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Electric Power System Modeling and Analysis

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Overview

- Introduction to Power Systems Modeling
  - Systems
  - Modeling Approaches
  - Application
- Introduction to Resilience Analysis
  - Motivation
  - Methods
- Demonstration

INTRODUCTION TO POWER SYSTEMS MODELING

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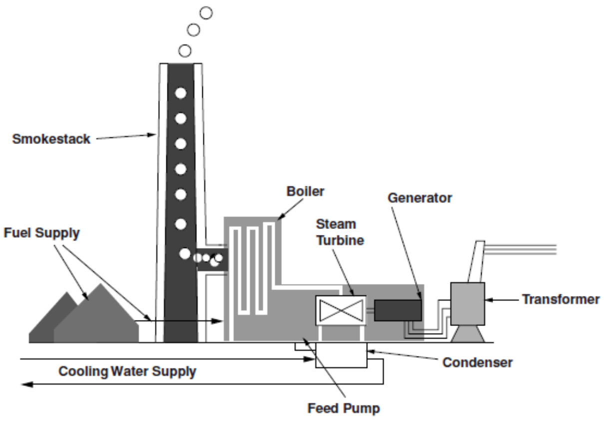
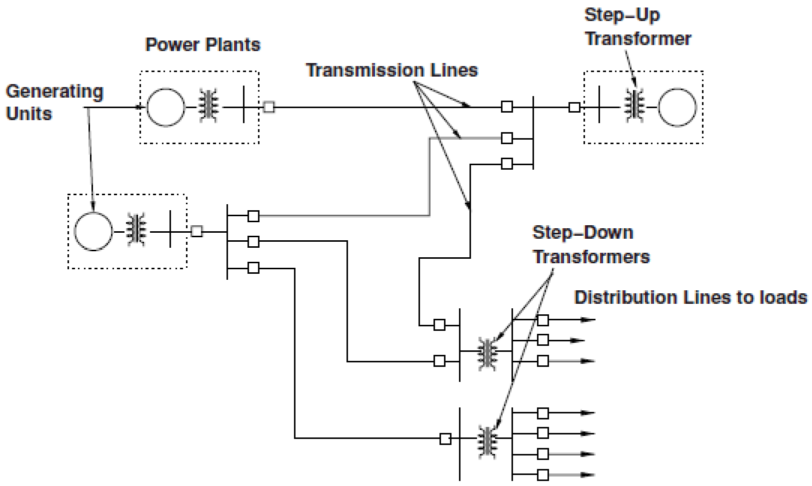
Electric Power Systems

The purpose of a power system is to generate power , transmit this power and to distribute it to customers at voltage levels and reliability that are appropriate to various users

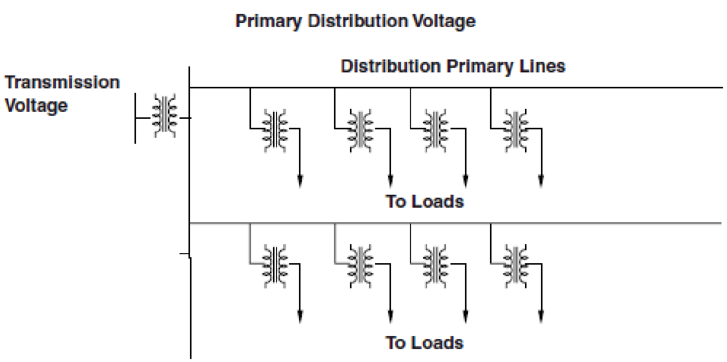
Fossil Fuel Plant



Transmission System



Distribution System



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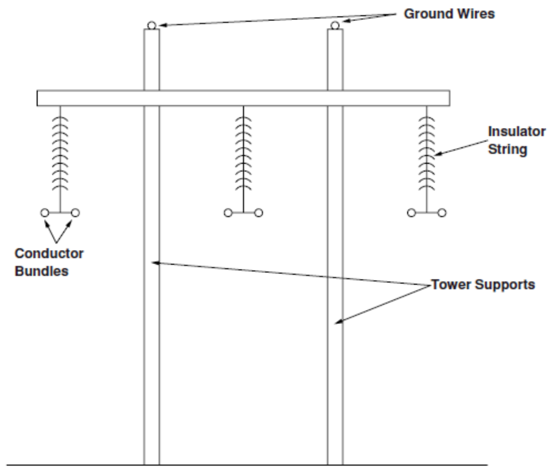
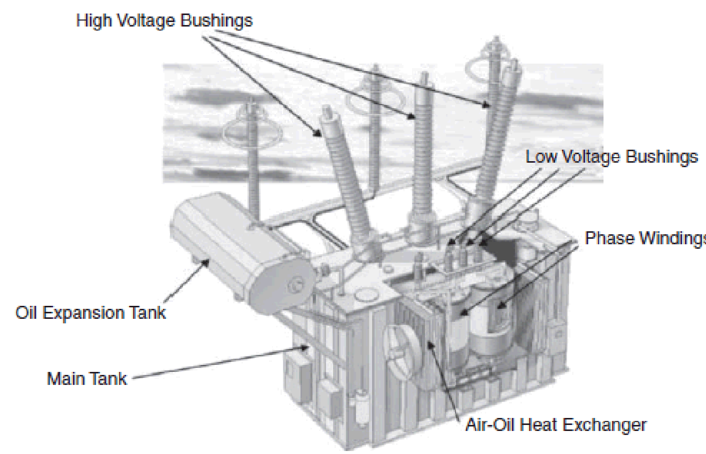
Power Component Models

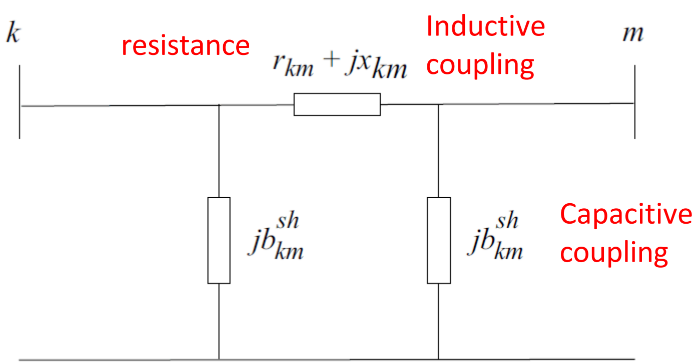
Power Line



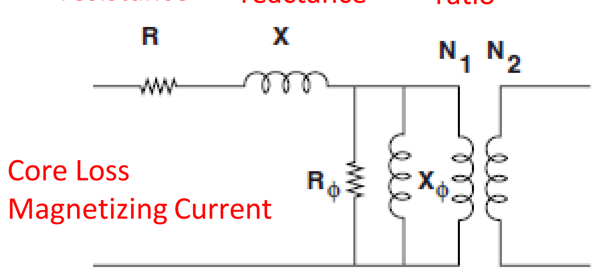
Transformer



Power Line ∏ model



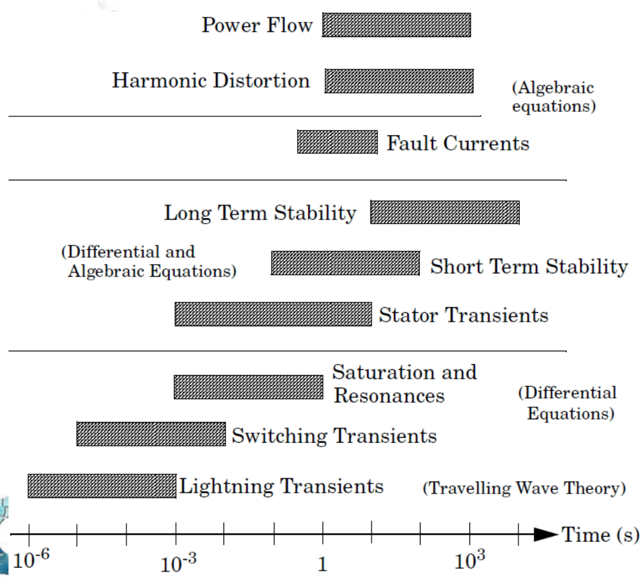
Transformer Model

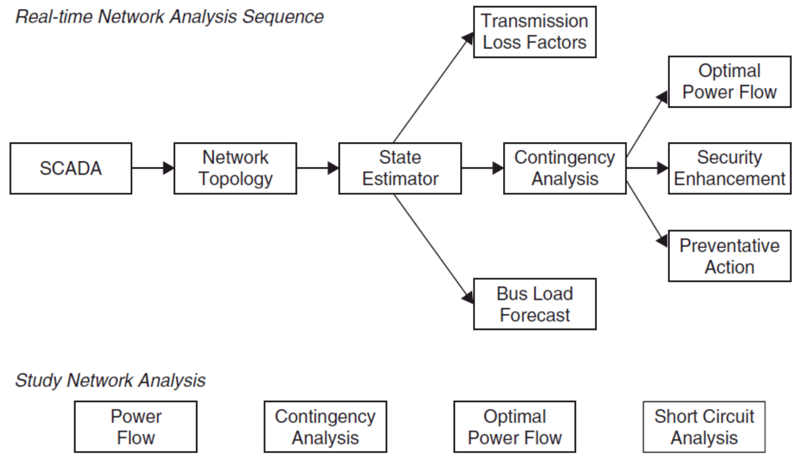


Power System Analysis

Main Categories

- Power Flow
- Stability/Contingency
- Short Circuit





- Topology processor: Processes real-time status measurements to determine an electrical connectivity (bus) model of the power system network.
- State estimator: Uses real-time status and analog measurements to determine the "best" estimate of the state of the power system. It uses a redundant set of measurements; calculates voltages, phase angles, and power flows for all components in the system; and reports overload conditions.
- Power flow: Determines the steady-state conditions of the power system network for a specified generation and load pattern. Calculates voltages, phase angles, and flows across the entire system.
- Contingency analysis: Assesses the impact of a set of contingencies on the state of the power system and identifies potentially harmful contingencies that cause operating limit violations.
- Optimal power flow: Recommends controller actions to optimize a specified objective function (such as system operating cost or losses) subject to a set of power system operating constraints.
- Security enhancement: Recommends corrective control actions to be taken to alleviate an existing or potential overload in the system while ensuring minimal operational cost.
- Preventive action: Recommends control actions to be taken in a "preventive" mode before a contingency occurs to preclude an overload situation if the contingency were to occur.

- Bus load forecasting: Uses real-time measurements to adaptively forecast loads for the electrical connectivity (bus) model of the power system network.
- Transmission loss factors: Determines incremental loss sensitivities for generating units; calculates the impact on losses if the output of a unit were to be increased by 1 MW.
- Short-circuit analysis: Determines fault currents for single-phase and three-phase faults for fault locations across the entire power system network.

Power Flow Analysis

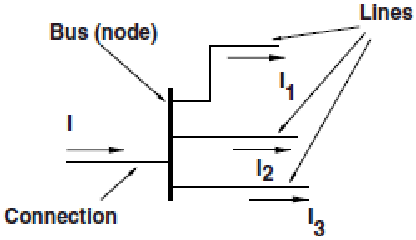
A **power-flow study (load-flow study)** is an analysis of the voltages, currents, and power flows in a power system under **steady-state conditions (> 1 sec changes)**. The simplest way to perform power-flow calculations is by iteration.

1. Create a bus admittance matrix Y_{bus} for the power system based upon power component values;
2. Make an initial estimate for the voltages at each bus in the system;
3. Update the voltage estimate for each bus (one at a time), based on the estimates for the voltages and power flows at every other bus and the values of the bus admittance matrix: since the voltage at a given bus depends on the voltages at all of the other busses in the system (which are just estimates), the updated voltage will not be correct. However, it will usually be closer to the answer than the original guess.
4. Repeat this process to make the voltages at each bus approaching the correct answers converge at a specified tolerance

Power Flow Analysis Equations

The basic equation for power-flow analysis is derived from the nodal analysis equations for the power system:

$$Y_{bus} V = I$$



For the four-bus power system, this becomes

$$\begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix}$$

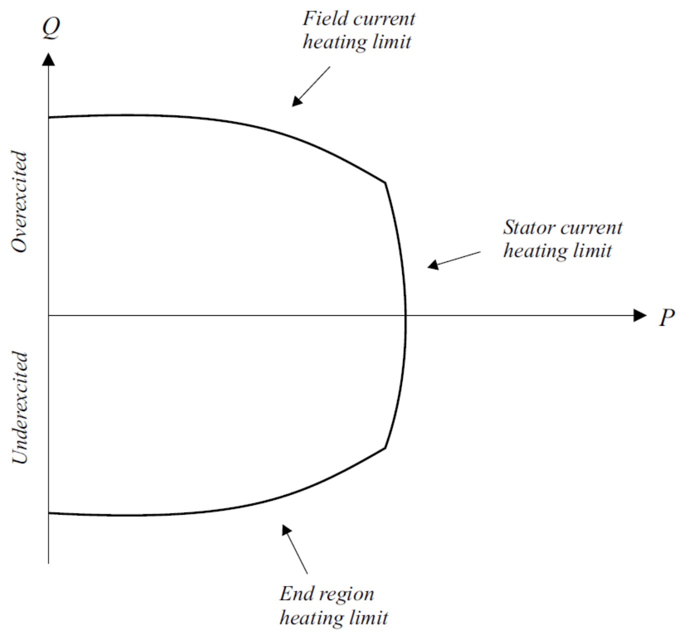
where Y_{ij} are the elements of the bus admittance matrix, V_i are the bus voltages, and I_i are the currents injected at each node. For bus 2 in this system, this equation reduces to

$$Y_{21}V_1 + Y_{22}V_2 + Y_{23}V_3 + Y_{24}V_4 = I_2$$

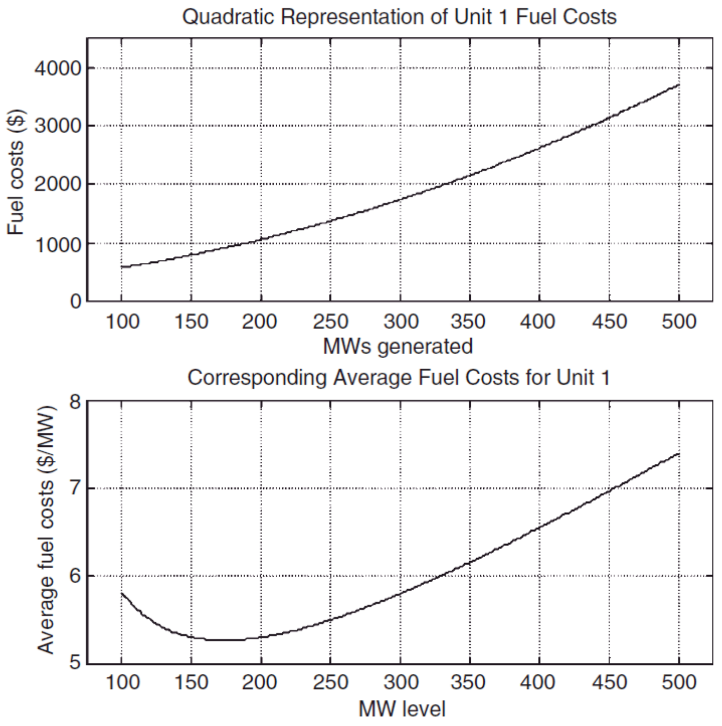
Optimal Power Flow

Incorporates economic dispatch of generators with power system limitations

Example Generator Output Curve



Example Generator Fuel Cost Curve



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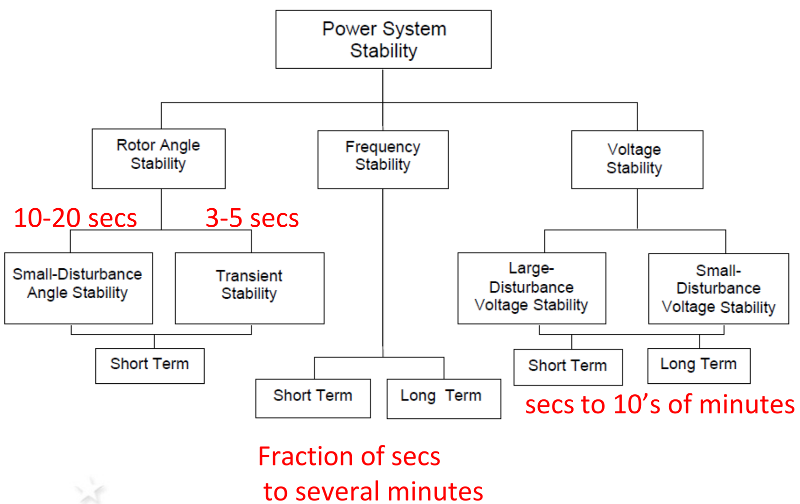
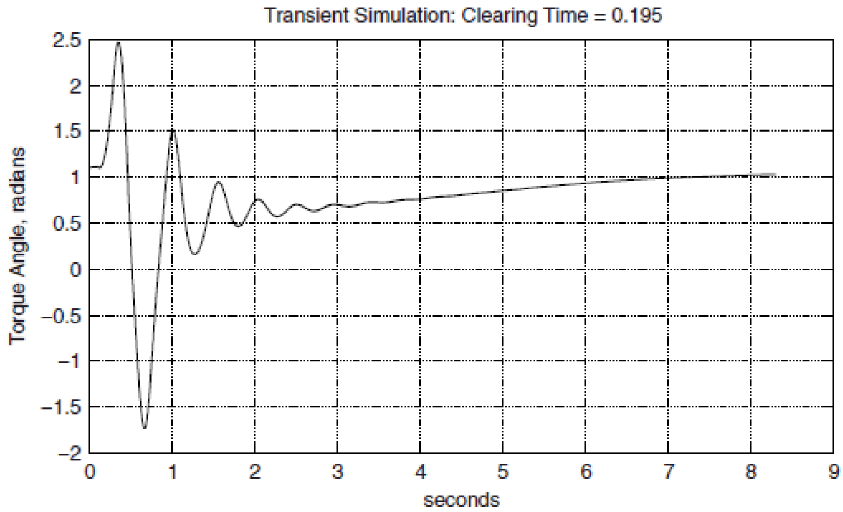
Power Flow and Stability

Power flow is steady state – Stability is for alterations following disturbances or large sudden load changes





Rotor Angle Stability – ability of machines to remain in sync following disturbance
Frequency Stability – ability of power system to maintain steady frequency following severe disturbances resulting in imbalance between generators and loads
Voltage Stability – ability of power system to maintain steady voltages following disturbance

Stability/Contingency Analysis

- N-1 Criterion: NERC Operating Policy 2.A—Transmission Operations: "All CONTROL AREAS shall operate so that instability, uncontrolled separation, or cascading outages will not occur as a result of the most severe single contingency"
- Bulk electrical systems must be operated at all times to ensure that the system remains in a stable condition (remains intact) following the loss of the most important generator or transmission facility (worst anticipated contingency) during the most stressed system conditions anticipated (such as winter and summer peak load conditions).
- Power operators perform
  - offline system studies such as power flow and transient stability studies to anticipate and plan for systems to withstand worst case scenarios and still maintain reliable power service by determining response actions necessary if such events occur
  - online tools such as power system state estimation programs which gather current power system data with additional simulation tools to determine the effects of additional outages on a stressed system to be able to take actions if possible to avert or contain effects of large scale power outages
  - Transient stability analysis involves more detailed models than power flow which takes into account additional generator and switching dynamic changes over milliseconds (vs. seconds to minutes associated with power flow analysis) to model system responses to N-1 contingencies during extreme loading conditions

Additional Analyses

- ***Availability:*** *The probability that a device, or system, will perform its intended function at a stated instant of time for a stated period of time.*
- ***Reliability:*** *The probability that a device, or system, will perform its intended function without failure under stated conditions for a stated period of time.*

INTRODUCTION TO RESILIENCE ANALYSIS

Motivating Resilience Analysis

- Historically, infrastructure security policies focused on "protection"
- Infrastructures face array of different evolving threats
  - It is impossible to protect every asset from every threat all of the time
- National, Homeland, and Infrastructure security policies now promote resilience as a complement to protection
- Resilient infrastructure systems
  - Resist the effects of disruptive events
  - Adapt to adverse conditions
  - Recover rapidly and efficiently

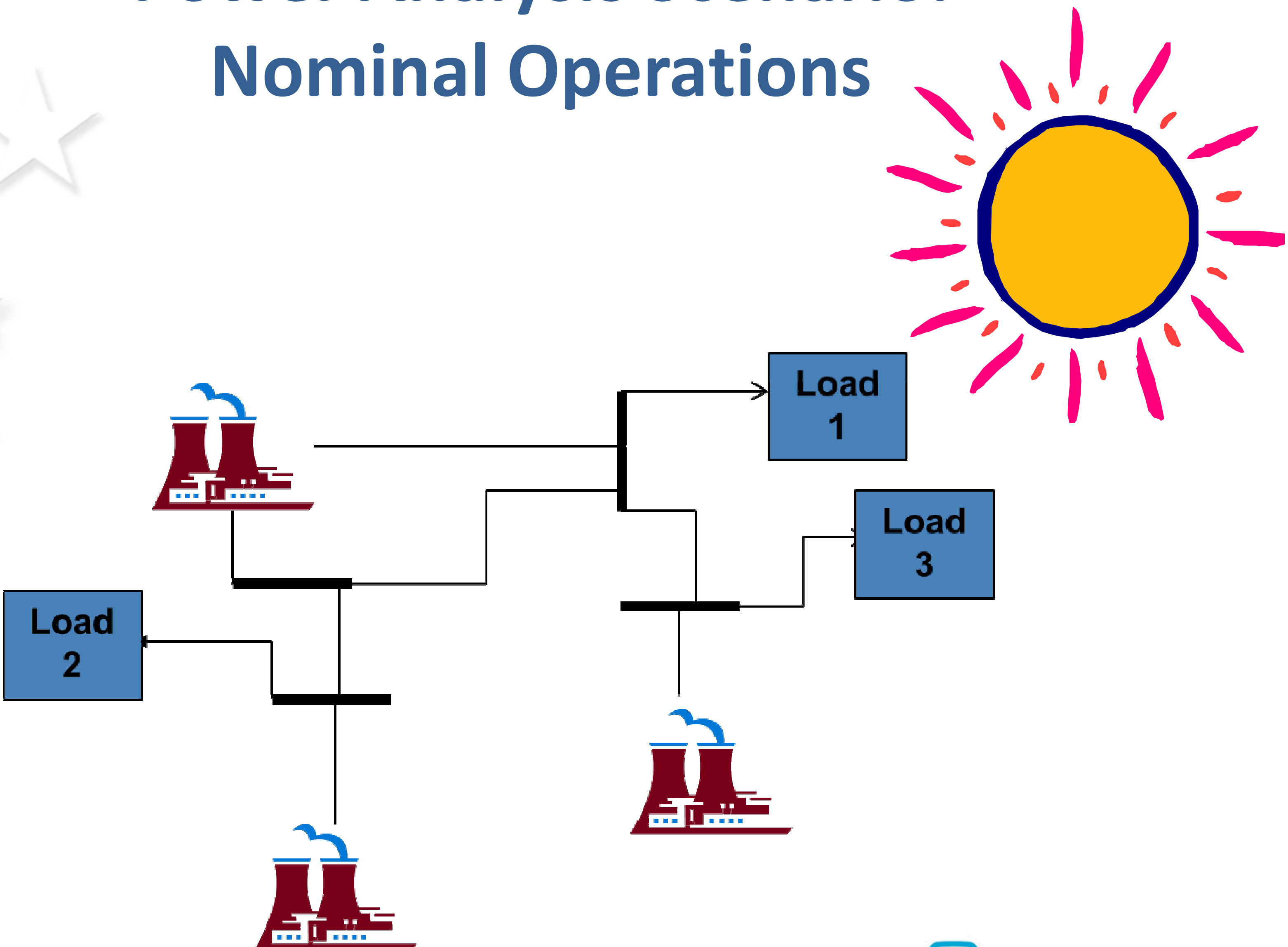
"We are working every day to ensure our country stands ready to respond to any disaster or emergency -- from wildfires and hurricanes, to terrorist attacks and pandemic disease. Our goal is to ensure a more resilient Nation."

– U. S. President Barack Obama, September 4, 2009

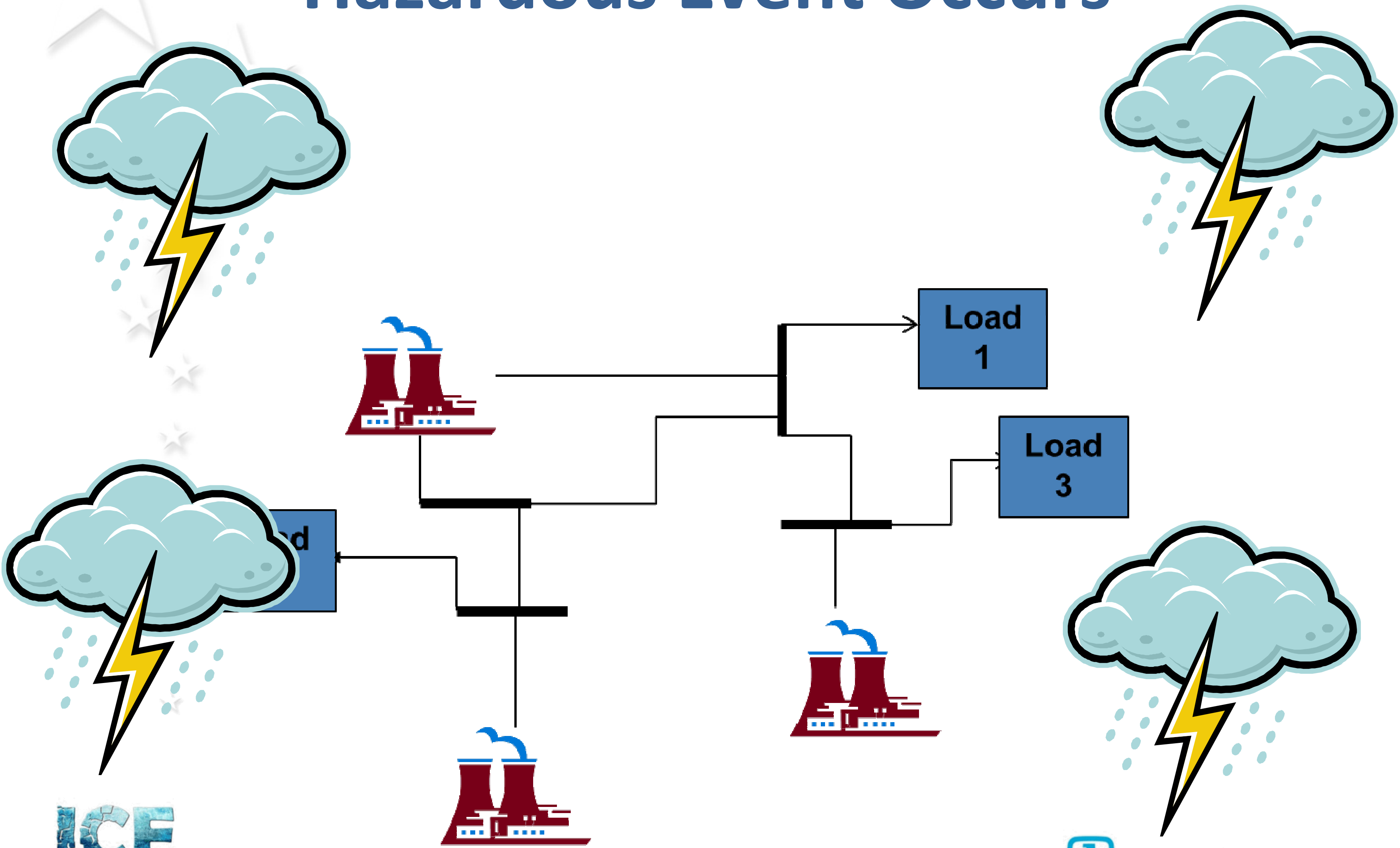
Moving Beyond N-1 Analysis

- N-1 criteria are appropriate for regulatory purposes
  - They establish minimum operating criteria for hazards with "reasonable likelihood"
  - Hazards have limited direct impact
- N-1 criteria are generally not sufficient for security objectives that frequently address "low probability" events with regional impact
  - E.g., Hurricane Sandy, California earthquakes, terrorism, etc.

Power Analysis Scenario: Nominal Operations

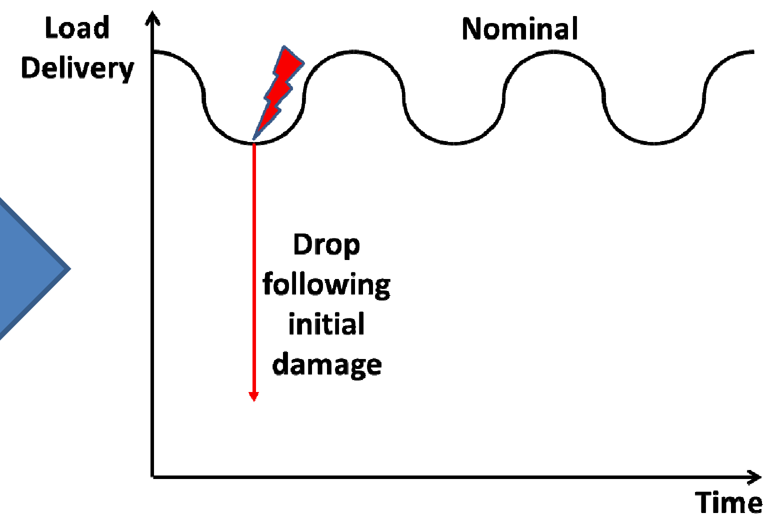


Hazardous Event Occurs



Damage to System Limits load Delivery

System Components experience physical damage- cascading may lead to additional damage.



Damaged system cannot continue nominal load delivery

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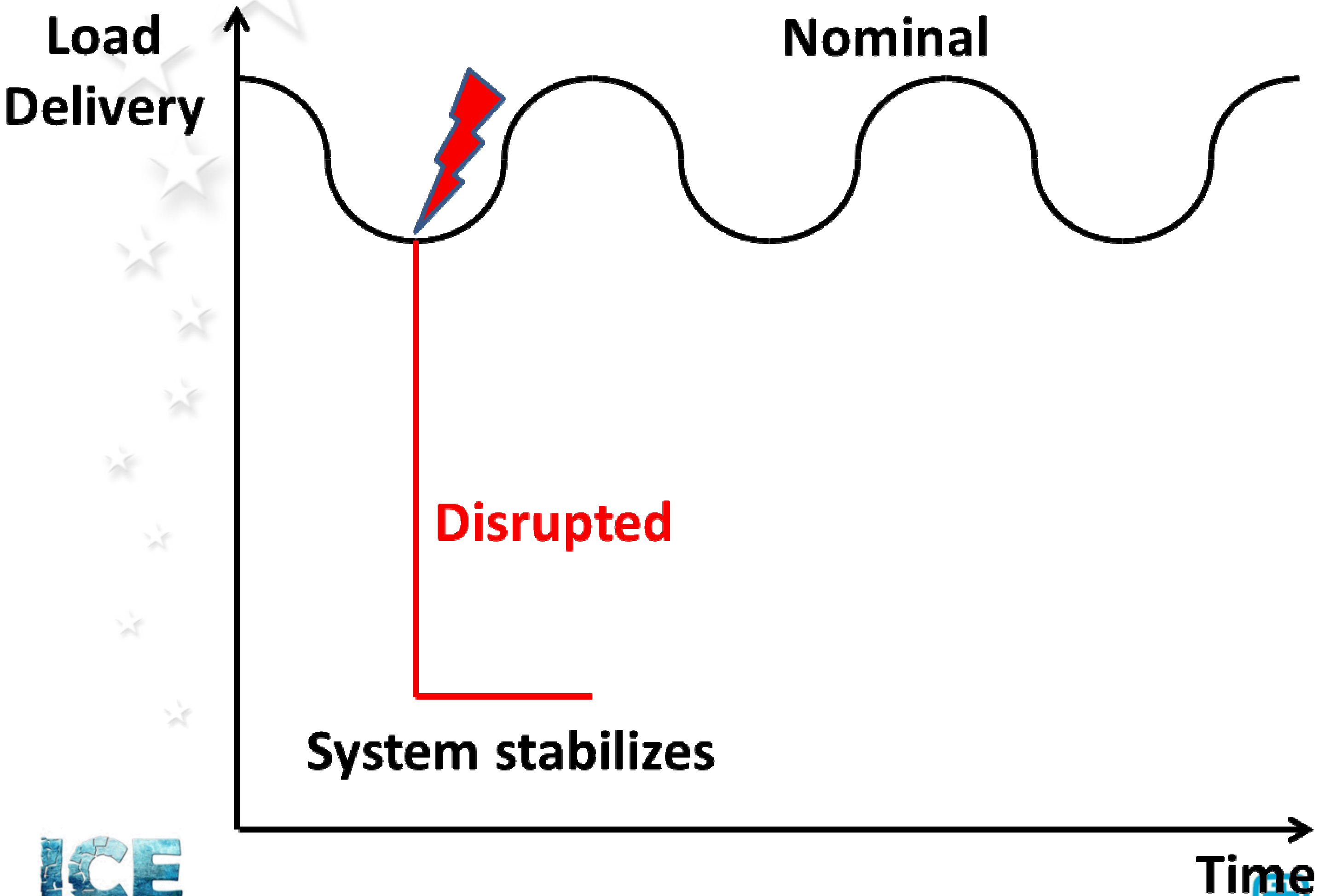
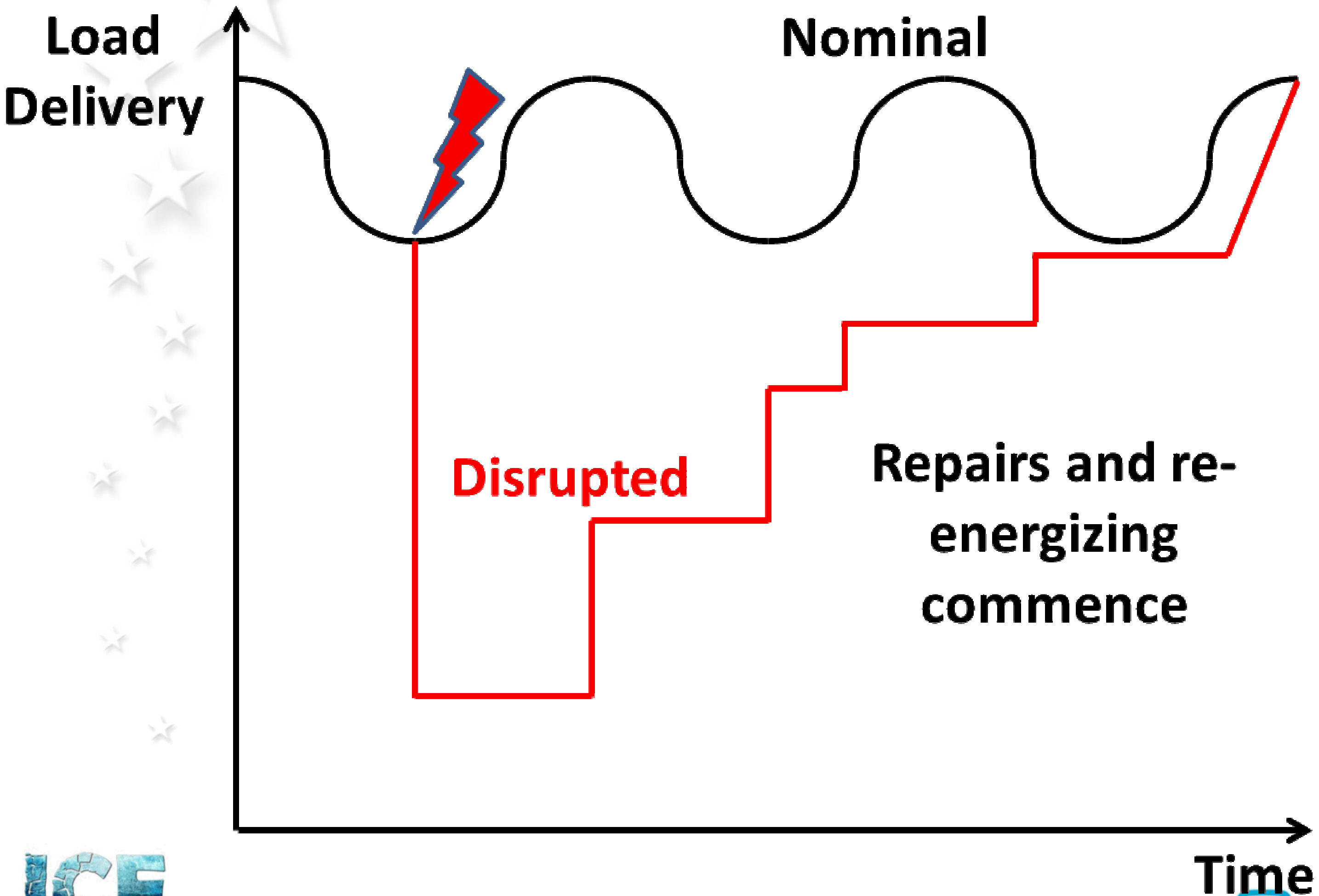
Response

- Utility takes action to limit cascading damage (e.g., load shedding)
- Prioritization of loads and repairs
- Repairs begin/complete
- Re-energize repaired components
- Re-allocate load
- Nominal capability restored
- Process is iterative

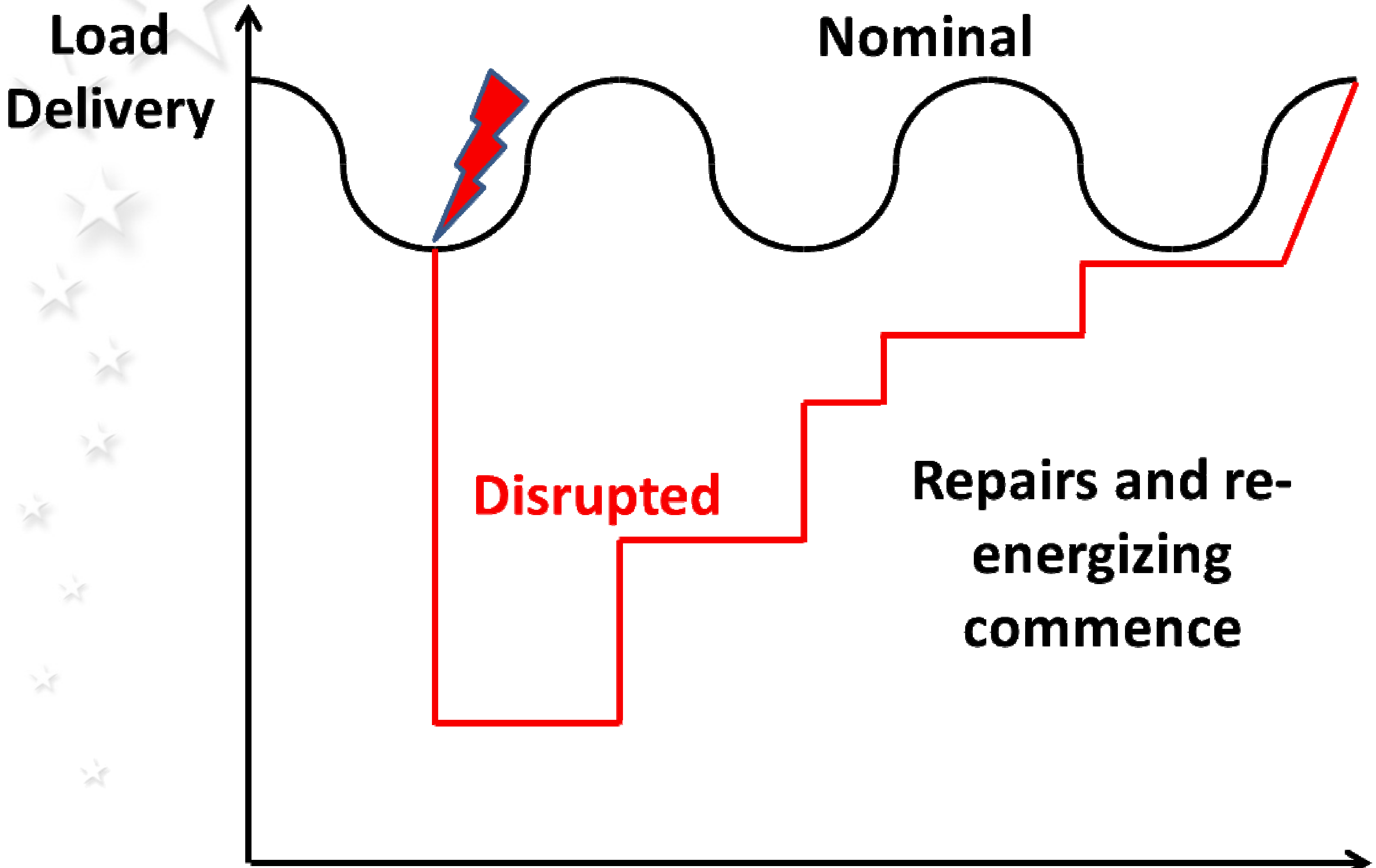
Initial Action Limits Further Loss of Load



Recovery Activities Restore Load

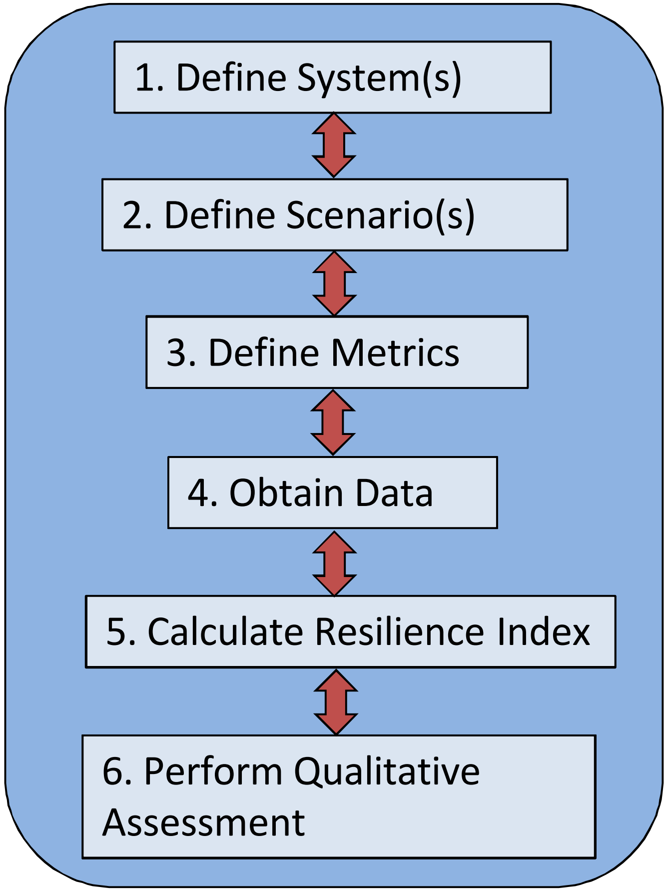


Recovery Activities Restore Load



Resilience analysis for electric power systems must capture all of the steps/actions of the disaster timeline and their impact on load delivery.

Resilience Analysis Process



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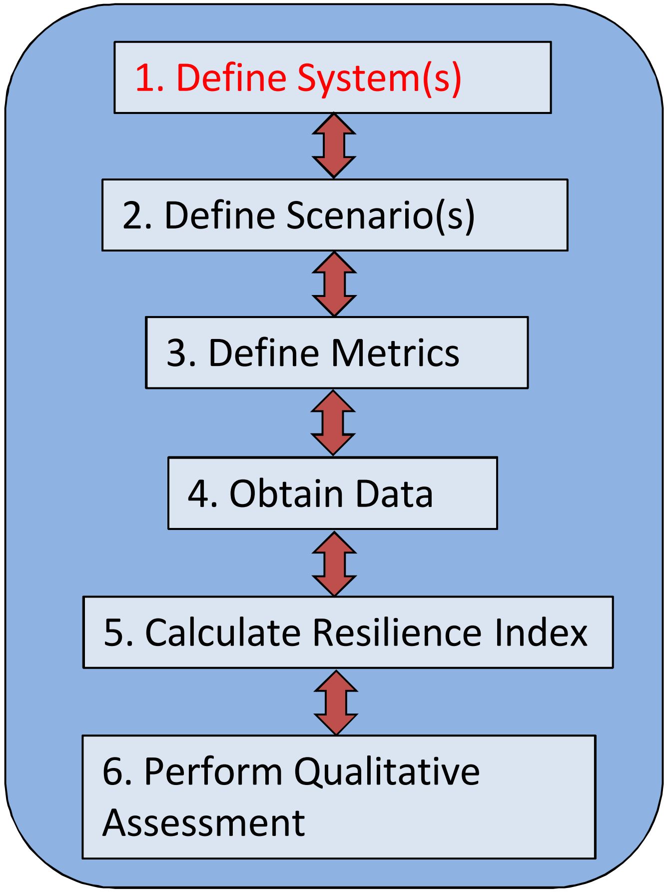
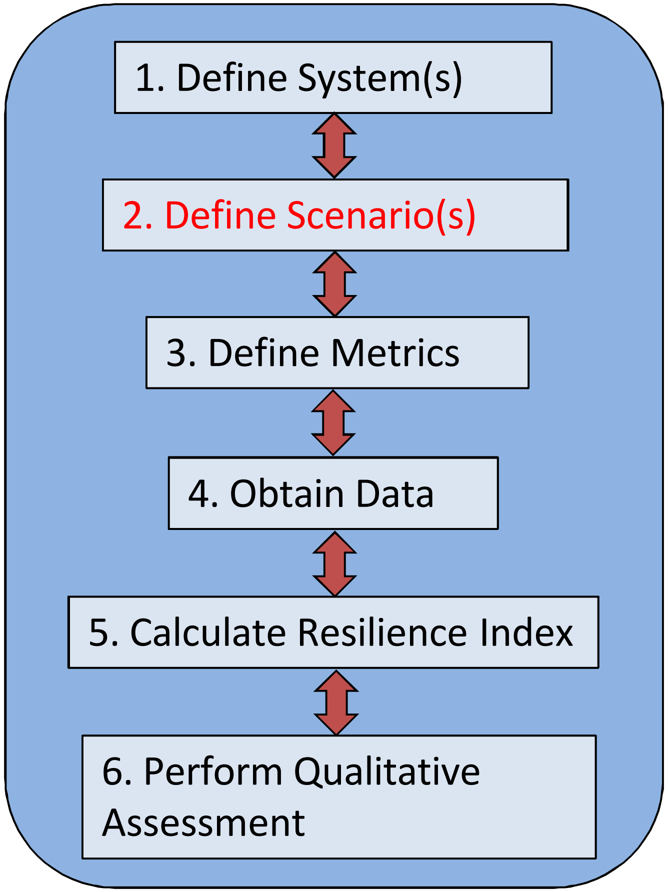
Resilience Analysis Process: Define System(s)

- What system is being considered?
- What are boundaries of system?
- Factors to consider:
  - Generation and/or transmission and/or distribution?
  - Include customers or not?
  - Are some customers a higher priority than others (e.g., hospitals, military bases, etc.)?
  - What do normal operations look like?



Resilience Analysis Process: Define Scenario(s)

- What hazards do we care about?
- What response options are available?
- Factors to consider:
  - What physical damage is expected to system components?
  - Do dependencies lead to cascading damage?
  - What are impacts to system from damage sustained?
  - What are possible response options?
  - What are constraints on system for recovery?
  - What are requirements (time and resource) for repairs and restarts?



Resilience Analysis Process: Define Metrics

- Systemic Impact (SI): consequence of inability to provide load

$$SI = \int_{t0}^{tf} \left\{ \sum_j q_j(t) \left[TSP_j(t) - SP_j(t) \right] \right\} dt.$$

- TSP_j: targeted load delivered to customer j
- SP_j : actual load delivered to customer j
- q_j : priority load weighting factor
- $t0$: disruption initiates
- tf : recovery complete

- Total Recovery Effort (TRE): cost of recovery actions (equipment, labor, and adaptations)

$$TRE = \int_{t0}^{tf} \left\{ \sum_k r_k(t) \left[RE_k(t) \right] \right\} dt$$

- RE_k: recovery activity k
- r_k : cost of activity k

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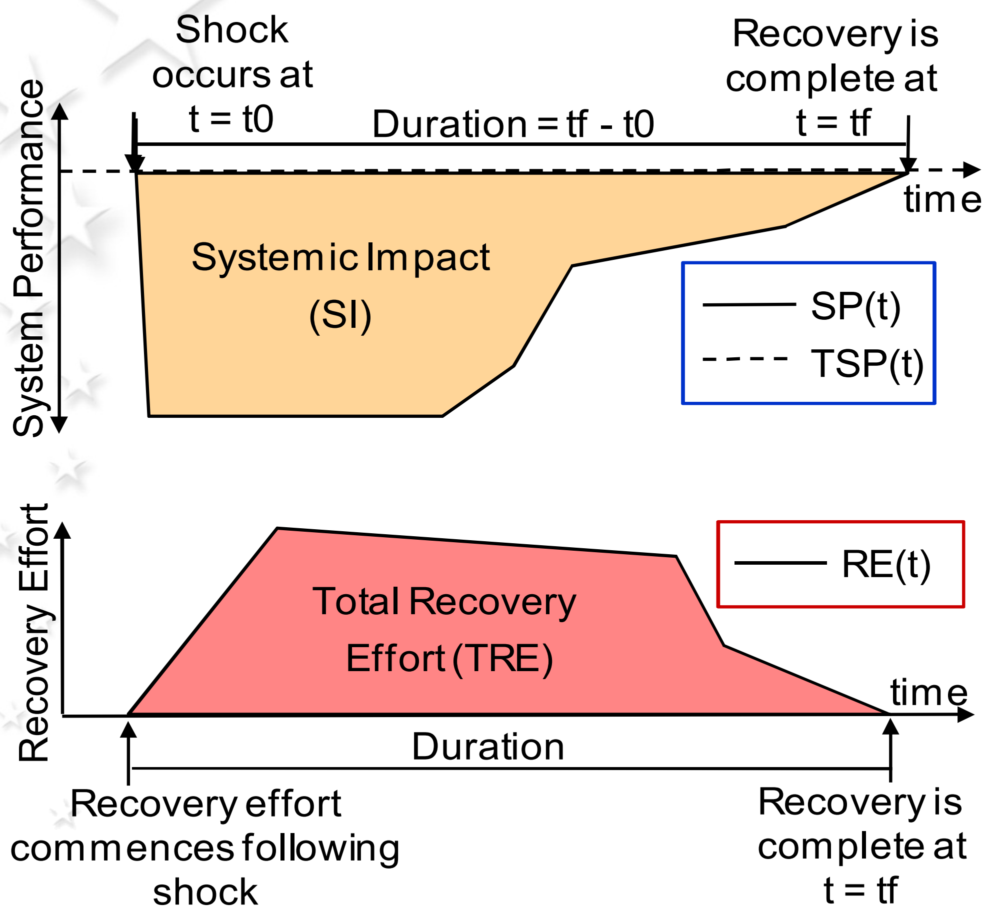
Resilience Analysis Process: Define Metrics



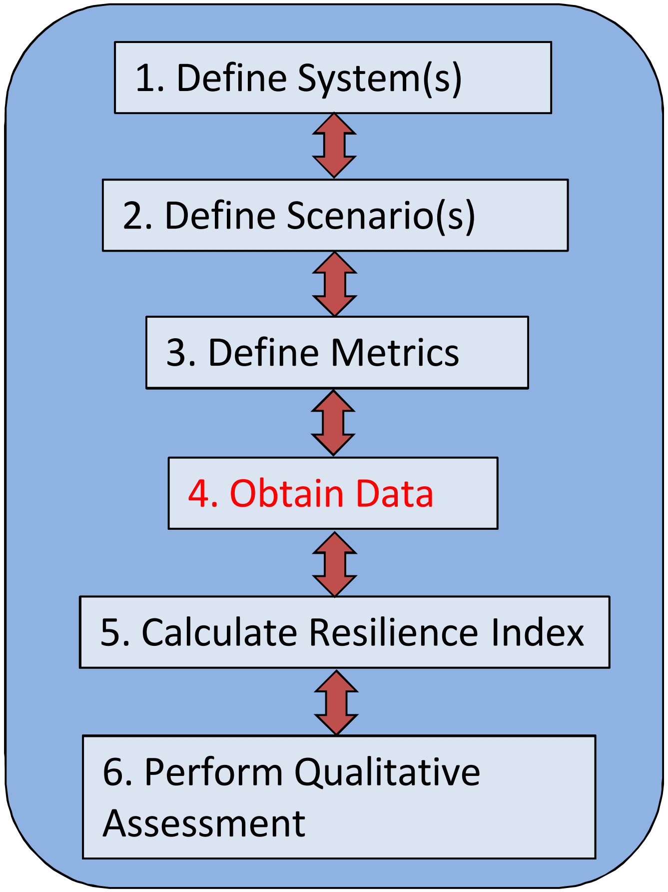
Resilience Index

=

$$\frac{SI + \alpha \times TRE}{\int_{t0}^{tf} \left|TSP(t)\right| dt}$$

Resilience Analysis Process: Obtain Data

- Load delivery (by customer or system level)
- Priority weighting
- Recovery actions
- Cost of recovery actions
  - Data may be acquired through simulation, historical data, or expert judgment



Resilience Analysis Process: Calculate Index

- Use metrics and obtained data to calculate resilience indices
- Demonstration will show results

DEMO OF ENERGY SECURITY RESTORATION MODEL (ESRM)

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Summary

- Several types of power systems exist
  - Generation ,transmission, distribution
- Several electrical power system modeling options
  - Selection of modeling approach depends on analysis objective
- Resilience is a new approach to securing infrastructure systems, including power systems
- Grid resilience tools and techniques are currently under development
  - ESRM enables planners to identify impacts of recovery decisions and constraints upon grid resilience

Additional Slides

Creating Clarity from Complexity

Example 4 Bus System

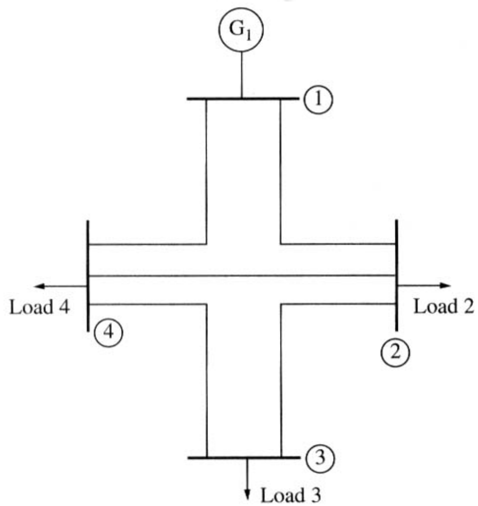

Table of Busses:

Bus 1	Slack bus
Bus 2	Load bus
Bus 3	Load bus
Bus 4	Load bus

line #	Bus to bus	Series Z (pu)	Series Y (pu)
1	1-2	0.1+j0.4	0.5882-j2.3529
2	2-3	0.1+j0.5	0.3846-j1.9231
3	2-4	0.1+j0.4	0.5882-j2.3529
4	3-4	0.5+j0.2	1.1765-j4.7059
5	4-1	0.5+j0.2	1.1765-j4.7059

$$Y_{bus} = \begin{bmatrix} 1.7647 - j7.0588 & -0.5882 + j2.3529 & 0 & -1.1765 + j4.7059 \\ -0.5882 + j2.3529 & 1.5611 - j6.6290 & -0.3846 + j1.9231 & -0.5882 + j2.3529 \\ 0 & -0.3846 + j1.9231 & 1.5611 - j6.6290 & -1.1765 + j4.7059 \\ -1.1765 + j4.7059 & -0.5882 + j2.3529 & -1.1765 + j4.7059 & 2.9412 - j11.7647 \end{bmatrix}$$

$$V_1 = 1.0\angle 0^\circ\ pu$$
$$V_2 = 0.964\angle -0.97^\circ\ pu$$
$$V_3 = 1.0\angle 1.84^\circ\ pu$$
$$V_4 = 0.98\angle -0.27^\circ\ pu$$

From voltages, currents and power flows can be derived

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