Innovative Control of a Flexible, Adaptive Energy Grid

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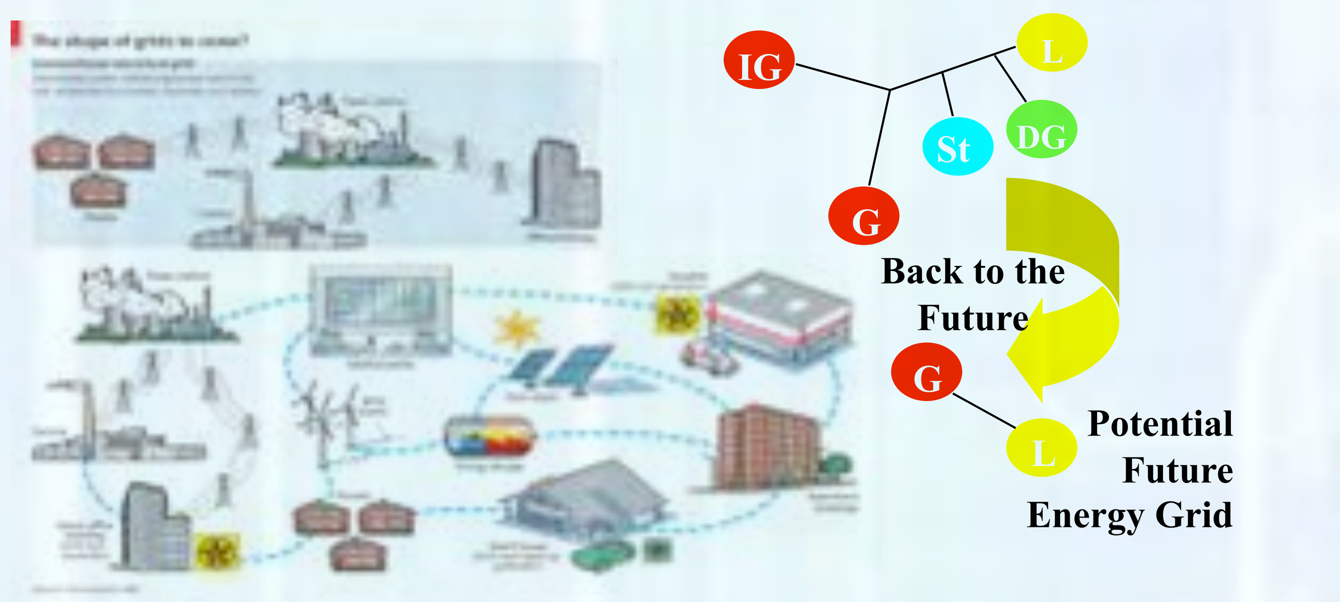
Problem

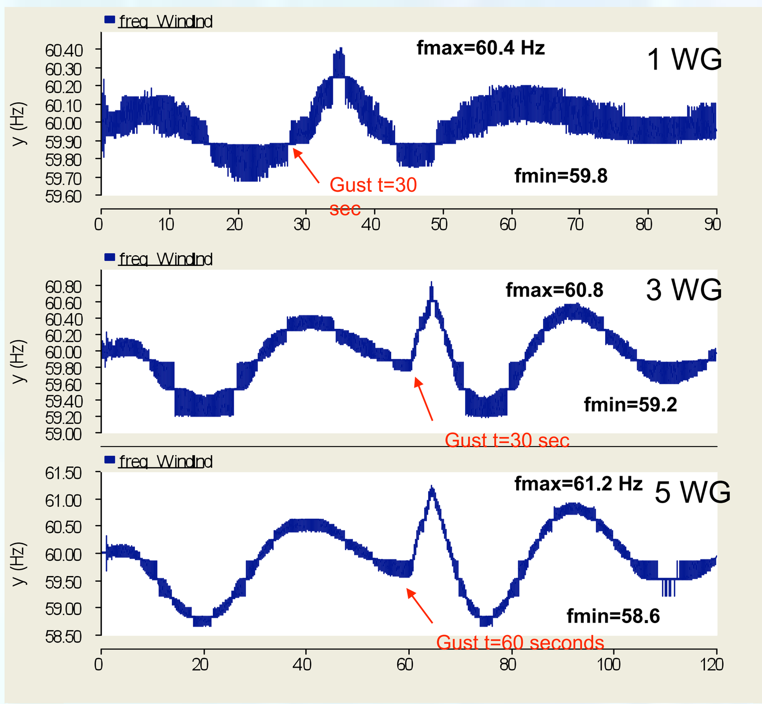
- The current energy infrastructure is in a state of transition where intermittent electricity generation sources (e.g., wind and solar) are being proposed as major elements of the future energy mix.
- Uncertainties as to how these technologies will impact energy infrastructure reliability and efficiency; they are not designed for "easy" integration.
- In addition, the electric grid is being operated closer to instability limits, to maximize resources. Consequently, better approaches are needed to understand, engineer, manage, and control the energy grid.



Courtesy of: California ISO

Kauai, HI Model — Example Wind Gust Comparison Data

- Model PSCAD Kauai 12 bus system - 60 KV, 70 MW load with diesel & gas generation
- Examined dynamics with addition of 1, 3, and 5 - 3MW PSCAD MOD-2 modeled wind induction generators (WG)
- Examined changes in voltage, frequency and power flow for: startup, opening of wind generators, load increase, fault, wind ramp and wind gust conditions
- For example, wind gusts induce similar duration but larger- magnitude frequency changes when more generators are included; but voltage changes are less affected
- Wind Gust Model: windspeed baseline 15 m/s, Gust 30 m/s, duration 5 seconds.



Summary: Frequency variations due to wind intermittency may cause frequency instabilities

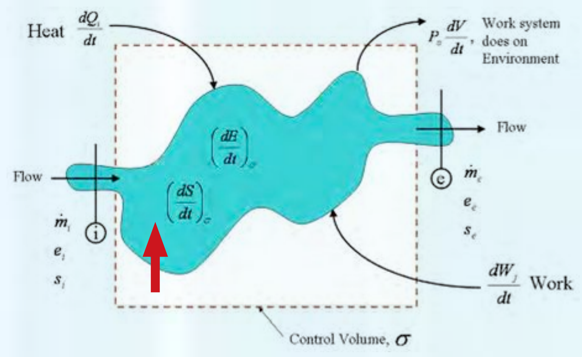
Approach

Project Goals and Approach

- Develop a scalable closed-loop nonlinear analysis and control technique based on exergy and irreversible entropy production supporting engineering of a flexible, adaptive energy infrastructure, more resilient to stresses and disruptions.
- The technical approach combined R&D of: 1) general theory for closed-loop control with information feedback and design of robust critical infrastructures; with 2) numerical simulations using Matlab/Simulink/SimPowerSystems toolbox; and 3)experimental validation using Opal-RT real-time simulator for validation of electric power grids model to test new control and design approaches for specific and analogous applications.

Results

Unifying Theory: Sorting Power Terms and Physical/ Information Exergies



- **Energy rate equation**

$$\dot{E} = \sum_i \dot{Q}_i + \sum_j \dot{W}_j + \sum_k \dot{m}_k (h_k + ke_k + pe_k + \cdots)$$

- **Entropy rate equation**

$$\dot{S} = \sum_i \frac{\dot{Q}_i}{T_i} + \sum_k \dot{m}_k s_k + \dot{S}_i = \dot{S}_e + \dot{S}_i$$

- **Exergy rate equation (derived from available work)**

$$\dot{\Xi} = \dot{E} - T_o \dot{S} = \sum_i \left(1 - \frac{T_o}{T_i}\right)\dot{Q}_i + \sum_j \left(\dot{W}_j - p_o \frac{dV}{dt}\right) + \sum_k \dot{m}_k \xi_k^{flow} + T_o \dot{S}_i$$

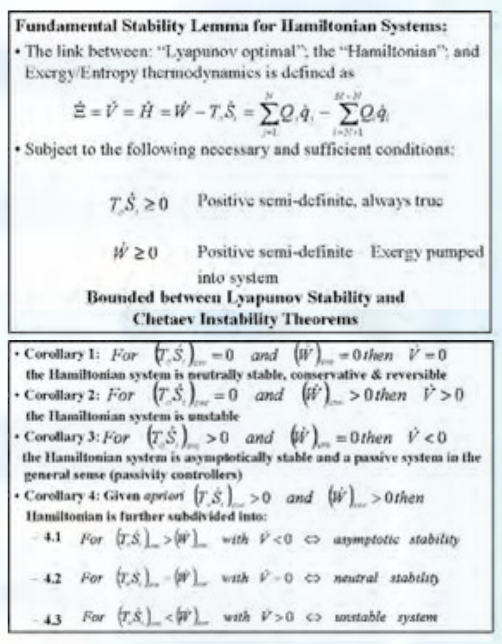
- **Where i,j,k are entry/exit locations, 3rd term in exergy equation is called flow exergy analogous to enthalpy in energy equation**

The power grid is treated as an open thermodynamic system where the electricity is pure exergy flowing through a self-organizing adaptive network system to provide an impedance and capacity-matched persistent exergy source that will maximize the irreversible entropy production by maximizing the serviceable load.

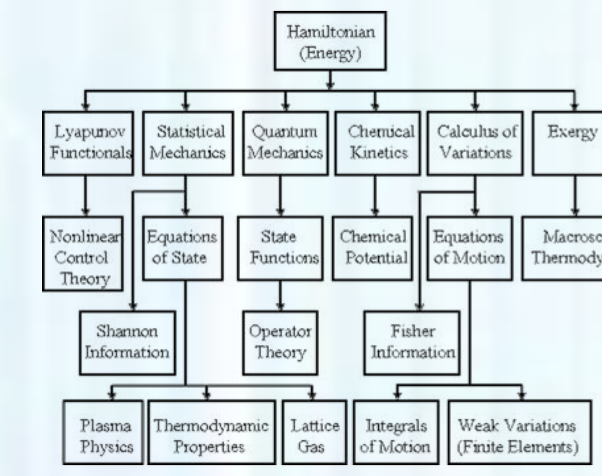
Hamiltonian mechanics and connections to describe how the electrical power grid is modeled as an open thermodynamic system: the loads (L) are equivalent to the irreversible entropy and the generators (G) are equivalent to the work in.

Results (cont.)

Unifying Theory: Nonequilibrium Thermodynamics

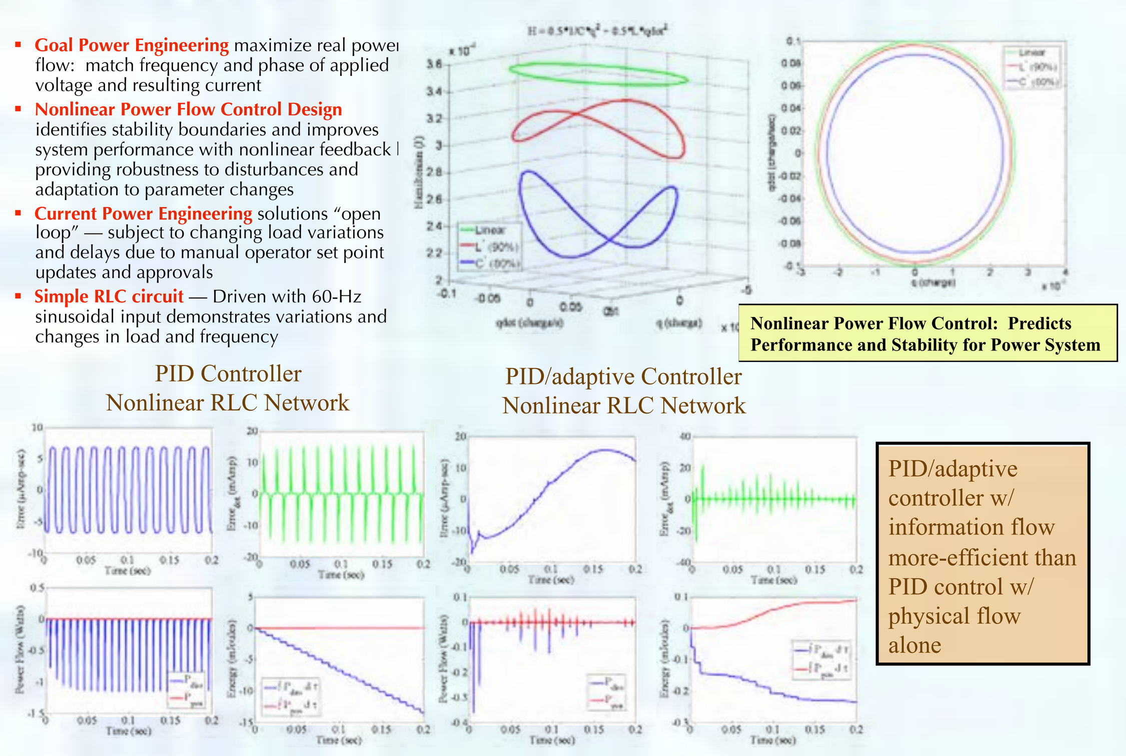


Unique Contribution to Nonlinear Control Technical Community

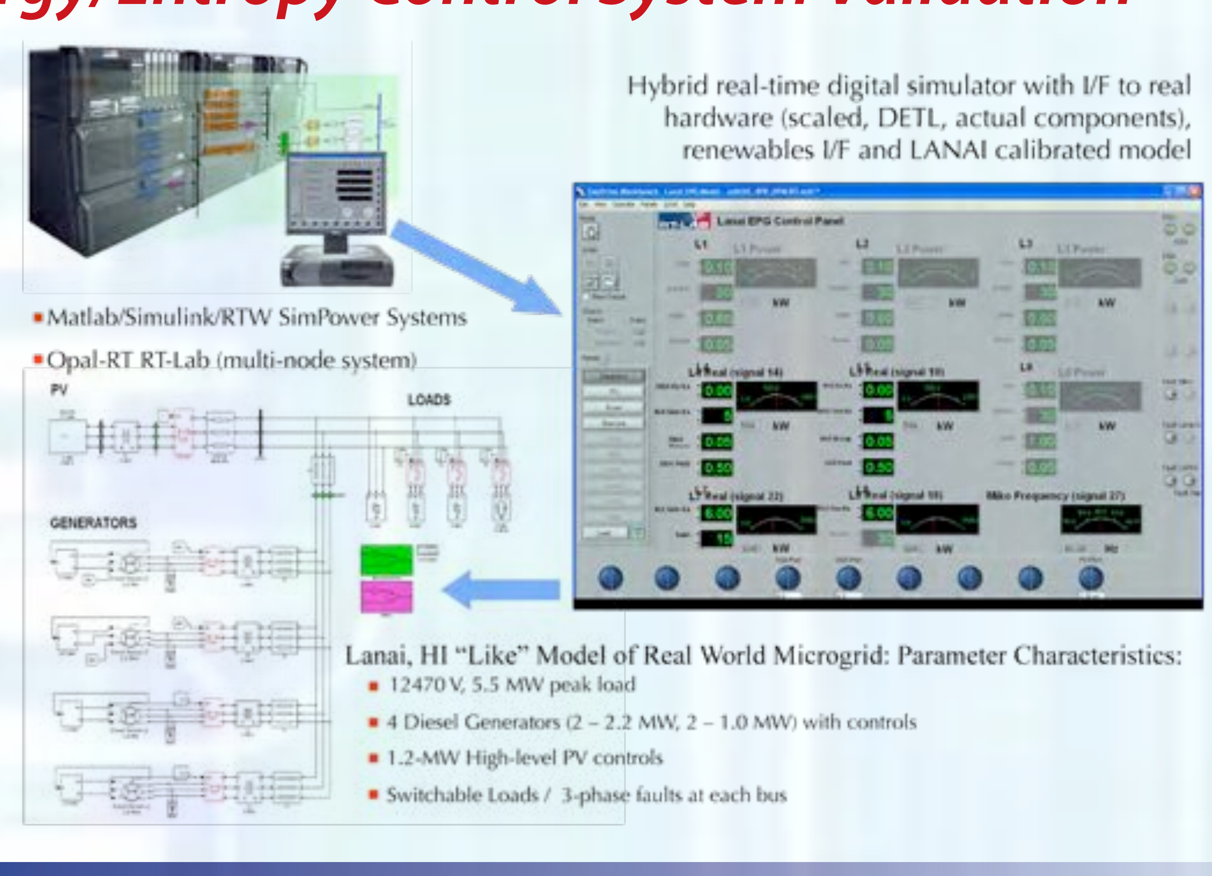


The Hamiltonian is a scalar function used to describe the evolution of dynamical systems; these can be either deterministic or statistical. Hamilton's principle assumes that the systems under consideration are characterized by two energy (stored exergy) functions: kinetic and potential. In addition, formulation utilizes extended Hamilton's principle which accounts for nonconservative forces to connect Hamiltonian mechanics, irreversible and nonequilibrium thermodynamics, nonlinear control theory (from Lyapunov functionals), and self-organizing systems to collective systems by way of information theory.

Nonlinear Power Flow Control Design: Power Grid Applications



Rapid-Prototyping Environment for Real-Time Exergy/Entropy Control System Validation



Significance

Innovative Control of a Flexible, Adaptive Energy Grid

- Project delivers challenging mix of science-based engineering activities (theory, modeling, experiment)
- Participated in 4 national/international conferences
- Presented one-day workshop at the 47th IEEE Conference on Decision and Control, Cancun, Mexico
- Formally documented results in 5 engineering technical archival journals
- Generated 3 patent pending applications and 2 technical advances
- One book contract signed

Highlights

R.D. Robinett III and D.G. Wilson, *Decentralized Exergy/Entropy Thermodynamic Control for Collective Robotic Systems*, Proceedings of the ASME IMECE 2007 Conference, November 11-15, 2007, Seattle, WA. (**Best Theory Paper**).

R.D. Robinett III and D.G. Wilson, *What is a Limit Cycle?,* Int'l J. of Control, 81(12), Dec. 2008, pp. 1886-1900.

R.D. Robinett III and D.G. Wilson, *Exergy and Irreversible Entropy Production Thermodynamic Concepts for Nonlinear Control Design*, Int'l J. of Exergy, 6(3) 2009, pp. 357-387.

R.D. Robinett III and D.G. Wilson, *Hamiltonian Surface Shaping with Information Theory and Exergy/Entropy Control for Collective Plume Tracing*, accepted for publication to the Int'l J. of Systems, Control and Communication, Nov. 2008.

R.D. Robinett III and D.G. Wilson, *Exergy and Irreversible Entropy Production Thermodynamic Concepts for Control System Design*, SD#10138, **Patent Pending**, March 2008.

R.D. Robinett III and D.G. Wilson, **Nonlinear Power Flow Control Design: Utilizing Exergy, Entropy, Static and Dynamic Stability, and Lyapunov Analysis,** Springer-Verlag London Ltd., **Book Contract Signed for Publication,** July 2010.

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