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In Search of the Holy Grail of PMU Applications for Visualization and Prediction of Cascading Outages

Steve Lee

May 10, 2007

NASPI Meeting, Carson, California

Outline

- Prior EPRI results in search of the Holy Grail
  - structural degradation
  - system stress indices
- Hierarchical visualization for operators and engineers
- Proposed research project with PMU and EMS data with utility participation
- Where is the meat?

Prior EPRI research results on structural degradation, deterministic and probabilistic system stress indices

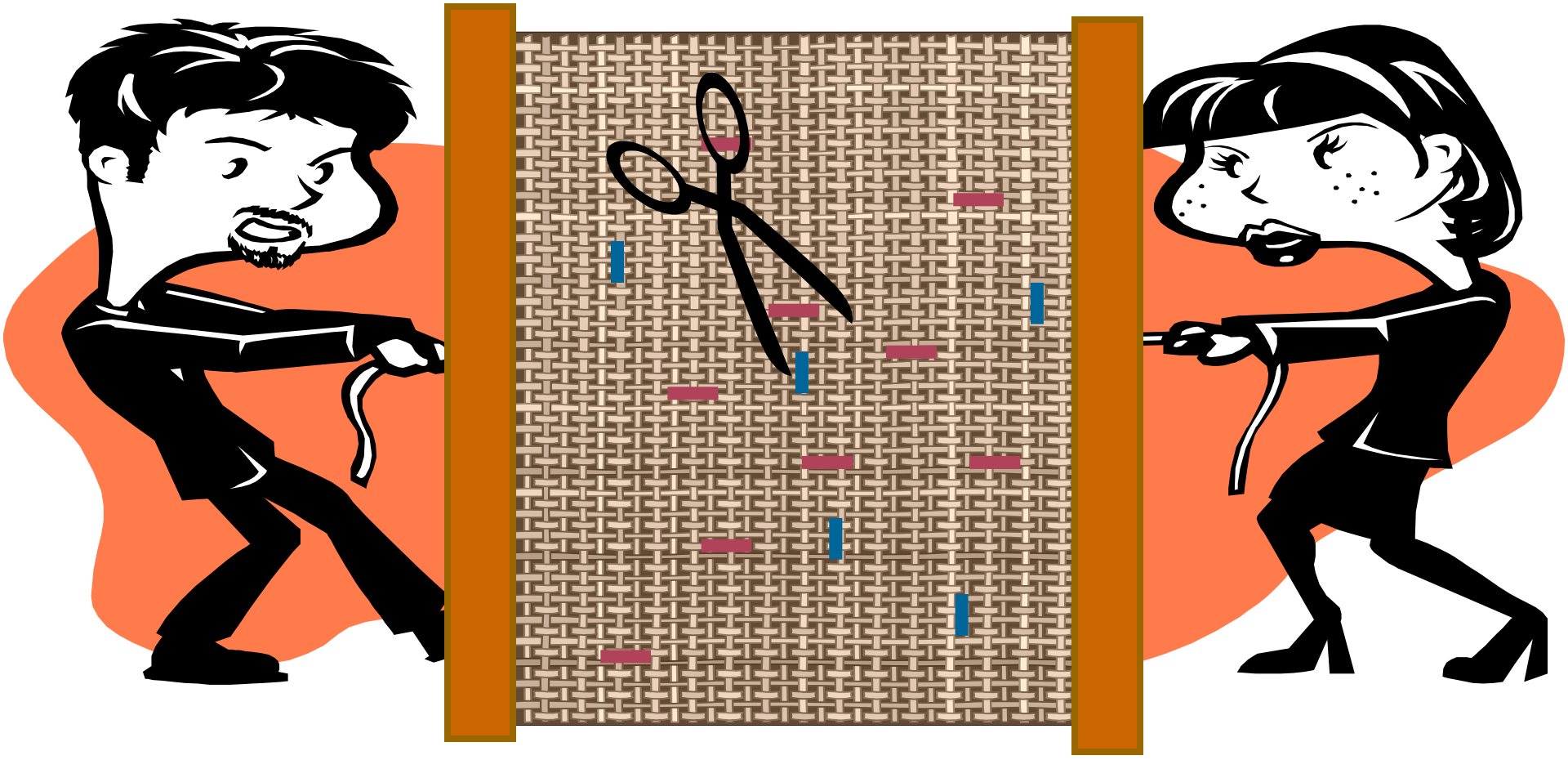
- Lots of Data but still in search of …
- Holy Grail – Extract succinct information - Diagnose and Advise
- The goal is not massive or impressive visualization
- But a “Predictive” Vulnerability Index that measures the risk of cascading outages
- Broader situational awareness about the most dangerous threats (contingencies)
- Factors leading to cascading outages:
  - Structural Degradation
    - Scheduled and unscheduled outages
  - System Stresses
    - Load level
    - MVA flows, MW losses, MVAR losses

Vulnerability Indices Research

- Structural Degradation: Cut-sets (Interface, Circular)
  - Continuous computation and monitoring
- System Stress Indices:
  - Measured:
    - Load levels,
    - MVA power flows (across cut-sets), system MW losses, system MVAR losses
    - voltages,
    - reserves (spinning & quick-start, dynamic & static reactive)
    - Frequency (oscillations)
  - Computed:
    - Thermal margins,
    - voltage stability margins,
    - transient stability margins
- Vulnerability Index:
  - Composite Index of All Above
  - Capability of Triggering Alarms for Operators/Engineers
  - Should have a probabilistic element to be sensitive and predictive

Testing the Strength of a Holely Fabric

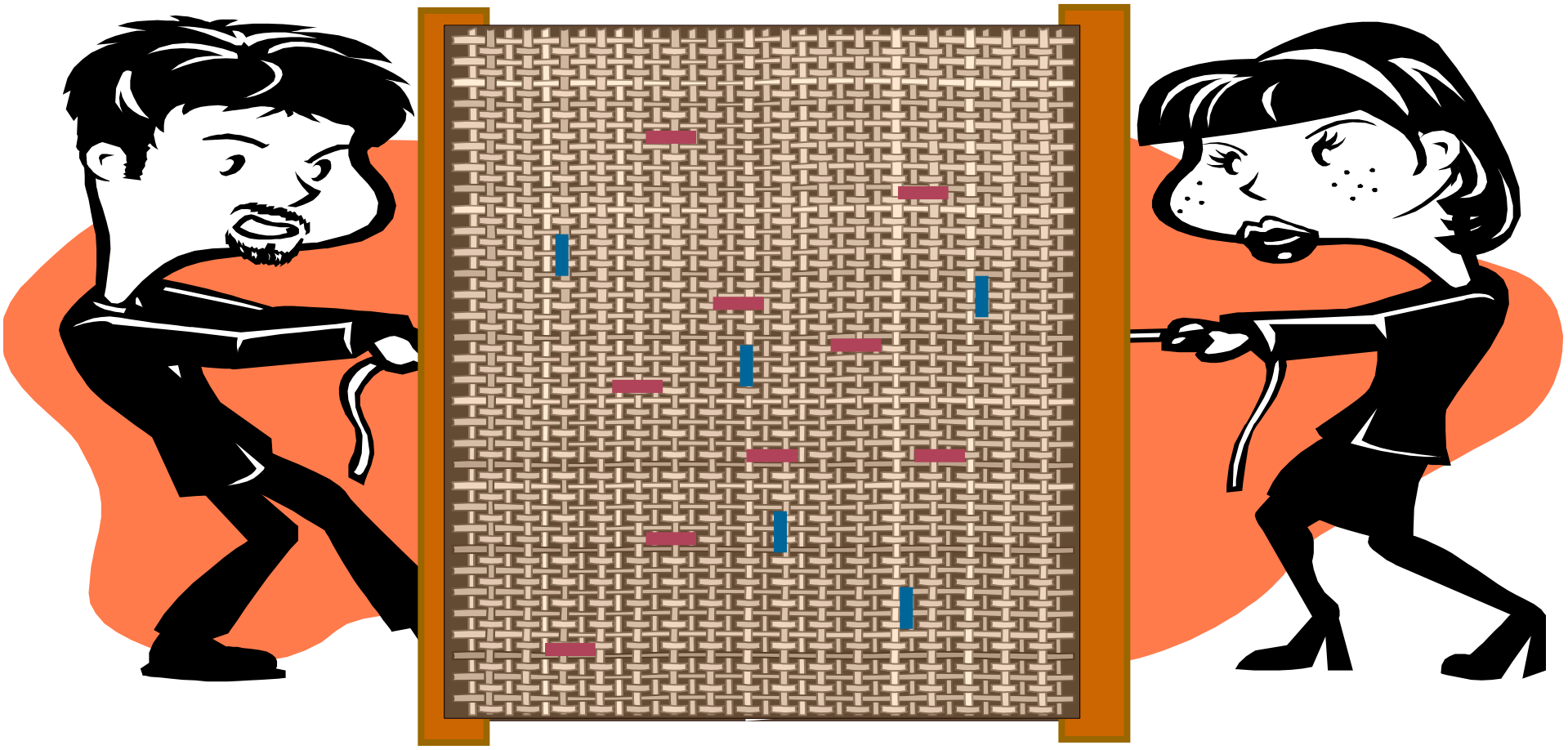
Pulling in the West-East Direction for Vulnerability to Higher W-E Transfer



Scheduled and forced line outages are like cuts on the fabric

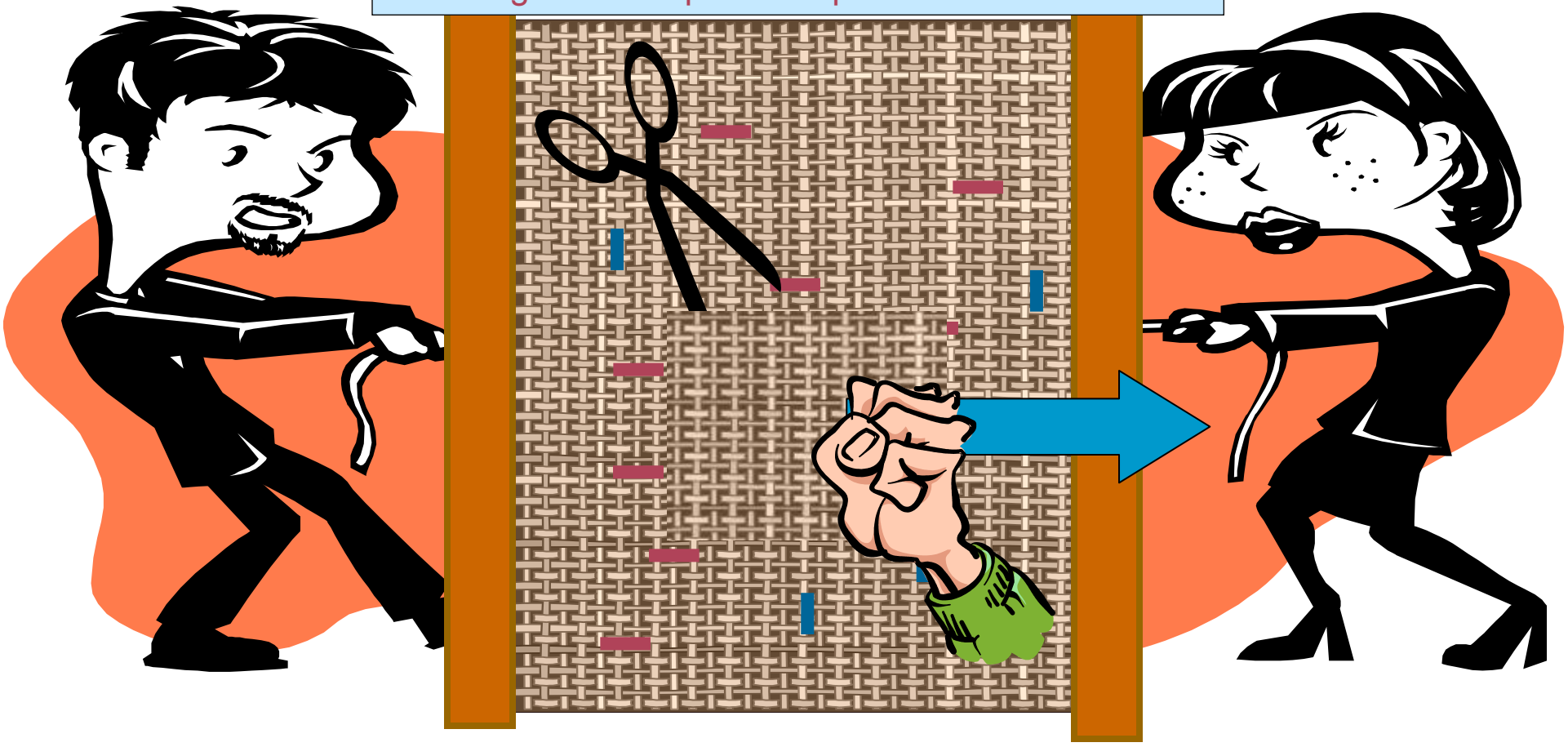
Testing the Strength of a Holely Fabric

Pulling in the West-East Direction for Vulnerability to Higher W-E Transfer

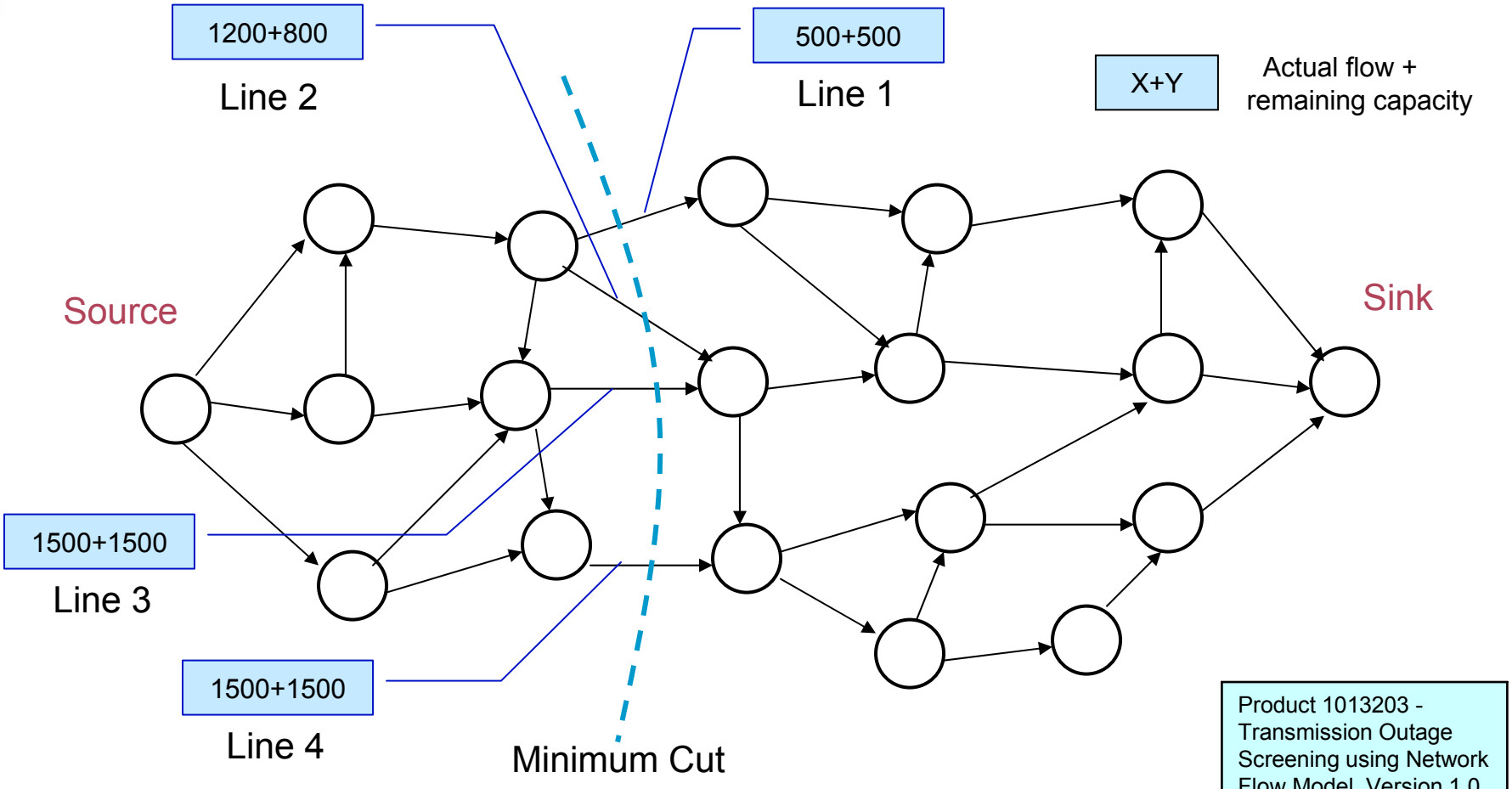


Testing the Strength of a Holely Fabric

Pulling at a location of the fabric tests vulnerability to
Higher net export or import in a local area



EPRI has developed software to determine Minimum Cut Set



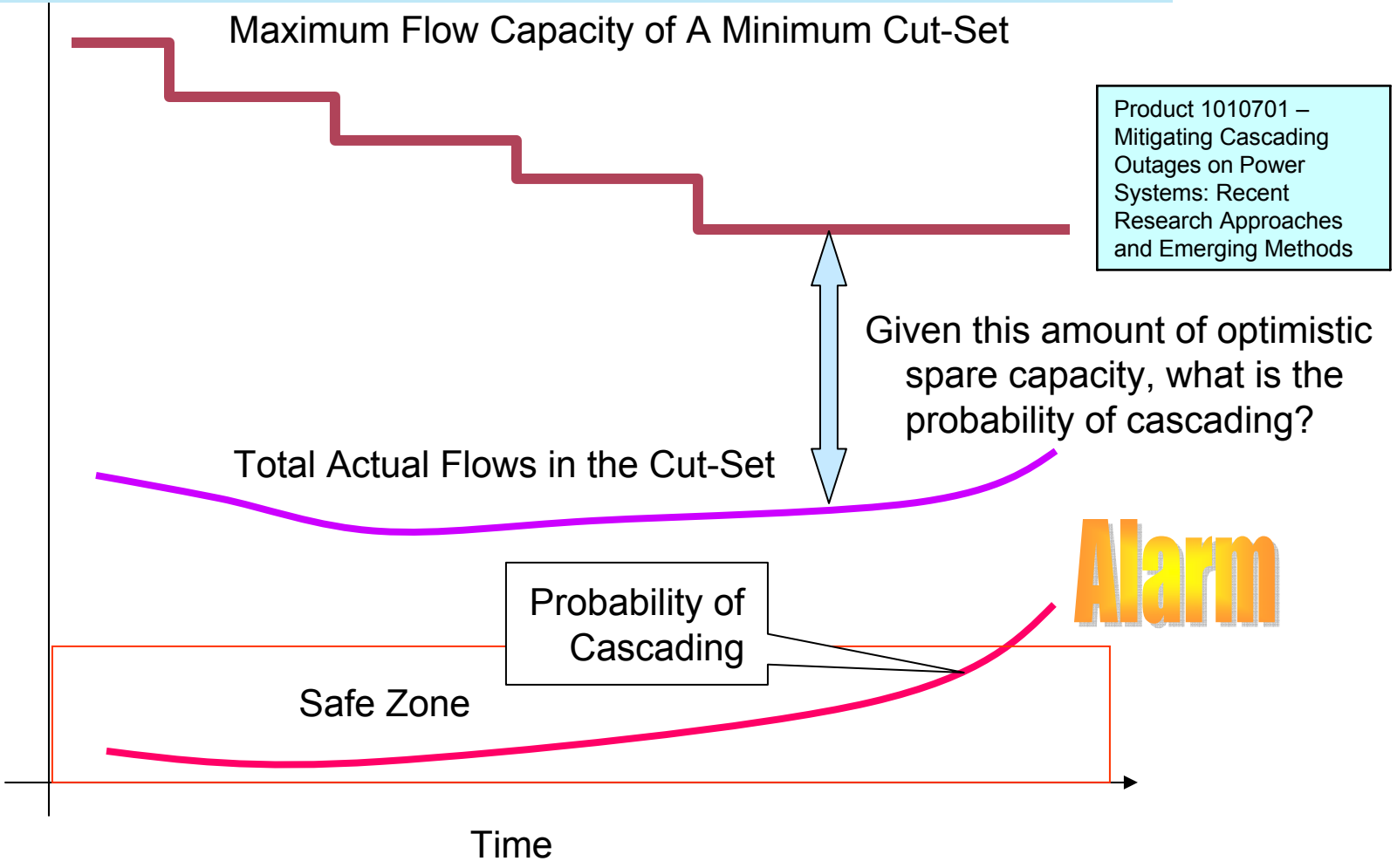
Incremental Max Transfer = 4300 = 800+500+1500+1500

Total actual flow = 4700 = 500+1200+1500+1500

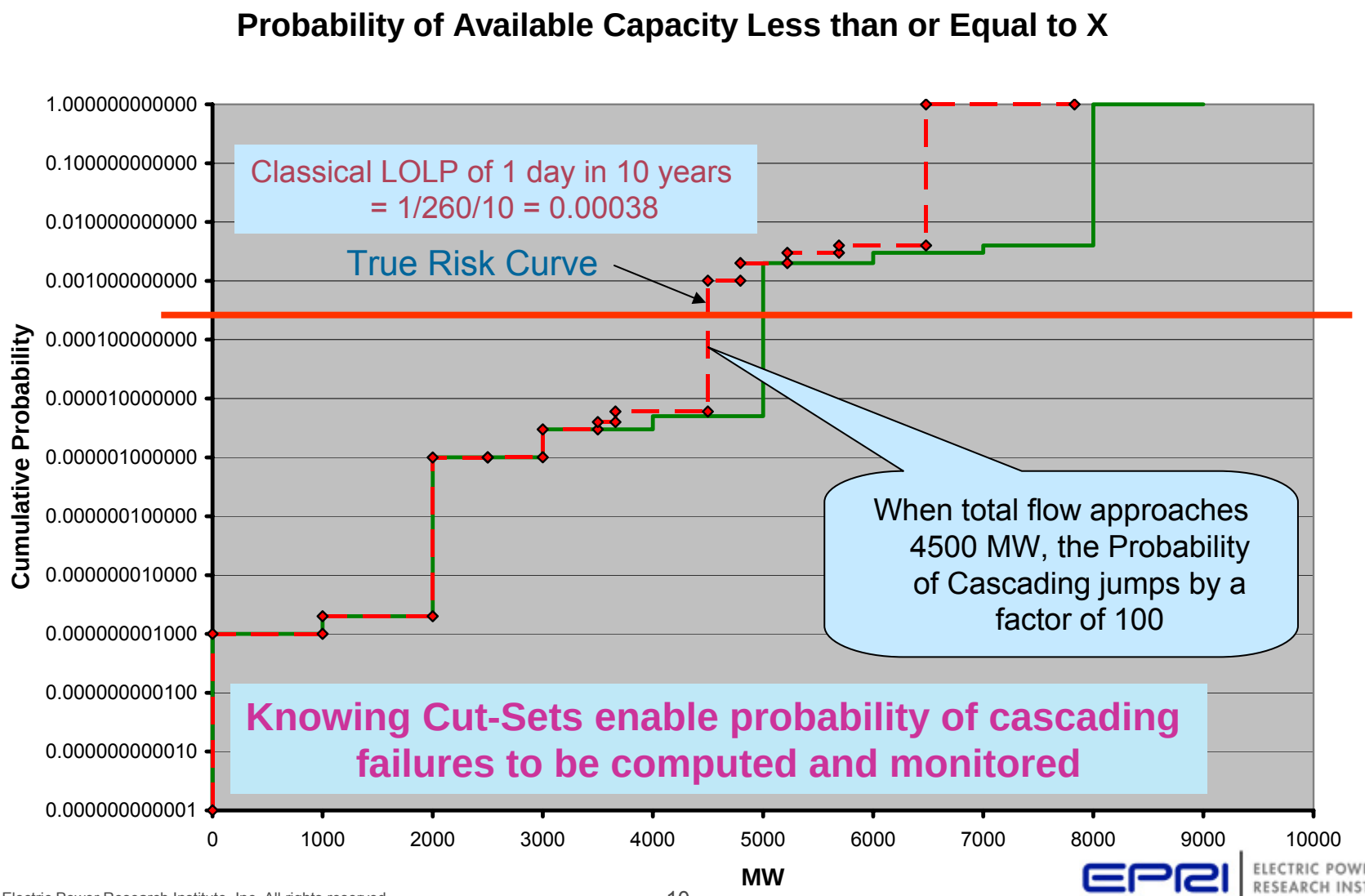
Total capacity = 9000 = 1000+2000+3000+3000

Stress Indicator

EPRI's research in Cut-Sets is a key to know the structural integrity or degradation of the power grid



Probabilistic Stress Indicator



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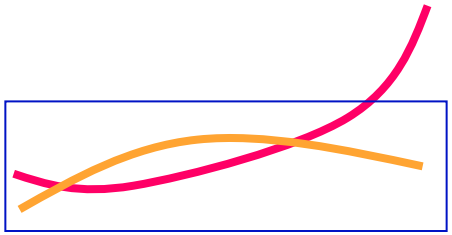
EPRI Technology Innovation Project: Predicting Cascading Outages (ongoing)

- "Smart logic" was used to divide a power system network into a number of groups (clusters) that are connected with other groups by "critical" lines (a circular cut-set), starting from generator sources
- If one or more of these "critical" lines is/are outaged, it can start cascading effect
- It takes ~ 1 min. to determine the "critical" circular cut-sets in an Eastern Interconnection case with 35,000 buses
- An algorithm can identify all initiating N-1 line outages which will result in "automatic" tripping of "overload protection relays" in multiple tiers, which then result in system collapse.
- Future work will identify critical circular cut-sets starting from load centers

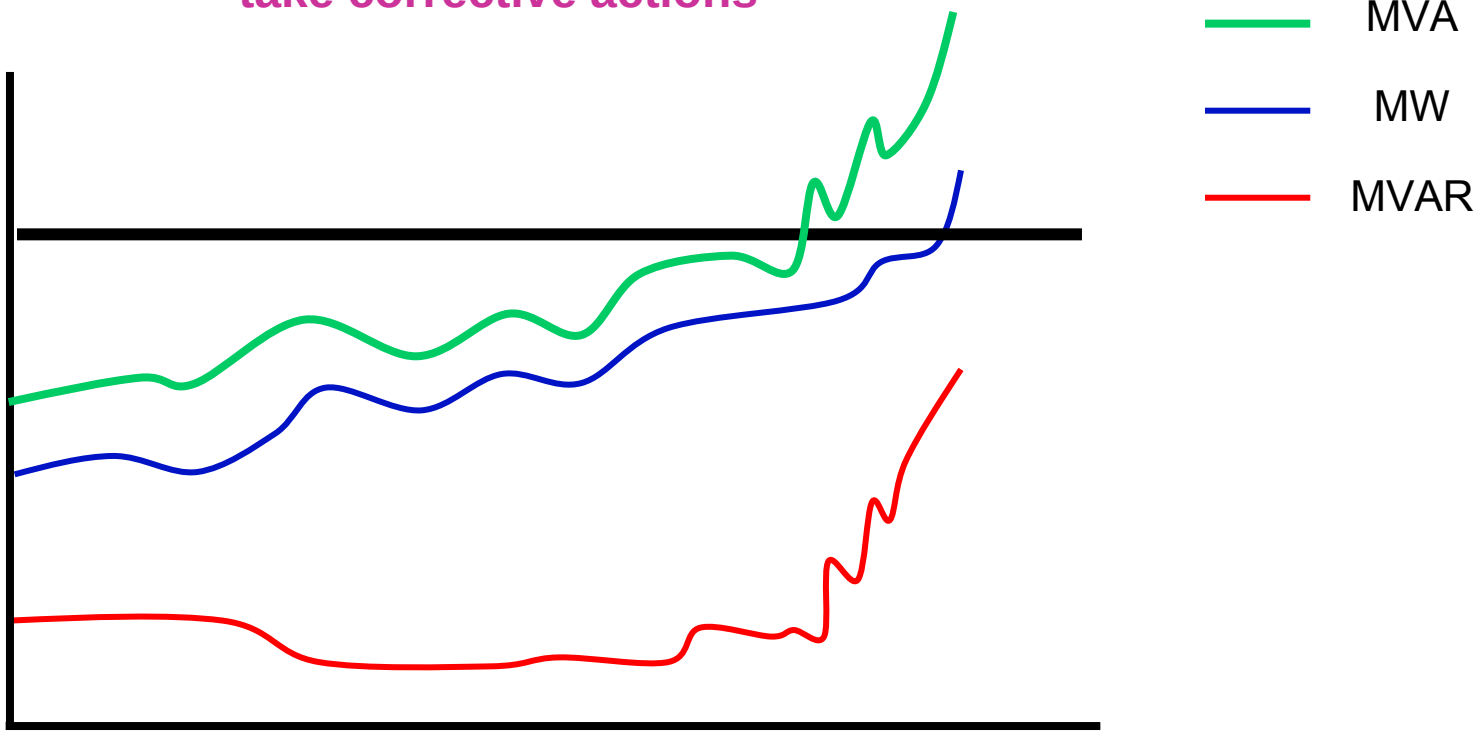
Implications

- For each State Estimator case, spend 1 minute of computer time to identify most dangerous threats
- EPRI project on Fast Fault Screening determined top 20 most severe fault locations for transient stability
- EPRI project on Potential Cascading Circuits (PCC) determined:
  - all sets of N-k contingencies that cascade after an initiating N-1, with probability not much smaller than an N-1 or N-2 contingency
  - rank them according to order of likelihood (even without knowing the outage rates)
  - Compute these indices of likelihoods and plot them over time (from SE to SE case) to warn operators



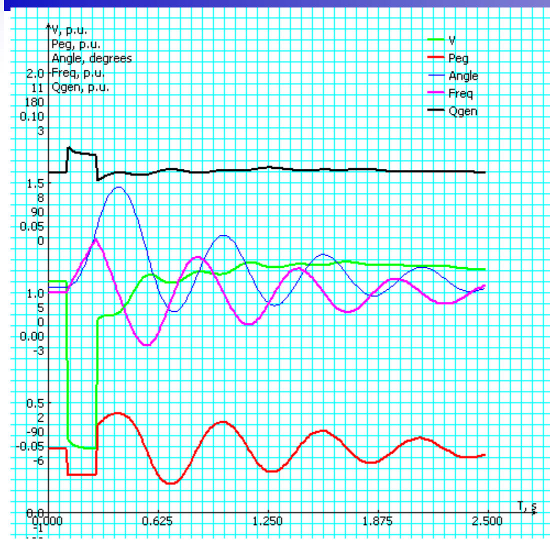
Reactive Power Flow is a Precursor

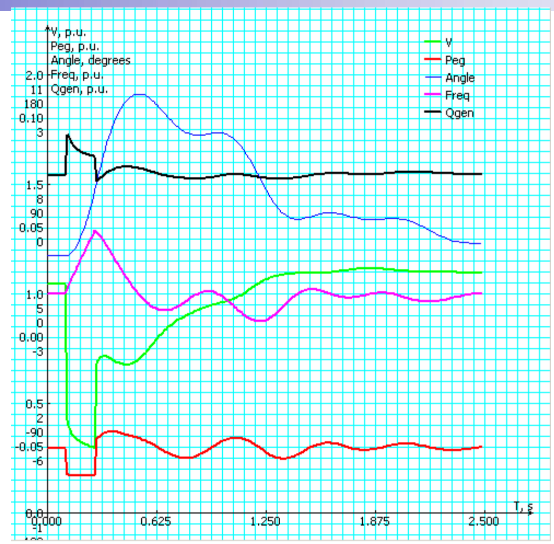
Precursors are valuable for warning operators with enough time to take corrective actions

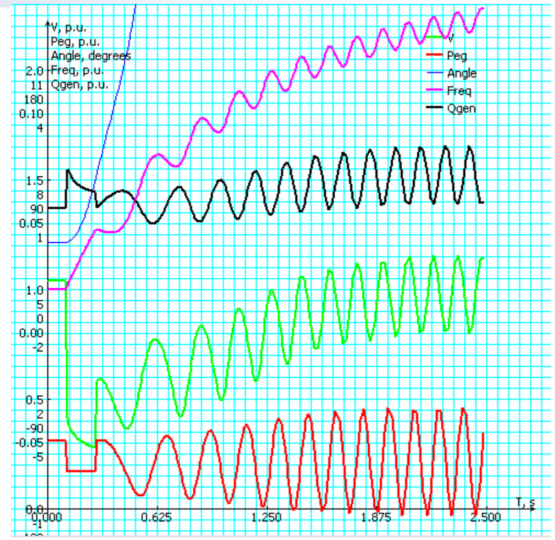


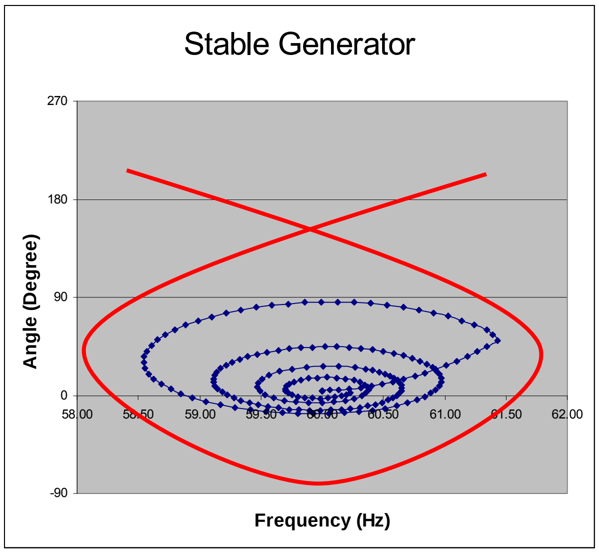
Time Period = 15 minutes

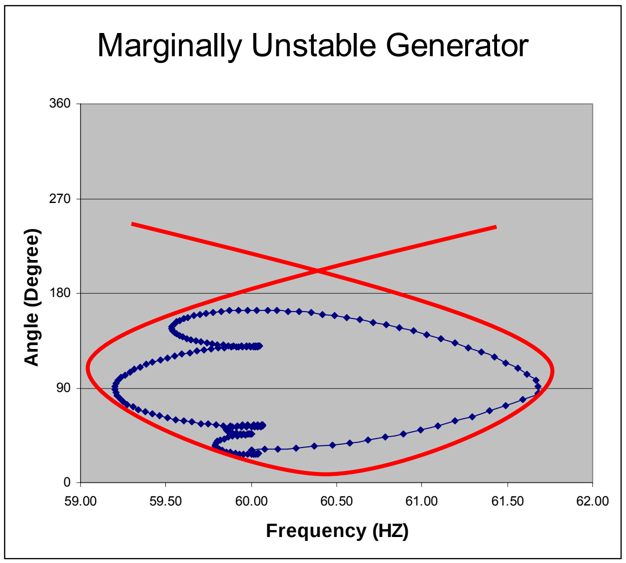
Visualization in Phase Space vs. Time Domain

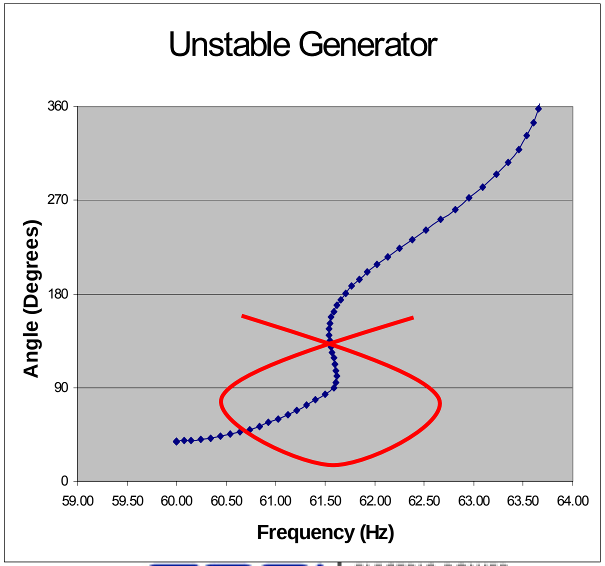












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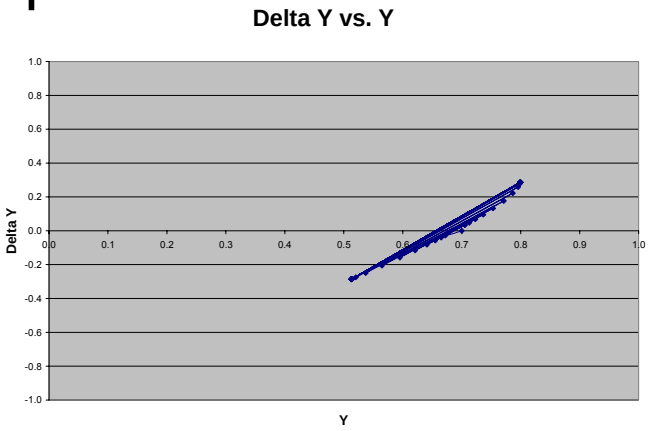
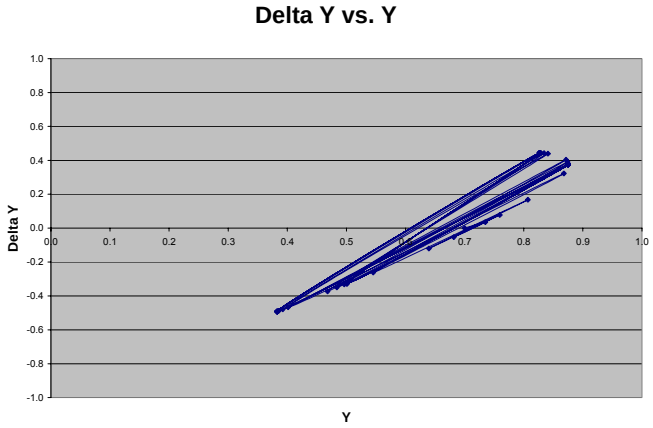
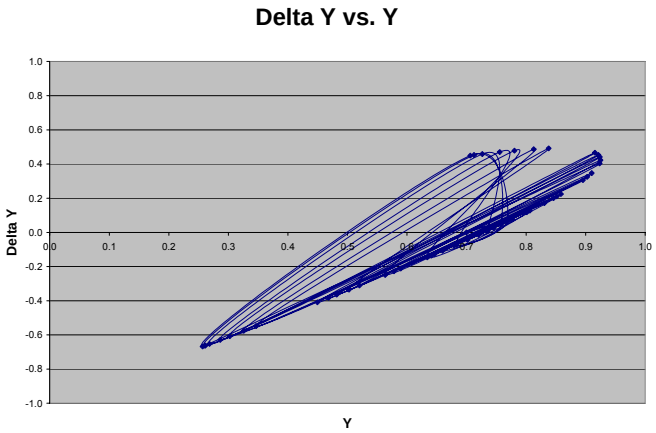
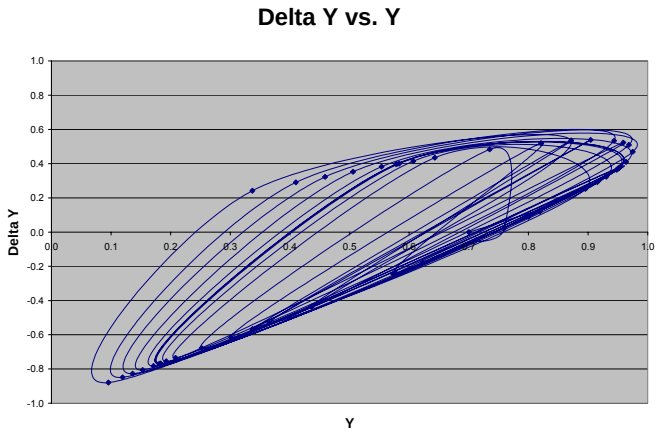
Phase Space May be Approximated

- A Delta Tool can be turned into approximate Phase Space

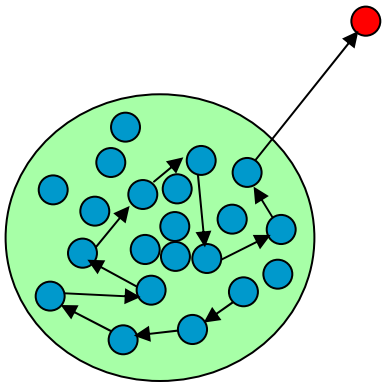






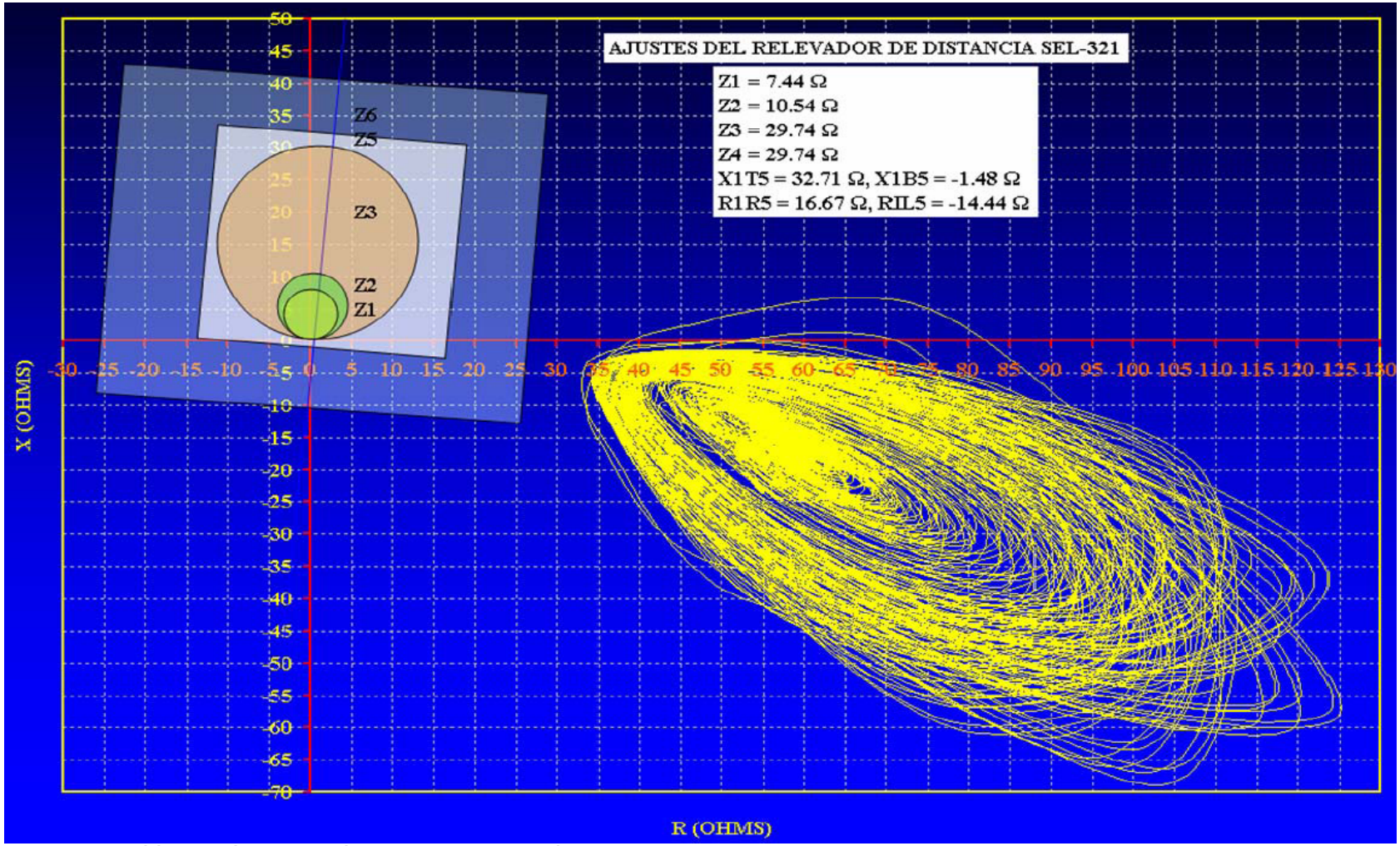


Cluster Analysis to Identify Precursors



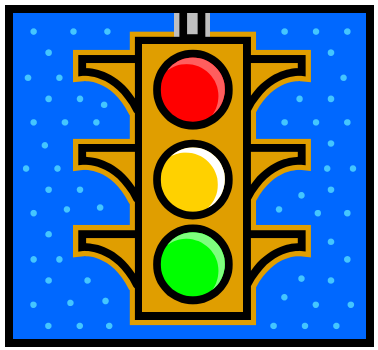
- A sudden departure from a recent cluster's neighborhood is an indication of some sudden abnormal events
- These cluster alarms are numerous and distributed
- Can be organized and diagnosed in a hierarchical framework

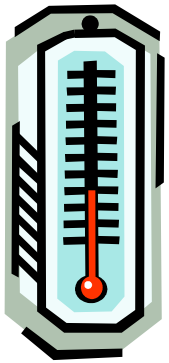
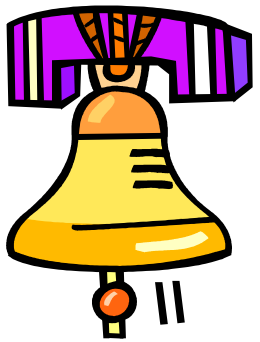
Visualization of Relay Protection as Precursor



Presented by Enrique Martinez M., CFE Mexico,
at EPRI/PG&E Protection and Control Workshop, March 1-2, 2007

Hierarchical Visualization for Operators and Engineers



- Operators want minimum and clearest information to get their attention:
  - Geographical awareness
  - Facilities awareness
  - Controllability awareness
  - Predictive awareness
- Operators want to know what to do with the information
  - Take remedial actions
  - Get more information from engineers
- Engineers want capability to drill into the depth of the analysis to diagnose unusual problems and recommend remedial actions

Hierarchical Visualization for Operators and Engineers

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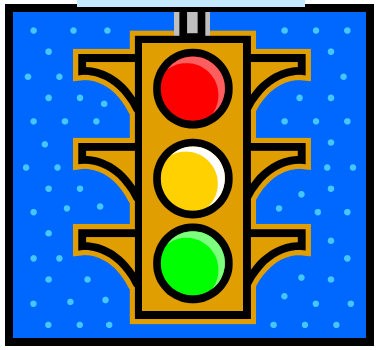
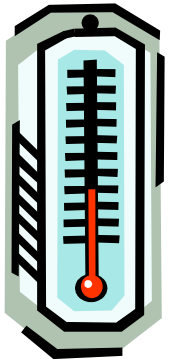
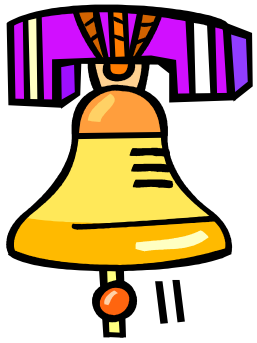


Type 1 - Overload

Type 2 – Frequency



Type 3 - Voltage



Type 4 - Stability

Alarm Indicators for Different Types of Problems

↓

Geographical Visualization of the Location of That Problem

↓

One-line Diagram Visualization of the Facilities with That Problem

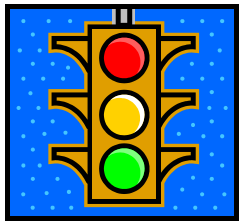
Wide Area Visualizations

Layers of Information

- Frequency
- Voltage
- Line Flows
- Reactive Reserve
- Etc.

Underlying Trend

Click here



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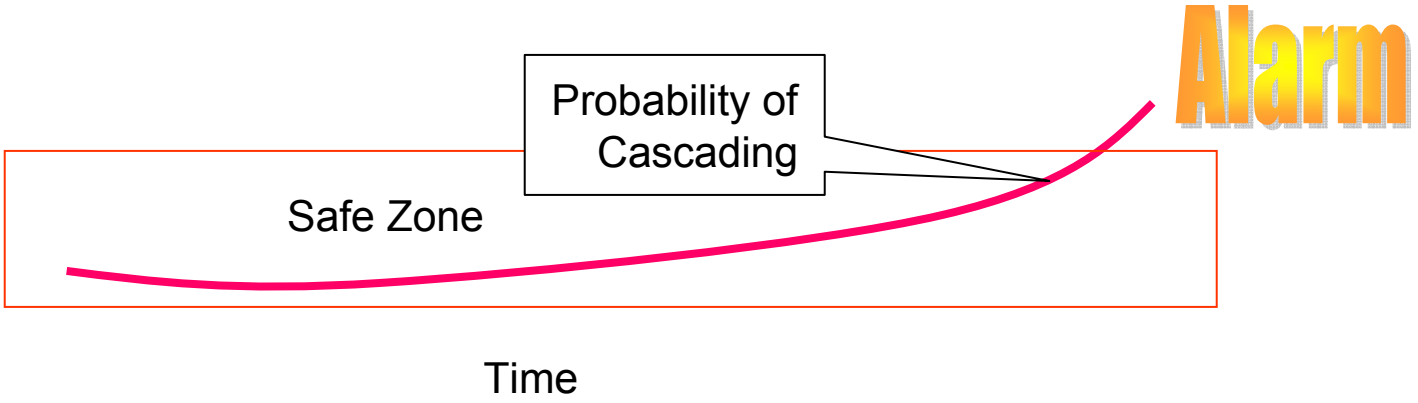
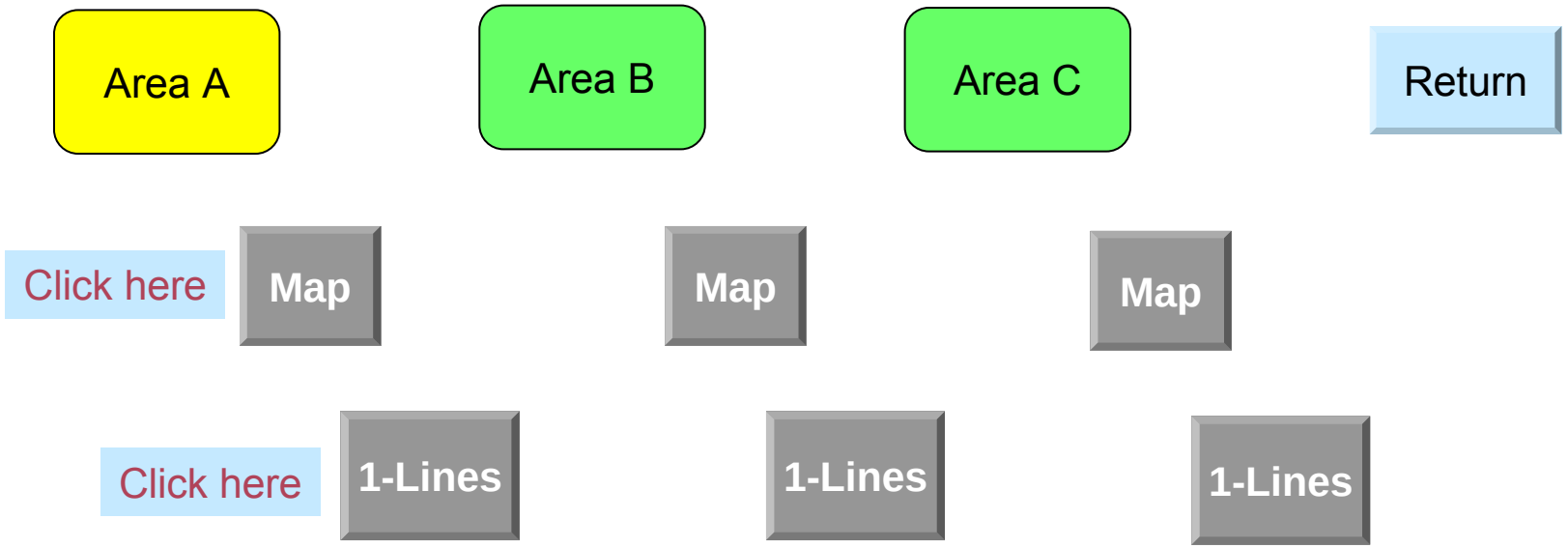


Geographical Areas



Geographical Visualization of the Location of That Problem

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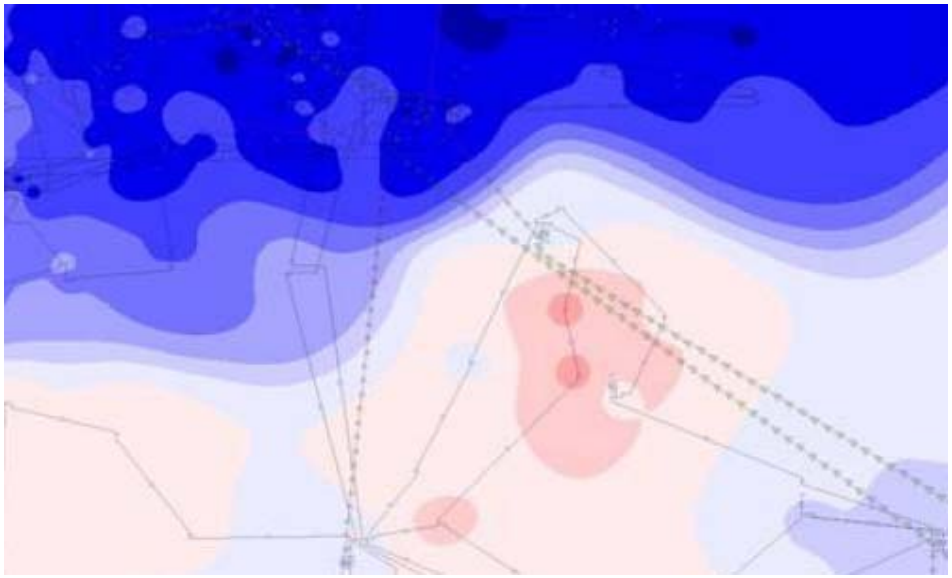
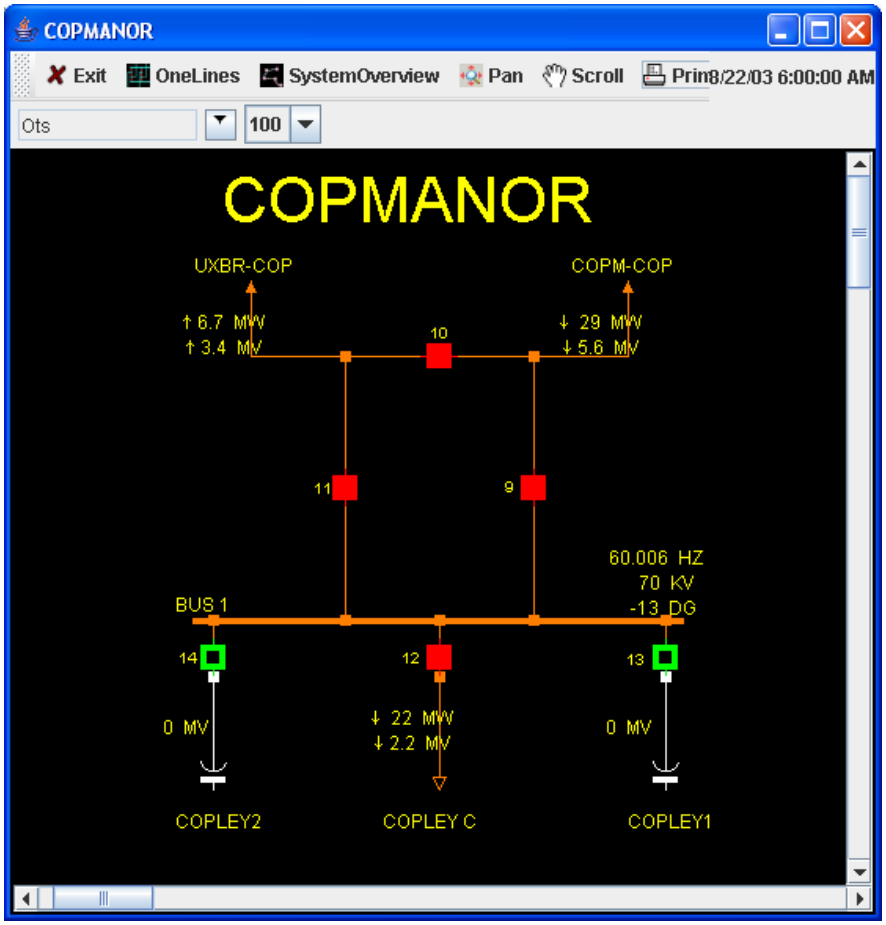


One-line Diagram Visualization of the Facilities with That Problem



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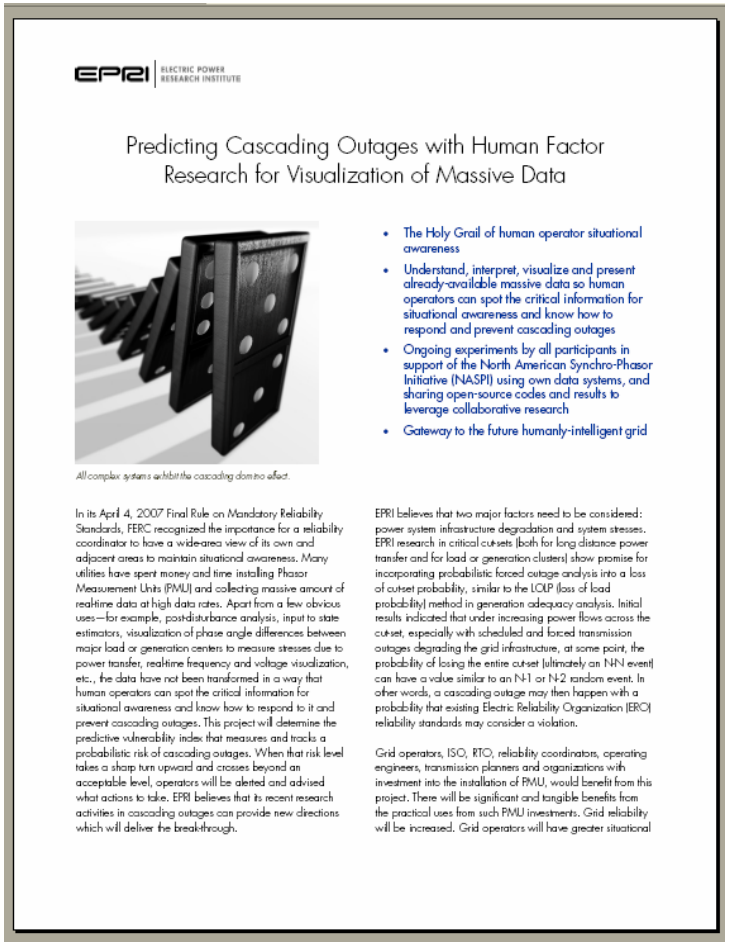
Proposed research project on predicting cascading outages with human factor research

- Collaborative Research Opportunity with EPRI
  - In coordination with NASPI
  - Task force meetings and webcasts
  - Pooling of resources
    - Funding to support research in methodologies and human factors
    - Inhouse resources to support coding of computation and visualization modules
    - Sharing of results and codes
  - Enable experiments for each participant, using own EMS or PI servers



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Predicting Cascading Outages with Human Factor Research for Visualization of Massive Data

All complex systems exhibit the cascading domino effect.

- The Holy Grail of human operator situational awareness
- Understand, interpret, visualize and present already-available massive data so human operators can spot the critical information for situational awareness and know how to respond and prevent cascading outages
- Ongoing experiments by all participants in support of the North American Synchro-Phasor Initiative (NASPI) using own data systems, and sharing open-source codes and results to leverage collaborative research
- Gateway to the future humanly-intelligent grid

In its April 4, 2007 Final Rule on Mandatory Reliability Standards, FERC recognized the importance for a reliability coordinator to have a wide-area view of its own and adjacent areas to maintain situational awareness. Many utilities have spent money and time installing Phasor Measurement Units (PMU) and collecting massive amount of real-time data at high data rates. Apart from a few obvious uses—for example, post-disturbance analysis, input to state estimators, visualization of phase angle differences between major load or generation centers to measure stresses due to power transfer, real-time frequency and voltage visualization, etc., the data have not been transformed in a way that human operators can spot the critical information for situational awareness and know how to respond to it and prevent cascading outages. This project will determine the predictive vulnerability index that measures and tracks a probabilistic risk of cascading outages. When that risk level takes a sharp turn upward and crosses beyond an acceptable level, operators will be alerted and advised what actions to take. EPRI believes that its recent research activities in cascading outages can provide new directions which will deliver the break-through.

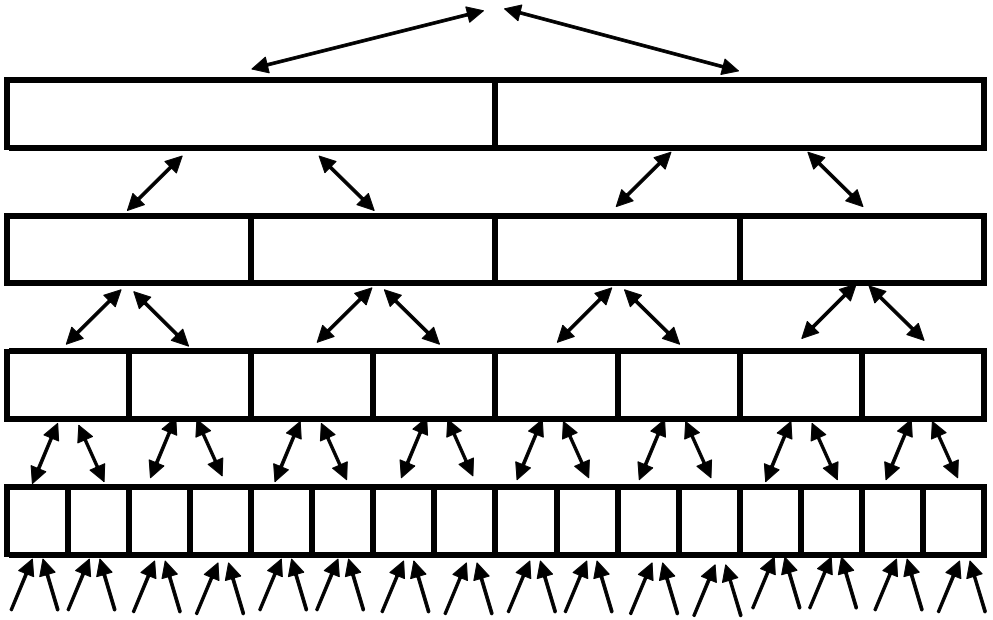
EPRI believes that two major factors need to be considered: power system infrastructure degradation and system stresses. EPRI research in critical cut-sets (both for long distance power transfer and for load or generation clusters) show promise for incorporating probabilistic forced outage analysis into a loss of cut-set probability, similar to the LOLP (loss of load probability) method in generation adequacy analysis. Initial results indicated that under increasing power flows across the cut-set, especially with scheduled and forced transmission outages degrading the grid infrastructure, at some point, the probability of losing the entire cut-set (ultimately an N-N event) can have a value similar to an N-1 or N-2 random event. In other words, a cascading outage may then happen with a probability that existing Electric Reliability Organization (ERO) reliability standards may consider a violation.

Grid operators, ISO, RTO, reliability coordinators, operating engineers, transmission planners and organizations with investment into the installation of PMU, would benefit from this project. There will be significant and tangible benefits from the practical uses from such PMU investments. Grid reliability will be increased. Grid operators will have greater situational

Where is the Meat?

- Research in Human Cognition
- Human brain is much faster and more correct than supercomputers in:
  - Learning from massive data to discover causes in the world
  - Given new input data, infer causes from past knowledge
  - Make short term prediction unconsciously
  - Use observed deviations from prediction to detect anomalies
  - React to anomalies with reflex action
  - Capable of thinking and apply lessons from more distant past
- Human cortex works in layers / hierarchies
  - Successive layers apply filters and association to form higher abstraction (beliefs) from sensory data

Human Brain



Beliefs

- Line X-Y tripped
- P MW of generation in CAj tripped
- CAk in risk of voltage collapse

Anomalies in adjacent brain cells infer causes -> beliefs

- Geographical location
- Association across data types

Sensory Data

Distributed according to electrical neighborhoods

V, I, f, δ, MW, MVAR, MVA

Predicting Cascading Outages with Human Factor Research for Visualization of Massive Data

- Turn PMU Data into Useful Information for Operators
  - Wide-area situational awareness
  - Human operators' visualization requirements
- Forum for Operators and Researchers in support of NASPI
  - Develop visualization tools
  - Sharing of open-source code and visualization approaches
- Deliverables:
  - Webcasts, Open-source library, annual conferences
- Status:
  - EPRI base and TI research funding will increase leverage
  - New collaborative effort
- Key Research Questions
  - Precursor vulnerability signals for potential cascading outages
  - Human factors and human intelligence
- Cost to Participate: $30,000 ($15k+$15k) per year for two years
- Technical Contact: Stephen Lee, slee@epri.com