Self-healing Electricity Infrastructure

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Utility construction expenditures
Capital Invested as % of electricity revenue

Power Law Distributions:
Frequency & impacts of major disasters

- Hurricanes and Earthquake Losses 1900–1989
- Flood Losses 1986–1992
- Electric Network Outages 1984–2000

Loss Per event (million 1990 dollars)

Cumulative Number of Events per Year

- Hurricanes
  - Model: $D = -0.98$
- Earthquakes
  - Model: $D = -0.41$
- Floods
  - Model: $D = -0.74$

Legend:
- 10 times per year
- Once a year
- Once per decade
- Once per century
Historical Analysis of U.S. outages in terms of the amount of electric load lost (1991-2000)

1991 – 1995 Outages
- 66 Occurrences over 100 MW
- 798 Average MW

1996 – 2000 Outages
- 76 Occurrences over 100 MW
- 1,067 Average MW

Historical Analysis of U.S. outages in terms of Affected Customers (1991-2000)

1991-1995 Outages
- 41 Occurrences over 50,000 Consumers
- 355,204 Average Consumers

1996 – 2000 Outages
- 58 Occurrences over 50,000 Consumers
- 409,854 Average Consumers
## So what are we doing about it?

**Security Related Programs within EPRI**

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Program Name</th>
<th>Key Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Tools that enable secure, robust and reliable operation of interdependent infrastructures with distributed intel. &amp; self-healing</td>
</tr>
<tr>
<td>Y2K&gt;2000-present</td>
<td>Enterprise Information Security (EIS)</td>
<td>• Information Sharing</td>
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<tr>
<td></td>
<td></td>
<td>• Intrusion/Tamper Detection</td>
</tr>
<tr>
<td></td>
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<td>• Comm. Protocol Security</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Risk Mgmt.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Enhancement High Speed Encryption</td>
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<tr>
<td>2002-present</td>
<td>Infrastructure Security Initiative (ISI)</td>
<td>Response to 9/11 Tragedies</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Strategic Spare Parts Inventory</td>
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<tr>
<td></td>
<td></td>
<td>• Vulnerability Assessments</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Red Teaming</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Secure Communications</td>
</tr>
<tr>
<td>2001-present</td>
<td>Consortium for Electric Infrastructure to Support a Digital Society (CEIDS)</td>
<td>• Self Healing Grid</td>
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</tbody>
</table>

**Recent Directions: EPRI/DOD Complex Interactive Network/Systems Initiative**

"We are sick and tired of them and they had better change!"

*Chicago Mayor Richard Daley on the August 1999 Blackout*

### Complex interactive networks:
- **Energy infrastructure**: Electric power grids, water, oil and gas pipelines
- **Telecommunication**: Information, communications and satellite networks; sensor and measurement systems and other continuous information flow systems
- **Transportation and distribution networks**
- **Energy markets, banking and finance**

**1999-2001**: $5.2M / year — Equally Funded by DoD/EPRI

Develop tools that enable secure, robust and reliable operation of interdependent infrastructures with distributed intelligence and self-healing abilities.
EPRI/DOD Complex Interactive Network/Systems (CIN/S) Initiative

The Reason for this Initiative: “Those who do not remember the past are condemned to repeat it.”
George Santayana

- Two faults in Oregon (500 kV & 230 kV) led to…
  - …tripping of generators at McNary dam
  - …500 MW oscillations
  - …separation of the Pacific Intertie at the California-Oregon border
  - …blackouts in 13 states/provinces
- Some studies show with proper “intelligent controls,” all would have been prevented by shedding 0.4% of load for 30 minutes!

Everyone wants to operate the power system closer to the edge. A good idea! but where is the edge and how close are we to it.

CIN/SI Funded Consortia

107 professors in 28 U.S. universities were funded: Over 360 publications, and 19 technologies extracted, in the 3-year initiative

- Defense Against Catastrophic Failures, Vulnerability Assessment
- Intelligent Management of the Power Grid
- Modeling and Diagnosis Methods
- Minimizing Failures While Maintaining Efficiency / Stochastic Analysis of Network Performance
- Context Dependent Network Agents
- Mathematical Foundations: Efficiency & Robustness of Distributed Systems
Infrastructure Interdependencies

- Critical system components
- Interdependent propagation pathways and degrees of coupling
- Benefits of mitigation plans

Source: ANL

Power Laws

US Power Outages
1984-Present

Model

Data

August 10, 1996

Frequency (Per Year) of Outages > N

N= # of Customers Affected by Outage

Data from NERC

EPR/DoD CIN/S Initiative
Background: The Self Healing Grid

Background: The Case of the Missing Wing

Believe it or not, this is not a joke! This F-15, with half its wing missing, is a good example of what is currently considered an "unflyable" aircraft. However, the pilot's quick thinking and some help from NASA's Aeronautics Systems Division's Flight Dynamics Laboratory allowed it to make it back to the runway safely. The F-15's unique configuration and control surfaces worked together to keep the aircraft stable and in control. This F-15 is equipped with special memory functions in the control system to reconfigure control surfaces as needed, helping to keep the aircraft stable. According to FDL, this type of advanced technology can make the F-15 a valuable asset in future missions. 

Goal: Optimize controls to compensate for damage or failure conditions of the aircraft*

Roll Axis Response of the Intelligent Flight Control System

IFCS DAG 0 full lateral stick roll at 20,000 ft, 0.75 Mach, Flt 126

lateral stick (inches)

roll rate (deg/sec)
Accomplishments in the IFCS program

• The system was successfully test flown on a test F-15 at the NASA Dryden Flight Research Center:
  – Fifteen test flights were accomplished, including flight path control in a test flight envelope with supersonic flight conditions.
  – Maneuvers included 4g turns, split S, tracking, formation flight, and maximum afterburner acceleration to supersonic flight.
• Stochastic Optimal Feedforward and Feedback Technique (SOFFT) continuously optimizes controls to compensate for damage or failure conditions of the aircraft.
• Flight controller uses an on-line solution of the Riccati equation containing the neural network stability derivative data to continuously optimize feedback gains.
• Development team: NASA Ames Research Center, NASA Dryden Flight Research Center, Boeing Phantom Works, and Washington University.

Self-healing Grid

Building on the Foundation:
• Anticipation of disruptive events
• Look-ahead simulation capability
• Fast isolation and sectionalization
• Adaptive islanding
Look-Ahead Simulation Applied to Multi-Resolution Models

• Provides faster-than-real-time simulation
  – By drawing on approximate rules for system behavior, such as power law distribution
  – By using simplified models of a particular system

• Allows system operators to change the resolution of modeling at will
  – Macro-level (regional power systems)
  – Meso-level (individual utility)
  – Micro-level (distribution feeders/substations)

Control Strategies

• Centralized

• Perfectly decentralized

• Distributed
Context-Dependent Network Agents

- collaboration techniques
- distributed computation
- real-time infrastructure
- learning
- diagnostics
- adaptation

Agent Network

multi-objective hybrid strategies

distributed control

applications of synchronized sampling

Physical Network

EPRI/DoD CIN/S Initiative: CMU, TAMU, U MN, U IL

Agent-1: Min $f_1 = 44.76x_1^2 - 28.87x_1x_2 + 10.24x_2^2 - 150x_1 - 50x_2$

Agent-2: Min $f_2 = 19.49x_1^2 - 34.48x_1x_2 + 25.51x_2^2 - 120x_1$

SOLUTIONS FOR A TWO-AGENT SYSTEM

NASH VS. PARETO

<table>
<thead>
<tr>
<th></th>
<th>$f_1$</th>
<th>$f_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nash</td>
<td>-213</td>
<td>-220</td>
</tr>
<tr>
<td>Pareto_1</td>
<td>-310</td>
<td>-220</td>
</tr>
<tr>
<td>Pareto_2</td>
<td>-246</td>
<td>-328</td>
</tr>
<tr>
<td>Pareto_3</td>
<td>-335</td>
<td>+7</td>
</tr>
<tr>
<td>Pareto_4</td>
<td>+501</td>
<td>-459</td>
</tr>
</tbody>
</table>

Contour of $f_1$

Contour of $f_2$

P

EPRI/DoD CIN/S Initiative: CMU, TAMU, U MN, U IL
THE EFFECT OF ADDING CONSTRAINTS

Agent-1: Min \( f_1 \)
\[
\begin{align*}
\text{s.t.} & \quad x_1 + x_2 \geq 6 \\
& \quad x_1 + x_2 \leq 10
\end{align*}
\]

Agent-2: Min \( f_2 \)
\[
\begin{align*}
\text{s.t.} & \quad x_1 + x_2 \geq 6 \\
& \quad x_1 + x_2 \leq 10
\end{align*}
\]

CDNA: An Example

- distributed rolling horizon strategies
- power flow
- Markov modeling
- multi-mode learning
- evaluation of reactive power control in deregulated markets
- dependable & secure protective relaying strategies
- context-dependent FACTS controls
- context-dependent PSS controls
- remote-access real-time control emulator
- protocols for dynamic collaboration
Background: The Self-Healing Grid

- Dependability/Robustness/Self-Healing (min-hours)
- Autonomy/Fast Control (msec)

- Vulnerability Assessment Agents
- Reconfiguration Agents
- Event Identification Agents
- Planning Agents
- Restoration Agents
- Knowledge/Decision Exchange
- Command Interpretation Agents
- Event/Alarm Filtering Agents
- Model Update Agents
- Plan/Decision Consistency
- Fault Isolation Agents
- Generator Agents
- Frequency Stability Agents
- Protection Agents
- Inhibitor Signal Controls
- Power System Inputs
- Real System

Background: Intelligent Adaptive Islanding

- 230 kV
- 345 kV
- 500 kV

- Event/Alarm Filtering Agents
- Model Update Agents
- Inhibitor Signal Controls
- Power System Inputs
Background: Simulation Result

No Load Shedding Scheme

New Scheme

EPRI’s Reliability Initiative-- Sample Screen of Real-time Security Data Display (RSDD)
Example of In Depth Analysis: Critical Contingency Situations

Critical Root Causes in the Proba/Voltage Impact State space (Region Cause: all, Affected Region: all)

Impact (kV)

0.0574983 0.000001 0.00001 0.001 0.01 0.1 1

Logarithmic Probability (direct)

Most significant root cause

Implementation Targets (EPRI)

Advanced sensor development and sensor placement

0 - 4 Years

Robust control with wide area measurements

Available today - applicability in next 3 years

Advanced communication systems designs / robust designs incorporating time delays

Available today - applicability in next 4 years

Real Time Implementation With Topology Processing and On-Line Update Of Islands

5 Years
Electricity Market Simulation

- Power market simulator made up of computer agents
- Agents make decisions based on available information
- Adaptive algorithms let agents learn from experience
- Costs much less to simulate on a computer than to experiment in the real world!
- Facilitates power market design

Agent Architecture and Adaptation. Agent design determines when and how Online Algorithms modify internal state based on experience.

Load schedule function and Load Company Agent (LCA).

LCA must decide: When to issue an RFQ; Hours and Amounts in the RFQ; Expiration date for RFQ; Whether to accept a quote; and When to accept a quote.
Example of Market-Grid Interactions: Setup

- Example shows unique ability to combine simulation of both dollars and watts in same model.

- Figure shows how two generators compete:
  - Because of tie-line bottleneck, one generator can sell more readily to customers inside own zone.
  - But remote generator can compete by underselling local generator, up to limits of the tie-line.

Example of Market-Grid Interactions: Results

- **Top graph (price):** Equilibrium reached with remote generator (lower line) offers power at slightly lower price.

- **Middle graph (power sales):** Local generator (upper line) more affected by demand variations.

- **Lower graph (profit):** Reflects variations in sales curve, indicating accurate simulation of coupling of generation and profit.
... four regions with diverse loads and 15 generators

Interdependencies: Dynamically Interacting Grids

Seven Dynamically Interacting Grids

1. Customers Grid
2. Transmission Grid
3. “Smart” Self-Healing Grid
4. Electricity Market Grid
5. Ownership/Investor Grid
6. Regulatory Grid
7. Economy Grid

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The Infrastructure for a Digital Society

A Complex Set of Interconnected Webs:
Security is Fundamental

Excellent Power System Reliability
Exceptional Power Quality
Integrated Communications
Compatible Devices and Appliances

Integrated Electric and Communications Systems
Deploy Local Computational Agents

Apply Fault Anticipation
Apply Electronic Power Flow Control

Enable A Self-Healing Power Delivery System
Technology Must Support This Transformation

• Several failure modes persist...

• Creating a smart grid with self-healing capabilities is no longer a distant dream, as considerable progress has been made;

• Can we master the complexity of the grid before chaos masters us?