ISO new england

Architecting the Future Grid

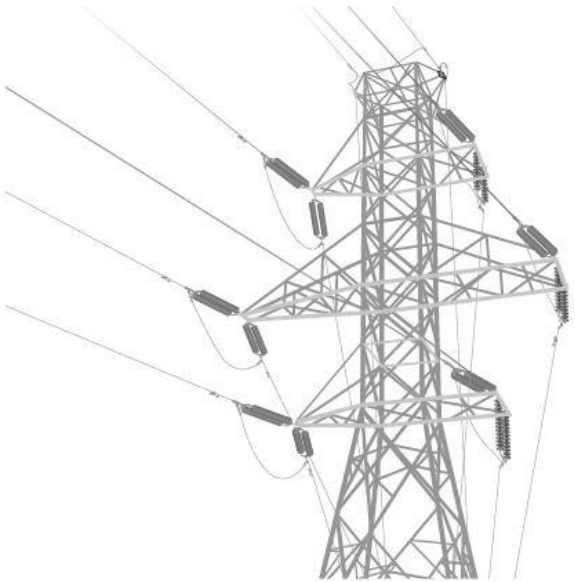
Grid Science Conference

Eugene Litvinov

…complex systems are counterintuitive. That is, they give indications that suggest corrective action which will often be ineffective or even adverse in its results.

Forrester, Jay Wright

Power System: A Traditional View

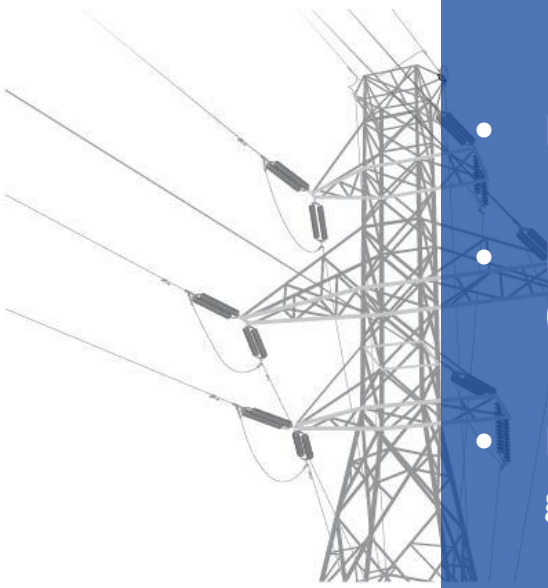


Bulk Power System

Distribution System

Two separate systems

The Line Between Transmission and Distribution is Blurring



- Increase in Distributed Generation (DG)
- Introduction of Virtual Power Plants (VPP)
- Demand Resources (DR) playing a greater role

Result: traditional power system becomes more “open” and vulnerable to disturbances and attacks

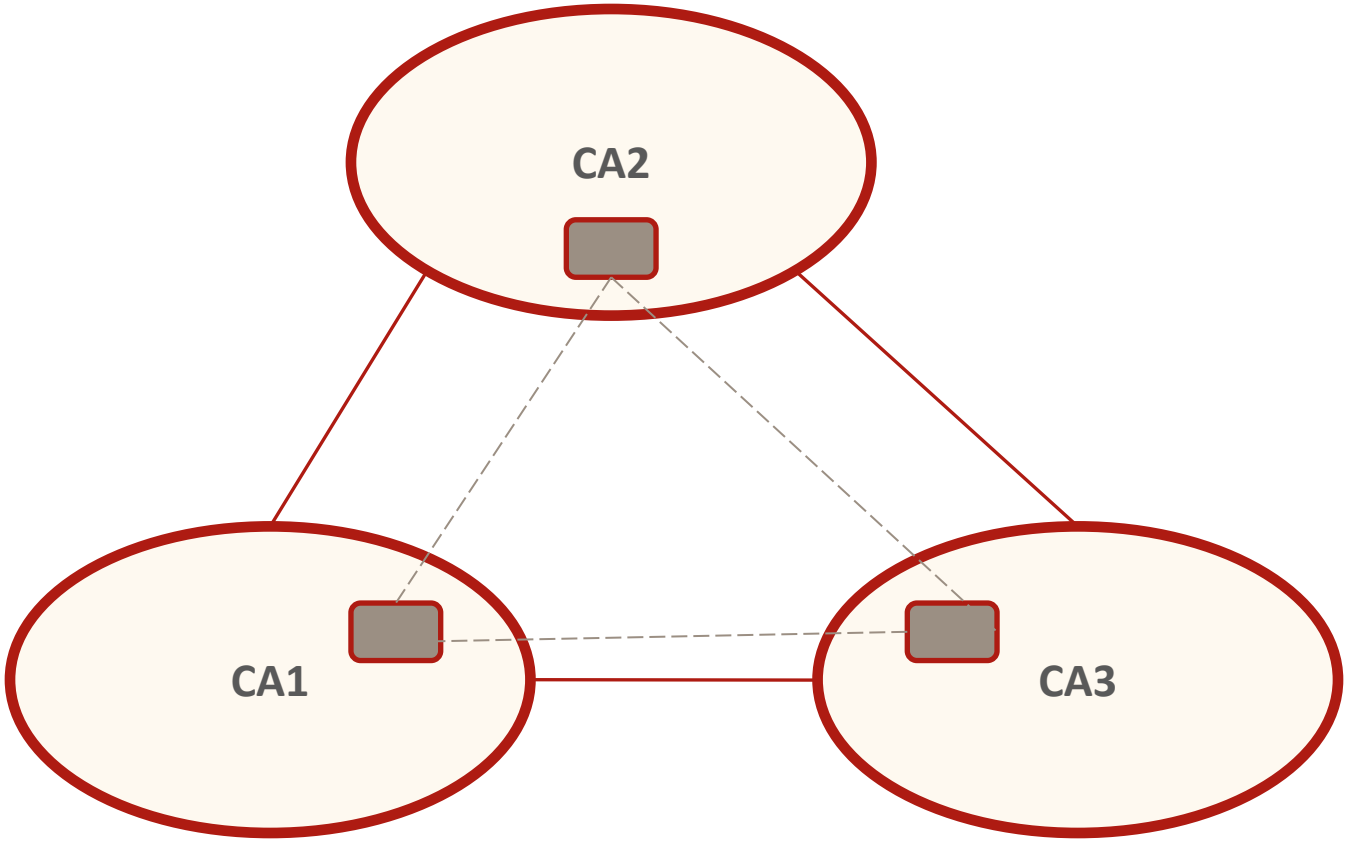
The Smart Grid

Bulk Power System

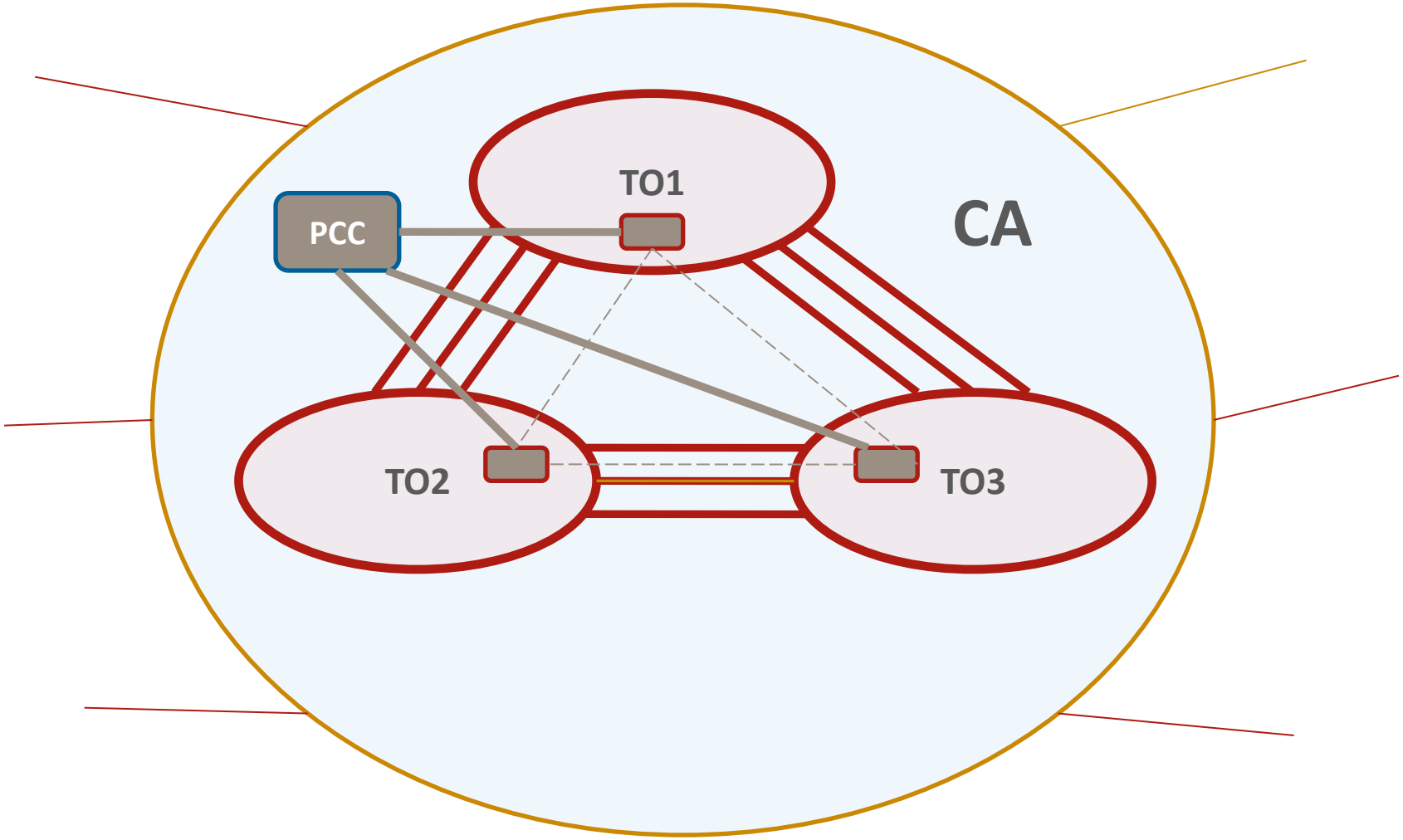
Distribution System

Common policies, reliability and control standards

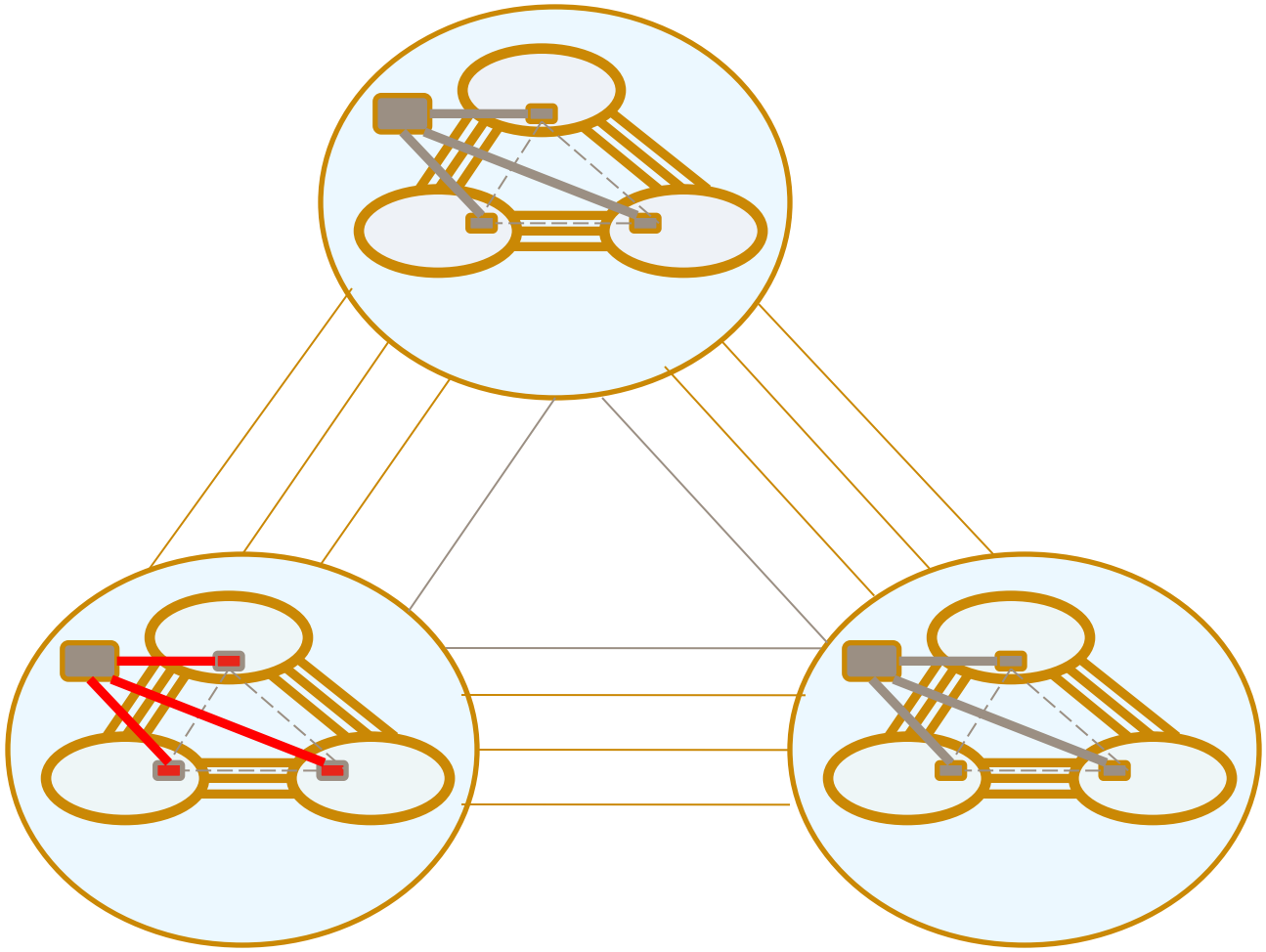
Power System Architecture Evolution (before 1966)



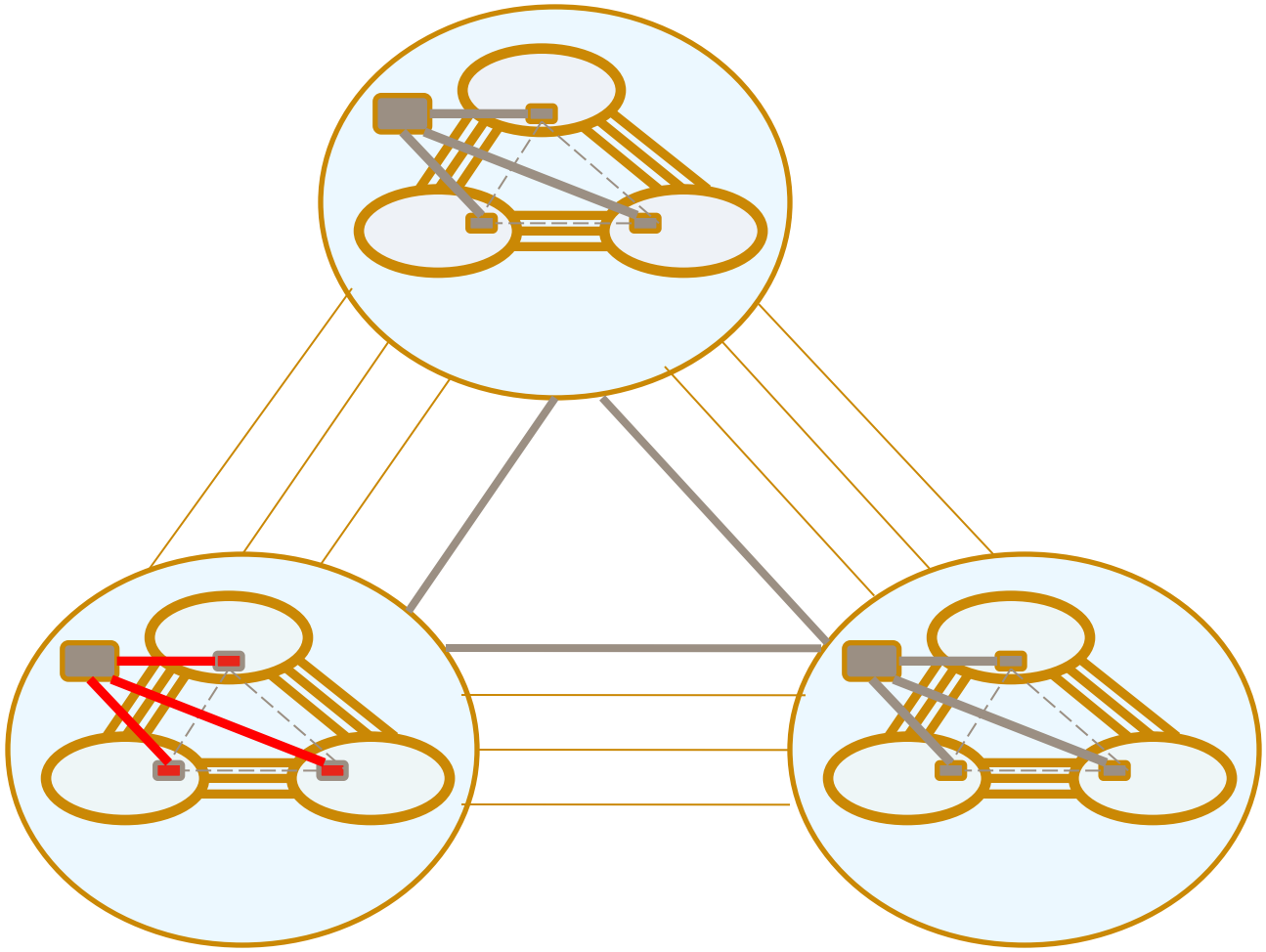
Power System Architecture Evolution (creation of pools)



Power System Architecture Evolution (markets)

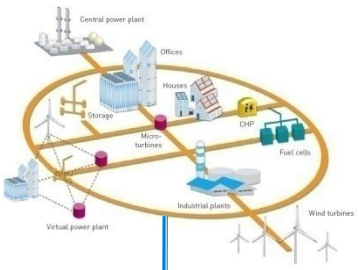


Power System Architecture Evolution (coordinated markets)

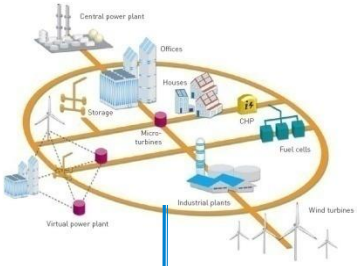


Power System Architecture Evolution (what's next?)

µGrid



µGrid



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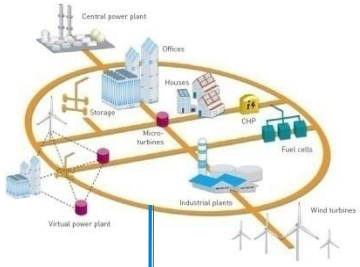


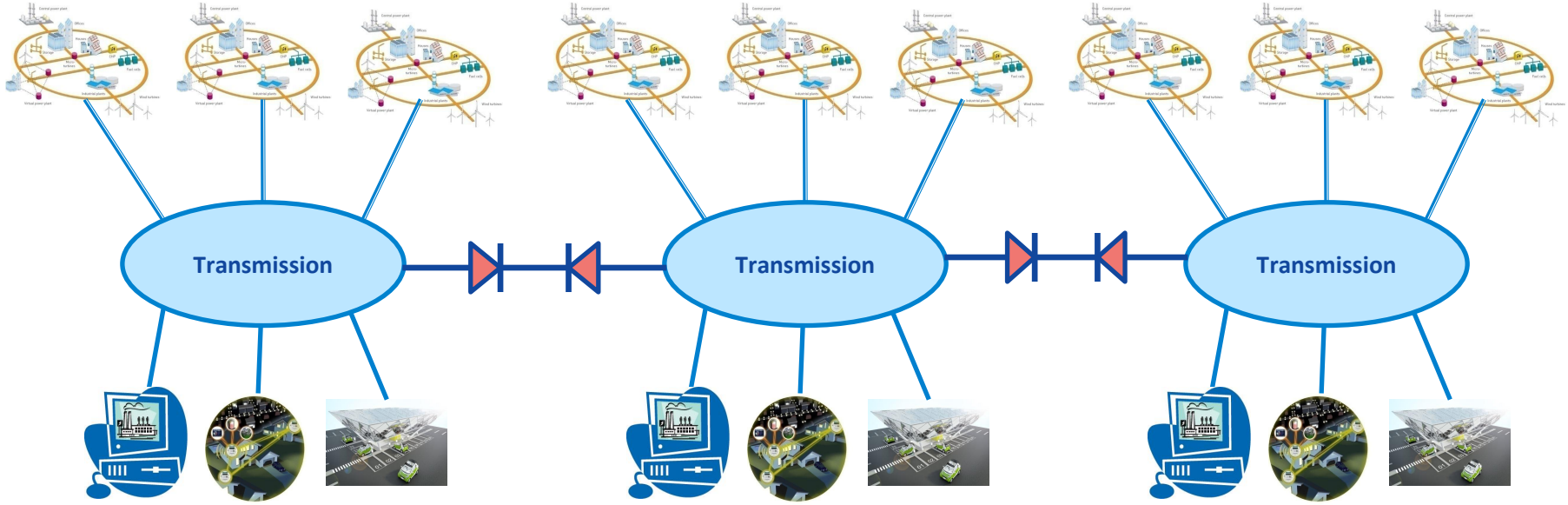
Transmission Backbone

Virtual Power Plants

Demand Aggregators

PHEV Aggregators

Power System Control Evolution (what's next?)



Maybe this?

The Need for Greater Flexibility

New Planning and Protection Concepts

- Rapid response to different disturbances
- Greater reliance on corrective actions
- System integrity protection
- Power quality standards
- System survivability

New Transmission Technologies

- Power electronics
- Energy storage
- Superconductors
- HVDC and HVDC-lite
- Nanotechnologies

New Operation and Control Strategies

- Risk-based operation
- Wide-area monitoring
- Adaptive islanding
- Transmission switching
- Online constraints calculation
- Dynamic and adaptive line ratings
- Adaptive and distributed control
- New optimization algorithms: robust and stochastic optimization

Reliability

NERC defines reliability as:
Adequacy + Operating Reliability[1]

Challenges to this conventional reliability concept:

- Distributed resources and microgrids
  - System is unbounded – operator cannot completely control perimeter
  - Contingency definition is nontrivial
- Evolving contingency definitions
  - Binary contingency definition → probability distributions
  - Greater effect of computer & communication contingencies
  - Ambiguous definition of "loss-of-load" events with responsive loads
- Non-uniform quality of service and reliability needs

[1] NERC, *Definition of "Adequate Level of Reliability,"* 2007

OE-417 Analysis Overview

- About the data: who reports and what is reported
- Types and frequency of events
- Problems with the data
- Evaluation of historical reliability indices (2002-2011)
- Power law distribution of events

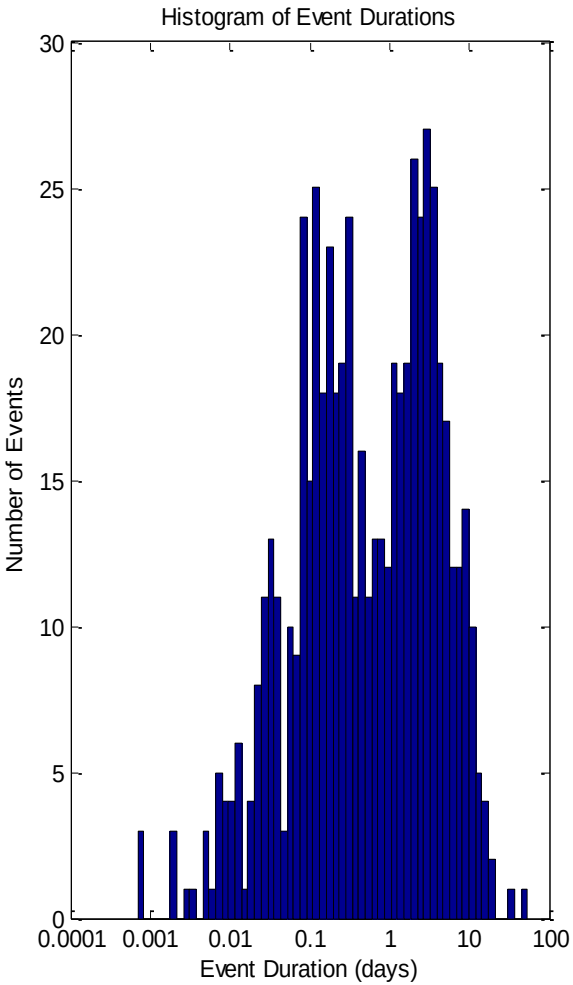
OE-417 Data – Who Reports?

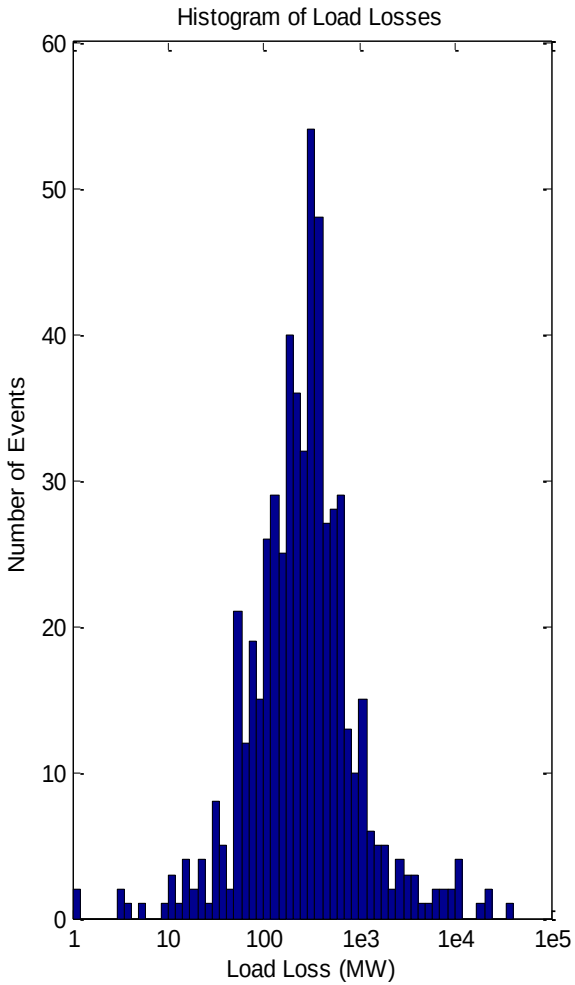
1. Electric Utilities
2. Balancing Authorities
3. Reliability Coordinators
4. Generating entities
5. Local utilities in AK, HI, PR

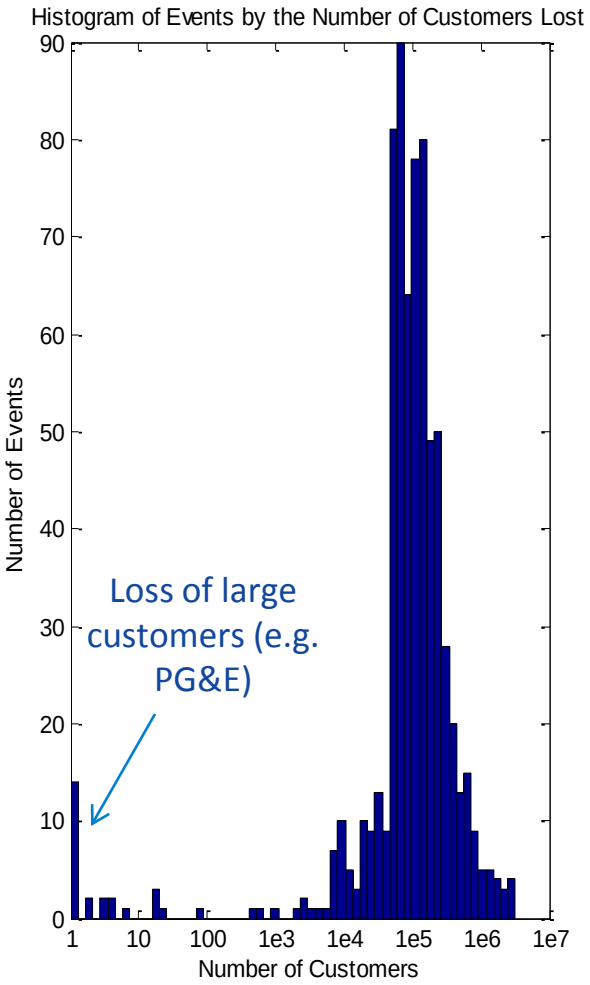
OE-417 criteria for reporting incidents:

1. Physical, cyber, or communications attack
2. Complete operational failure of transmission and/or distribution
3. Electrical system islanding
4. Uncontrolled loss of 300 MW or more load for 15 or more minutes
5. Load shedding of 100 MW or more
6. System-wide voltage reductions of 3% or more
7. Public appeals to reduce the use of electricity

Event duration and size of losses







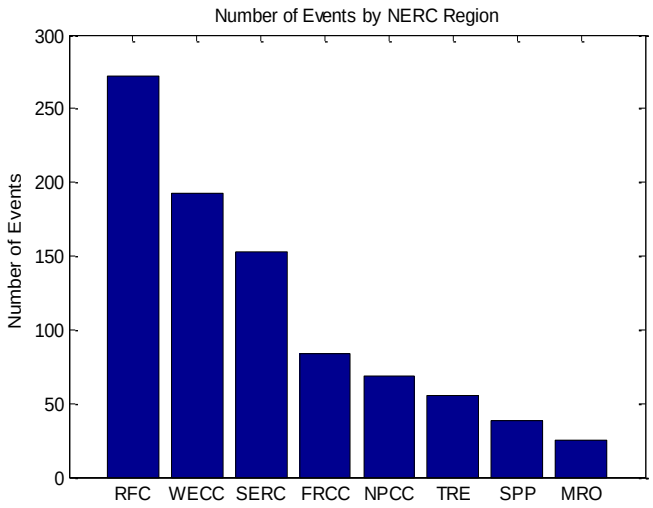
Problems with the data

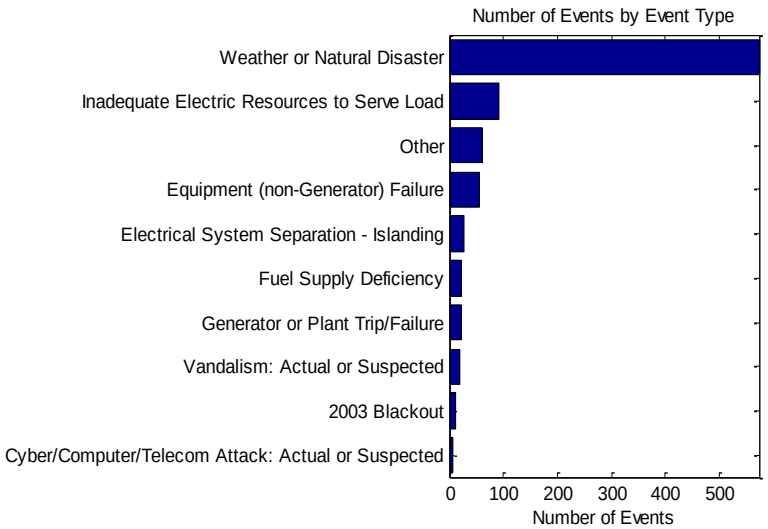
- Event losses are reported either in MW or number of customers, usually not both
  - Limits the useful portion of the data set to about 50%

- Event duration is provided, but the duration of the loss of load is not provided – this inhibits the evaluation of energy-related indices

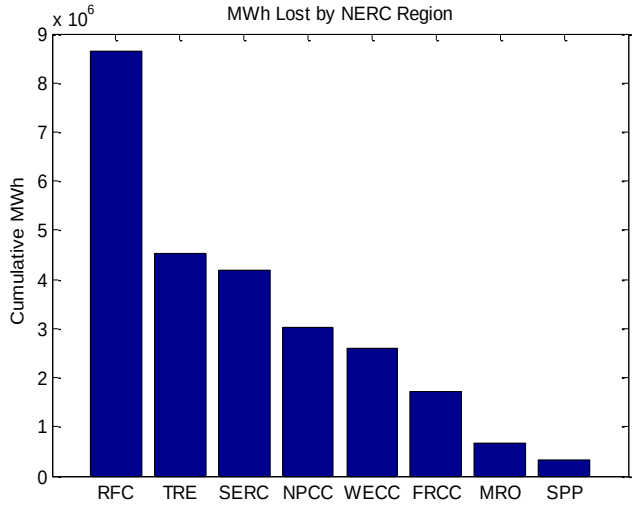
Breakdown of Events by NERC Region and Incident Type

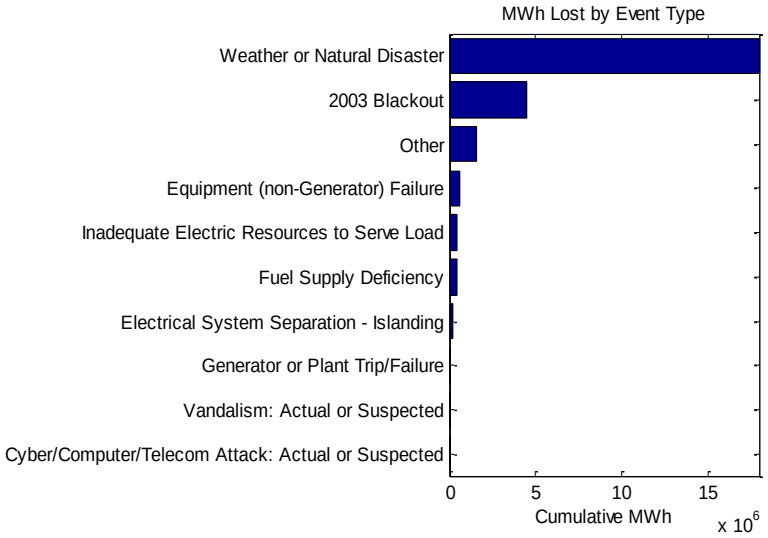
Number of Events





Magnitude of Events (sum of LOL times duration)

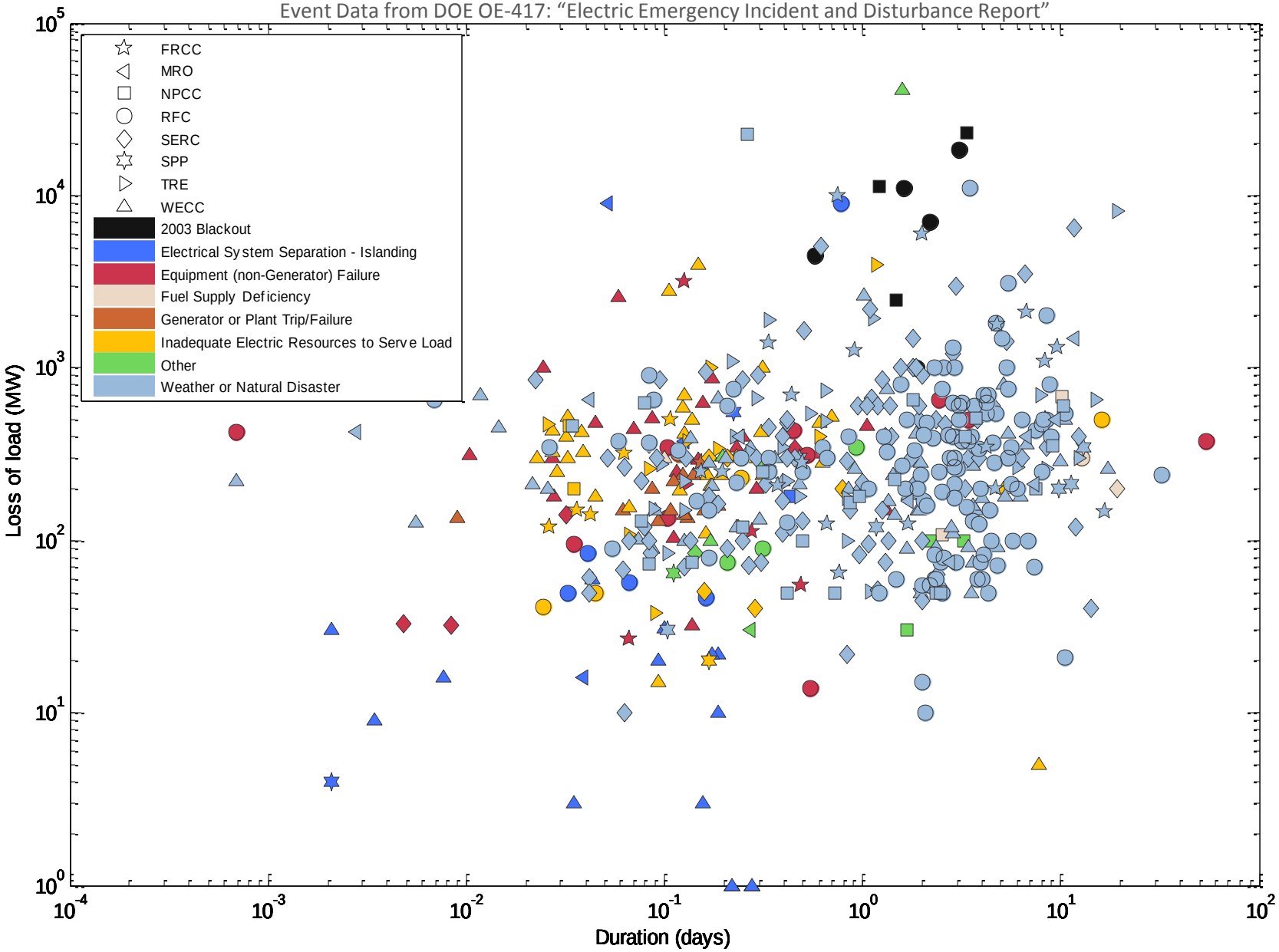




*Note: Since the duration of the event may not correspond to the duration of the loss-of-load, all results regarding unserved energy are inconclusive

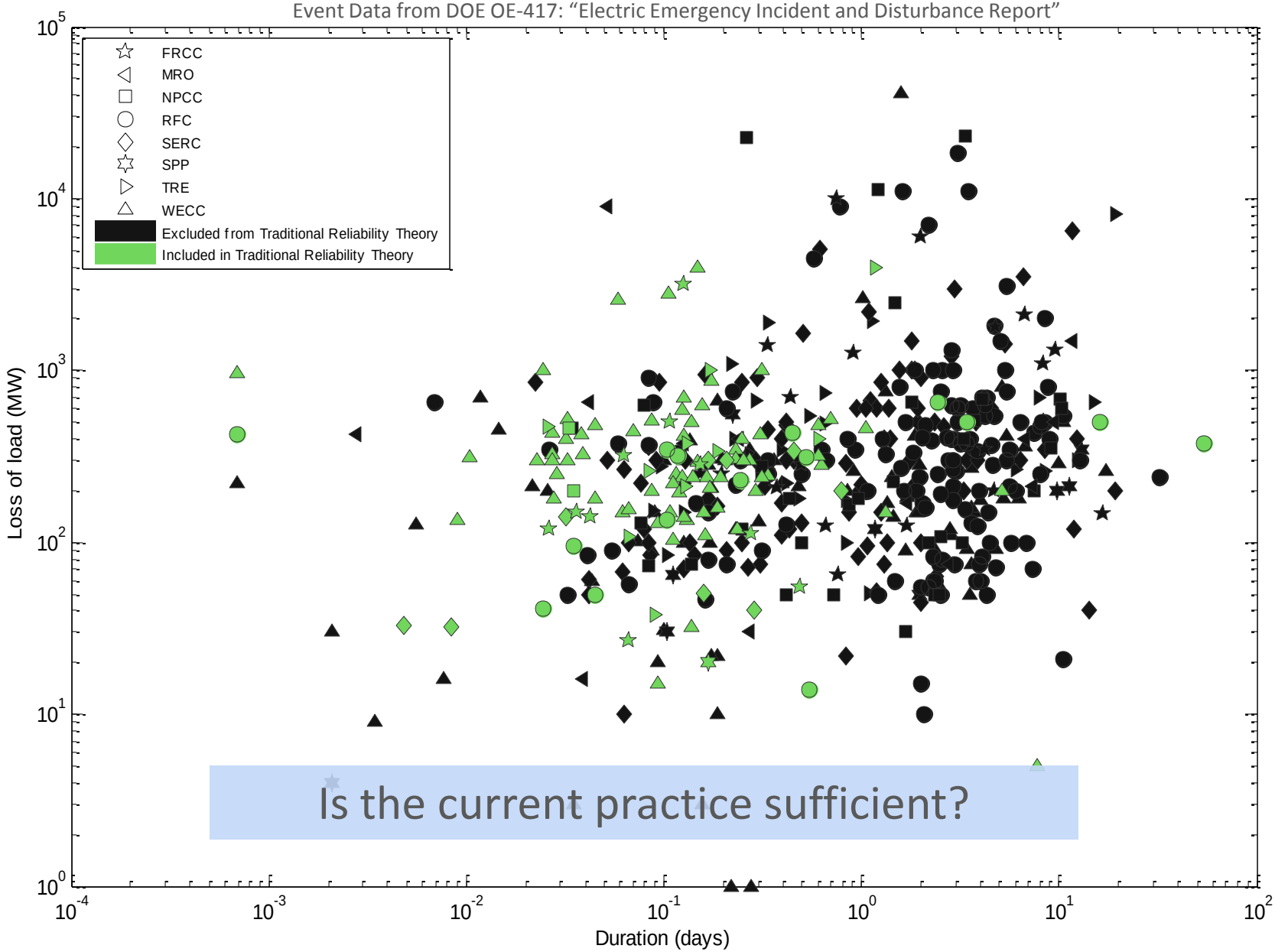
U.S. Power Disturbances Since 2002: By NERC Region and Incident Type

Event Data from DOE OE-417: "Electric Emergency Incident and Disturbance Report"



Many System Disturbances are Not Explicitly Modeled in Traditional Reliability Theory

Event Data from DOE OE-417: "Electric Emergency Incident and Disturbance Report"

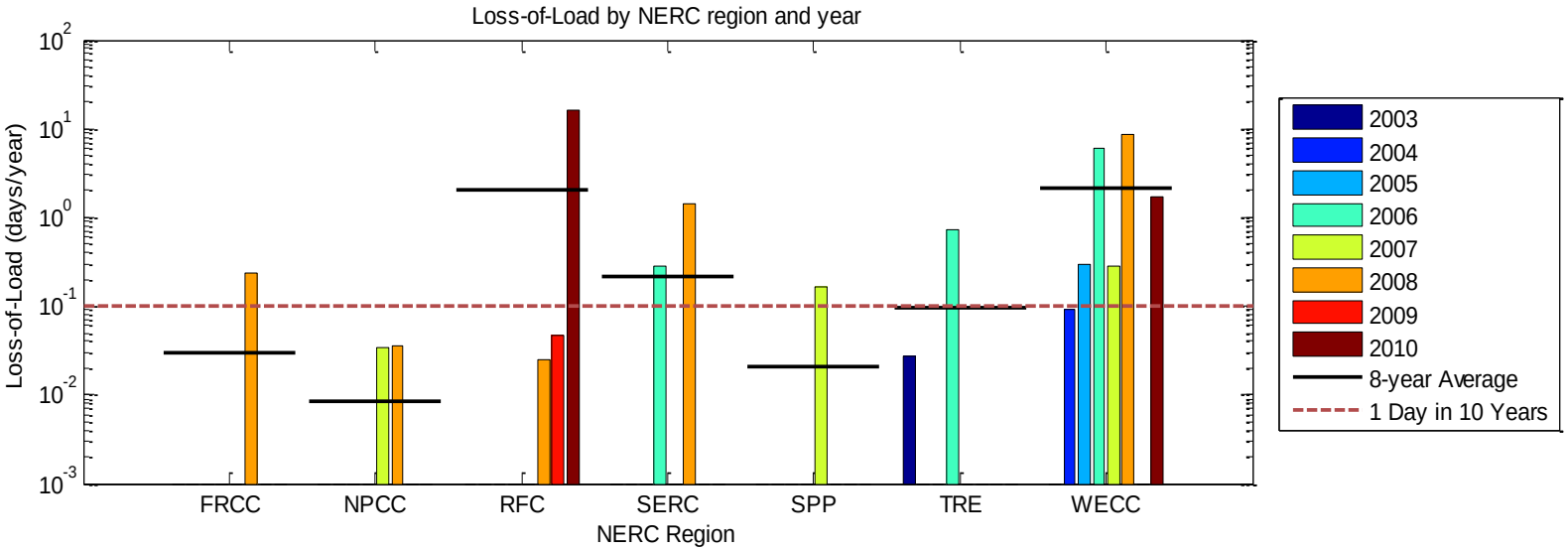


Is the current practice sufficient?

Calculated reliability indices using events categorized as "Inadequate Electric Resources to Serve Load" only.

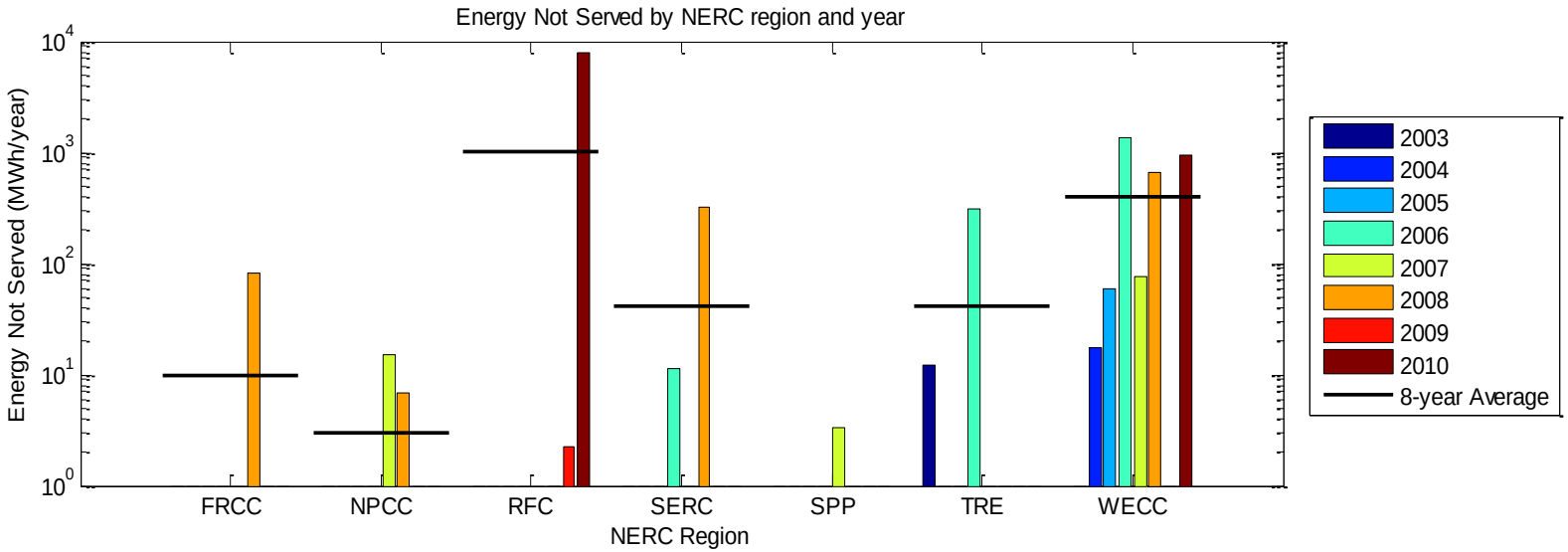
Average Loss-of-Load

1 Day in 10 Years



Average Energy Not Served:

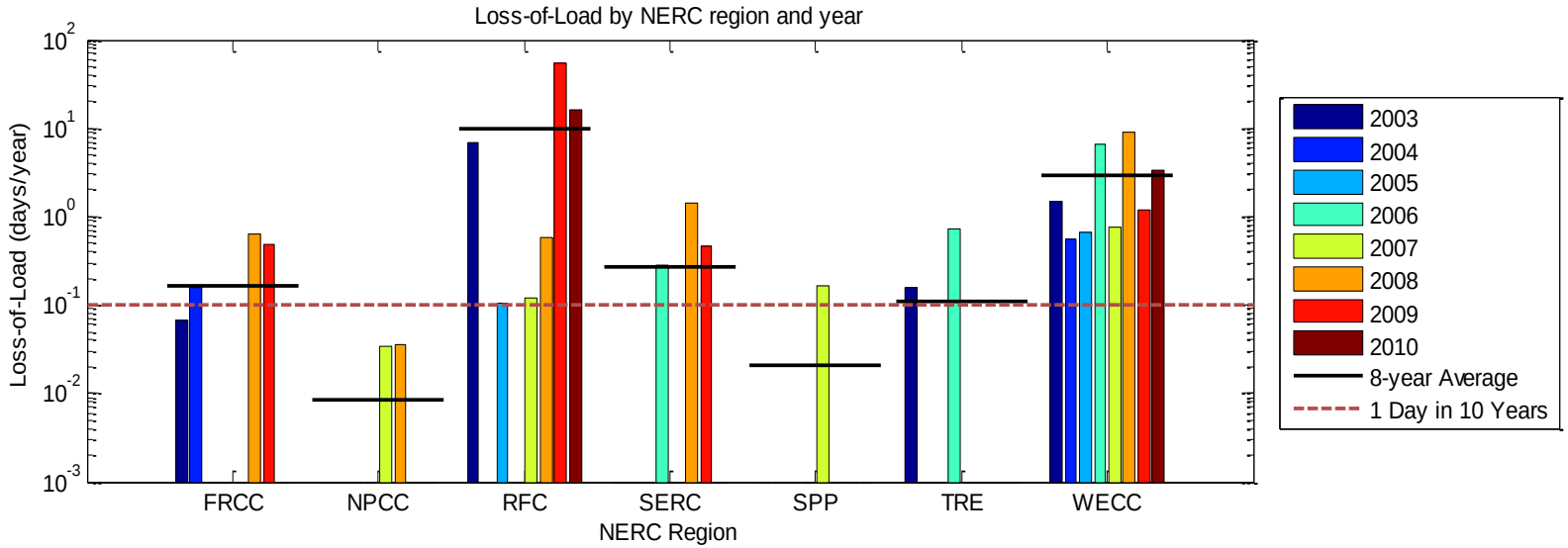
*Note: Since the duration of the event may not correspond to the duration of the loss-of-load, all results regarding unserved energy are inconclusive



Calculated reliability indices using events categorized as "Inadequate Electric Resources to Serve Load," Equipment (non-Generator) Failure," or "Generator or Plant Trip/failure."

Average Loss-of-Load

1 Day in 10 Years



Average Energy Not Served:

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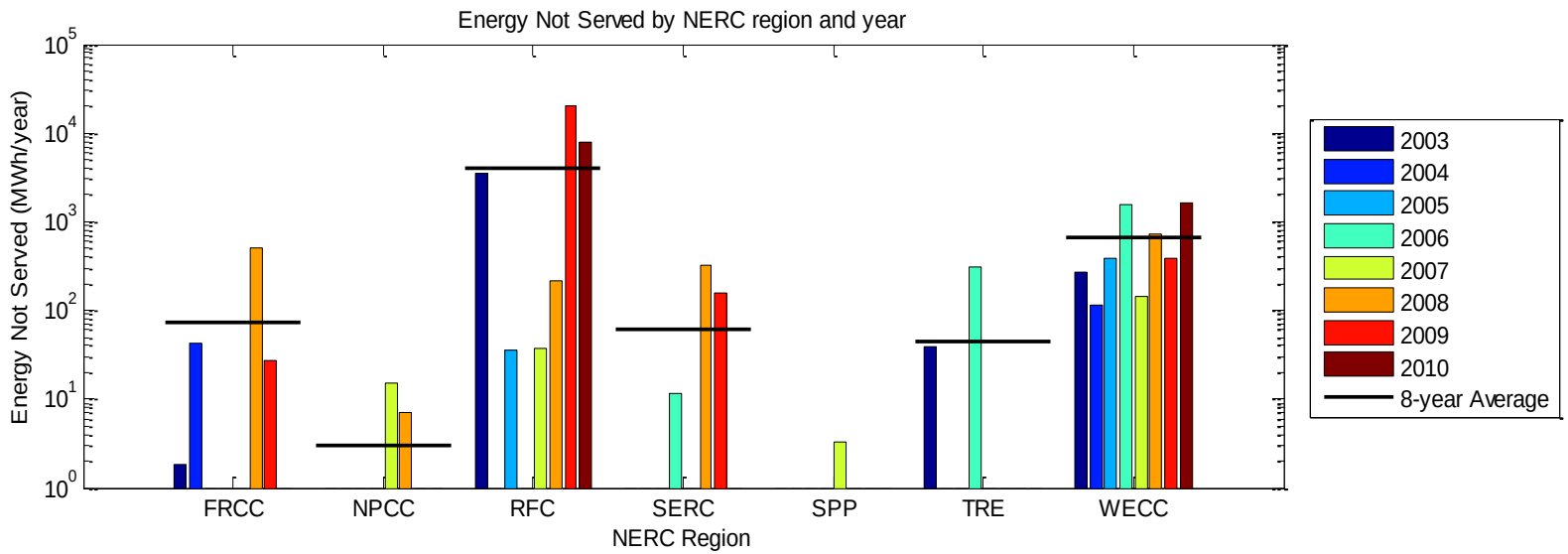
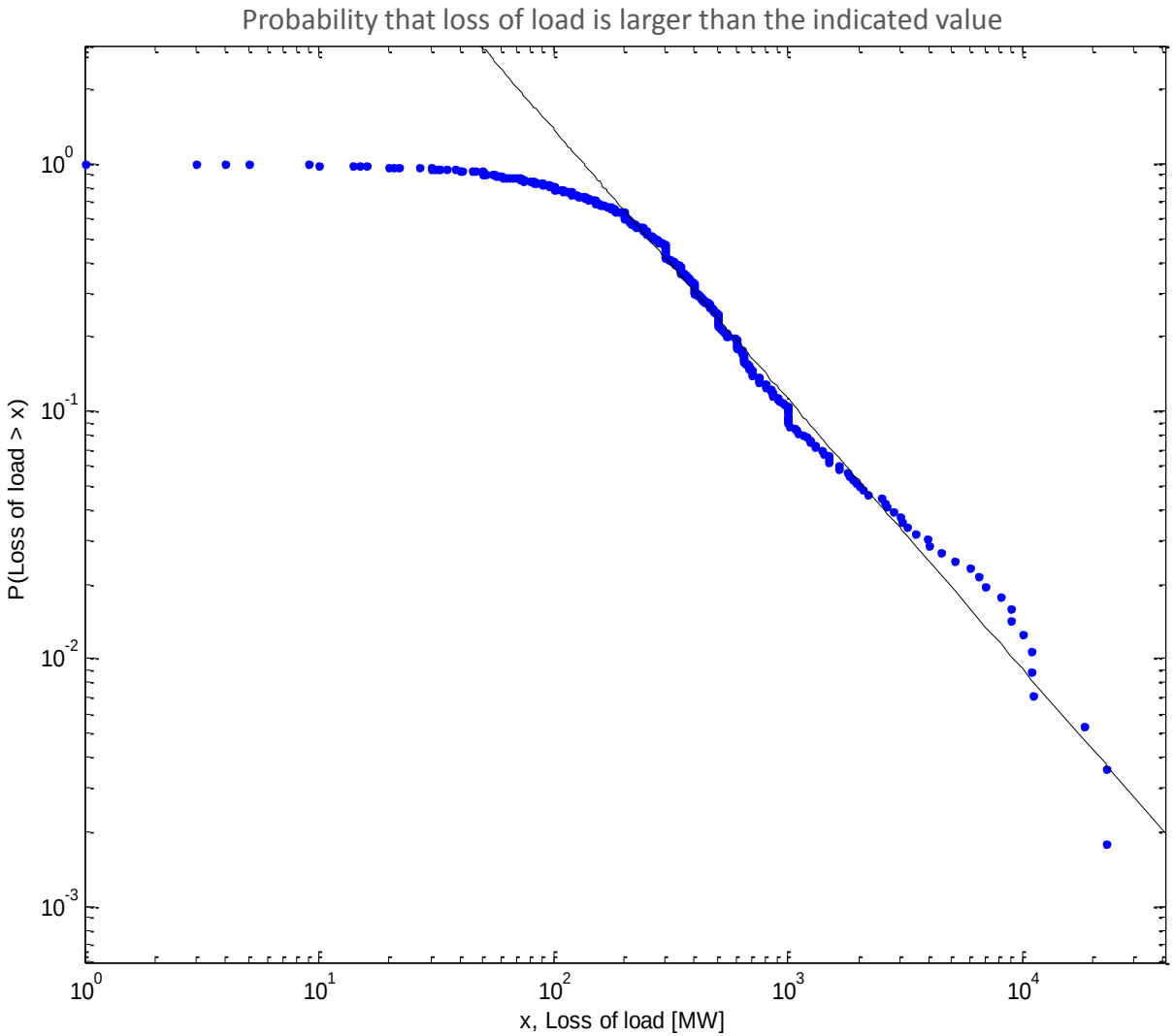


Extreme Events appear to follow a power law distribution

- Data: All continental U.S. events with MW losses of load reported from mid-2003 through mid-2011 through OE-417
- The tail appears to follow a power law distribution
- Confirms the findings of a number of studies that there is non-negligible probability in the tails of the distribution. The distribution in heavy-tailed



Conclusions

- The available historical data may not be comprehensive enough to accurately evaluate all reliability indices

- Traditional reliability indices cover the effects of a fraction of total events – this may suggest expanding the theory

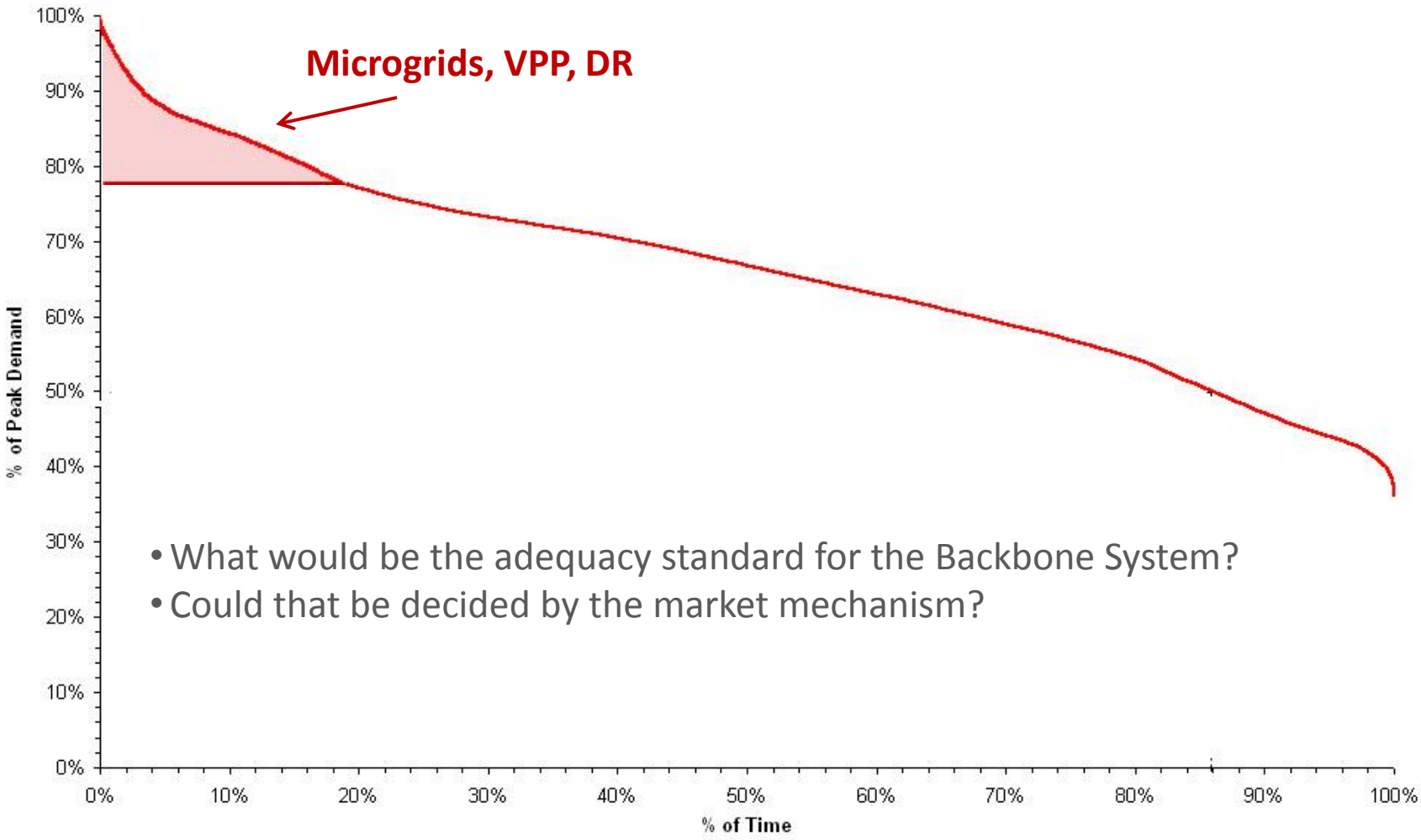
- Major power system events may follow a power law distribution

Reliability Standards

- Are we compliant?
  - Not enough statistics and evidence to answer
- What do our standards mean?
- What happens if they are relaxed?

New system challenges suggest expanding the framework of traditional reliability theory

Reliability

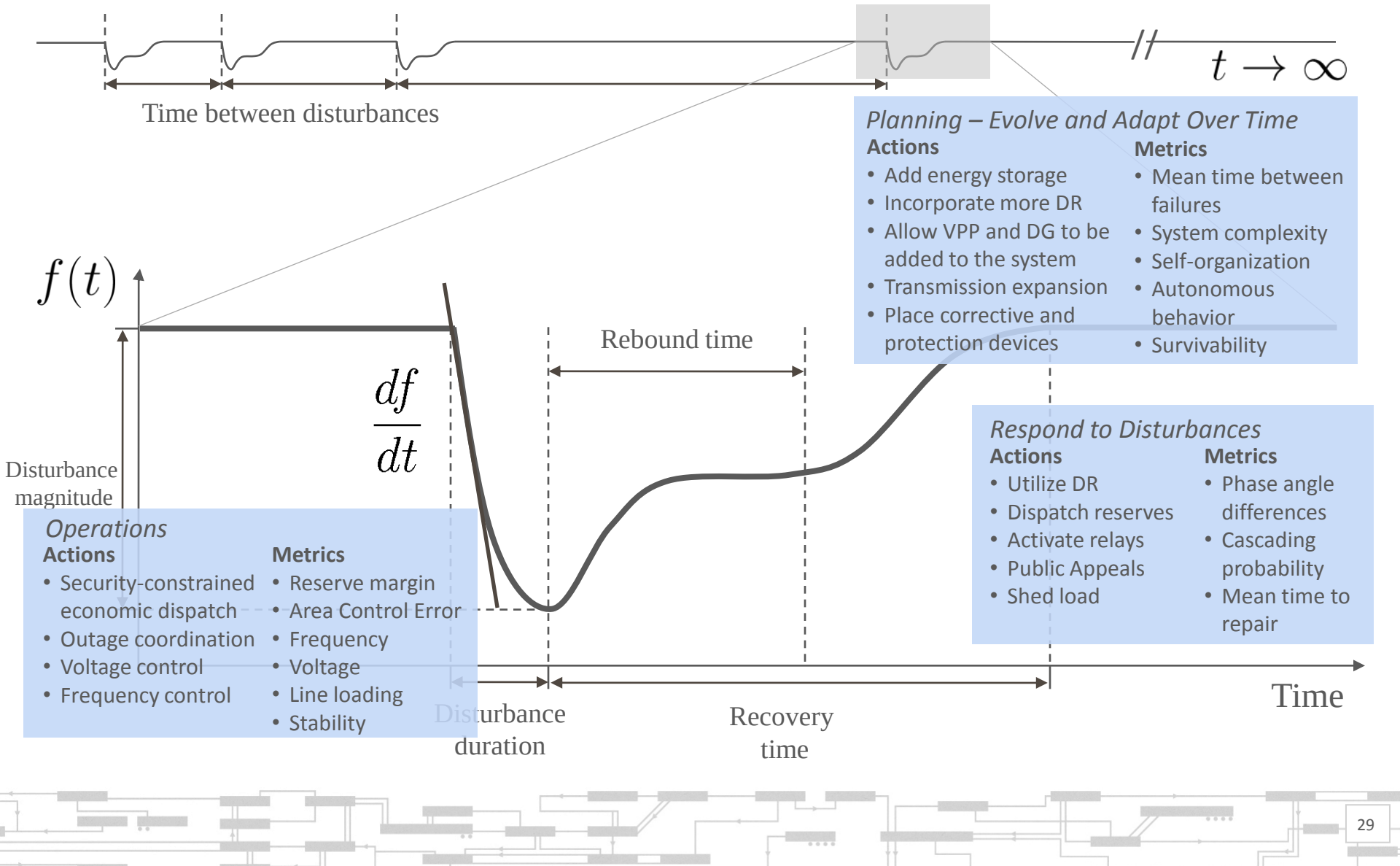


- What would be the adequacy standard for the Backbone System?
- Could that be decided by the market mechanism?

Survivability

- New technologies will lead to emergent behavior – not necessarily positive
  - Self-Organized Criticality: Blackout cannot be avoided by tightening the current reliability criteria
- Concepts of survivability, resilience and robustness
  - Survivability is an *emergent property* of a system – desired system-wide properties "emerge" from local actions and distributed cooperation
  - The realization of a survivable system will rely on advanced detection, control and coordination techniques
  - How do you effectively model, simulate, and visualize survivability?

Survivability



Planning – Evolve and Adapt Over Time

Actions
- Add energy storage
- Incorporate more DR
- Allow VPP and DG to be added to the system
- Transmission expansion
- Place corrective and protection devices

Metrics
- Mean time between failures
- System complexity
- Self-organization
- Autonomous behavior
- Survivability

Respond to Disturbances

Actions
- Utilize DR
- Dispatch reserves
- Activate relays
- Public Appeals
- Shed load

Metrics
- Phase angle differences
- Cascading probability
- Mean time to repair

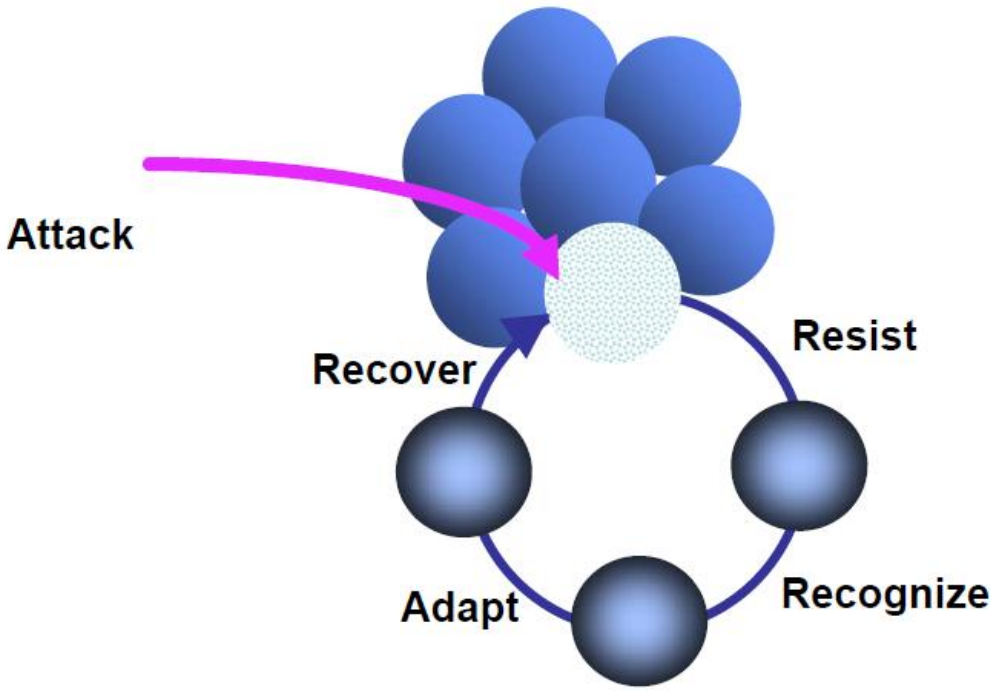
Operations

Actions
- Security-constrained economic dispatch
- Outage coordination
- Voltage control
- Frequency control

Metrics
- Reserve margin
- Area Control Error
- Frequency
- Voltage
- Line loading
- Stability

Survivability

- The ability of the system to continuously provide energy to the customers in the presence of a failure or attack on the system



© 2000, 2001 by Carnegie Mellon University

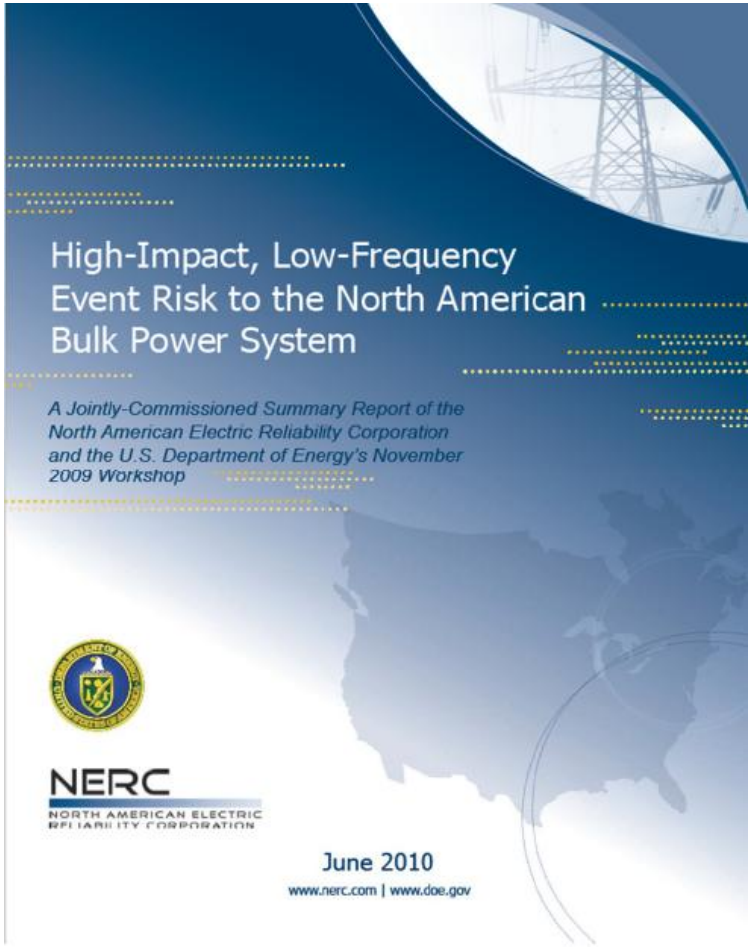
Survivability

- Four properties of survivability:
  - Resistance to attack – system design, short term planning
  - Recognition of intrusion – local and wide-area monitoring
  - Recovery of essential or full service after attack – protection, emergency control, SPS/RAS, WASIP, reconfiguration
  - Adaptation/evolution to reduce effect of future attacks – cognitive systems
- Why is it so difficult to define the metrics for survivability? Rare but high impact events!

High Impact Low Frequency Report

- NERC/DOE report June 2010
- Based on the results of the HILF workshop

http://www.nerc.com/files/HILF.pdf



Survivability Characteristics

Survivability

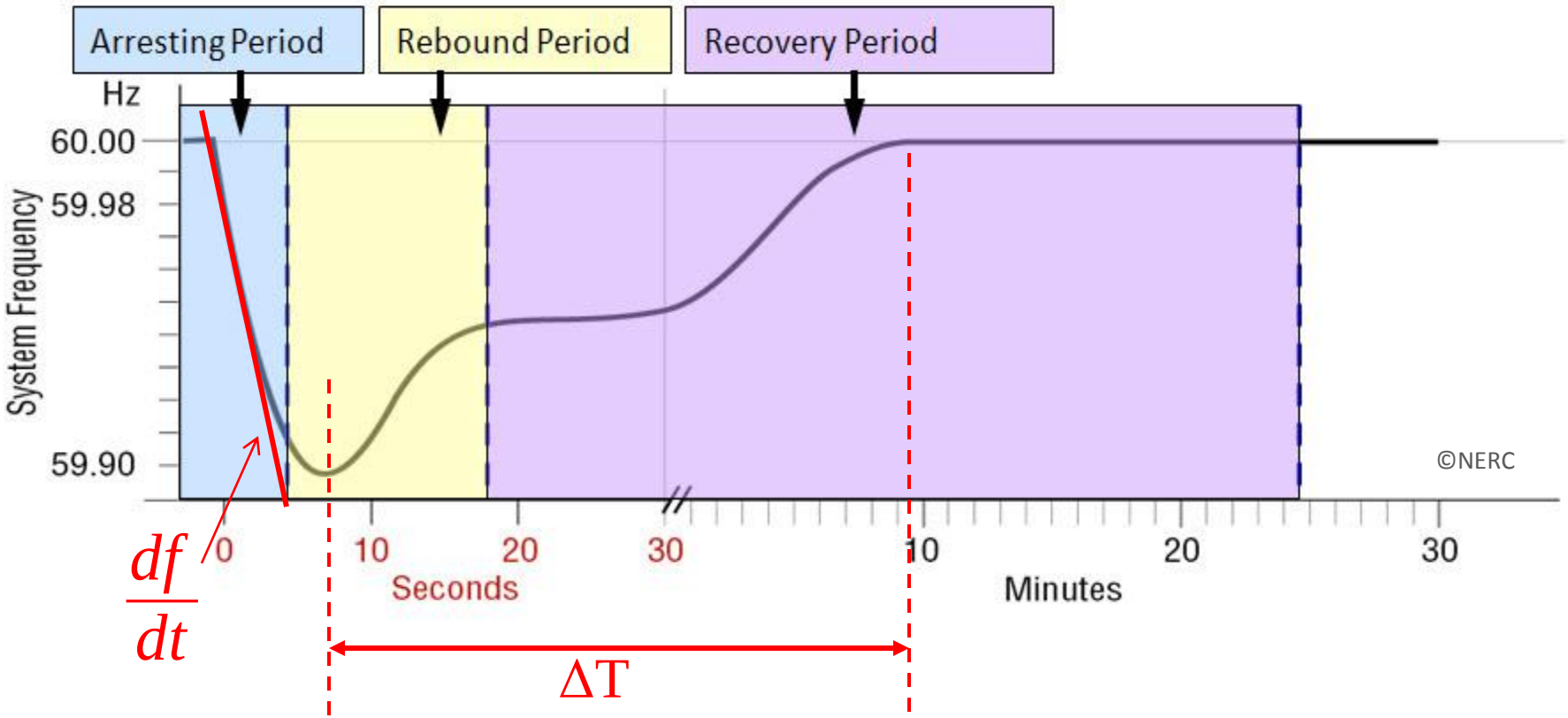
	Disturbance prevention & System operation far from critical points	Ensuring Quality of Service, Value-delivery, & Rapid Recovery
Normal Operation	Stability	Reliability
Endogenous Disturbances (e.g. component failures)		
Exogenous Disturbances (e.g. weather, physical attacks, etc.)	Robustness	Resilience

time

- Evolution & Adaptation
- Improved reliability, stability, robustness, and resilience
- New functionality
- Ensure beneficial complexity (Self-organization, autonomous behavior)
- Cooperation versus coordination

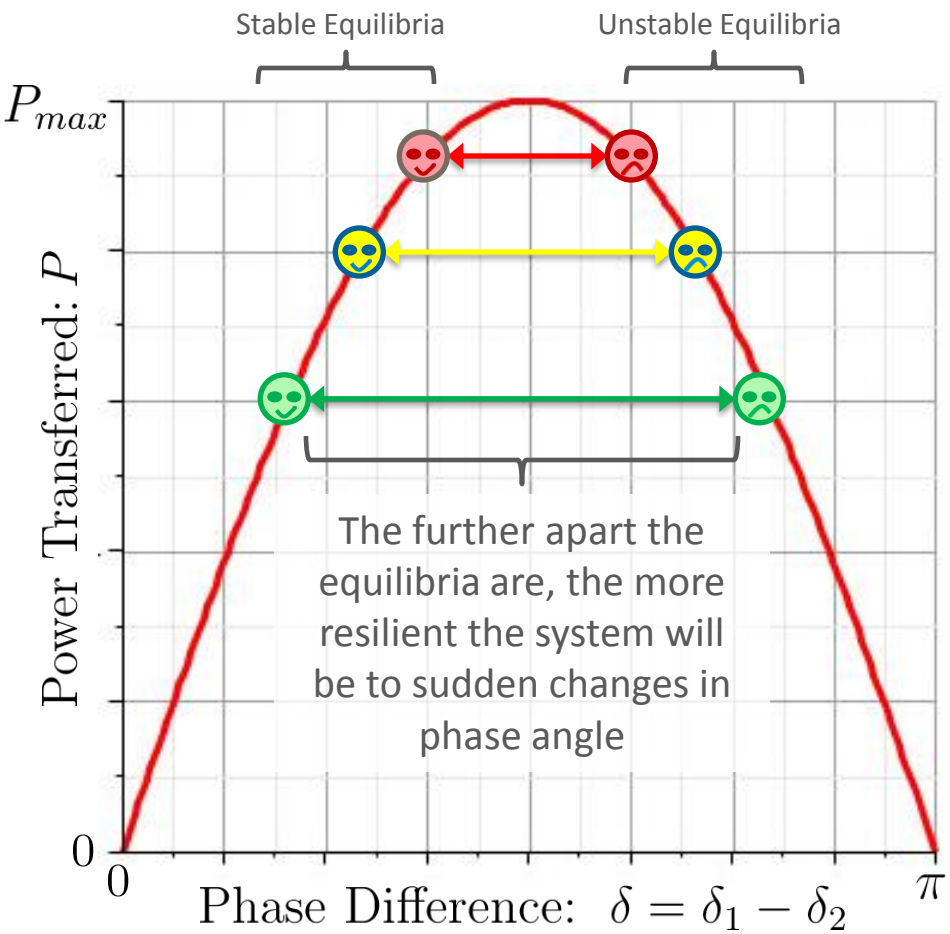
Survivability and Resilience: early detection and fast recovery

Survivability Metrics



During a disturbance, the rate of change of frequency and the time to recover may be used to measure survivability

Survivability Metrics (cont'd)



Flexibility (Motivation)

- The variability of renewable resources requires the system to have the ability to react to a sudden change of system condition and accommodate new state within acceptable time and cost tolerance.
- The importance of flexibility is well recognized, but there is lack of a unified framework for defining and evaluating flexibility.
- A single flexibility framework can
  - Serve as a basis for comparison of different power system designs.
  - Enable the integration of flexibility in the design of power systems

Literature Review

- In finance, flexibility can be reflected by liquidity, i.e. the degree to which assets can be converted to capital.
- In manufacturing system, flexibility represents the capability of manufacturing system to modify manufacturing resources to produce different products efficiently maintaining an acceptable quality. [Sethi et al, 1992]
- In information system, flexibility is the ability of the system to accommodate a certain amount of variation regarding the requirements of the supported business process [Applegate et al, 1999]

Literature Review: Flexibility in Power System

- A flexible plan is the one that enables the utility to quickly and inexpensively change the system's configuration or operation in response to varying market and regulatory conditions. [Hobbs et al, 1994]
- Flexibility is the ability of a system to deploy its resources to respond to changes in the demand not served by variable generation. [Lannoye et al, 2011]
  - They suggest reliability criteria to assess flexibility of a system, similar to the LOLE for capacity adequacy.
- Flexibility is the potential for capacity to be deployed within a certain timeframe. [Bouffard et al, 2011]
  - They associate flexibility with reserves.
- Flexibility is defined as the attitude of the transmission system to adapt, quickly and with limited cost, to every change, from the initial planning conditions. [Capasso et al, 2005]
- A flexibility index is borrowed from the process control literature, and is associated with reserves. [Menemenlis et al, 2011]

Definition of Flexibility

- Flexibility is the ability of a system to respond to a range of uncertain future states by taking an alternative course of actions within acceptable cost threshold and time window.
- Four elements are the determinants of flexibility
  - Response time window (T)
  - Set of corrective actions ($\boldsymbol{a}$)
  - Range of uncertainty ($\boldsymbol{u}$)
  - Response cost threshold ($\bar{C}$)

Target Range of Uncertain State Deviation

- The first step in accounting for flexibility is to define and clarify the target range of uncertain state deviation.
- A system aims to accommodate the uncertainty within the target range.
- For example, while a system is flexible with respect to the N-1 criterion, it may not be flexible with respect to the N-2 criterion.

Response Time Window

- Indicate how fast the system is expected to react to state deviations and restore the system to normal states.
- Short/Long time windows focus on the short-term/long-term flexibility of a system.
- A system may show more flexibility in long term while lacking flexibility in short term.

Set of Corrective Actions

- It represents the corrective actions that can be taken within the response time window under certain operating procedure.

	Control Actions						
Time	AGC	Economic Dispatch	Unit Commitment	Voltage Control	Interchange Scheduling	Short-term Outage Coordination	Long-term Outage Coordination
4 Sec							
5 Min							
1 Hr							
Day							
Month							

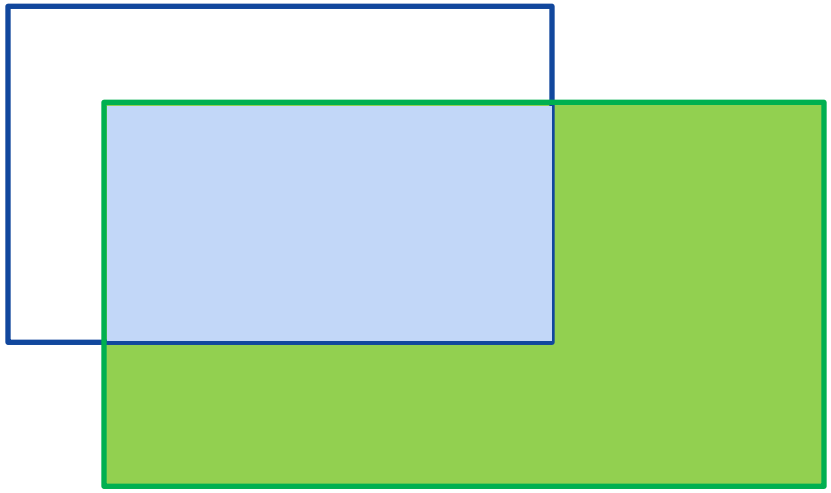
Other Related Complementary Concepts

- *Flexibility*: Ability of the system to be modified to do jobs NOT originally included in the requirement.
- *Robustness*: Ability of the system to do its job in unexpected environments.
- *Adaptability*: Ability of the system to be modified to do jobs in expected environments.
- *Reliability*: Probability that the system will do the job it was asked to do.

FLEXIBILITY METRIC

- Flexibility metric is defined as the following

$$Fledex = \frac{\text{The size of the largest range of uncertainty the system can sustain within the target range}}{\text{The size of the target range of uncertainty}}$$



The largest range of uncertainty the system can sustain

The largest range of uncertainty the system can sustain within the target range

The target range of uncertainty

The Range of Uncertainty

- For each time interval t within the response time window T, the range of uncertainty is assumed to be a hypercube

$$\mathcal{U}_t = \left\{ s_t \in \mathbb{R}^n \mid s_t^{LB} \leq s_t \leq s_t^{UB} \right\}$$

- The target range of uncertainty

$$\mathcal{U}_t^{\text{target}} = \left\{ s_t \in \mathbb{R}^n \mid \underline{s}_t^{LB} \leq s_t \leq \overline{s}_t^{UB} \right\}$$

Formulation of the Largest Range of Uncertainty Problem

$$\max_{s^{LB}, s^{UB}, a(\bullet)} \sum_{t=1}^{T} e^T (s_t^{UB} - s_t^{LB})$$ → Find the largest range of uncertainty $\mathcal{U}_t^{\max}$

$$\text{s.t.} \quad A_t a_t(s) + B_t s_t \le b_t, \quad \forall s_t \in [s_t^{LB}, s_t^{UB}], \ \forall t = 1, \ldots, T$$ → Corrective action

$$c_t^T a_t(s) \le \bar{C}_t, \quad \forall s_t \in [s_t^{LB}, s_t^{UB}], \ \forall t = 1, \ldots, T$$ → Response cost threshold

$$\underline{s}_t^{LB} \le s_t^{LB} \le s_t^{UB} \le \bar{s}_t^{UB}, \quad \forall t = 1, \ldots, T$$ → Limitation on the range

Size of the largest range of uncertainty $\mathcal{U}_t^{\max}$ at time t:

$$s_t^{\max} = e^T (s_t^{UB} - s_t^{LB})$$

→ $Fledex_t = s_t^{\max} / s_t^{\text{target}}$

Size of the target range of uncertainty $\mathcal{U}_t^{\text{target}}$ at time t:

$$s_t^{\text{target}} = e^T (\bar{s}_t^{UB} - \underline{s}_t^{LB})$$

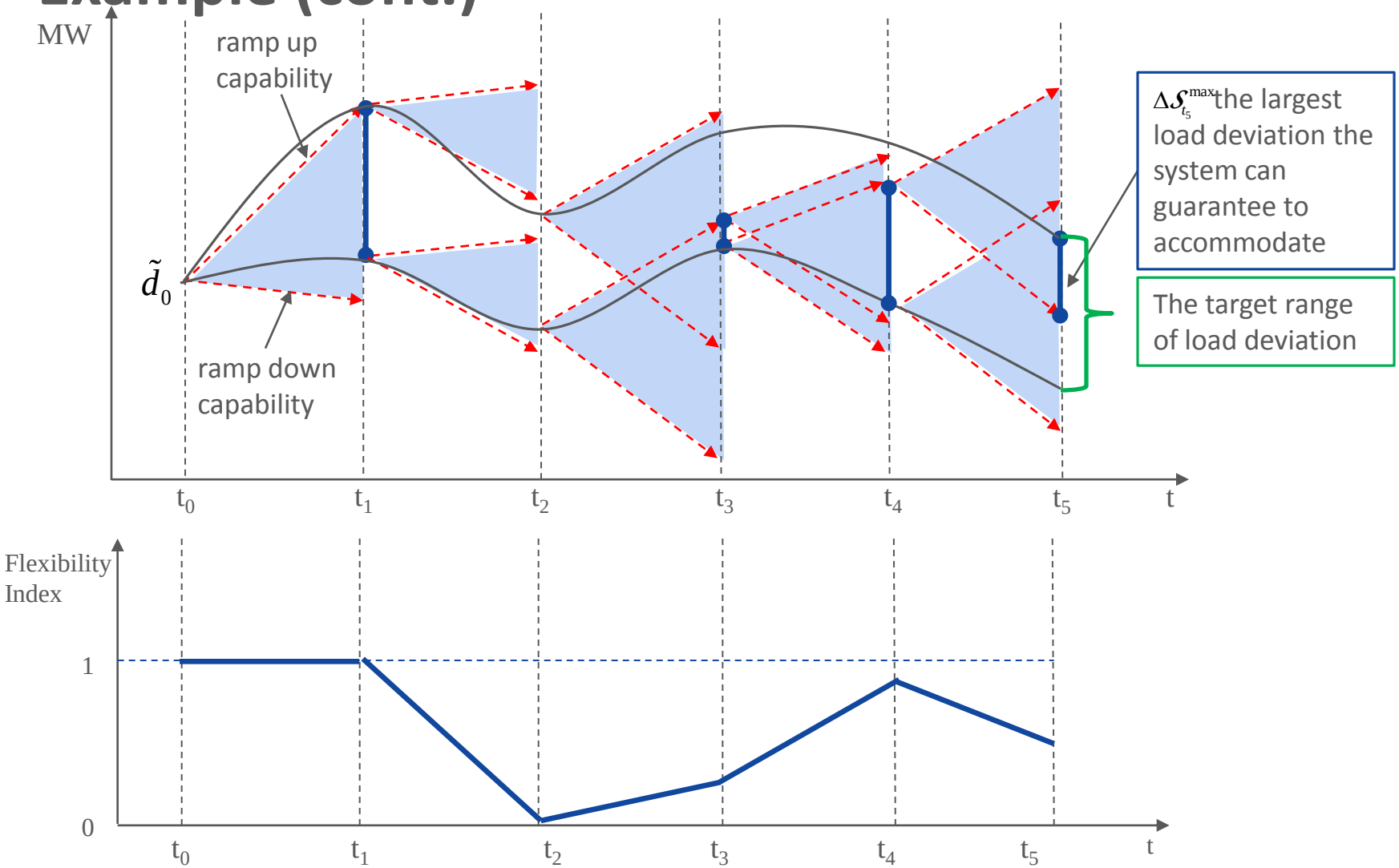
Not a Standard Robust Optimization Problem

- A standard robust optimization problem:
  - Given a range of uncertainty, would I be able to accommodate the worst case?
- Our problem:
  - Given what I can do, what is the largest range of uncertainty I can accommodate?

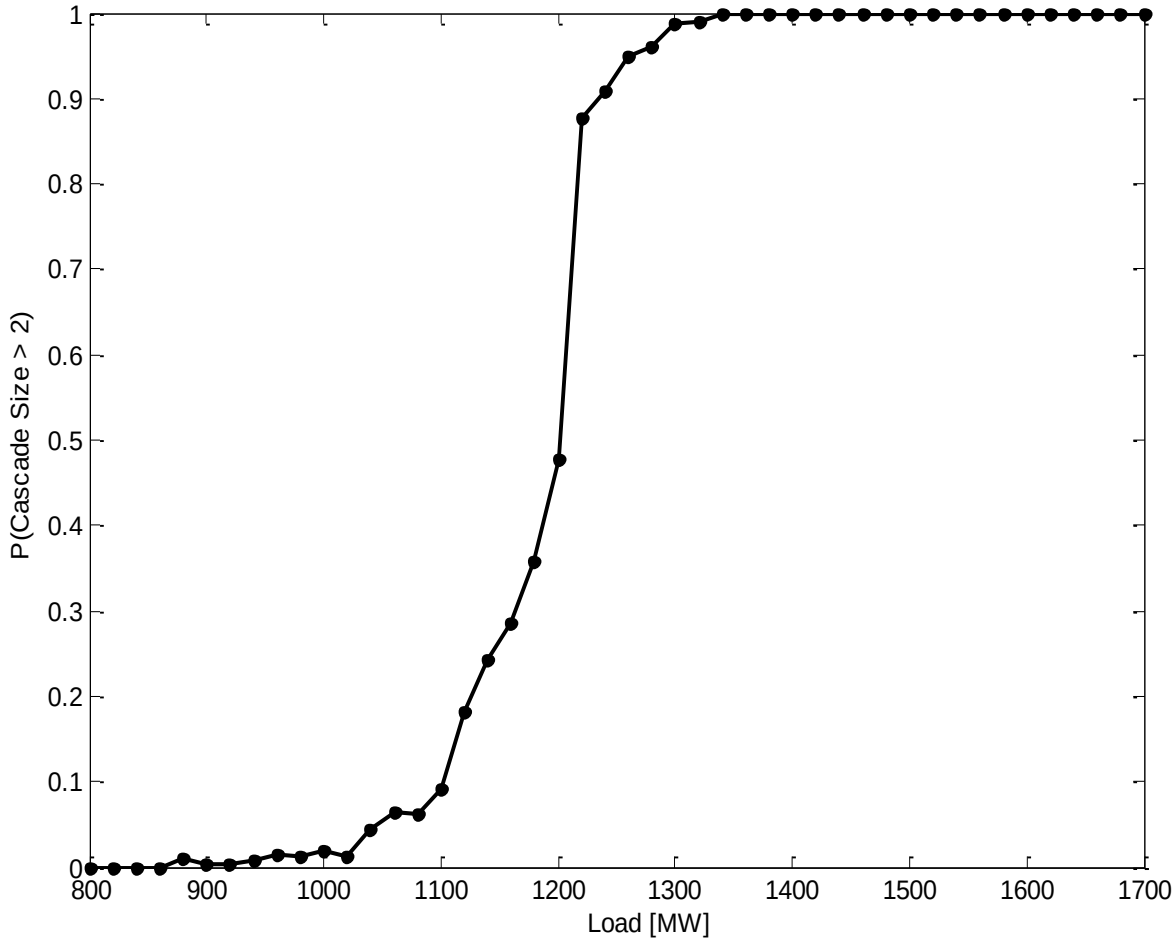
Example

- Do we have sufficient ramping capability to follow system load deviation?
- Use the flexibility index to reflect the possibility and magnitude of the ramping problem in the look-ahead horizon.
- Assumptions:
  - Response time window is 5 minutes
  - No cost threshold
  - Only consider re-dispatch as corrective action
  - Uncertain state deviation is a range of possible future load realizations in the load-ahead horizon
- No transmission constraints are modeled.

Example (cont.)



Probability of Cascading Failure Under System Stress



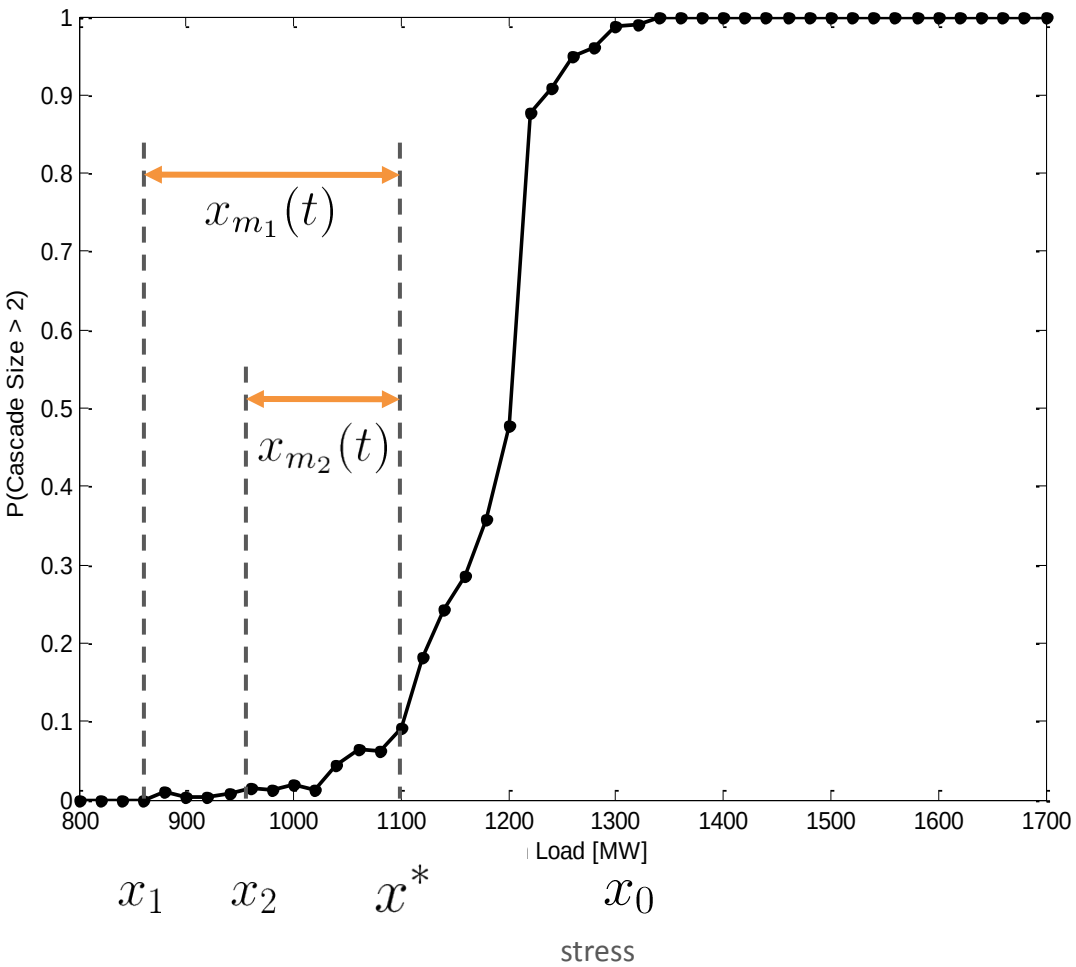
stress

The load (a measure of system stress) is varied from 800 MW to 1700 MW and the system is subjected to:

- Independent generator forced outages
  - FOR = 0.08 (NERC GADS)
- Independent line forced outages
  - FOR = 0.00434 (NERC TADS)

The ordinate is the probability of a cascade in excess of 2 lines (or a loss of load of 20% or more)

Metrics of system stress, resilience, and flexibility:
Flexibility Metric



$x(t)$ = system stress at time *t*

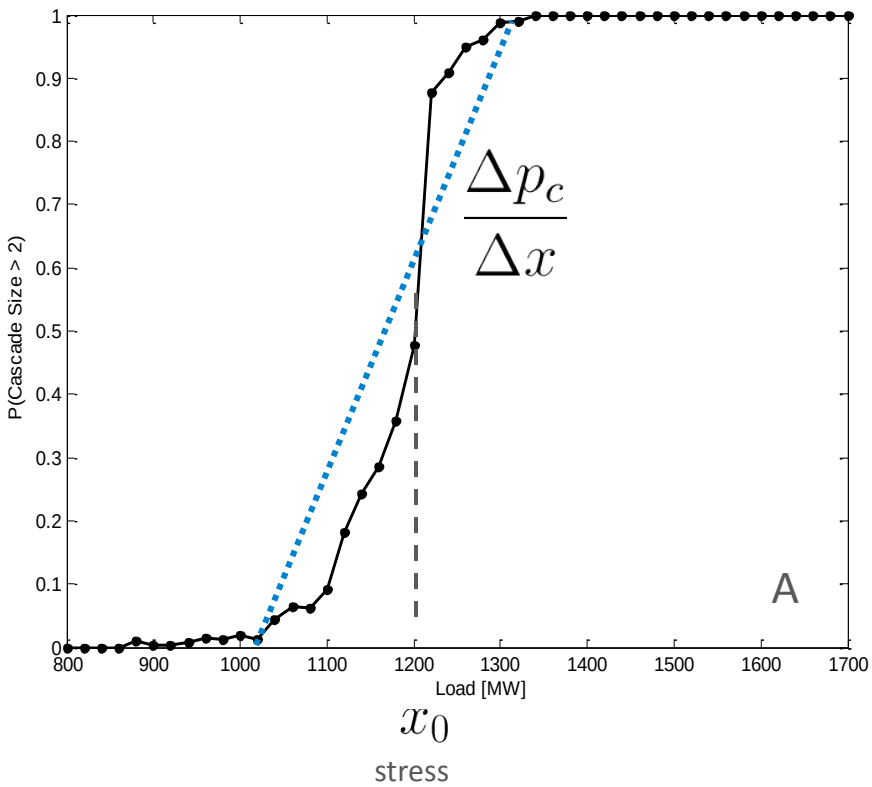
x^* = Phase change threshold for system stress

$x_m(t)$ = Stress margin at time *t*

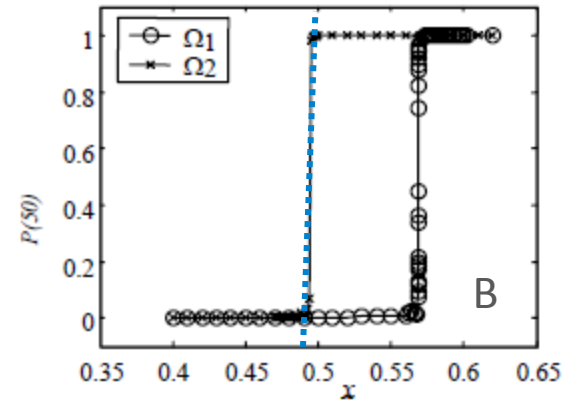
In this case, the system operating at x_1 has a greater margin to work with than x_2. The stress margin can be thought of as a metric of flexibility

Metrics of system stress, resilience, and flexibility

Resilience Metric



Compare the example, A, to the example from [1], B:



It should be clear that: $\xi_B > \xi_A$

Since the smaller the slope the more gracefully the system degrades, this metric can be thought of as a measure of system resilience

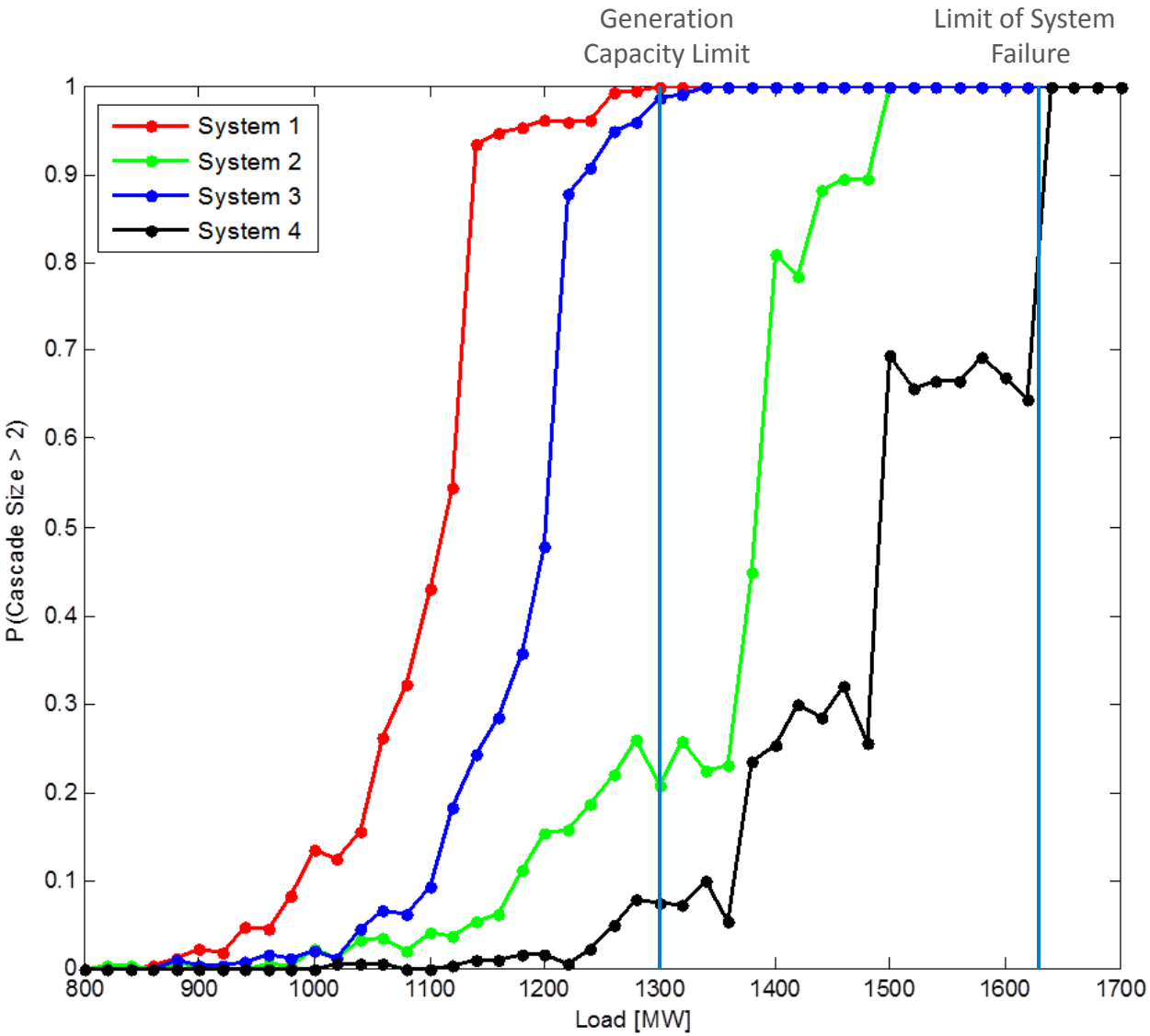
$p_c = P(C \geq c)$ = Probability of a cascade of size *c* or greater

$$\xi = \frac{\Delta p_c}{\Delta x}$$

= Rate of change in the cascade probability with respect to system stress

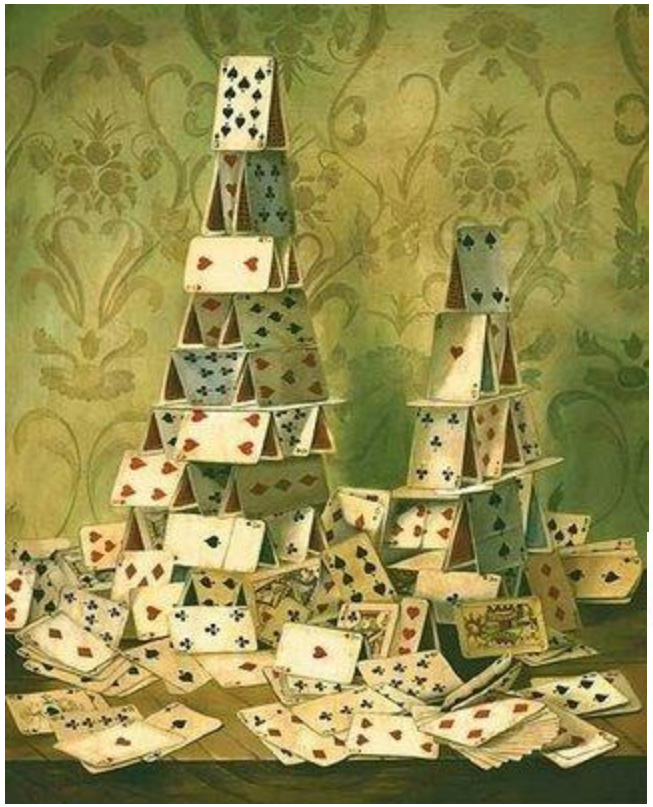
[1] Liao, Apt, and Talukdar, "Phase Transitions in the Probability of Cascading Failures," 2004.

Comparing Test Systems



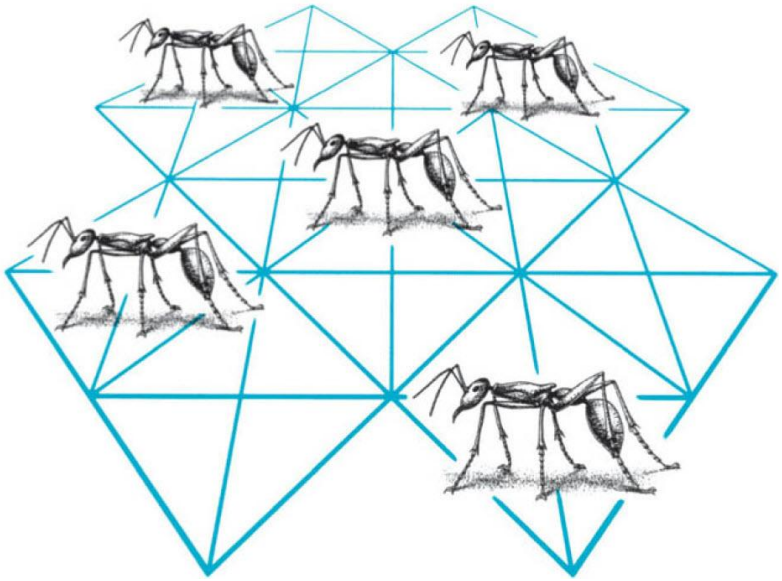
- Each of the systems were identical, except for the location of generators and loads
- Even with such similarity, each system has a substantially different cascade probability profile

System Complexity and Vulnerability



New Control Architecture

- Decentralized, loosely coupled system is more resilient
- Cooperation vs. Coordination among subsystems
- Methods and algorithms to support spontaneous ad-hoc cooperation between subsystems
- Complexity must be measured and controlled during design
- Corrective vs. Preventive control
- Wide-area SPS, RAS, SIP – not less reliable than DR



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Questions