Future of the Grid

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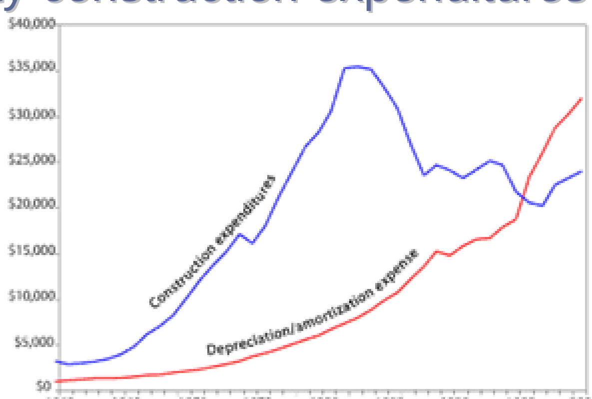
*Most of the material and findings for this presentation were developed while the author was at the Electric Power Research Institute (EPRI) in Palo Alto, CA . EPRI's support and feedback from colleagues at EPRI is gratefully acknowledged.

EPRI Grid Reliability & Power Markets
Enterprise Information Security (EIS) Program
September 30, 2003

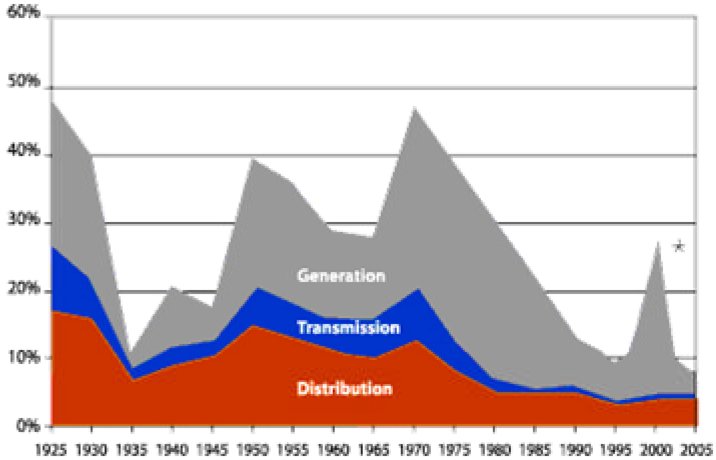
The Past and Present Context: Utility construction expenditures



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*

The Past and Present Context:
Capital Invested as % of electricity revenue



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

Capital invested as % of electricity revenues

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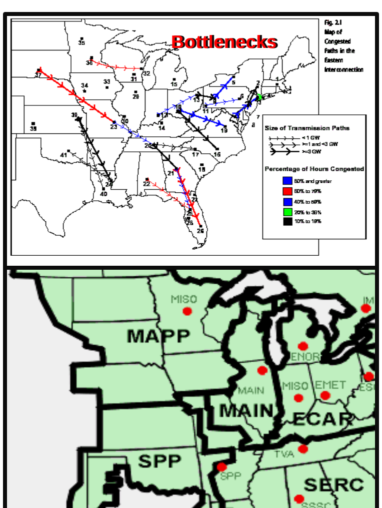
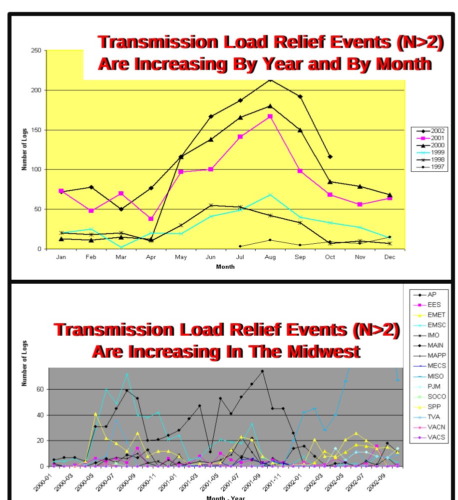
Context: Transmission Bottlenecks Are Impacting Interconnected Regions





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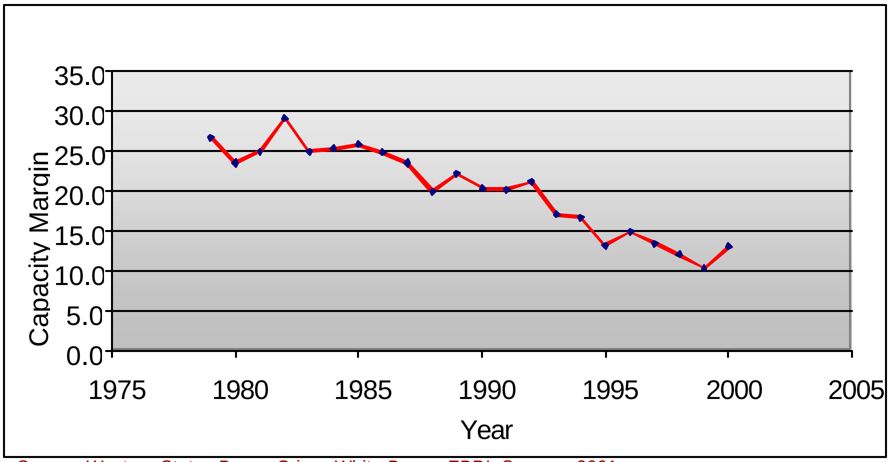
Context: Generation Capacity Margin in North America



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

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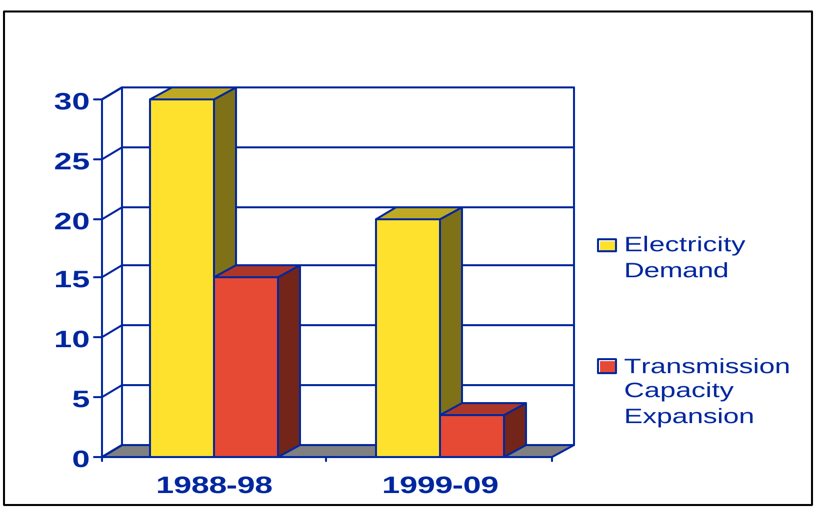
Context: Transmission Additions in The U.S.



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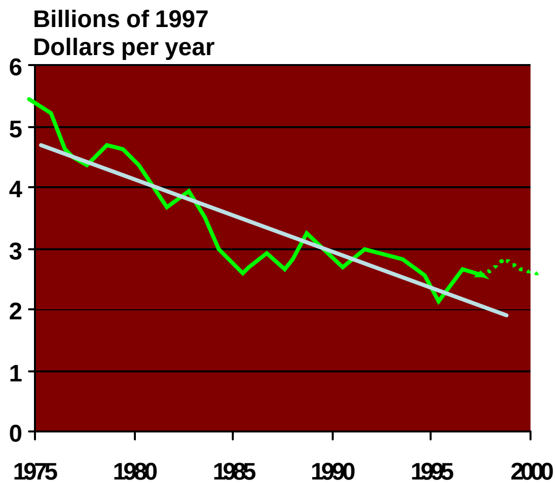
Transmission Investment, 1975-2000



Source: Electric Perspectives, July/August 2001

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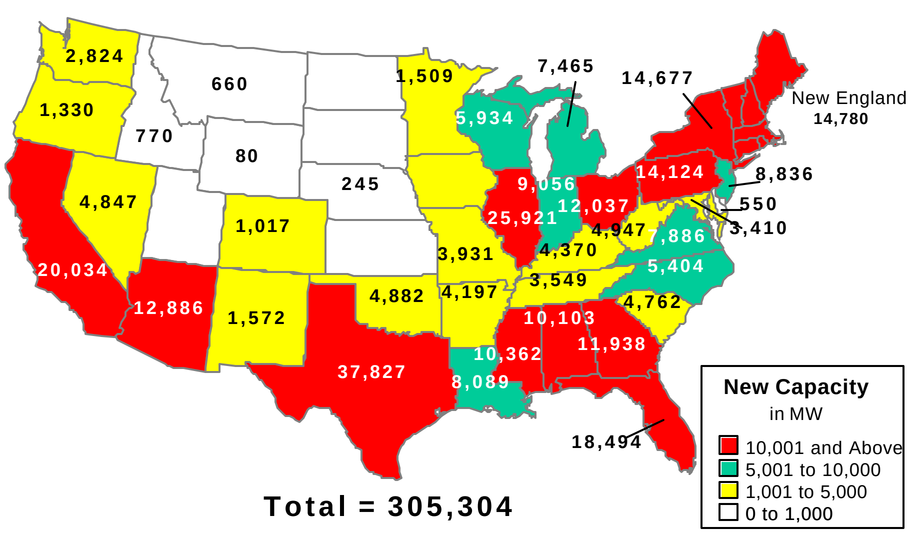
Context: U.S. Actual and Planned Capacity Additions 1998 – 2007



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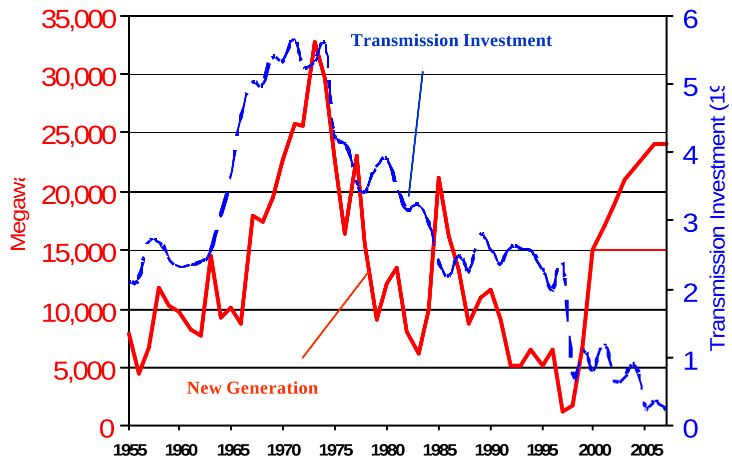
Past Practice is Inadequate



- Many more bottlenecks showing up

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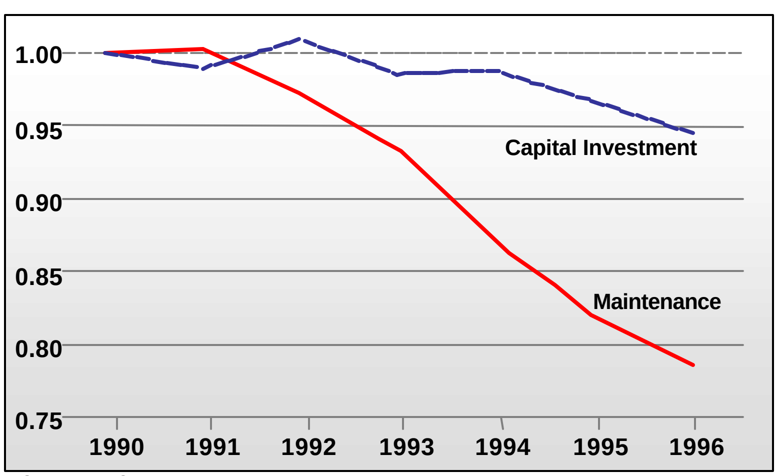
Context: Spending Less on Transmission



Source: FERC, EIA

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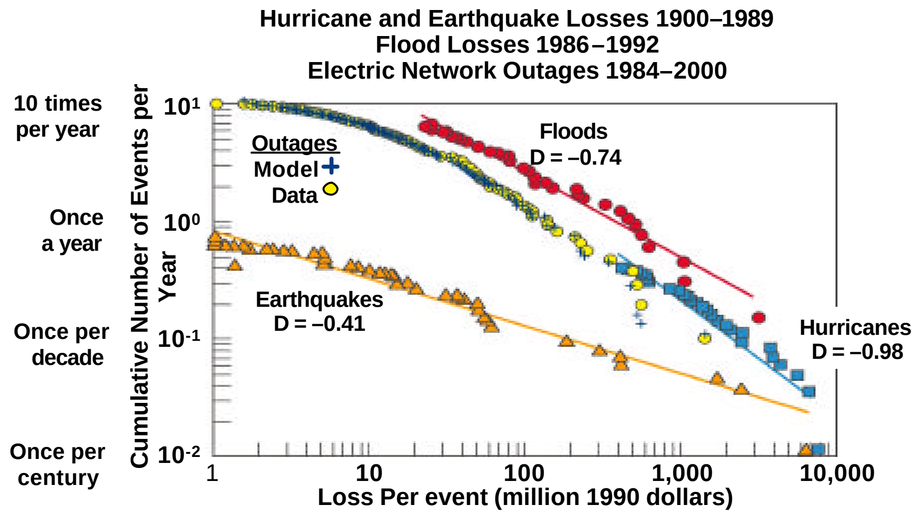
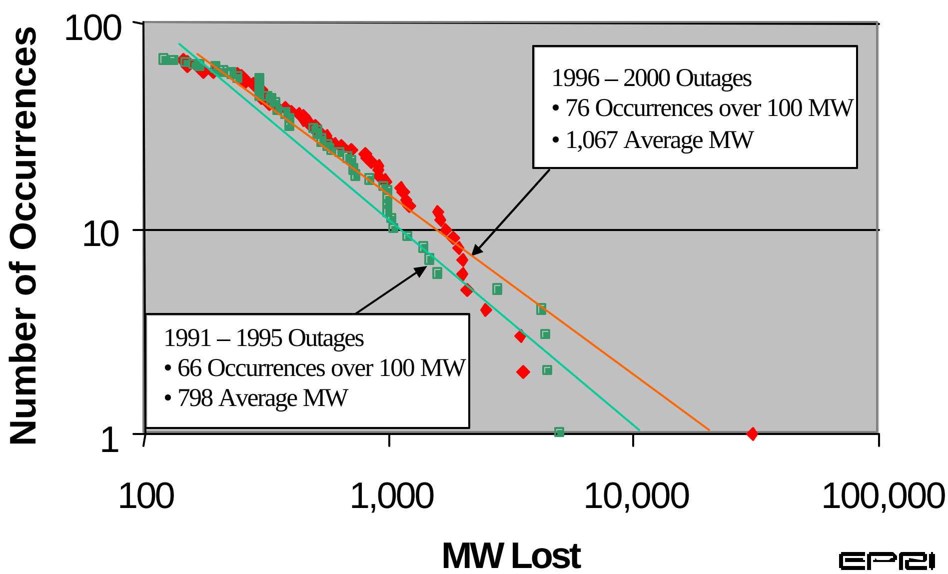
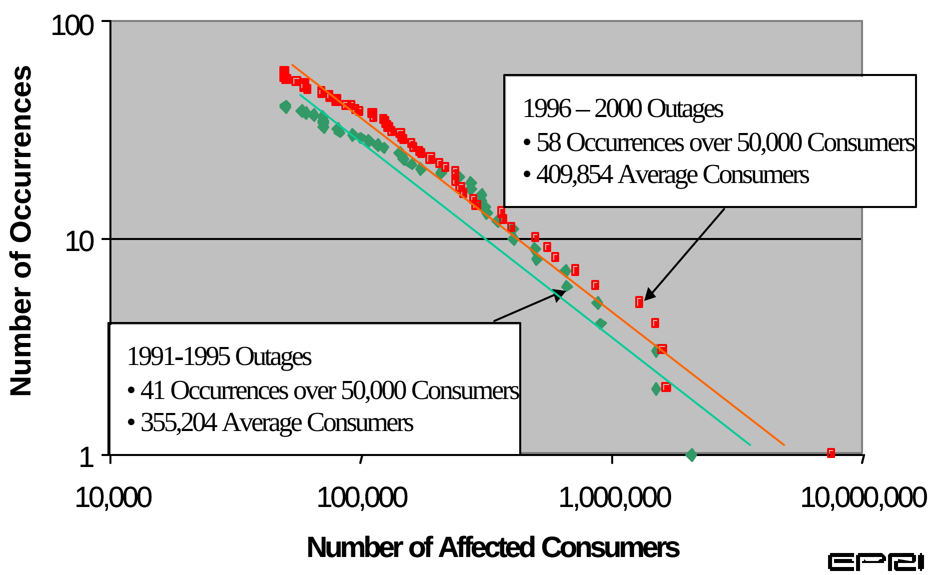
Power Law Distributions:
Frequency & impacts of major disasters



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)



Context: Major Recent Changes

- Energy infrastructure security issues in the wake of the 9/11 attack
- Western states power crisis and subsequent ongoing financial crisis
- Loss of investor confidence
- Restructuring slowdown and issues surrounding SMD
- Environmental issues and progress in addressing them
- Technology advances on a broad front -- but incentives to invest have not kept pace
- Major outages of August and September 2003 in the US, UK and Italy…

Summary of August 14 Blackout Statistics

- **Reported as affecting 50 million people**
- **60-65,000 MW of load initially interrupted**
  - Approximately 11% of Eastern Interconnection
- **400+ Generating units tripped**
- **Cascading lasted approximately 12 seconds**
- **Thousands of discrete events to evaluate**

Source: NERC and Joint U.S.-Canada Task Force

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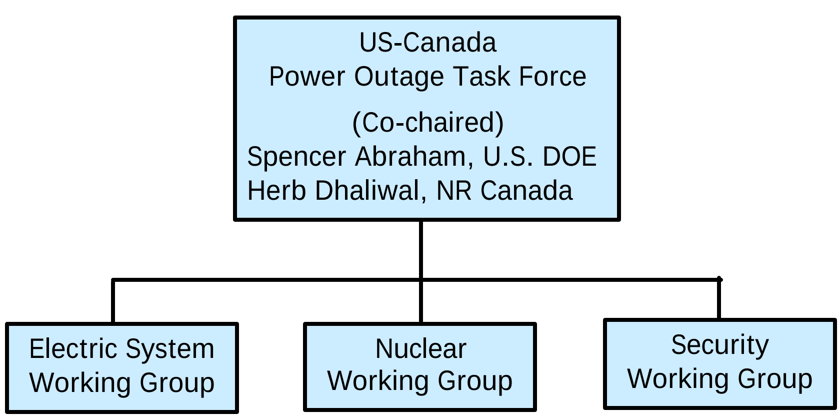
Joint U.S.-Canada Task Force



Source: NERC and Joint U.S.-Canada Task Force

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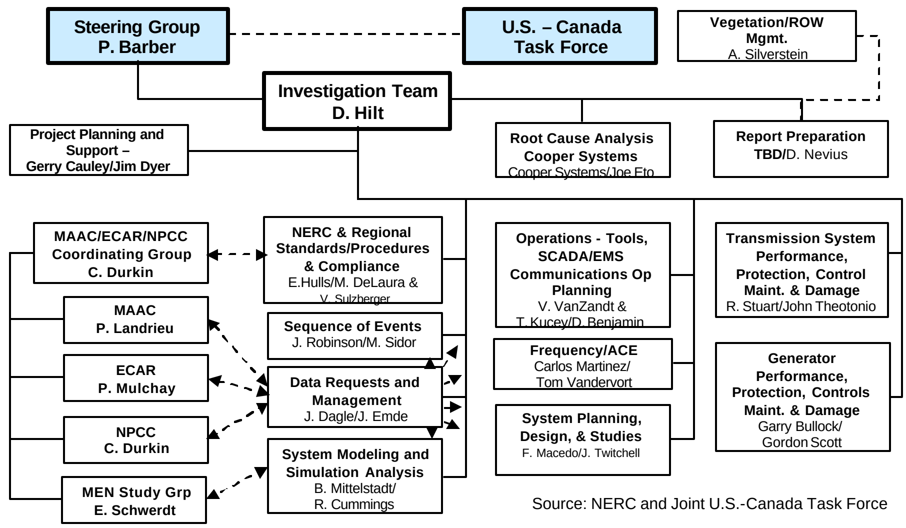
Investigation Organization Overview



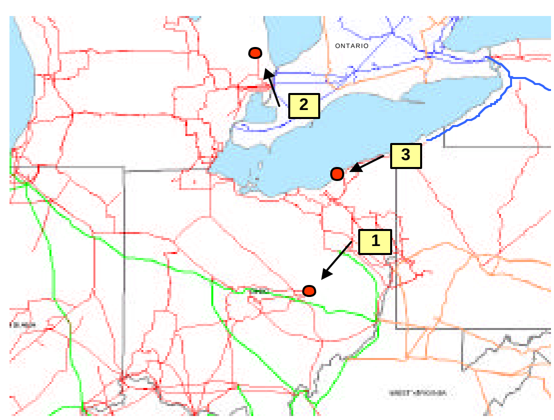
Source: NERC and Joint U.S.-Canada Task Force

12:05:44 – 1:31:34 PM

"Preliminary Disturbance Report"

Source: NERC

Several generator trips between noon and 1:30 pm in central and northern Ohio and in the Detroit area, caused the electric power flow pattern to change.



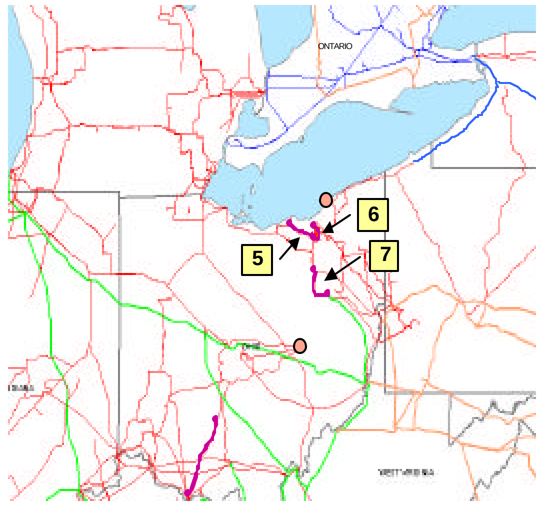
2:02 – 3:41:33 PM

"Preliminary Disturbance Report"

Source: NERC

Between 3:06 and 3:41 three transmission lines in Ohio tripped-- part of the pathway into northern Ohio from eastern Ohio.

One of these lines is known to have tripped due to contact with a tree, but the cause of the other line trips has not been confirmed.

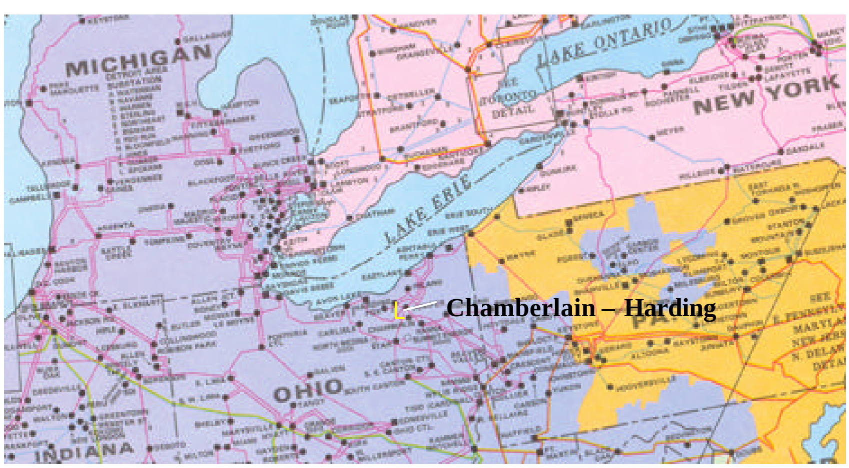


"Preliminary Disturbance Report"

3:06 pm EDT

Chamberlain – Harding 345kV line tripped

Cause not reported



Graphics developed by Jeff Dagle (DOE/PNNL) August 16, 2003
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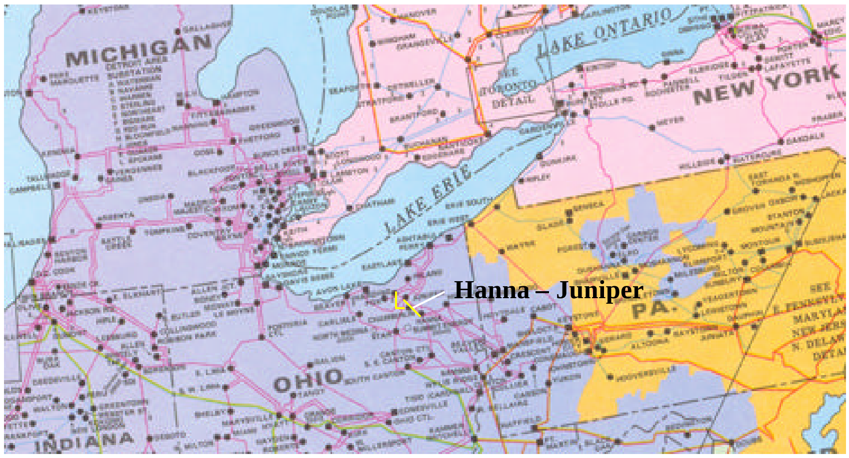
"Preliminary Disturbance Report"

3:32 pm EDT

Hanna – Juniper 345kV line sagged and tripped



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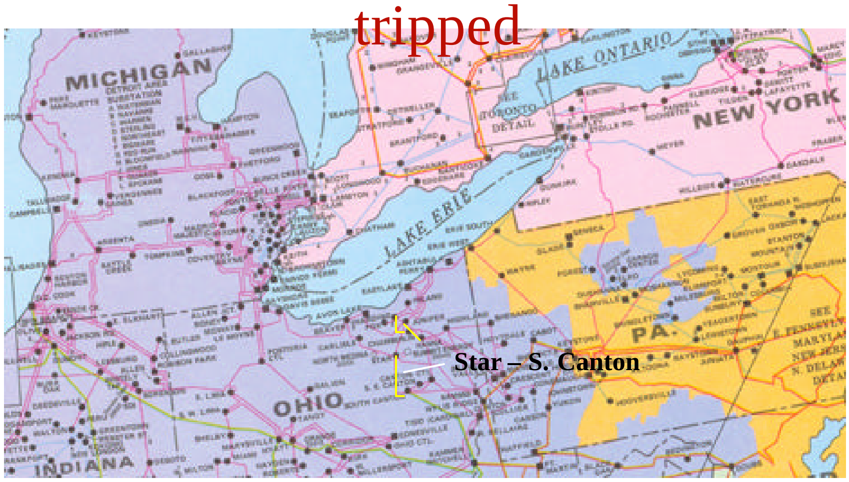
"Preliminary Disturbance Report"

3:41 pm EDT

Star – S. Canton 345 kV line tripped



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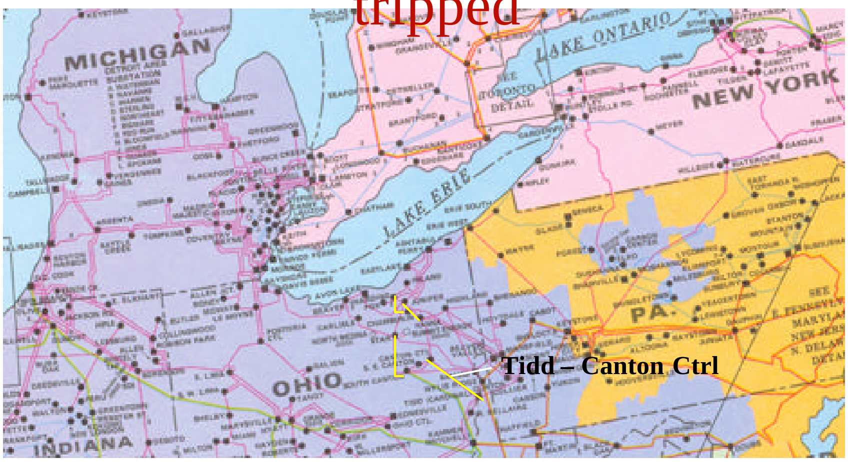
3:46 pm EDT

Tidd – Canton Ctrl 345 kV line tripped



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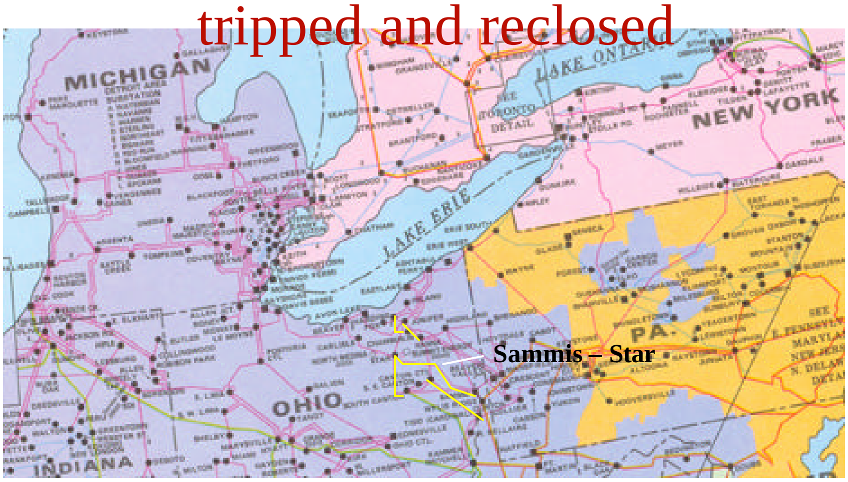
4:06 pm EDT

Sammis – Star 345 kV line tripped and reclosed



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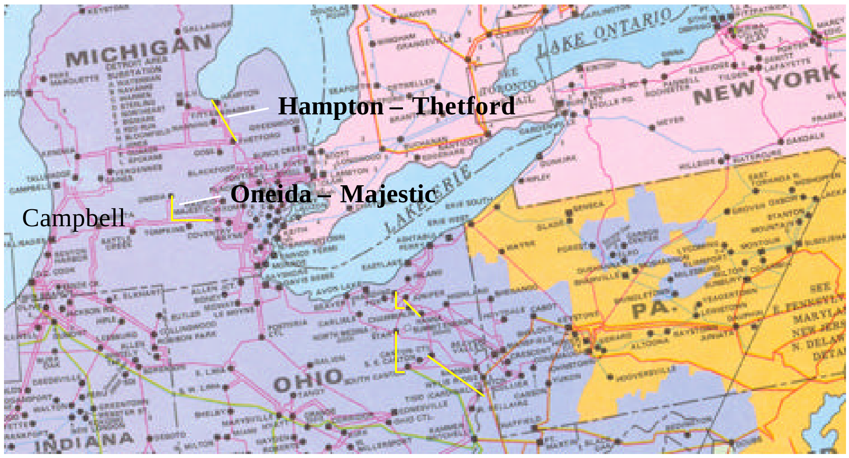
"<u>Preliminary</u> Disturbance Report"

4:10 pm EDT

Campbell #3 Tripped ?

Hampton – Thetford 345 kV line tripped

Oneida – Majestic 345 kV line tripped



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4:11 pm EDT

Avon Unit 9 Tripped

Beaver – Davis Besse

Midway – Lemoyne – Foster 138 (?) kV line tripped

Perry Unit 1 tripped

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Map © 2000 North American Electric Reliability Council

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"Preliminary Disturbance Report"

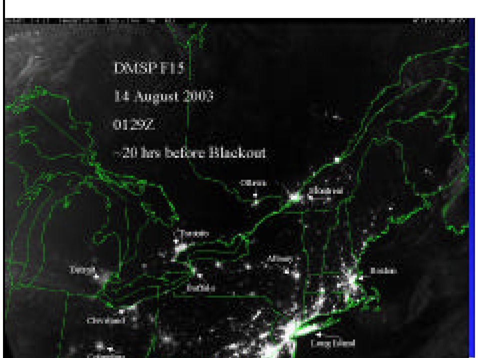
4:15 pm EDT: Sammis – Star 345 kV line tripped and reclosed

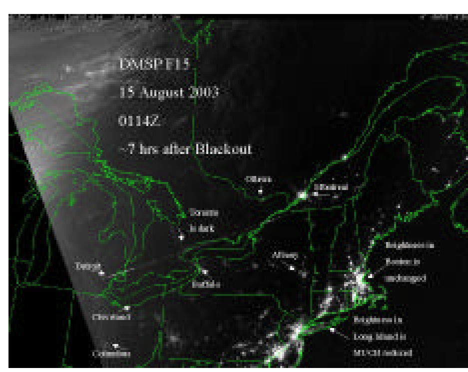
4:17 pm EDT: Fermi Nuclear tripped

4:17 – 4:21 EDT: Numerous lines in Michigan tripped

Graphics developed by Jeff Dagle (DOE/PNNL) August 16, 2003

Cascading failures of August 14th, 2003: ~ 20 hrs before, and 7 hrs after





Source: NOAA
http://www.noaanews.noaa.gov/nightlights/blackout081403-20hrsbefore-text.jpg
http://www.noaanews.noaa.gov/nightlights/blackout081503-7hrsafter-text.jpg

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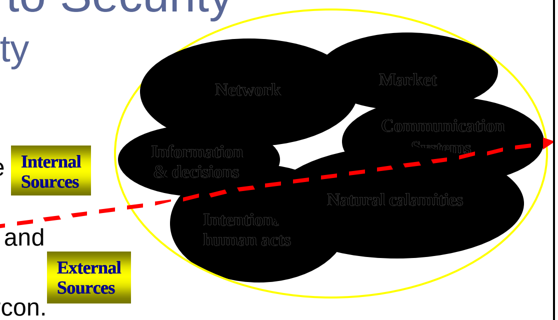
Context: Threats to Security

Sources of Vulnerability



- Transformer, line reactors, series capacitors, transmission lines...
- Protection of ALL the widely diverse and dispersed assets is impractical

  -- 202,835 miles of HV lines (230 kV and above

  -- 6,644 transformers in Eastern Intercon.
- Control Centers
- Interdependence: Gas pipelines, compressor stations, etc.; Dams; Rail lines; Telecom – monitoring & control of system
- Combinations of the above and more using a variety of weapons:
- Truck bombs; Small airplanes; Gun shots – line insulators, transformers; EMP more sophisticated modes of attack…

- Hijacking of control
- Biological contamination (real or threat)
- Over-reaction to isolated incidents or threats
- Internet Attacks – 30,000 hits a day at an ISO
- Storms, Earthquakes, Forest fires & grass land fires
- Loss of major equipment – especially transformers…

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So What Are We Doing About It?

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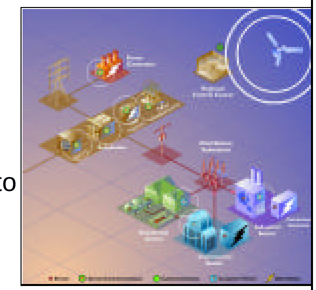
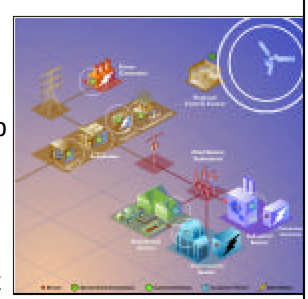
Enabling Technologies



- **Monitoring:** WAMS, OASIS, SCADA, EMS:
  - Wide-Area Measurement Systems (WAMS), integrate advanced sensors with satellite communication and time stamping using GPS to detect and report angle swings and other transmission system changes.
- **Analysis:** DSA/VSA, PSA, ATC, CIM, TRACE, OTS, ROPES, TRELSS, market/risk assessment, …
  - Information systems and on-line data processing tools such as the Open Access Same-time Information System (OASIS); and Transfer Capability Evaluation (TRACE) software-- determine the total transfer capability for each transmission path posted on the OASIS network, while taking into account the thermal, voltage, and interface limits.

Enabling Technologies (cont.)

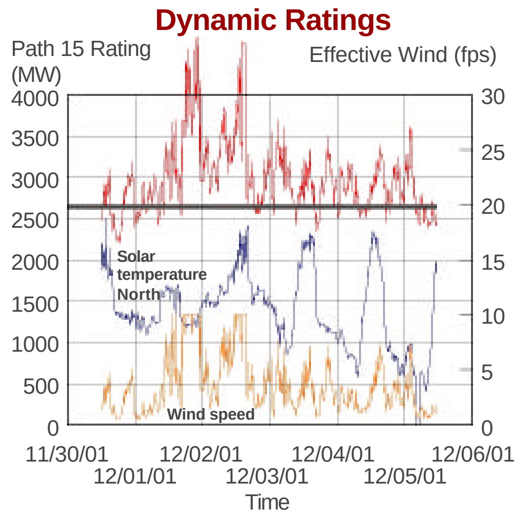


- **Control:** FACTS; Fault Current Limiters (FCL)., …
  - Flexible AC Transmission System (FACTS): Up to 50% more power controlled through existing lines.
  - Fault Current Limiters (FCLs)-- large electrical "shock absorbers" for a few cycles
  - Intelligent Electronic Devices with security built in- combining sensors, computers, telecommunication units, and actuators-- "intelligent agent" functions
- Materials science: High-temperature superconducting cables, advanced silicon devices and wide-bandgap semiconductors for power electronics.
- Distributed resources such as small combustion turbines, solid oxide and other fuel cells, photovoltaics, superconducting magnetic energy storage (SMES), transportable battery energy storage systems (TBESS), etc.

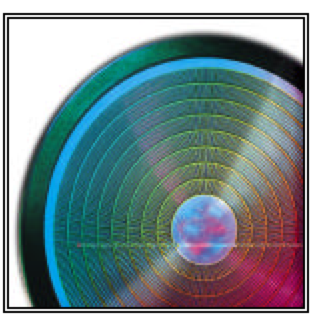
Example-- Technology Solutions:
Maximize Utilization of Existing Assets

Dynamic Circuit Rating

- **Direct line monitoring**
- **DTCR Software**
- **10-15% Capacity Increase Typical**



Example-- Technology Solutions: Flexible Power Delivery System



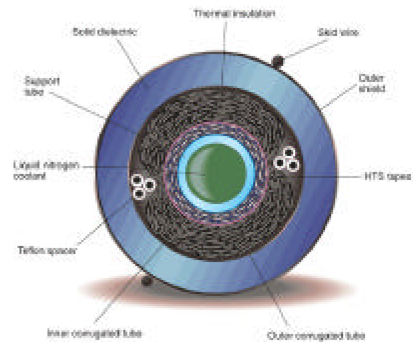
Flexible AC Transmission Systems (FACTS)

- **A collection of electric transmission power flow and control technologies that have extremely fast time response capabilities**
- **Devices are based on very high-power solid state electronic switches**
- **Fast and continuous active control of the transmission network**
- **Allows for continental dispatch of transmission capacity**
- **Facilitates open access**

Technology Solutions: Maximize Utilization

Superconducting Cables

- **2 to 5 times the current**
- **Can be used to retrofit existing ducts and pipes**
- **Need to reduce cost, improve reliability of cryogenic system and gain more operating experience**



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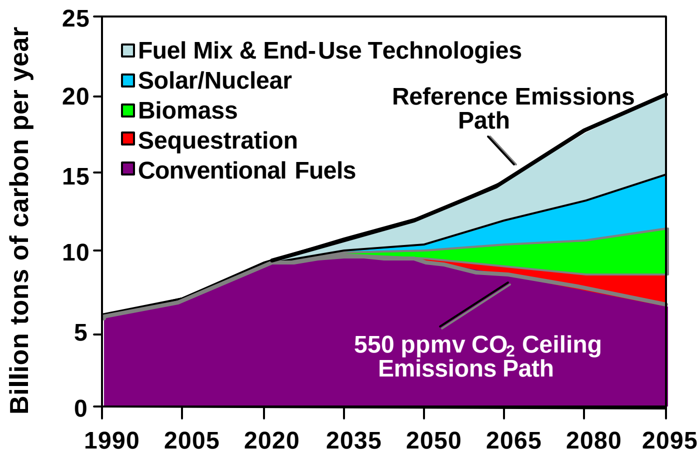
Energy Technologies to Fill the Global CO_2 Emissions Gap

(an illustrative example)



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Technologies that may Fill the Gaps

Technologies that may make sense anyway:

- End-use efficiency
- Plant improvement
- Nuclear
- Renewables
- Biomass

Technologies for a carbon-constrained world:

- Capture and disposal
- Tree planting and soil carbon

Technology Breakthroughs

- Zero Emission Power Plants (ZEPPs)
- Low-temperature water splitting

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So what are we doing about it?

Selected Recent Security & Reliability Related Programs in EPRI

1999-2001	Y2K→2000-present	2002-present	2001-present
EPRI/DoD Complex Interactive Networks (CIN/SI)	Enterprise Information Security (EIS)	Infrastructure Security Initiative (ISI)	Consortium for Electric Infrastructure to Support a Digital Society (CEIDS)
Underpinnings of Interdependent Critical National Infrastructures Tools that enable secure, robust & reliable operation of interdependent infrastructures with distributed intel. & self-healing	▪ Information Sharing ▪ Intrusion/Tamper Detection ▪ Comm. Protocol Security ▪ Risk Mgmt. ▪ Enhancement ▪ High Speed Encryption	**Response to 9/11 Tragedies** ▪ Strategic Spare Parts Inventory ▪ Vulnerability Assessments ▪ Red Teaming ▪ Secure Communications	▪ Self Healing Grid

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An Example of Recent Programs: EPRI/DOD Complex Interactive Network/Systems Initiative (CIN/SI)

"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 CIN/SI: Widespread Interest & Participation

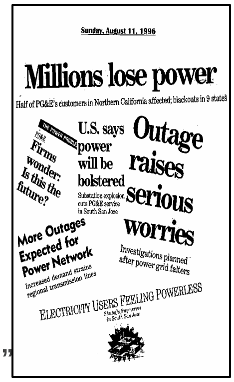
- Direct participation and collaboration:
  - Exelon and TVA are partners with Purdue, UTenn, Fisk U.
- EPRI / SS&T Interest Group review and advice:
  - AEP, BPA, CEC, CA-ISO, ConEd, CPS-SATX, Duke, EDF, ESKOM, Fortum, GPU Nuclear, Idaho Power, IL Power, ISO-NE, Keyspan Energy, Manitoba Hydro, NYPA,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

EPRI

Background: EPRI/DOD Complex Interactive Network/Systems Initiative (CIN/SI)

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*.

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Background: 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 – Defense Against Catastrophic Failures, Vulnerability Assessment
- Purdue, U Tennessee, Fisk U, TVA, ComEd – Intelligent Management of the Power Grid
- Harvard, UMass, Boston, MIT, Washington U. – Modeling and Diagnosis Methods
- Cornell, UC-Berkeley, GWU, Illinois, Washington St., Wisconsin – Minimizing Failures While Maintaining Efficiency / Stochastic Analysis of Network Performance
- CMU, RPI, UTAM, Minnesota, Illinois – Context Dependent Network Agents
- Cal Tech, MIT, Illinois, UC-SB, UCLA, Stanford – Mathematical Foundations: Efficiency & Robustness of Distributed Systems

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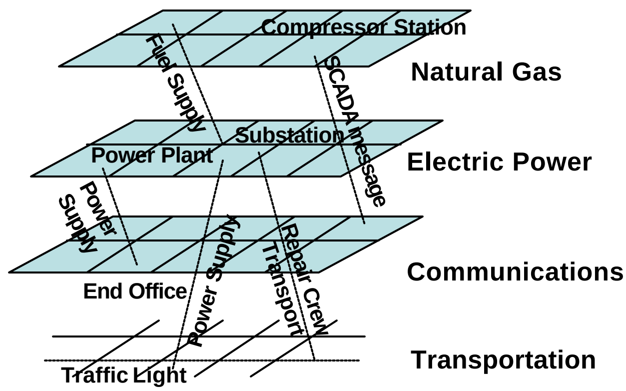
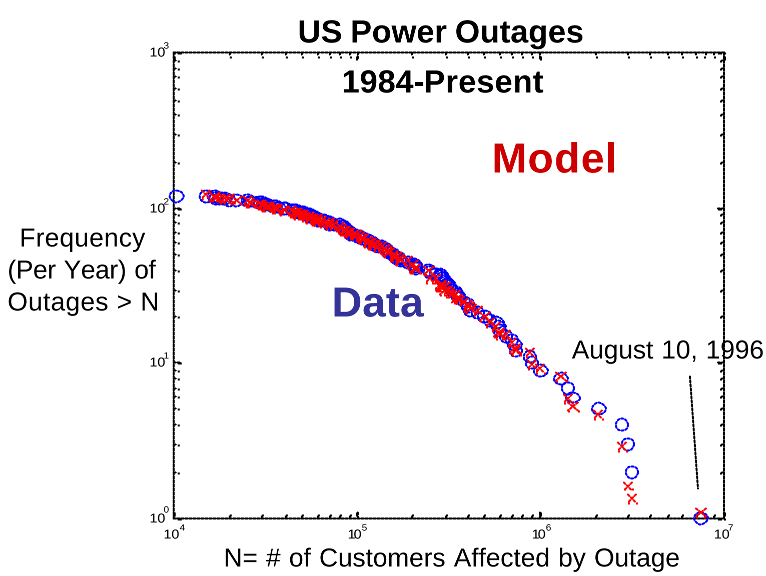
Infrastructure Interdependencies



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

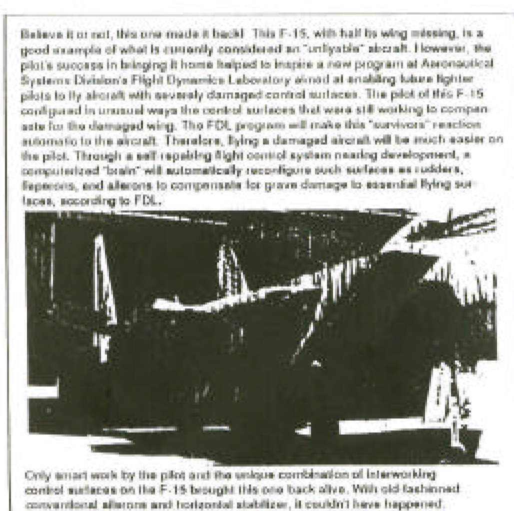
Background: Power Laws



EPRI/DoD CIN/S Initiative

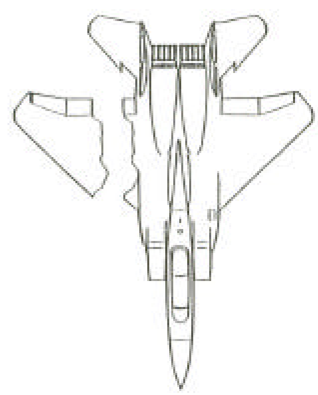
The Self Healing Grid

Background: The Case of the Missing Wing



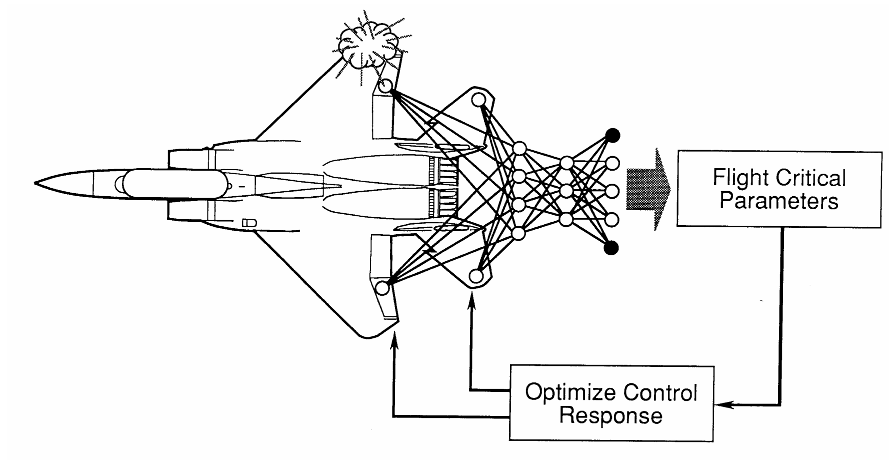
Believe it or not, this one made it back! This F-15, with half its wing missing, is a good example of what is currently considered an "unflyable" aircraft. However, the pilot's success in bringing it home helped to inspire a new program at Aeronautical Systems Division's Flight Dynamics Laboratory aimed 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 nearing 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.

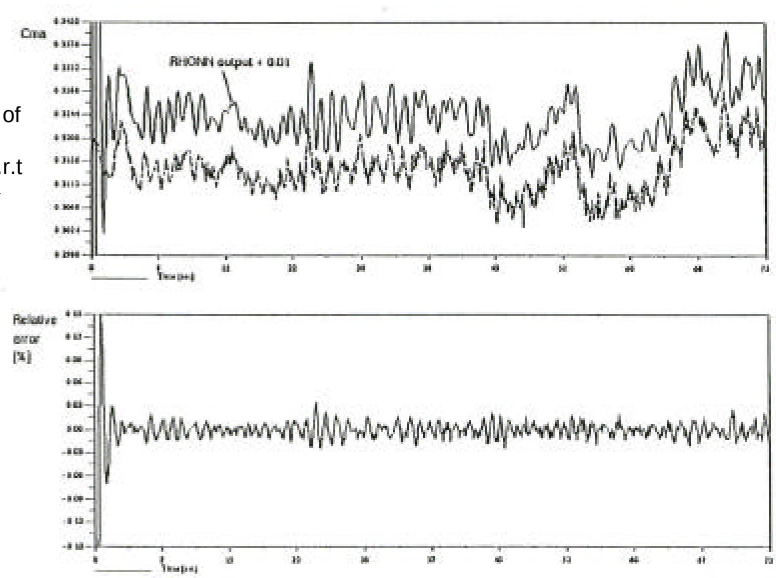
Goal: Optimize controls to compensate for damage or failure conditions of the aircraft*



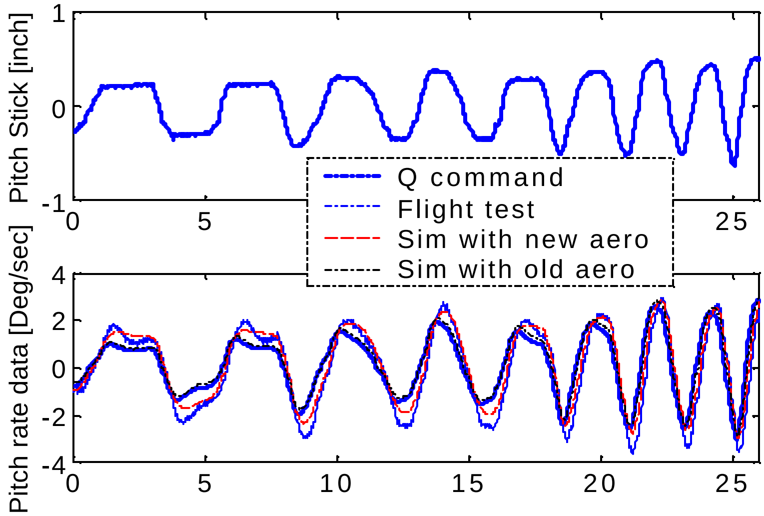
NASA/MDA/WU IFCS

On-Line Learning Without Baseline Network

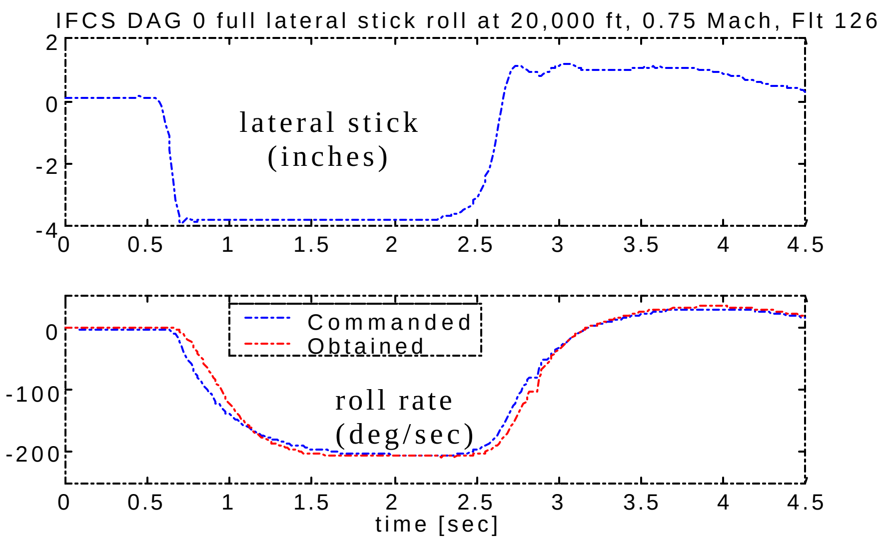
Partial Derivative of Pitching moment w.r.t AoA (d)-1



Verification of the C_{Ma} Modeling Error



Roll Axis Response of the Intelligent Flight Control System



Accomplishments in the IFCS program

- 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.
- 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.
- Development team: NASA Ames Research Center, NASA Dryden Flight Research Center, Boeing Phantom Works, and Washington University.

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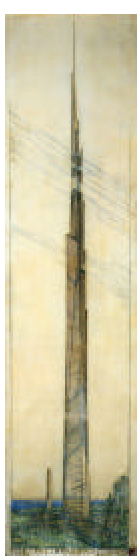
Self-healing Grid



Building on the Foundation:

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

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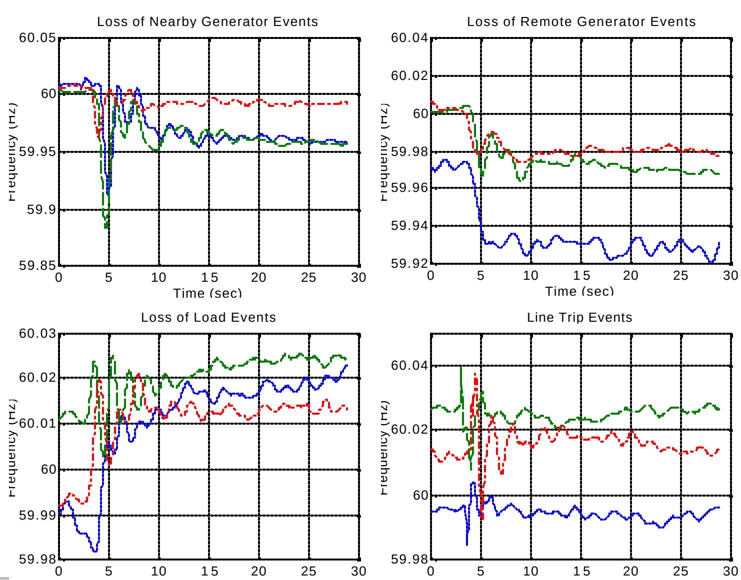
Challenges

- Management of Precursors and their Signatures (Identifying & Measuring Precursors), including DDRs, WAMS…
- Fast look-ahead simulation and modeling capability
- Adaptive and Emergency Control; Rapid Restoration
- Impact of all pertinent dynamic interactive layers including:
  - Communication and Protection layers
  - Electricity Markets and Policy/Regulatory layers
  - Ownership and investor layer (investment signals)
  - Customers layer (demand response, smart meters, reliability/quality)
  - …

Detecting Precursors: Classification of fault signatures



Disturbance Feature Extraction

Disturbance	Frequency change	Frequency derivative	Line flow change
Loss of nearby generation	Negative	Steep	Large
Loss of remote generation	Negative	Moderate	Negligible
Loss of load	Positive	Moderate	Detectable
Line trip close to DRD	Negligible	Steep	Large
Oscillations	Negligible	Small	oscillations

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Time-Scale of Actions & Operations Within the Power Grid

Action or Operation	Timeframe
Wave effects (fast dynamics such as lightning)	Microseconds to milliseconds
Switching overvoltages	Milliseconds
Fault protection	100 milliseconds or a few cycles
Tie-line load frequency control	1 to 10 seconds
Economic load dispatch	10 seconds to 1 hour
Load management, load forecasting, generation scheduling	1 hour to 1 day or more

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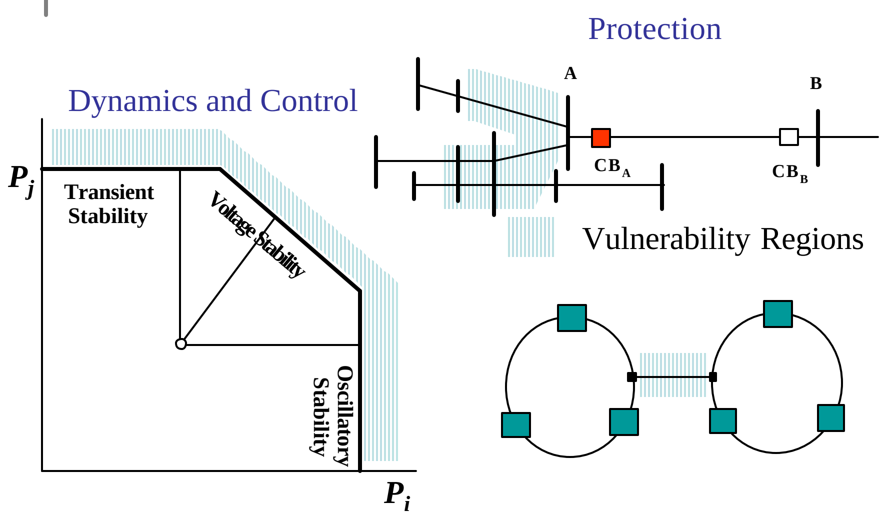
Communication Requirements

Power System Tasks	Bandwidth Requirement	Current Response Time
Load Shedding (Local Decision)	Low	Seconds
Adaptive Relaying (e.g., Blocking relay)	Low	Not Available
Hierarchical Data Acquisition and Transfer	High	Seconds (e.g., 2-12 seconds / scan for RTUs)
Line / Bus Reconfiguration	Low	Minutes (manual)
Control Devices (e.g., FACTS, Transformer,…)	Medium	Seconds (by manual)
Fault Event Recorder Information	Medium	Minutes
Generator Control	Low	Seconds
Strategic Power Infrastructure Defense & Coordination with Control Centers	High	Not Applicable

Protection Schemes & Communication Requirements

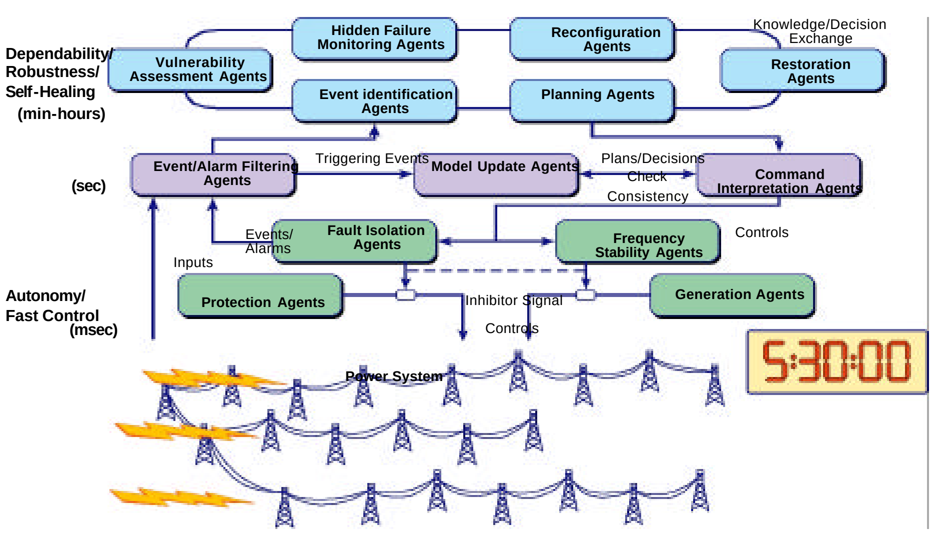
Type of relay	Data Volume (kb/s)		Latency	
	Present	Future	Primary (ms)	Secondary (s)
Over current protection	160	2500	4-8	0.3-1
Differential protection	70	1100	4-8	0.3-1
Distance protection	140	2200	4-8	0.3-1
Load shedding	370	4400	0.06-0.1 (s)	
Adaptive multi terminal	200	3300	4-8	0.3-1
Adaptive out of step	1100	13000	Depends on the disturbance	

Vulnerability Indices



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

Background: The Self-Healing Grid



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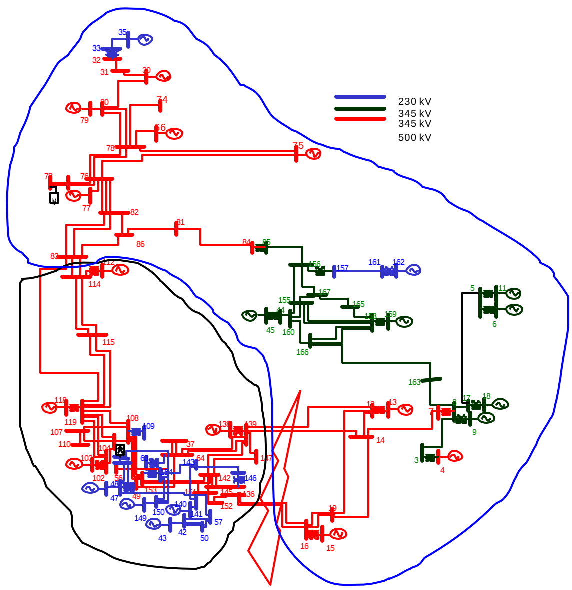
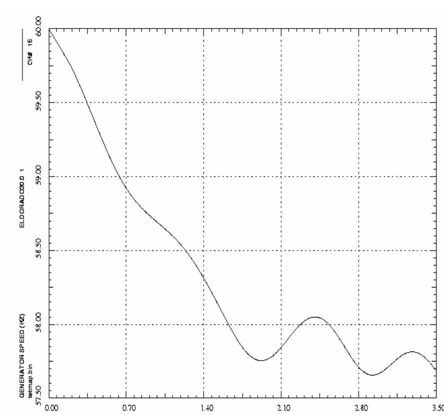
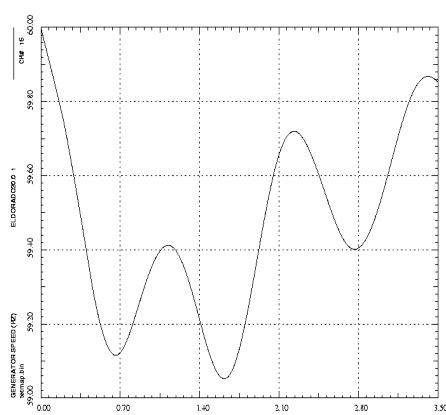
Background: Intelligent Adaptive Islanding



Background: Simulation Result



No Load Shedding Scheme



New Scheme

Results of CIN/SI Advisors' Feedback: Technical Areas Identified

Bundle 1:

A) Wide area system protection (sensing, measurement and control)

B) Intelligent/ Adaptive Islanding

N) Context-dependent Network Agents (CDNA) for real-time System Monitoring and Control

O) CDNA for System Security and Control

Bundle 2: *(TC)*

H) Transmission/distribution entities with on-line self-healing (TELOS) testing and integration

G) Anticipatory Dispatch

Advisors' Feedback: Wide Area Sensing, Measurements, and Control

Advanced sensor development and sensor placement →	**0 - 4 Years**
GPS synchronization →	**2 Years**
Advanced communication systems designs / robust designs incorporating time delays →	**Available today - applicability in next 4 years**
Robust control with wide area measurements →	**Available today - applicability in next 3 years**

Advisors’ Feedback (Cont.): Adaptive Self-Healing Techniques

- **Real Time Implementation With Topology Processing and On-Line Update Of Islands** → 5 Years
- **Feasibility Demonstration With Off-Line Studies In an EMS Environment** → 3 Years
- **Islanding Criteria with Wide Area Measurements** → 2 Years
- **Procedure to Form Islands and Demonstrate Feasibility with Simulation** → Available Today

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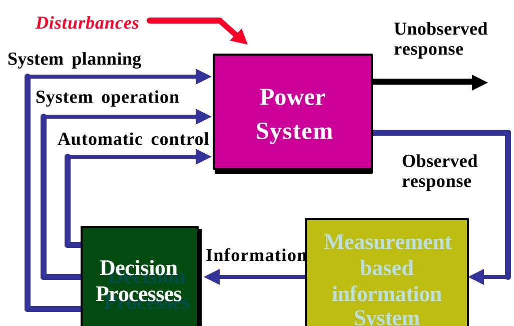
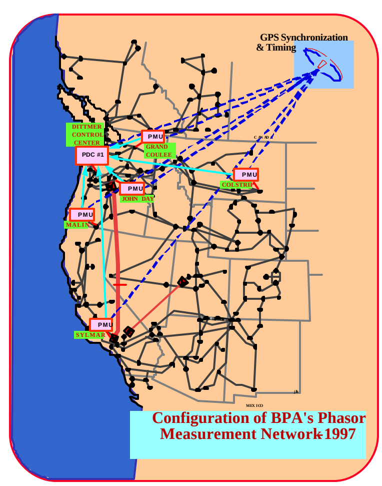
Wide-Area Measurement System

Integrated measurements facilitate system management

“Better information supports better - and faster - decisions.”





Configuration of BPA's Phasor Measurement Network 1997

Source: DOE/EPRI WAMS project - BPA & PNNL

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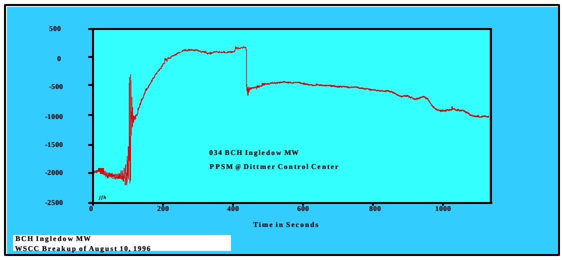
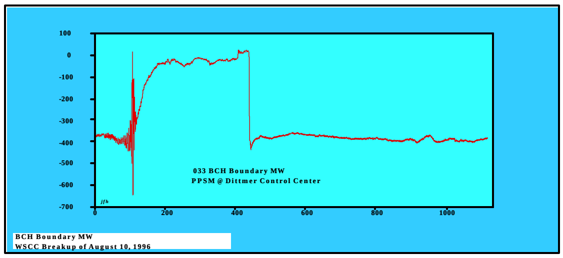
Detecting Precursors
Disturbance records the August 10, 1996





Source: DOE/EPRI WAMS project

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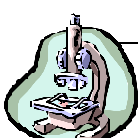
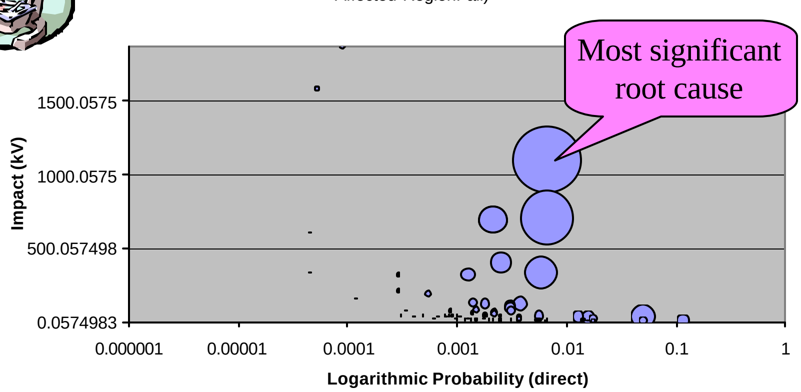
EPRI's Reliability Initiative:
Example of In Depth Analysis-- Critical Contingency Situations





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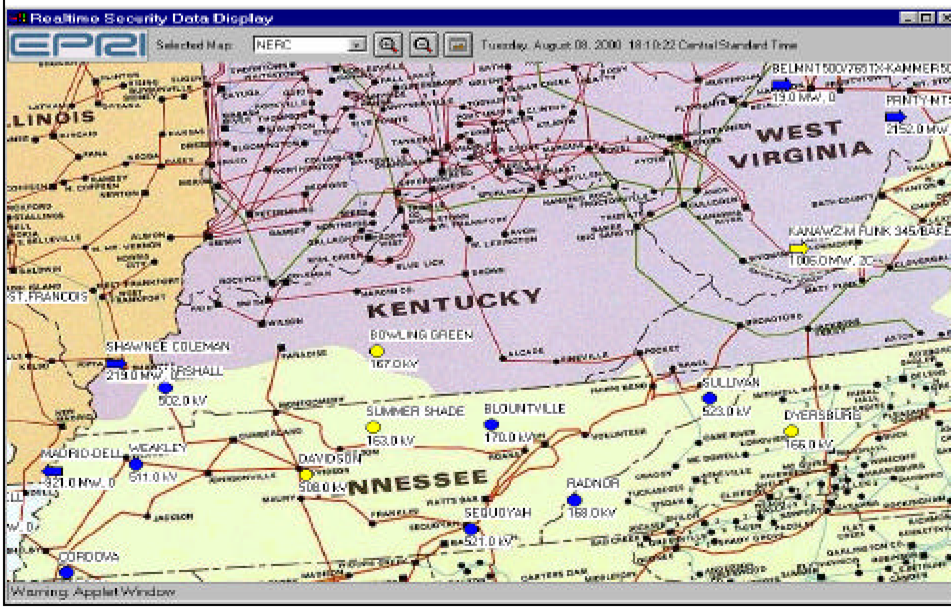
EPRI's Reliability Initiative-- Sample Screen of Real-time Security Data Display (RSDD)



CEIDS: Fast Simulation & Modeling (FSM)

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)

CEIDS:
Fast Simulation & Modeling (FSM) Program

Benefits-- **Value of the work:**

- Improved system simulation models
- Improved observability of system operation and control
- Refined definition of system operating limits
- Improved management of system reliability & assets
- Enhanced understanding of the whole system
- Enhanced sensing, computation, communication and control systems for electricity infrastructure

- *Key Functionalities:*
  - On Line calibration of dynamic system models
  - Real-Time tuning of FACTS devices and system stabilizers
  - Distributed sensing, computation and control
  - Faster than real-time simulations with look ahead what if contingency analysis
  - Integrated market, policy and risk analysis into system models, and quantify their effects on system security and reliability

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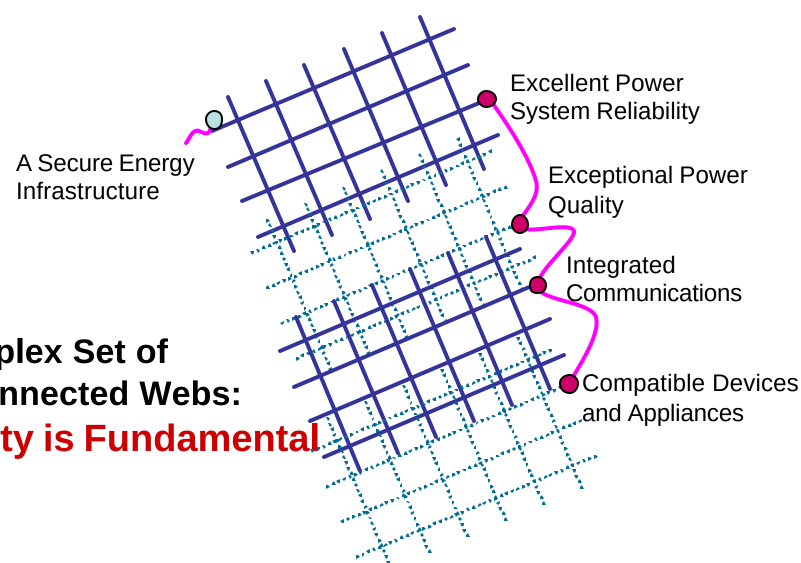
The Infrastructure for a Digital Society



A Complex Set of Interconnected Webs:
Security is Fundamental

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Technology Must Support This Transformation: Infrastructure Technology Gaps

- Sensors for real-time monitoring and complex network control
- Electronic power flow control
- Real-time dispatch of distributed resources
- Interference-free power line communications
- Load management and customer choice
- Premium power and DC service
- Energy solutions for end-use digital applications
- Enhanced end-use energy efficiency
- Digital devices with greater tolerance to power disturbances

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Electricity Infrastructure Security

R&D Priorities

- Extend probability risk assessment combined with "dynamics" and intelligent agents to the entire electricity system
- Develop & deploy integrated smart network control technology
- Enable the self-healing grid by developing the Strategic Power Infrastructure Defense (SPID) system
- Develop advanced electromagnetic threat detection, shielding and surge-suppression capabilities
- Develop the tools and procedures to ensure a robust and secure marketplace for electricity
- Develop the portfolio of advanced power generation technologies needed to assure energy security

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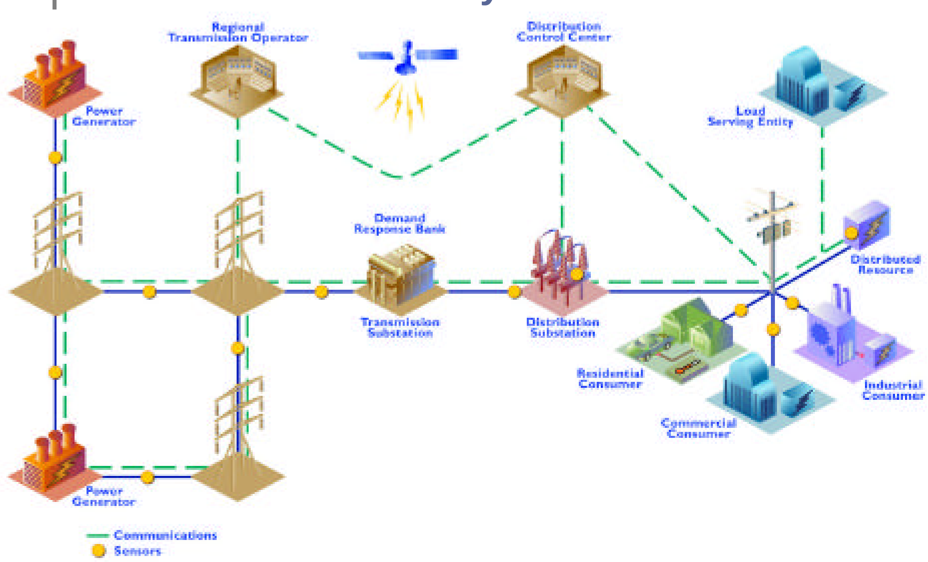
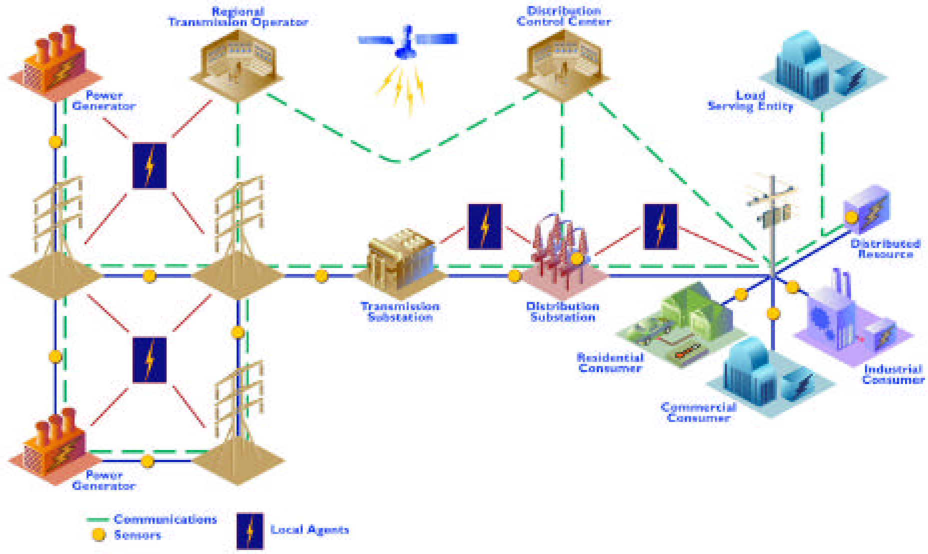
Longer-Term Actions

- Undertake a risk assessment of long-term US reliance on predominantly single source fuel generation
- Expand price signals and competitive market dynamics to all customers
- Create a planning process to design more effective and efficient power markets
- Develop and implement a comprehensive architecture for the power system infrastructure
- Expedite construction of new, higher-efficiency generation
- Accelerate R&D on advanced nuclear, renewable and coal-based systems to manage supply risks
- Establish a regional transmission agency

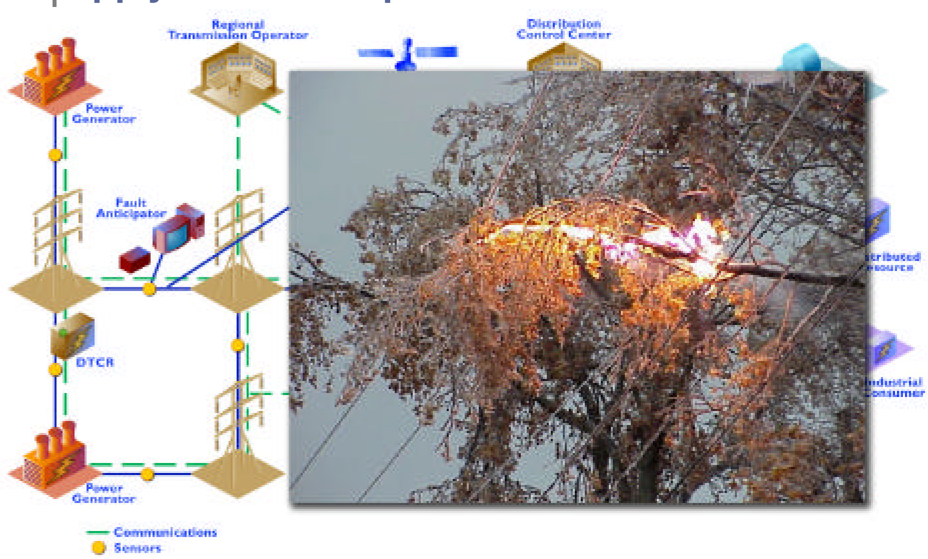
Next Steps: Integrated Electric and Communications Systems



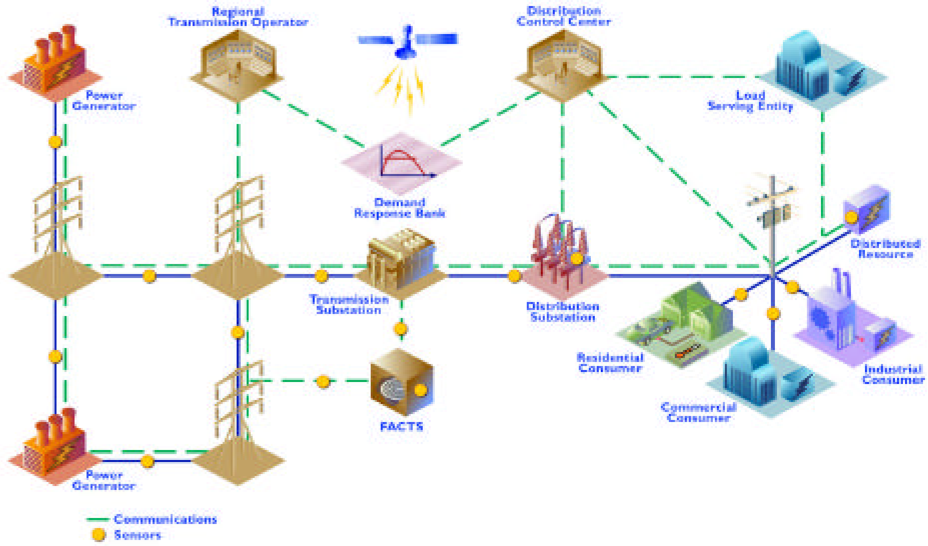
Next Steps: Deploy Local Computational Agents



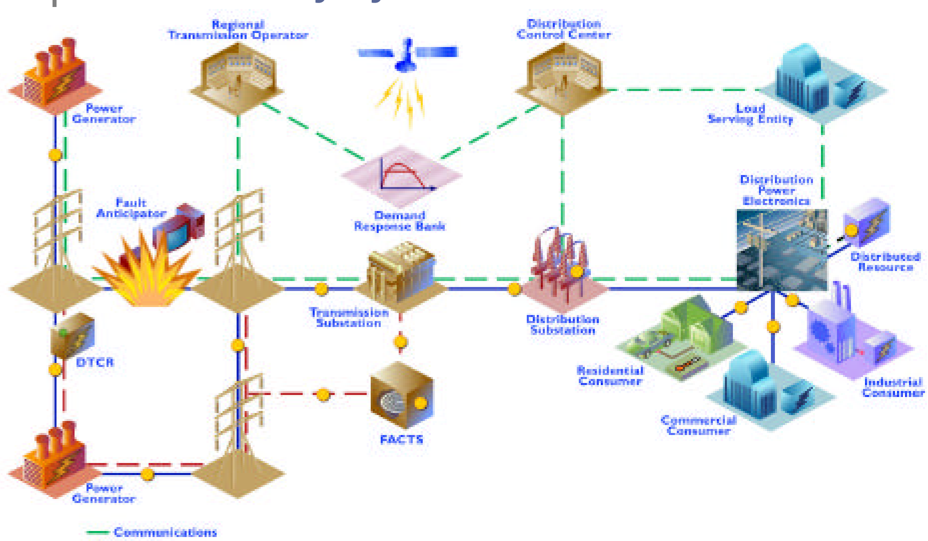
Next Steps: Apply Fault Anticipation



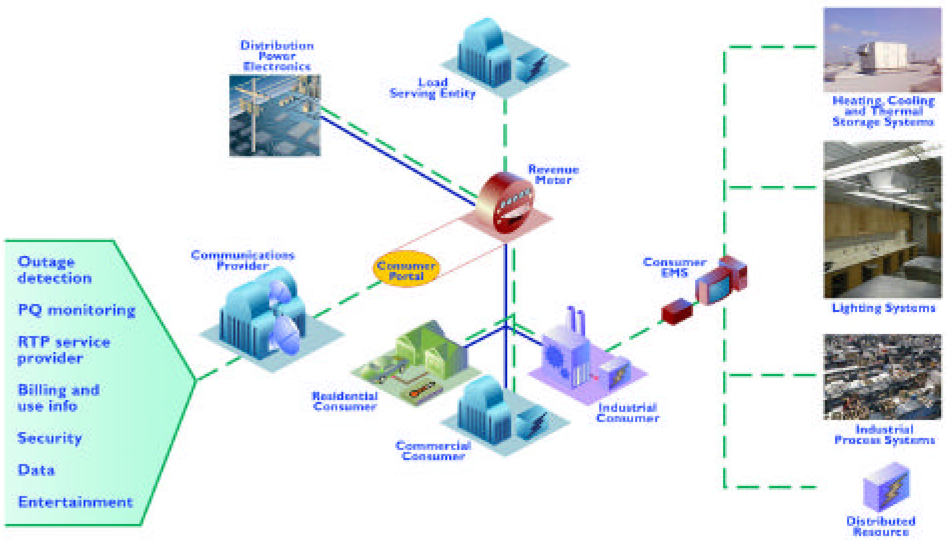
Next Steps:
Apply Electronic Power Flow Control



Enable A Self-Healing
Power Delivery System

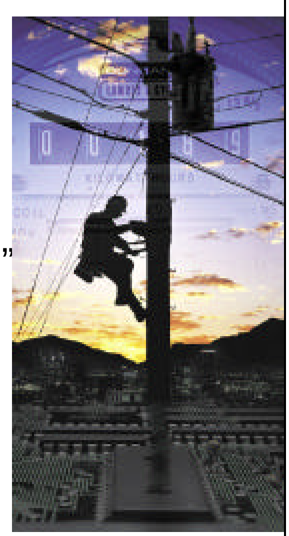


Consumer Portal



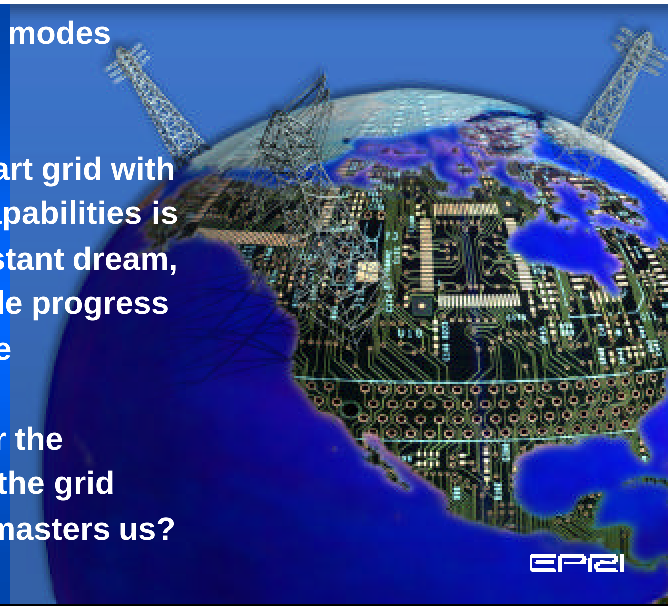
Recommendations

- 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

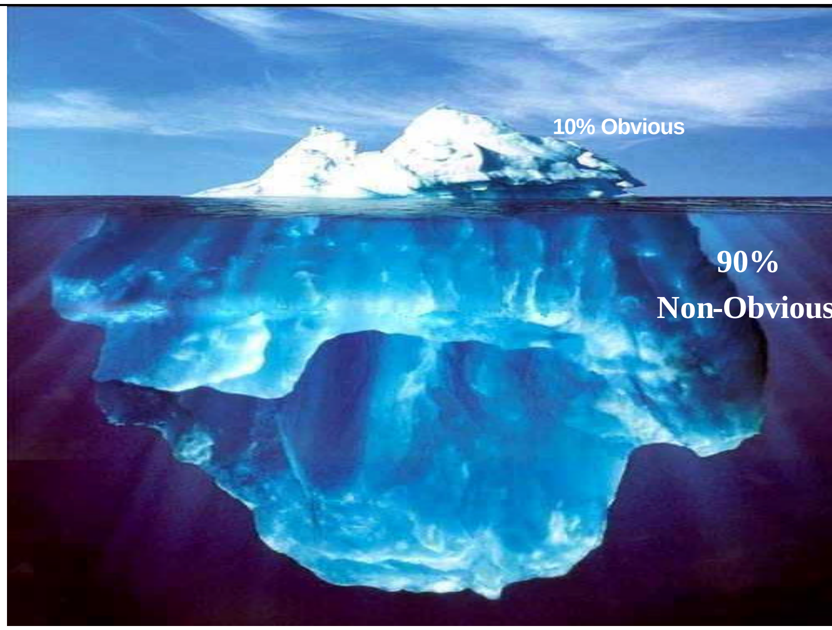
- Several failure modes persist…
- Creating a smart grid with self-healing capabilities is no longer a distant dream, as considerable progress has been made
- Can we master the complexity of the grid before chaos masters us?



Self Healing Grid

"Civilization advances by extending the number of important operations which we can perform without thinking about them"

- Alfred North Whitehead
(b.1861 - d.1947), British mathematician, logician and philosopher



But, avoid the Pygmalion Syndrome!

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Appendix:

Additional Resources:

1) EPRI's Electricity Technology Roadmap
2) Follow-up Difficult Challenges Reports
3) CIN/SI: 1999-2001-- Technical Progress and Time-line to Testing and Deployment
4) Recently Sponsored Workshops and Their Findings
5) Next Steps: CEIDS-sponsored Fast Simulation and Modeling Program

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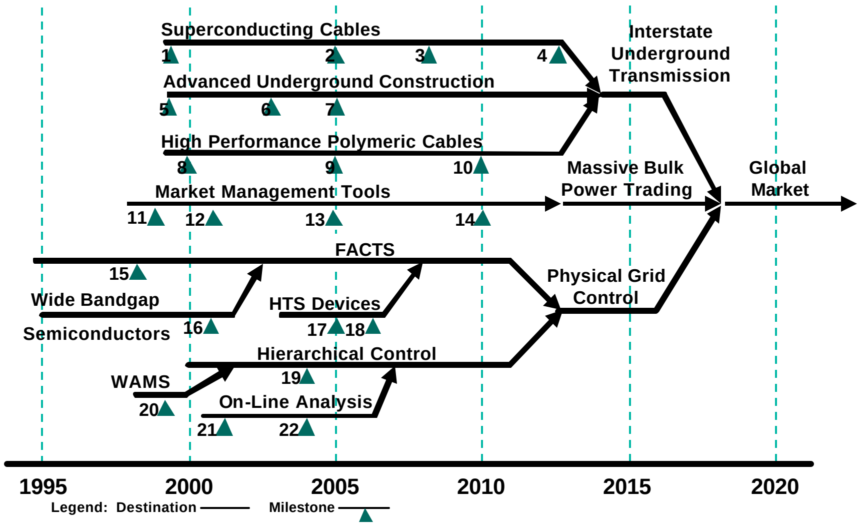
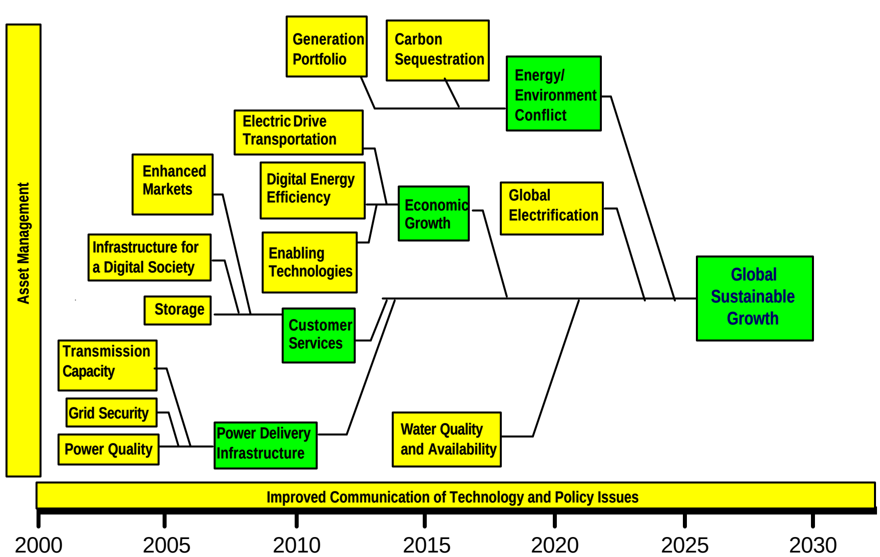
Electricity Technology Roadmap: Tree for Power Delivery Technologies



Electricity Technology Roadmap: Difficult Challenges



CIN/SI: 1999-2001
Technical Progress and Time-line to Testing and Deployment (1)

Wide area measurement and control:

- Application of WAMS: 1-2 years
  - Advanced sensor development and placement
  - GPS synchronization
  - Advanced communications 1-3 yr
- Adaptive self-healing techniques (adaptive protection and Islanding)
- System vulnerability assessment tool (incorporating indices for power system dynamics and control, protection and communication systems)
- Tools for real-time determination of regions of vulnerability and analyses of hidden failures– display of vulnerability index

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CIN/SI: 1999-2001
Technical Progress and Time-line to Testing and Deployment (2)

- Impact of protection systems on major system disturbances:
  - Detailed simulation of significant events/sample paths– soft-spot determination (Ready for next step)
  - Mitigation schemes for hidden failures in relays and maintenance (Start commercial product development)
  - Grid monitoring and operation with Quality of Service (QoS– consisting of performance and fault-tolerance) demo --1 year
- Strategic power infrastructure defense integration and testing
- Automated on-line fault detection, analysis and classification
- Substation state estimation (using advanced 3-phase state estimation) (1-2 years for demo with data)
- Transaction monitoring

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CIN/SI: 1999-2001
Technical Progress and Time-line to Testing and Deployment (3)

- Local-area grid modeling and anticipatory dispatch of small units
- Predictive modeling of loads (neuro-fuzzy approach with wavelet-based signature extraction) 1 yr
- Automated learning of the consumption patterns and tracking unexpected demand transients– extend to a few days ahead.
- Genetic Algorithm based approach to OPF, generator dispatch and use of energy storage units 1-2 yr for GUI
  > 3 yr for commercial
- Transmission/distribution entities with on-line self-healing testing and integration 2 yrs for TELOS demo

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CIN/SI: 1999-2001
Technical Progress and Time-line to Testing and Deployment (4)

- Automated simulation testing of market (auction) preliminary designs for electricity 1 yr
- OPF with incorporation of congestion constraints in the dispatch– sensitivity analysis > 1- 2 yrs
- Coloring electrons: Determination of root causes/entities responsible for losses Ready 6 months
- Transmission Service Provider:
  - Capacity optimization 2 yrs to handle large systems
  - Value-based transmission resource allocation under market and system uncertainties
- Congestion management– extension to multi-region scenarios and addressing SEAMS 6 months--ready for conceptual testing

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CIN/SI: 1999-2001
Technical Progress and Time-line to Testing and Deployment (5)

- Complexity-based evaluation of models using index of complexity--
  Algorithm is ready but needs1-2 yrs testing
- Probabilistic methods/models for Critical Infrastructure Protection (CIP) and reduction of vulnerabilities of the information systems--
  Early stage, needs 2-3 yrs
- Power system diagnostics dynamic recording devices (DRD) – Integ. of Disturbance Event Analyzer with Fault Diagnostic-- 2-3 yrs for demo
- Adaptive coherency, signal selection for control design, adaptive tuning (applications to HTSC, FACTS, PSS, etc) 1-2 yrs
- Power system modeling uncertainty and probabilistic modeling – based on small systems, new method for dynamic system reduction
  2-3 yrs for larger systems
- Repertoire/catalog of control design strategies for systems with many controllers 1-2 yrs

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Background:
NSF/DOE/EPRI Workshop on "Future Research Directions for Complex Interactive Electric Networks" Washington D.C., Nov. 2000.

- Several pertinent research directions were identified in the four main technical thrust areas:
  - Power System Economics
  - Real-time Wide Area Sensing, Communications, and Control of Large Scale Networks
  - Distributed Generation, Fuel Cells, and New Technology
  - Prescriptive and Predictive Model Development
- More details on each of the four areas are available at: http://ecpe.ee.iastate.edu/powerworkshop/.

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NSF/EPRI Workshop 1: Urgent Opportunities for Transmission System Enhancement

October 11-12, 2001; EPRI, Palo Alto, CA

Grand Challenges:

1. Lack of Transmission Capability
2. Operation in a Competitive Market Environment
3. Power Infrastructure Vulnerability

Proceedings of the workshop are available at:
http://www.ee.washington.edu/energy/apt/nsfepri/welcome.html

Steering Committee:

Chen-Ching Liu, U of Washington
James Momoh and Paul Werbos, NSF
Massoud Amin, Aty Edris, and Acher Mosse, EPRI

Participation: 48 attendees from Universities, Industry, & Government

EPRI

Brainstorming on the impact of data-based modeling on electricity infrastructure operations and security applications (EPRI, Palo Alto, Nov. 19, 2001)

Objective:

Create a strategic vision extending to a decade, or longer, for a data-based paradigm enabling secure and robust systems operation, security monitoring and efficient energy markets

Emphasis on:

1) Infrastructure sensing/measurement,
2) Sources of data and required scales,
3) Data/information processing and protection, communications, system security,
4) Integration with models/techniques based on physics and first principles,
5) All implications/applications of data-based modeling

Participants	Organization
Joe Chow	RPI
Mladen Kezunovic	Texas A&M University
Richard Oehlberg	EPRI
Joe Hughes	EPRI
Robert Schainker	EPRI
Bruce Wollenberg	University of Minnesota
Luther Dow	EPRI
Joe Weiss	EPRI
Jim Fortune	EPRI
Jeff Dagle	PNNL
John Hauer	PNNL
Massoud Amin	EPRI
Dejan Sobajic	EPRI
Aty Edris	EPRI
Tariq Samad	Honeywell Labs
Revis James	EPRI
Peter Hirsch	EPRI
Paul Grant	EPRI

EPRI

Brainstorming session on the impact of data-based modeling on electricity infrastructure operations and security applications (EPRI, Palo Alto, Nov. 19, 2001)

Issues:

Identify Information needs of the "new" energy infrastructure:

End-to-end integrated assessments using real data
Control/Operations
Planning and Management
Couplings with Energy Markets
Data Reporting
"Security"-- Physical/cyber security & electronic needs

Data needs for "closed-loop" Architecture:

- Integrate 1st principle / physics together with data / numerical methods
- Sensed and processed locally
- Data Integration at Substation – SCADA
- Institutional & information exchange rates, accountability

Responsibilities

- RTOs/ connect to control centers
- NERC / FERC / State Regulatory Authority Centers
- Utilities
- Non-utility generators

Customers

- Load modeling
- Integration of operating
- Response to pricing
- Public Sector Interest

EPRI

Brainstorming session on the impact of data-based modeling on electricity infrastructure operations and security applications (EPRI, Palo Alto, Nov. 19, 2001)

Issues:

1. KWH on minute-by-minute basis from smart meters.
   - Power Quality Measurers
   - Gateway to customer network (data on customized individual Circuits/appliances)

2. Electrical, Mechanical, and Chemical Parameters

3. Data mining
   Local processing / archiving of all data
   Management of Heterogeneous Network

4. Management of individual components
   Precursors to disturbances and prediction of failure

5. Synchronized Phasor Measurements (SPM)
   Integrated Phasor Meas. (IPM), Digital PSS, Relays, DTRs, IEDs

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Brainstorming session on the impact of data-based modeling on electricity infrastructure operations and security applications (EPRI, Palo Alto, Nov. 19, 2001)

Issues:

6. Standards on data & device models
   - Data "Visualization"
   - Security and openness
   - Security policies for entire power industry
   - Real time pricing data

7. Control paradigm of related architecture as well as migration issues and strategies.

8. Reliability management – who does what?
   - Uncertainty in future systems – Disciplined uncertainty/management
   - Rationalize investment – who pays?

9. Need flexible down selection in data – intelligent processor, aggregators; disaggregators.

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Brainstorming session on the impact of data-based modeling on electricity infrastructure operations and security applications (EPRI, Palo Alto, Nov. 19, 2001)

Hurdles:

OWNERSHIP (who owns what?) E.g. IP

INFORMATION SHARING AND PROTECTION MARKET RULES

Consistent architecture for data and information security

HIERARCHY / ORGANIZATION

Functionality analysis

INTEGRATION

Data-driven "multimodeling" with explicit consideration of uncertainty

IMPROVED MODEL VALIDATION METHODS

Applications along with Functionality/Performance/Security integrated assessments

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NSF/EPRI Workshop 2: Economics, Electric Power and Adaptive Systems

March 28-29, 2002; Arlington, Virginia

Grand Challenges:

1. The Challenge for Economics: Designing Competitive Electric Power Markets
2. The Challenge for Electric Power Engineering: Redefining Power System Planning and Operation in the Competitive Era
3. The challenge for Adaptive Systems: Solving Power System Problems with Adaptive Control Technologies

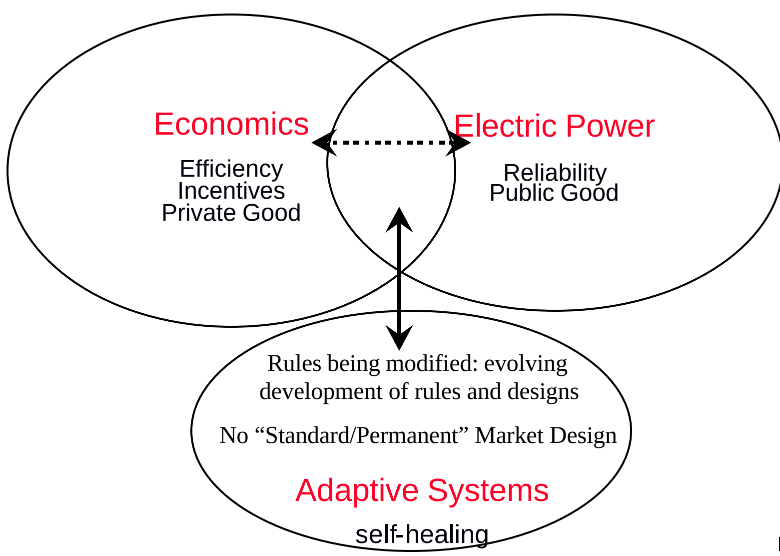
Participation: 40 attendees from Universities, Industry & Government

Proceedings of the workshop:
http://www.ece.umn.edu/groups/nsfepriworkshop/

Steering Committee:

Bruce Wollenberg, U of Minnesota
James Momoh and Paul Werbos, NSF
Massoud Amin and Hung-po Chao, EPRI

Context for Workshop 2:
Economics, Electric Power and Adaptive Systems



EPRI/NSF Workshop 3: Global Dynamic Optimization of the Electric Power Grid

April 10-12, 2002; Playacar, Mexico

Grand Challenges:

1. "Optimum" selection of type, mix and placement of control hardware
2. Integrated network control
3. Centralized or decentralized control; how to coordinate?
4. What infrastructure hardware will various strategies require?
5. A benchmark network is needed for testing theories
6. Pilot schemes to prove validity of concepts after simulation

Proceedings of the workshop: http://users.ece.gatech.edu/~rharley/EPRI.htm

Participation: 30 attendees from Universities, Industry & Government

Steering Committee:

Ronald Harley, Georgia Institute of Technology
Paul Werbos and James Momoh, NSF
Massoud Amin and Aty Edris, EPRI

Workshop 4: Co-sponsored by NSF, Entergy, EPRI, & DOE Modernizing The National Electric Power Grid

Nov. 18-19, 2002, New Orleans, LA

Proceedings of the workshop:
http://eent1.tamu.edu/nsfw/

Please also see the "Presentations" section at:
http://eent1.tamu.edu/nsfw/presentations.htm

Participation: Over 50 attendees from Universities, Industry & Government

Steering Committee:

Mladen Kezunovic, Texas A&M University
Floyd Galvan, Entergy
James Momoh, NSF
Abbie Layne, DOE
Massoud Amin, EPRI

CIN/SI Tech Transition to CEIDS: Fast Simulation & Modeling (FSM) Program

Background

- Self-Healing Grid (SHG)
  - Automatically anticipates and responds to system disturbances
  - Continually optimizes normal system performance
  - SHG architecture now under development
  - Next step will involve addition of Intelligent Network Agents (INAs)
    - Distributed sensing, computation and control
    - Gather and communicate system data
    - Make decisions about local control functions
    - Coordinate decisions with overall system requirements

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CEIDS: Fast Simulation & Modeling (FSM) Program

Objectives

- FSM Program will augment SHG capabilities in three ways:
  - Provide faster-than-real-time, look-ahead simulations to avoid previously unforeseen disturbances
  - Perform what-if analysis for large-region power systems from both operations and planning points of view
  - Integrate market, policy and risk analysis into system models and quantify their effects on security and reliability

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CEIDS:
Fast Simulation & Modeling (FSM) Program

FSM Projects

- Multi-Resolution Modeling
  - Enable operators to "zoom" in or out to visualize parts of a system
- Modeling of Market and Policy Impacts on Reliability
  - Enable planners to simulate the effects of new market designs before putting them into practice
- Validation of Integrated Models with Real-Time Data
  - Reveal vulnerable operating conditions using data from major power systems

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Multi-Resolution Modeling

- Build on improvements in basic modeling techniques from CINSI
  - Apply fast-simulation algorithms to real power systems
  - Eventually use real-time data from INAs
- Improve quality and speed of state, topology, and parameter estimation for complex power networks
- Key feature is look-ahead simulation
  - Like chess player anticipating opponent's moves
  - Ask "what-if" questions about possible system contingencies

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Look-Ahead Simulation Applied to Multi-Resolution Models

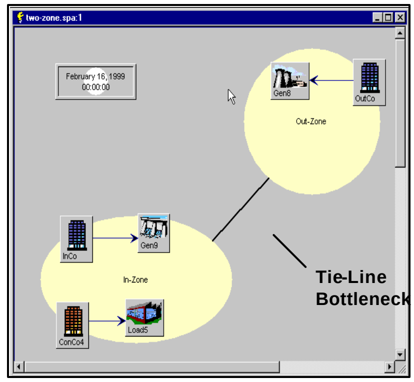
- Provides faster-than-real-time simulation
  - By drawing on approximate rules for system behavior, such as power law distribution
  - By using simplified models of a particular system
- Allows system operators to change the resolution of modeling at will
  - Macro-level (regional power systems)
  -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

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

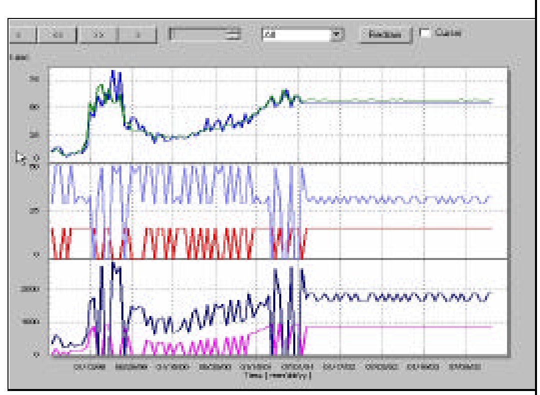
Example of Market-Grid Interactions: Setup

- 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



Advantages of Integrated Modeling

- Being able to model both the physical system and market/policy impacts permits breakthrough investigations of how they are coupled
- Permits testing of regulatory changes based on solid engineering models of power system
- Enables system planners to determine how regulatory changes may affect network security and stability
- Eventually such models could include devices at the customer level

Validation of Integrated Models with Real-Time Data

- Fundamental capabilities of fast simulation and modeling will be demonstrated first using test data
- Then the models will be validated using real-time data, off-line at control centers
- Parallel to this effort will be enhancement and expansion of the Wide-Area Measurement System (WAMS)
- Eventually both the fast simulation algorithms and data collection/communication capabilities will be incorporated into INAs

What to Expect from Integrated Models

- Fast simulation techniques are based on statistical analysis rather than deterministic calculations
- Thus results can reveal the risks and trade-offs involved in operating a power system beyond certain limits
- Such knowledge will help operators respond when a system gets overloaded
- Potential vulnerabilities can be easily visualized