



## Self-healing Power Delivery Infrastructure

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**Solving America's Electric Problems: The Benefits of Research and Development**



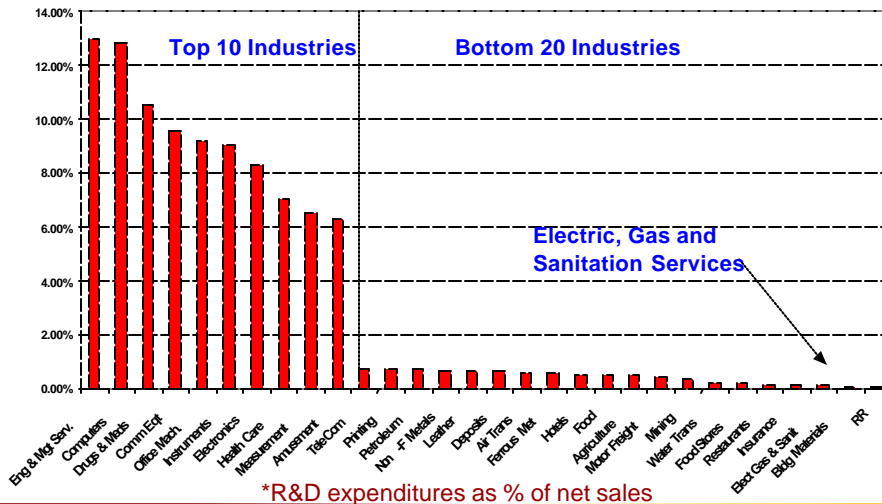
October 29, 2003



The vast networks  
of electrification are the  
greatest engineering achievement  
of the 20th century.

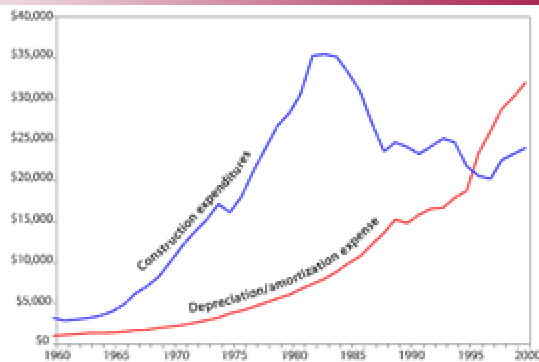
*– U.S. National Academy  
of Engineering*

## Context: R&D Expenditures\*



\*R&D expenditures as % of net sales

## Utility construction expenditures

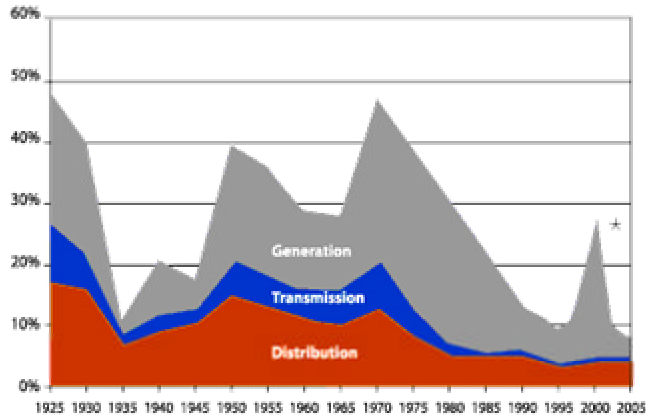


### Utility construction expenditures and depreciation/amortization expense

In recent years, the investor-owned utility industry's annual depreciation expenses have exceeded construction expenditures. The industry is now generally in a "harvest the assets" mode rather than an "invest in the future of the business" mode.

Source: "Historical Statistics of the Electric Utility Industry" and "EEI Statistical Yearbook" - EEI  
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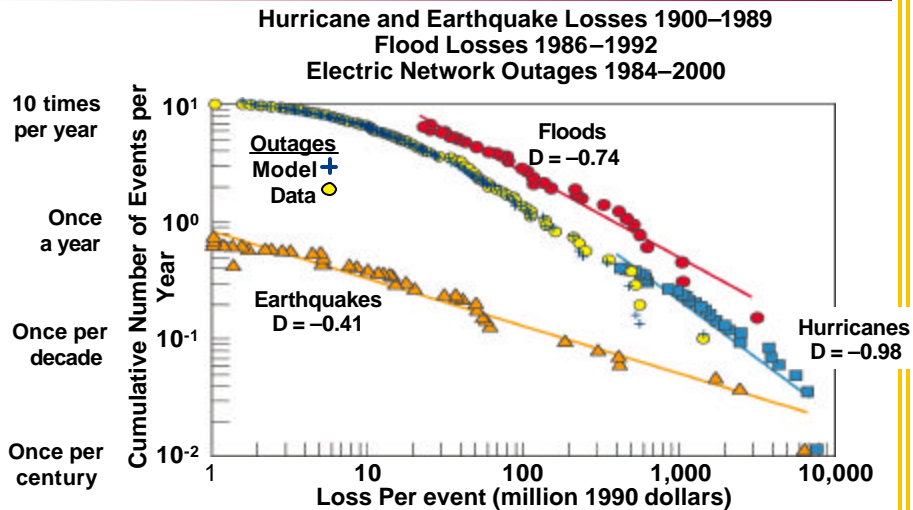
## Capital Invested as % of electricity revenue



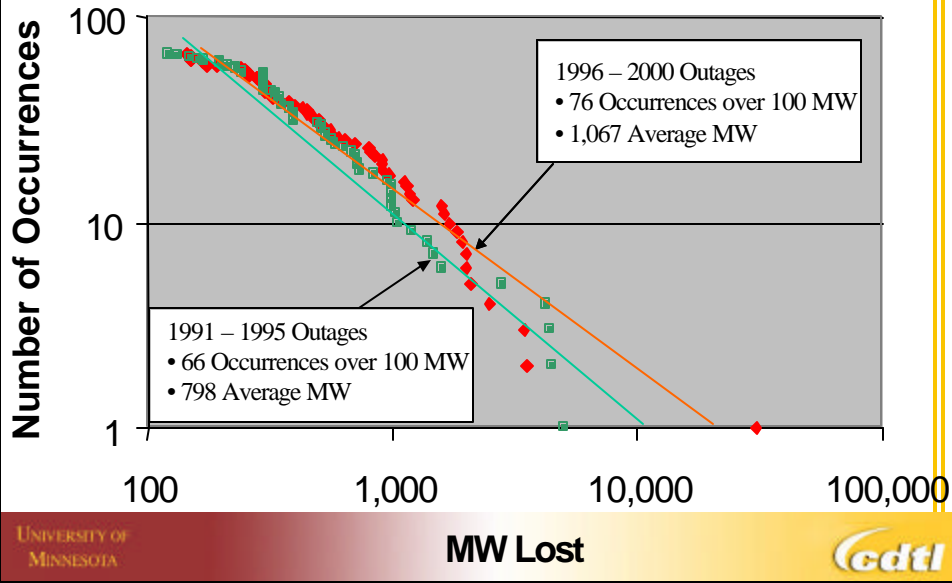
Sources: Electric Utility Industry Statistics, and 2001 Financial Review, Edison Electric Institute

Capital invested as % of electricity revenues

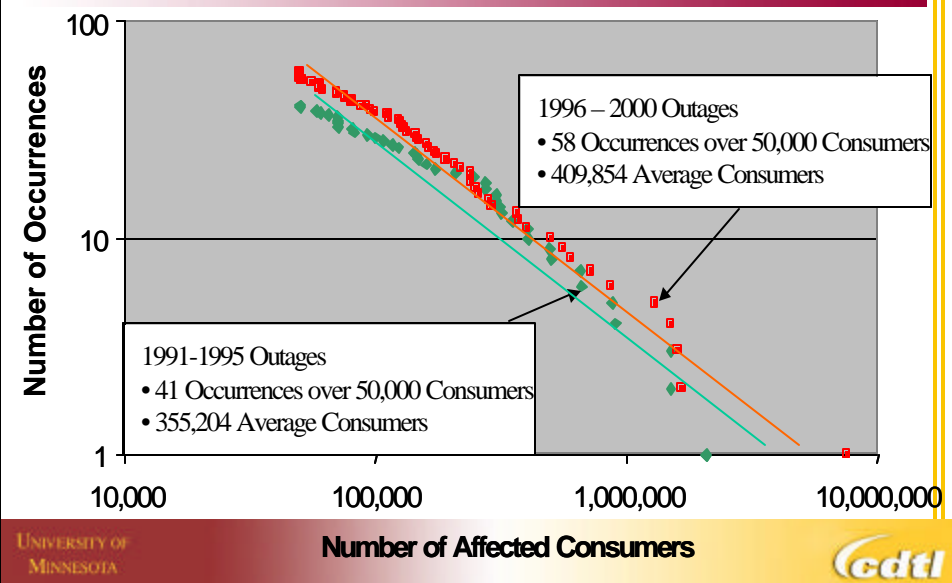
## Power Law Distributions: Frequency & impacts of major disasters



## Historical Analysis of U.S. outages in terms of the amount of electric load lost (1991-2000)



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



## So what are we doing about it? Security Related Programs within EPRI

1999-2001	Y2K→2000-present	2002-present	2001-present
<b>EPRI/DoD Complex Interactive Networks (CIN/SI)</b>	<b>Enterprise Information Security (EIS)</b>	<b>Infrastructure Security Initiative (ISI)</b>	<b>Consortium for Electric Infrastructure to Support a Digital Society (CEIDS)</b>
<p>Underpinnings of Interdependent Critical National Infrastructures</p> <p>Tools that enable secure, robust and reliable operation of interdependent infrastructures with distributed intel. &amp; self-healing</p>	<ul style="list-style-type: none"> <li>Information Sharing</li> <li>Intrusion/Tamper Detection</li> <li>Comm. Protocol Security</li> <li>Risk Mgmt.</li> <li>Enhancement</li> <li>High Speed Encryption</li> </ul>	<p><b>Response to 9/11 Tragedies</b></p> <ul style="list-style-type: none"> <li>Strategic Spare Parts Inventory</li> <li>Vulnerability Assessments</li> <li>Red Teaming</li> <li>Secure Communications</li> </ul>	<ul style="list-style-type: none"> <li>Self Healing Grid</li> </ul>

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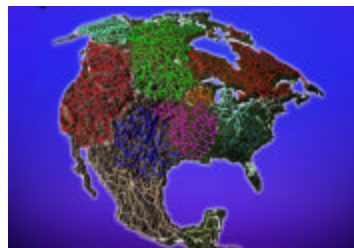


## Recent Directions: EPRI/DOD Complex Interactive Network/Systems Initiative

**“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

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# 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!



August 10, 1996

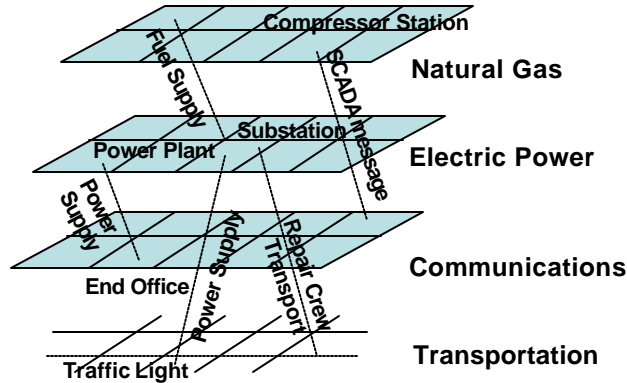
Everyone wants to operate the power system closer to the edge. A good idea! but *where is the edge and how close are we to it.*

## 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**

- |  |  |
|--|--|
| <ul style="list-style-type: none"> <li>• U Washington, Arizona St., Iowa St., VPI</li> <li>• Purdue, U Tennessee, Fisk U, TVA, ComEd</li> <li>• Harvard, UMass, Boston, MIT, Washington U.</li> <li>• Cornell, UC-Berkeley, GWU, Illinois, Washington St., Wisconsin</li> <li>• CMU, RPI, UTAM, Minnesota, Illinois</li> <li>• Cal Tech, MIT, Illinois, UC-SB, UCLA, Stanford</li> </ul> | <ul style="list-style-type: none"> <li>- Defense Against Catastrophic Failures, Vulnerability Assessment</li> <li>- Intelligent Management of the Power Grid</li> <li>- Modeling and Diagnosis Methods</li> <li>- Minimizing Failures While Maintaining Efficiency / Stochastic Analysis of Network Performance</li> <li>- Context Dependent Network Agents</li> <li>- Mathematical Foundations: Efficiency &amp; Robustness of Distributed Systems</li> </ul> |
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# Infrastructure Interdependencies



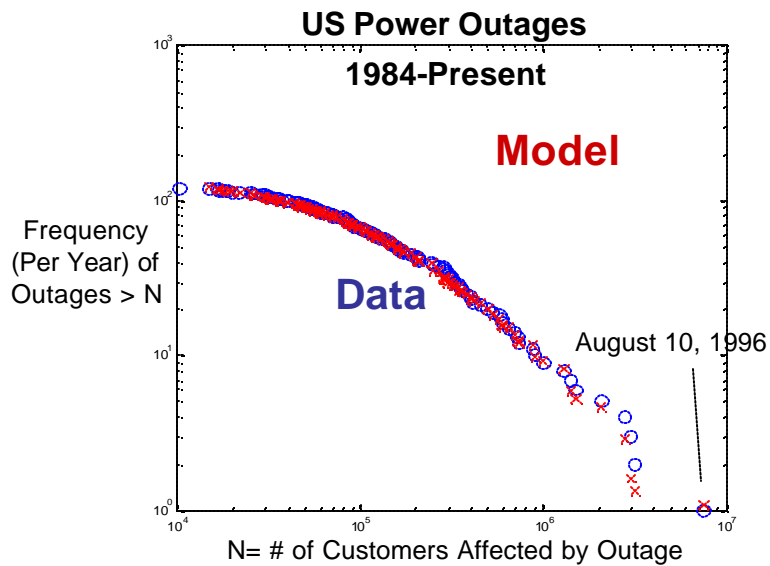
- Critical system components
- Interdependent propagation pathways and degrees of coupling
- Benefits of mitigation plans

Source: ANL

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# Power Laws



Data from NERC

EPRI/DoD CIN/S Initiative

# Background: The Self Healing Grid

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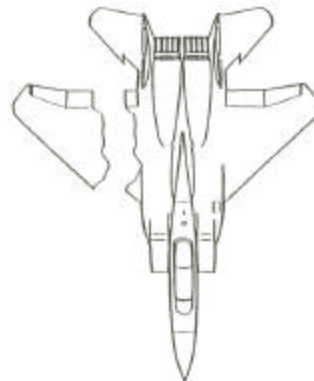


## Background: The Case of the Missing Wing

Believe it or not, this one made it back! This F-15, with half its wing missing, is a good example of what is currently considered an "unflyable" aircraft. However, the pilot's success in bringing it home helped to inspire a new program at Aeronautical Systems Division's Flight Dynamics Laboratory aimed at enabling future fighter pilots to fly aircraft with severely damaged control surfaces. The pilot of this F-15 configured in unusual ways the control surfaces that were still working to compensate for the damaged wing. The FDL program will make this "survivors" reaction automatic to the aircraft. Therefore, flying a damaged aircraft will be much easier on the pilot. Through a self-repairing flight control system rearing development, a computerized "brain" will automatically reconfigure such surfaces as rudders, flaperons, and ailerons to compensate for grave damage to essential flying surfaces, according to FDL.



Only smart work by the pilot and the unique combination of interworking control surfaces on the F-15 brought this one back alive. With old-fashioned conventional ailerons and horizontal stabilizer, it couldn't have happened.



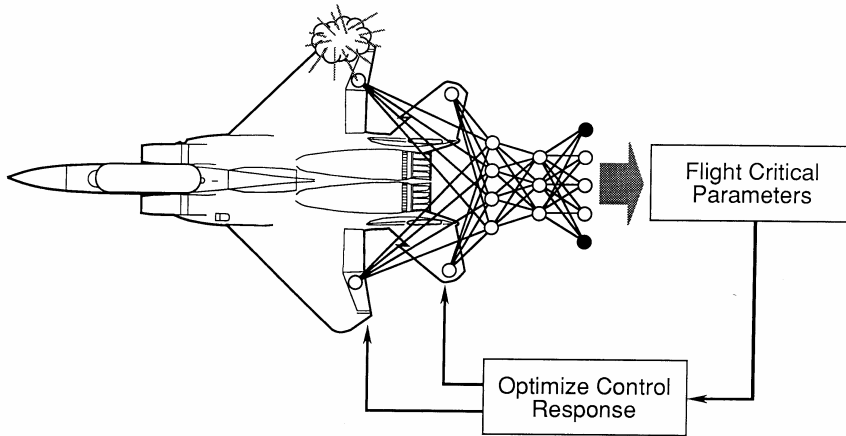
NASA/MDA/WU IFCS: NASA Ames Research Center, NASA Dryden Flight Research Center, Boeing Phantom Works, and Washington University in St. Louis.

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



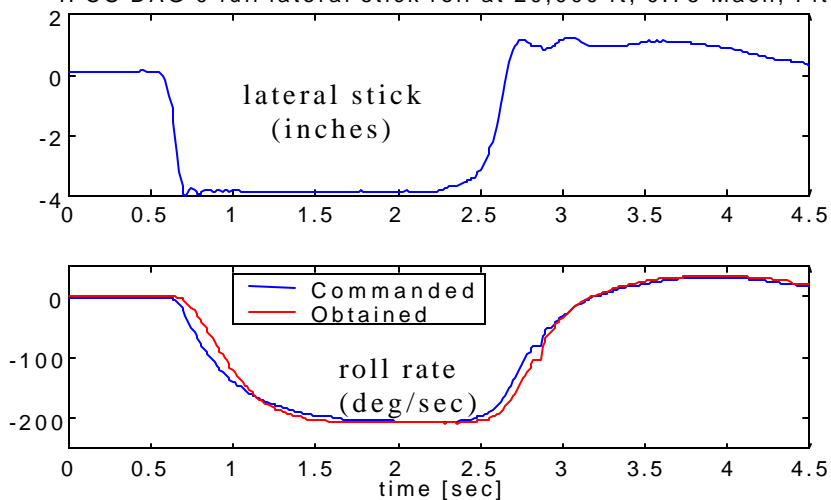
NASA/MDA/WU IFCS

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## 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



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## 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.

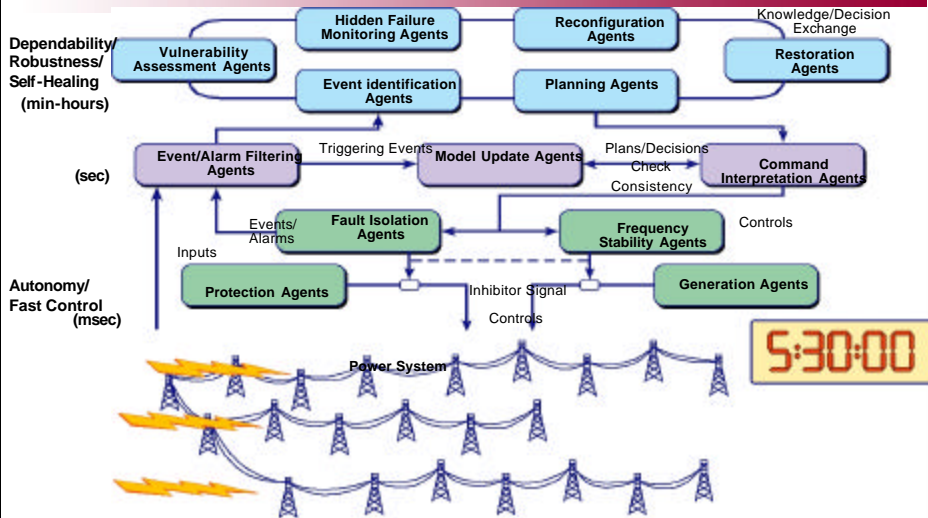
## Self-healing Grid



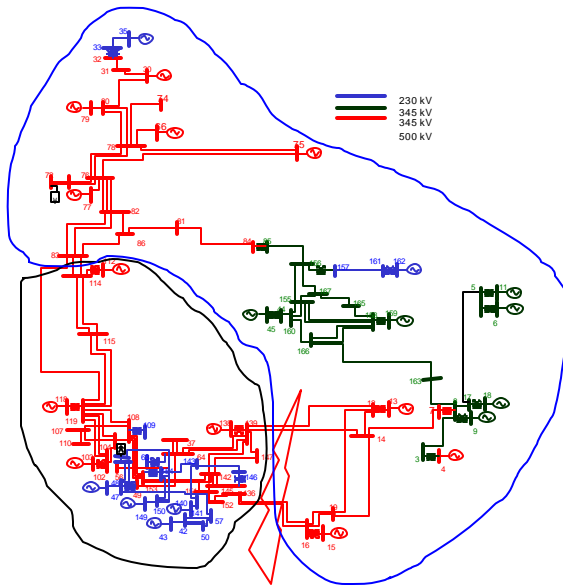
### Building on the Foundation:

- Anticipation of disruptive events
- Look-ahead simulation capability
- Fast isolation and sectionalization
- Adaptive islanding

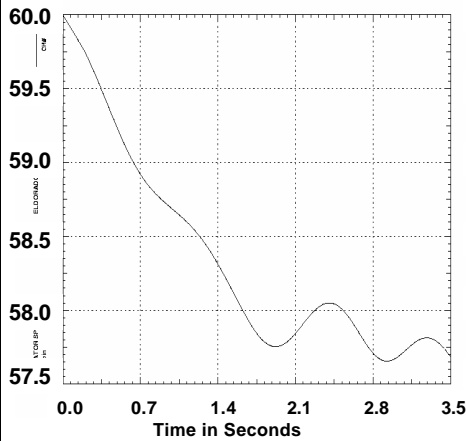
# Background: The Self-Healing Grid



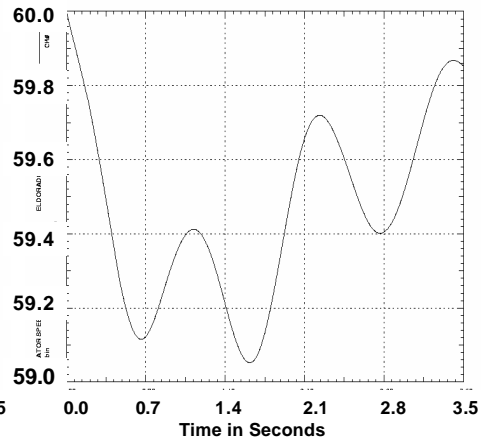
# Background: Intelligent Adaptive Islanding



# Background: Simulation Result

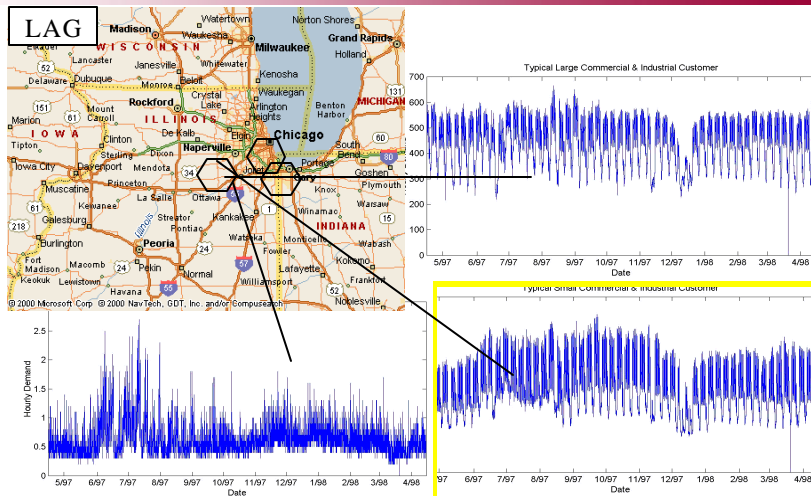


**No Load Shedding Scheme**



**New Scheme**

# Local area grids (LAG)

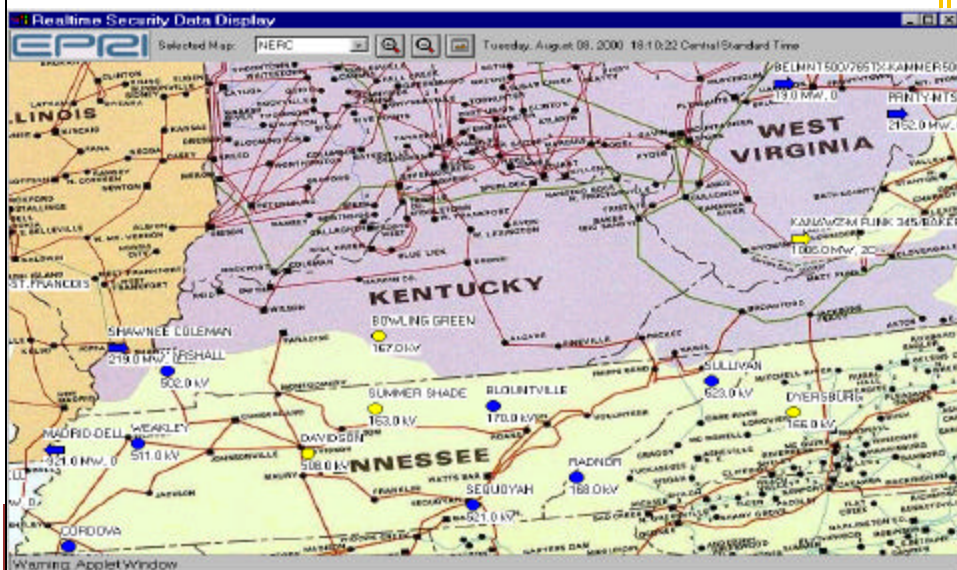


# Look-Ahead Simulation Applied to Multi-Resolution Models

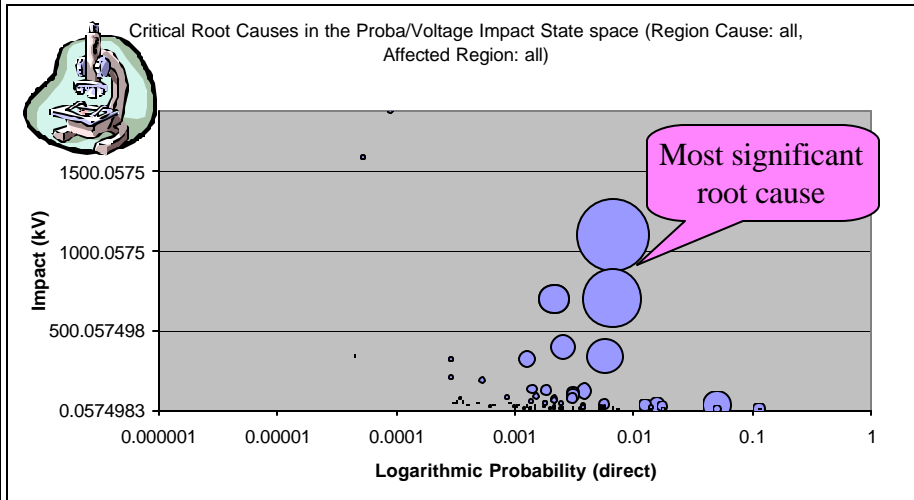
- Provides faster-than-real-time simulation
  - By drawing on approximate rules for system behavior, such as power law distribution
  - By using simplified models of a particular system
- Allows system operators to change the resolution of modeling at will
  - Macro-level (regional power systems)
  - Meso-level (individual utility)
  - Micro-level (distribution feeders/substations)



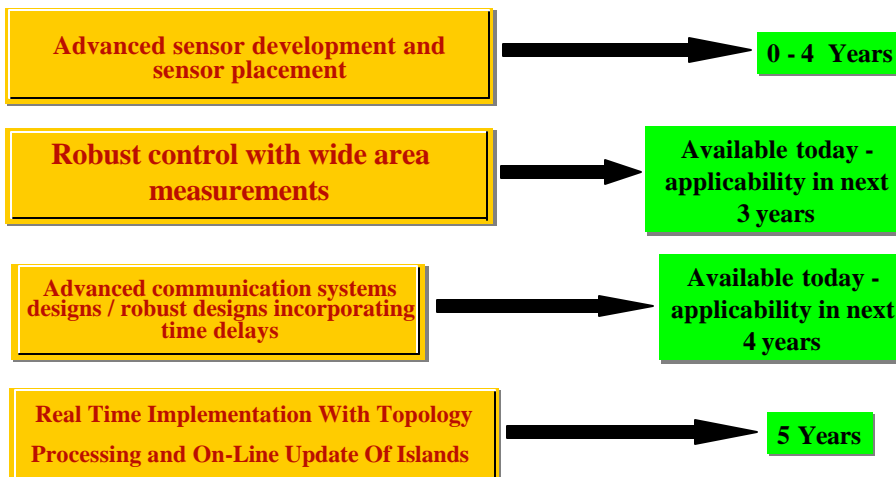
## EPRI's Reliability Initiative-- Sample Screen of Real-time Security Data Display (RSDD)



## Example of In Depth Analysis: Critical Contingency Situations



## Implementation Targets (EPRI)



# The Infrastructure for a Digital Society

A Secure Energy Infrastructure

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

**A Complex Set of Interconnected Webs:**  
**Security is Fundamental**

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# Integrated Electric and Communications Systems

Power Generator

Regional Transmission Operator

Distribution Control Center

Load Serving Entity

Demand Response Bank

Transmission Substation

Distribution Substation

Residential Consumer

Commercial Consumer

Industrial Consumer

Distributed Resource

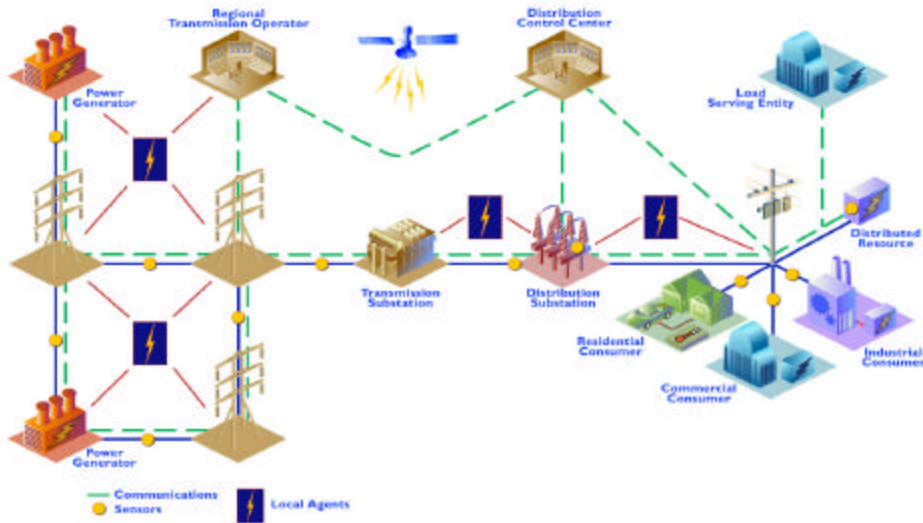
Power Generator

Communications

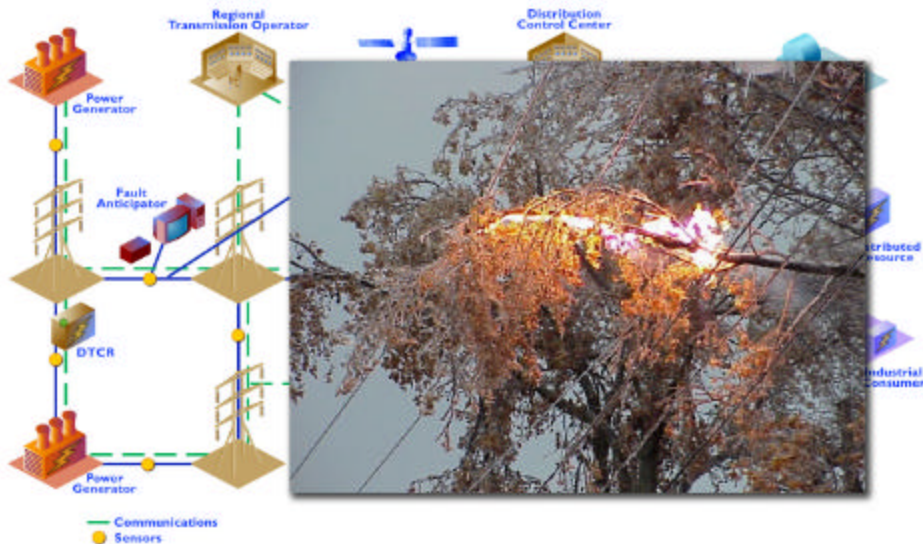
Sensors

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## Deploy Local Computational Agents

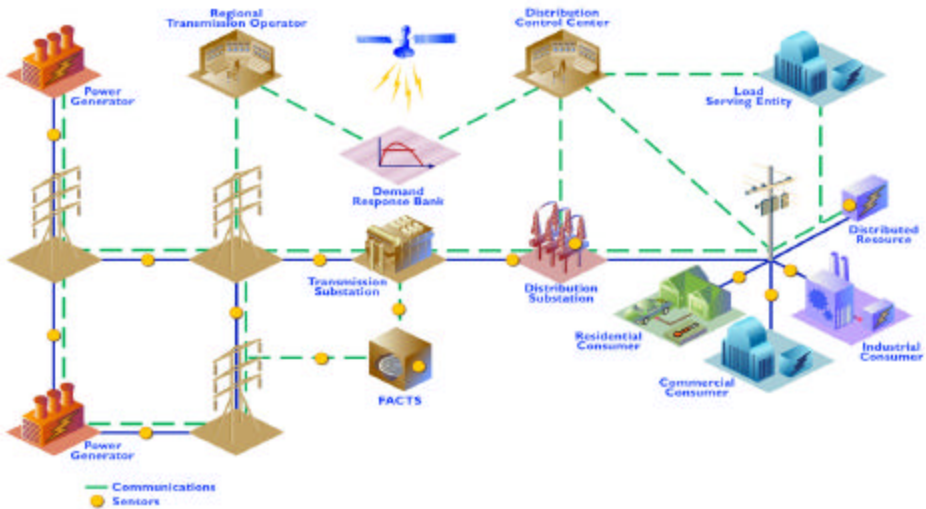


## Apply Fault Anticipation

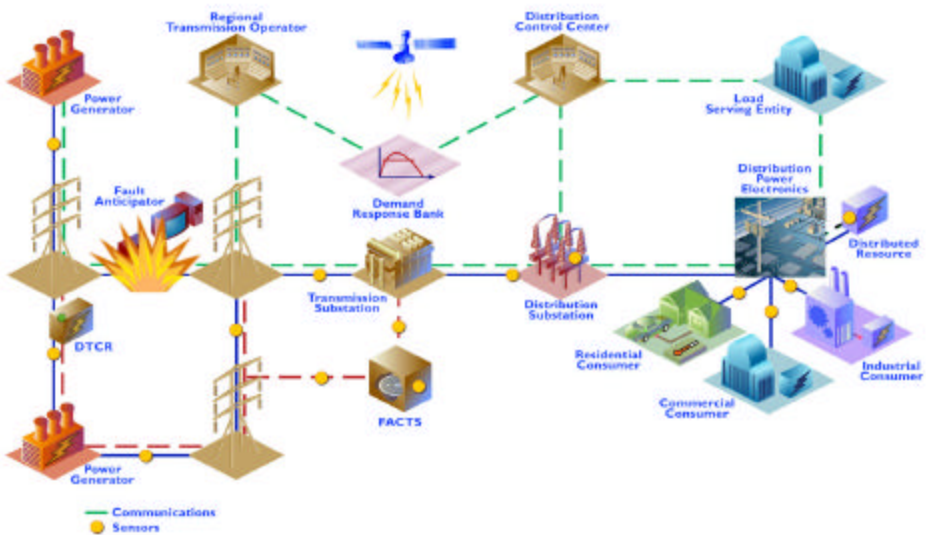




# Apply Electronic Power Flow Control



# Enable A Self-Healing Power Delivery System

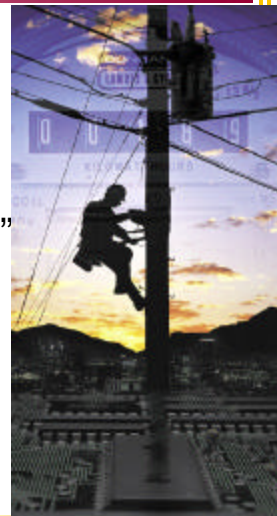


## Consumer Portal



## Recommendations

- Establish the “Smart Grid” as a national priority
- Authorize increased funding for R&D and demonstrations of the “Smart Grid”
- Revitalize the national public/private electricity infrastructure partnership needed to fund the “Smart Grid” deployment



## 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?

