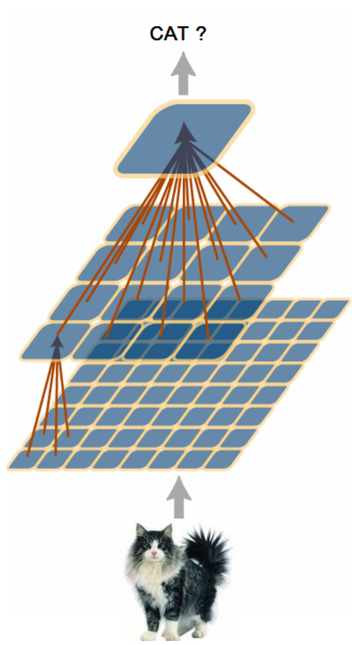


ELECTRIC POWER RESEARCH INSTITUTE

HTM based Power System Stability Pattern Recognition

Kai Sun

September 6, 2007

NASPI, Montreal

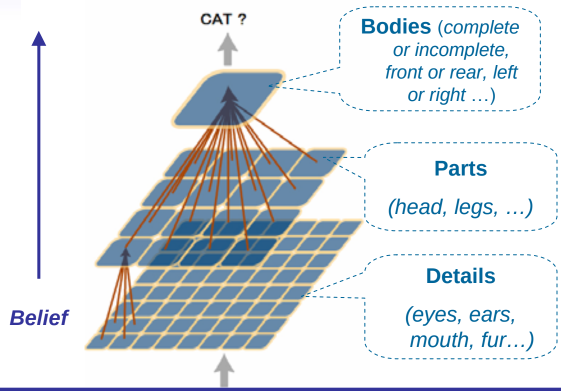
HTM Technology

Numenta®

- HTM (Hierarchical Temporal Memory) by Jeff Hawkins
  - The memory system best simulating the learning process of the human brain (neo-cortex)
- NuPIC (Numenta Platform for Intelligent Computing)
  - A functions library to realize HTM algorithms
  - First version was released in Mar. 2007
- System Requirements for NuPIC
  - Operation Systems: Linux, Mac OS X and Windows (Released on Aug 28, 2007)
  - Programming Language: Python v2.4.4

ELECTRIC POWER RESEARCH INSTITUTE

How Does HTM (Neo-cortex) Work?



- **"Spatial"** & "**Temporal"**
  - Discovers spatial and temporal correlations of representatives to abstract few patterns
- **"Hierarchical"**
  - Layered and increasing beliefs
  - An efficient way to store massive (exponentially explosive) data by limited space

 3 EPRI ELECTRIC POWER RESEARCH INSTITUTE

What Can HTM Do?

- Generally speaking, HTM can do something easy for humans but hard for traditional AI technologies
  - By hierarchical inference, it can understand whether cases A and B belong to the same object despite their spatial or temporal differences.
- In detail, four functions:
  - ***Classifying*** *patterns:*
    - Making use of **available sensor inputs**
  - ***Predicting*** *forward in Time:*
    - Predicting the **coming sensor inputs** to identify potentially harmful situations
  - ***Completing*** *patterns:*
    - Able to tolerate noisy and **missing sensor inputs**
  - ***Detecting*** *surprising events:*
    - Signal an anomaly when detecting **unmatched sensor inputs** (the actual values are different from the values predicted)

 4 EPRI ELECTRIC POWER RESEARCH INSTITUTE

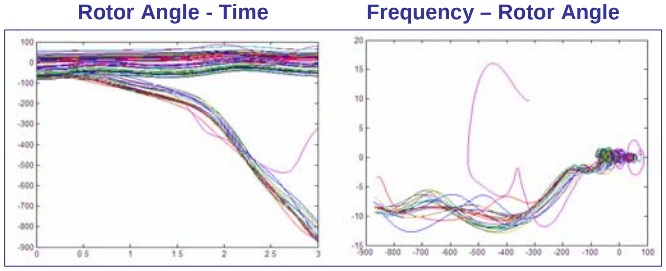
A Case Study: Classifying Stability Patterns

- Classify post-contingency transient rotor angular curves
  - 2-second time windows
  - Typical "stable" and "unstable" phase-space curves from Eastern Interconnection systems are selected as training cases (32x32 pixels bitmap images)
  - A HTM network was trained to classify "stable" and "unstable" patterns
  - A GUI-based stability pattern recognition program was developed in both Linux and Windows XP

Post-Contingency Curves of EI Systems

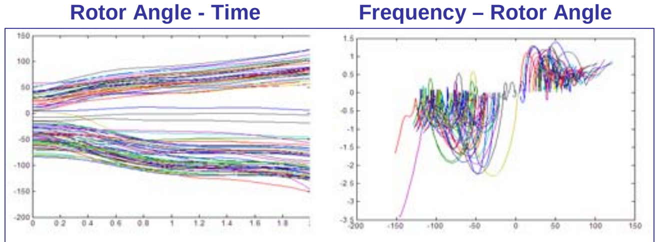
Rotor Angle - Time | Frequency – Rotor Angle

Scenario 1

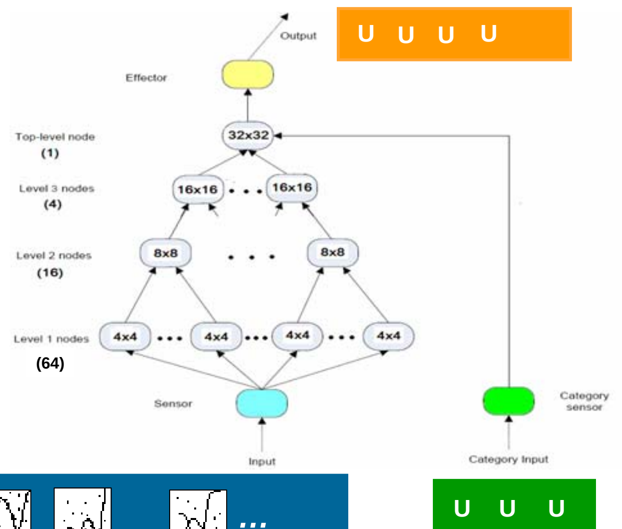


Rotor Angle - Time | Frequency – Rotor Angle

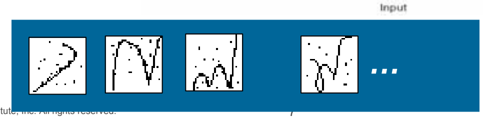
Scenario 2



The HTM Network Developed



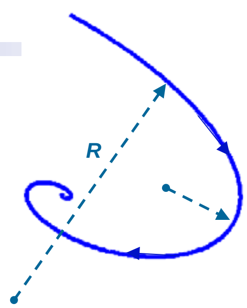
32x32 pixels images:

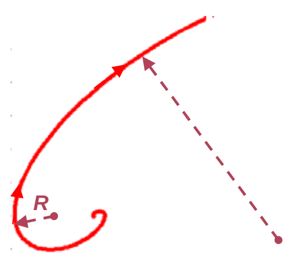


EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Common Knowledge

- **Trend to "Stable":**
  - The arc radius *R* tends to be smaller
- **Trend to "Unstable":**
  - The arc radius *R* tends to be larger

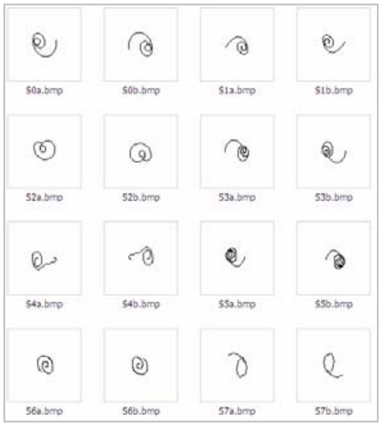




EPRI | ELECTRIC POWER RESEARCH INSTITUTE

All Cases Used for Learning

Typical "stable" frequency vs. rotor angle curves:



Clean images

Images with noise

EPRI ELECTRIC POWER RESEARCH INSTITUTE

All Cases Used for Learning

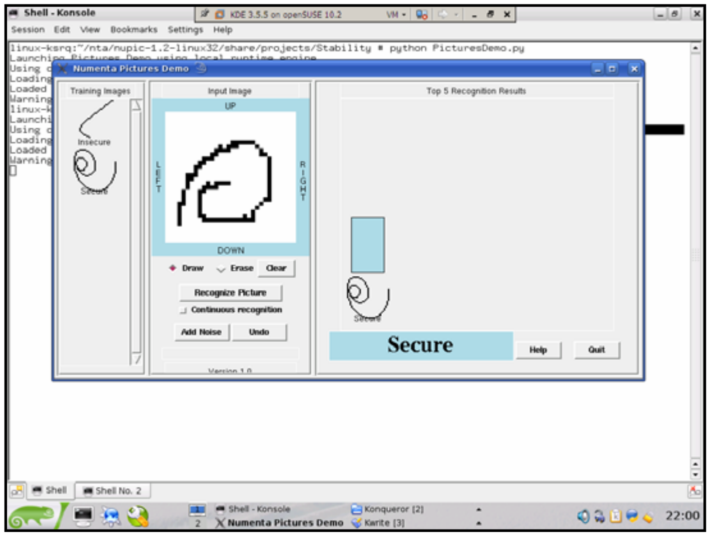
Typical "unstable" frequency vs. rotor angle curves:

Clean images

Images with noise

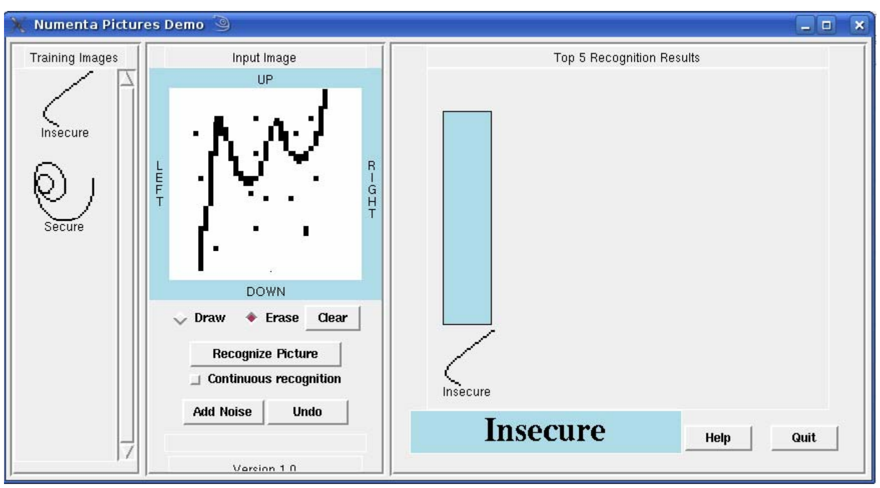
EPRI ELECTRIC POWER RESEARCH INSTITUTE

Stability Pattern Recognition Program



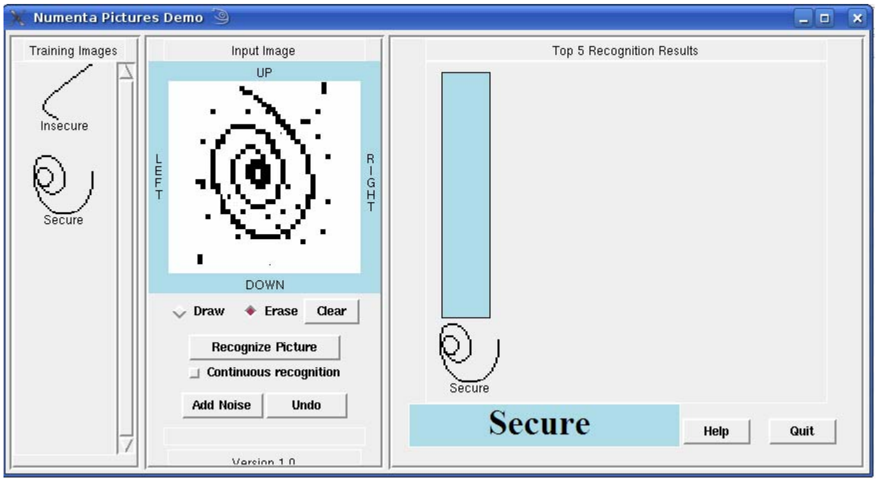
ELECTRIC POWER RESEARCH INSTITUTE

Stability Pattern Recognition Program - Insecure



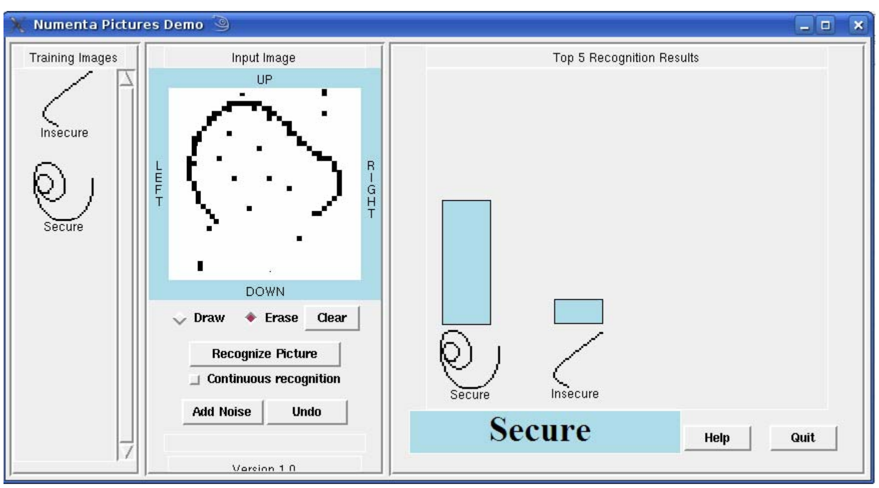
ELECTRIC POWER RESEARCH INSTITUTE

Stability Pattern Recognition Program - Secure

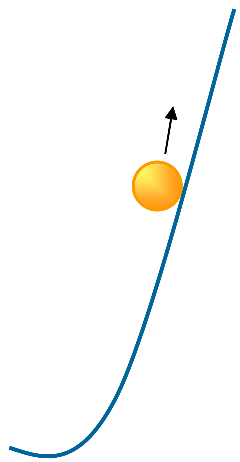


ELECTRIC POWER RESEARCH INSTITUTE

Stability Pattern Recognition Program – More Likely Secure Than Insecure



ELECTRIC POWER RESEARCH INSTITUTE

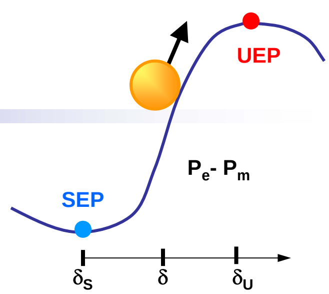


ELECTRIC POWER RESEARCH INSTITUTE

Investigation into the Use of Energy Functions for Detecting Precursor Signals of Cascading Outages

---

Potential Energy

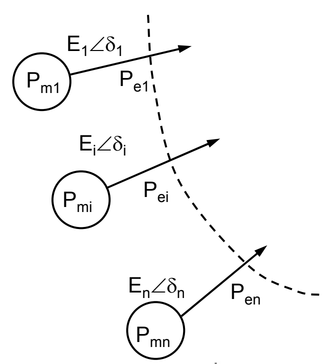


- Potential Energy is a simple, important security index
  - SEP ~ Zero Potential Energy
  - UEP ~ Maximal Potential Energy (V_{CR})

$$V_p \overset{\text{def}}{=} \sum_{i=1}^{n} \int_{\delta_S}^{\delta} (P_{ei} - P_{mi}) d\delta_i$$

$$P_{ei} = E_i^2 G_{ii} + \sum_{j=1, j \neq i}^{n} (E_i E_j B_{ij} \sin \delta_{ij} + E_i E_j G_{ij} \cos \delta_{ij})$$

- E_i and δ_i ← PMU measurements
- G_{ij} and B_{ij} ← Network topology



16

ELECTRIC POWER RESEARCH INSTITUTE

Potential Energy

- Calculation

$$V_p = V_\Delta + V_{Pos} + V_{Loss}$$

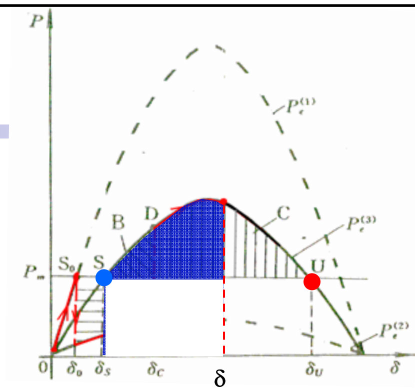
$$V_\Delta = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} E_i E_j B_{ij} (\cos\delta_{S,ij} - \cos\delta_{ij})$$

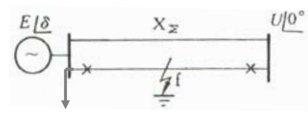
$$V_{Pos} = -\sum_{i=1}^{n} (P_{mi} - E_i^2 G_{ii})(\delta_i - \delta_{S,i})$$

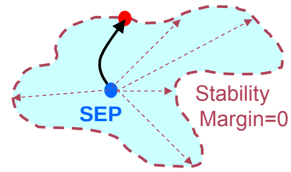
  - Needs to know the zero-potential-energy point

$$V_{Loss} = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \int_{\delta_S}^{\delta} E_i E_j G_{ij} \cos\delta_{ij} \cdot d(\delta_i + \delta_j)$$

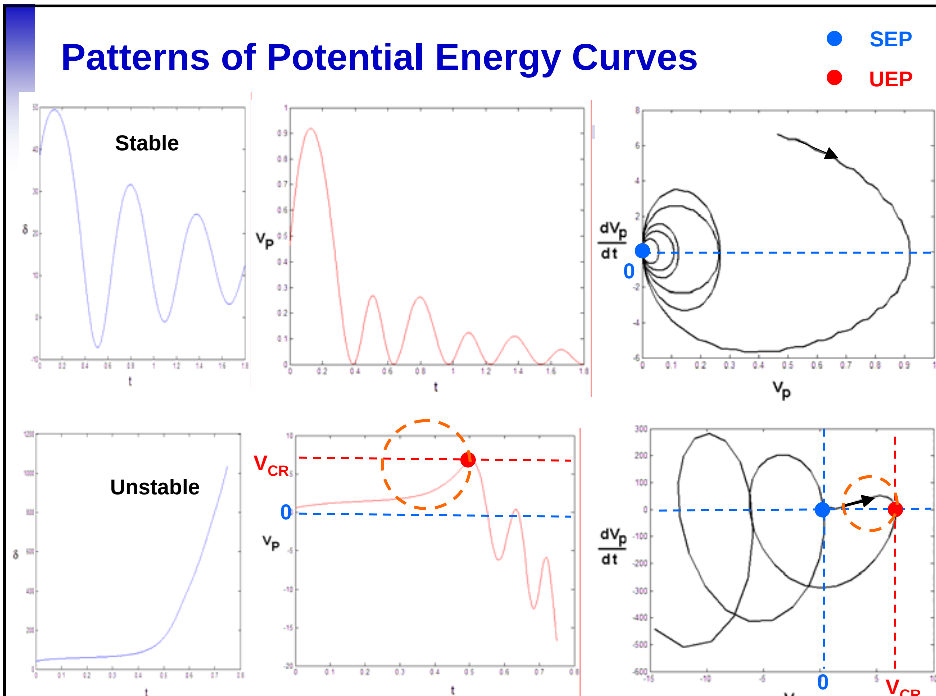
  - Depends on the unknown "δ_S- δ" path







Patterns of Potential Energy Curves



Recognize Potential Cascading Outages

- Define an energy-like function V(X)
  - Doesn't have to be a real energy function
  - Can indicate how far the system is away from the original operating point X_0 ($V(X_0)=0$)
  - Can be calculated in real time by measurements (WAMS)

- Identify danger patterns of V(X) when the system approaches the edge of cascading outages (stability margin → 0)

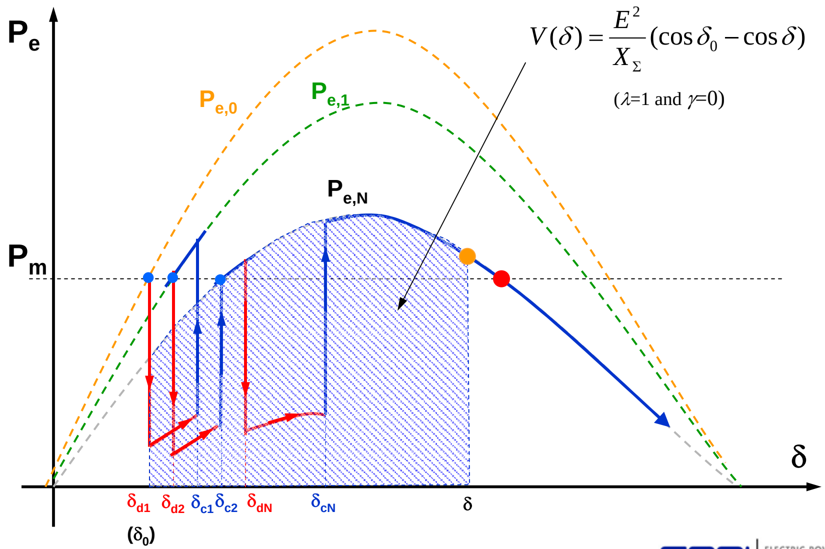
Definition of Energy Function V

- Assume: any changes in topology can be detected in real time

$$V(\delta) = \lambda \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} E_i E_j B_{ij} (\cos \delta_{0,ij} - \cos \delta_{ij}) - \gamma \sum_{i=1}^{n} (P_{mi} - E_i^2 G_{ii})(\delta_i - \delta_{0,i})$$

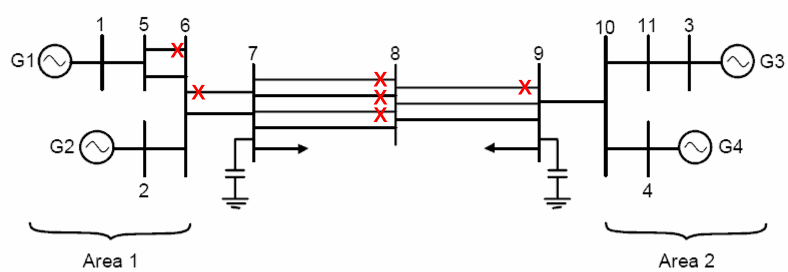
  - $\delta_{0,ij}$: Original operating point X_0 (not the zero potential energy point)
  - δ_{ij} : Current operating point from PMU measurements
  - G_{ij} and B_{ij} : Real-time updated network topology
    - If the during-fault topology is unknown, the old topology is used
    - The post-fault topology is the network with fault lines removed
  - E_i : From PMU measurements

Single Machine Infinite Bus System



EPRI ELECTRIC POWER RESEARCH INSTITUTE

Two-area System Simulations

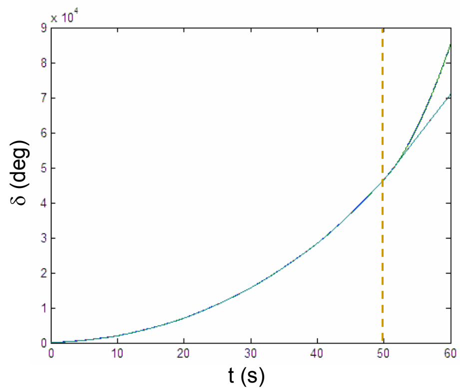


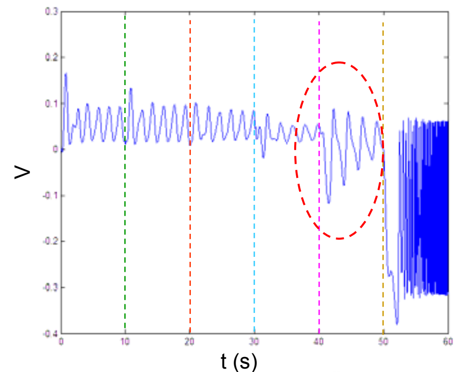
- 6 faults occur successively at 0s, 10s, 20s, 30s, 40s, and 50s and are cleared by opening the lines after 6 cycles
- Instability occurs after the fault 6 (at about 50s)

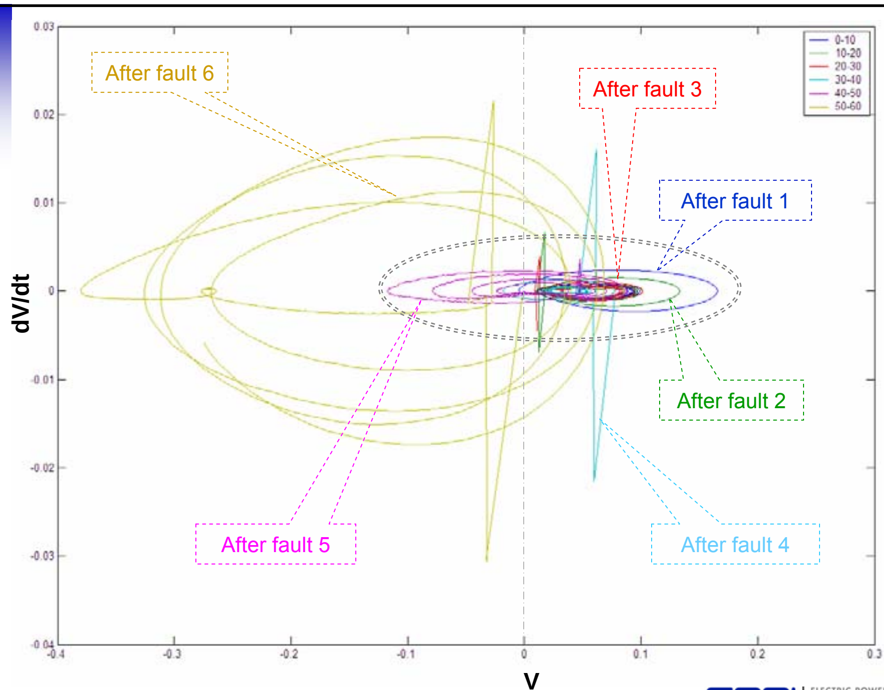
EPRI ELECTRIC POWER RESEARCH INSTITUTE

Simulation Results

- Instability occurs after fault 6 but V(X) patterns after fault 5 have become abnormal
- That means the system's stability margin has approached zero
- HTM might predict this to prevent potential cascading outage







Consideration of Re-initialization

- Main idea:
  - Critical energy (stability margin=0) is hard to be estimated
  - But V(X) pattern may look abnormal when the stability margin is close to 0.
  - Changes in Topology and Generation Status may necessitate re-initialization of V to $V(X_0)=0$

Questions?