Toward a Secure and Smart Self-Healing Grid

Massoud Amin
Manager, Mathematics and Information Sciences
mamin@epri.com
(650) 855-2452

Strategic Science & Technology
EPRI Research Advisory Committee (RAC)

Adaptive Infrastructures

Tuesday, January 27, 1998

EPRI

Goal: Enable a Smart Self-healing Grid and Resilient National Infrastructures

- Develop tools that enable secure, robust and reliable operation of interdependent critical infrastructures with distributed intelligence and self-healing abilities

- Joint innovative research program to be undertaken by EPRI and U.S. DoD (DDR&E) to address:
  - Underpinnings of complex and dynamically-coupled Interdependent Critical National Infrastructures

- Government Industry Cooperative University Research (GICUR)

Multi-Scale Time Hierarchy of Power Systems

ACTION / OPERATION	TIME FRAME
Wave effects (fast dynamics, lightning caused overvoltages)	Microseconds to milliseconds
Switching overvoltages	Milliseconds
Fault protection	100 milliseconds or a few cycles
Electromagnetic effects in machine windings	Milliseconds to seconds
Stability	60 cycles or 1 second
Stability Augmentation	Seconds
Electromechanical effects of oscillations in motors & generators	Milliseconds to minutes
Tie line load frequency control	1 to 10 seconds; ongoing
Economic load dispatch	10 seconds to 1 hour; ongoing
Thermodynamic changes from boiler control action (slow dynamics)	Seconds to hours
System structure monitoring (what is energized & what is not)	Steady state; on-going
System state measurement and estimation	Steady state; on-going
System security monitoring	Steady state; on-going
Load Management, load forecasting, generation scheduling	1 hour to 1 day or longer; ongoing.
Maintenance scheduling	Months to 1 year; ongoing.
Expansion planning	Years; ongoing
Power plant site selection, design, construction, environmental impact, etc.	10 years or longer

Technical Objectives:
Develop tools/techniques that enable large-scale Infrastructures to *self-stabilize, self-optimize, self-heal*

- **Modeling:** Understanding the "true" dynamics-- To develop techniques and simulation tools that help build a basic understanding of the dynamics of complex infrastructures.

- **Measurement:** Knowing what is or will be happening-- To develop measurement techniques for visualizing and analyzing large-scale emergent behavior in complex infrastructures.

- **Management:** Deciding what to do-- To develop distributed systems of management and control to keep infrastructures robust and operational.

Definition: Smart Self-Healing Grid

- What is a Smart Self-healing grid?

  The term "smart grid" refers to the use of computer, communication, sensing and control technology which operates in parallel with an electric power grid for the purpose of enhancing the reliability of electric power delivery, minimizing the cost of electric energy to consumers, and facilitating the interconnection of new generating sources to the grid.

- What are the power grid's emerging issues? They include

  1) integration and management of DER, renewable resources, and "microgrids";
  2) use and management of the integrated infrastructure with an overlaid sensor network, secure communications and intelligent software agents;
  3) active-control of high-voltage devices;
  4) developing new business strategies for a deregulated energy market; and
  5) ensuring system stability, reliability, robustness, security and efficiency in a competitive marketplace and carbon constrained world.

Definition: Smart Self-Healing Grid

- What is "self healing"?
  - A system that uses information, sensing, control and communication technologies to allow it to deal with unforeseen events and minimize their adverse impact

- Why is self healing concept important to the Electric Power Grid and Energy Infrastructure?
  - A secure "architected" sensing, communications, automation (control), and energy overlaid infrastructure as an integrated, reconfigurable, and electronically controlled system that will offer unprecedented flexibility and functionality, and improve system availability, security, quality, resilience and robustness.

Context: IT interdependencies and impact

Dependence on IT: Today's systems require a tightly knit information and communications capability. Because of the vulnerability of Internet communications, protecting the system will require new technology to enhance security of power system command, control, and communications.

Increasing Complexity: System integration, increased complexity: call for new approaches to simplify the operation of complex infrastructure and make them more robust to attacks and interruptions.

Centralization and Decentralization of Control: The vulnerabilities of centralized control seem to demand smaller, local system configurations. Resilience rely upon the ability to bridge top-down and bottom-up decision making in real time.

Assessing the Most Effective Security Investments: Probabilistic assessments can offer strategic guidance on where and how to deploy security resources to greatest advantage.

Critical System Dynamics and Capabilities

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

re·sil·ience, *noun,* 1824: The capability of a strained body to recover its size and shape after deformation caused especially by compressive stress; An ability to recover from or adjust easily to misfortune or change

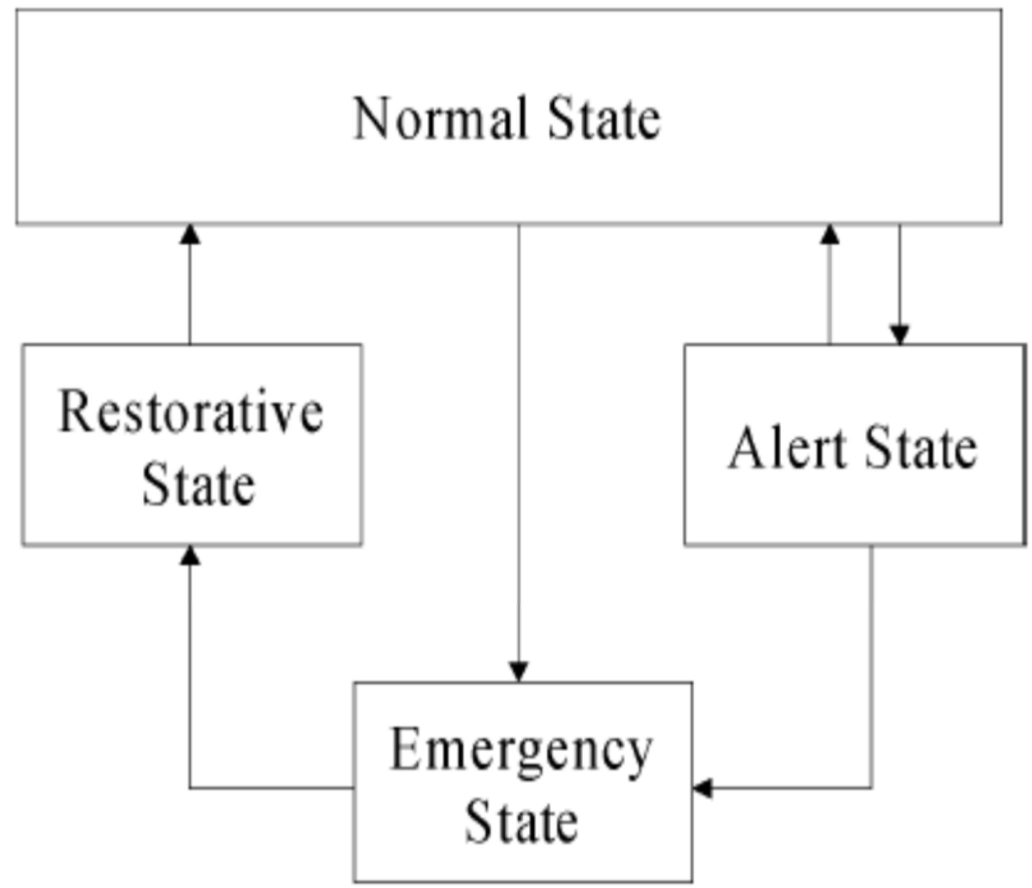
Resilience enables "Robustness": A system, organism or design may be said to be "robust" if it is capable of coping well with variations (internal or external and sometimes unpredictable) in its operating environment with minimal damage, alteration or loss of functionality.

Understanding Complex Dynamical Systems

… Systems' operations, mathematical foundations, and guidance on how to measure and adapt to disturbances:

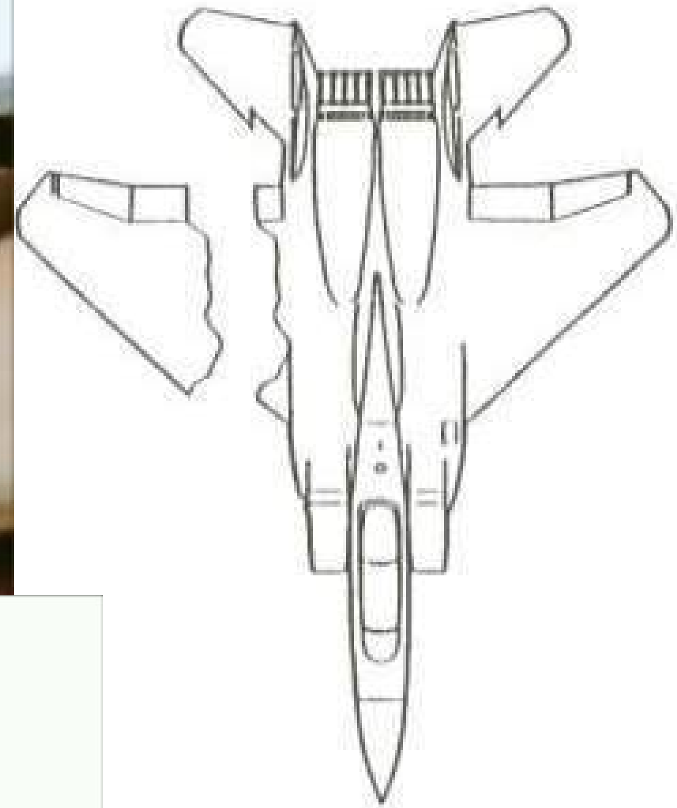
System is characterized as having multiple states, or "modes," during which specific operational and control actions/reactions are taking place:

- *Normal mode:* economic dispatch, load frequency control, maintenance, forecasting, etc.;
- *Alert mode:* red flags, precursor detection, reconfiguration and response;
- *Emergency/Disturbance mode:* stability, viability, and integrity -- instability, load shedding, etc.;
- *Restorative mode:* rescheduling, resynchronization, load restoration, etc.



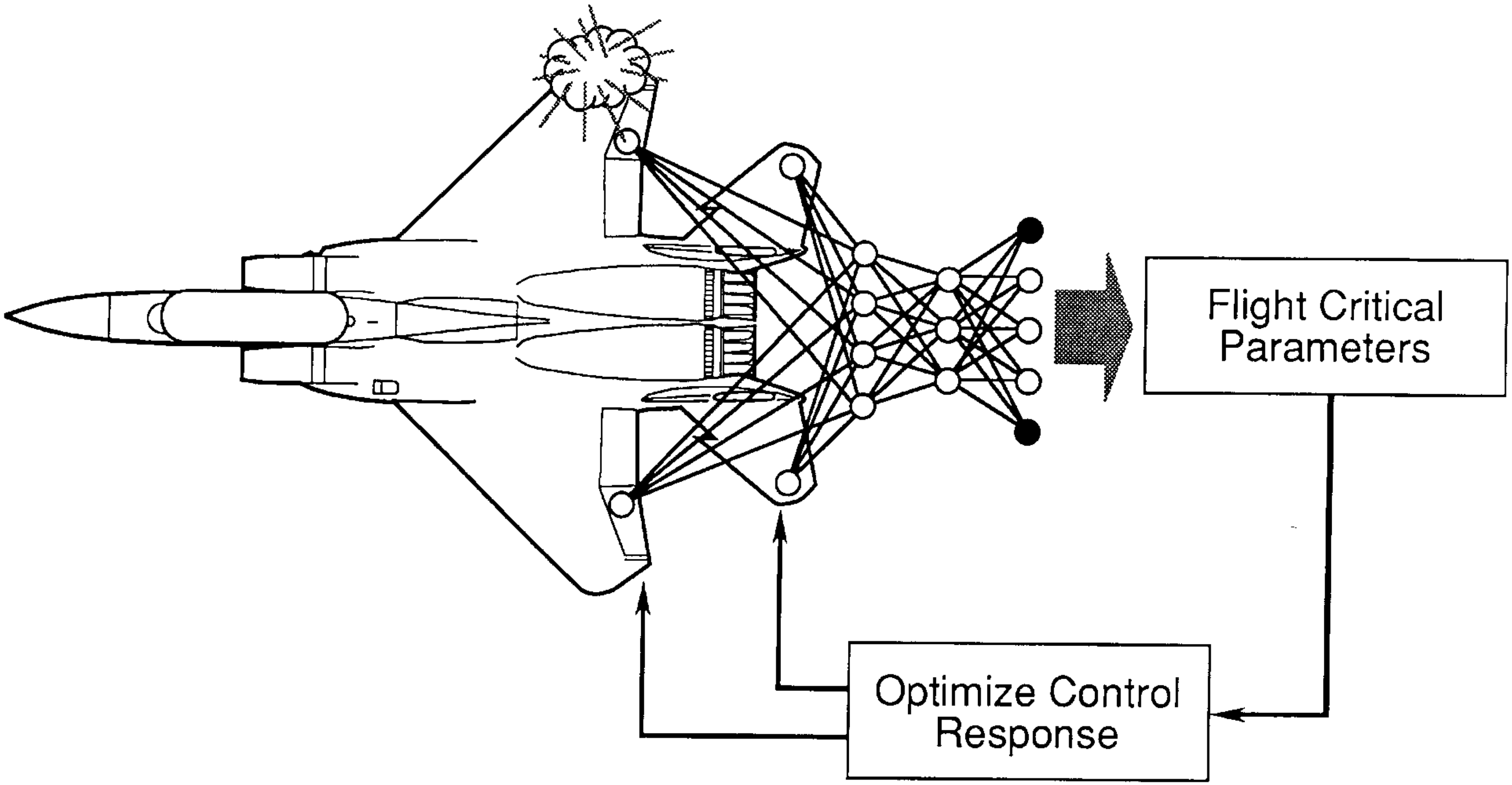
Background:
The Smart Self Healing Grid

Saving systems from collapse: The Case of the Missing Wing (1983-1997)

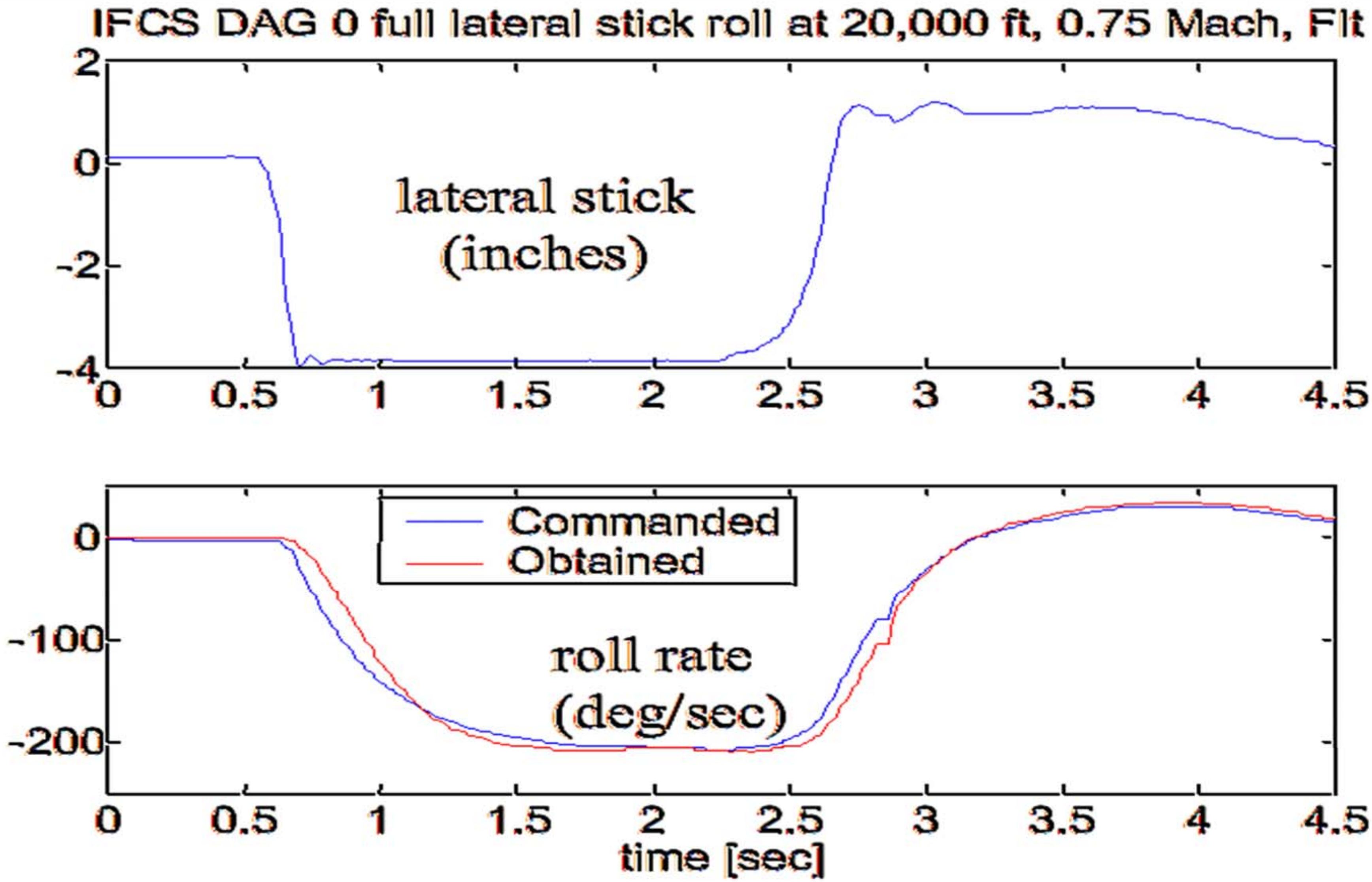


NASA/MDA/WU IFCS: NASA Ames Research Center, NASA Dryden, Boeing Phantom Works, and Washington University in St. Louis.

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



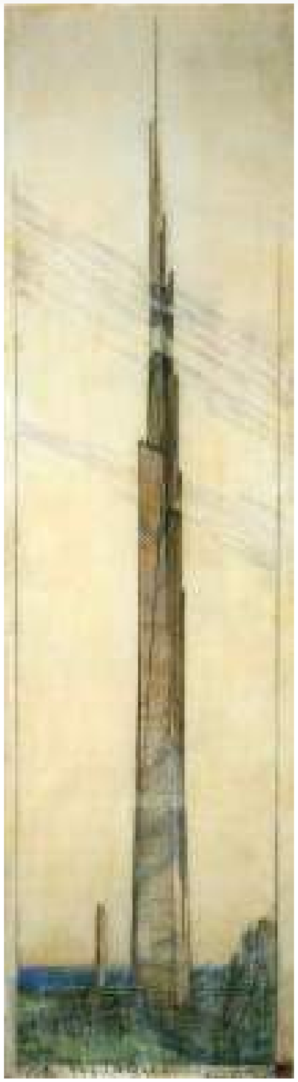
Intelligent Flight Control System: Example – complete hydraulic failure (1997)



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.

Smart Self-healing Grid



Building on the Foundation:

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

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)

Complex Interactive Network/Systems

Complex interactive networks:

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

Develop tools that enable secure, robust and reliable operation of interdependent infrastructures with distributed intelligence and self-healing abilities

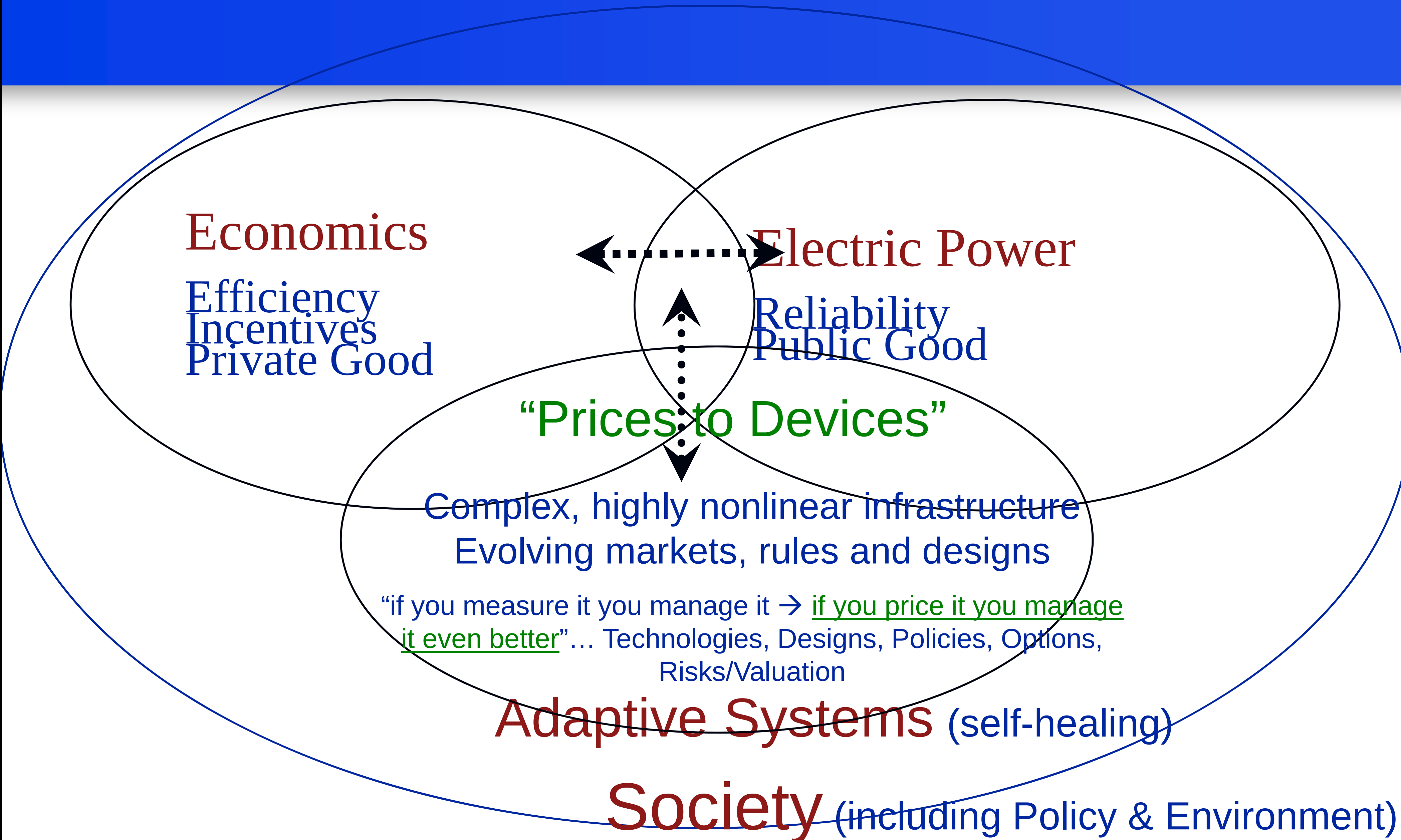
EPRI

Complex Interactive Networks

- Systems' approach to complex networks: advancing mathematical and system-theoretic foundations

- Overall focus and results (theoretical and applied) for increased dynamic network reliability and efficiency:
  - ❖ Identification, characterization and quantification of **failure mechanisms**
  - ❖ 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**

Energy Infrastructure, Economics, Efficiency, Environment, Secure Communications and Adaptive Dynamic Systems



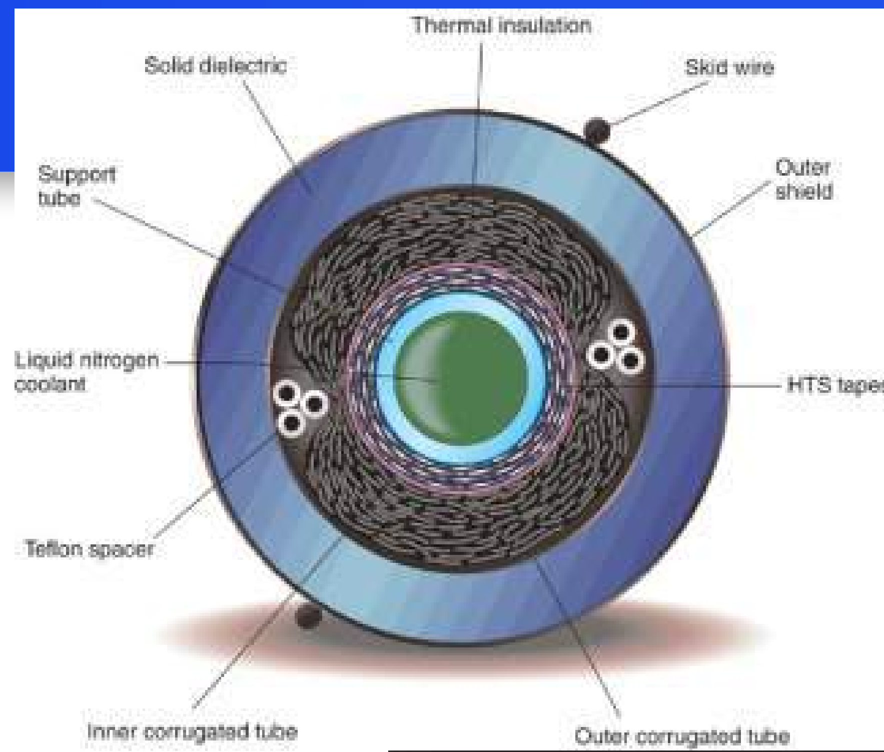
What are we doing about it?
Enabling Technologies

- 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.

What are we doing about it? 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.
- Power Electronics to enable integration of intermittent sources, connection to smart grid, and increased controllability.
- 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.

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

Foci in Mathematics and Systems Theory

- **Modeling:** Idealized models, consisting of static graph-theoretic models, and interactive dynamic models, such as interconnected differential-algebraic systems; Hybrid Models.
- **Robust Control:** Design of smart self-healing systems requires the extension of the theory of robust control in several ways beyond its present focus on the relatively narrow problem of feedback control.
- **Complex Systems:** Theoretical underpinnings of complex interactive systems.
- **Dynamic Interaction in Interdependent Layered Networks:** Characterization of uncertainty in large distributed networks: Multi-resolutional techniques where various levels of aggregation can co-exist.
- **Disturbance Propagation in Networks:** Prediction and detection of the onset of failures both in local and global network levels.
- **Forecasting, Handling Uncertainty and Risk:** Characterizing Uncertainties and Managing Risk**;** Hierarchical and multi-resolutional modeling and identification; Stochastic analysis of network performance; Handling Rare Events.

Bigger Picture

- Systems' approach to complex networks: advancing mathematical and system-theoretic foundations
- Direct applications to energy infrastructure sensing, monitoring, & protection; markets & communications networks
- Greater understanding of role of integrated sensing, modeling, simulation, optimization and robust control
- Overall results (theoretical and applied) for increased dynamic network reliability, security and efficiency
- Crosscutting themes in large-scale networks… Value shedding

Next Steps

- Near-Term: Extract the most promising technologies for testing with real data and further development; e.g.:
  - Intelligent Adaptive Islanding Schemes: Identify and correlate hidden failure mechanisms for systems and components
  - Systems' approach: Provide a greater understanding of how advanced power electronics, DR, and other technologies might fit into the continental grid, as well as guidance for their effective deployment and operation:
    - *In Vivo* vs. *In Silico* simulation testing of devices in the context of the whole system-- the grid, markets, communication and protection.
    - If implemented for California, some of this work could possibly model an "artificial" or "incomplete" deregulation scenario
- Integration and Security impacts to enable a "Digital Society"?
- Feedback and additional participation is welcomed.