Complex Interactive Networks: Toward Self-healing Infrastructures

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Collectives and the Design of Complex Systems 2002

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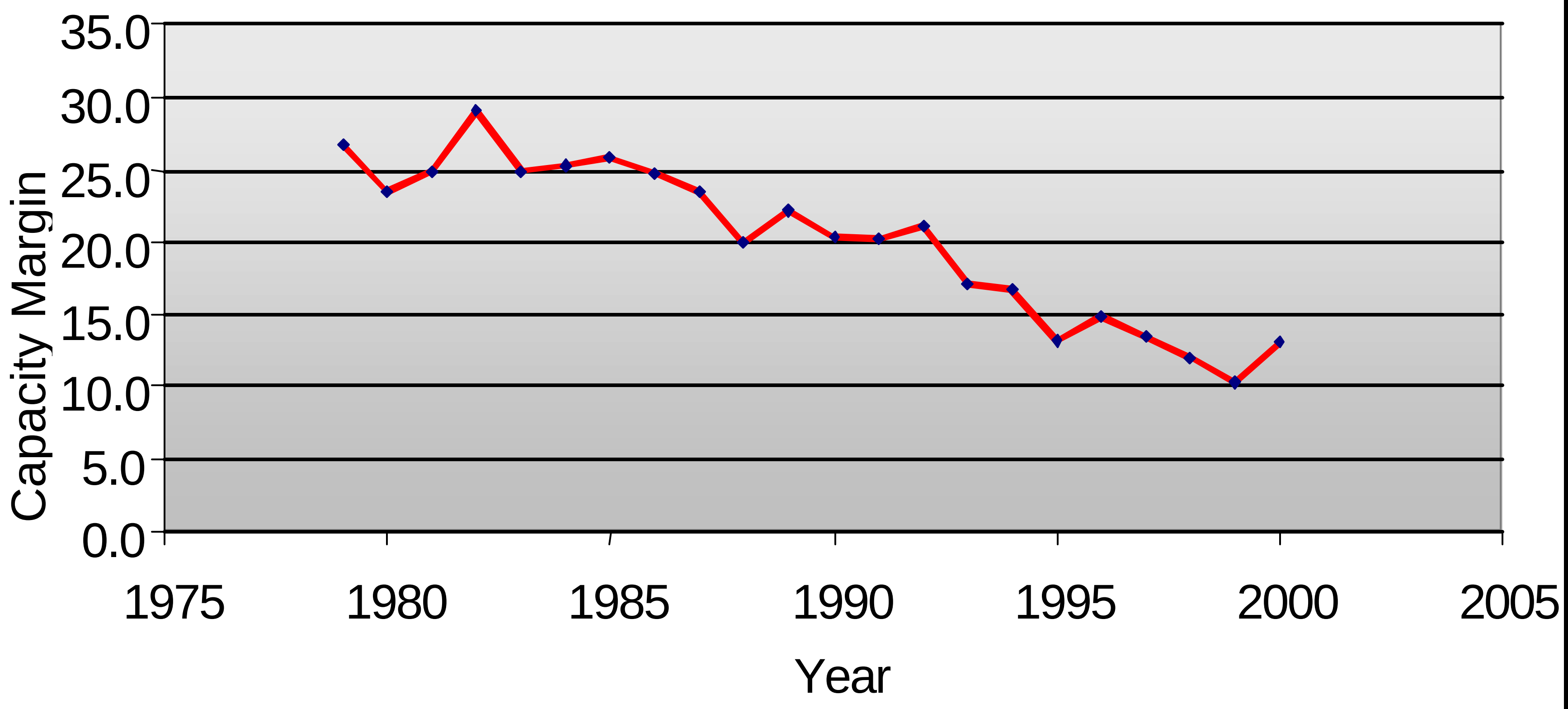
EPRI

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

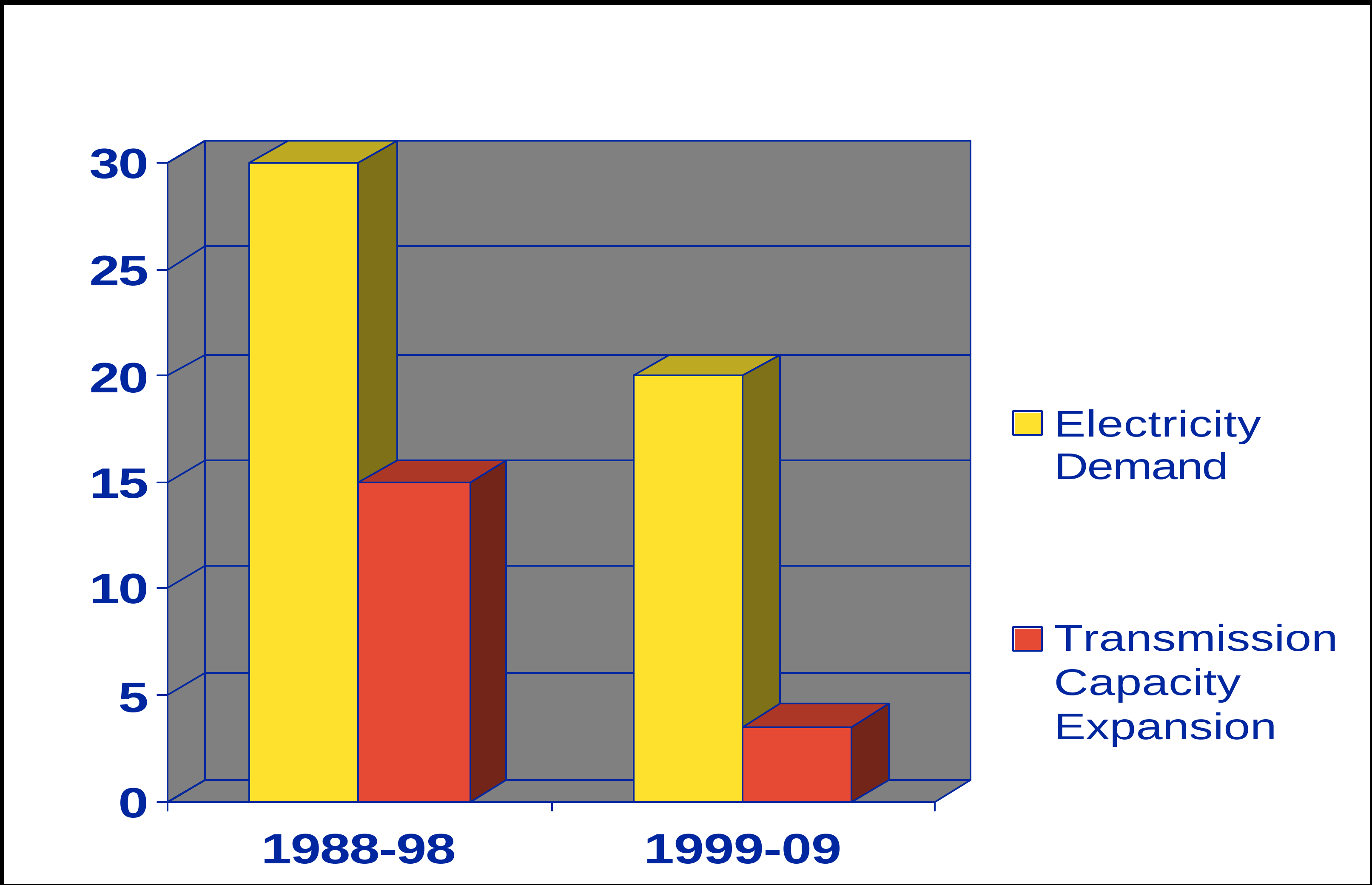
– U.S. National Academy of Engineering

Context: Generation Capacity Margin in North America

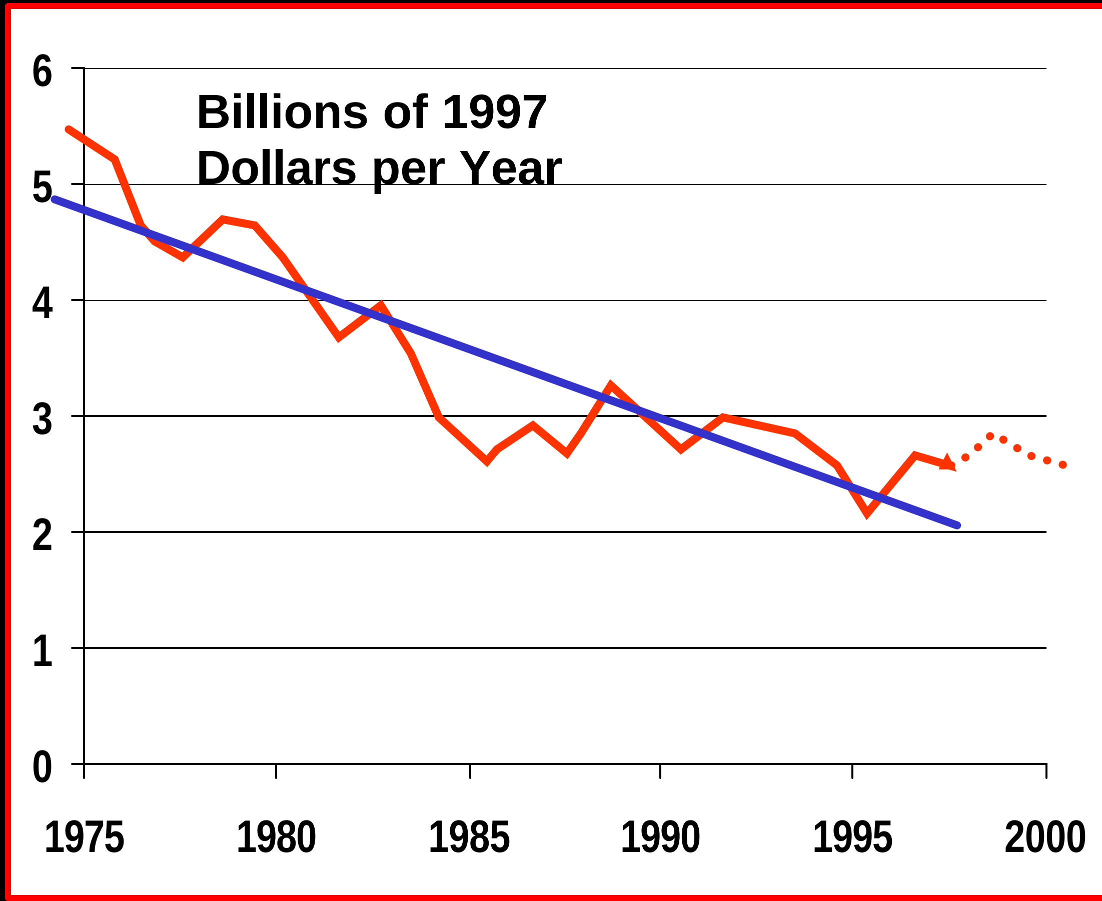


Source: Western States Power Crises White Paper, EPRI, Summer 2001

Context:
Transmission Additions in The U.S.

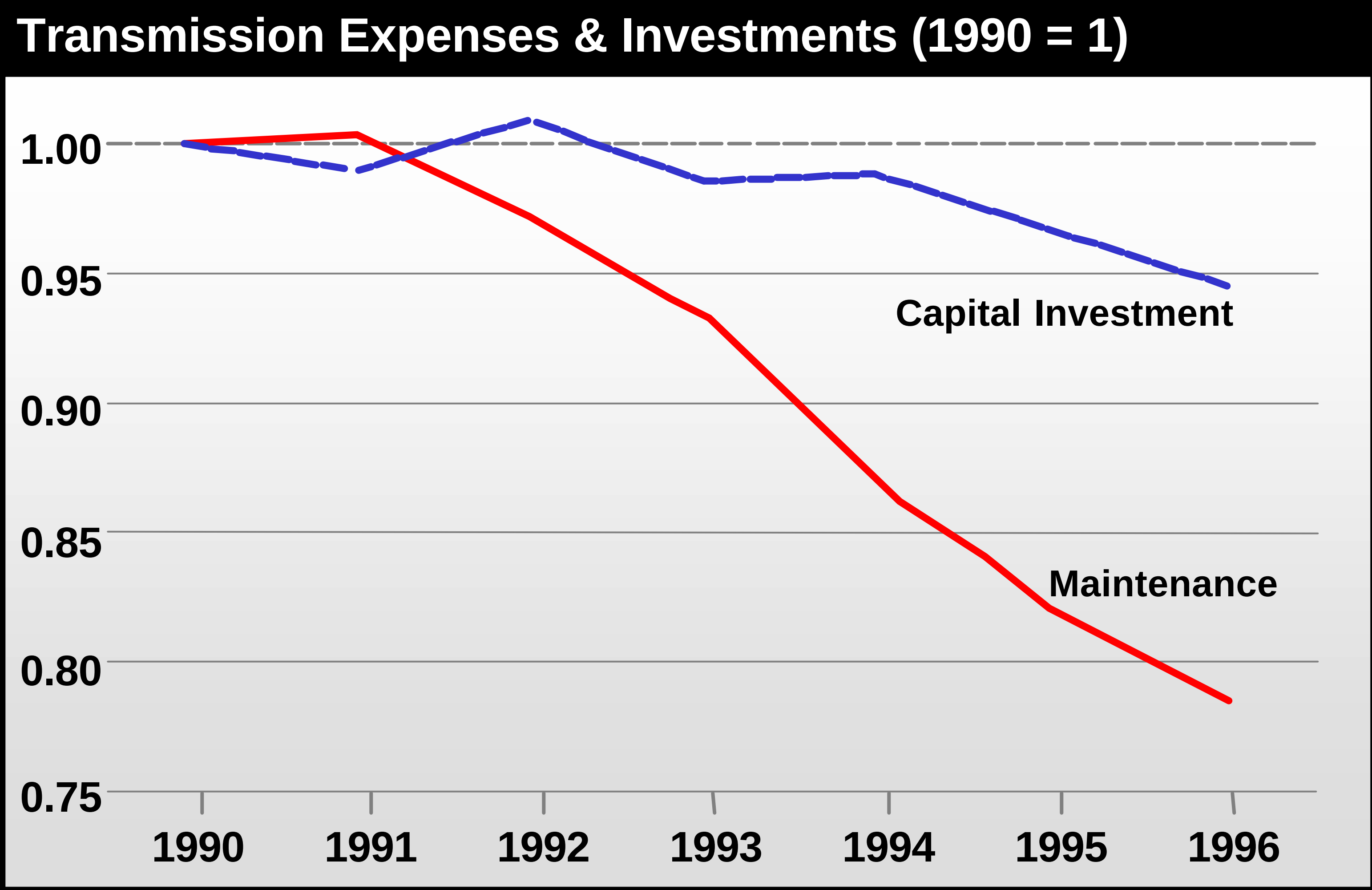


Context:
Transmission Investment, 1975-2000



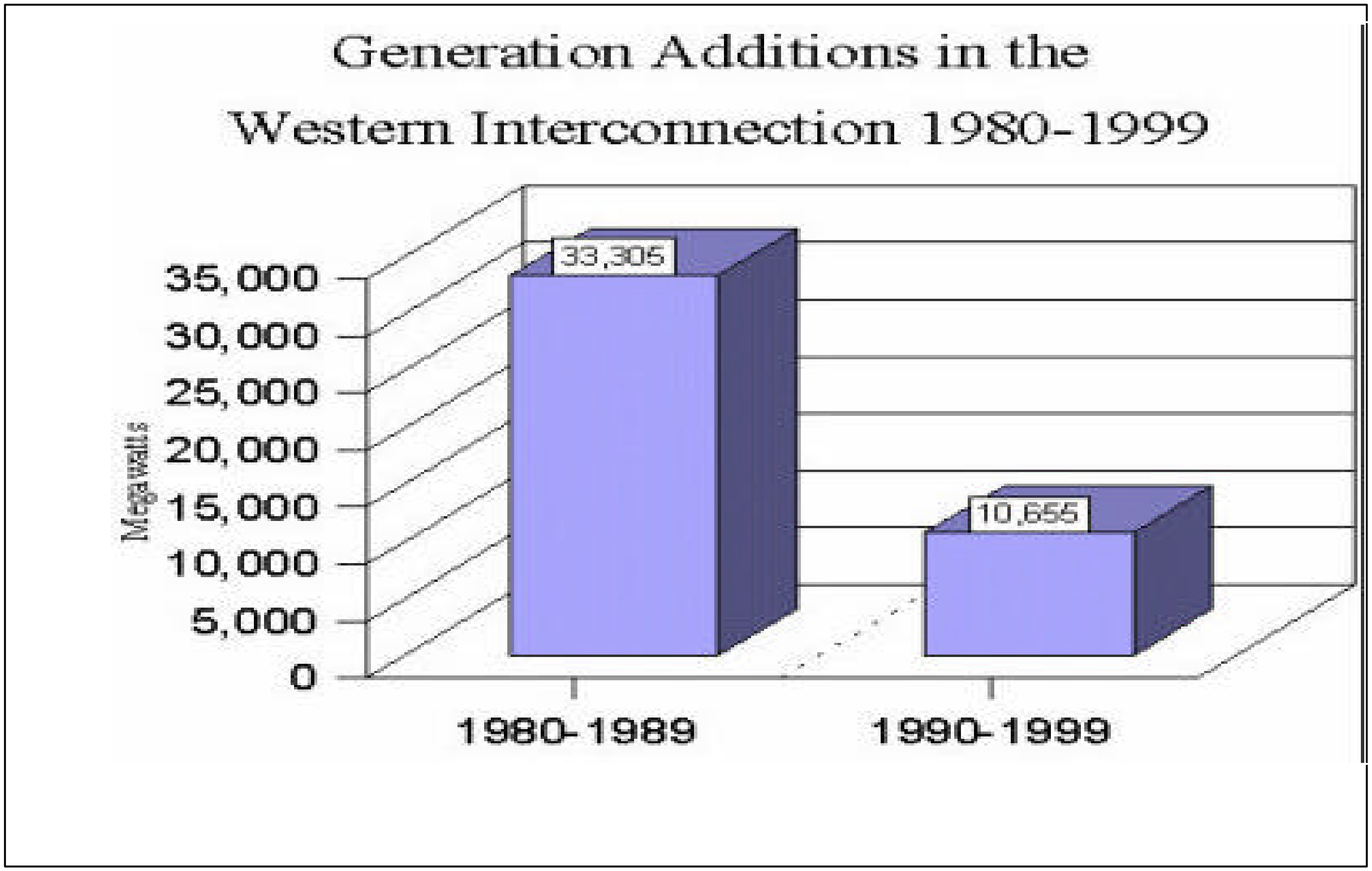
Source: Electric Perspectives, July/August 2001

Context:
Spending Less on Transmission



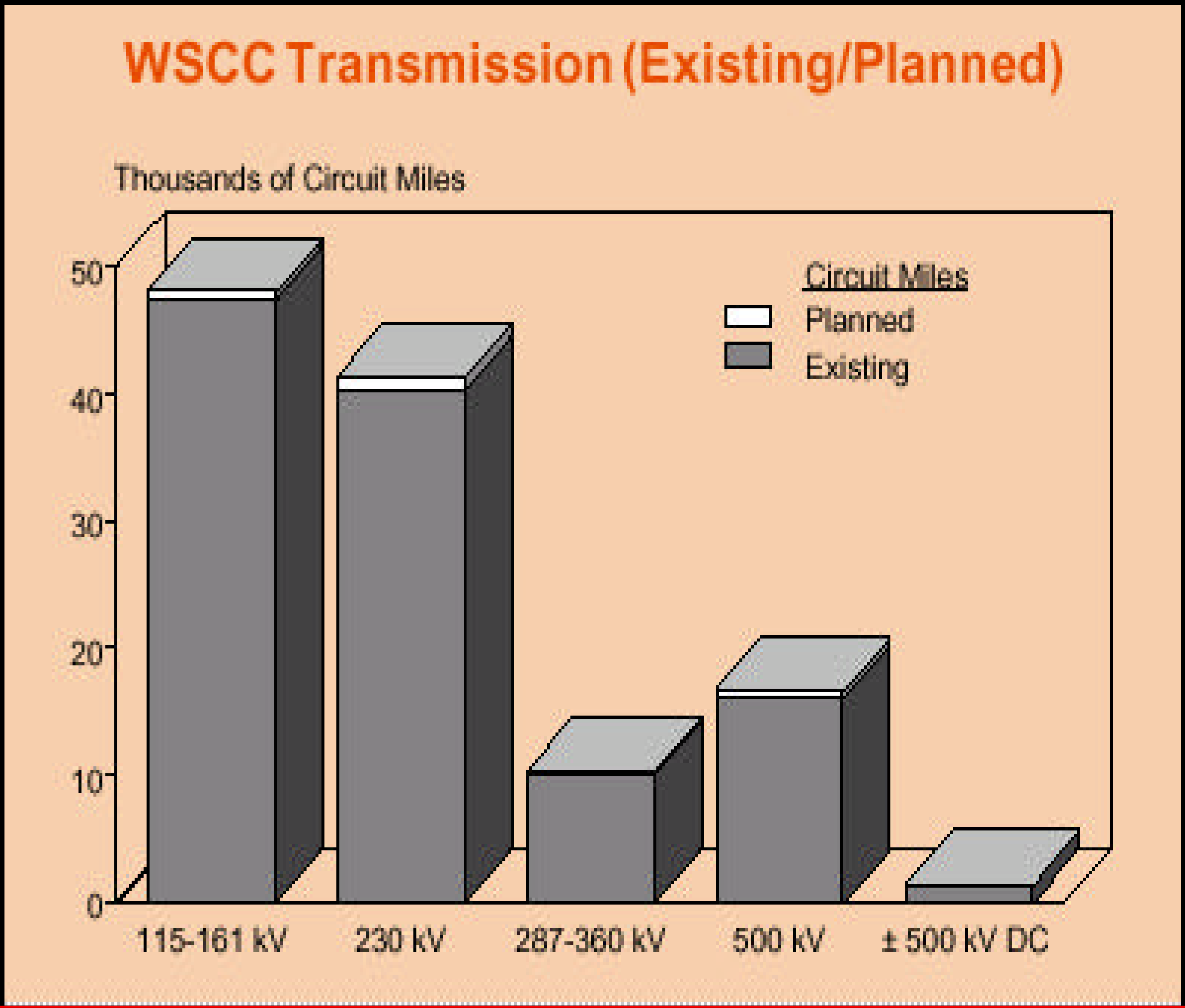
Source: FERC, EIA

Context: Generation Additions in Western U.S.



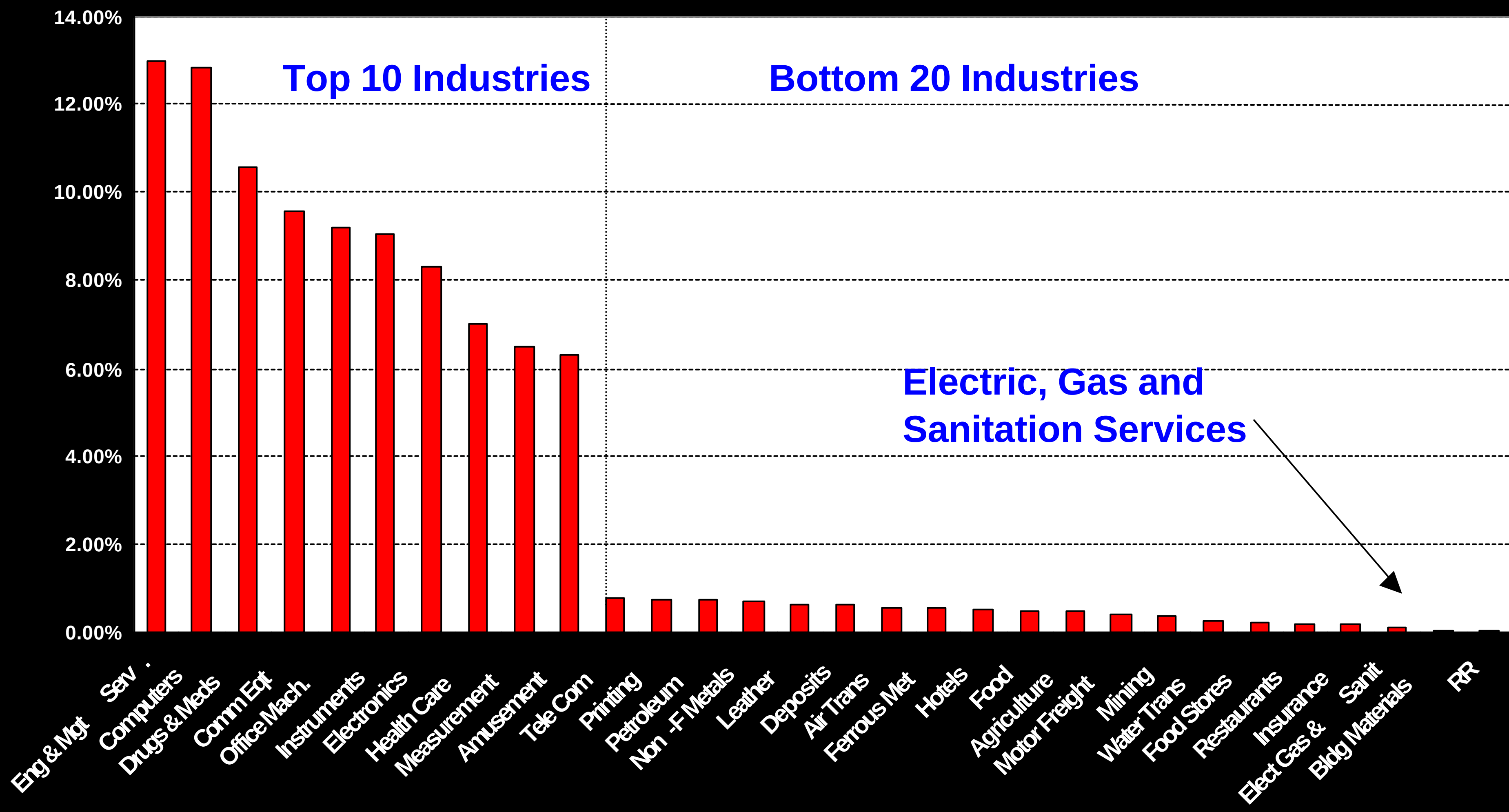
Source: Western Governors' Association

Western Region: Existing and Planned Transmission



- Existing as of 1/1/00
- Planned: 0.23% per year, even though load growth is projected to be over 1.8% per year

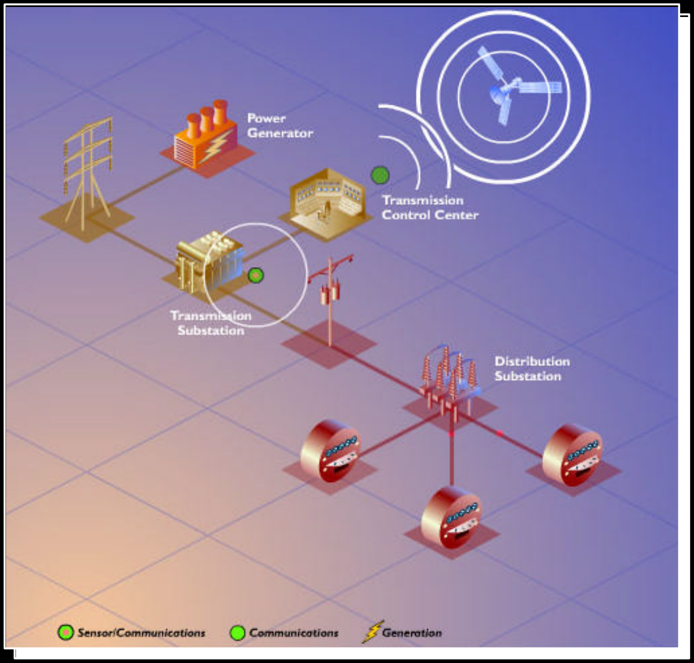
Context: R&D Expenditures*



*R&D expenditures as % of net sales

Context: Today's Power System Increasingly Stressed Infrastructure

- Infrastructure expansion has not kept up with demand: generation & transmission capacity margins are shrinking
- Transition to competition is creating new demands
  - Power transactions are growing exponentially
  - Grid capacity is severely limited
  - Power disturbances cost customers $120 billion/yr
- Technology can meet these demands, but uncertainties on ROI are discouraging investments
- Many distribution systems have not been updated with current technology
- Proliferation of distributed resources – little DR is connected to the grid
- National infrastructure security assessment adds to concern



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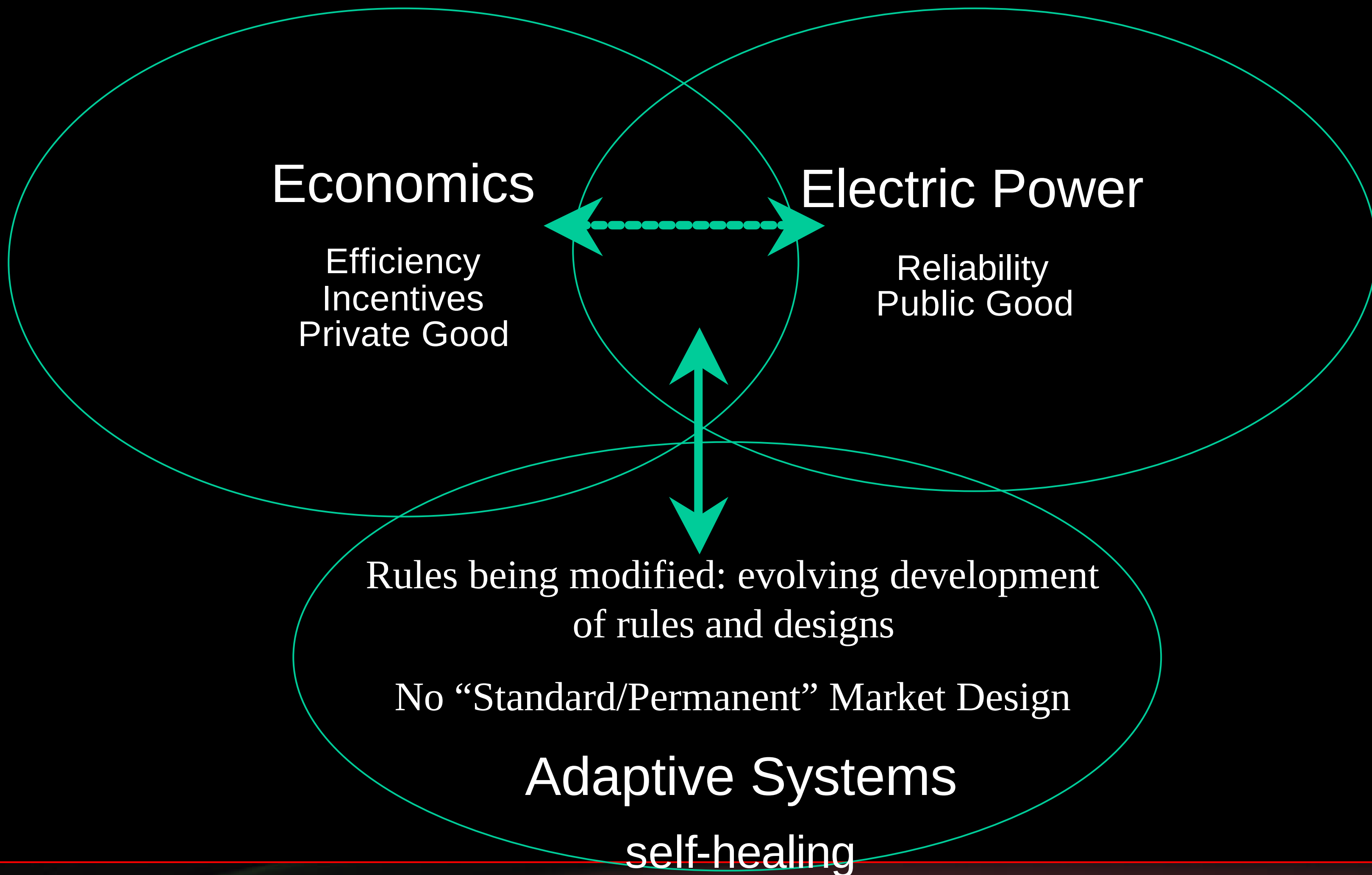
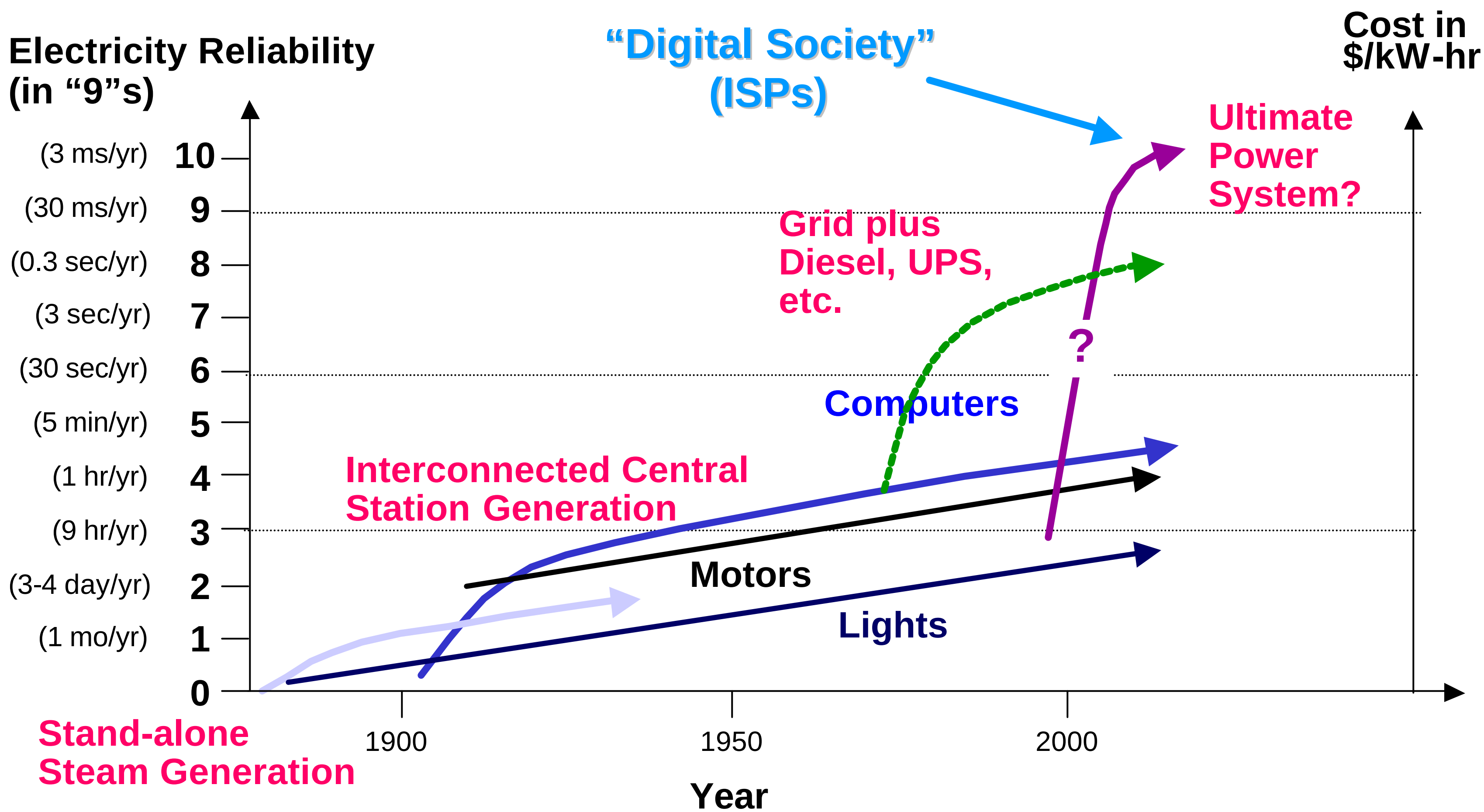
Context: Economics, Electric Power and Adaptive Systems



Key Issue

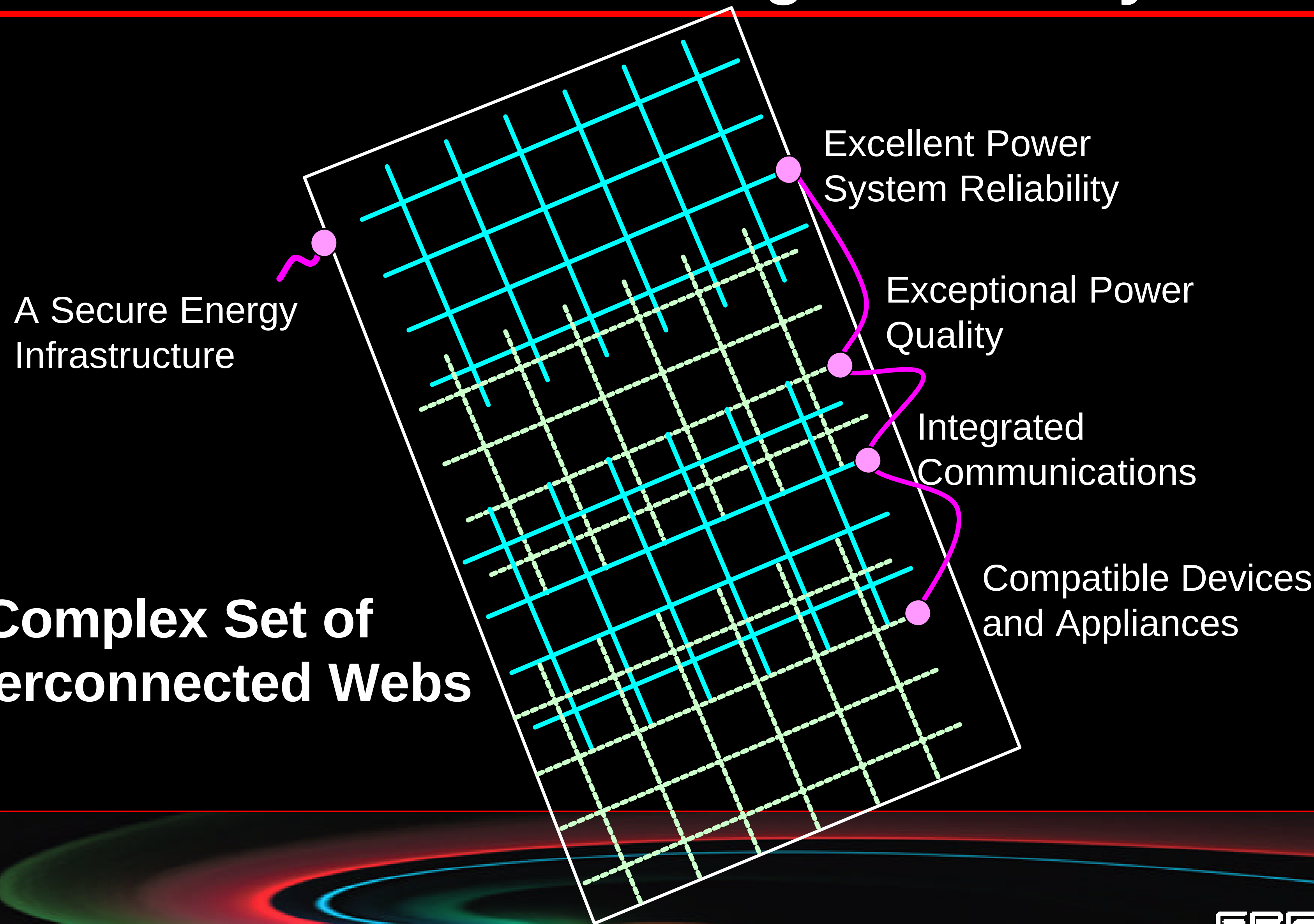
Will the bulk electricity system evolve to become the critical infrastructure supporting the digital society of the 21st century, or be left behind as an industrial relic of the 20th century?

Technology Challenge for Powering the Digital Society



How do we make the leap to the next generation?

The Infrastructure for a Digital Society



A Complex Set of Interconnected Webs

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 26 U.S. universities are funded: Over 360 publications, and 19 technologies extracted, in the 3-year initiative

- U Washington, Arizona St., Iowa St., VPI
- Purdue, U Tennessee, Fisk U, TVA, ComEd
- Harvard, UMass, Boston, MIT, Washington U.
- Cornell, UC-Berkeley, GWU, Illinois, Washington St., Wisconsin
- CMU, RPI, UTAM, Minnesota, Illinois
- Cal Tech, MIT, Illinois, UC-SB, UCLA, Stanford

- 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

EPRI/DoD CIN/SI: Widespread Interest & Participation

- Direct participation and collaboration
  - ComEd and TVA are partners in one of the consortia
- EPRI / SS&T Interest Group review and advice:
  - AEP, BPA, CEC, CA-ISO, ConEd, CPS-SATX, Duke, EDF, ESKOM, Fortum, GPU Nuclear, Idaho Power, IL Power, ISO-NE, Keyspan Energy, Manitoba Hydro, NYPA, Orange & Rockland Util., Southern Company, TXU, VTT Energy, Wisconsin Energy, WAPA
- Government: DOC, DOD, DOE, the National Labs., DOS, DOT, FAA, NAE, NGA, NSF, and the White House OSTP.
- Other Industry: ABB, CESI, Intel, Pirelli, Powertech, Raytheon, …
- European Union and Asia

EPRI

Complex Interactive Networks

107 professors and over 210 students in 26 U.S. universities were funded
Over 360 publications and 19 technologies in the 3-year Initiative

- Overall results (theoretical and applied) for increased dynamic network reliability and efficiency:

  Identification, characterization and quantification of **failure mechanisms**

  In Silico testing of devices and policies in the context of the whole system-- the grid, markets, communication and protection

  Fundamental understanding of interdependencies, **coupling and cascading**

  Development of **predictive** models

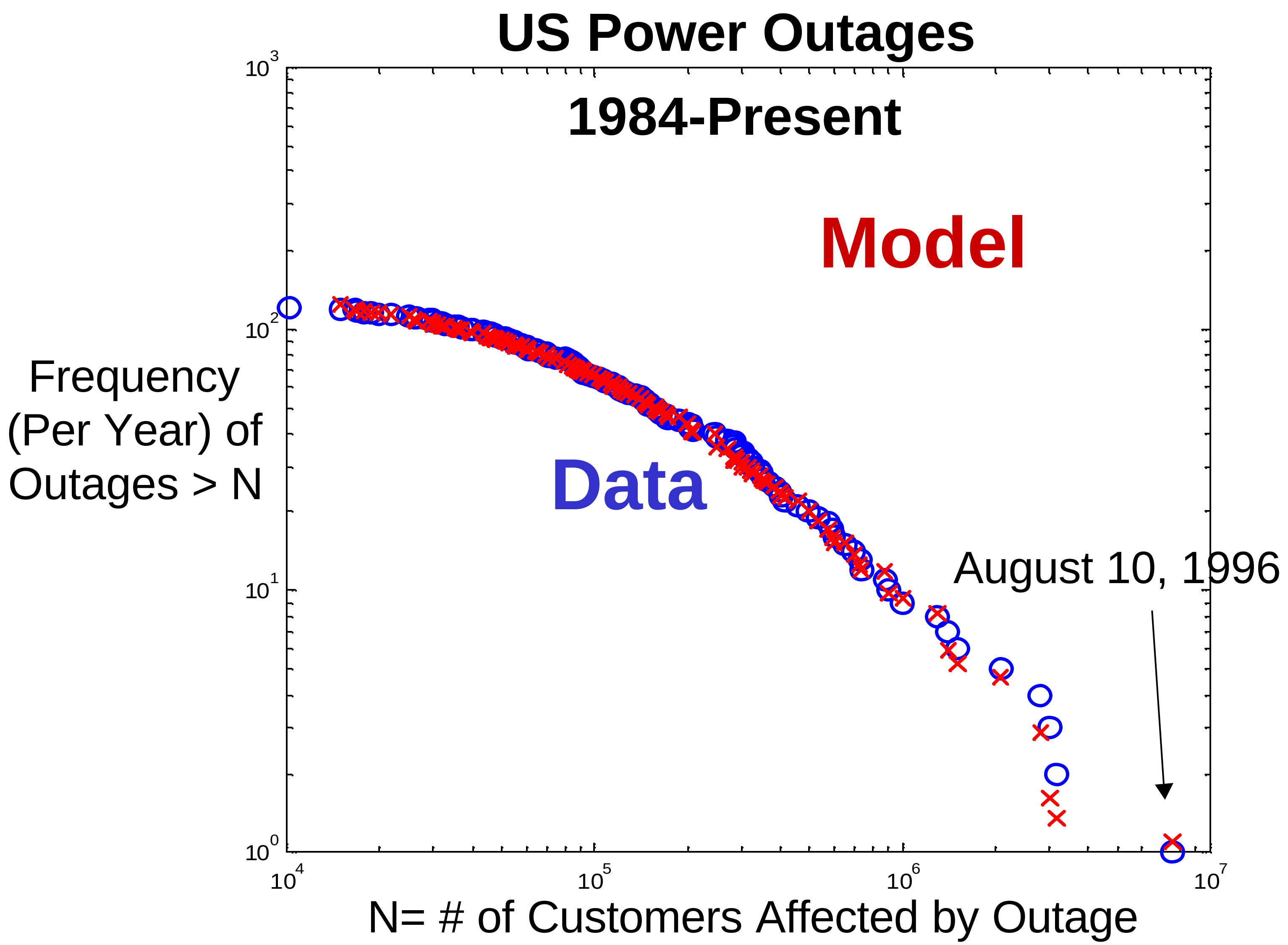
  Development of prescriptive procedures and **control strategies** for mitigation or/and elimination of failures

  Design of **self-healing and adaptive** architectures

  Trade-off between **robustness and efficiency**

- **Near-Term:** Extract a few of the most promising technologies for testing with real data and further development.

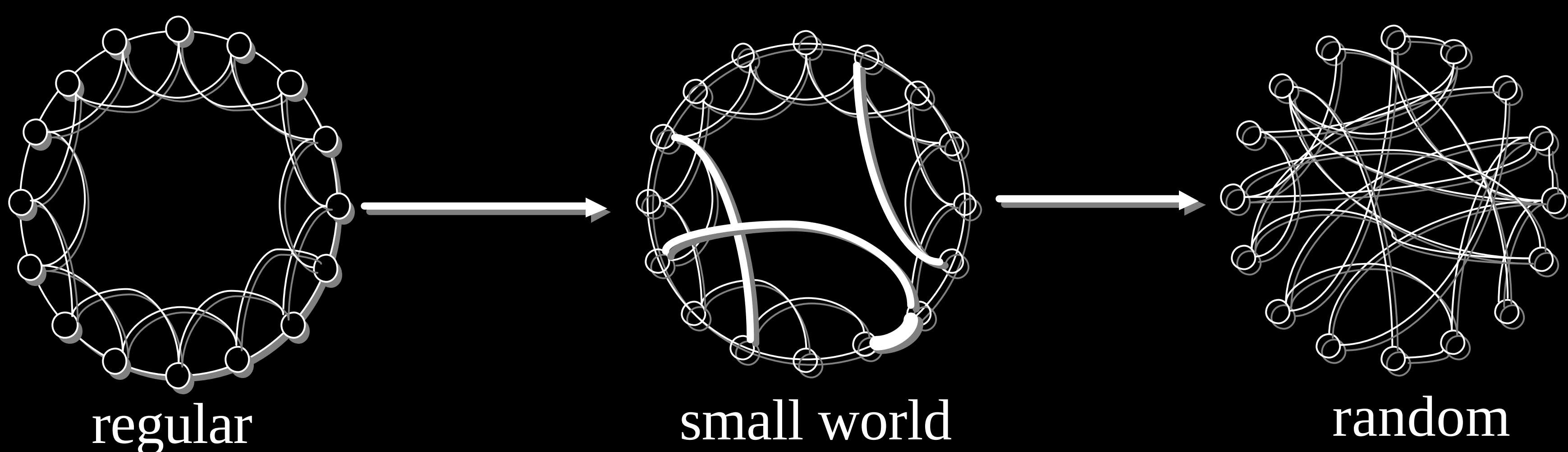
Complex Interactive Networks Initiative



EPRI/DoD CIN/S Initiative

Efficient and designed networks
… relations to Topology &Dynamics?

- Topology affects dynamics (Watts/Strogatz ‘98; Watts’99).
  - “small world” topology enhances signal propagation.
  - Dynamics of cascading failures is related to the topology of the telecommunication network or power grid.
  - The Transmission network of Western U.S. has a small world topology (Watts & Strogatz, ‘98; Watts, ‘99)



Small-World Models: Objectives

- Develop protection strategies that are:
  - self-optimizing
    - minimize the load lost due to disturbances
  - self-healing
    - provide efficient restoration
- First step: understand collapse phenomena.

Crude Propagation Model

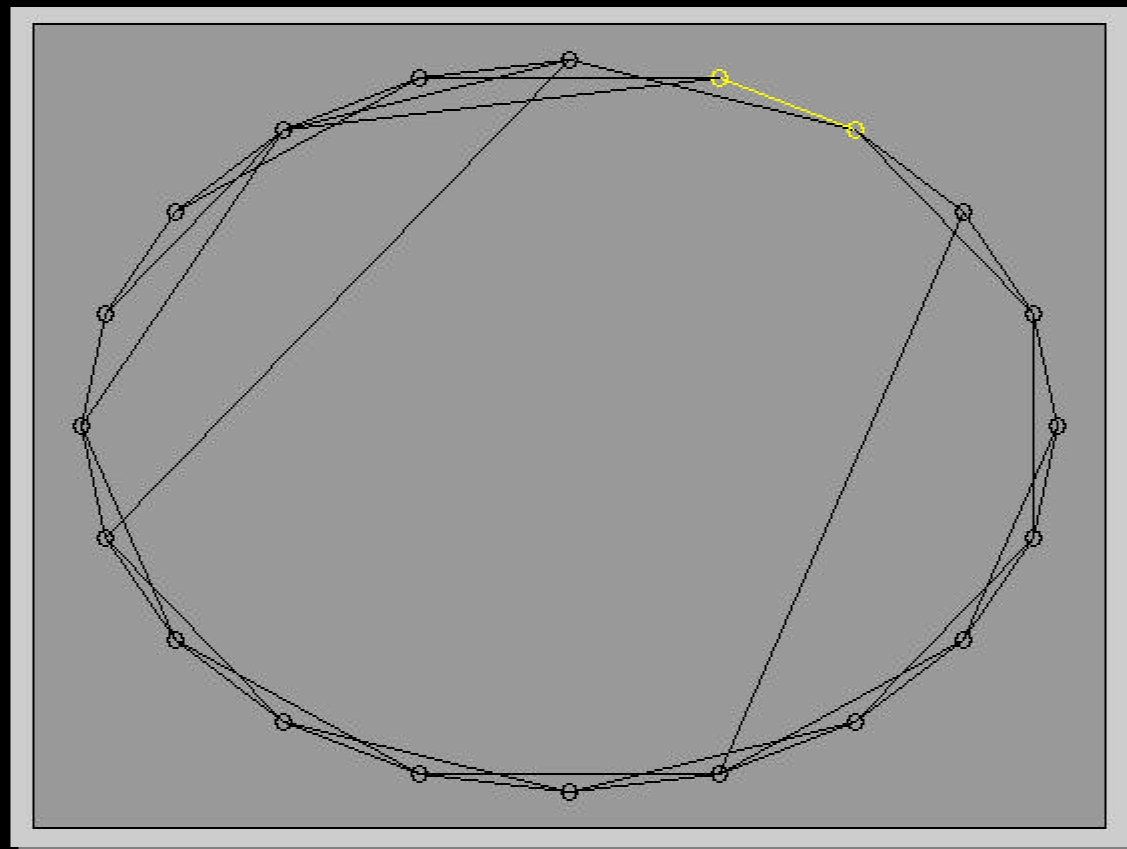
Circuit Breaker Action
? virus spreading

1) Lightening strikes a line.

2) Induced transient trips breakers at neighboring busses with probability 0? *q* ? 1.

3) Continue until cascade stops.

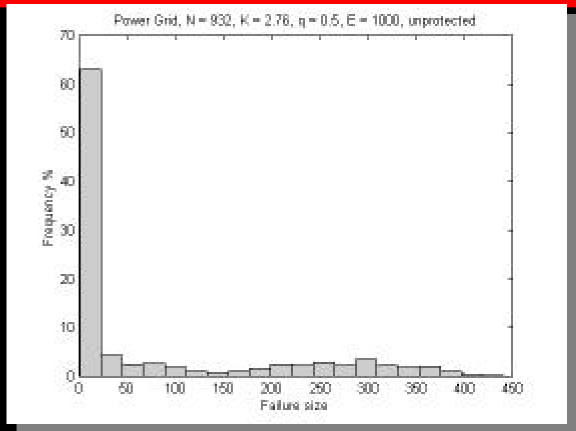
4) Blackout size ? number of busses affected.



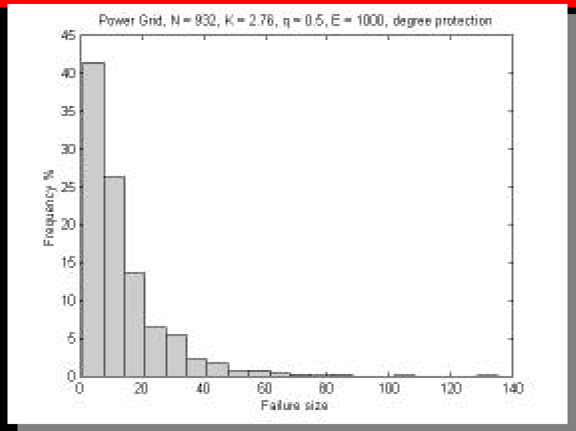
Fortification: Illustration (real topology data)

Experiments conducted using topology data for a portion of the Western U.S. power grid.

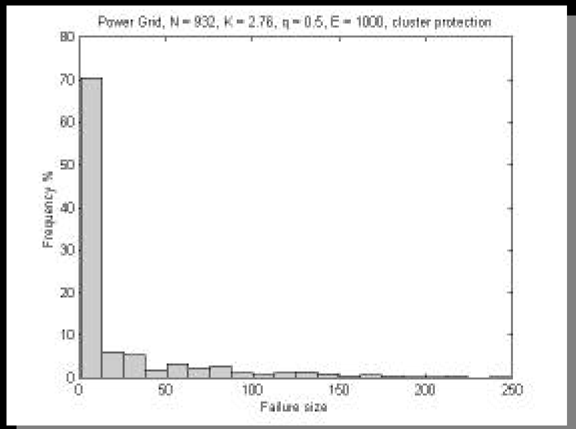
- 932 busses
- 1288 lines



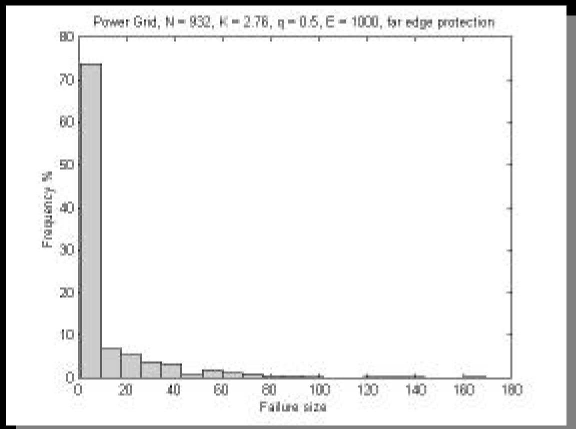
No short cut fortification
mean = 78.96



Heuristic 1: Degree fortification
mean = 13.36



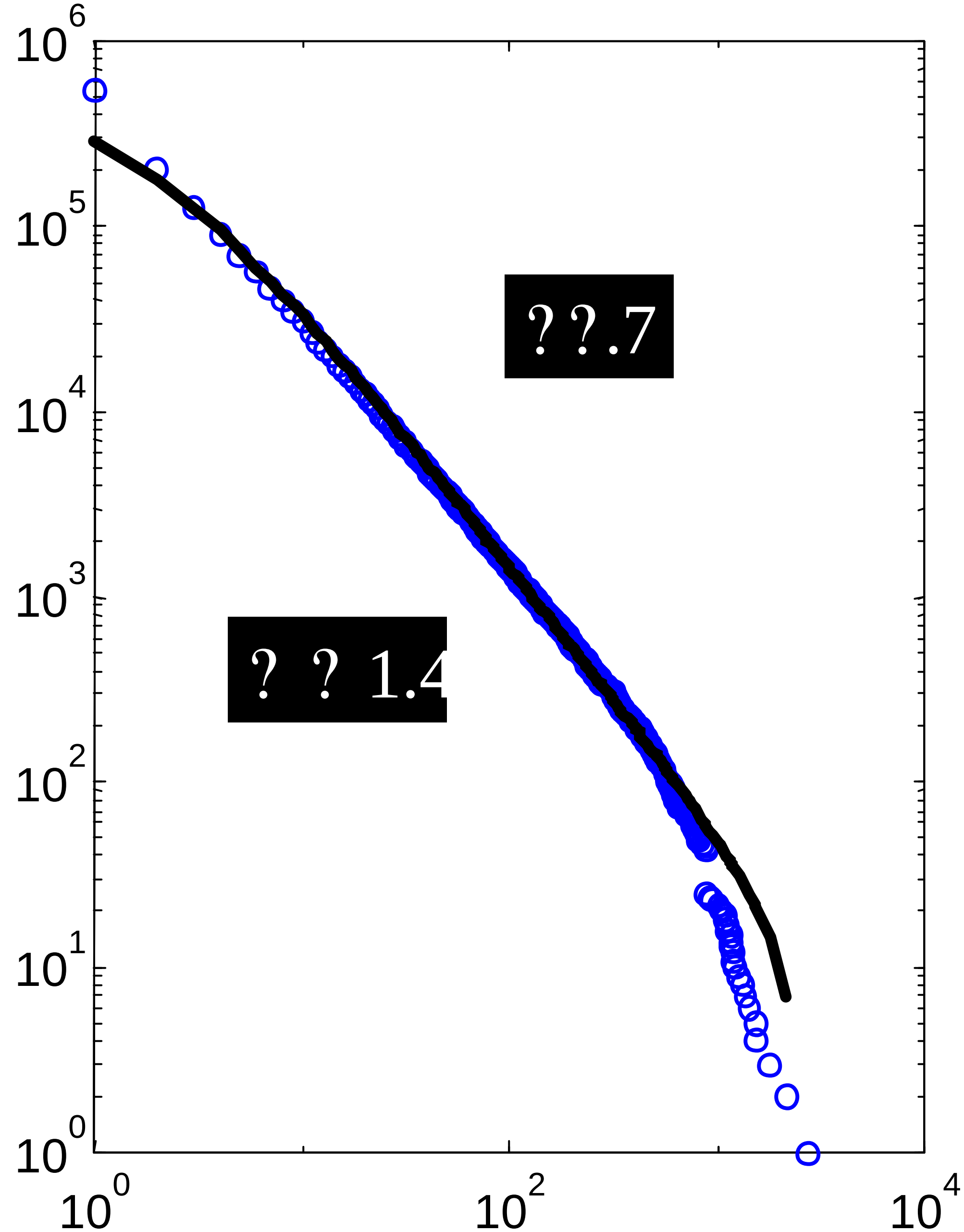
Heuristic 2: Cluster fortification
mean = 22.90



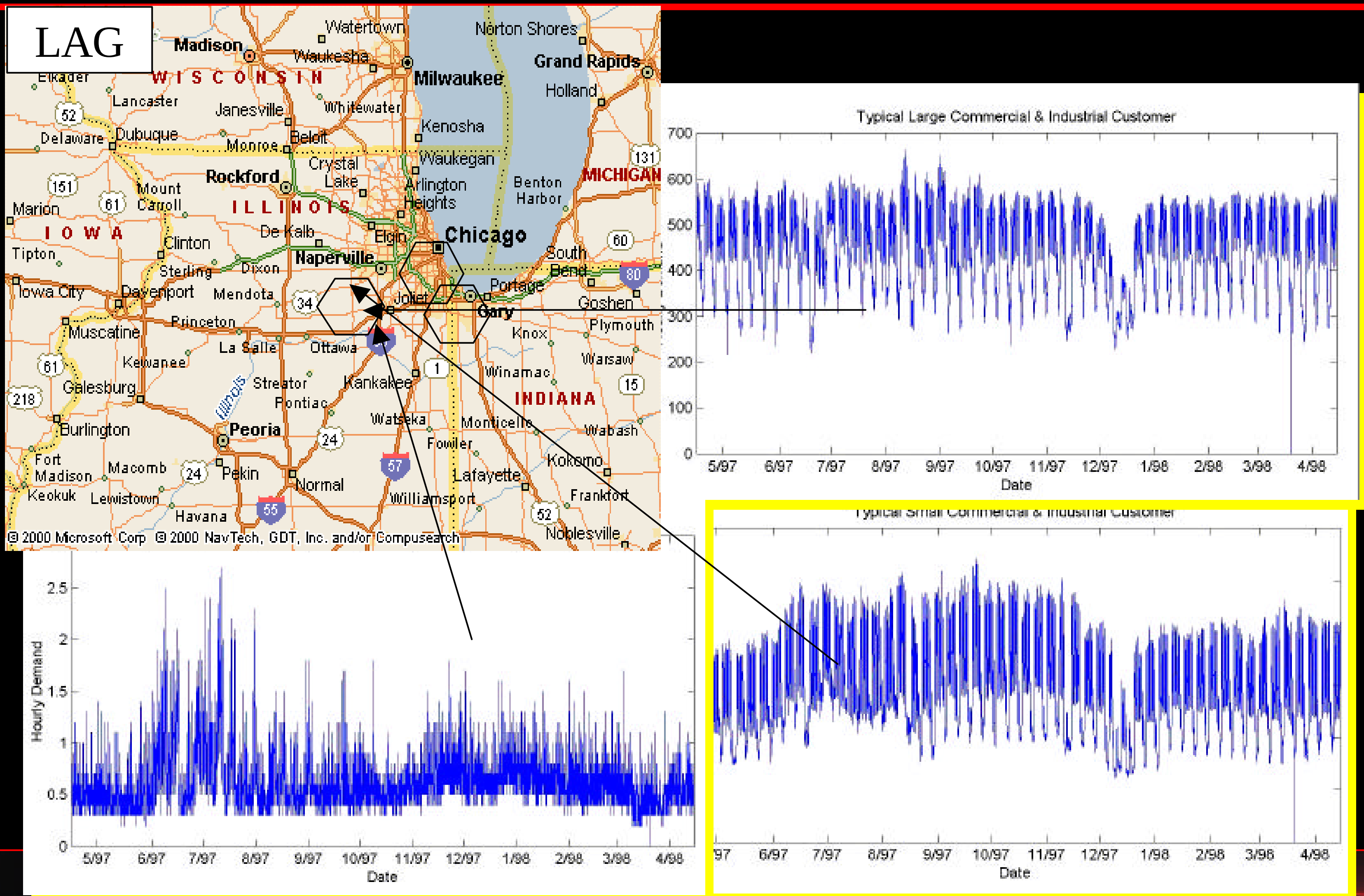
Heuristic 3: Far Edge fortification
mean = 11.62

Simulation on 932-bus Power Grid

- PG&E network graph
- Failure size = time-accumulated number of failed nodes resulting from single initiating failure.
- Failure sizes are reported when all failed nodes induced by the initiating failure have recovered.
- 500K events



Local area grids (LAG)

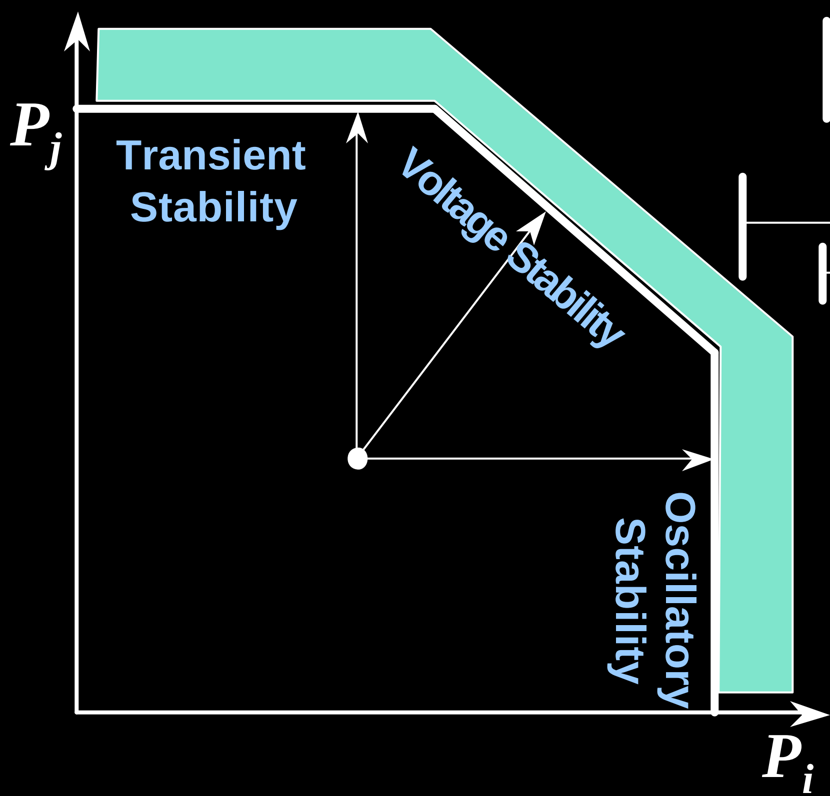


Look-Ahead Simulation Applied to Multi-Resolution Models

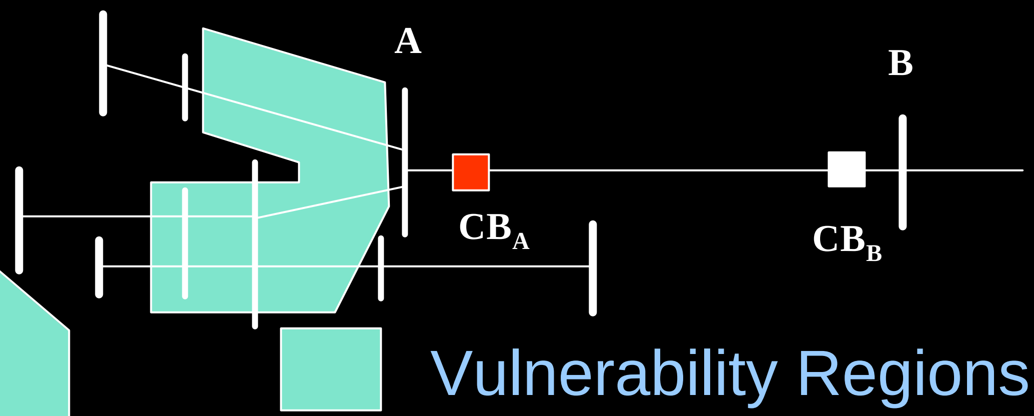
- Provides faster-than-real-time simulation
  - By drawing on approximate rules for system behavior, such as power law distribution
  - By using simplified models of a particular system
- Allows system operators to change the resolution of modeling at will
  - Macro-level (regional power systems)
  -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

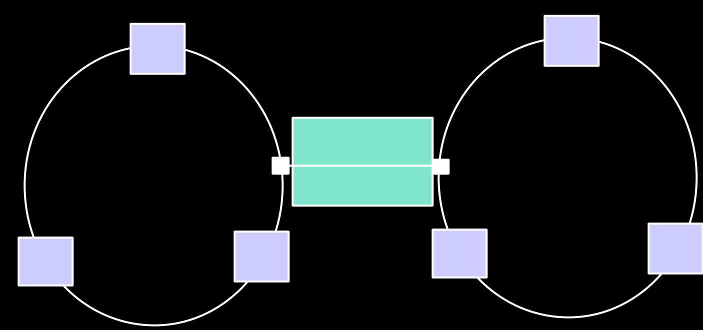
Vulnerability Indices

Dynamics and Control



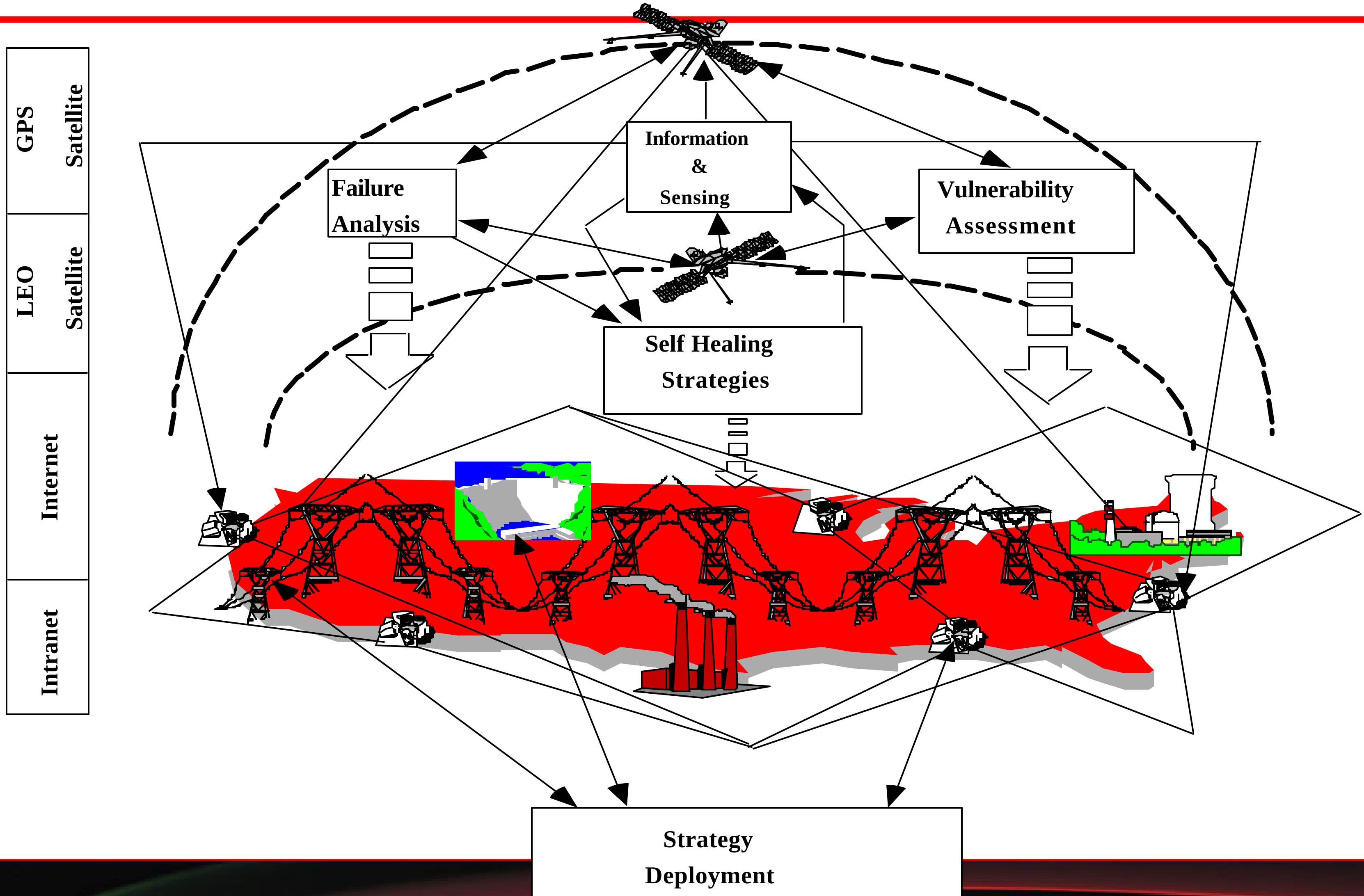
Protection



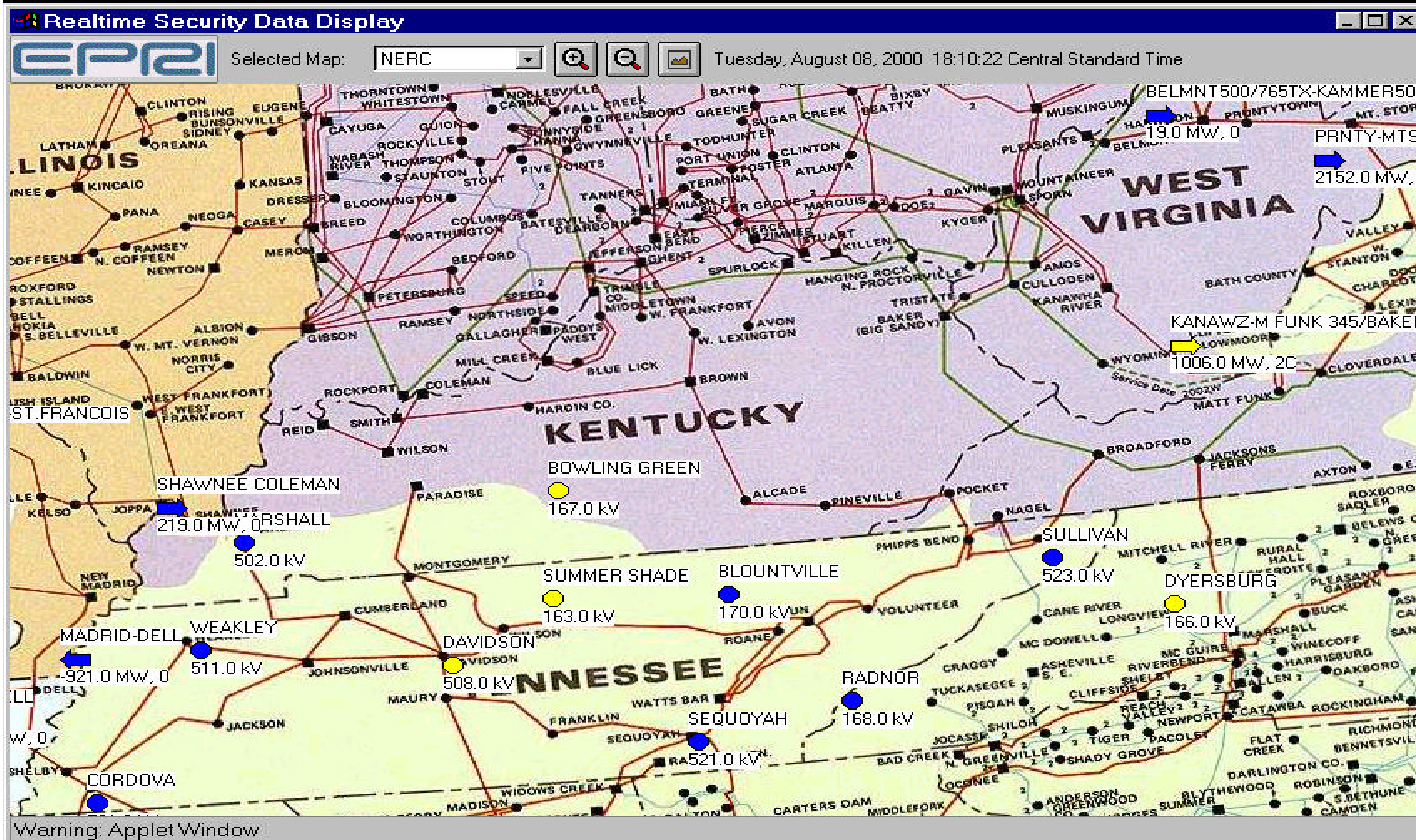


A new method to measure the vulnerability of the communication system and its impact on the performance of the power grid; will be extended to use the PRA and sensor data

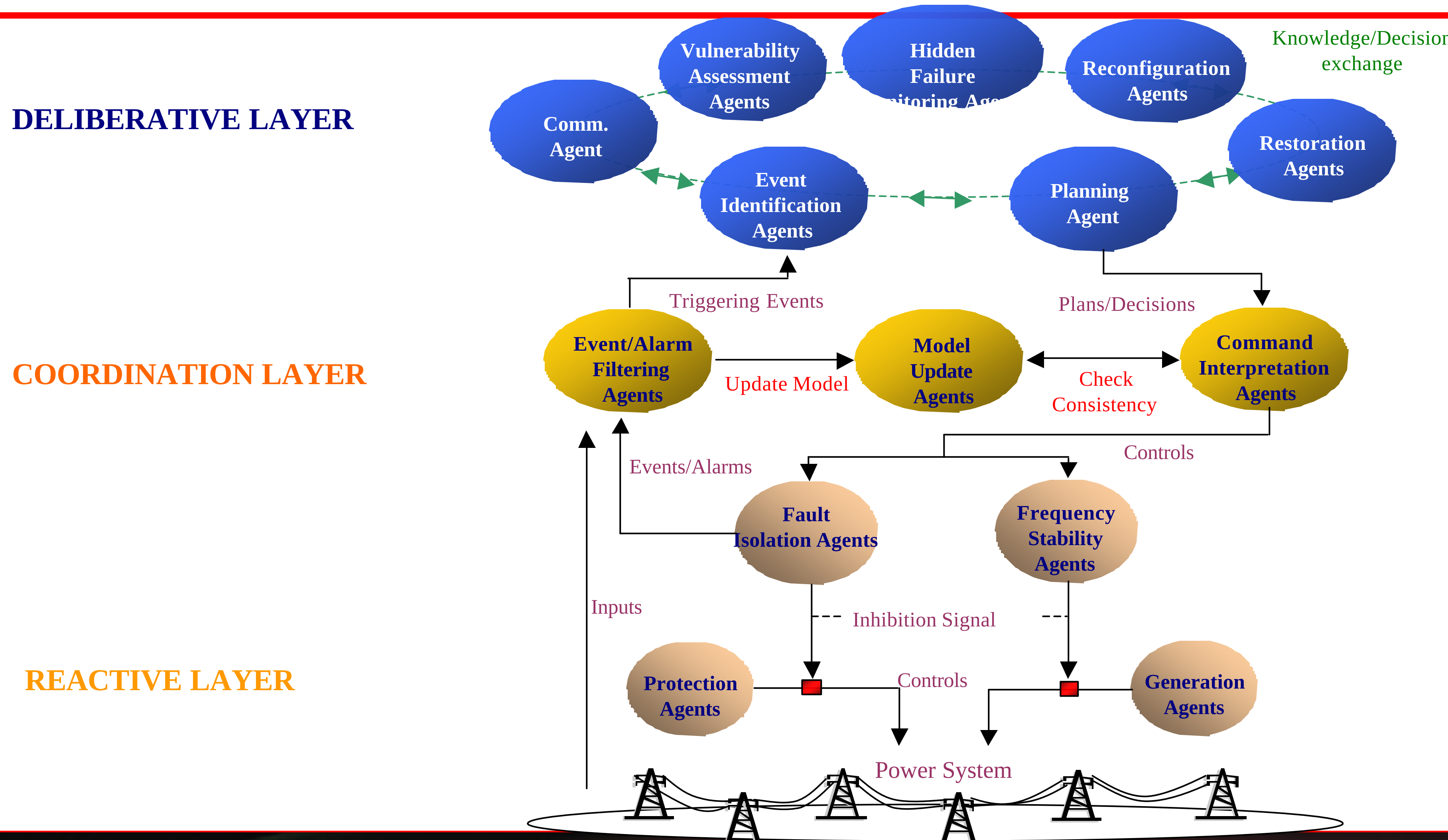
Complex Interactive Networks



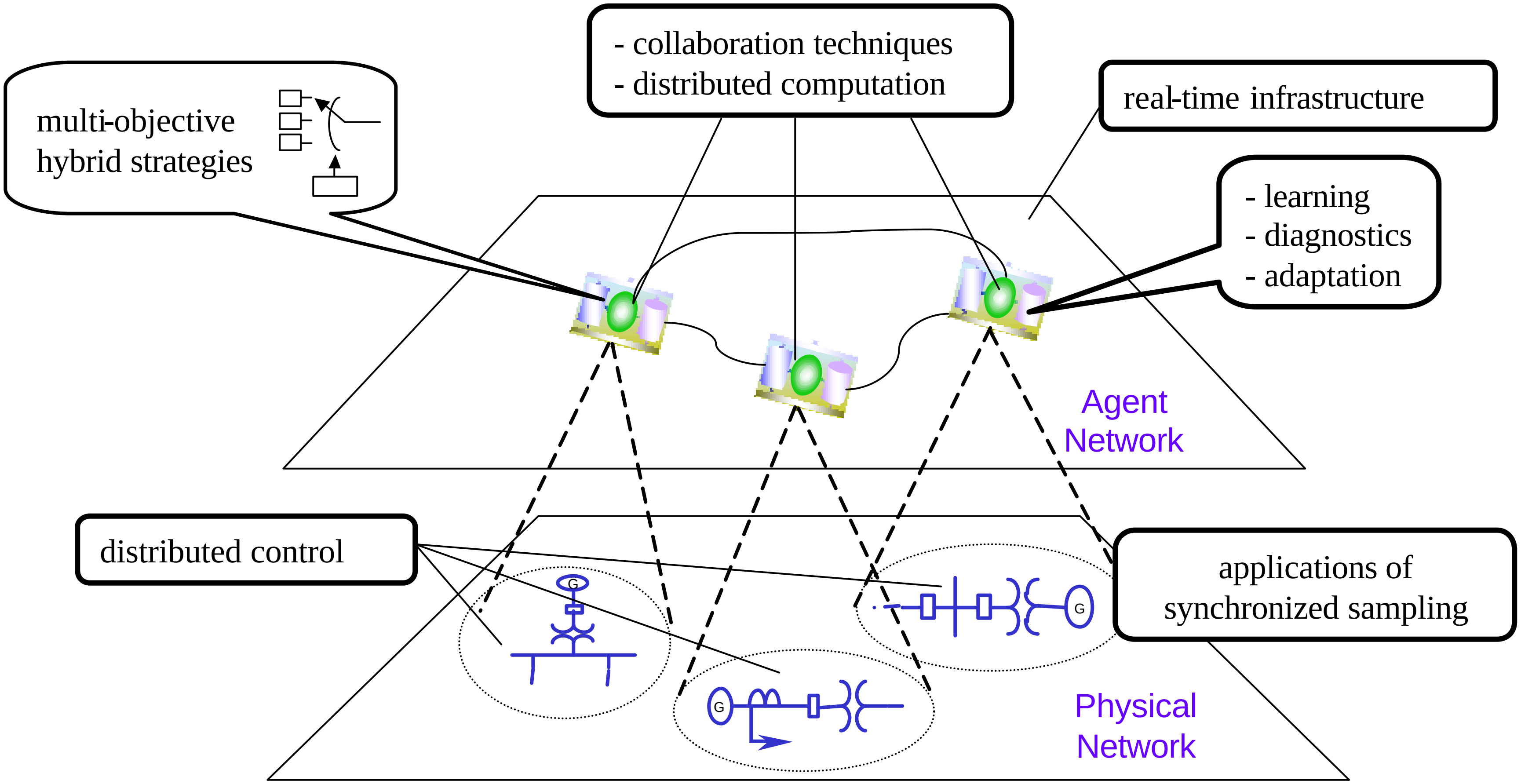
EPRI's Reliability Initiative-- Sample Screen of Real-time Security Data Display (RSDD)



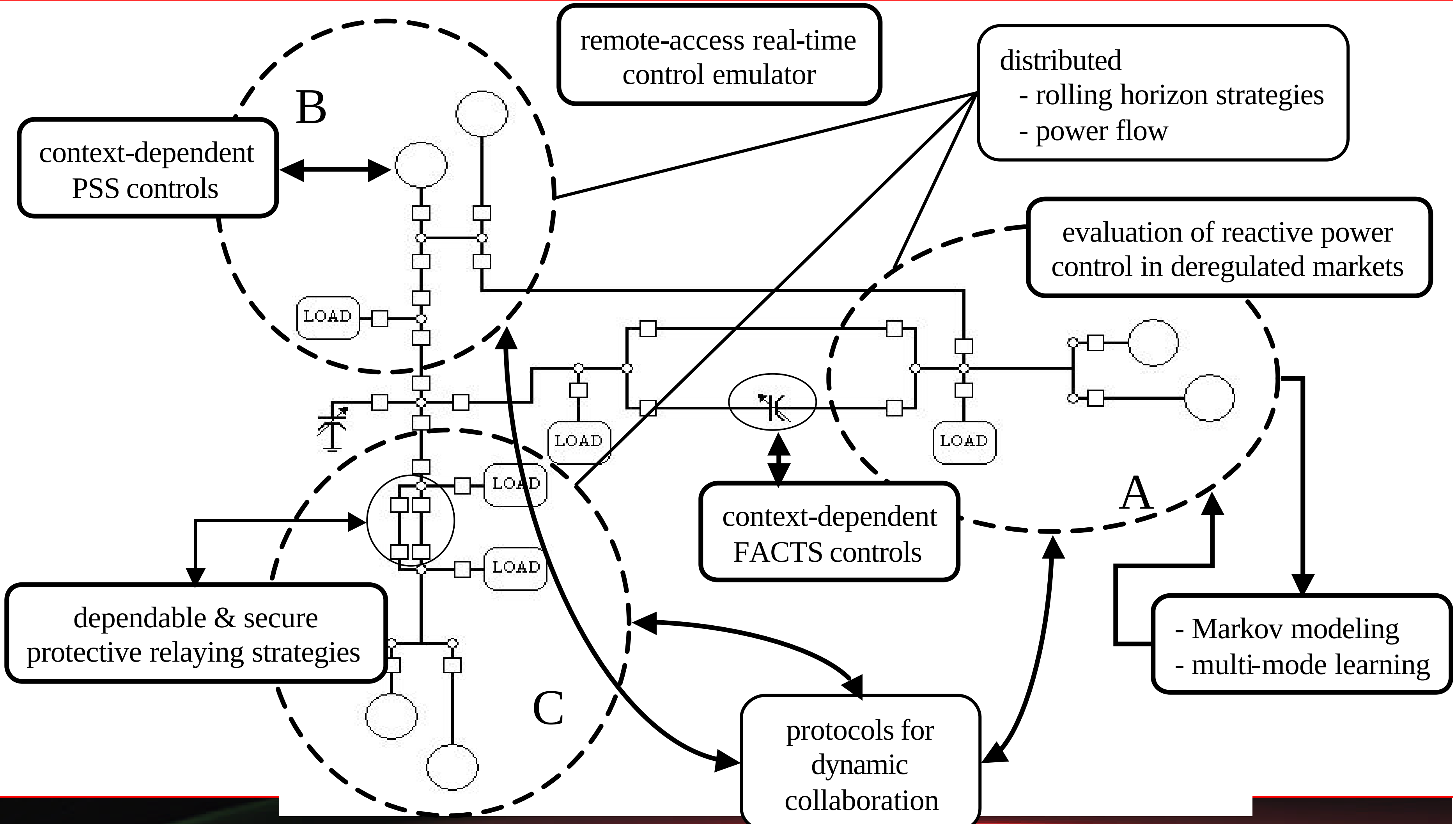
Integrated Infrastructure Protection and Control via Multi-Agent Systems



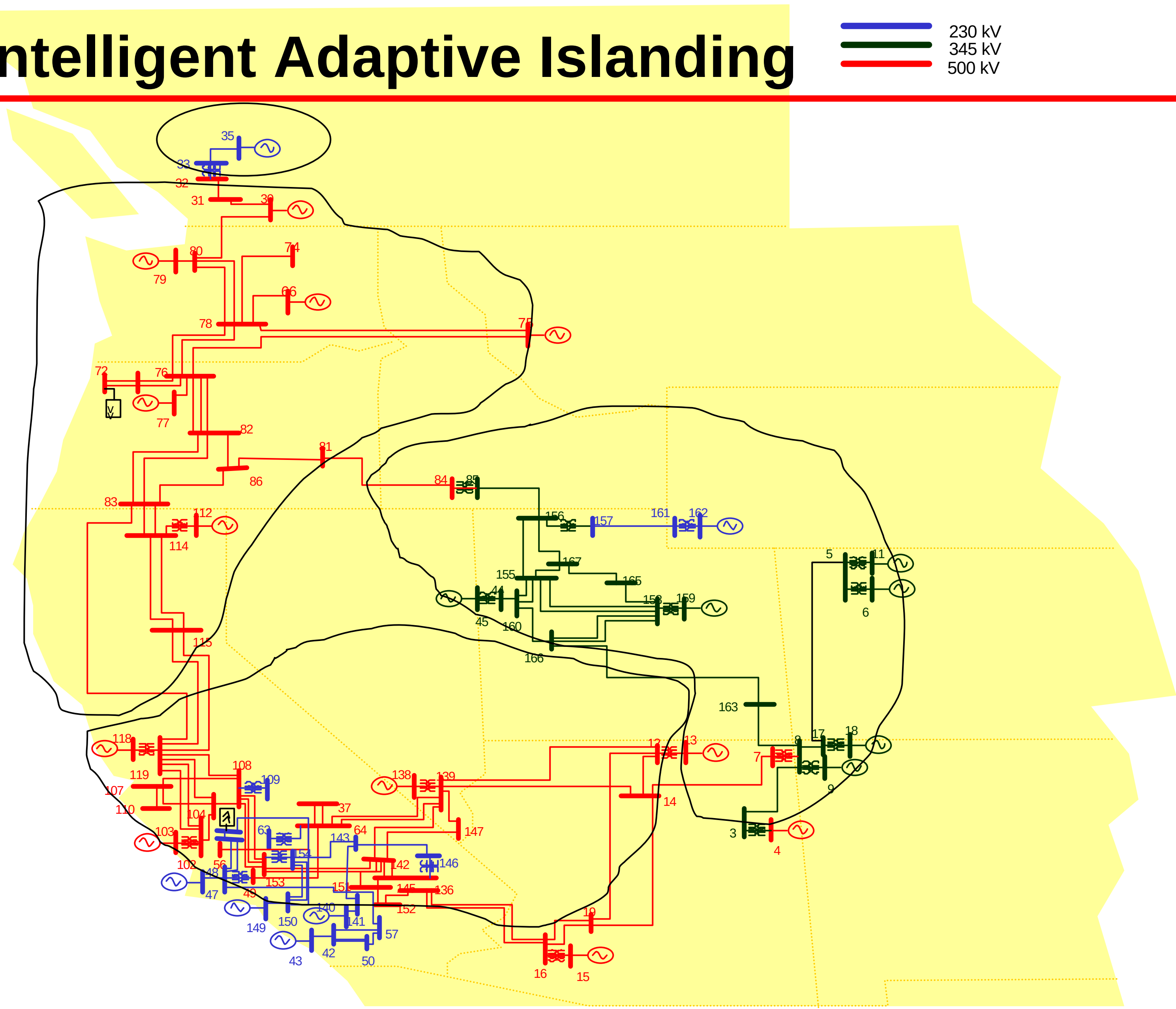
Context-Dependent Network Agents



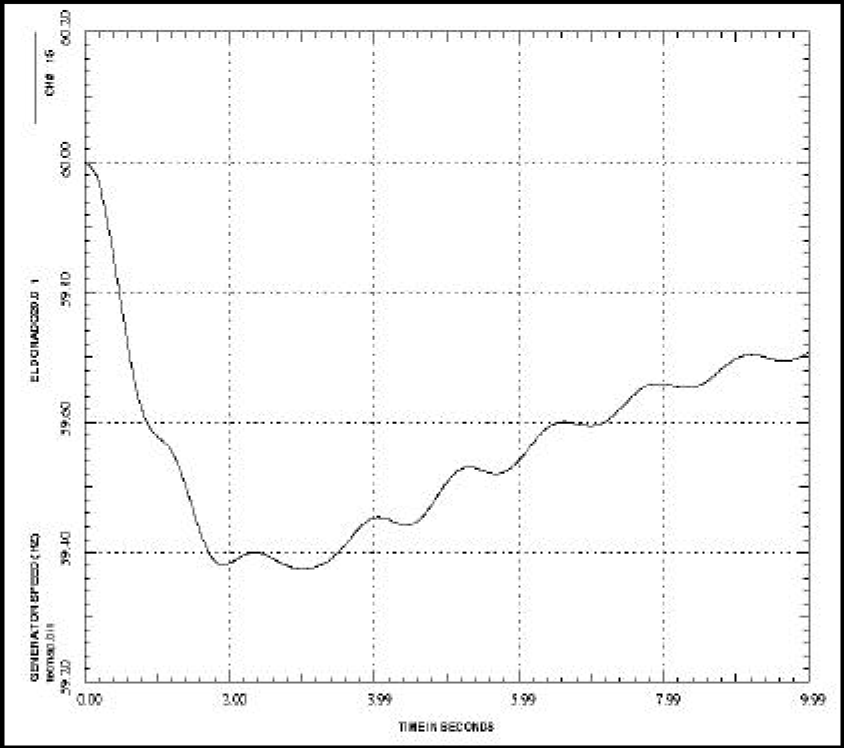
CDNA: An Example

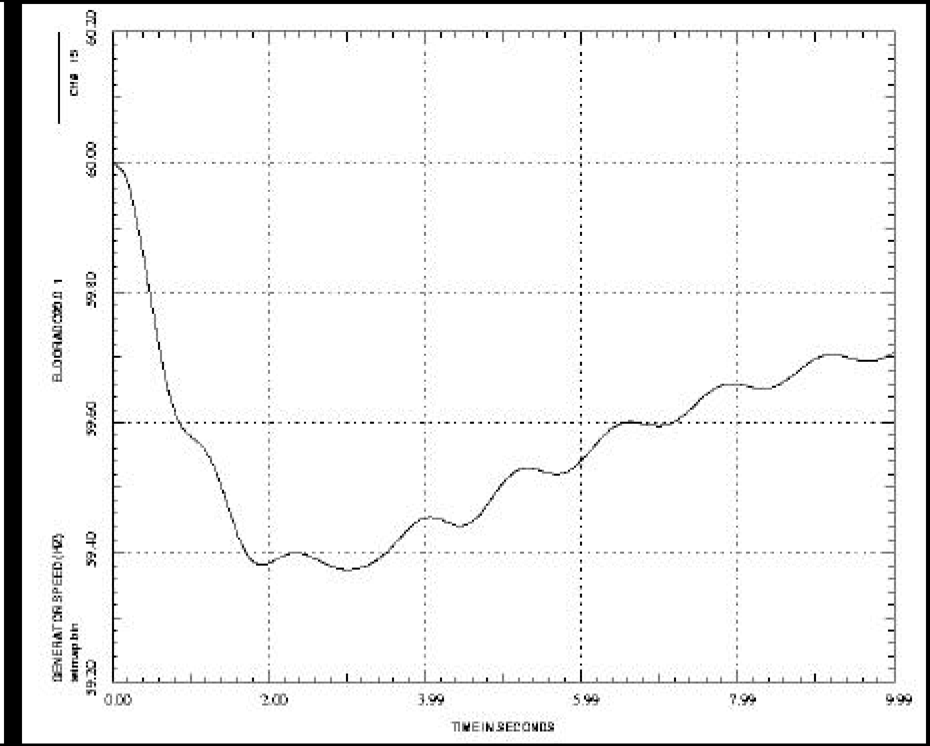


Intelligent Adaptive Islanding



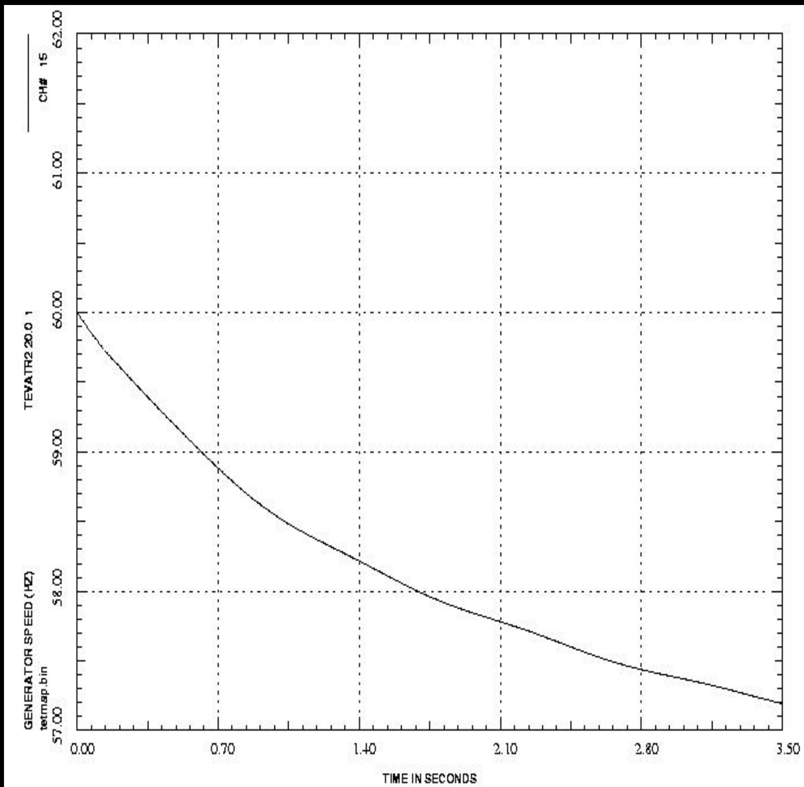
Simulation Result:
Machine in South Island



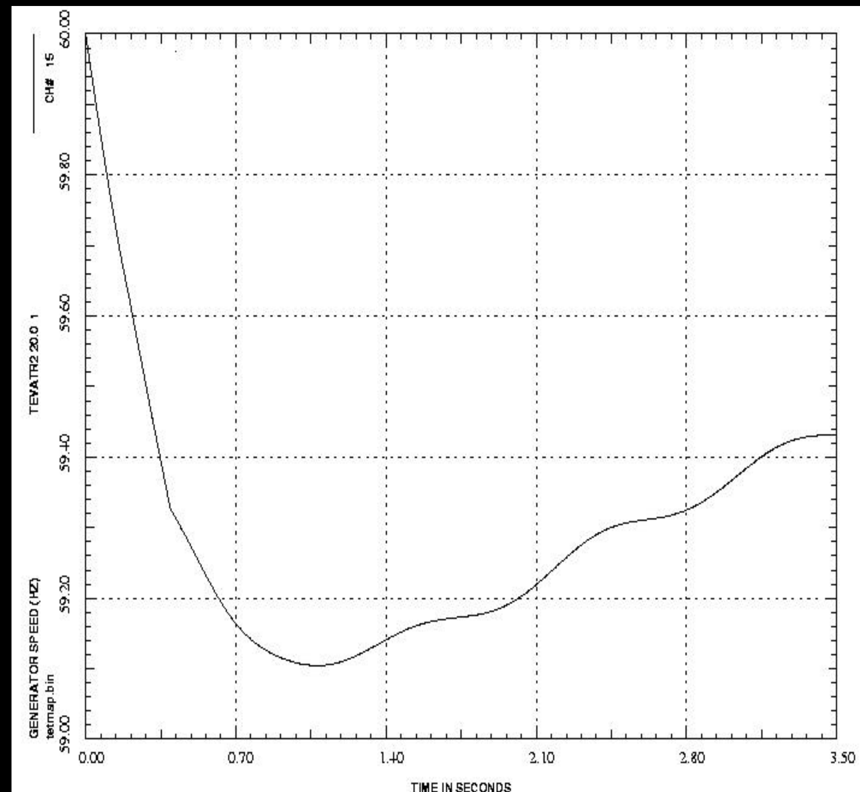


No Load is Needed to be Shed in the South Island

Simulation Result:
Machine in Central Island



No Load Shedding



New Load Shedding Scheme

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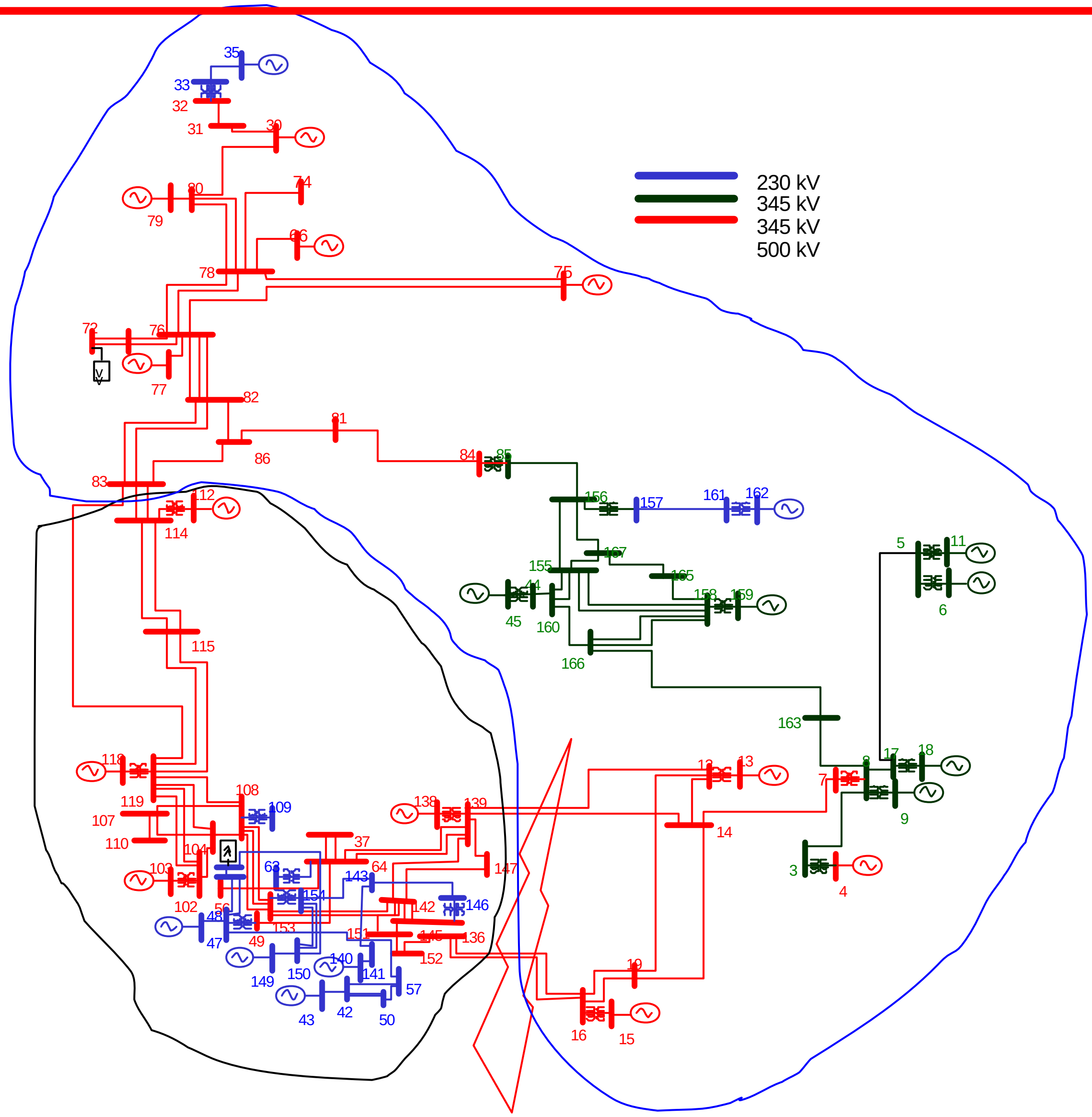
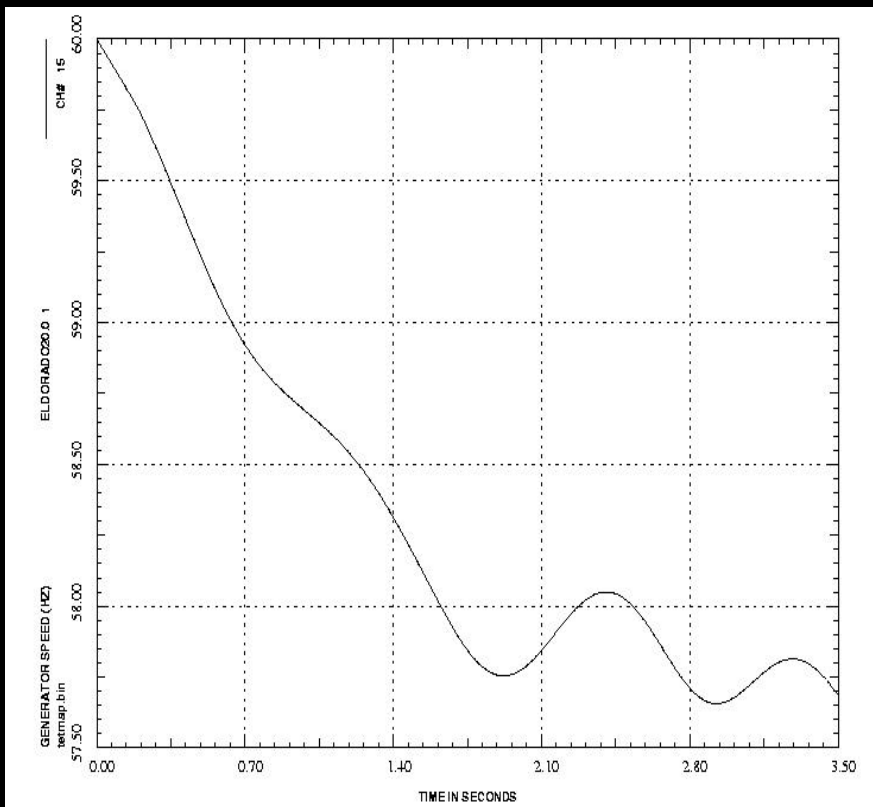
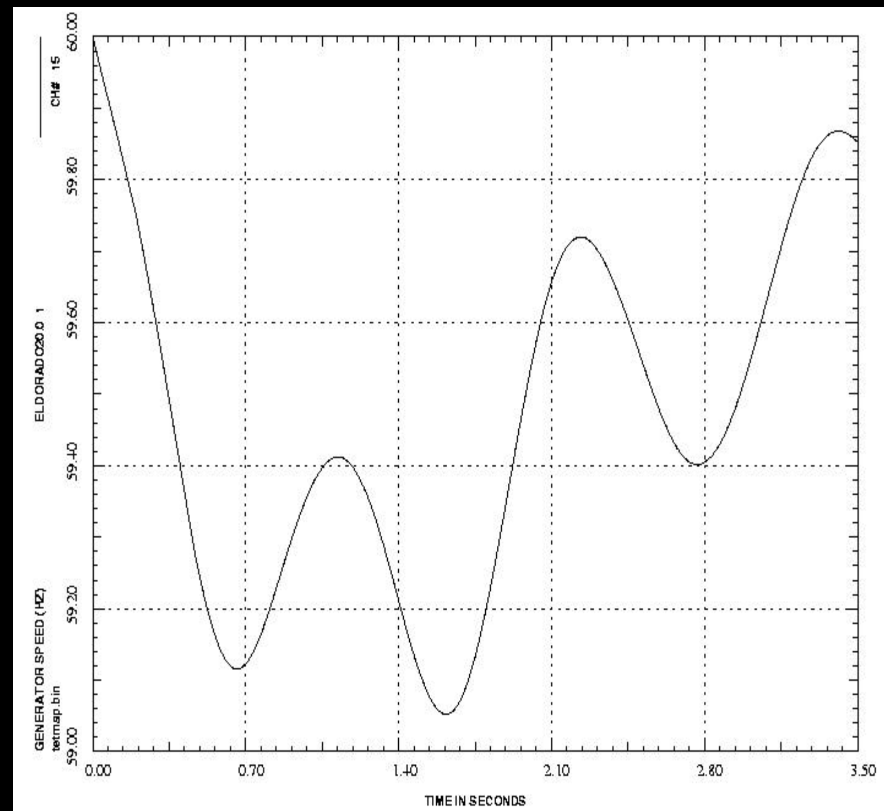
Islanding by Slow Coherency(2)



Simulation Result

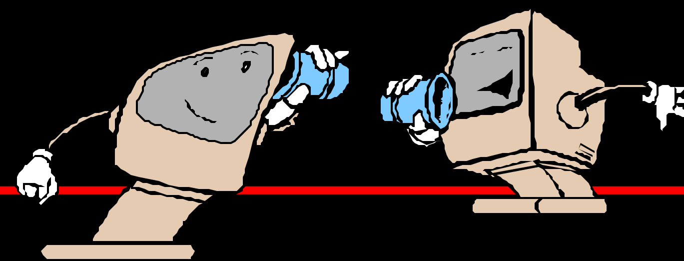


No Load Shedding Scheme

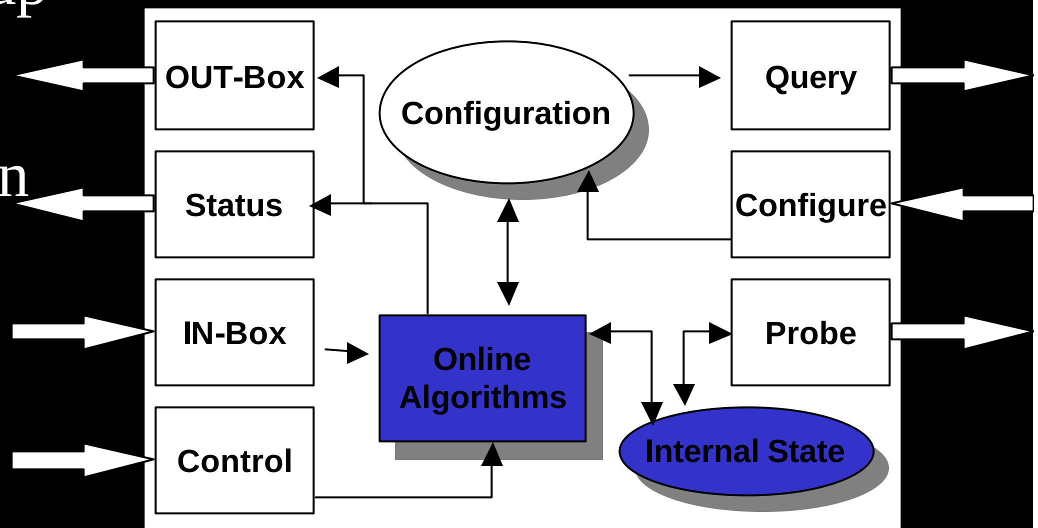


New Scheme

Electricity Market Simulation

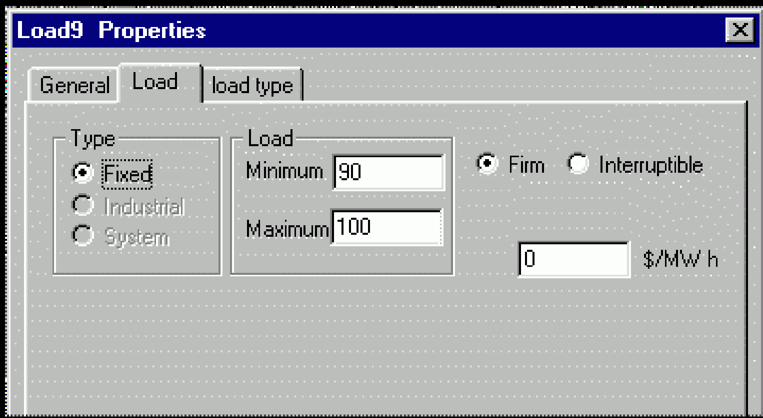


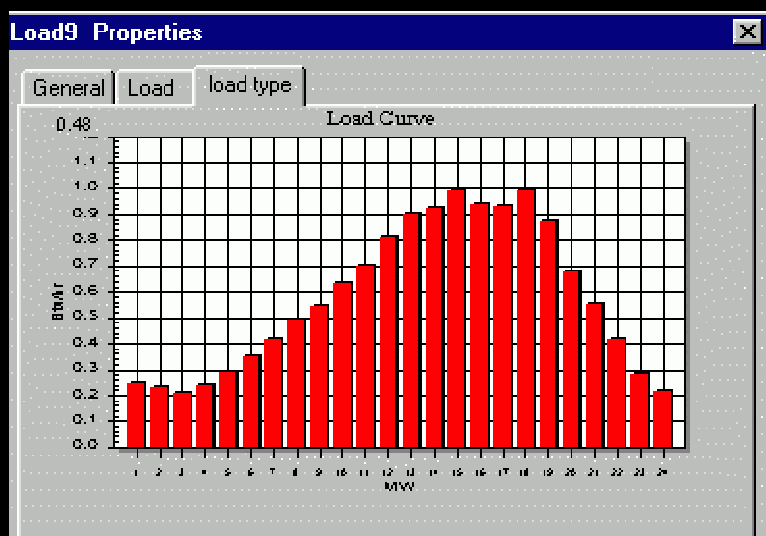
- Power market simulator made up of computer agents
- Agents make decisions based on available information
- Adaptive algorithms let agents learn from experience
- Costs much less to simulate on a computer than to experiment in the real world!
- Facilitates power market design

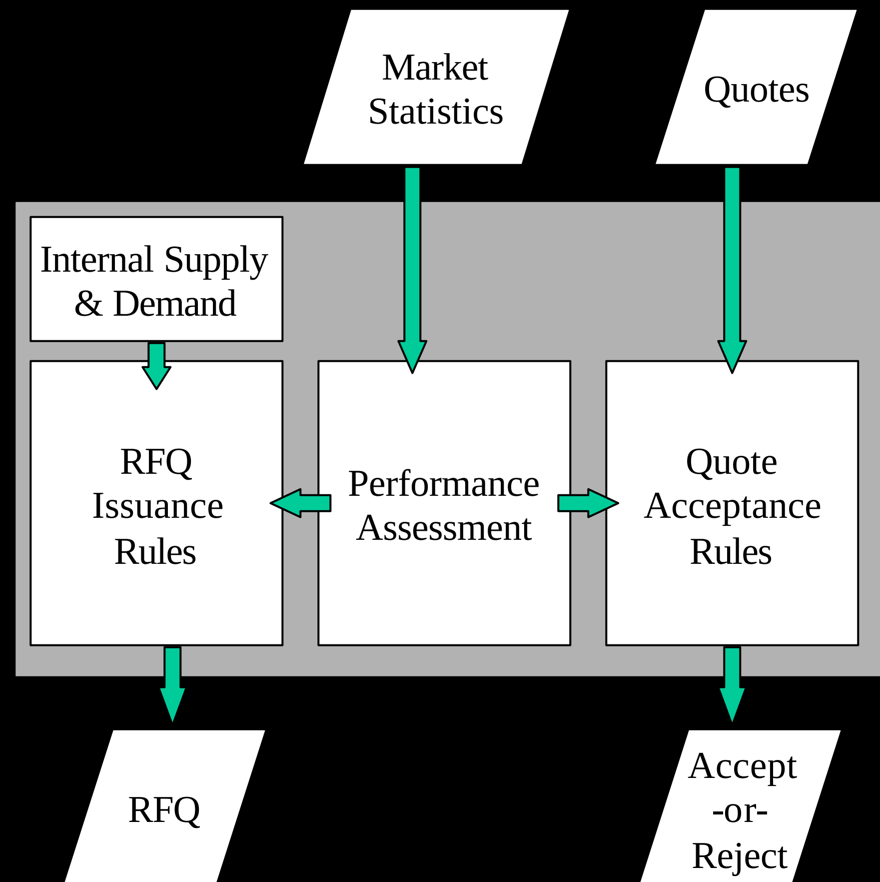


Agent Architecture and Adaptation. Agent design determines *when* and *how* Online Algorithms modify internal state based on experience

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







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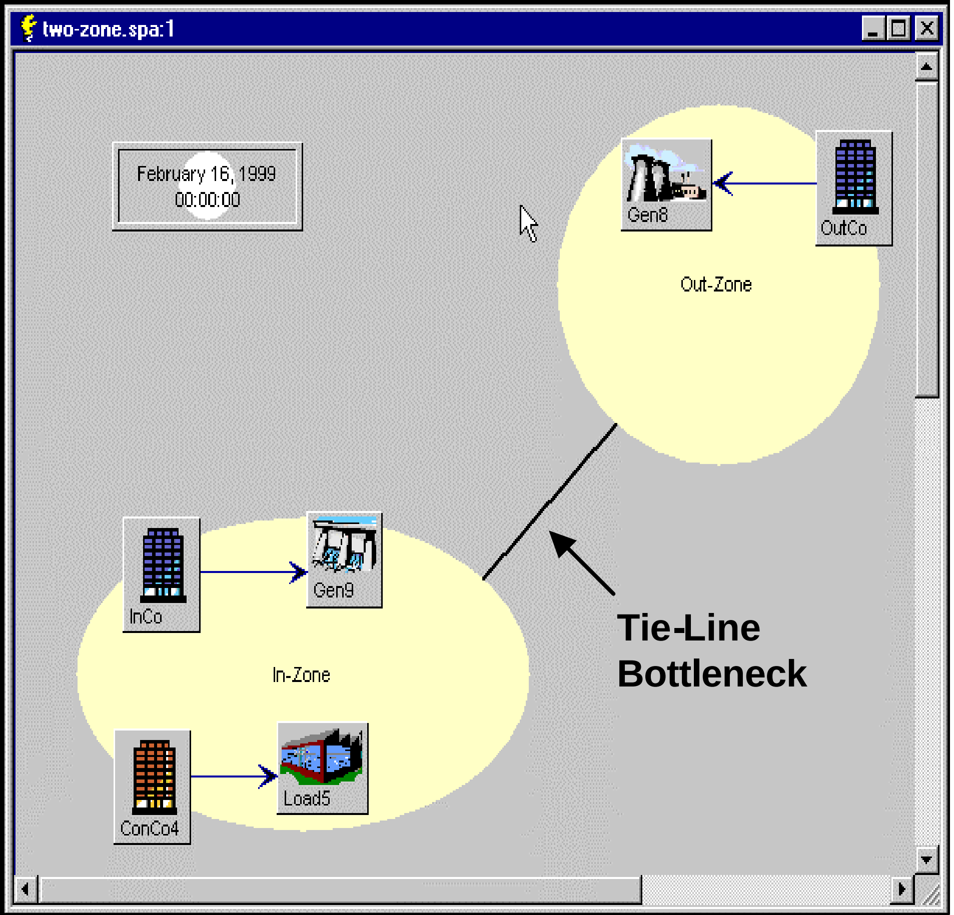
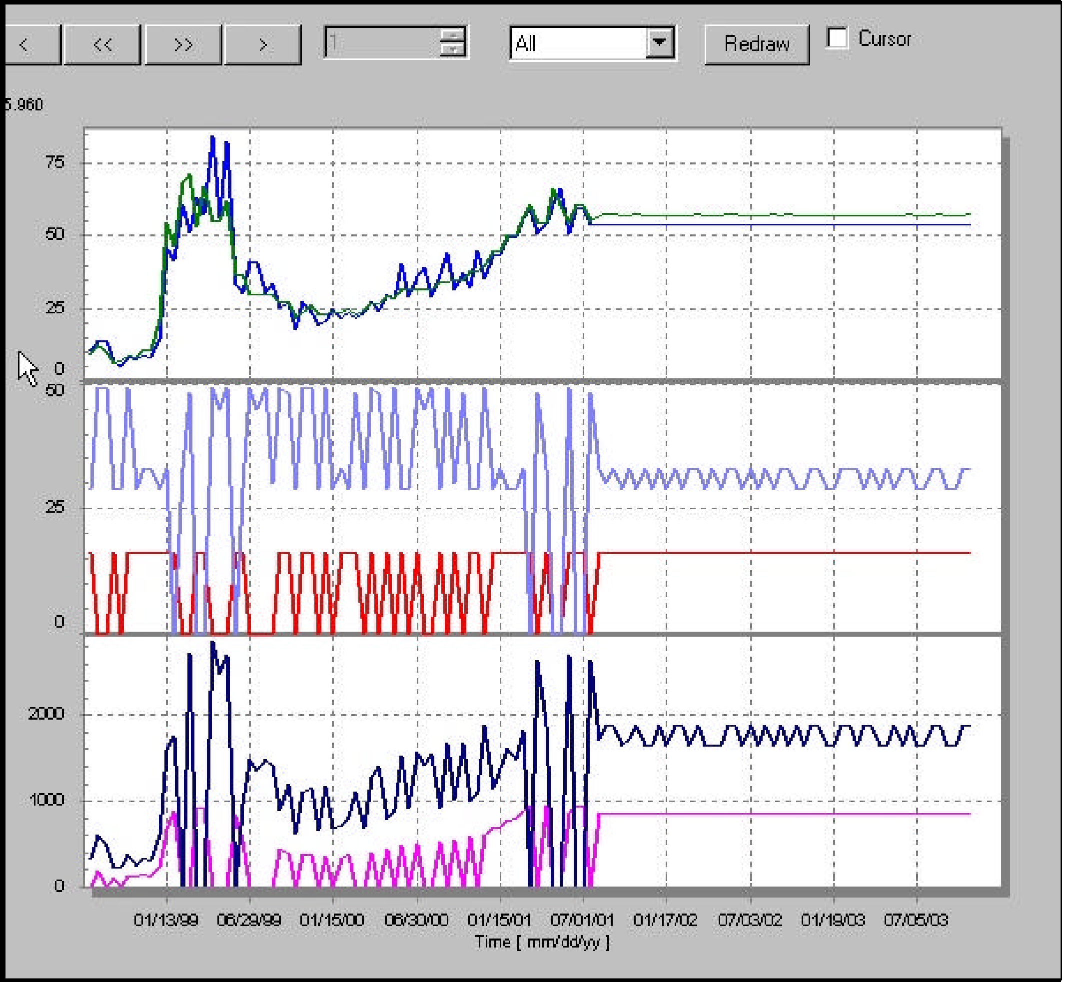
Example of Market-Grid Interactions: Setup

- 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



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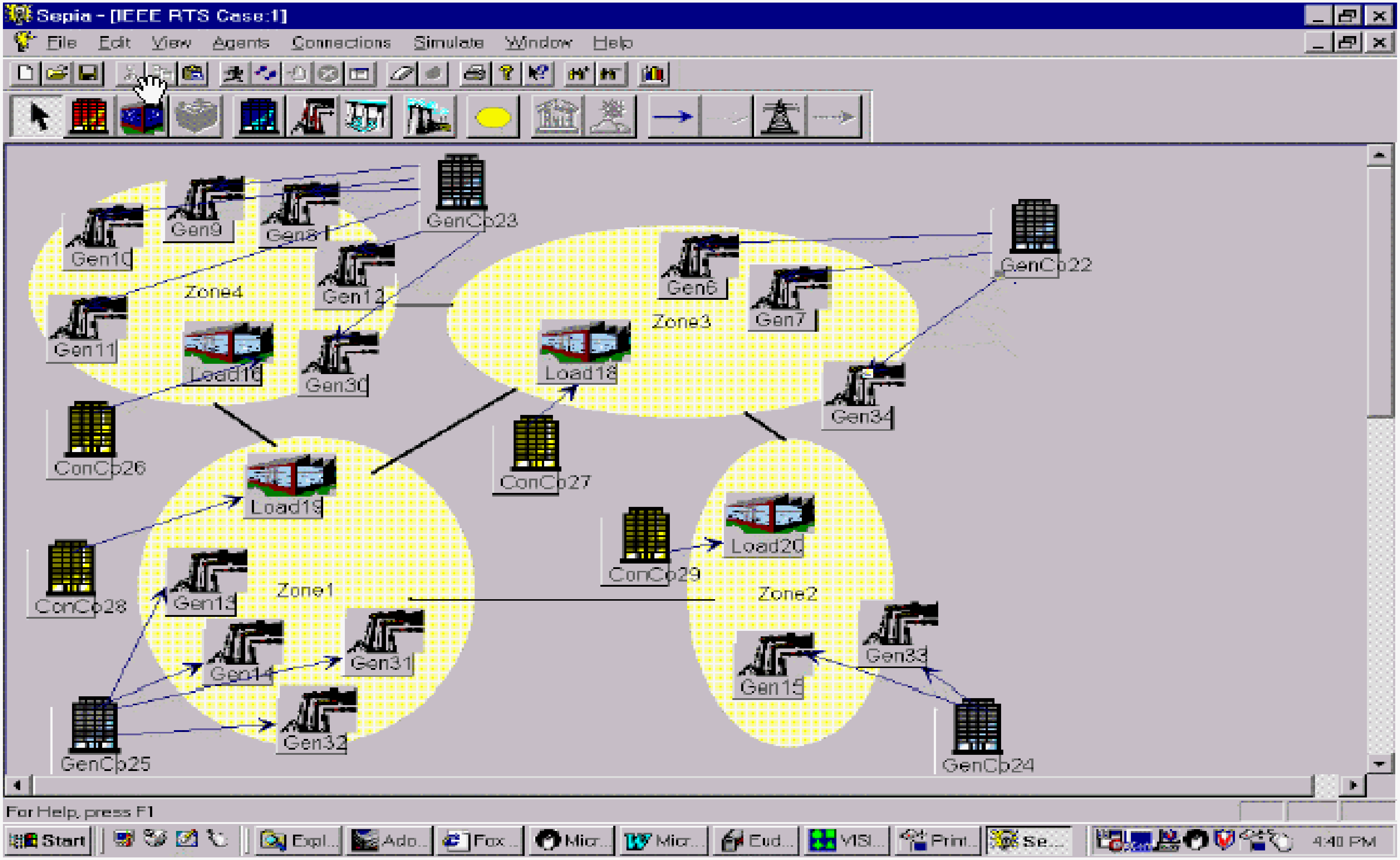
… four regions with diverse loads and 15 generators

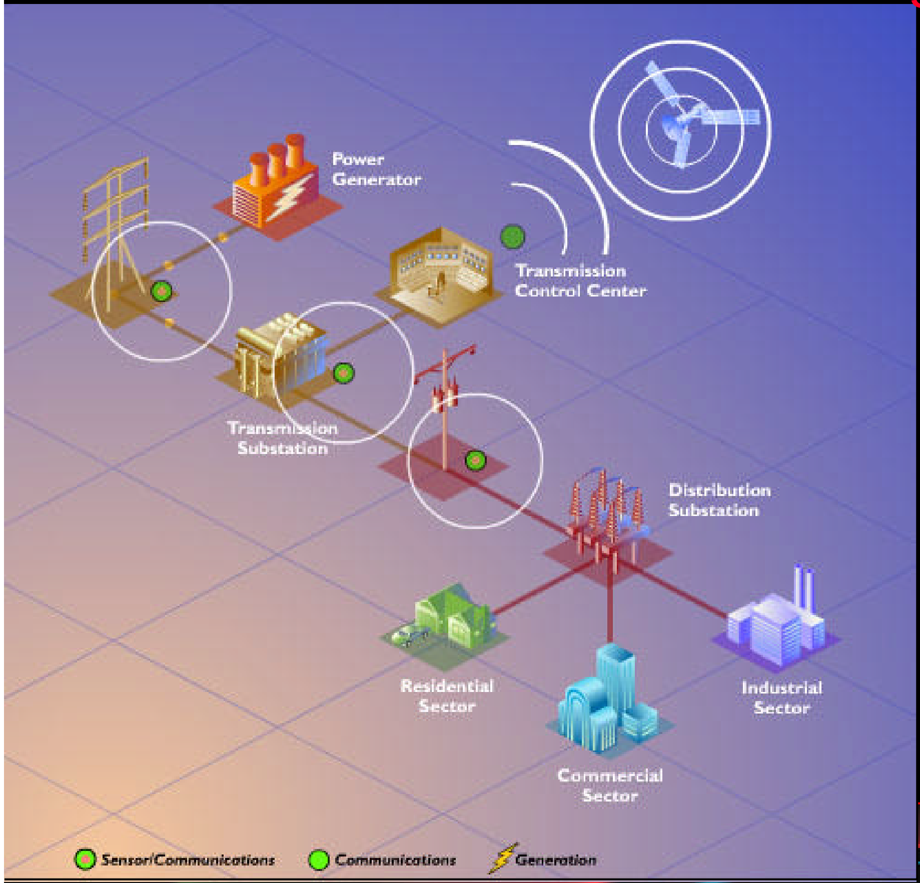


Modeling of Market and Policy Impacts on Reliability

- Development of multi-resolution models provides opportunity to test new regulatory policies and market designs before putting them into practice
- Market players can also use the models to identify participation strategies
- Enhanced modeling will aid system planners in determining how new physical devices (e.g. FACTS controllers) will affect a power system

A vision for the future: Integrated Network Control (INC)

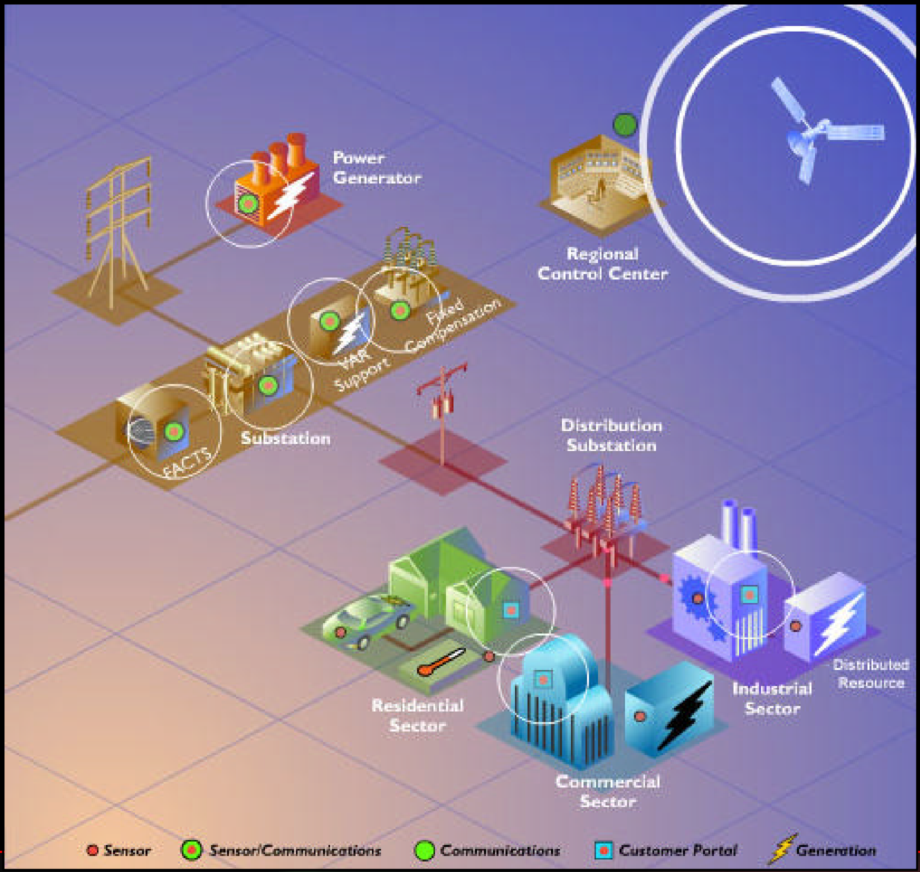
Accelerate development of technologies needed by power system of future. Emphasis on self-healing grid technologies, including wide-area monitoring and control.



- Increase the control, capacity, and reliability of power delivery systems
- Develop end-use technologies with greater tolerance for disturbances
- Provide consumers with access to new electricity-related services
- Enable consumers to manage and use energy more efficiently

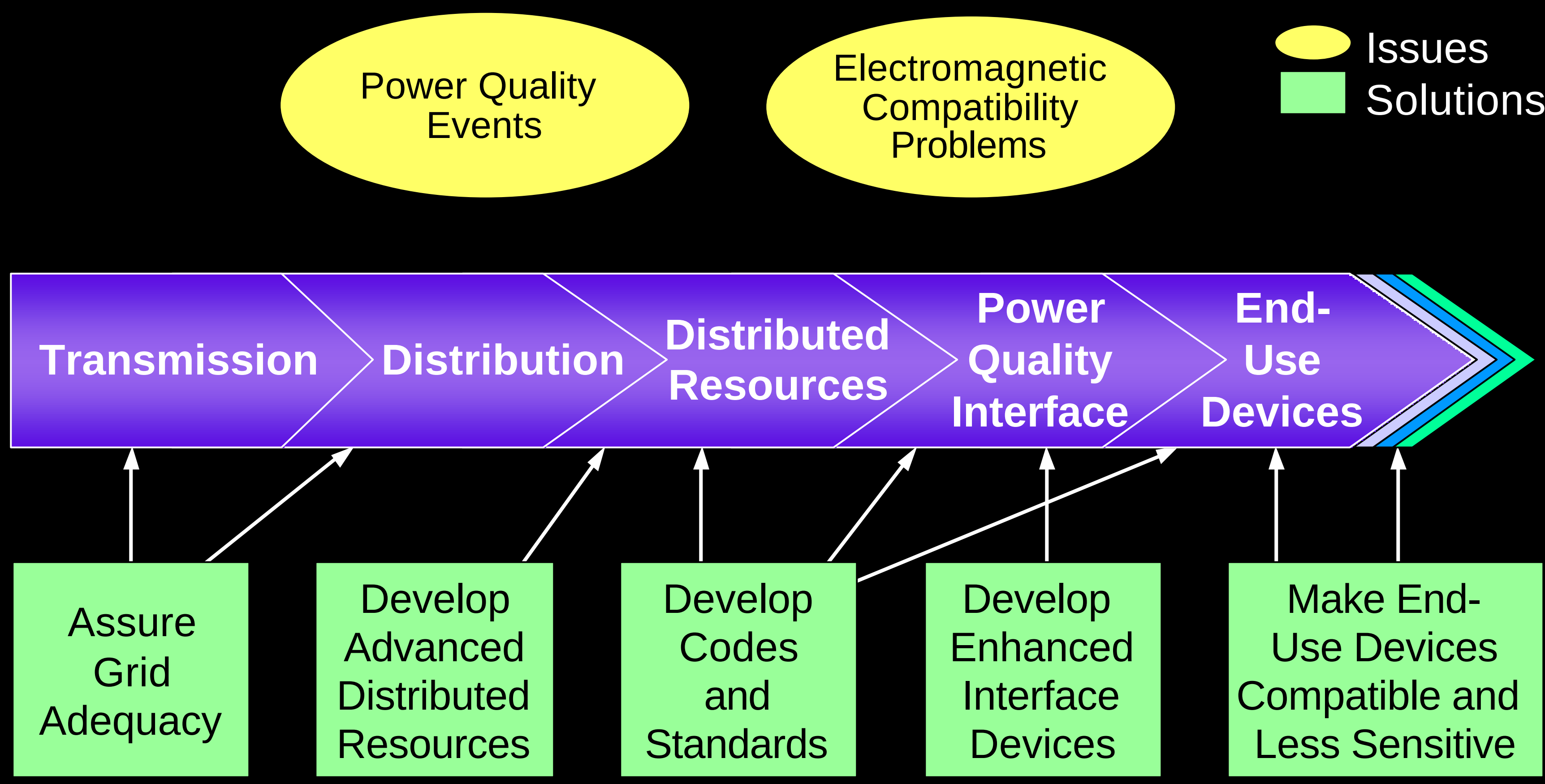
Power system with fully Integrated Network Control (INC)

Enable more flexible system operations to meet changing customer needs; coordinate all major power system functions on a regional basis

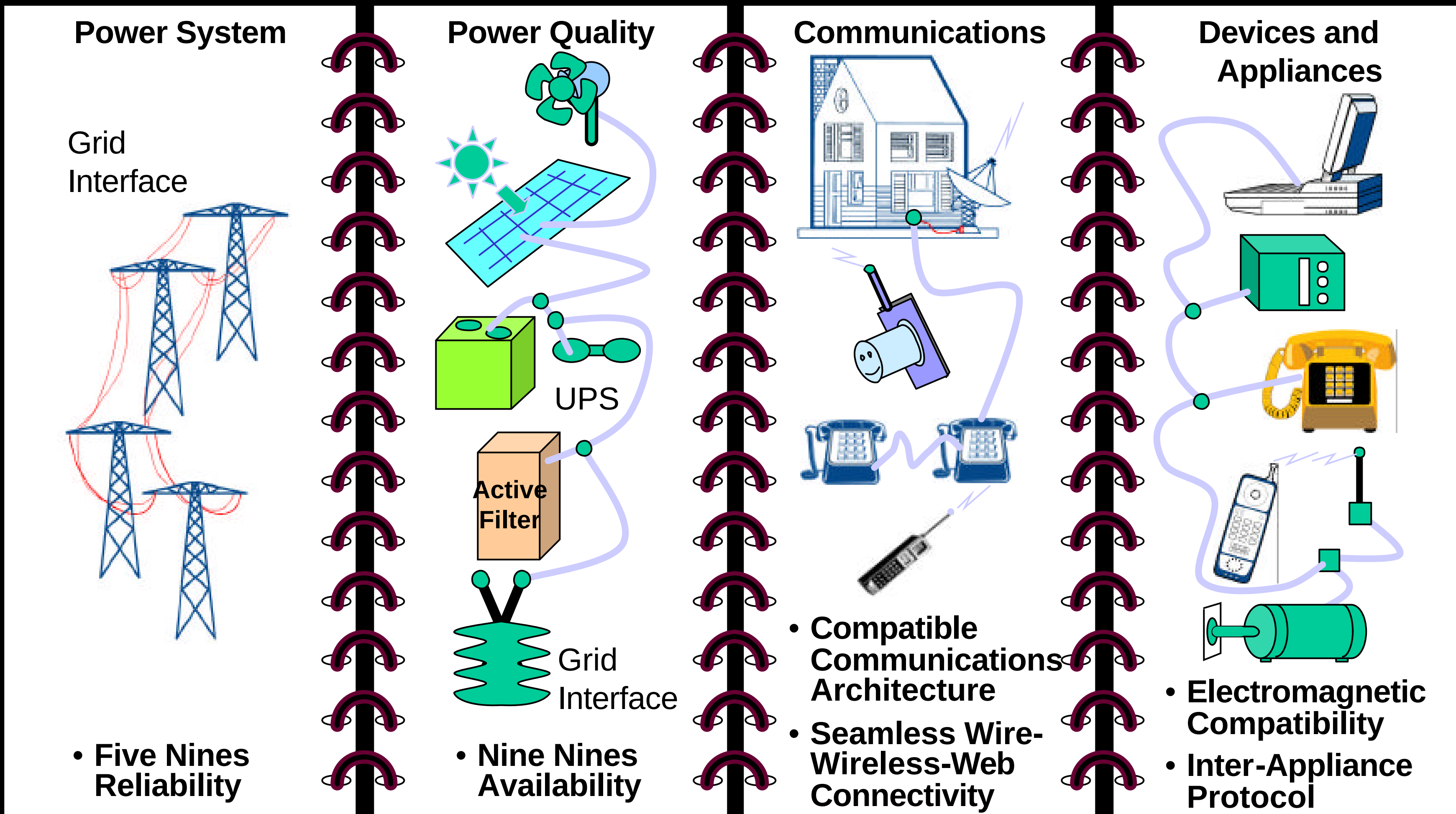


- Data gathered from all parts of the system and analyzed in real time
- Resources dispatched on a regional basis to keep up with load changes
- Power flow controlled instantaneously using power electronic devices
- Consumers fully integrated into electricity markets by electronic meters with two-way communications

Creating the Infrastructure for the Digital Society



The Infrastructure for a Digital Society

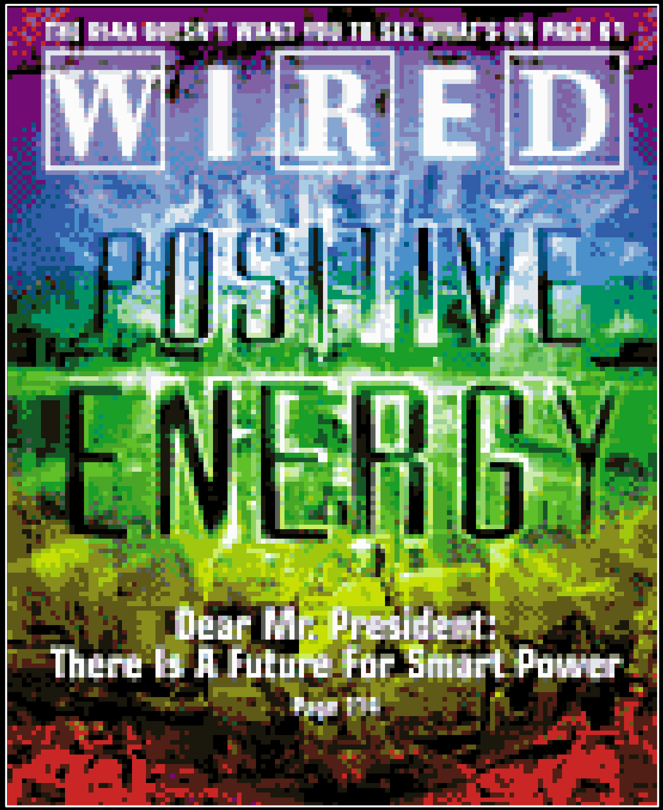


…Bigger Picture: "Not to sell light bulbs, but to create a network of technologies and services that provide illumination …"

The Energy Web:

"The best minds in electricity R&D have a plan: Every node in the power network of the future will be awake, responsive, adaptive, price-smart, eco-sensitive, real-time, flexible, humming - and interconnected with everything else."

-- Wired Magazine, July 2001



http://www.wired.com/wired/archive/9.07/juice.html

Shaping the Future: “Anything we can imagine, we can build”