability of the transmission is ignored, and the only concern is in estimating the necessary generating capacity to satisfy the system demand and to perform corrective and preventive maintenance on the generating units.
- Traditionally, this problem was handled in one of two ways:
- Require the reserve to be equal to or greater than a fixed percentage of either the installed capacity or the predicted load.
- Require the reserve to be equal to the capacity of the largest connected unit.

# Functional Zones and Hierarchical Levels

## *Hierarchical level I (HL-I)*



# Functional Zones and Hierarchical Levels

## *Hierarchical level II (HL-II)*

- HL-II involves evaluation of two functional zones:  
    generation and  
    transmission.
- HL-II evaluation is commonly referred to as G&T, composite system, or bulk transmission system evaluation.
- HL-II evaluation has been an extremely challenging problem for three basic reasons:

# Generating Capacity Reliability

## 1. **Single-area reliability analysis**

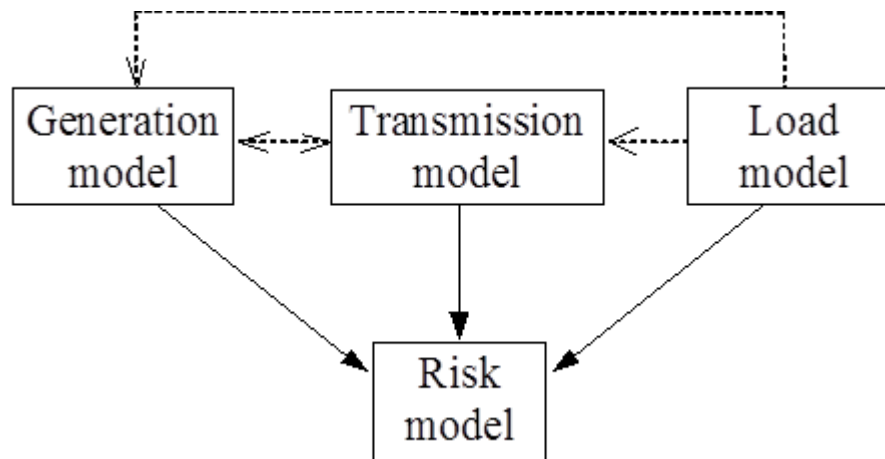
- All generators and loads are connected to a single bus

## 2. **Multi-area reliability analysis**

- Generators and loads within area are connected to a single bus
- Consider tie-lines between areas
- Limitation of intra-area transmission are included when determining inter-area transmission capability

# Functional Zones and Hierarchical Levels

## *Hierarchical level II (HL-II)*

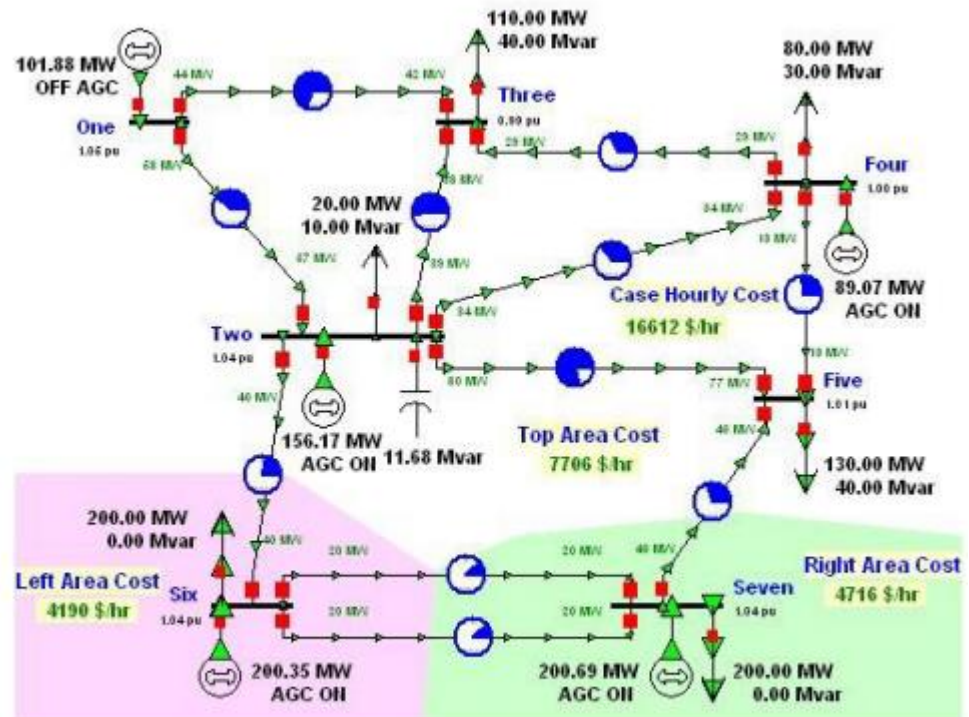


Conceptual tasks for HL II

# Composite System Reliability

Concern with generation and transmission capability adequacy

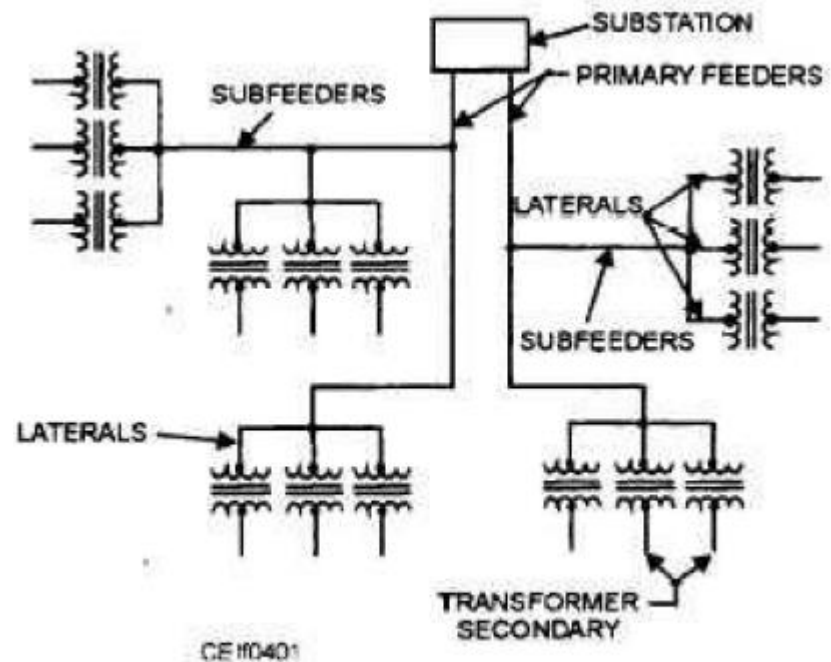
- High-voltage transmission lines
- May include high-voltage transformers, circuit breakers



<http://www.powerworld.com/images/7-bus%20Online.jpg>

# Distribution System Reliability

- Interest to find out the reliability level at load point
- Network configuration/topology
- Analysis takes into account reliability of the following low-voltage components,
  - Transformers
  - Circuit breakers



[http://www.tpub.com/content/construction/14027/css/14027\\_63.htm](http://www.tpub.com/content/construction/14027/css/14027_63.htm)

# Functional Zones and Hierarchical Levels

## Modeling: Models are required for

- failure/repair processes associated with generators, transformers, lines, and protection equipment,
- load
- effects of weather on failure/repair processes and load
- remedial actions including those of the operator

# Functional Zones and Hierarchical Levels

## Computations:

- It is necessary to achieve acceptable tradeoff between speed and accuracy. A particularly intensive part of the computations involves determination of whether each state is a failure state or not.
- Data: This is an issue for any probabilistic analysis, but it is particularly troublesome for HL-II because data is required for characterizing failure rates of all equipment, and there are many difficulties associated with the related collection procedures.

# Functional Zones and Hierarchical Levels

Method of representing stochastic nature of the operating conditions.

- By “operating conditions,” we are referring to the basecase network configuration (topology and unit commitment) together with the loading and dispatch.

# Functional Zones and Hierarchical Levels

## **Nonsequential:**

- The nonsequential approach assumes a particular network configuration to be evaluated.
- Then several loading conditions are selected based on their occurrence probability (as indicated by a load duration curve), and for each chosen loading condition, the dispatch is developed through an economic dispatch calculation (or an equivalent market-dispatch tool).
- The evaluation is performed once for each loading condition, and then indices are computed as a function of the loading probabilities.

# Functional Zones and Hierarchical Levels

## **Sequential:**

- The sequential approach assumes a particular network configuration to be evaluated together with an hourly or daily peak load forecast for an extended time period (e.g., year or several years).
- The method then steps through a series of sequential-in-time operating conditions, evaluating the reliability indices at each step, with final indices an accumulation of those evaluated at each step.
- Each sequential evaluation performed is called a trajectory. It is possible to compute indices based on a single trajectory or based on multiple trajectories.
- In the latter case, Monte-Carlo simulation may be used to select the trajectory.

# Functional Zones and Hierarchical Levels

Method of representing stochastic nature of contingencies:

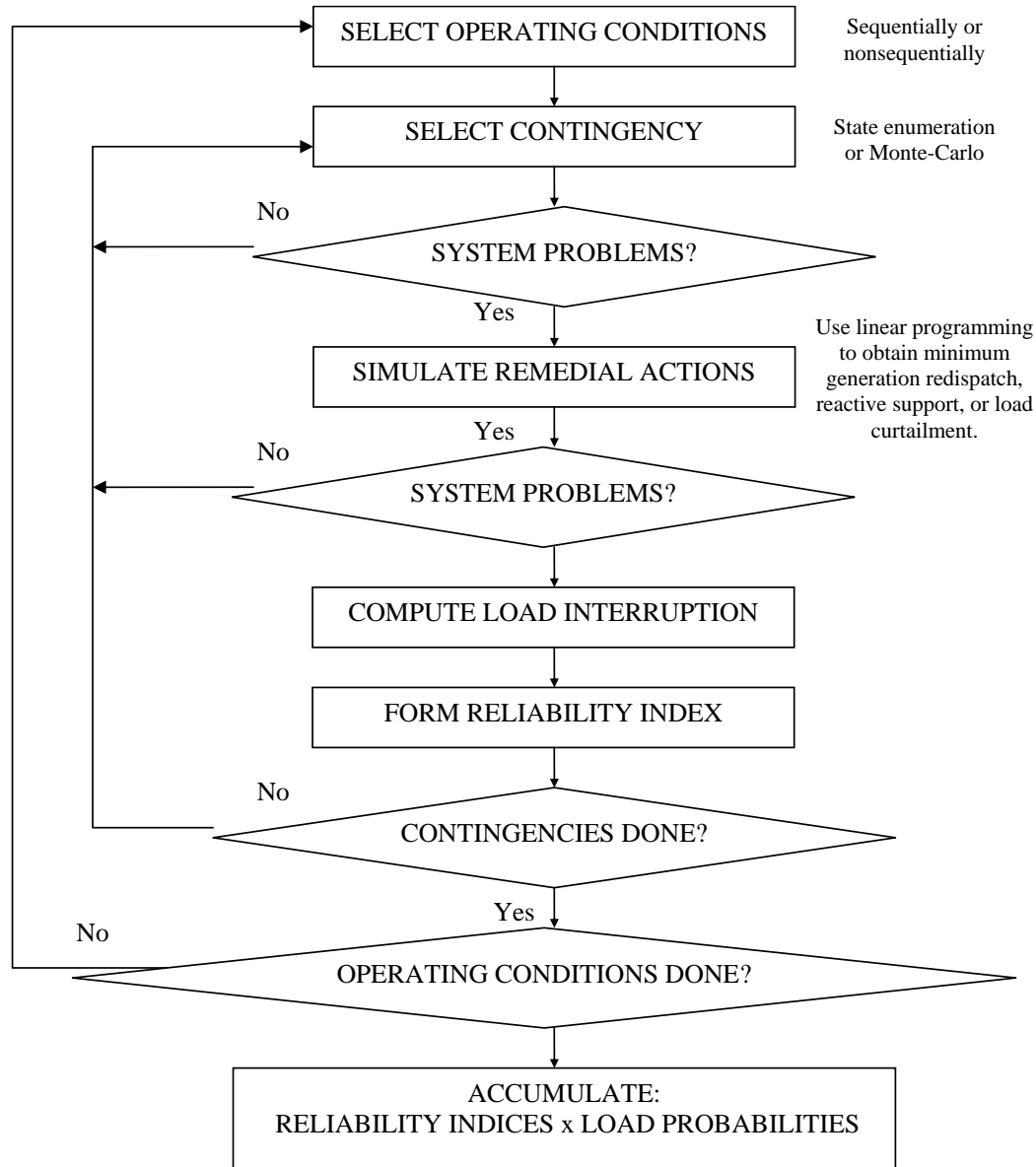
- Contingency enumeration:
  - Here, the “contingency states” corresponding to different numbers and combinations of outaged components are evaluated one by one, usually with some sort of intelligence to eliminate evaluation of some states.
- Monte-Carlo:
  - Here, the “contingency states” evaluated are chosen as a result of random draw where the chance of drawing a particular state is the same as the probability of that state.

# Functional Zones and Hierarchical Levels

## HL-II Evaluation approaches

Contingency selection	Operating Conditions		
	Non-sequential	Sequential, single-trajectory	Sequential, multi-trajectory
Enumeration	Non-sequential, with contingency enumeration	Sequential, with contingency enumeration	Sequential, multi-trajectory w/ contingency enumeration
Monte-Carlo	Non-sequential, with Monte-Carlo contingency selection	Sequential, with Monte-Carlo contingency selection	Sequential, multi-trajectory w/ Monte-Carlo contingency selection

# HL-II Evaluation approaches



# Functional Zones and Hierarchical Levels

The adequacy assessment is concerned with the evaluation of the *static* or *steady-state* conditions following a component failure, where related problems are:

- Circuit overloads and
- Bus voltage violations

# Functional Zones and Hierarchical Levels

The security assessment is concerned with the *dynamic or transient* conditions following a component failure, where related problems are:

- Voltage instability
- Transient voltage dips
- Early swing loss of synchronism
- Multi-swing loss of synchronism
- Oscillatory instability due to negative damping

# Distinguishing between adequacy and security in terms of failure modes and tools used (planning approach)

	Failure Mode	Decision-Horizon		
		Operational	Operational Planning	Planning
Static analysis using power flow	Circuit overload	G&T Adequacy		
	Bus voltage violation			
	Voltage instability			
Dynamic analysis using time domain simulation	Transient voltage dip			
	Early-swing loss of synchronism		Security	
	Multi-swing loss of synchronism			
	Oscillatory instability (undamping)			

# Distinguishing between adequacy and security in terms of failure modes and tools used (operating approach)

	Failure Mode	Decision-Horizon		
		Operational	Operational Planning	Planning
Static analysis using power flow	Circuit overload			G&T Adequacy
	Bus voltage violation			
	Voltage instability			
Dynamic analysis using time domain simulation	Transient voltage dip	Security		
	Early-swing loss of synchronism			
	Multi-swing loss of synchronism			
	Oscillatory instability (undamping)			

# System Reliability Indices

## *Indices for HL-I analysis*

- Common indices for HL-I analysis include basic and severity-based indices.
- The basic indices reflect the probability, frequency, or duration of losing load but not the amount of load lost.
- The severity-based indices reflect the probability, frequency, or duration of losing load and the amount of load lost. It is typically advantageous in any given study to obtain at least one basic index and at least one severity-based index.

# System Reliability Indices

## *Indices for HL-I analysis*

### **Basic indices:**

- **Probability of system failure:**

This is the proportion of time, in the long-run, when a system failure condition exists, denoted by  $P_F$ .

- **Expected frequency of losing load:**

This is the frequency of stays in, or entries into, a system failure state.

- **Average duration of losing load:**

This is the expected amount of time per stay in the failure state.

- **Loss of load expectation:**

The LOLE gives the expected number of days in a year in which a loss of load occurs. Note that whereas average duration gives time per stay, the LOLE gives cumulative time per year.

- **Probability of losing load (loss of load probability):**

The LOLP is the probability of system failure under the assumption (by convention) that the peak load of each day lasts all day. It is often expressed as the number of days per year that the load will not be met, which is denoted as  $LOLP_0$  (and given by  $LOLP \cdot 365$ ).

## *Indices for HL-I analysis*

### **Severity-based indices:**

- expected unserved demand per year
- expected unserved energy per year
- system minutes

an equivalent number of minutes per year for which a demand equal to the peak load would be interrupted.

## *Indices for HL-II analysis*

- Common indices for composite (G&T) reliability include the same ones for HL-I analysis together with a set of “load point” or “delivery point” indices seen by each individual network node.
- The presence of the network model allows the computation of load-point indices.
- Common load point indices are similar to the basic and severity-based indices identified for HL-I analysis, except that they are computed on a per-bus basis rather than a per-system basis.

## *Indices for HL-II analysis*

- Another type of index that is unique to HL-II analysis are the failure probabilities, frequencies, and duration associated with specific network conditions such as circuit overload and bus voltage out of limits.

# POWER SYSTEMS RELIABILITY INDEXES AND CRITERION

## **Power Systems Reliability Indexes**

- **Deterministic indexes**
  - Do not take into account the uncertainties that affect reliability
  - Simple calculation
  - Require less data
- **Probabilistic indexes**
  - Reflect uncertainties in the system
  - Require failure statistics of the devices

# Deterministic Indexes

- **Operating reserve margin**
  - Excess generation capacity in case of emergency
- **Percentage reserve**
  - Amount of reserve capacity as a percentage of the total peak load
- **Reserve margin as the largest unit online**
  - Amount of reserve equals to the capacity of the largest unit online

# Probabilistic Indexes

- **Loss of load probability**
  - Probability that generation will not meet demand in a year
  - Commonly shown as number of hours/days. (by multiply LOLP by number of hours/days in a year)
- **Loss of load frequency**
  - How often does the system fail in a year
- **Expected Energy Not Supplied (EENS) or Expected Unserved Energy (EUE)**

# Why need reliability criterion?

- Develop standardized quantity
- Planning and Operation purposes
  - To avoid catastrophic failures
- Design problems

# Power Systems Reliability Criterion

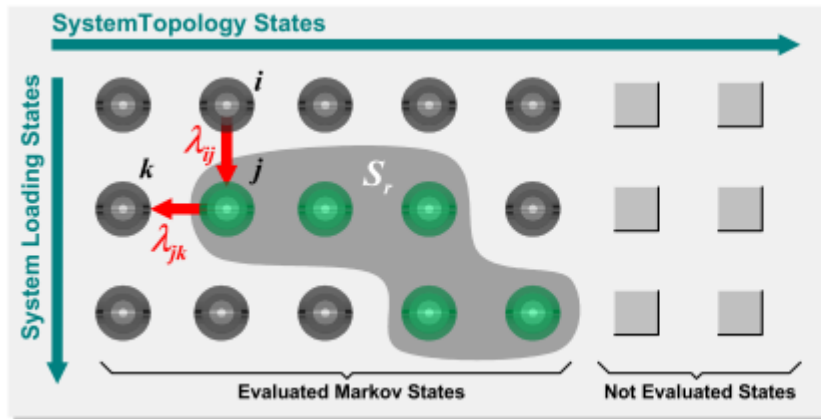
- **Deterministic criteria**

- N-m contingency analysis
- System with 'N' components should be able to serve peak load when loss 'm' components
- Sometimes called security analysis

- **Probabilistic criteria**

- Loss of load expectation, for example, 1 day in 10 years

# System Reliability Indices



$S_r$ : Event  
(Voltage, LOL, etc.)

Probability Index

$$\Pr[S_r] = \sum_{i \in S} p_j$$

Frequency Index

$$f = \sum_{j \in S_r} p_j \sum_{j \in S_r, k \notin S_r} \lambda_{jk}$$

Duration Index

$$T = \frac{\Pr[S_r]}{f}$$

# Data and models for power system reliability analysis

- Reliability data is often quoted in the literature. For example, an engineer gave the following information:

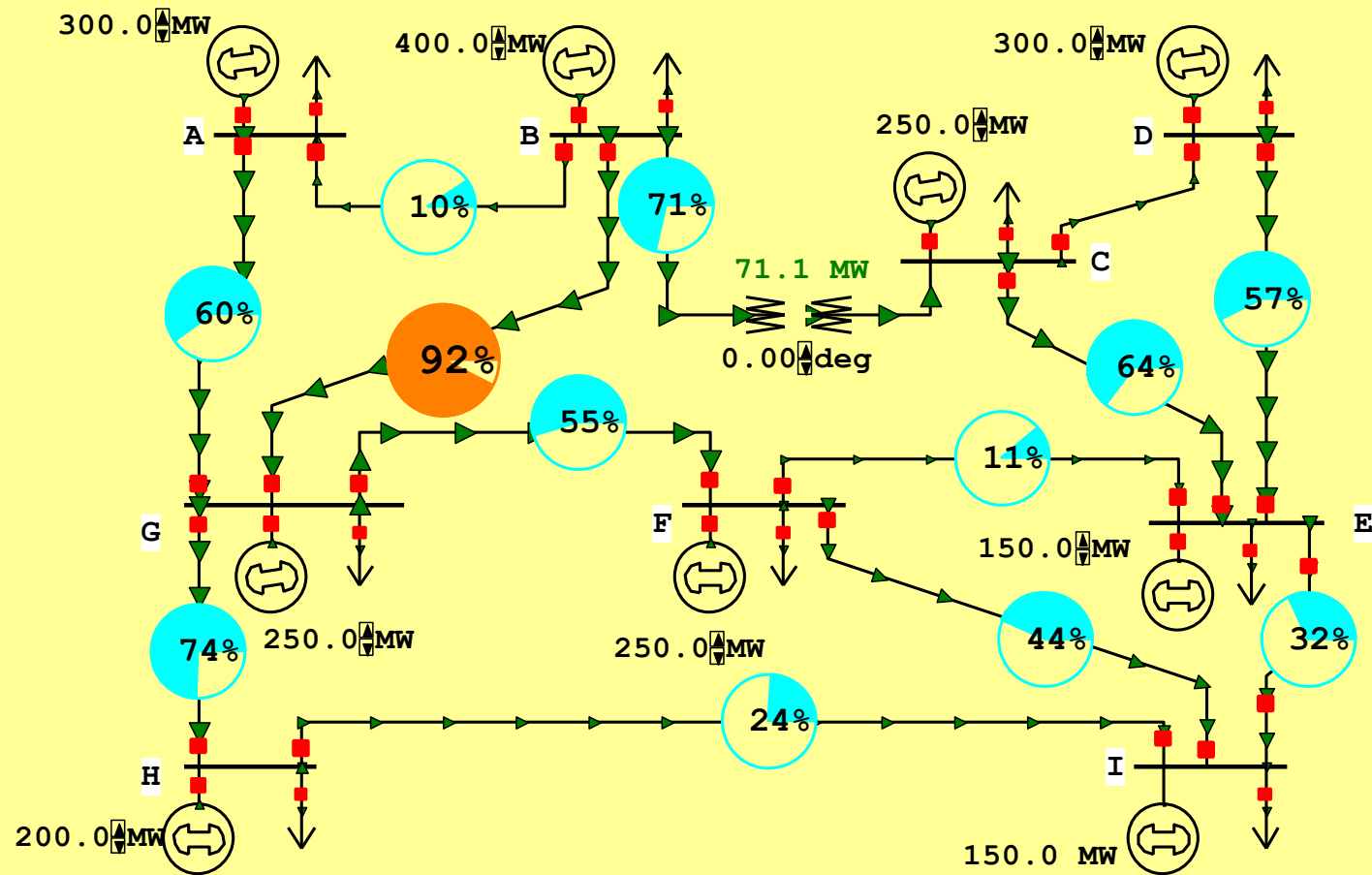
<b>Generator</b>	<b>Force Outaged Rate</b>	<b>Average Outage Duration (hours)</b>
Hydro Unit	0.04	50
Thermal Unit	0.10	50

<b>Lines</b>	<b>Frequency (occ./km/year)</b>	<b>Average Outage Duration (hours)</b>
230 kV Line	0.01	100
115 kV Line	0.01	7
69 kV Line	0.07	7

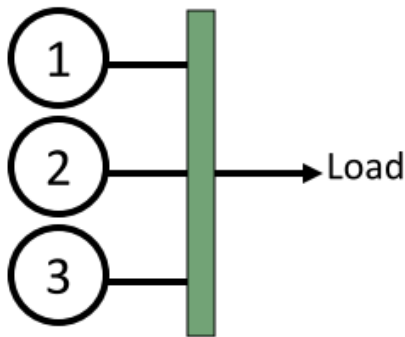
<b>Transformers</b>	0.10	3
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# APPLICATION TO POWER SYSTEMS

# APPLICATION TO POWER SYSTEMS

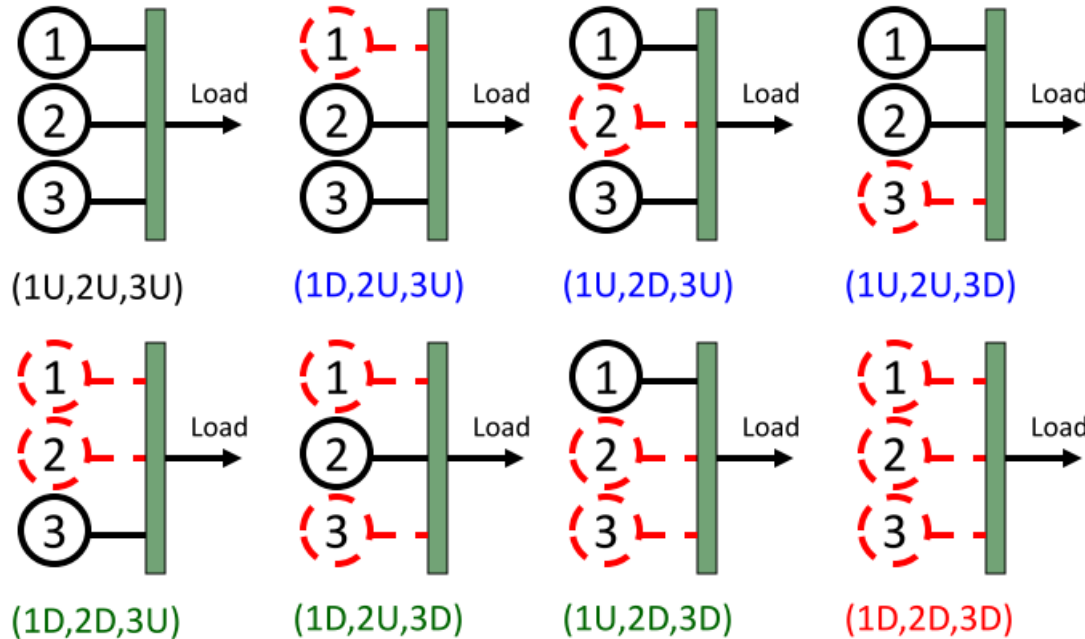
## Example



- 3 generators
- Each 50 MW
- Identical probability of failure = 0.01
- Assume that each generator fails **independently**.
- Find probability distribution of generating capacity.

# APPLICATION TO POWER SYSTEMS

## State Space



State space =  $\{(1U, 2U, 3U), (1D, 2U, 3U), (1U, 2D, 3U), (1U, 2U, 3D), (1D, 2D, 3U), (1D, 2U, 3D), (1U, 2D, 3D), (1D, 2D, 3D)\}$

# Generating Probability Distribution

- Find probability associated with each generating capacity level
- 4 capacity levels, 0 MW, 50 MW, 100 MW, and 150MW
- Let
  - $E_0$  be an event that generating capacity is 0 MW
  - $E_1$  be an event that generating capacity is 50 MW
  - $E_2$  be an event that generating capacity is 100 MW
  - $E_3$  be an event that generating capacity is 150 MW

# Capacity 0 MW

- $E_0 = \{(1D, 2D, 3D)\}$

$$P(E_0) = P(1D \cap 2D \cap 3D)$$

- Using multiplication rule,

$$P(E_0) = P(1D) \times P(2D) \times P(3D)$$

$$P(E_0) = 0.01 \times 0.01 \times 0.01 = 0.000001$$

# Capacity 50 MW

- $E_1 = \{(1D, 2D, 3U), (1D, 2U, 3D), (1U, 2D, 3D)\}$

$$P(E_1) = P\{(1D, 2D, 3U) \cup (1D, 2U, 3D) \cup (1U, 2D, 3D)\}$$

- Using addition rule,

$$P(E_1) = P\{(1D, 2D, 3U)\} + P\{(1D, 2U, 3D)\} + P\{(1U, 2D, 3D)\}$$

$$P(E_1) = P(1D \cap 2D \cap 3U) + P(1D \cap 2U \cap 3D) + P(1U \cap 2D \cap 3D)$$

- Using multiplication rule,

$$P(E_1) = P(1D) \times P(2D) \times P(3U) + P(1D) \times P(2U) \times P(3D) + P(1U) \times P(2D) \times P(3D)$$

- Using complementation,

$$P(1U) = 1 - P(1D) = 1 - 0.01 = 0.99$$

- Then,  $P(E_1) = 0.000297$

# Capacity 100 MW

- $E_2 = \{(1D,2U,3U), (1U,2D,3U), (1U,2U,3D)\}$

$$P(E_2) = P\{(1D,2U,3U) \cup (1U,2D,3U) \cup (1U,2U,3D)\}$$

- Using addition rule,

$$P(E_2) = P\{(1D,2U,3U)\} + P\{(1U,2D,3U)\} + P\{(1U,2U,3D)\}$$

$$P(E_2) = P(1D \cap 2U \cap 3U) + P(1U \cap 2D \cap 3U) + P(1U \cap 2U \cap 3D)$$

- Using multiplication rule,

$$P(E_2) = P(1D) \times P(2U) \times P(3U) + P(1U) \times P(2D) \times P(3U) + P(1U) \times P(2U) \times P(3D)$$

- Using complementation,

$$P(1U) = 1 - P(1D) = 1 - 0.01 = 0.99$$

- Then,  $P(E_2) = 0.029403$

# Capacity 150 MW

- $E_3 = \{(1U, 2U, 3U)\}$

$$P(E_3) = P(1U \cap 2U \cap 3U)$$

- Using complementation,

$$P(1U) = 1 - P(1D) = 1 - 0.01 = 0.99$$

- Using multiplication rule,

$$P(E_3) = P(1U) \times P(2U) \times P(3U)$$

$$P(E_3) = 0.99 \times 0.99 \times 0.99 = 0.970299$$

# Generating Probability Distribution

Capacity (MW)	Probability
0	0.000001
50	0.000297
100	0.029403
150	0.970299

# Loss of Load Probability

- Assume that load has distribution shown on right, find loss of load probability.
- Let E be the event that system suffers loss of load, then

$$E = \{\text{Generation} < \text{Load}\}$$

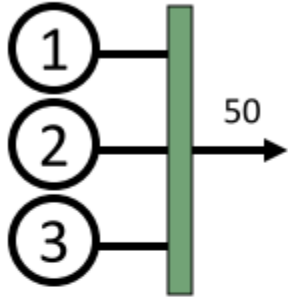
Load (MW)	Probability
50	0.20
100	0.75
150	0.05

- Let
  - $B_1$  be an event that load is 50 MW
  - $B_2$  be an event that load is 100 MW
  - $B_3$  be an event that load is 150 MW
- Then, using Bayes' rule,

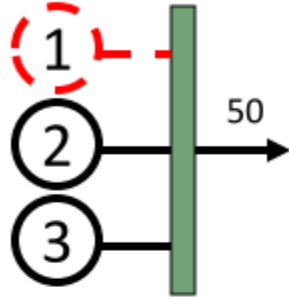
$$P(E) = P(E | B_1) \times P(B_1) + P(E | B_2) \times P(B_2) + P(E | B_3) \times P(B_3)$$

$$P(E) = P(E | B_1) \times 0.20 + P(E | B_2) \times 0.75 + P(E | B_3) \times 0.05$$

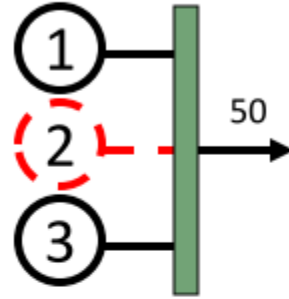
# Load 50 MW



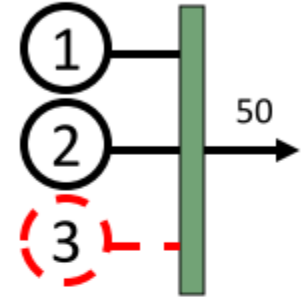
150  
(1U,2U,3U)



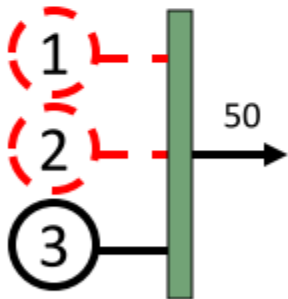
100  
(1D,2U,3U)



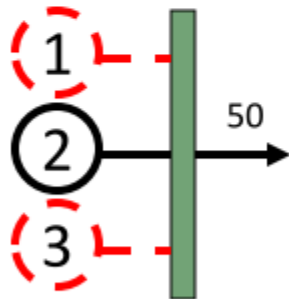
100  
(1U,2D,3U)



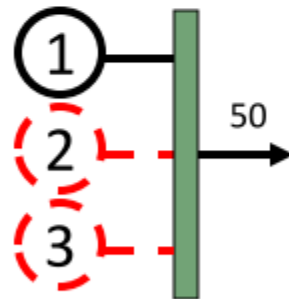
100  
(1U,2U,3D)



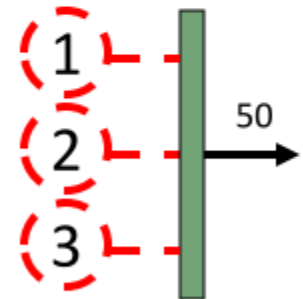
50  
(1D,2D,3U)



50  
(1D,2U,3D)



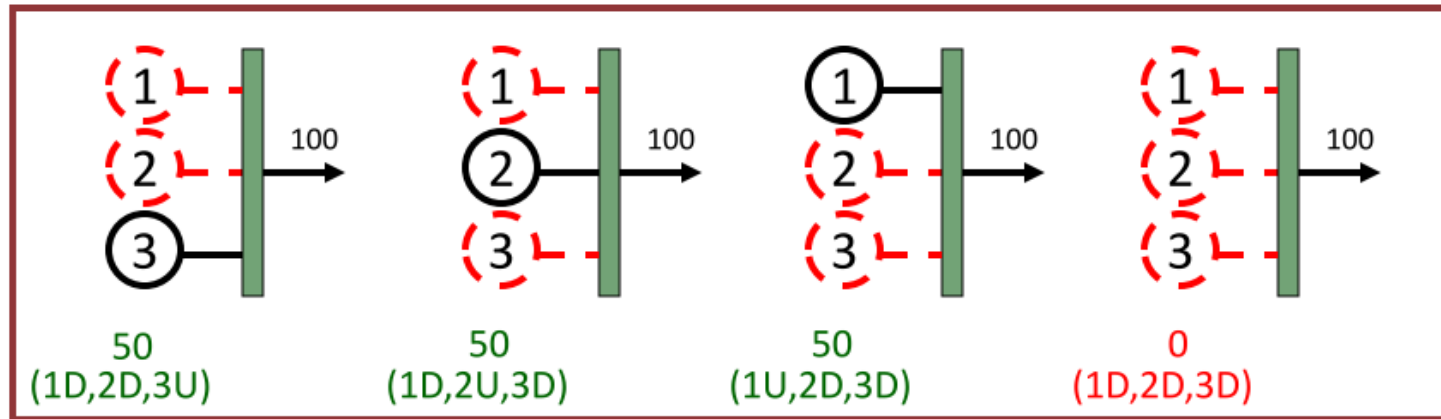
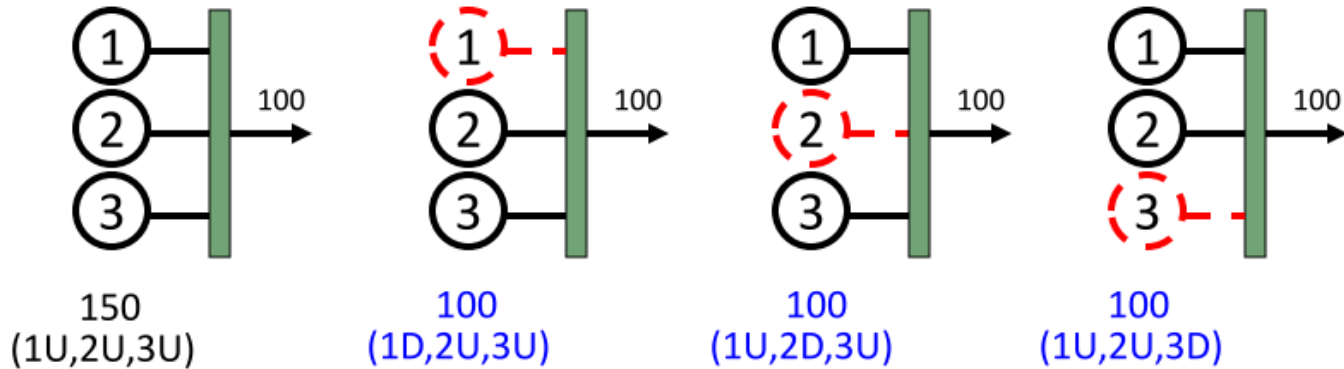
50  
(1U,2D,3D)



0  
(1D,2D,3D)

$$P(E | B_1) = P\{ (1D,2D,3D) \} = 0.000001$$

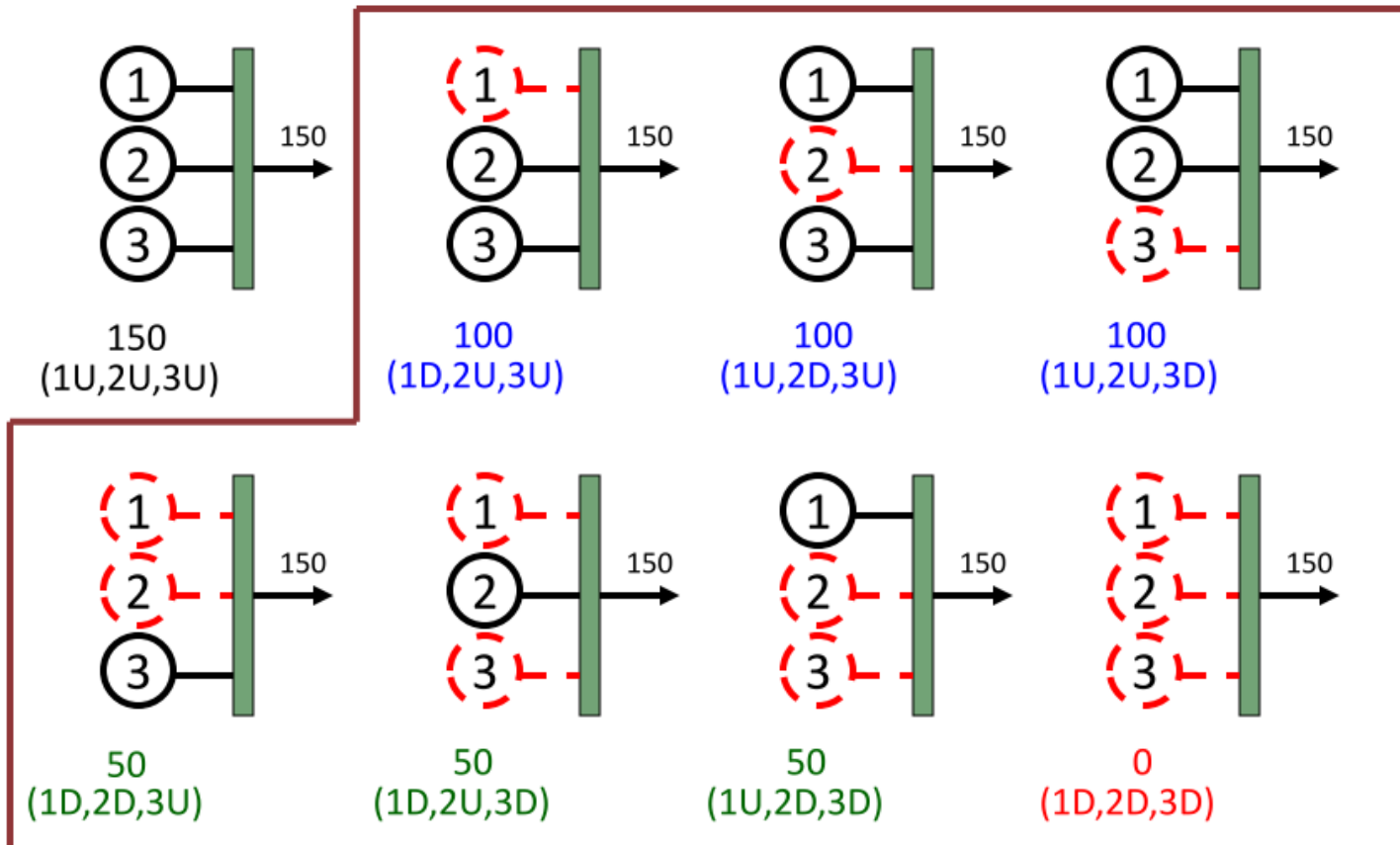
# Load 100 MW



$$P(E | B_2) = P\{(1D, 2D, 3U), (1D, 2U, 3D), (1U, 2D, 3D), (1D, 2D, 3D)\}$$

$$P(E | B_2) = 0.000297 + 0.000001 = 0.000298$$

# Load 150 MW



$$P(E | B_3) = 1 - P\{ (1U,2U,3U) \} = 0.029701$$

- Loss of load probability is,

$$P(E) = P(E | B_1) \times 0.20 + P(E | B_2) \times 0.75 + P(E | B_3) \times 0.05$$

$$P(E) = 0.000001 \times 0.20 + 0.000298 \times 0.75 + 0.029701 \times 0.05$$

$$P(E) = 0.00170875$$

- One definition of power system reliability is “the degree to which the performance of the system results in electricity being delivered to customers within accepted standards and in the amount desired.”