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Design and Validation of Advanced Controls for Networked Power Systems

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Sandia National Laboratories

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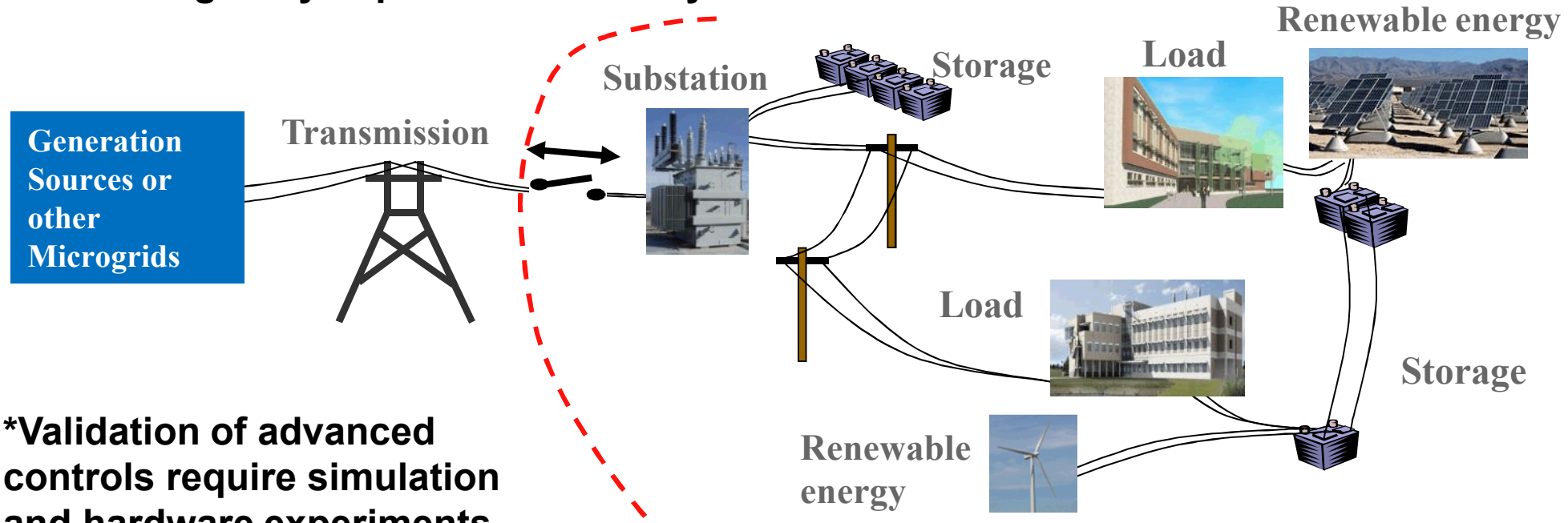
Our Research Program Investigates Advanced Methods of Control / Coordination of Distributed Power System Assets

Research Focus is on Networked Power Systems, with equal consideration of power and information flow.

Objectives Include:

- **Greater penetration of stochastic renewable sources through dynamic power flow control and optimized energy storage.**
- **Reduction of excess centralized generation capacity reducing our dependence on fossil fuel based generation and associated fuel transportation logistics.**
- **Self-healing, self-adapting, self-organizing decentralized architectures. This could greatly improve the security of critical infrastructure.**



***Validation of advanced controls require simulation and hardware experiments**

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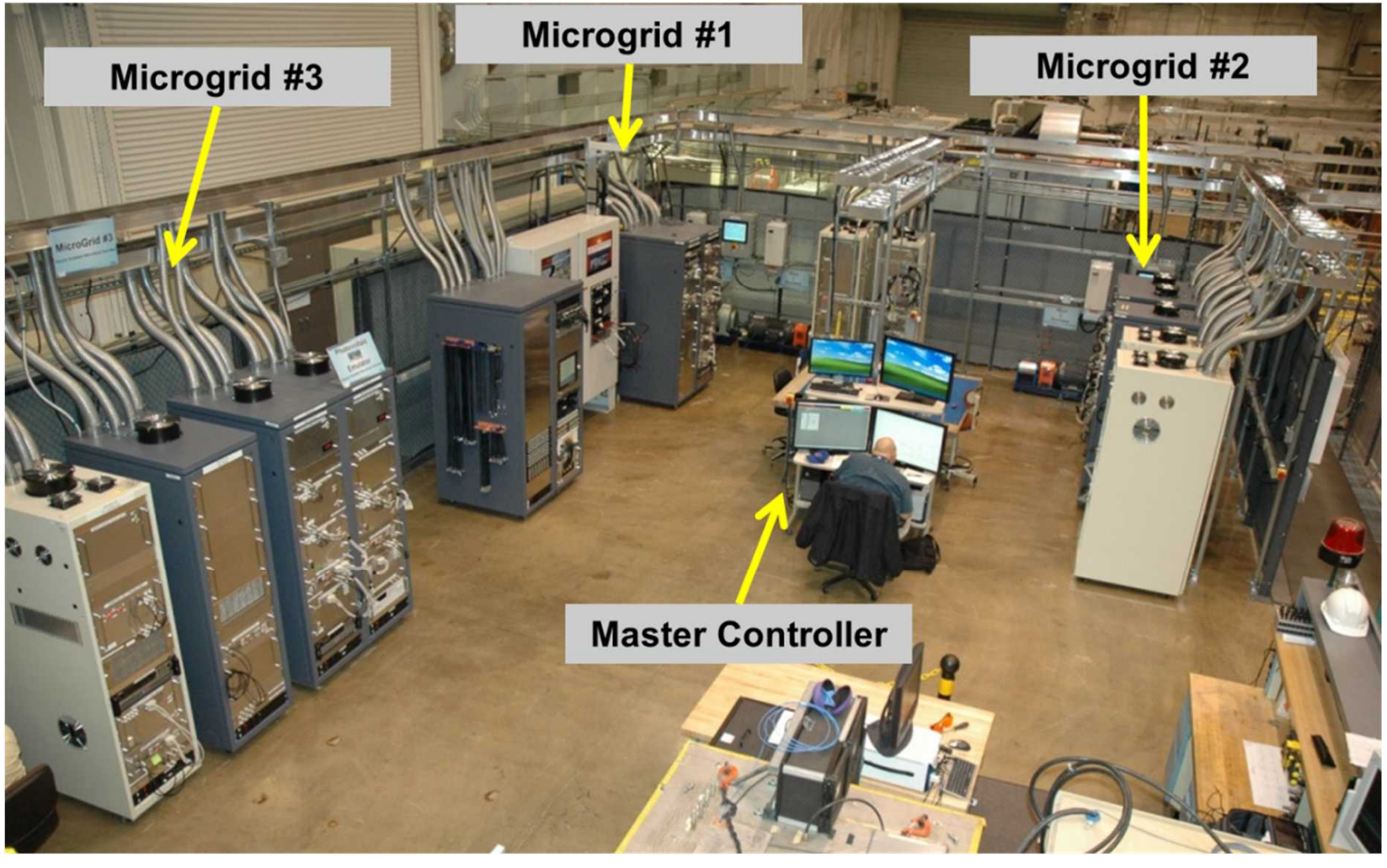
Secure Scalable Microgrid (SSM) Testbed Enables Hardware Testing of Networked Power Systems

- Testbed allows for a high-volume of flexible, repeatable experiments
- Hardware Testbed includes components representing generation, loads, energy storage and transmission/transfer
- Component building blocks enable a variety of system configurations



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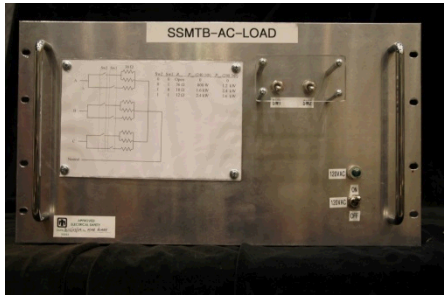
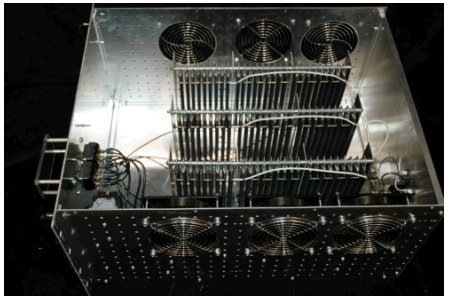
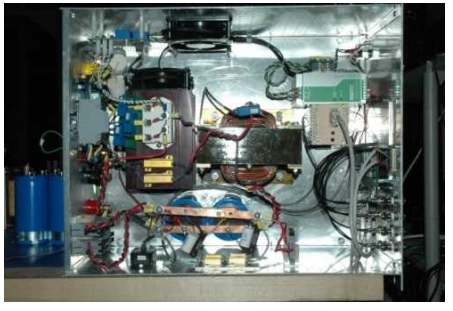
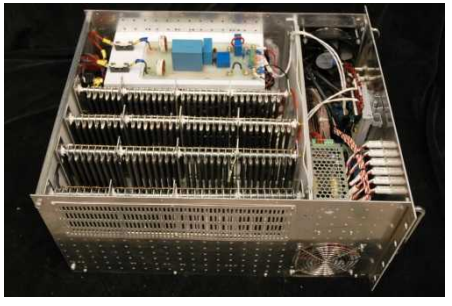
- Testbed includes
  - Programmable Loads
  - Programmable Generators/Emulators
  - Reconfigurable Bus
  - Power Electronic Converters
  - Energy Storage Emulators
  - Automated Experiment Orchestration
  - High speed data acquisition system

- Master Controller controls load profiles, system settings and the “weather”









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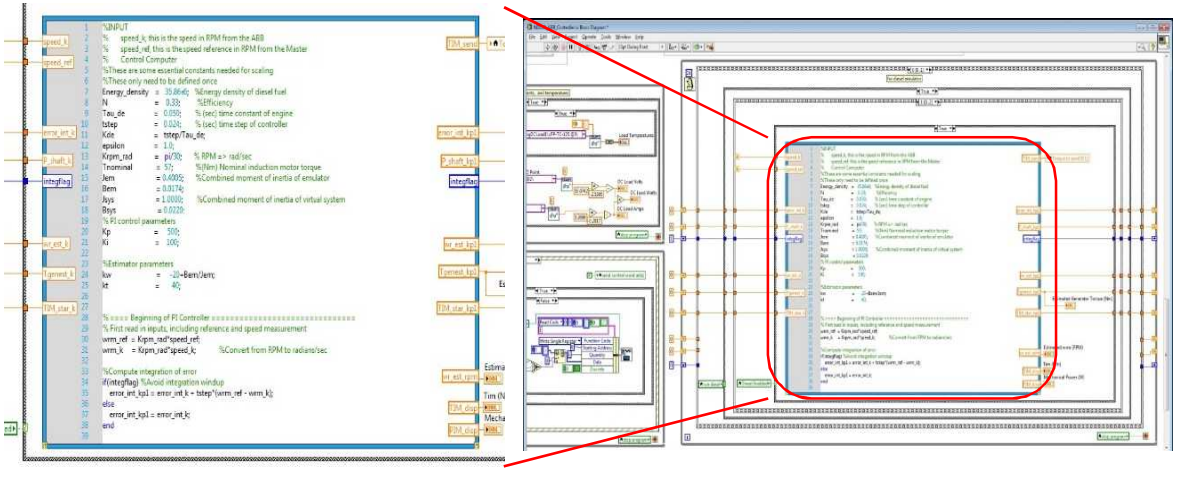
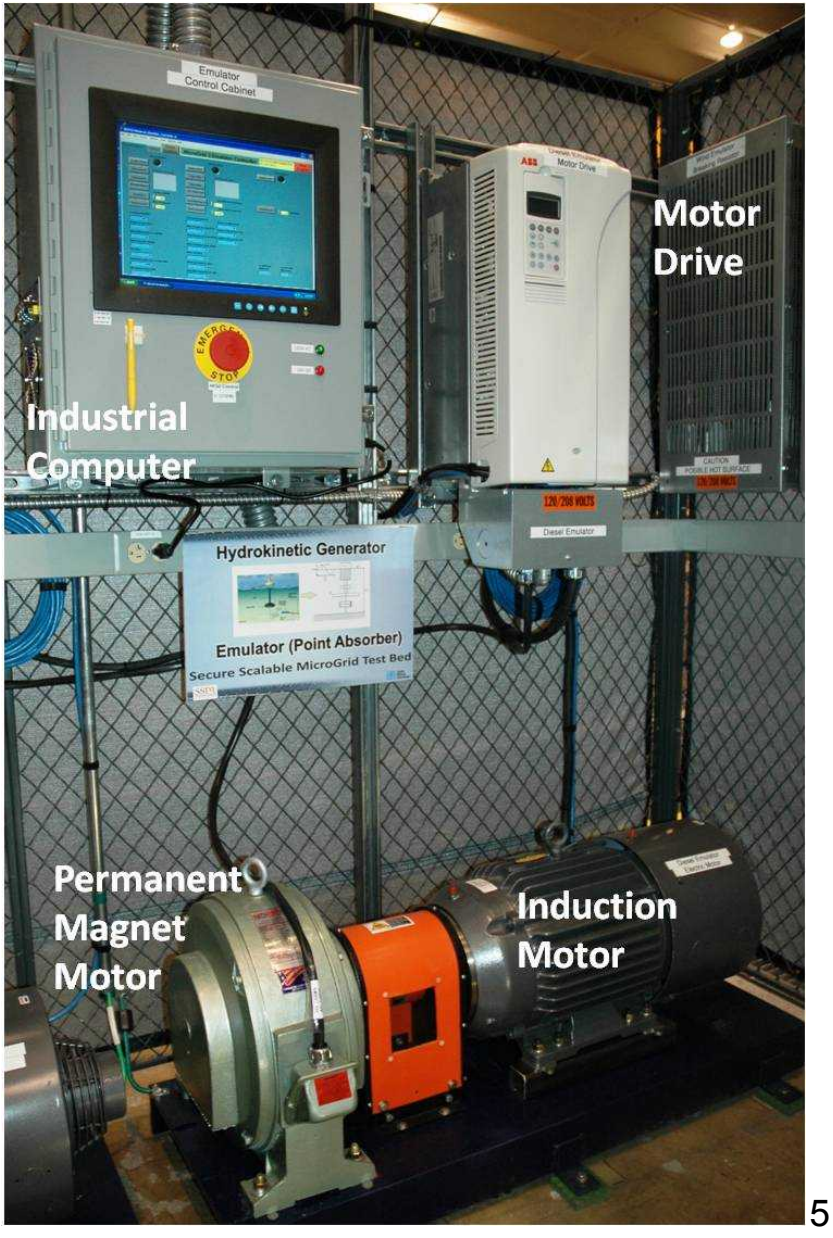
Generator and Renewable Source Dynamics are Modeled and Reproduced in the Laboratory

- Baldor 15 HP Induction Motor with speed encoder
- ACS800 ABB drive
- 10 kW Georator 36-013-1 or 7 kW Alxion 190STK4M Permanent magnet alternator
- Computer runs LabVIEW 2011 with Mathscript RT toolkit
- Software selectable emulation of various sources: diesel, wind, hydrokinetic





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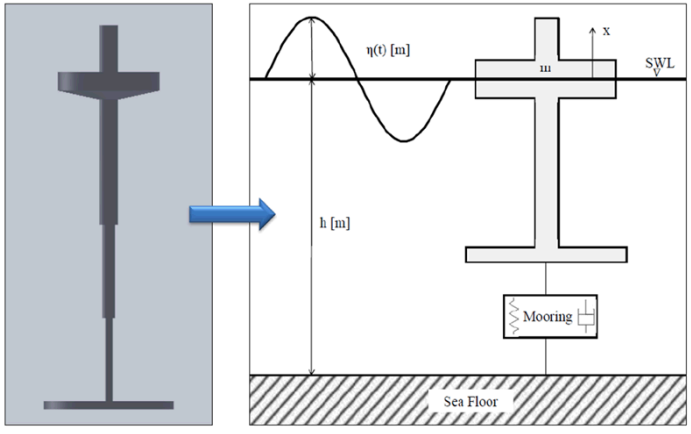
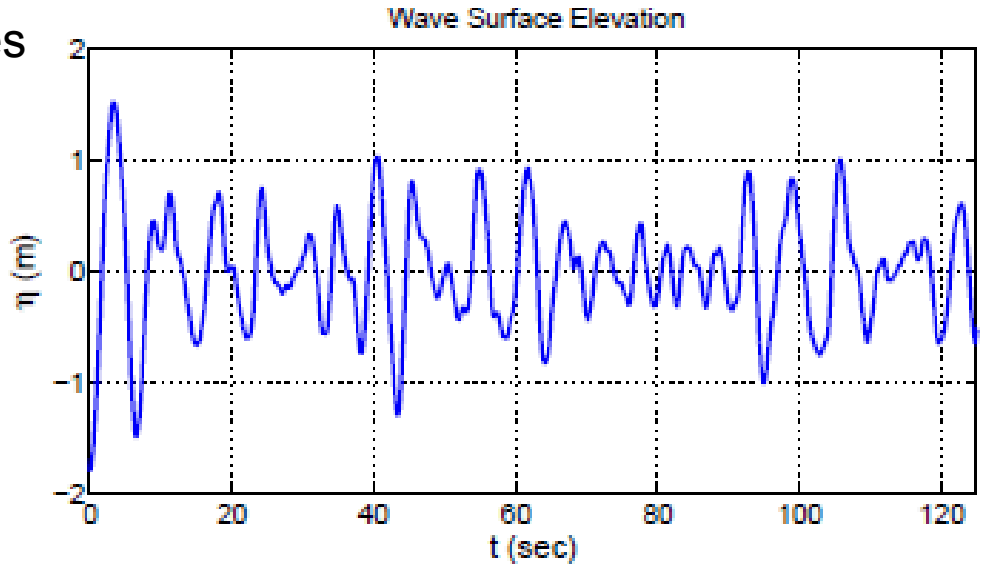
Generator and Renewable Source Dynamics are Modeled and Reproduced in the Laboratory

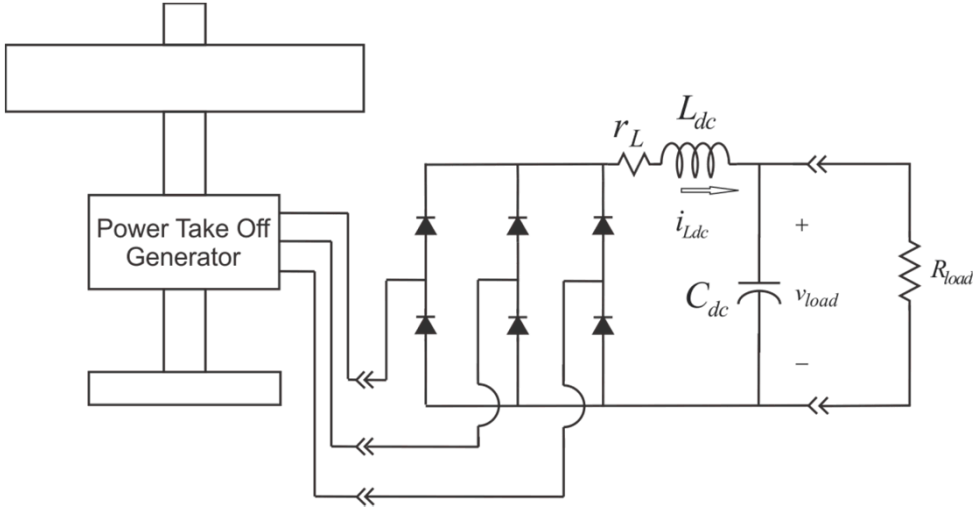
- This emulator concept has been applied to even the most challenging renewable sources

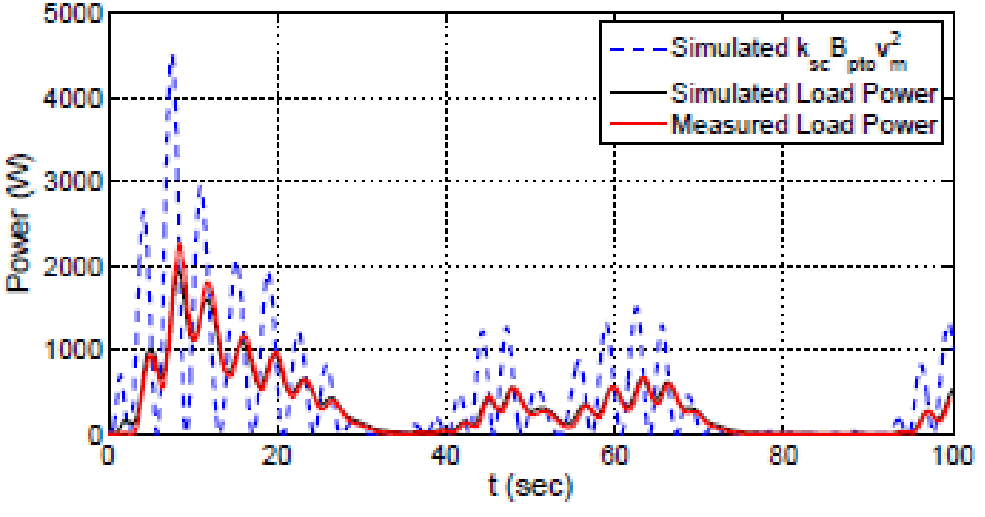
Wave Energy Converter (WEC)





- The emulator was implemented and tested for Wave Energy Converter (WEC) with irregular wave profile[1]





[1]Recorded from a data buoy time-series from Umpqua 46229 in June 2008

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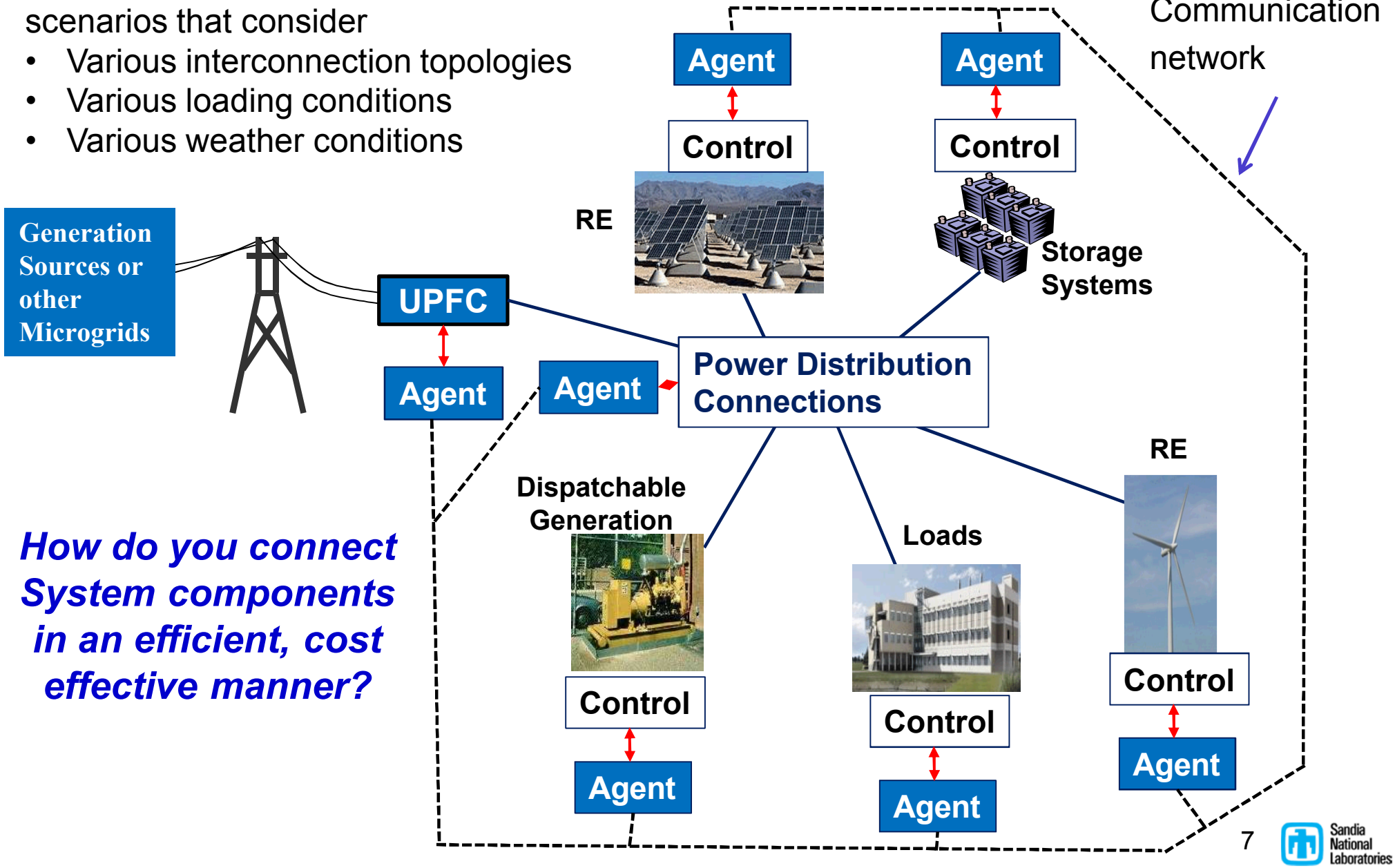
Validation of Advanced Controls is Essential to a Highly Interconnected Microgrid

New controls must be tested for many scenarios that consider

- Various interconnection topologies
- Various loading conditions
- Various weather conditions



How do you connect System components in an efficient, cost effective manner?

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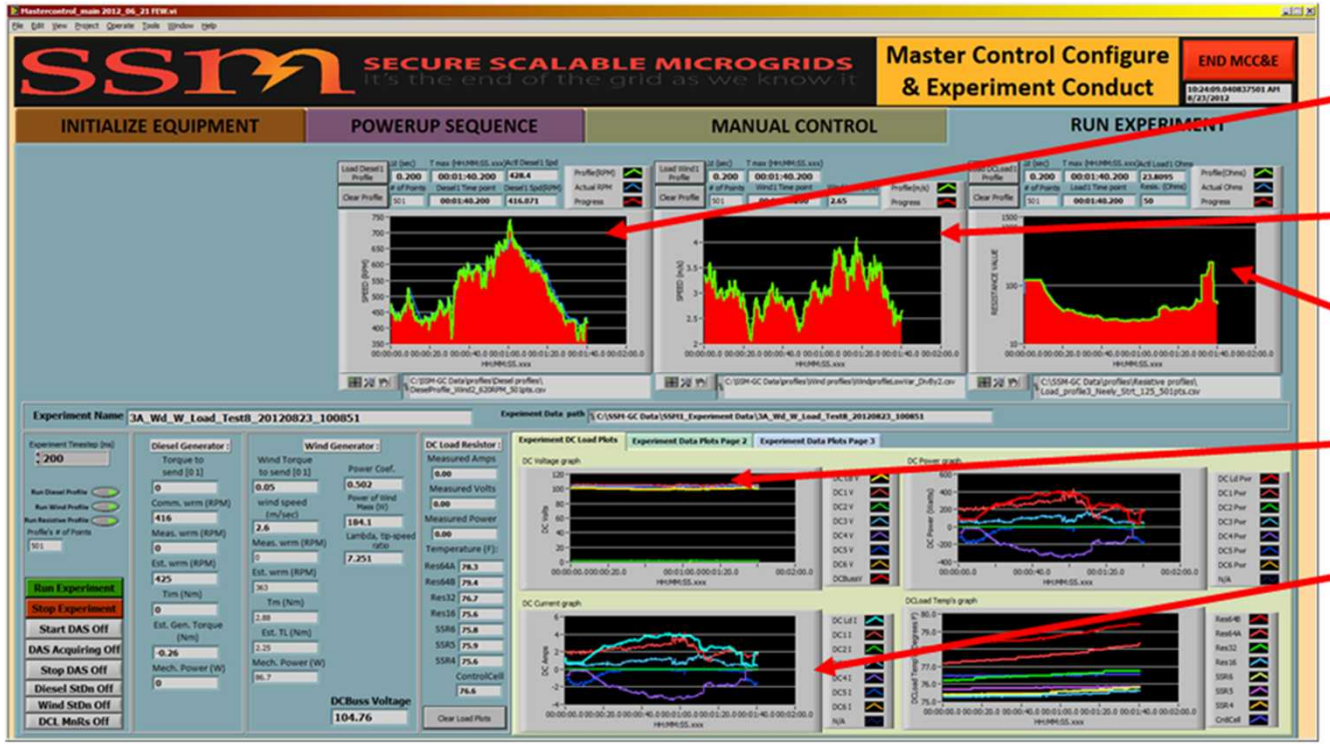
Secure Scalable Microgrid (SSM) Testbed Enables Repeated Experimentation of the Same Scenarios

- The Master Controller allows for scripted experiments that include
  - Load profiles
  - Weather Conditions
  - Topological/Architectural constraints
- Identical scenarios with different controls can be tested as a “batch run” of experiments, each leading to different outcomes



Emulator Profile 1

Emulator Profile 2 (m/s)

Digital Resistor (Ω)

Bus voltage (V)

Currents into bus (A)

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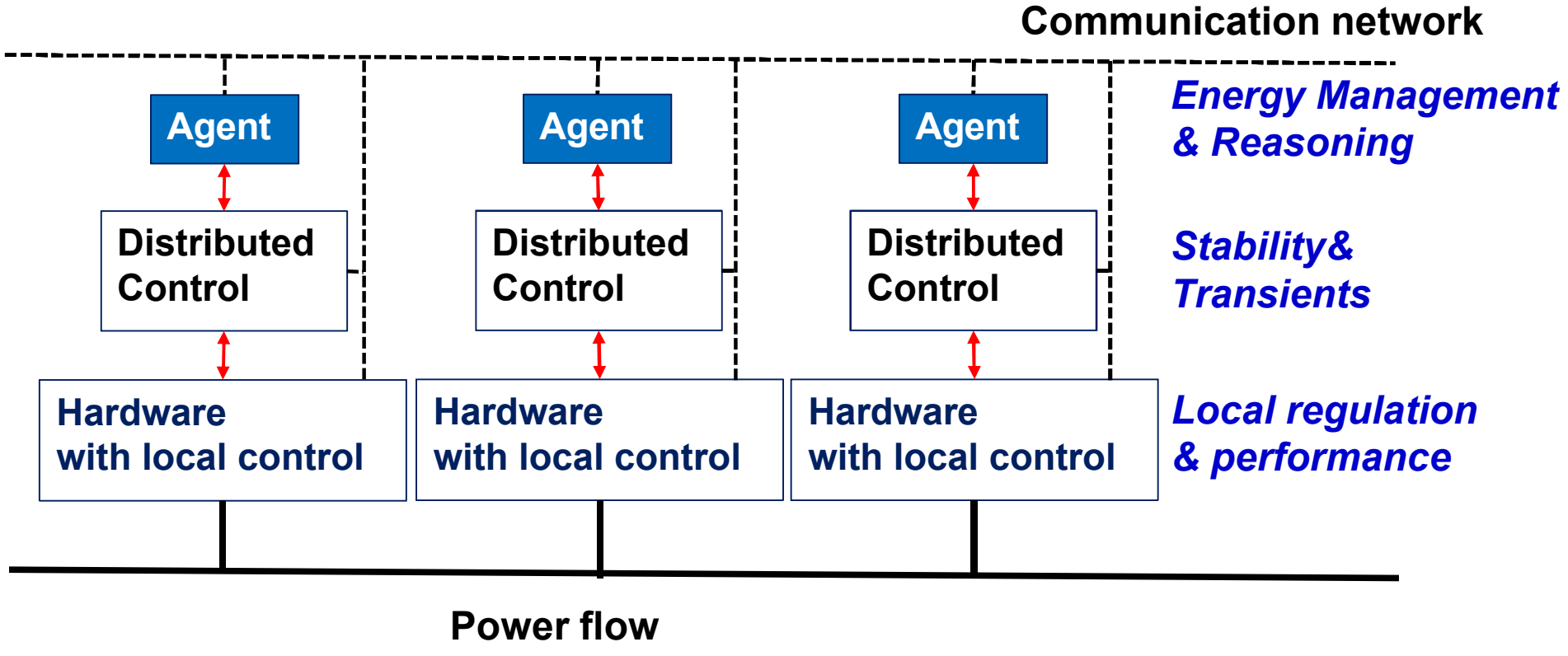
Our Basic Control Structure adds Capability and Supports Flexibility



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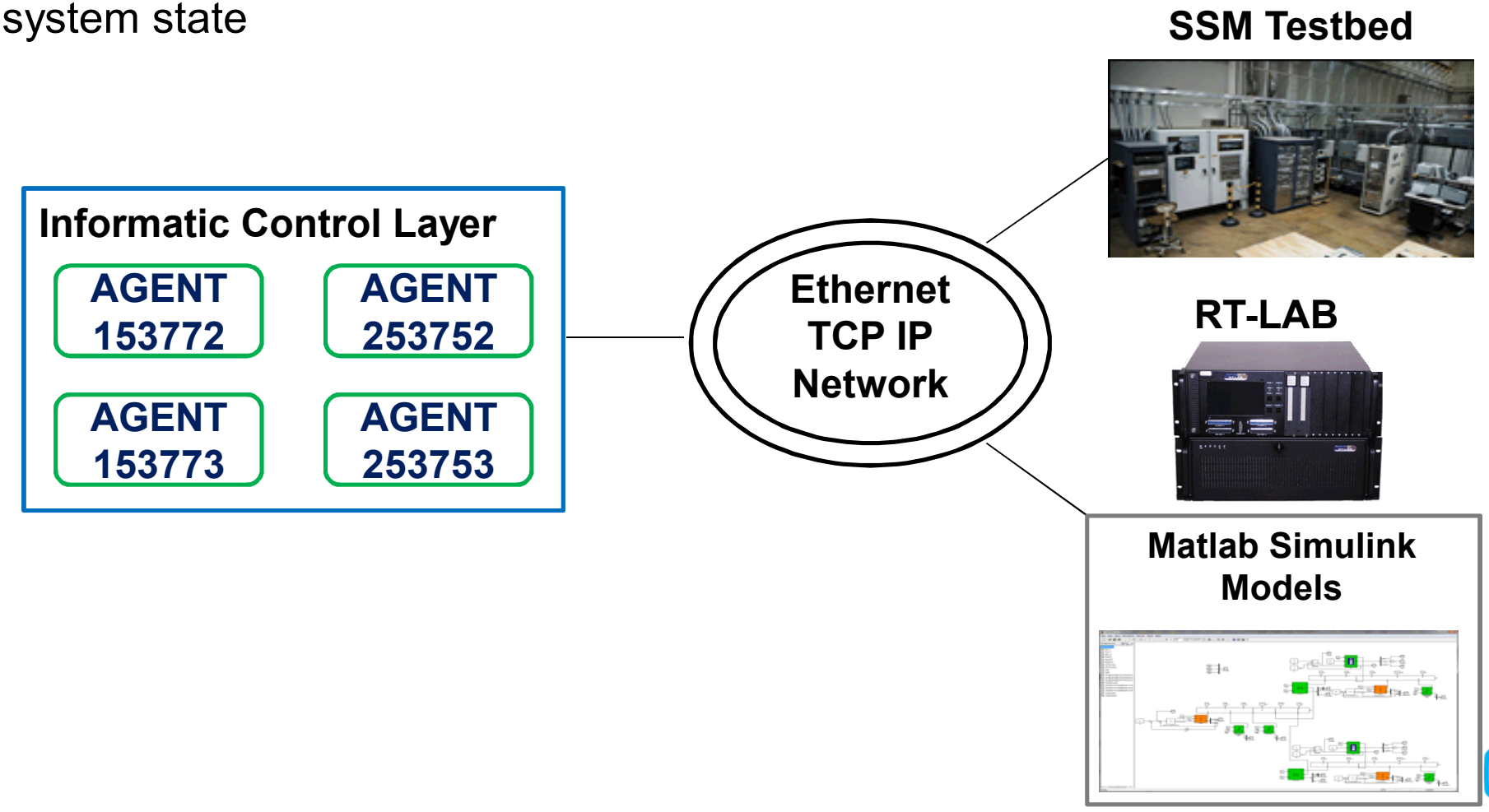
Our Energy Management is Done Over Ethernet

- Informatic Controls layer monitors system state and send control actions via hardwired ethernet
- Low level controllers send periodic measurements via UDP packets at ~800 per second
- Software agents interpret measurement data to form a global model of the energy system state



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Informatics Incorporates Optimization

- Optimizer can be a computer resource on the IP network, called remotely, or can be run directly on the agent platform
- Informatic Control Layer sends optimization parameters to an optimizer based on measurements and system objectives
- Optimizer returns *reference points* that are used by the Informatic Control Layers to drive low level controllers
- Optimizer supports preferences towards particular generation sources within the energy mix

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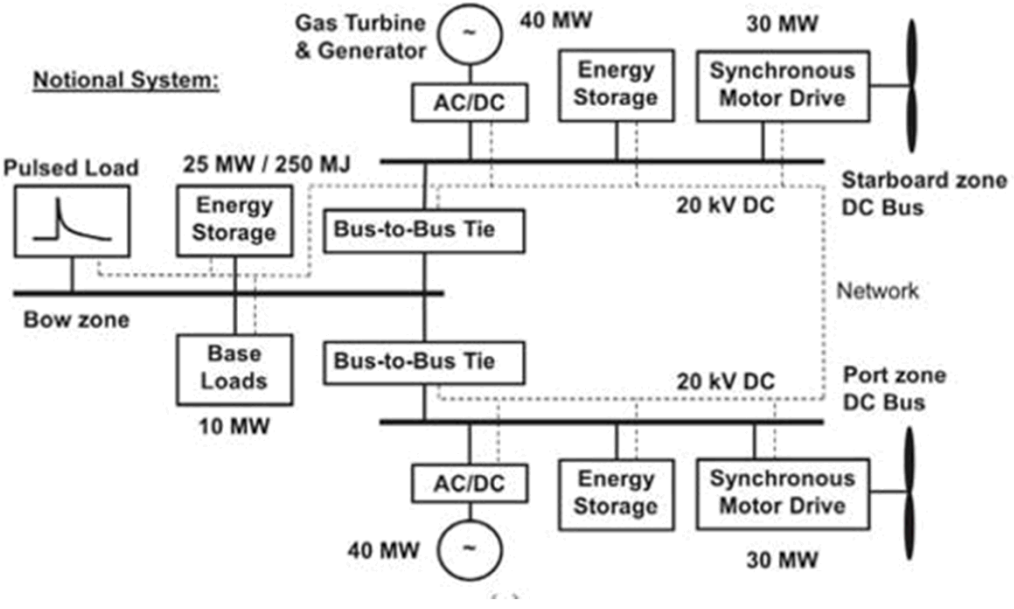
Energy System Optimizer

- Electrical system circuit equations
- Variables with bounds
- Allows flexibility in microgrid configurations
- Multi-objective problem specifications
- Optimizes nonlinear constrained problems

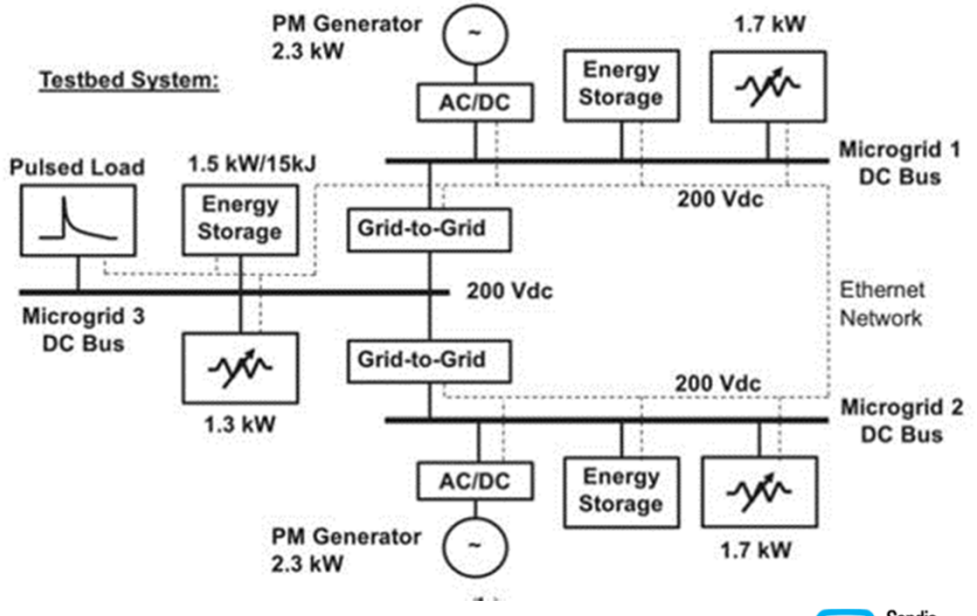
Experiments have been done to Evaluate Power Flow Control for an All-Electric Warship

- A notional 3-zone power system was identified with candidate power and energy levels
- System includes propulsion, energy storage, thermal generation and a pulsed load
- Generation is coupled to DC bus through power electronics
- The notional system was per-unit scaled to be represented by the SSM testbed

Notional System



Scaled for Microgrid



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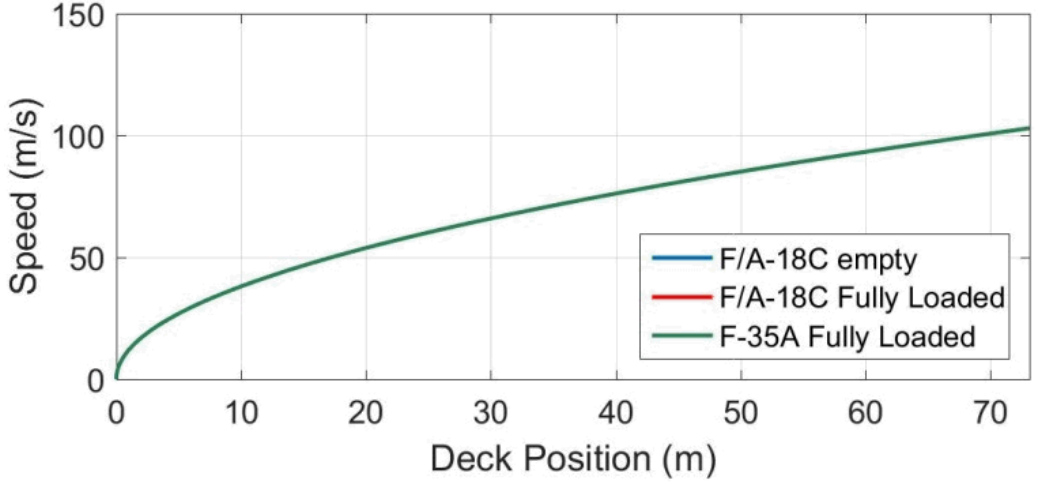
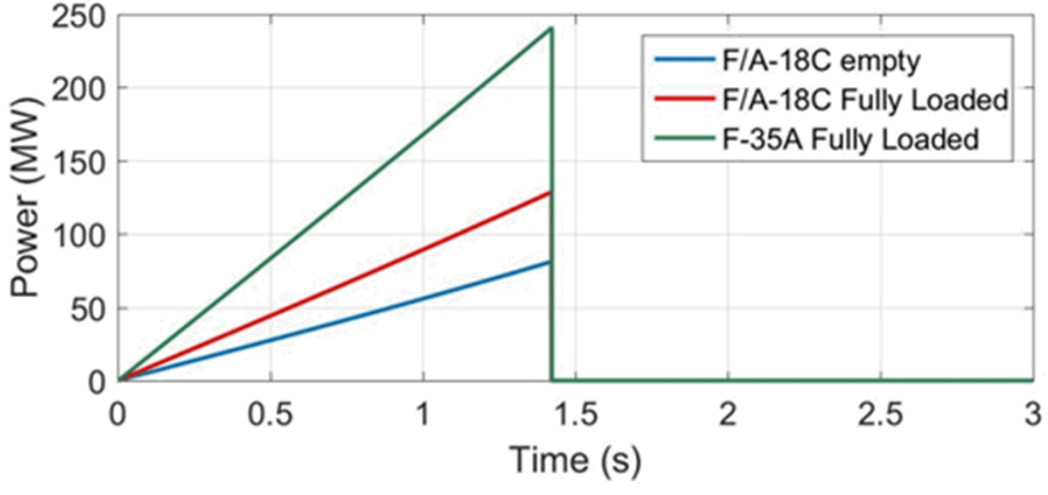
Power Flow Control for an All-Electric Warship with Pulsed Load

- The power consumption of an electromagnetic launch system (EMALS) was emulated for three aircraft
- EMALS model assumes same launch velocity and a given acceleration distance





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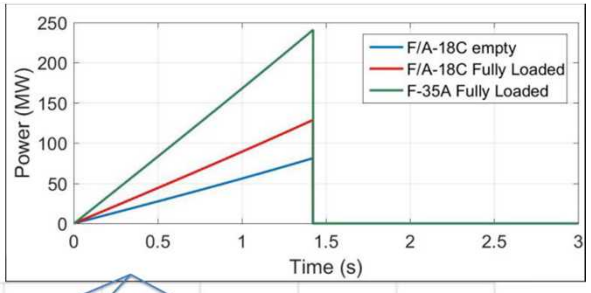
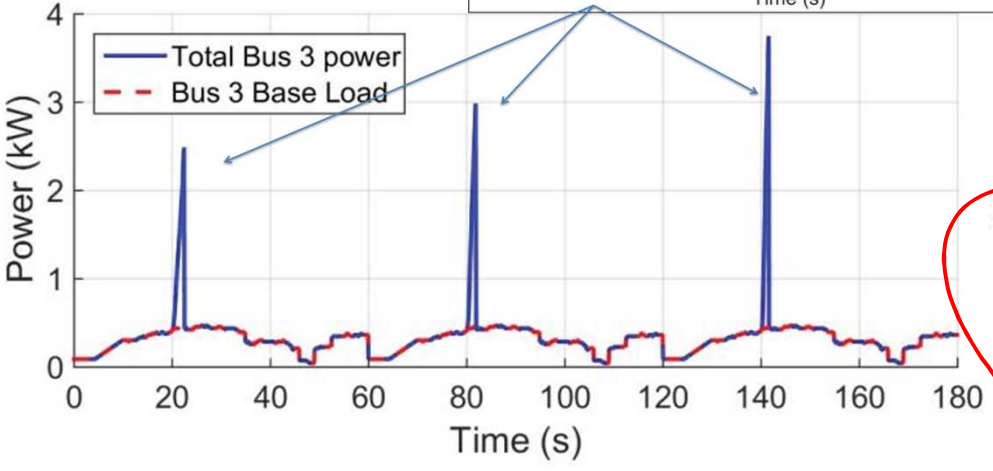
Power Flow Control for an All-Electric Warship with Pulsed Load

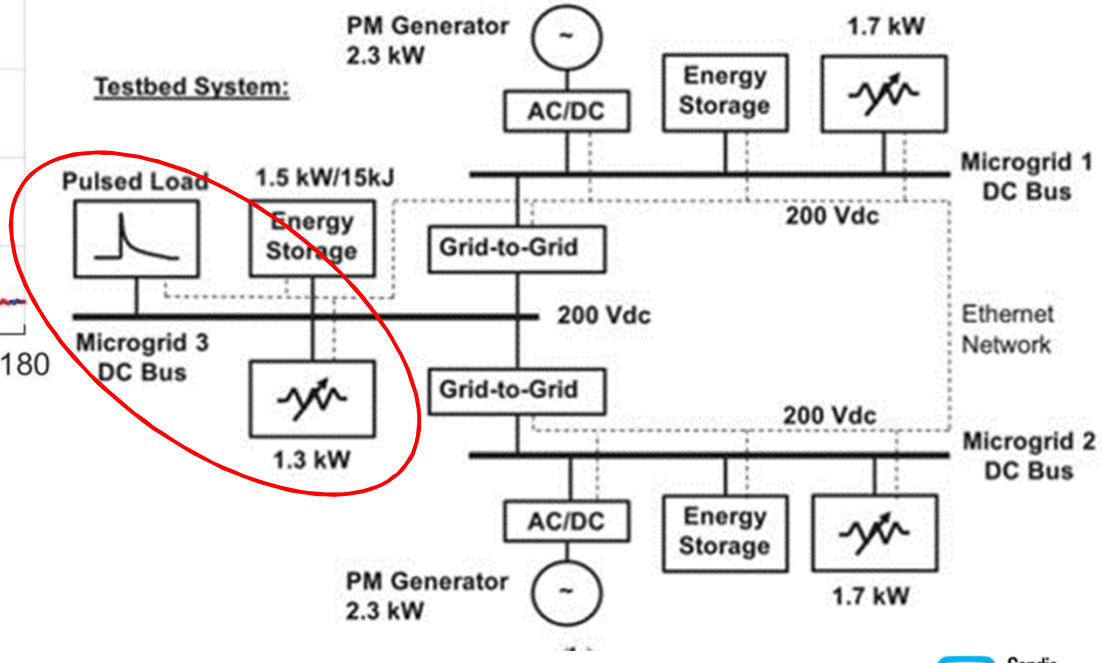
- The pulsed load model was built and integrated into the SSM testbed
- Additional “Deck Loads” are also included

EMALS Power Pulse:





Testbed System:



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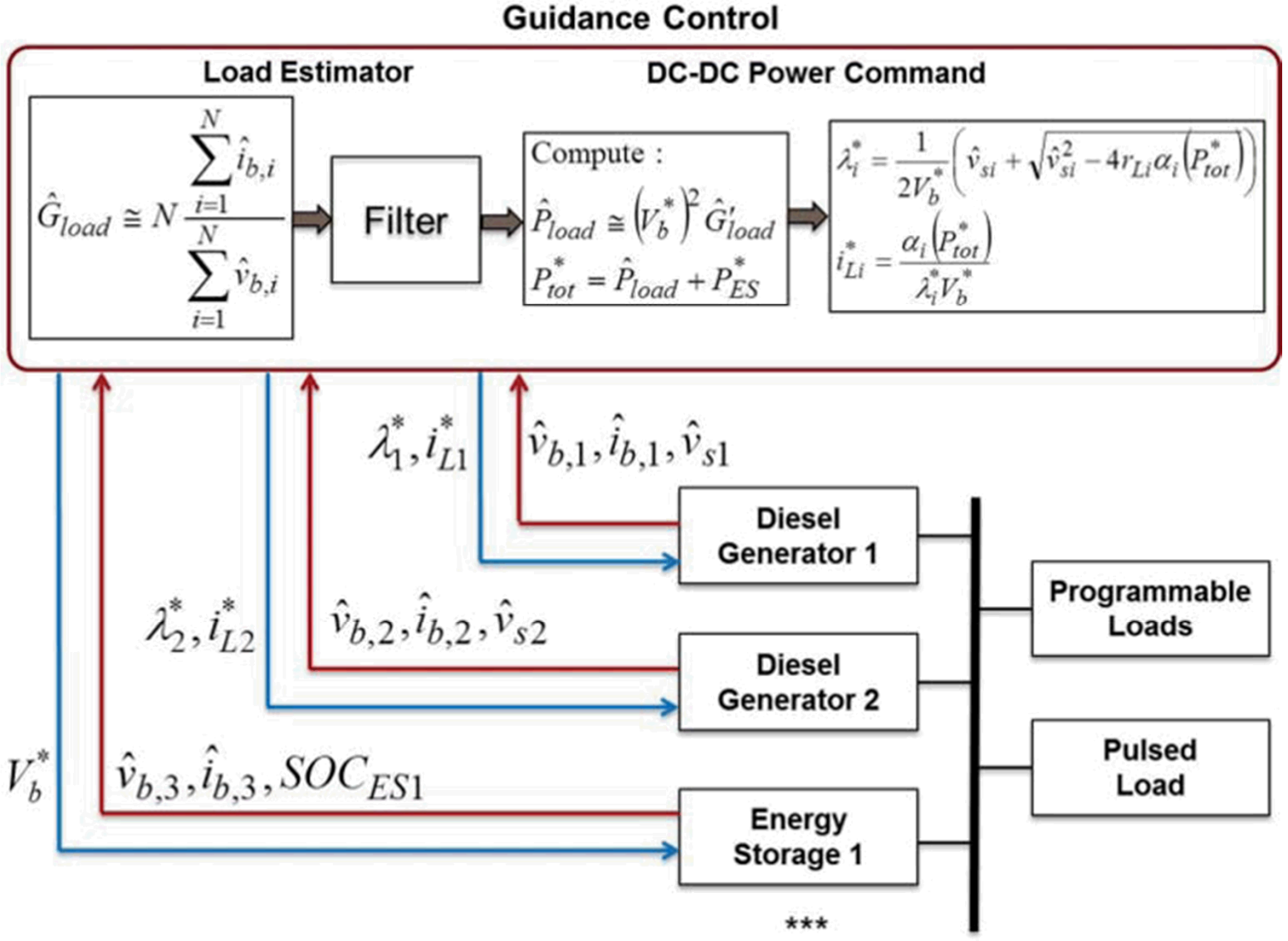
Agent Controls Coordinate Power Flow from Power Electronic Converters

- Agents attain “situational awareness” from measurement data
- Agents provide power commands to power converters



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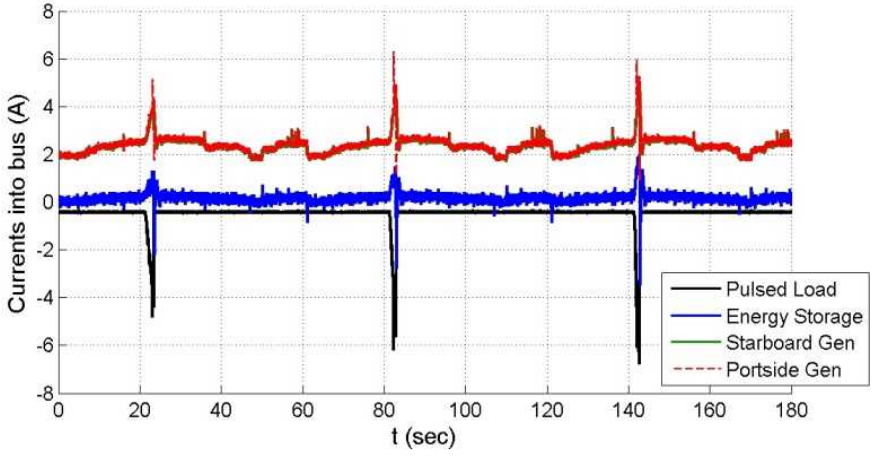
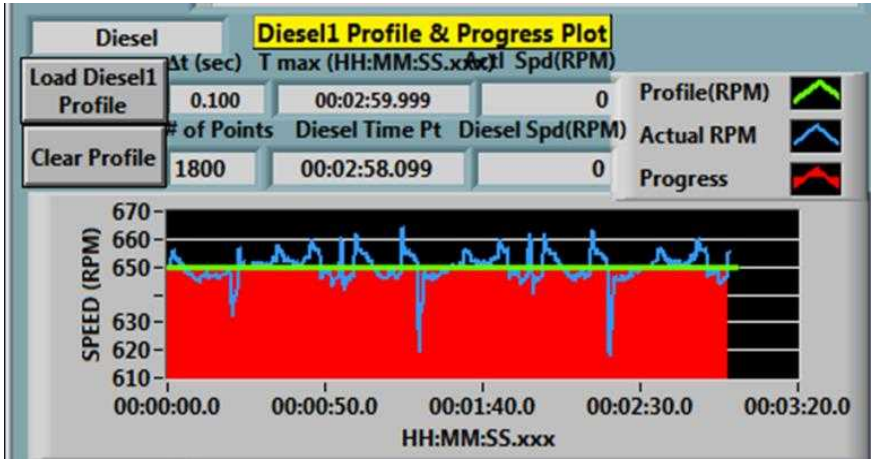
Agent Controls Coordinate Power Flow from Power Electronic Converters

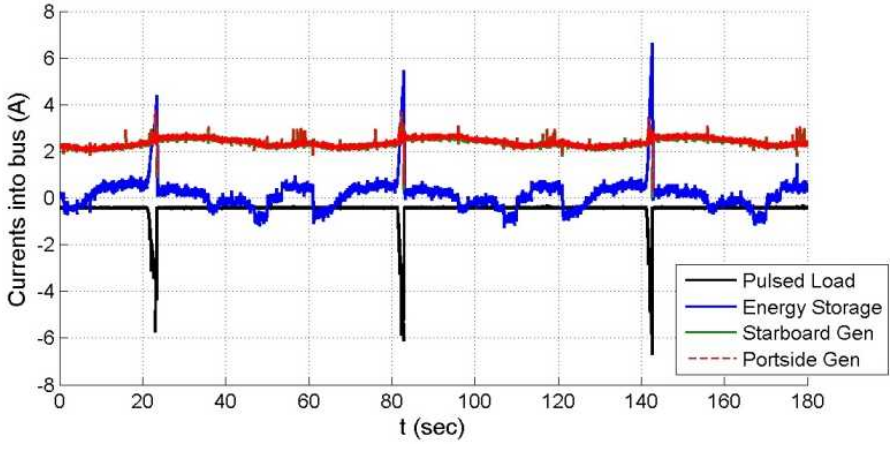
- Experiments were done to investigate trade-off between generator and energy storage

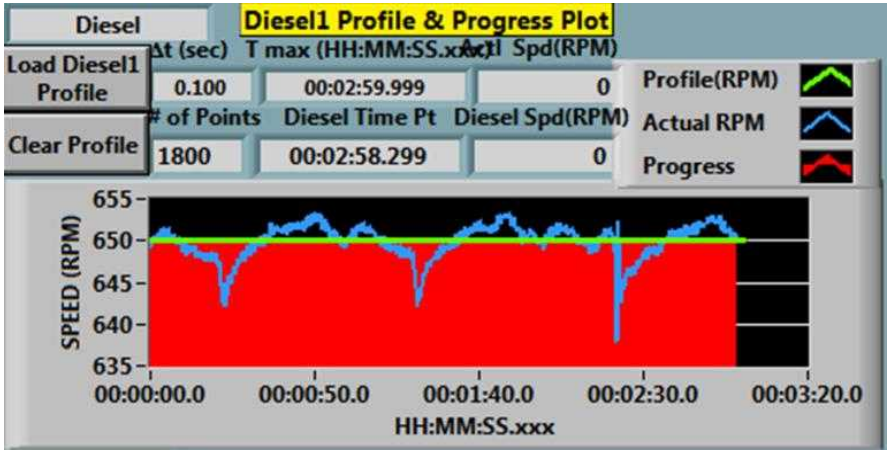
Experiment 1: Generators are more responsive to pulsed load





Experiment 5: Energy storage is more responsive to pulsed load





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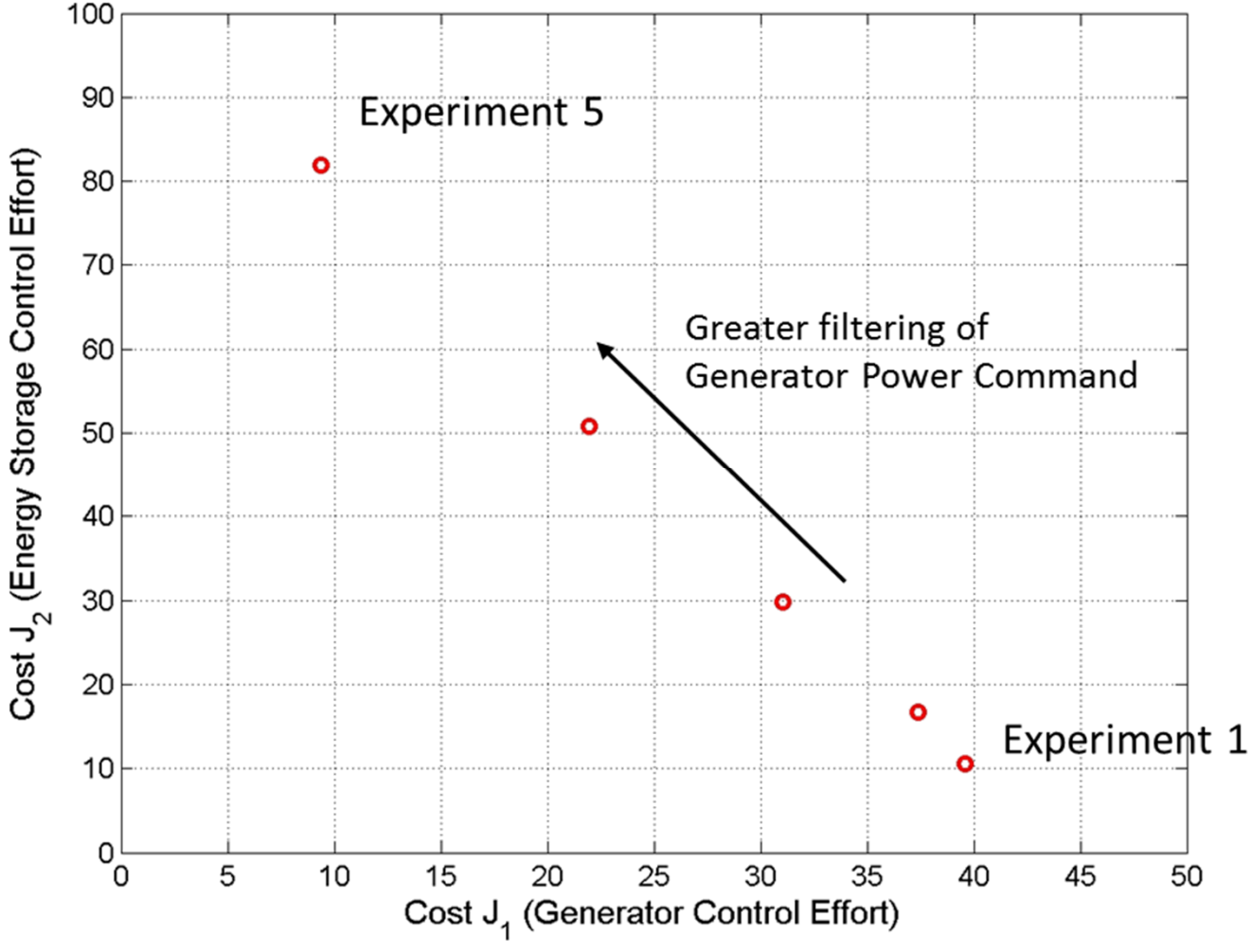
Agent Controls Coordinate Power Flow from Power Electronic Converters

- Experiment data is used to evaluate trade-offs in performance

$$J_1 = \int_{t_0}^{t_f} \left(\sum_{i}^{N_{Gens}} \left(i_{bi}(\tau) - \hat{i}_{bi} \right)^2 \right) d\tau$$

$$J_2 = \int_{t_0}^{t_f} \left(\sum_{i}^{N_{ES}} \left(i_{ESi}(\tau) - \hat{i}_{ESi} \right)^2 \right) d\tau$$



[Ref] J. Neely, L. Rashkin, M. Cook, D. Wilson, S. Glover, *Evaluation of Power Flow Control for an All-Electric Warship Power System with Pulsed Load Applications*, APEC 2016.

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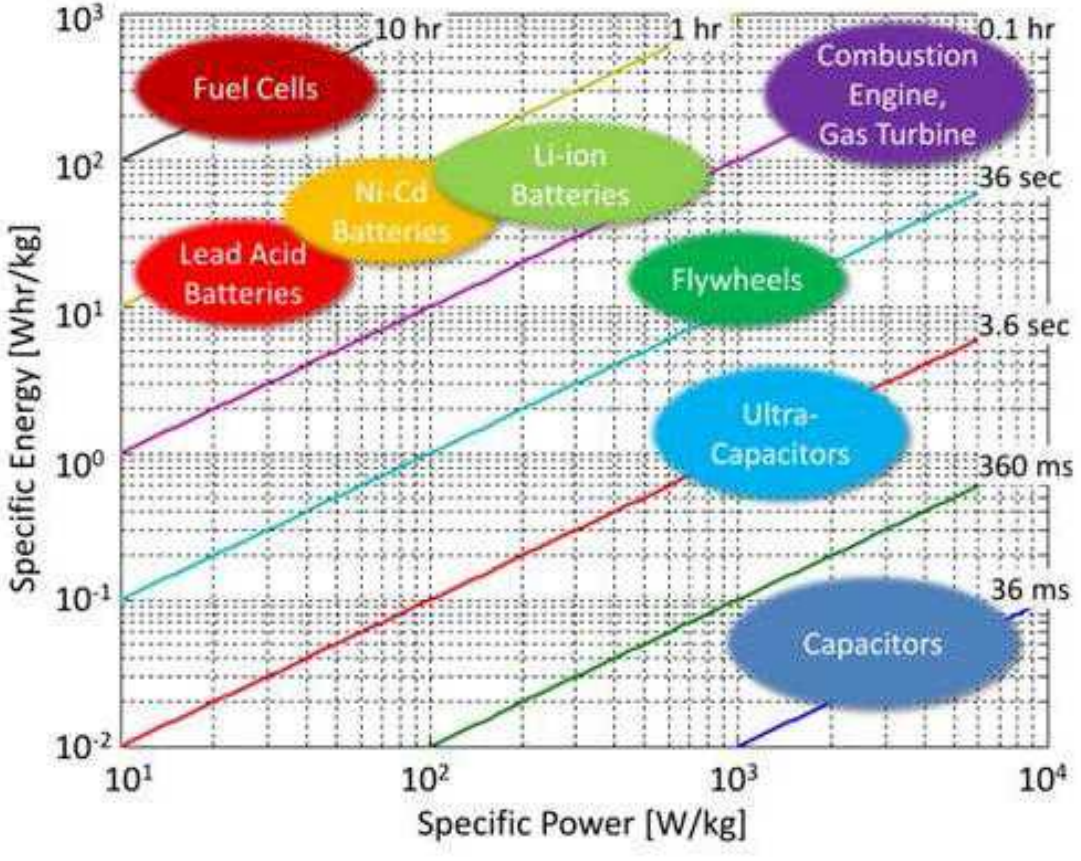
Experiment Results Inform Control and Hardware Design

- **Pulse load demands drive microgrid performance and energy storage requirements**

Ragone plot compares various energy storage/ propulsion technologies as a function of energy density vs power density. Diagonal lines define time constant/charge time.



[Ref] *Maxwell Tech., Inc. white paper, Ultracapacitor Usage in Wind Turbine Pitch Control Systems*

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Summary

- The SSM Program researches advanced controls that consider both power and information flow
- SSM Testbed provides a configurable microgrid testing environment for evaluating controls and component performance
- SSM Informatics performs closed loop control over an IP network to manage microgrid resources
- Recent research result efforts address risks and issues associated with pulse load demands in NAVAL ship applications.

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