

Enabling Secure, Scalable Networked Microgrids with High Penetration Renewables and Pulsed Power Loads

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Agenda

- 8:00 Energy Surety Requirements for Microgrid Development
- 8:50 Break
- 9:05 Microgrid Modeling using MATLAB/Simulink: Components-to-Systems
- 10:05 Break
- 10:20 Microgrid Optimal Control and Optimization
- 11:20 Lunch
- 12:20 Microgrid Agent-Based Control for Mediating Generation, Storage, Loads, Cyber Security
- 1:20 Break
- 1:35 Microgrid Control and Performance Analysis
- 2:35 Break
- 2:50 Sandia National Lab's Secure Scalable Microgrid Testbed: Capabilities and Collaboration
- 3:50 Wrap-up

Key collaborators

Universities

Purdue University

Michigan Technical University

University of Minnesota

Missouri University of Science and Technology

Texas A&M University

University of New Mexico

Stanford University

Industry & others

Paul C. Krause and Associates

OPAL RT

Perspectives

Closure Associates

Michael A Ekhaus

Patrick Chapman

Eastern Research Group Inc.

Amplitude Energy Analytics LLC

Leidos

Fiore

Defense Nuclear Facilities Safety Board

EAB

Mike Aimone

James Beckwith

James Boyd

Joe Eto

Daryl Hammond

Erfan Ibrahim

Tim McCoy

William Parks

Dan Ton

Ron Sega

David Whitehead

Co-Presenters

- ★ • **Steven Glover, Manager**
 - *Sandia National Laboratories, Albuquerque, NM*
- ★ • **Marvin Cook, R&D Software Engineer**
 - *Sandia National Laboratories, Albuquerque, NM*
- **Jason Neely, R&D Electrical Engineer**
 - *Sandia National Laboratories, Albuquerque, NM*
- ★ • **David G. Wilson, R&D Control Engineer**
 - *Sandia National Laboratories, Albuquerque, NM*
- **Rush D. Robinett III, Richard and Elizabeth Henes Professor**
 - *Mechanical Engineer, Michigan Tech*
- ★ • **Wayne Weaver, Associate Professor Electrical Engineering**
 - *Michigan Tech*
- ★ • **Gordon G. Parker, John and Cathi Drake Professor of Mechanical Engineering**
 - *Michigan Tech*
- **Steven Y. Goldsmith, Research Professor Mechanical and Electrical Engineering**
 - *Michigan Tech*



presenting

Michigan Tech Overview



Area

- Engineering
- Copper
- Snow
- Isle Royale NP

Michigan Tech

- Founded in 1885
- 7200 Students
- 83% STEM



Sandia National Laboratories is Located in Albuquerque, New Mexico, US



Albuquerque

- Founded in 1706
- 1619 m above sea level
- 557k people

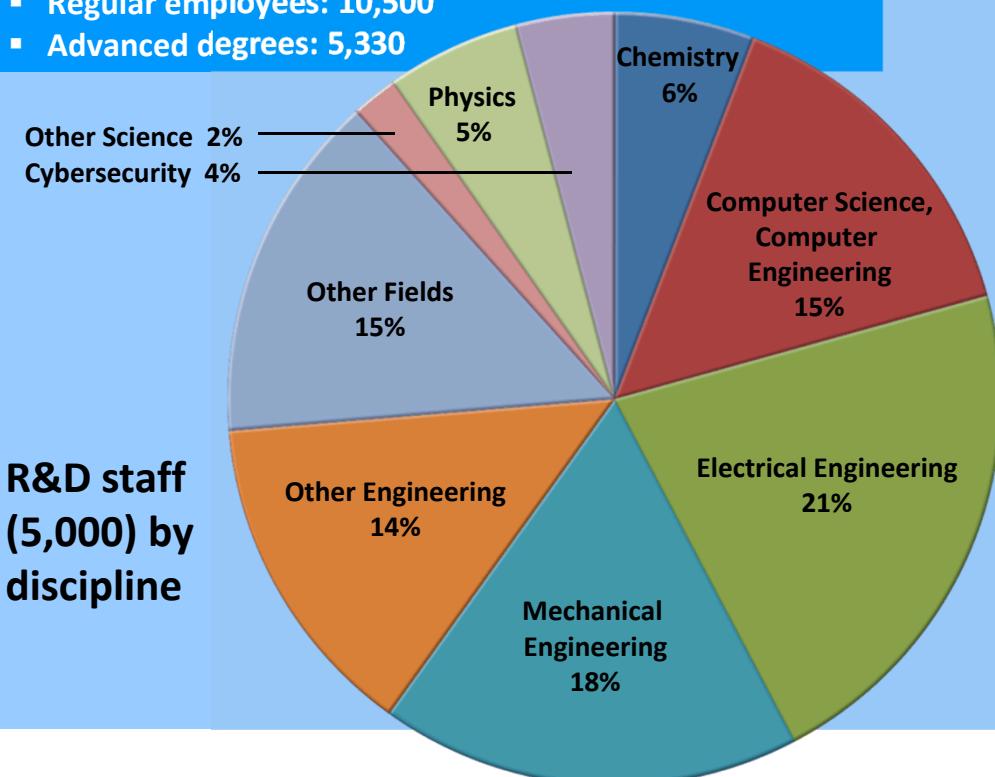


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Sandia Laboratory

- Highly educated workforce
- Strategically managed workforce of diverse skills and competencies
- Modern business practices and operations in support of our missions

- On-site workforce: 12,000
- Regular employees: 10,500
- Advanced degrees: 5,330



Six sites:
Albuquerque, NM
Livermore, CA
Kauai, Hawaii
Amarillo, Texas (Pantex Plant)
Tonopah, Nevada

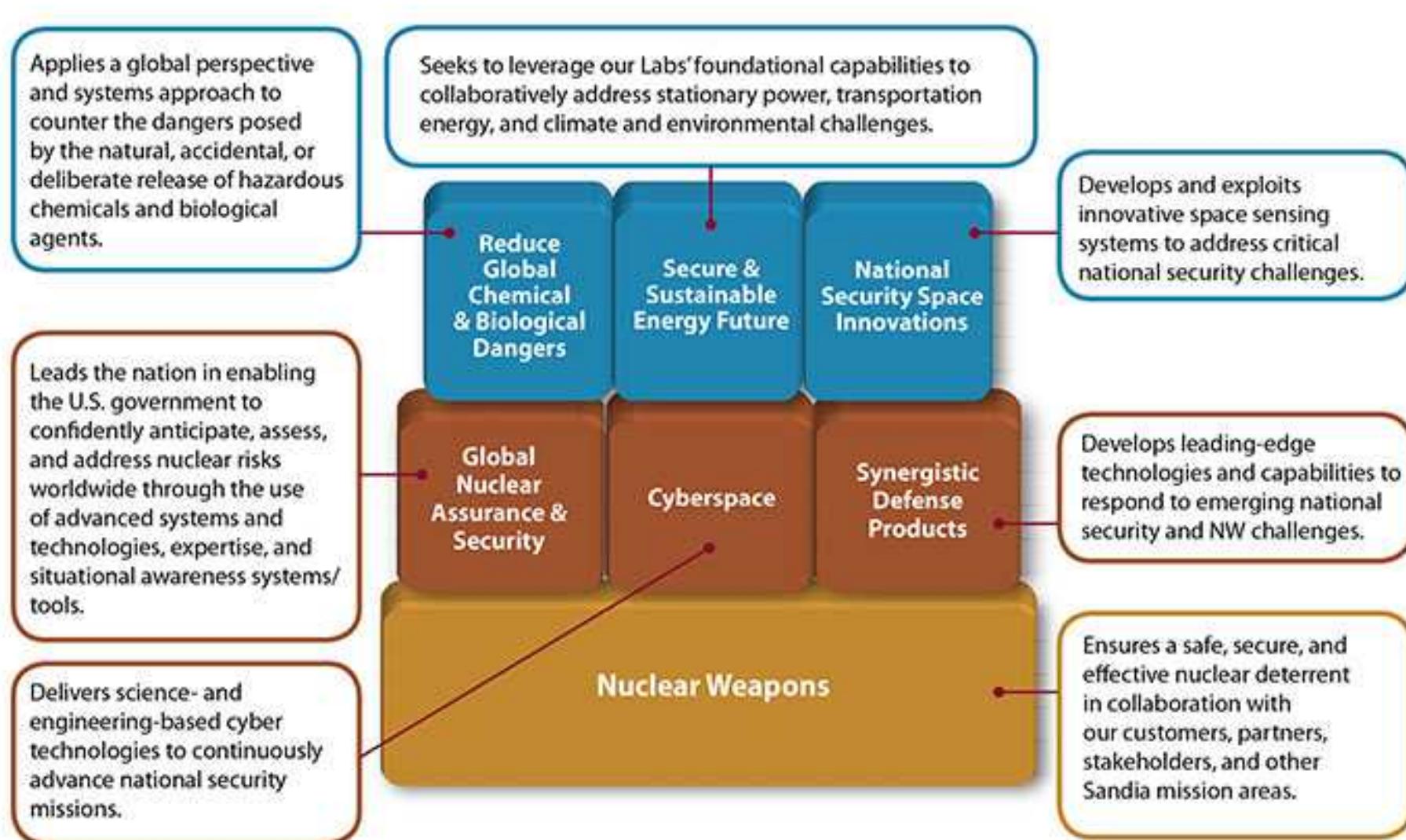


Vision and mission statements

- On behalf of our nation, we anticipate and solve the most challenging problems that threaten security in the 21st century.
- Our unique mission responsibilities in the nuclear weapons program create a foundation from which we leverage capabilities enabling us to solve complex national security problems.



Sandia's national security mission areas



We Collaborate with A Wide Range of Organizations

National security activities for and in collaboration with:

- **Department of Energy** (National Nuclear Security Administration, Office of Science, Office of Electricity)
- **Other federal agencies** (DOD-Army/USAF/NRL, DOT-Federal Aviation Administration, DOL – Mine Safety and Health Admin.)
- **Non-federal entities**
- **Industry** (Goodyear, FMC, Inc., Lockheed Martin Technology Research)
- **Universities**

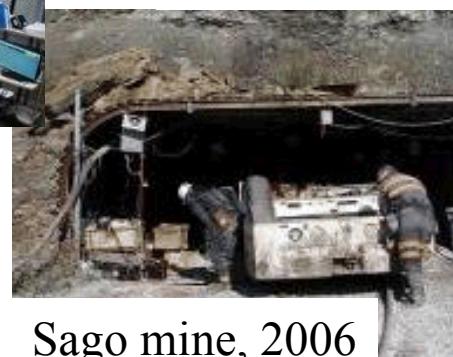


Power systems
All Electric Warship



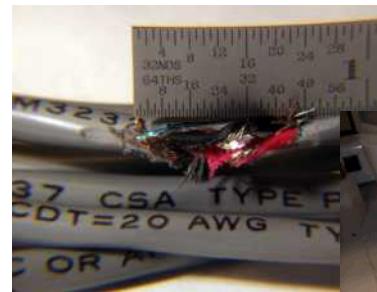
EMP coupling into facilities

Lightning protection

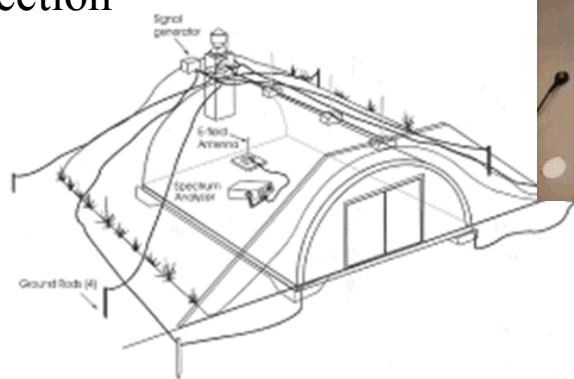


Sago mine, 2006

World class accelerator technology development & high heat flux research



ASTRONICS
CORPORATION

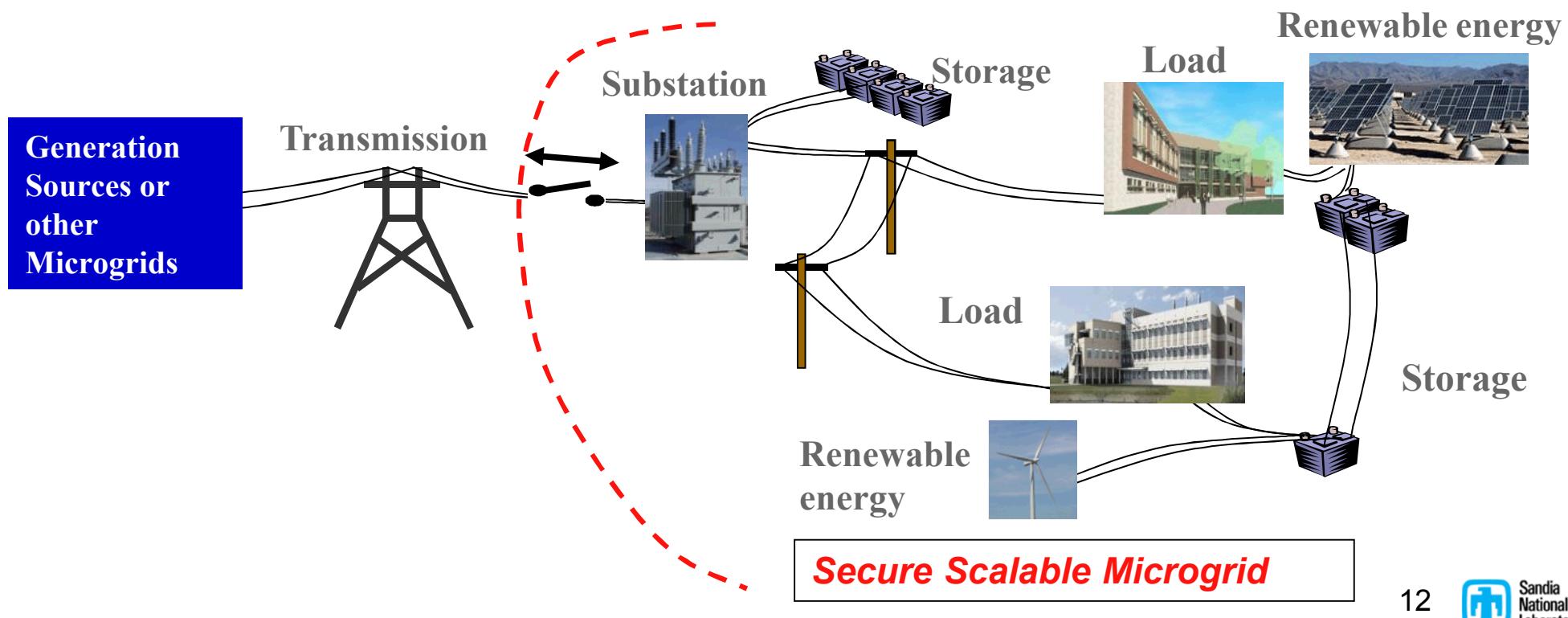


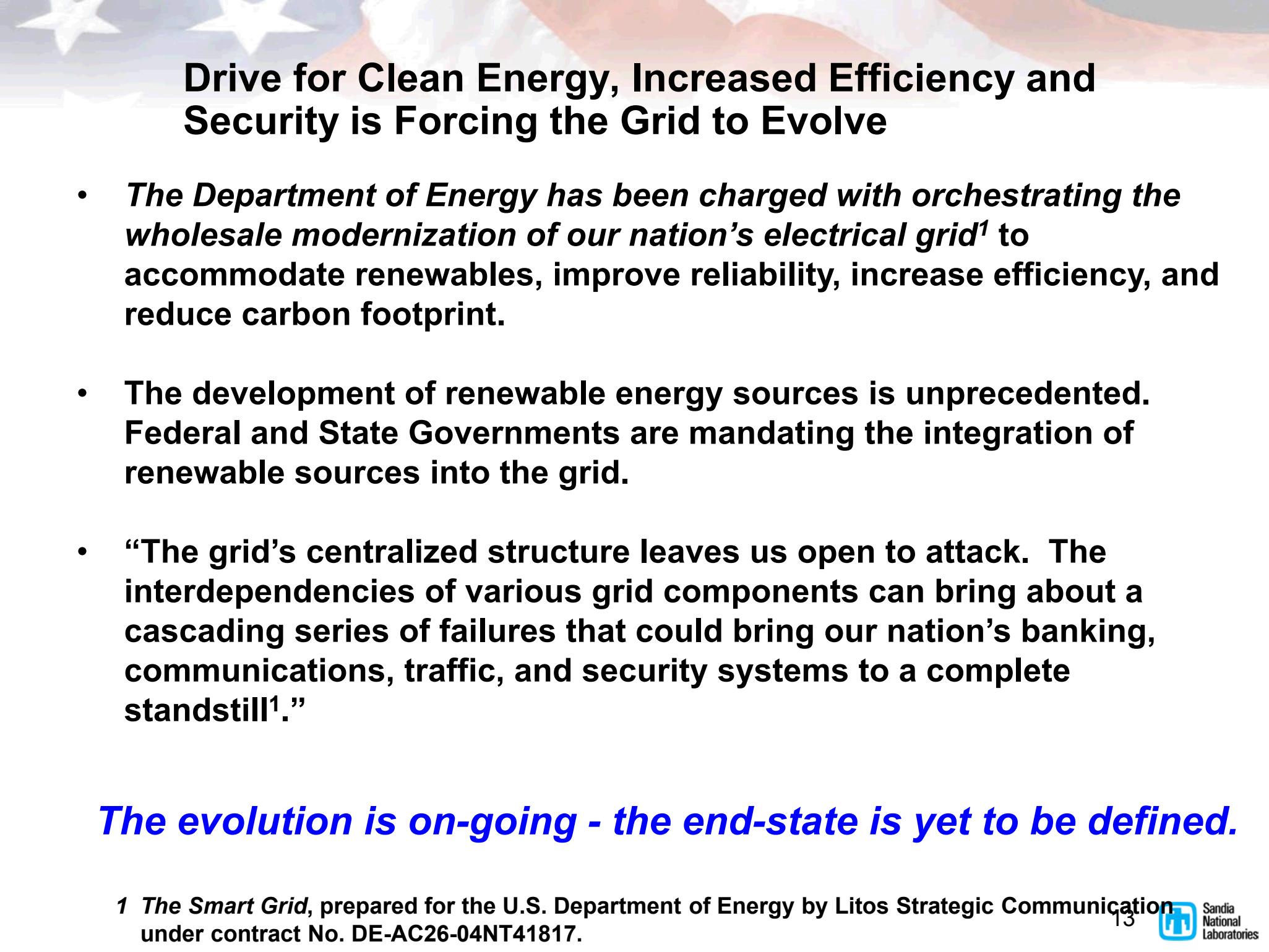
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This Research is Enabling a Revolutionary Step Towards Ideal Goals

- Unlimited use 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.



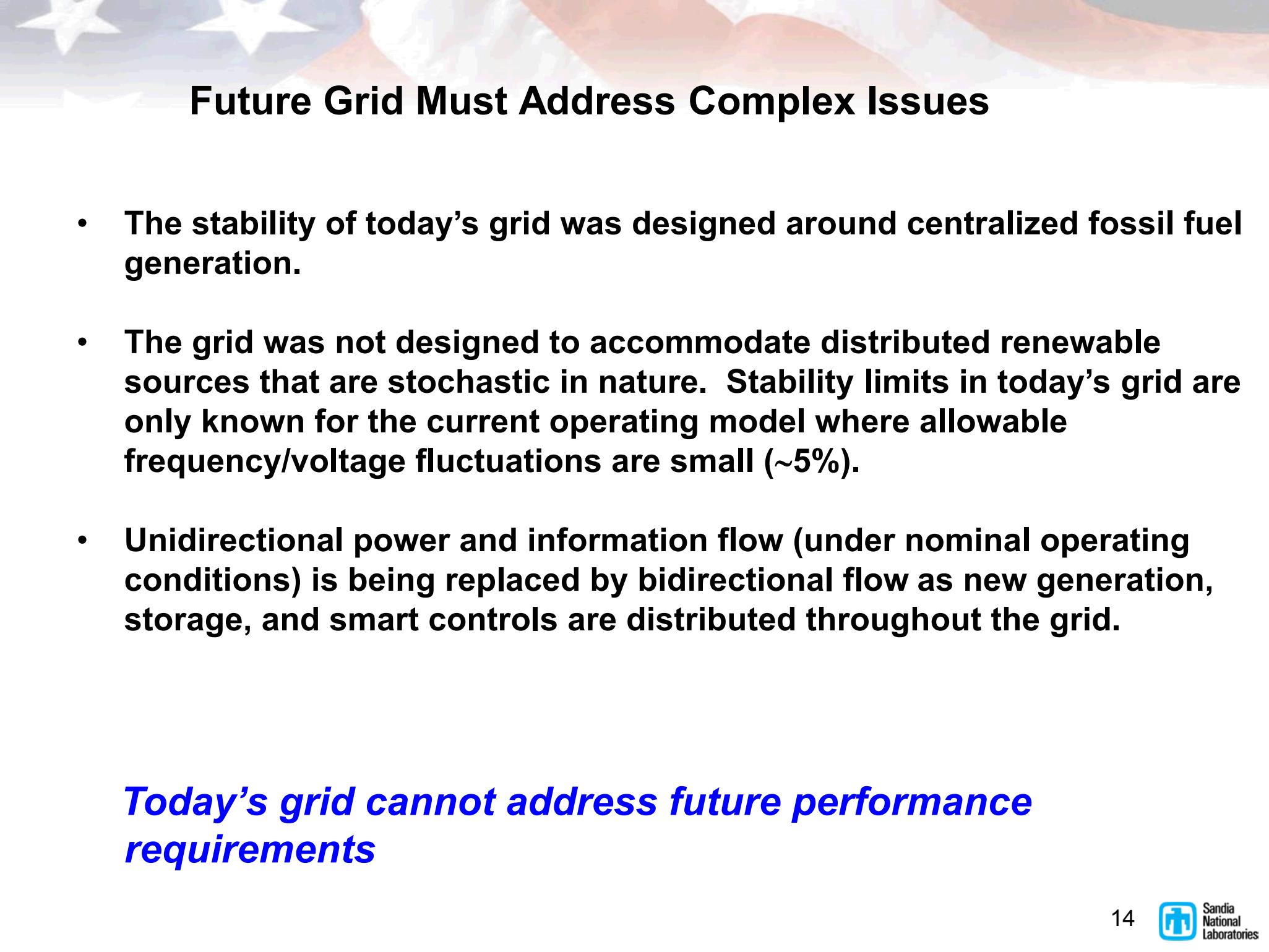


Drive for Clean Energy, Increased Efficiency and Security is Forcing the Grid to Evolve

- *The Department of Energy has been charged with orchestrating the wholesale modernization of our nation's electrical grid¹ to accommodate renewables, improve reliability, increase efficiency, and reduce carbon footprint.*
- The development of renewable energy sources is unprecedented. Federal and State Governments are mandating the integration of renewable sources into the grid.
- “The grid’s centralized structure leaves us open to attack. The interdependencies of various grid components can bring about a cascading series of failures that could bring our nation’s banking, communications, traffic, and security systems to a complete standstill¹.”

The evolution is on-going - the end-state is yet to be defined.

¹ *The Smart Grid*, prepared for the U.S. Department of Energy by Litos Strategic Communication under contract No. DE-AC26-04NT41817.



Future Grid Must Address Complex Issues

- The stability of today's grid was designed around centralized fossil fuel generation.
- The grid was not designed to accommodate distributed renewable sources that are stochastic in nature. Stability limits in today's grid are only known for the current operating model where allowable frequency/voltage fluctuations are small (~5%).
- Unidirectional power and information flow (under nominal operating conditions) is being replaced by bidirectional flow as new generation, storage, and smart controls are distributed throughout the grid.

Today's grid cannot address future performance requirements

Today's Analysis and Modeling Tools Cannot Address Random Sources

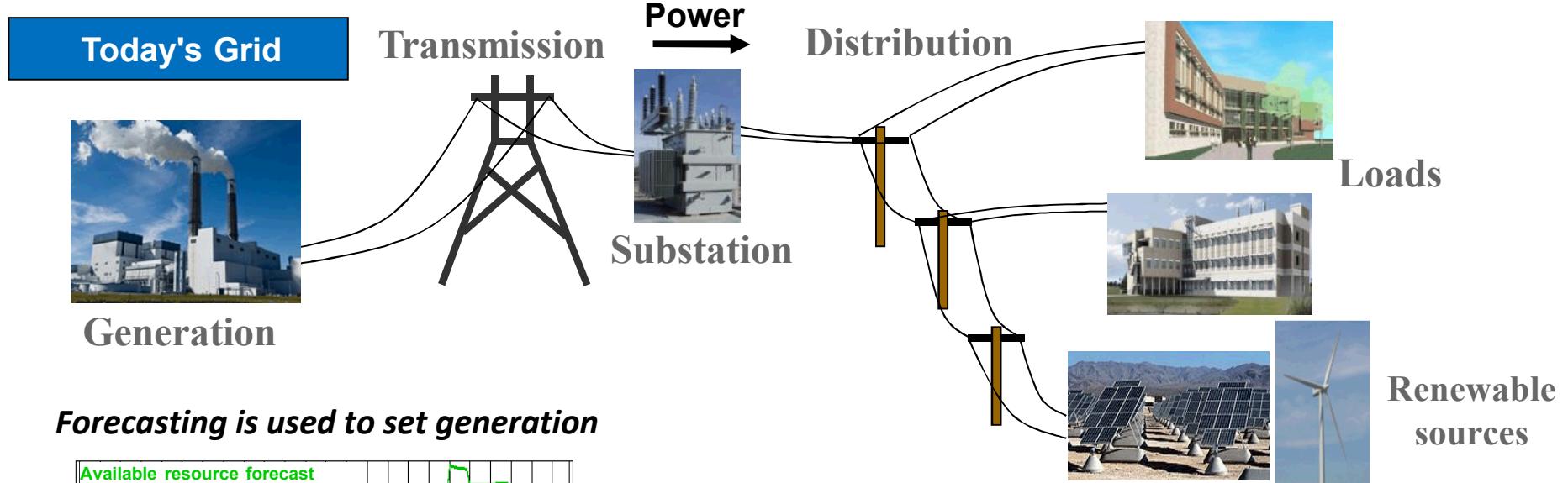
Dynamics of multi-machine power systems described by Reduced Network Models or Structure Preserving Models cannot tolerate variable input sources, significant variations in frequency or voltage (~5%).

RNM impedance loads are assumed constant. Smart loads of the future will be highly variable and controllable.

In SPM the dynamics of multi-machine power systems are described by differential algebraic equations assuming constant 60Hz sinusoidal network response. The future smart grid may not be constant frequency.

These approximations are made with integral manifolds. Physics and dynamic behavior is lost in component models. The future smart grid will be highly dynamic.

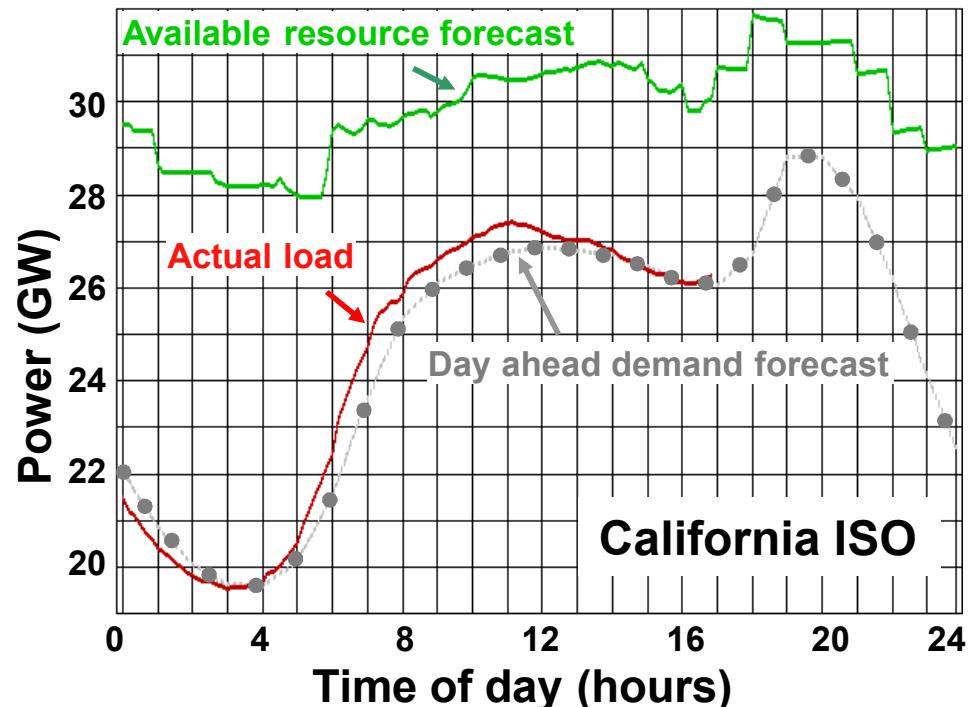
Current Grid is Evolving to Accommodate Different Energy Sources, Increased Reliability and Resiliency



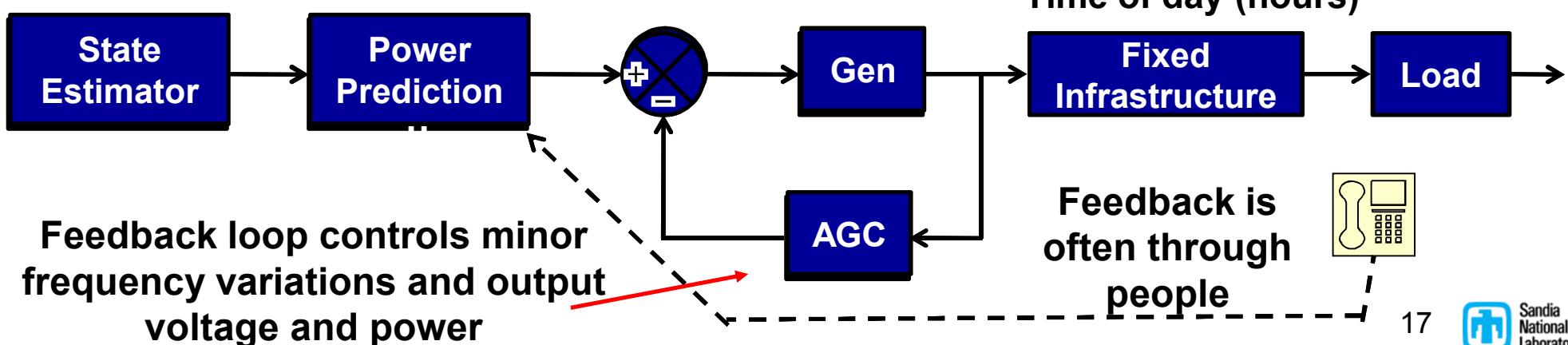
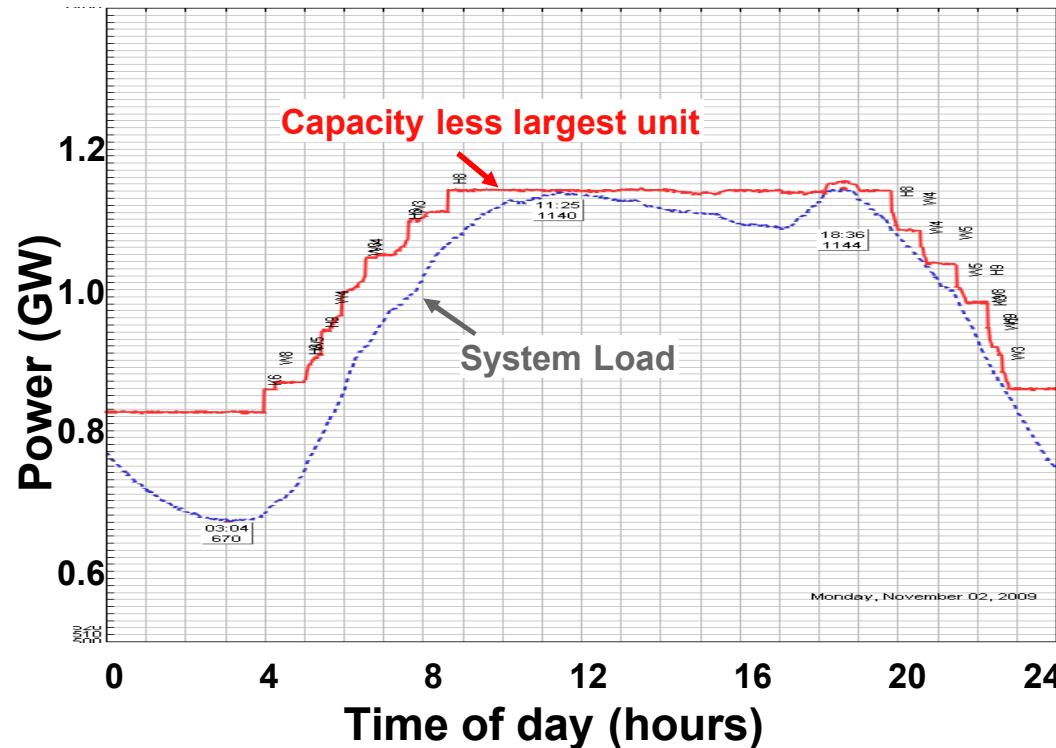
- Centralized generation
- Excess generation & fuel storage
- Fixed infrastructure
- Demand forecasting
- Essentially open loop control with human in the loop
- Limited ability to support renewable sources
- Limited ability to support disruptions
- Smart grid initiatives

Loads are Predictable allowing Essentially Open-loop Grid Control

Forecasting is used to set generation

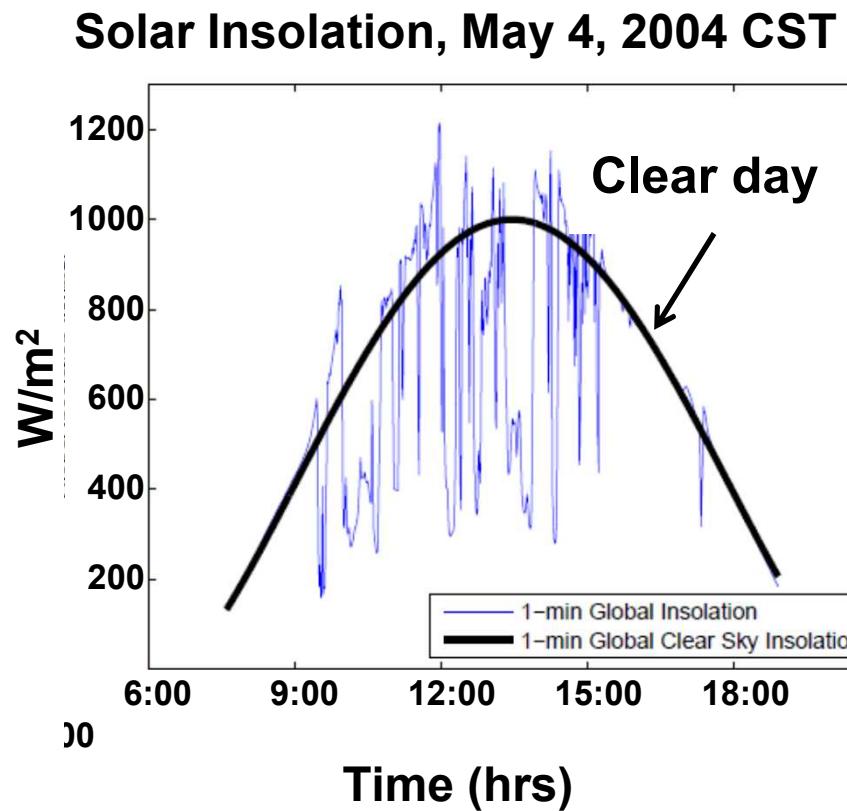
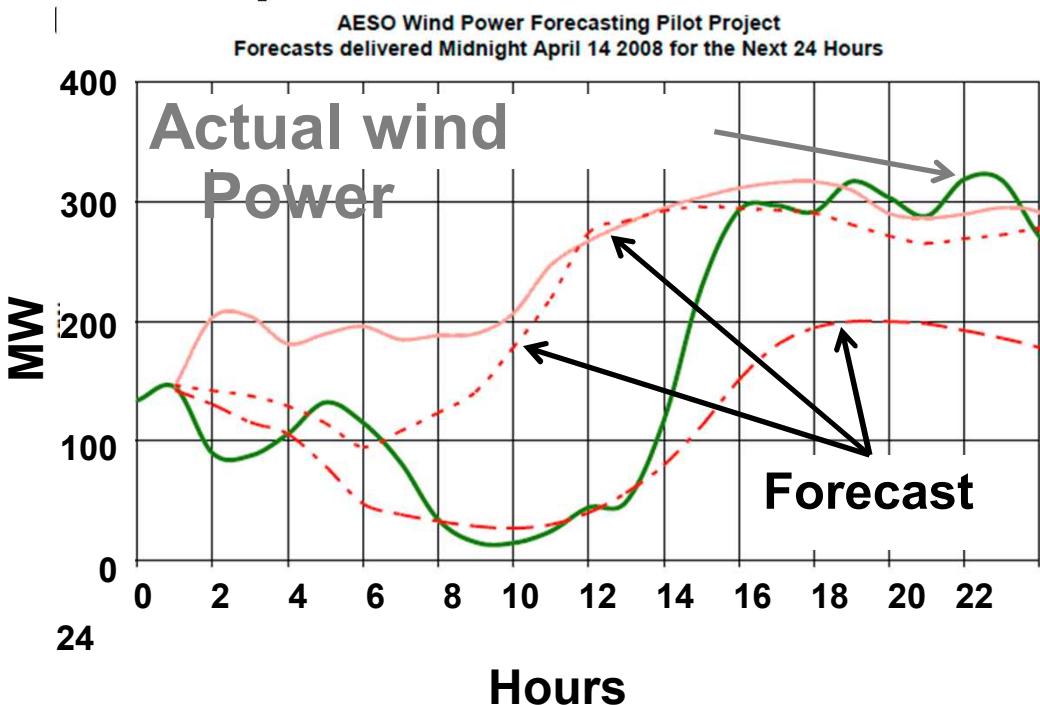


Hawaiian Electric Co. daily load vs capacity



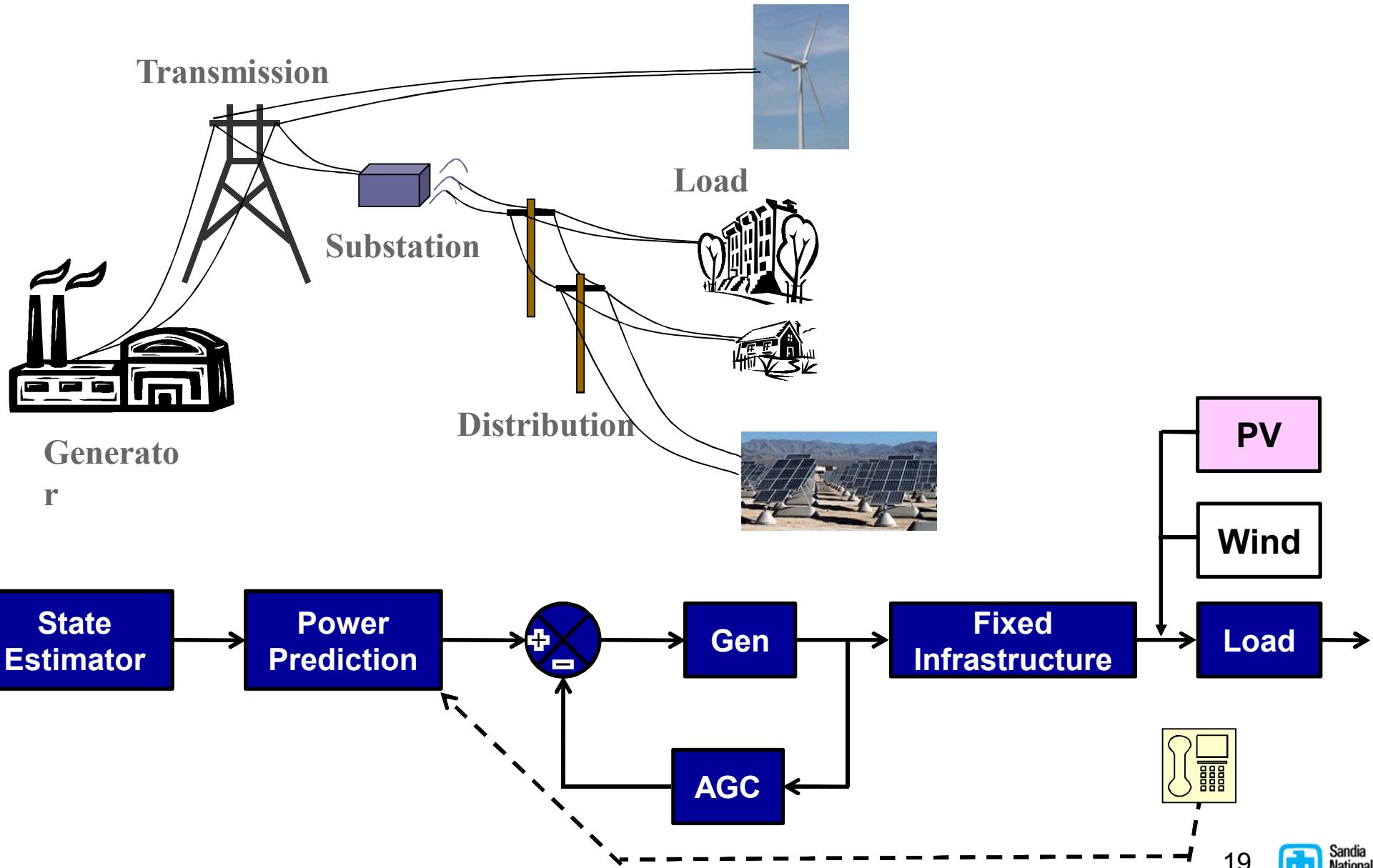
Stochastic Sources Complicate Grid Operation

Wind power forecasting



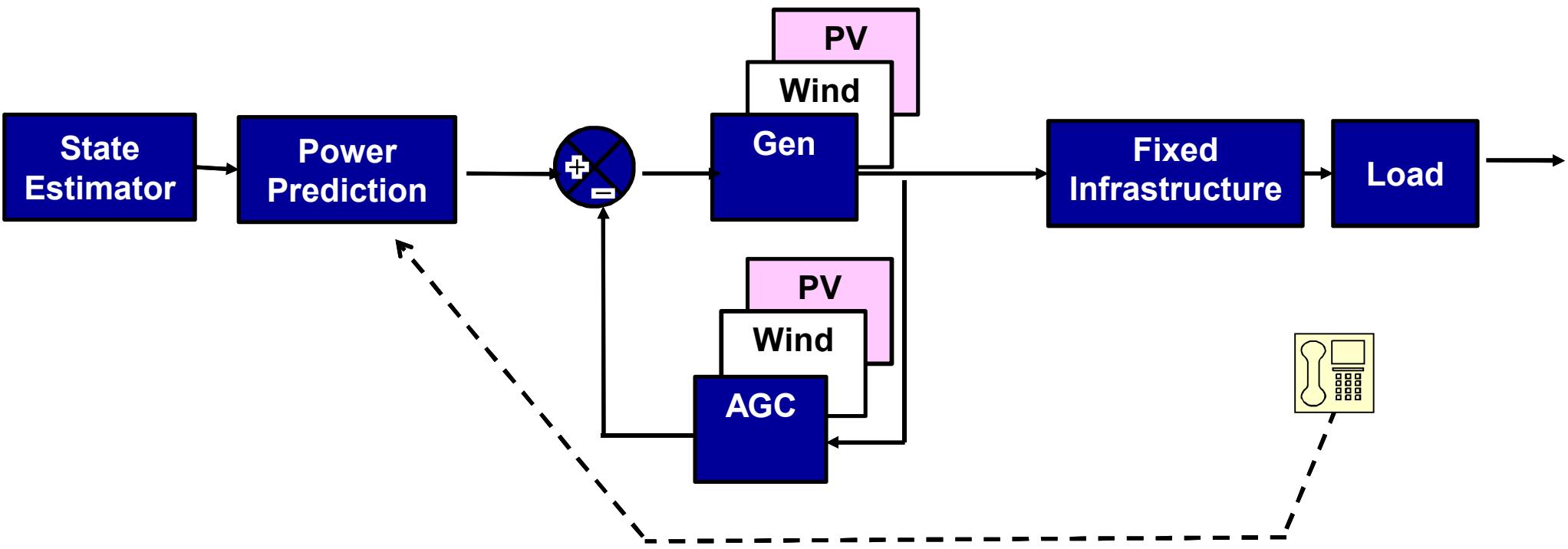
This is weather forecasting!

Today Stochastic Renewable Sources are often Treated as Negative Loads



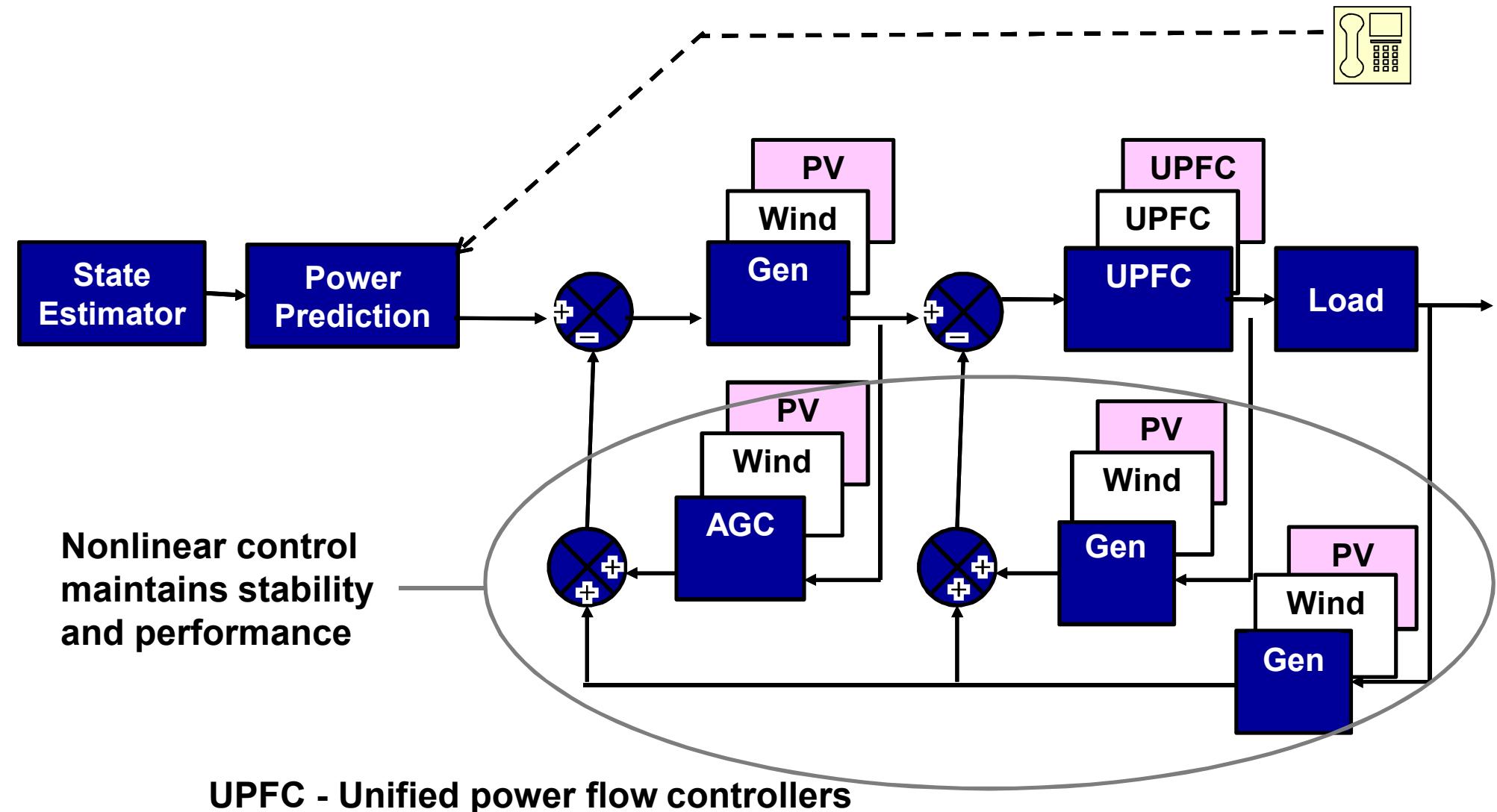
To Achieve Maximum Benefit Renewable Energy Needs to be Treated as a Source

System efficiency can increase with reduction in excess generation capacity.



Both our generation and our loads are now random!

Low Level Distributed Nonlinear Control Enables Stability and Transient Performance



SNL's Hamiltonian based Nonlinear Control Theory Addresses Stability and Performance

Uniqueness of Hamiltonian formulation

- Thermodynamics based
- Exergy is the unifying metric instead of entropy and provides a missing link in self-organizing systems
- Necessary and sufficient conditions for local and global stability and performance of a class of Hamiltonian systems

Kinetic Energy Potential Energy

$$H = [T(\dot{x}) + T_c(\dot{x})] + [V(x) + V_c(x)]$$

$$\dot{H} = [\dot{T}(\dot{x}) + \dot{T}_c(\dot{x})] + [\dot{V}(x) + \dot{V}_c(x)]$$

A method for optimizing microgrids through the use of Hamiltonians

- Enables minimization in fuel based sources
- Enables optimization of multiple cost functions

$$c = \int H dt$$

$$I + J = 8 \int [(\bar{T} + \bar{T}_c) + (\bar{V} + \bar{V}_c)] dt = 8 \int \bar{H} dt$$

Uniqueness of Fisher Information Equivalency

- Order rather than entropy based approach
- Includes information content and delay
- This approach provides an optimization functional to simultaneously minimize information flow and storage

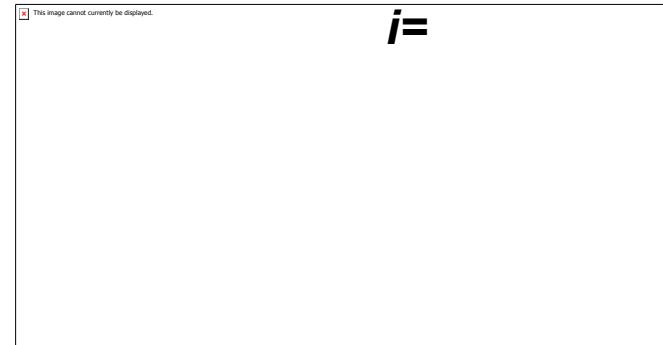
Control Theory Needs to be Expanded from Simple to Complex Systems

Example system with control input $v(t)$.



$$L \frac{di}{dt} + \frac{1}{C} \int idt = v(t) - Ri$$

$$L \ddot{q} + \frac{1}{C} q = v(t) - R \dot{q}$$



PID controller $v(t) = -k_p q - k_i \int q dt - k_d \dot{q}$

Hamiltonian $H = \frac{1}{2} L \dot{q}^2 + \left(\frac{1}{2C} q^2 + \frac{1}{2} k_p q^2 \right) = T(\dot{q}) + (V(q) + V_c(q))$

Control gains

$$\dot{H} = \left[L \ddot{q} + \left(\frac{1}{C} + k_p \right) q \right] \dot{q} = \left[-k_i \int q dt - (R + k_d) \dot{q} \right] \dot{q}$$

Storage Generation, G Load, L

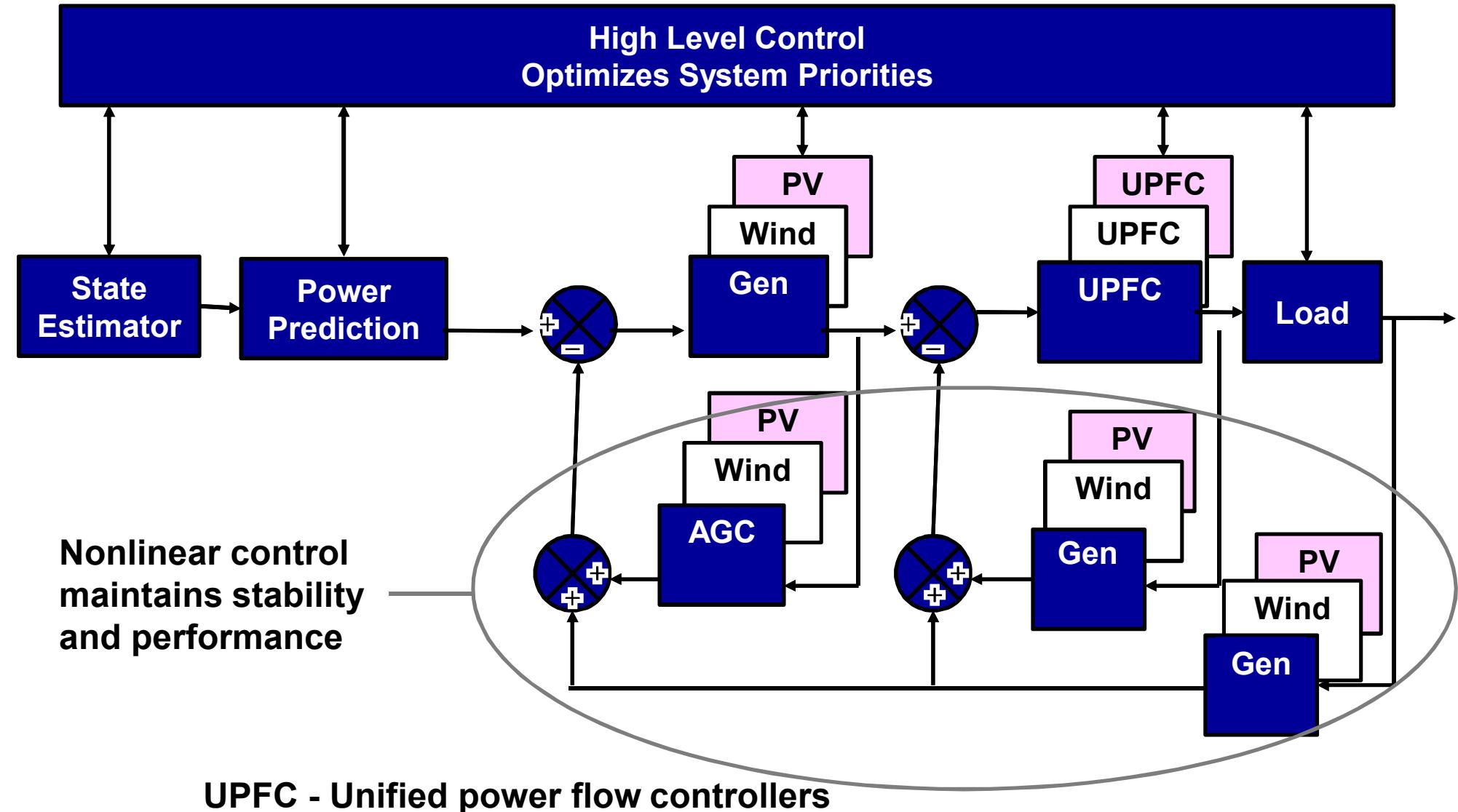
Derivative of the Hamiltonian

Controller gains are chosen for specific performance within the solution space defined by:

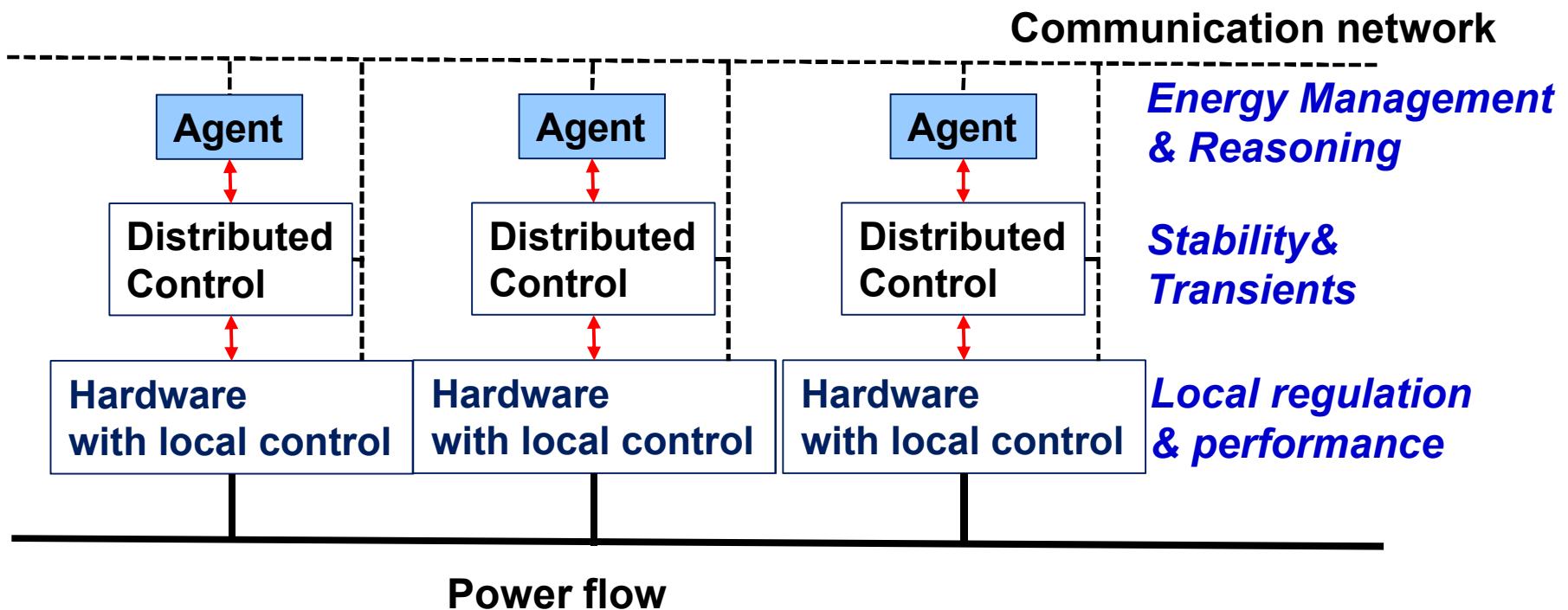
$$H = T(\dot{q}) + [V(q) + V_c(q)] > 0, \quad q \neq 0 \quad \text{where} \quad V(0) + V_c(0) = 0$$



Tiered Control Structure Enables Prioritization and System Adaptability

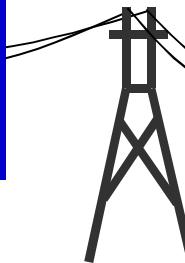


Our Basic Control Structure adds Capability and Supports Flexibility

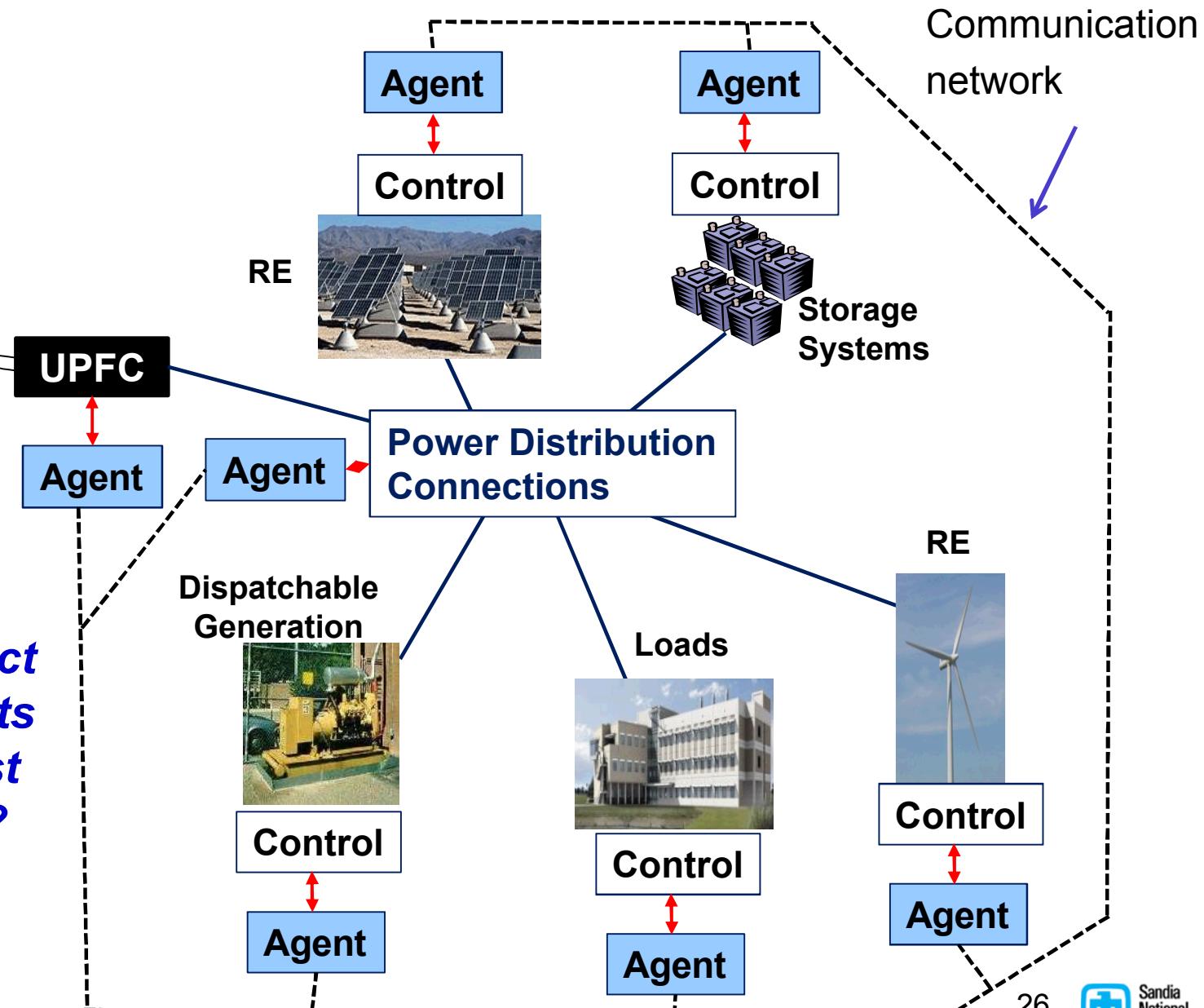


A Highly Interconnected Microgrid Will Result from these Advancements

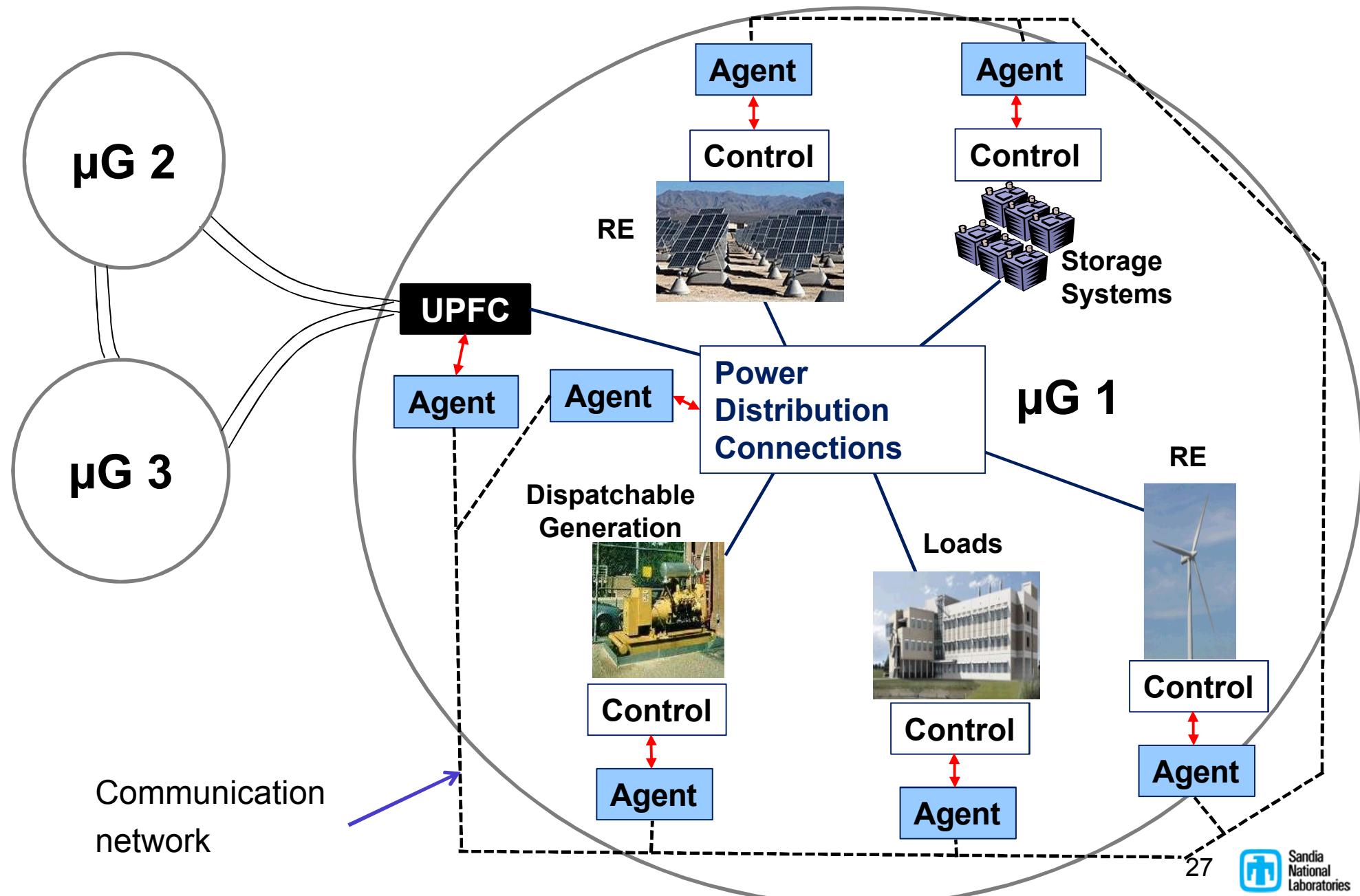
Generation Sources or other Microgrids



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

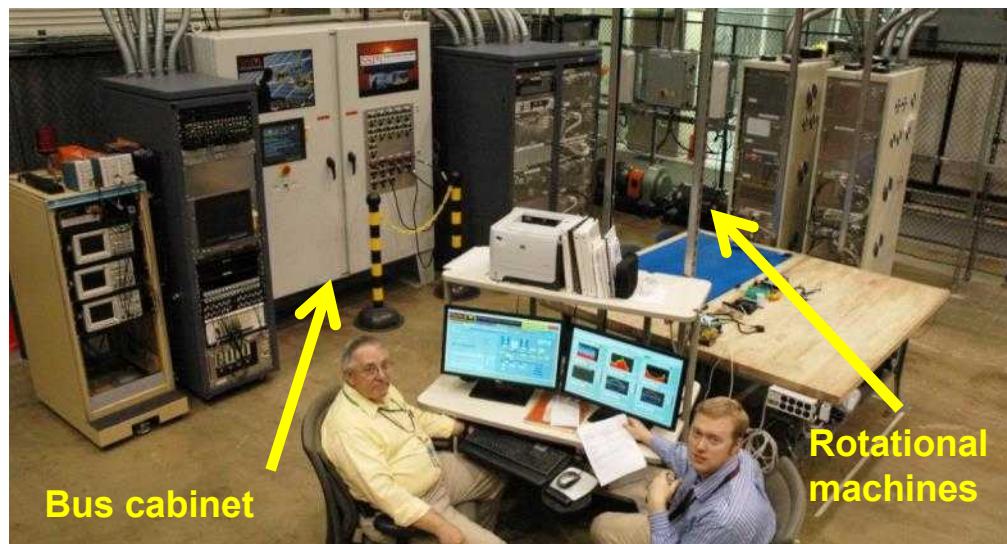
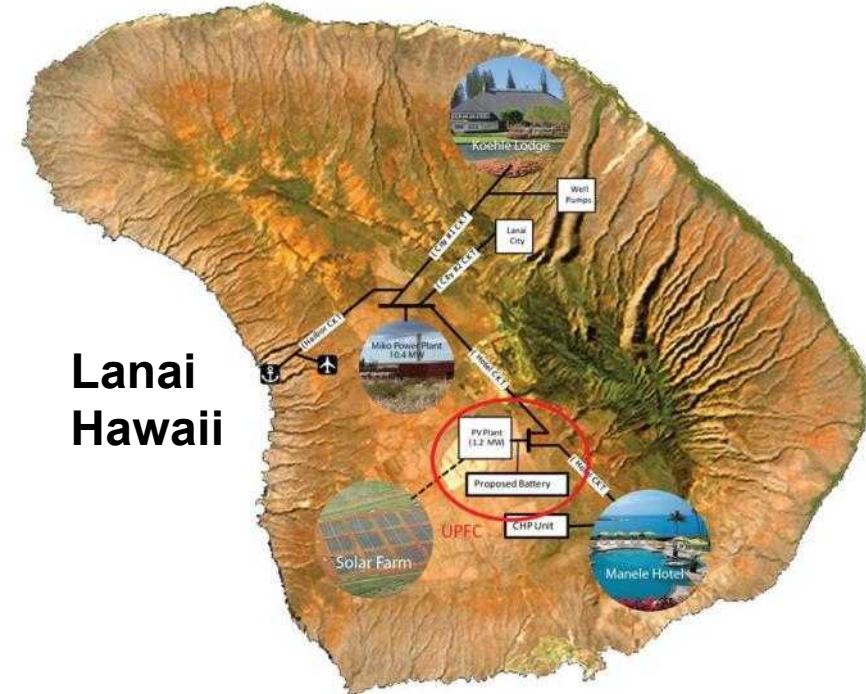


These Microgrids will be Building Blocks for Large Networks



Networked, Secure, Scalable Microgrids (SSM™) Enable High-Penetration Renewables and Improved Operations

- Ground breaking nonlinear control theory, informatics, and innovation.
- Tools are being developed for networked microgrids spanning from conventional to 100% stochastic generation.
- Potential impact:
 - **Unlimited use of renewable sources**
 - **Lower-cost provisioning at a given level of renewables**
 - **Reduction in centralized fossil fuel based sources**
 - **Self-healing, self-adapting architectures**
 - **Microgrids as building blocks for larger systems**



SSM test bed

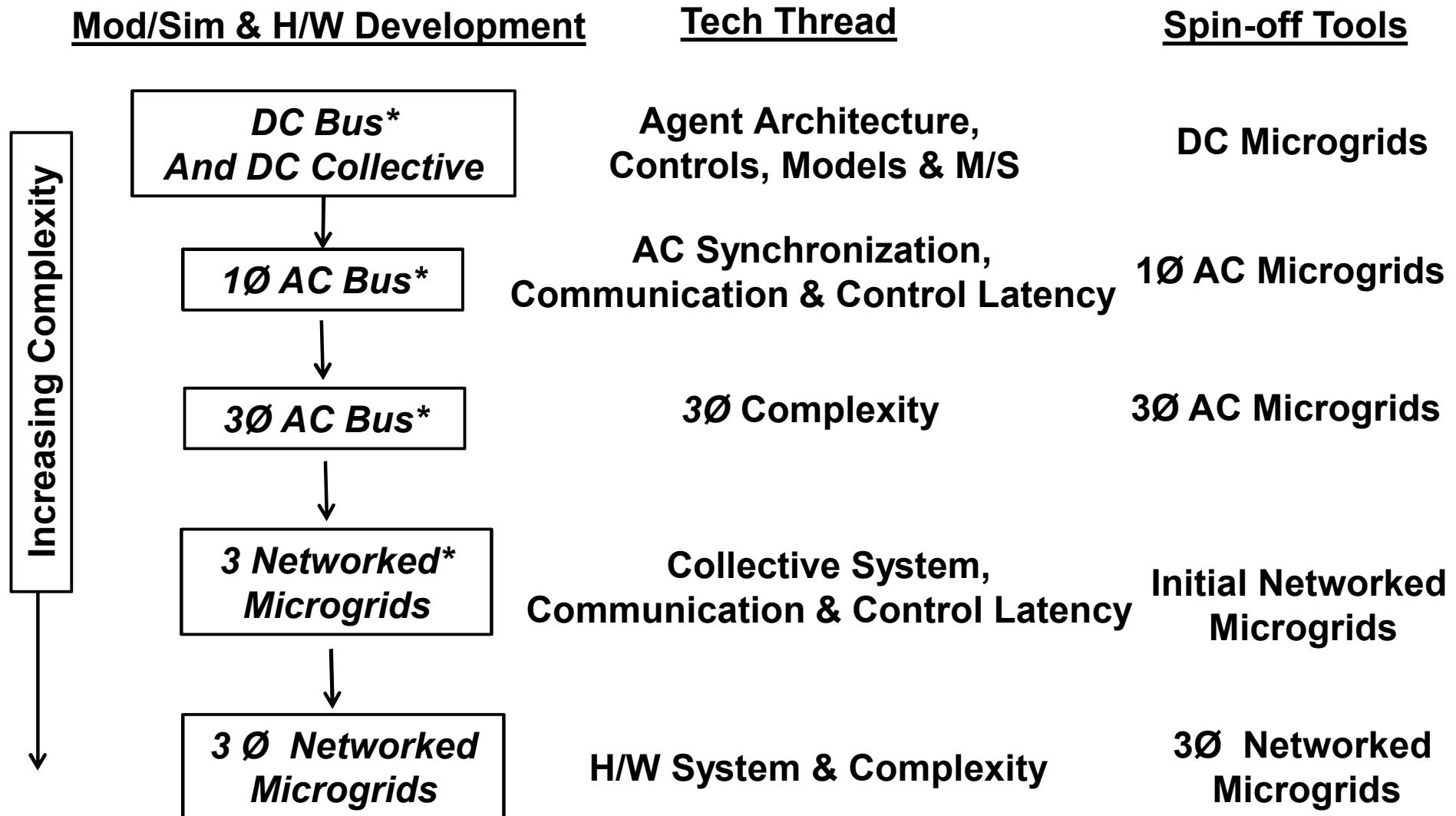
The Secure Scalable Microgrid Grand Challenge is Developing Important New Capabilities

In order to analyze the unconstrained behavior of microgrids and coupled microgrids, new models, theories and tools are needed.

These capabilities will allow the design of optimized microgrid systems. This will be achieved by developing:

- **Scalable, non-linear models of key components in a microgrid. *This will enable unconstrained systems analysis and design.***
- **Nonlinear control theory involving new formulations for microgrid analysis and a unifying theory linking energy and information flow. *This will enable the minimization of energy storage and information flow in the microgrid while assuring stability and transient performance.***
- **Grid informatics based controls that work cooperatively to achieve common goals. *This will enable self-healing, self-adapting, self-organizing microgrid system performance.***

Technology Threads, Spin-offs, and Risk Mitigation



* *Validations on the test bed*



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Microgrid Agent-Based Control for Mediating Generation, Storage, Loads, and Cyber Security

Marvin Cook

IEEE MSC Workshop: Enabling Secure, Scalable Networked Microgrids with High
Penetration Renewables and Pulse Power Loads

Sydney, Australia, September 20, 2015

Seminar Outline



30m Multi-agent systems

- agent introduction
- benefits and challenges
- design process



30m Microgrid controls



The agent universe



What are we talking about?

- **A weak notion of agency**
 - Agents are software constructs with some level of autonomy and situatedness
 - » Social ability, reactivity, and proactivity given in Ref. IV are based on being situated
 - Little contention: Focused on software with certain properties
 - » *Moderate* contention: *what* properties?
- **A strong notion of agency**
 - Approximately, “agents (are/should be/will be) like humans”
 - Much contention: “No, they (aren’t/shouldn’t/won’t/can’t)!”
 - Cf. Turing, Penrose, Searle, Dreyfus re computer intellect

How much should you trust an agent?

... but never mind all that:
What would make a *useful* agent?

- “It” is identifiable and has well-defined interfaces
- Controls its own internal state and external behavior
- Receives input from and acts on its environment (including other entities)
- Has, acts to achieve, and does achieve specific goals
- Recognizes and accommodates unforeseen circumstances that impede satisfaction of its goals
- Recognizes and protects itself from adversaries
- Suppose I had these useful agents ... how would I build a system out of them?

Agent Architectures

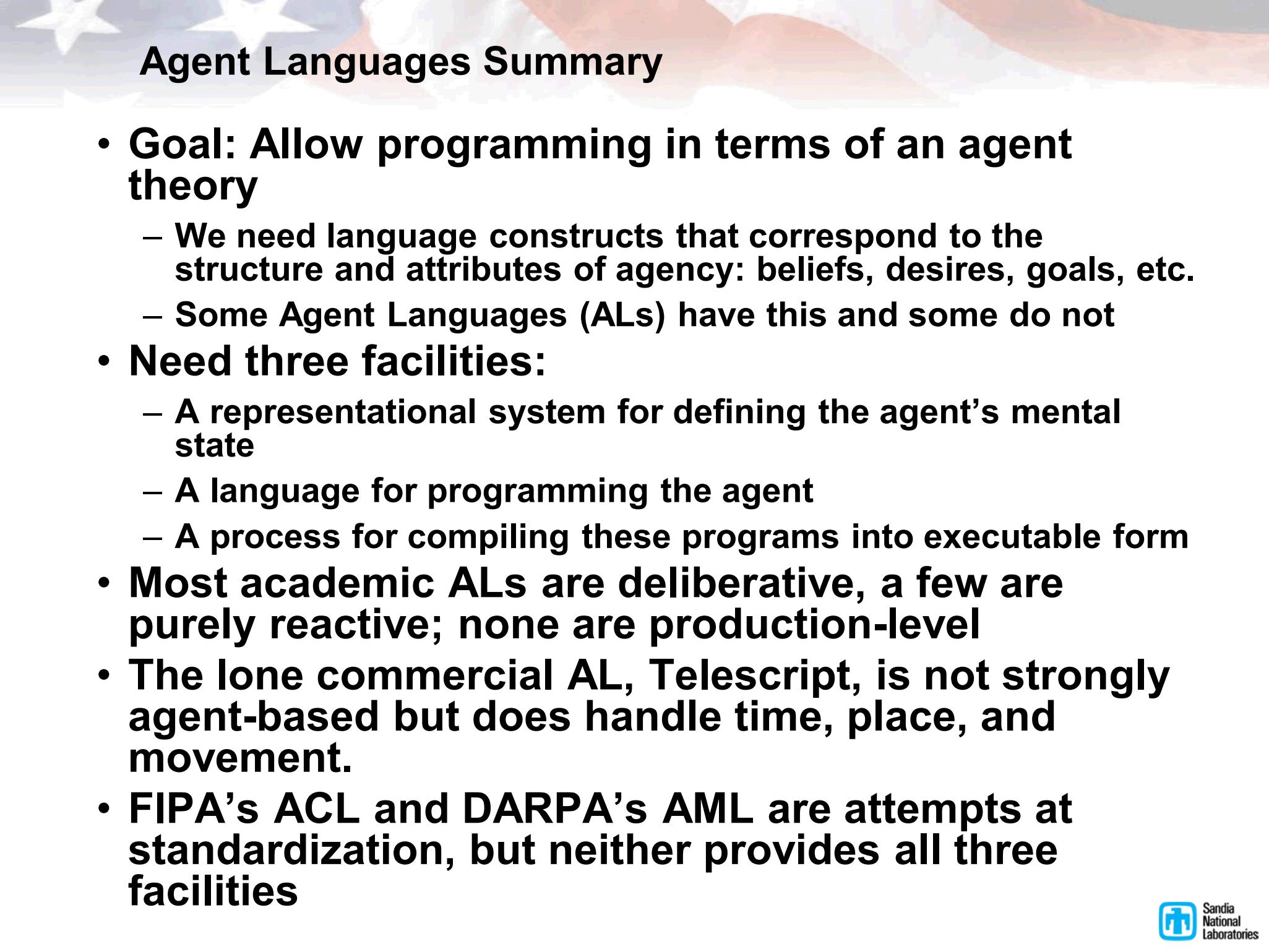
- An *architecture* is a representation of an agent as a set of component modules and their interactions
 - Specifies how sensed data and internal state determine the agent's next action and future state (i.e., it embodies a theory)
 - To generalize an architecture for different domains, we need a theoretical model
- Three approaches:
 - Deliberative (too formal!)
 - Reactive (too applied!)
 - Hybrid (just right!)

- **Main thesis: Deciding what to do next is a formal process executed on a symbolic description of part of the universe**
- **Main issue: bounded rationality vs. termination**
- **The deliberative paradigm is dominant:**
 - Theory is far along (much work already done in AI)
 - Associated technology and methodology is more mature
 - Proximity of symbolic processing to mathematical logic implies the semantics can be represented as a logical system

- **Main thesis:** To save time while executing, we'll "compile" the agent's behavior rules and knowledge into a "circuit" so the agent can just react instead of deliberating
- **Main issue:** sparse or absent methodology
- **Reactive architectures can successfully exploit local patterns if:**
 - Appropriate information is available
 - Global constraints don't interfere
 - The agent's goal structures, decision rules, and sensory structures can be compiled into a decisionmaking device
- **Implemented reactive systems to date have been hand-crafted through a lengthy experimental period**
 - Machine learning and genetic approaches have been suggested to assist

- **Main thesis: Combine the best of deliberative and reactive architectures**
- **Main issue: Combining interacting subsystems into a formally-motivated control framework is difficult**
 - Humans operate at several levels of abstract behavior without much trouble, but this hasn't been demonstrated for hybrid architectures
- **Well-motivated from a design point of view**

We use a hybrid architecture



Agent Languages Summary

- **Goal: Allow programming in terms of an agent theory**
 - We need language constructs that correspond to the structure and attributes of agency: beliefs, desires, goals, etc.
 - Some Agent Languages (ALs) have this and some do not
- **Need three facilities:**
 - A representational system for defining the agent's mental state
 - A language for programming the agent
 - A process for compiling these programs into executable form
- **Most academic ALs are deliberative, a few are purely reactive; none are production-level**
- **The lone commercial AL, Telescript, is not strongly agent-based but does handle time, place, and movement.**
- **FIPA's ACL and DARPA's AML are attempts at standardization, but neither provides all three facilities**

Agent Application Areas

- **Cooperative problem solving and distributed AI:**
 - Coordinating a group of agents to solve problems efficiently
- **Interface agents:**
 - Digital assistants cooperating with human users
- **Believable agents:**
 - Artificial entities capable of expressing emotion interacting with humans
- **Information agents and cooperative information systems:**
 - Combine heterogeneous information systems to respond to queries beyond the scope of the individual sources

distributed trustworthy command & control with IO capabilities

Why we ought to build systems from agents



Why consider an agent approach?

Thesis: **Agents can enhance our ability to design and build complicated systems**

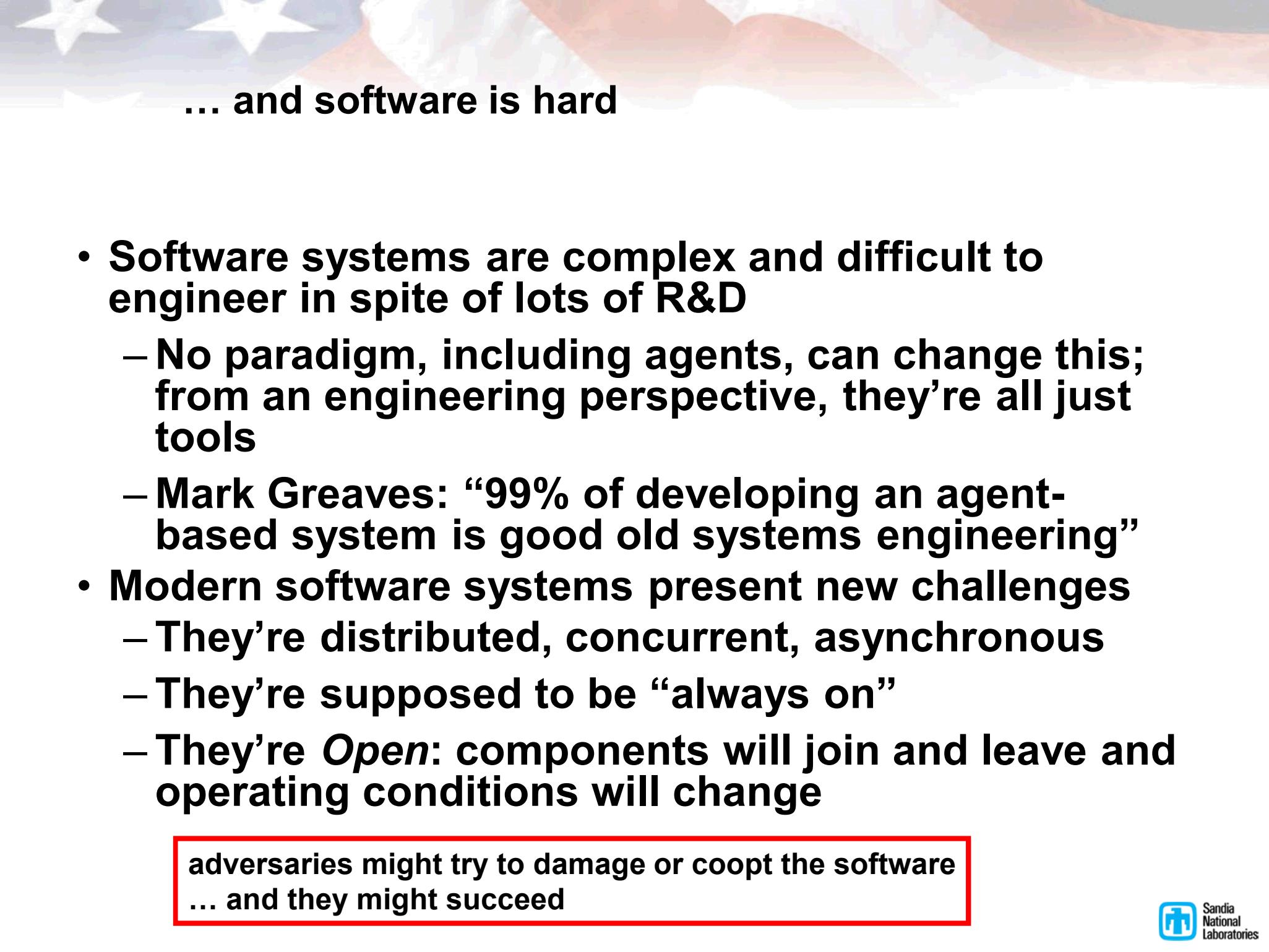
Claim: **Agent technology is mature enough to be a software engineering paradigm**

Summary: **The main argument in favor of agents is that they are an effective abstraction**

But agents are made of

SOFTWARE





... and software is hard

- **Software systems are complex and difficult to engineer in spite of lots of R&D**
 - No paradigm, including agents, can change this; from an engineering perspective, they're all just tools
 - **Mark Greaves: “99% of developing an agent-based system is good old systems engineering”**
- **Modern software systems present new challenges**
 - They're distributed, concurrent, asynchronous
 - They're supposed to be “always on”
 - They're *Open*: components will join and leave and operating conditions will change

adversaries might try to damage or coopt the software
... and they might succeed

Not to worry!

Real world
applications often have
constrained problems
and solutions... so
there is hope!

There are ways to deal with complexity

- The big wins (structured programming, object orientation, design patterns, etc.) rest on *abstraction*
 - Want to minimize the semantic difference between the units of analysis and the problem constructs
- Essential techniques:
 - Abstract: Define and deal with a model of the system that emphasizes some aspects and simplifies or ignores others.
 - Decompose: Divide problems into smaller sub-problems and deal with the sub-problems in isolation
 - Organize: Identify and manage the interrelationships among components
 - » Aggregate groups of elements into components
 - » Treat components as units
 - » Compose components into interacting cooperative structures

Agents are Timely

- **Decentralized systems**
 \Leftrightarrow Agent autonomy
- **Systems owned by different stakeholders**
 \Leftrightarrow modularity and encapsulation
- **Changing and unpredictable open environment**
 \Leftrightarrow high-level, dynamic interactions

When should you consider agents?

- When you need to construct a society of interacting autonomous entities
- When information and resources are distributed
- When system elements need agent properties
- When several legacy systems need to interact

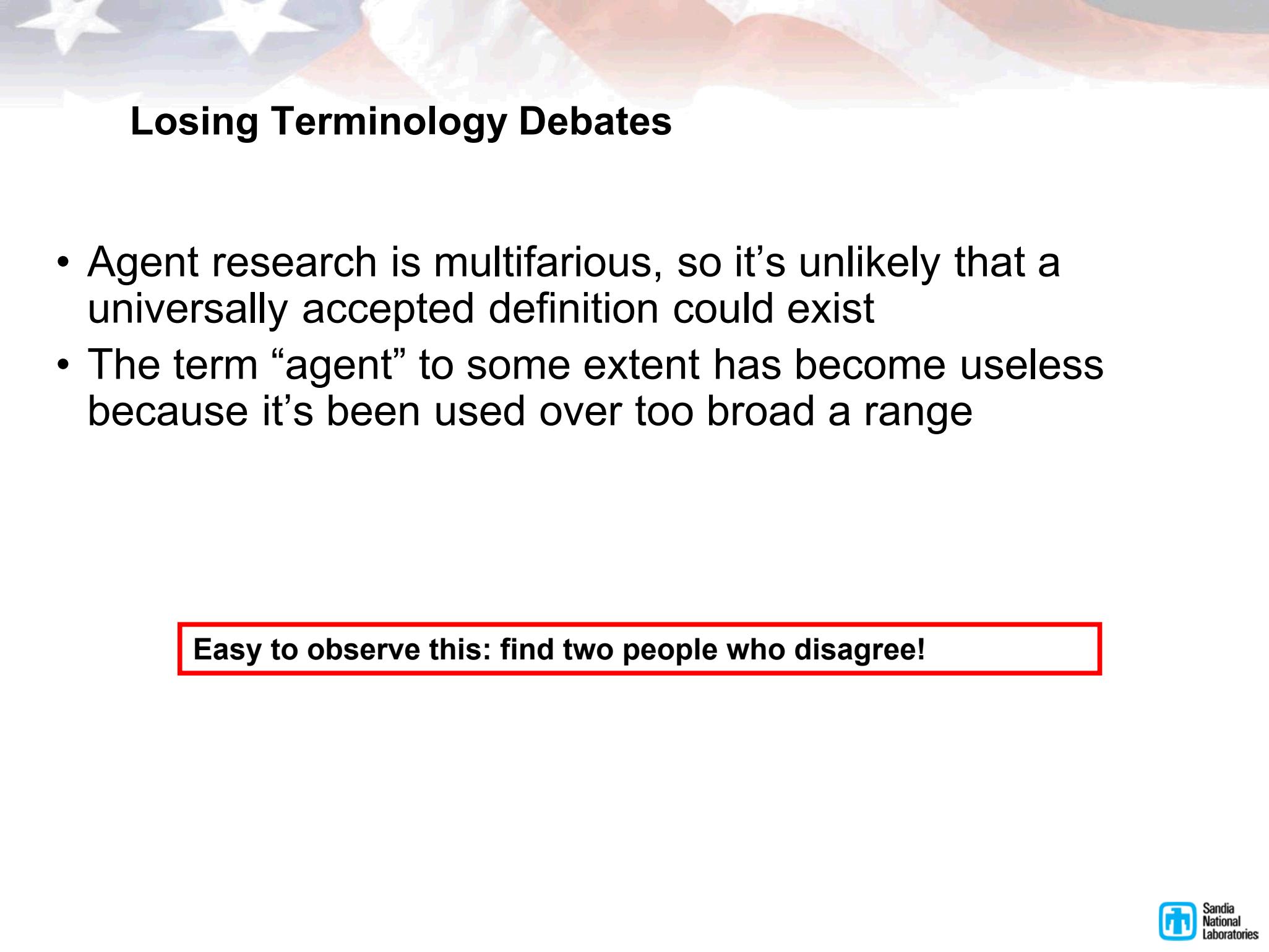
When security and trustworthiness matter

Problem Space vs. Agent Solution

- **Complex real-world systems are made up of:**
 - Components that interact according to their roles within the larger enterprise
 - Components linked by dynamic relationship networks
 - Collections of components treated as abstract units
 - Protocols for representing, forming, maintaining, and disbanding teams cooperating to achieve goals
- **The general agent-based infrastructure supports:**
 - *The entity lifecycle*: Creation, maintenance, and destruction of entities
 - *Programmability*: Executable description of entity-to-entity interaction
 - *Roles*: Collections of interaction descriptions (i.e., programs)
 - *Assignment of roles to entities*
 - *Entity collections* are first-class entities
 - *Relationships* are first-class entities

Difficulties and concerns of using agents: the 30,000-foot view





Losing Terminology Debates

- Agent research is multifarious, so it's unlikely that a universally accepted definition could exist
- The term “agent” to some extent has become useless because it's been used over too broad a range

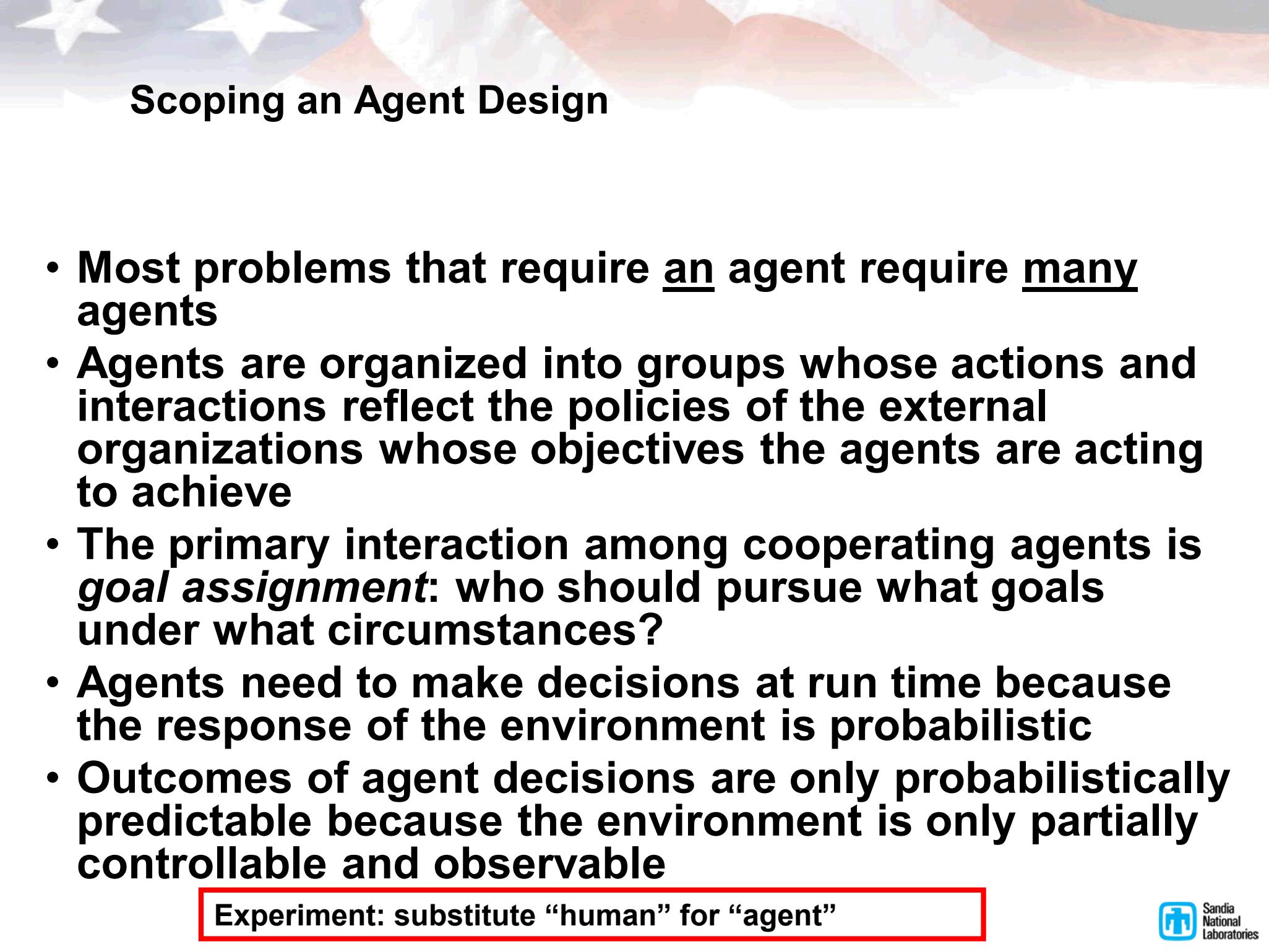
Easy to observe this: find two people who disagree!

Common Agent Usage Pitfalls

- **Political pitfalls**
 - Overselling
 - Dogmatism
- **Management pitfalls**
 - Unspecified or weak goals
 - Misapplication
 - **Overemphasis on Re-use:**
The system must still be designed!
- **Conceptual pitfalls**
 - You promise an order-of-magnitude improvement in development process
 - You don't follow fundamental software engineering process
 - You don't address the multithreading implied by lack of central control
- **Analysis and design pitfalls**
 - You ignore existing technologies
 - You don't exploit concurrency
 - You ignore legacy systems
- **Agent-level pitfalls**
 - You build your own architecture
 - You use too much experimental technology
 - You don't use any advanced technology
 - The line between “experimental technology” and “advanced technology” is thin!
- **Society-level pitfalls**
 - Too many agents (everything is an agent)
 - Too few agents (“god” agents that do everything)
 - Overemphasized infrastructure
 - Too much interaction
 - Not enough structure

Agent Design Process





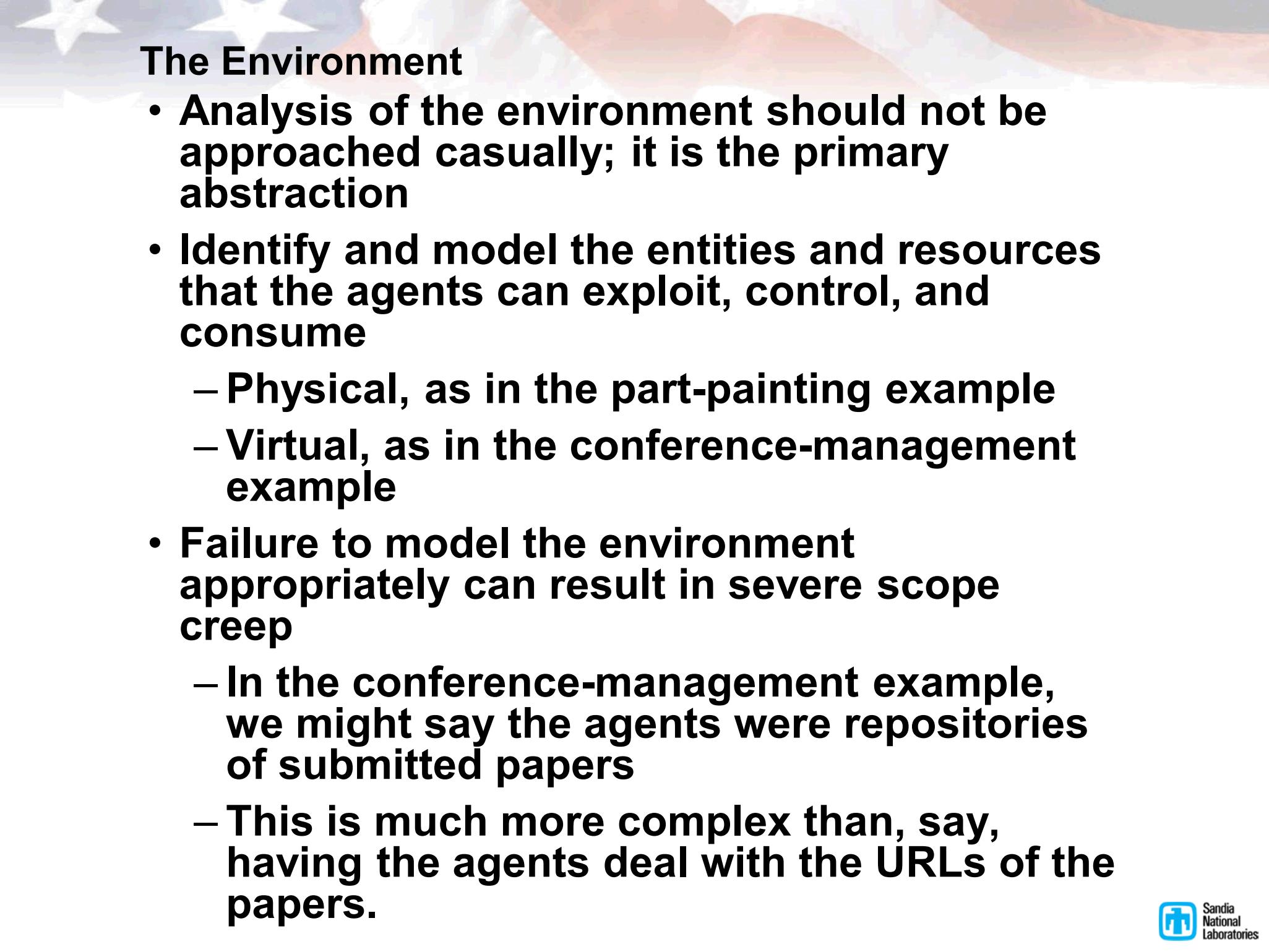
Scoping an Agent Design

- Most problems that require an agent require many agents
- Agents are organized into groups whose actions and interactions reflect the policies of the external organizations whose objectives the agents are acting to achieve
- The primary interaction among cooperating agents is *goal assignment*: who should pursue what goals under what circumstances?
- Agents need to make decisions at run time because the response of the environment is probabilistic
- Outcomes of agent decisions are only probabilistically predictable because the environment is only partially controllable and observable

Experiment: substitute “human” for “agent”

Required Abstractions & Definitions

- **Environment**: a collection of resources
- **Roles**: what the players do
- **Interactions**: who they do it with
- **Organizational rules**
- **Organizational structures**



The Environment

- Analysis of the environment should not be approached casually; it is the primary abstraction
- Identify and model the entities and resources that the agents can exploit, control, and consume
 - Physical, as in the part-painting example
 - Virtual, as in the conference-management example
- Failure to model the environment appropriately can result in severe scope creep
 - In the conference-management example, we might say the agents were repositories of submitted papers
 - This is much more complex than, say, having the agents deal with the URLs of the papers.

The following aspects of the environment should be addressed

- **Environmental resources the agents can sense and effect**
 - Accessibility (cost, existence of sensors, etc.)
 - Dynamics (ephemeral/permanent, scheduled, etc.)
- **Internal representation of salient elements of the environment**
 - Dependent on technology and scenarios
 - Are sensors passive or active?
 - Characteristics of services?
- **Elements of the scenarios of interest that need to be characterized as part of the environment**
 - What's an agent and what's a dynamic resource?
 - What's part of an agent (and thus part of the system being analyzed and designed) and what's part of the environment?

use case analysis
continues to be a very
useful approach

Roles and interactions

- A *role* is a well-defined position in the organization with an associated set of expected behaviors

Notion that the role is *assigned* (i.e., not synonymous with the agent) allows results to be useful beyond a single kind of agent

- Analysis should produce:
 - An *organizational role model* giving the functions, activities, responsibilities, and the interaction protocols and patterns of the organizational roles within the system scope.
 - An *organizational interaction model* that gives the protocols governing the interactions between the roles and when, how, and by whom a protocol needs to be executed

Organizational rules

- **Organizational rules are constraints on the roles**
- **Describe relations and constraints between roles, between protocols, and between roles and protocols**
- **Cannot be expressed in terms of individual roles or protocols but must refer to combinations thereof**
 - “A reviewer agent cannot also be an author agent” is a constraint that applies to the author role and the reviewer role
 - **Exception: In a closed system, since all roles are understood up front, organizational rules can be captured in the individual roles (by referring to the other roles); this does, however, make the roles more complex**

Organizational structures

- As the organizational role model defines the roles and their positions in the organization, it also indicates:
 - The topology of the interaction patterns
 - The control regime of the organization's activities
 - E.g.: A role model in which a “master” assigns work to “slaves” implies a hierarchical topology and a load-partitioning control regime.
- The MAS structure should be chosen with care, because:
 - The MAS structure will not always mimic its target real-word system
 - The real-world system might change on its own, forcing the MAS to change
 - A badly-chosen structure can make the rules hard to enforce
- Not immediately apparent, e.g., whether it's better to use a peer-to-peer system or a hierarchical system for part-painting

central control => locus of vulnerability

You are really close to
software
implementation... just
a few more design
considerations!!

Establish Agent Representations

- **Goal: Identify the agent classes that will play each of the necessary roles**
- **Denote how many instances of each will be instantiated**
- **Multiple related and interacting roles may be packaged in one agent class provided that:**
 - **Organizational efficiency is not greatly affected**
 - **Rationality bounds are not exceeded (i.e., the agent can figure out the answers in the time allotted)**
 - **Organizational rules are not violated**

Establish Service Representations

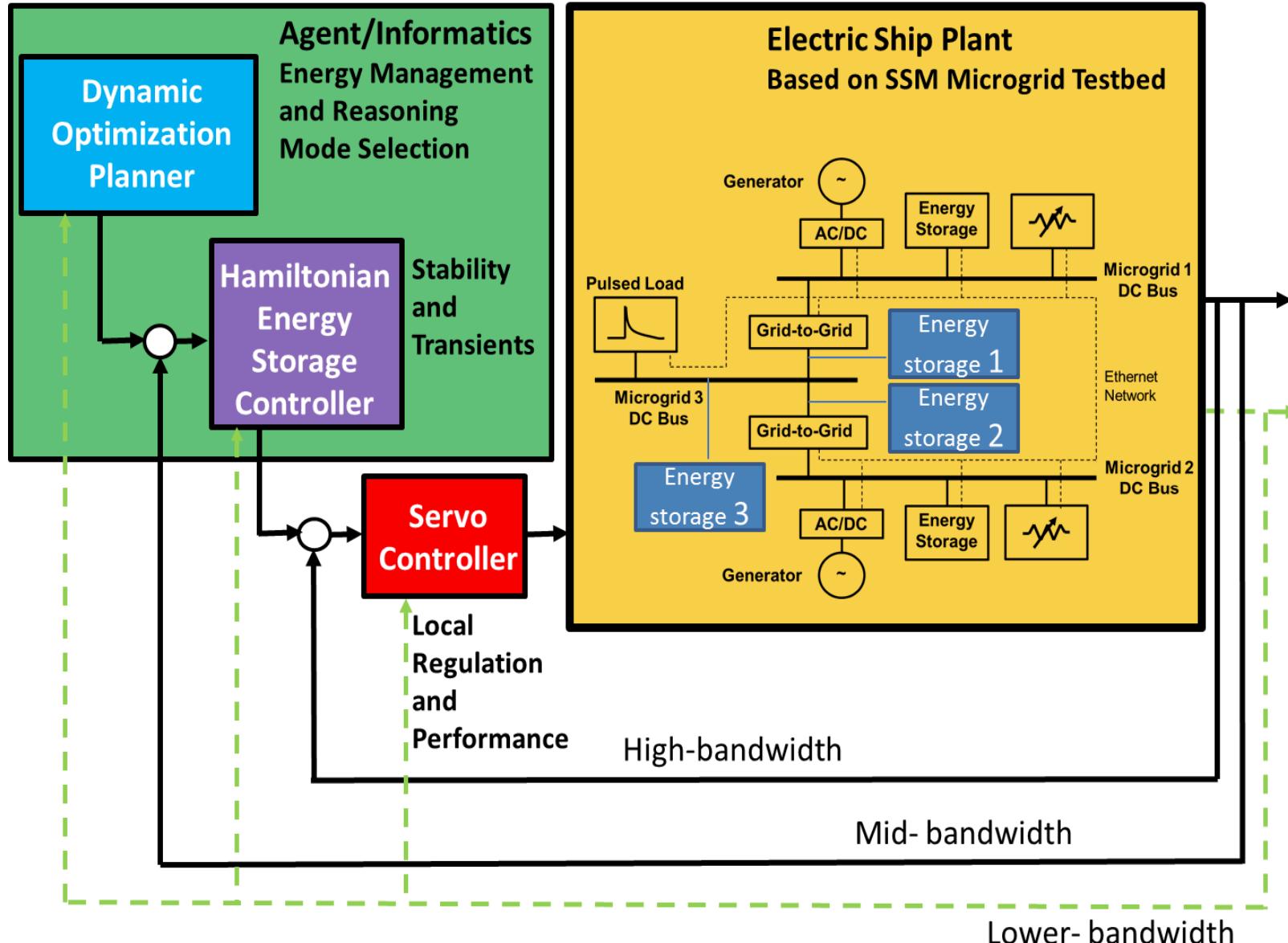
- **Goal: Identify the services associated with the roles**
- **A service is like an object's method, except:**
 - Services are not necessarily triggered by requests
 - Requests don't necessarily trigger services
- **Services are derived from the protocols, activities, responsibilities, and liveness properties of the role.**
- **Example: Assuming ReceivePaper, ReviewPaper, and SendReview always occur in sequence, the single service ProvideReview suggests itself**
 - Although we probably should allow a reviewer the right to refuse a paper, suggesting that ReceivePaper should be separate

Represent Service I/O and Effects

- For each service, document the
 - Inputs
 - Outputs
 - Pre-conditions
 - Post-conditions
- Input and outputs are derived from the protocols model and the environmental model
- Pre- and post-conditions are derived from safety properties and the organizational rules

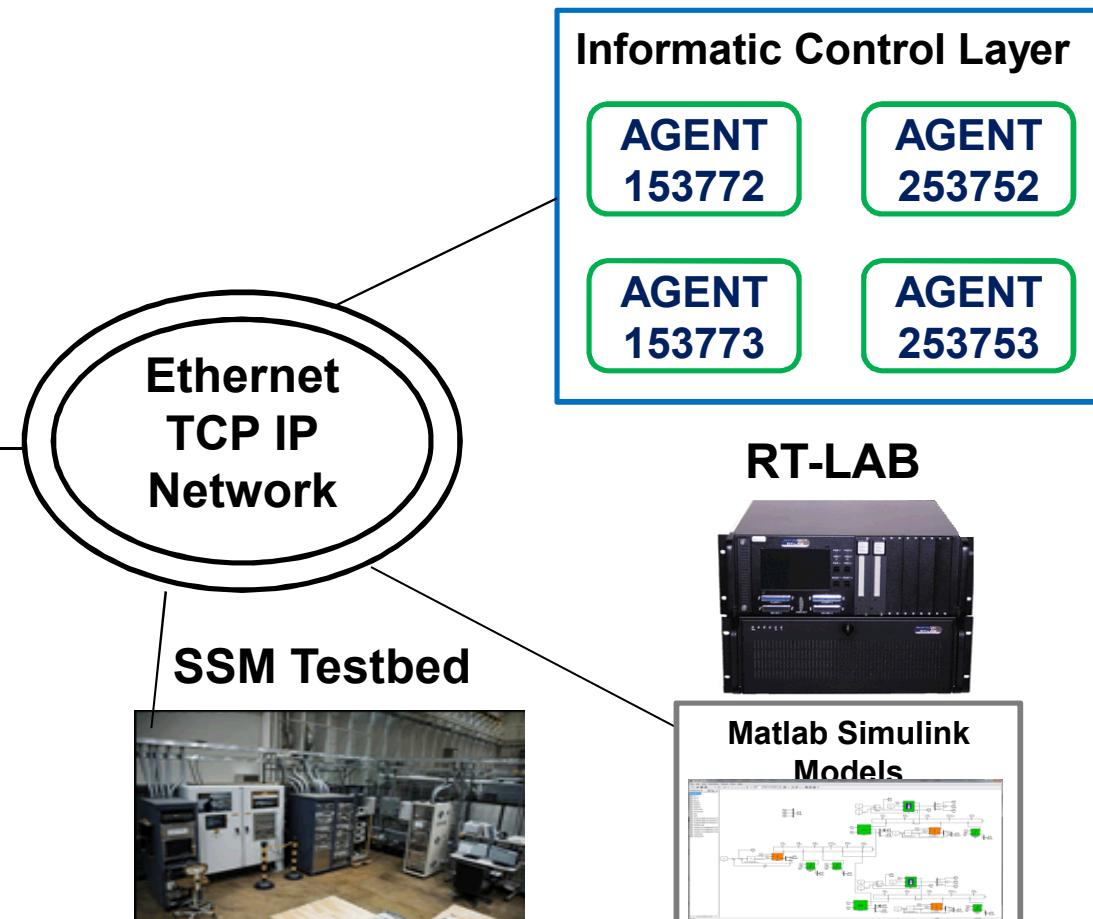
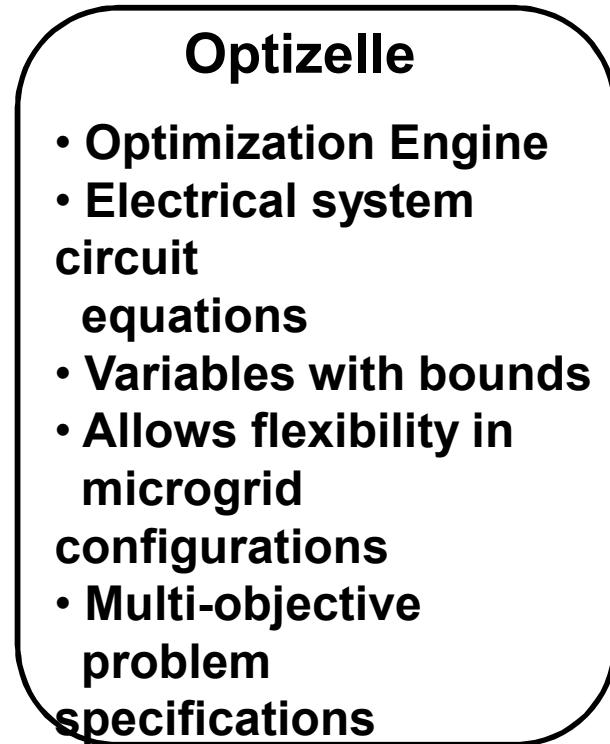
**Imagine achieving
power balance across
multiple microgrids
with agents
autonomously
choosing operating set
points periodically...**

Multiple Microgrid System Represents a Navy Electric Ship Configuration



A Dynamic Optimizer/Planner Computes Optimal Operating Points

- SSM Testbed controllers send periodic measurements to the Informatic Control Layer
- The Informatic Control Layer sends optimization parameters to Optizelle based on measurements and system objectives
- Optizelle returns optimal reference points that are used by the Informatic Control Layers to drive low level controllers



Dynamic Optimization with Optizelle

- **Optizelle is an open source software library designed to solve general purpose nonlinear optimization problems**
- **Extensions made to incorporate electrical system circuit equations and particular optimality constraints.**
- **Utilizes a composite-step, inexact, trust-region SQP algorithm combined with a primal-dual interior-point method.**
- **Fully integrated with Informatic control layer**
 - Agents form JSON input parameters for optimization based on periodic measurements (from physical testbed or simulation)
 - Agents interpret optimization results and send new reference points to servo controllers
- **Download Link:**
<http://www.optimojoe.com/products/optizelle/>

Optimization Problem Statement and Answer

Optizelle Communication with Agent

```
Optizelle Solving {"single": {"L": [[0.002], [0.002]], "R": [[0.145], [0.145]], "v": [[142.02616788103856D0], [52.199999999999996D0]], "R_o": [[150.0D0]], "C_o": [[0.004]], "Delta_t": [[0.01]], "i_min": [[2], [2]], "i_max": [[15], [15]], "u_min": [[-100], [-100], [-20]], "u_max": [[100], [100], [20]], "lambda_min": [[0.2], [0.2]], "lambda_max": [[0.99], [0.99]], "x_0": [[5], [5], [150]], "i_0": [[5], [5]], "v_B_0": [[150]], "lambda_0": [[0.7], [0.7]], "w": [[1], [0], [0], [0]]}}
```

Json solution:

```
{"single": {"lambda": [0.6999999997, 0.699999998], "xdot": [314.3452723, 295.0043224, 1282.806937], "x": [8.143452723, 7.950043224, 162.8280694], "u": [-26.23702817, 63.52241319, -5.048698938], "v_B": 162.8280694, "i": [8.143452723, 7.950043224]}, }
```

- JSON – JavaScript Object Notation is a syntax for data exchange (alternative to XML)
- Input describes system configuration, component values, measured states, and weighted objectives
- Output describes optimal reference points for boost converters and storage devices
- Supports various microgrid configurations (microgrid connections, varying storage, generation, and loads)

Model-Based Formulation

- **Guidance (duty cycle, set-points) algorithm utilizes single DC microgrid model**
 - 1) steady-state solution
 - 2) dynamic optimization formulation
- **General formulations identified for the following microgrid configurations:**
 - Single DC microgrid: Multiple boost converters on single DC bus
 - Multiple DC microgrid: Multiple boost converters on multiple DC buses connected by multiple DC transmission lines
 - Multiple AC microgrid: Multiple three phase inverters on multiple AC buses connected by multiple DC transmission lines
- **Concrete optimization codes developed using Optizelle for above formulations**

Single DC Microgrid Optimization Problem is Defined

$$\begin{array}{ll}\min & \frac{w_1}{2} \|\dot{\lambda}\|^2 + \frac{w_2}{2} \|u\|^2 + \frac{w_3}{2} i^T \text{Diag}(R)i + \frac{w_4}{2} (x^T u)^2 \\ \text{st} & M\dot{x} = [\bar{R} + \tilde{R}(\lambda)]x + v + u \quad \text{Circuit equations,} \\ & x = \begin{bmatrix} i \\ v_B \end{bmatrix} \quad \text{Definition of } x, \\ & x = x_0 + \Delta t \dot{x} \quad \} \quad \text{Discretization,} \\ & \lambda = \lambda_0 + \Delta t \dot{\lambda} \quad \} \\ & i_{\min} \leq i \leq i_{\max} \quad \} \\ & u_{\min} \leq u \leq u_{\max} \quad \} \\ & \lambda_{\min} \leq \lambda \leq \lambda_{\max} \quad \} \quad \text{Bounds.} \end{array}$$

where

$$\bar{R} = \begin{bmatrix} -R_1 & & & & \\ & \ddots & & & \\ & & -R_d & & \\ & & & -1/R_o & \end{bmatrix}, \quad \tilde{R}(\lambda) = \begin{bmatrix} -\lambda_1 & & & \\ & \ddots & & \\ & & -\lambda_d & \\ \lambda_1 & \cdots & | & \lambda_d \end{bmatrix}$$

Cyber Security & Energy Systems

- Future energy system architectures will have increased automation and communication paths
- Additional communication paths and more frequent information exchange increases risk
- Cyber based threats must be well understood with mitigation strategies
- Systems should aim to eliminate single points of failure
- Distributed/hybrid control designs potentially introduce new vulnerability paths

Achieving System Resiliency

- **Implement layers of protection:**
 - intrusion detection
 - intrusion tolerance
 - encryption
 - authentication
 - trusted platforms and operating systems
- **System architectures must recognize and adapt to the threat environment, by:**
 - Dynamically switching modes of communication, encryption, and authentication
 - Modifying team structures within distributed architectures
 - Enforcing n-man rules for command and control



– program terminates –

Acknowledgments

- **SNL GC/LDRD SSM Microgrid Work**
- **NAVSEA Naval Power Systems, Electric Ship PMS 320 Program**
- **Michigan Technological University**
 - Professor Gordon Parker (Optimization)
 - Research Professor Steve Goldsmith (Agents/Informatics Framework)

Hamiltonian Control Design Microgrid Control and Performance Analysis

David Wilson, SNL
Electrical Science and Experiments
R&D Controls Engineer
Controls Team:

Professor Rush D. Robinett III, Michigan Tech University
Dr. Joseph Young, OptimoJoe, LLC

Informatics/Power and Controls Engineering:
Marvin Cook, SNL; Jason Neely, SNL; Steve Glover, SNL;
Wayne Weaver, MTU; Gordon Parker, MTU

**IEEE MSC Workshop: Enabling Secure, Scalable Networked Microgrids with High
Penetration Renewables and Pulse Power Loads**

Sydney, Australia, September 20, 2015



Agenda

- 8:00 Energy Surety Requirements for Microgrid Development
- 8:50 Break
- 9:05 Microgrid Modeling using MATLAB/Simulink: Components-to-Systems
- 10:05 Break
- 10:20 Microgrid Optimal Control and Optimization
- 11:20 Lunch
- 12:20 Microgrid Agent-Based Control for Mediating Generation, Storage, Loads, Cyber Security
- 1:20 Break
- **1:35 Microgrid Control and Performance Analysis**
- 2:35 Break
- 2:50 Sandia National Lab's Secure Scalable Microgrid Testbed: Capabilities and Collaboration
- 3:50 Wrap-up

Outline

- Nonlinear Distributed Controller Design (HSSPFC)
- Secure Scalable Microgrid Testbed
- Microgrid Configurations and Modeling
- Dynamic Optimization/Planner
- Single DC Microgrid Results
- Energy Storage Systems
- Multiple Microgrid System Navy Electric Ship
- Conclusions

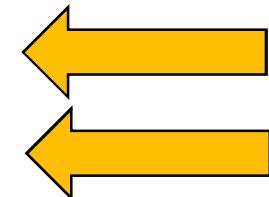
Nonlinear Control Design Based on Latest Grand Challenge LDRD Project

- **Unique features:**

- Nonlinear controllers for nonlinear systems
 - » Power flow approach balances generation and dissipation subject to power storage (kinetic and potential energies) for Hamiltonian systems
 - » Hamiltonian surface shaping provides static stability conditions
 - » Identifies limit cycles as part of dynamic stability conditions
 - » Provides both necessary and sufficient conditions for stability while simultaneously allowing for performance specifications
 - » Seamlessly integrates information theory concepts (information flow vs. energy storage)
 - » Does not require linearization about a nominal operating point
 - » Approach not limited to conventional passivity control design
 - » Conventional nonlinear control design energy shaping techniques unaware of what shaping the surface provides in sense of static stability

HSSPFC Key Pieces Accomplished on GC/LDRD and Follow-on Developments

- DC single microgrid
- DC networked microgrids
- AC single inverter-based microgrid
- AC networked inverted-based microgrids
- AC inverter/synchronous generator microgrids
- Hybrid DC/AC individual/networked microgrids
- Multi-spinning machines on AC bus



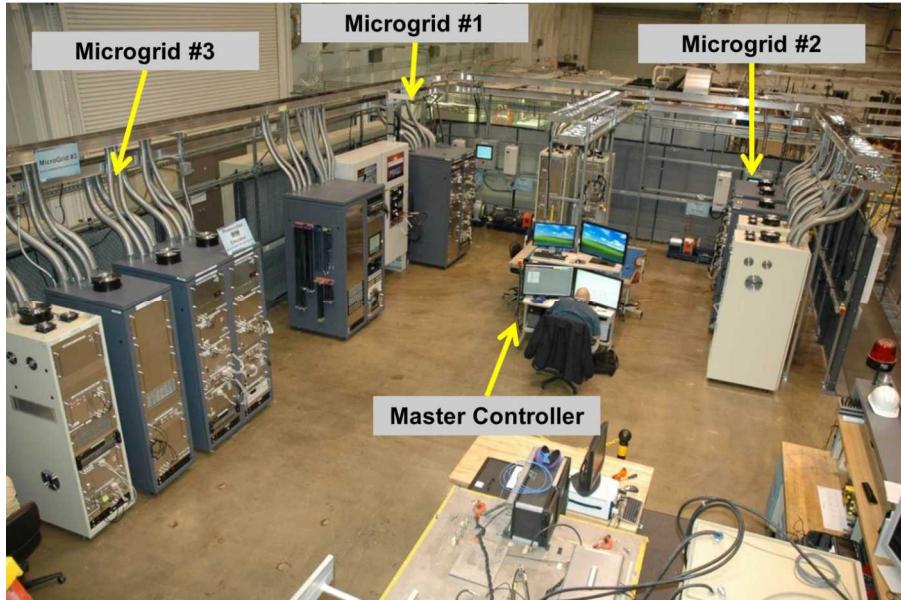
HSSPFC Summary

General Control Design Steps

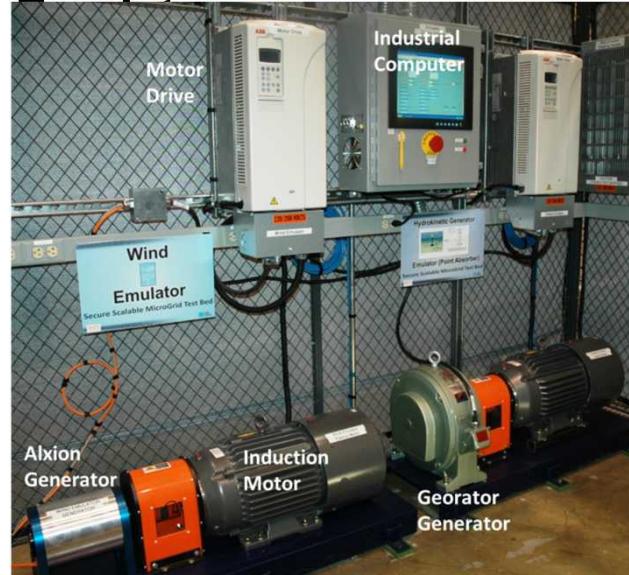
1. Define Reduced Order Model (ROM)
2. Formulate K.E. and P.E.
3. Formulate Hamiltonian (Energy surface)
4. Hamiltonian rate (Power flow)
5. Design nonlinear control laws
6. Determine static stability conditions
7. Determine dynamic stability conditions
8. Optimize control (Controller gains)
9. *Perform enterprising optimization*
10. *Minimize information flow and energy storage*

Secure Scalable Microgrid (SSM) Testbed Enables Hardware Testing of HSSPFC

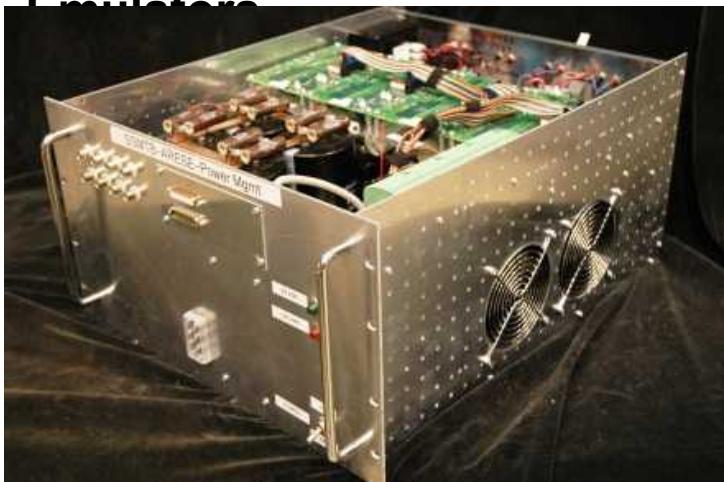
Multiple Microgrid Testbed



Mechanical Source



Energy Storage Emulators

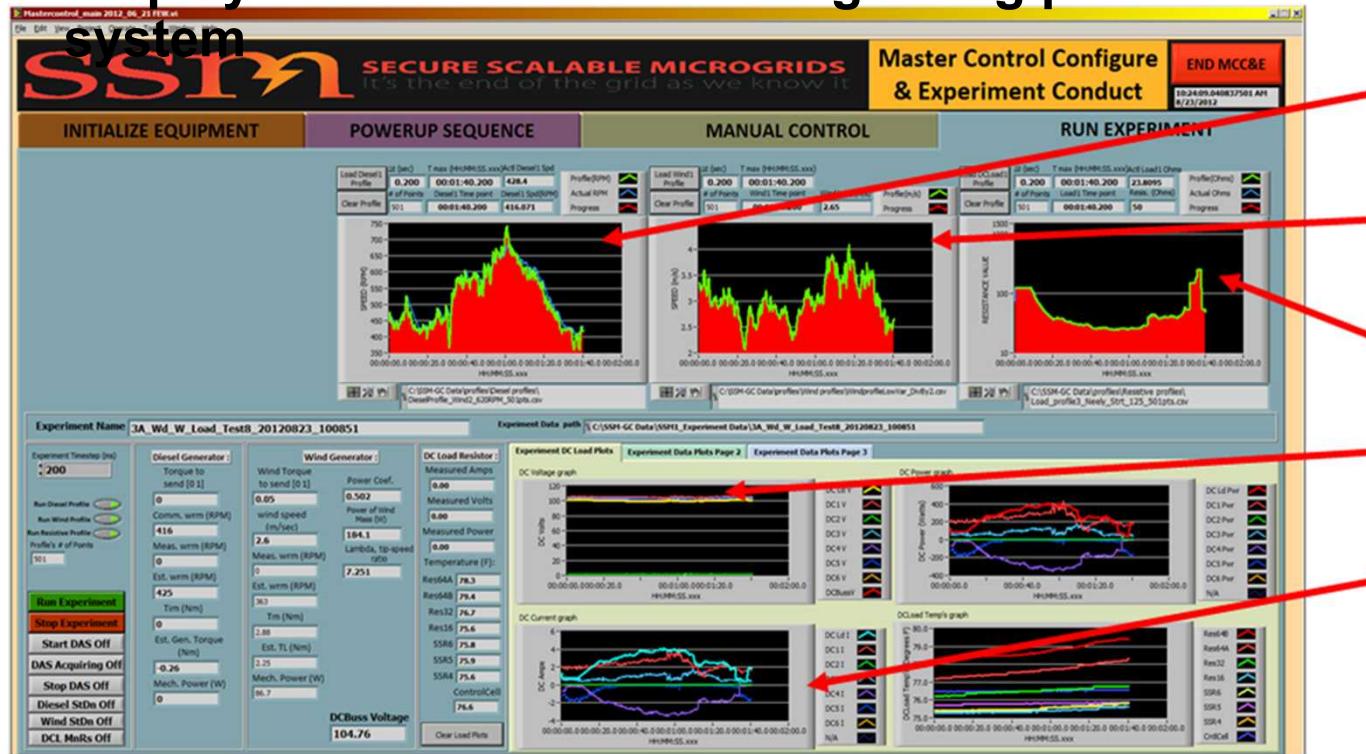


High Power Digital Resistor – Load Bank



SSM Master Controller Coordinates HSSPFC Control Experiments

- User interface allows coordinated start and end for experimental runs
- Allows specification of input profiles for each microgrid component
- Displays real-time feedback regarding performance of the energy system



Emulator Profile 1

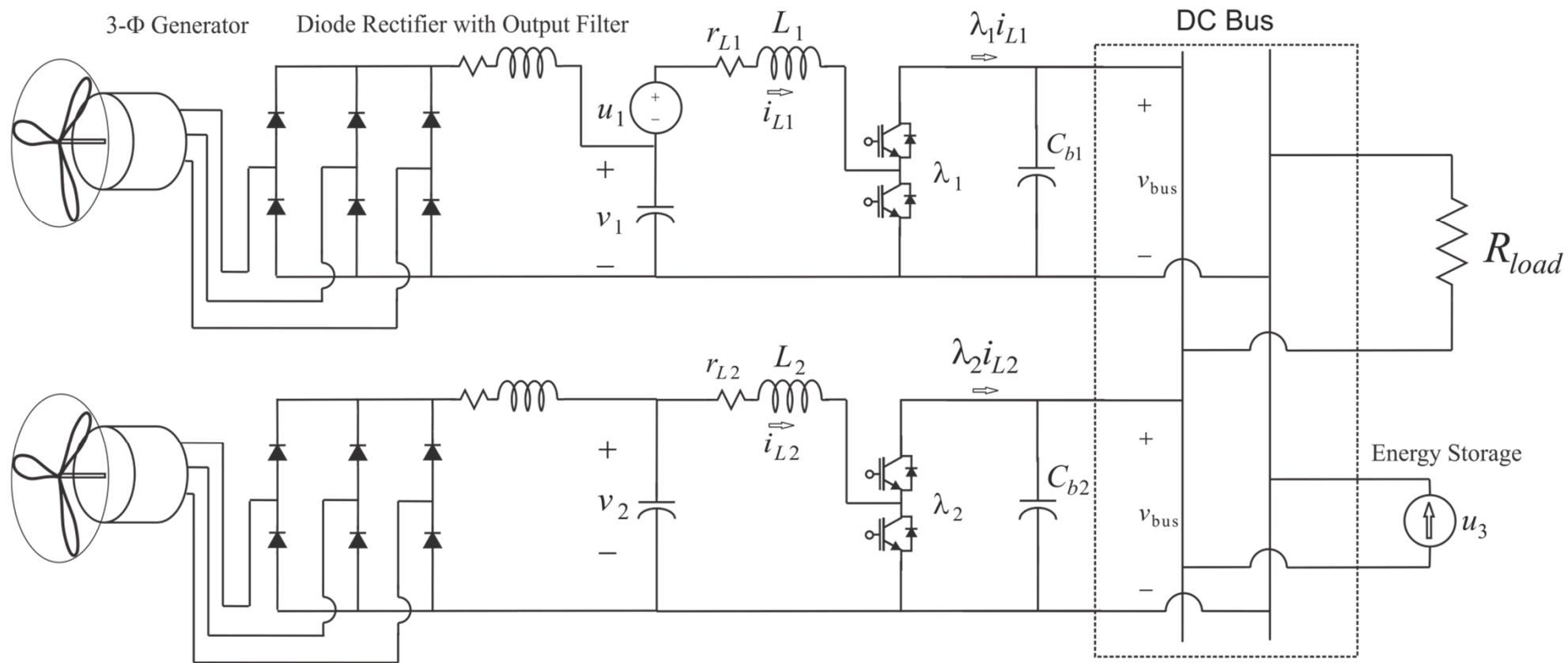
Emulator Profile 2 (m/s)

Digital Resistor (Ω)

Bus voltage (V)

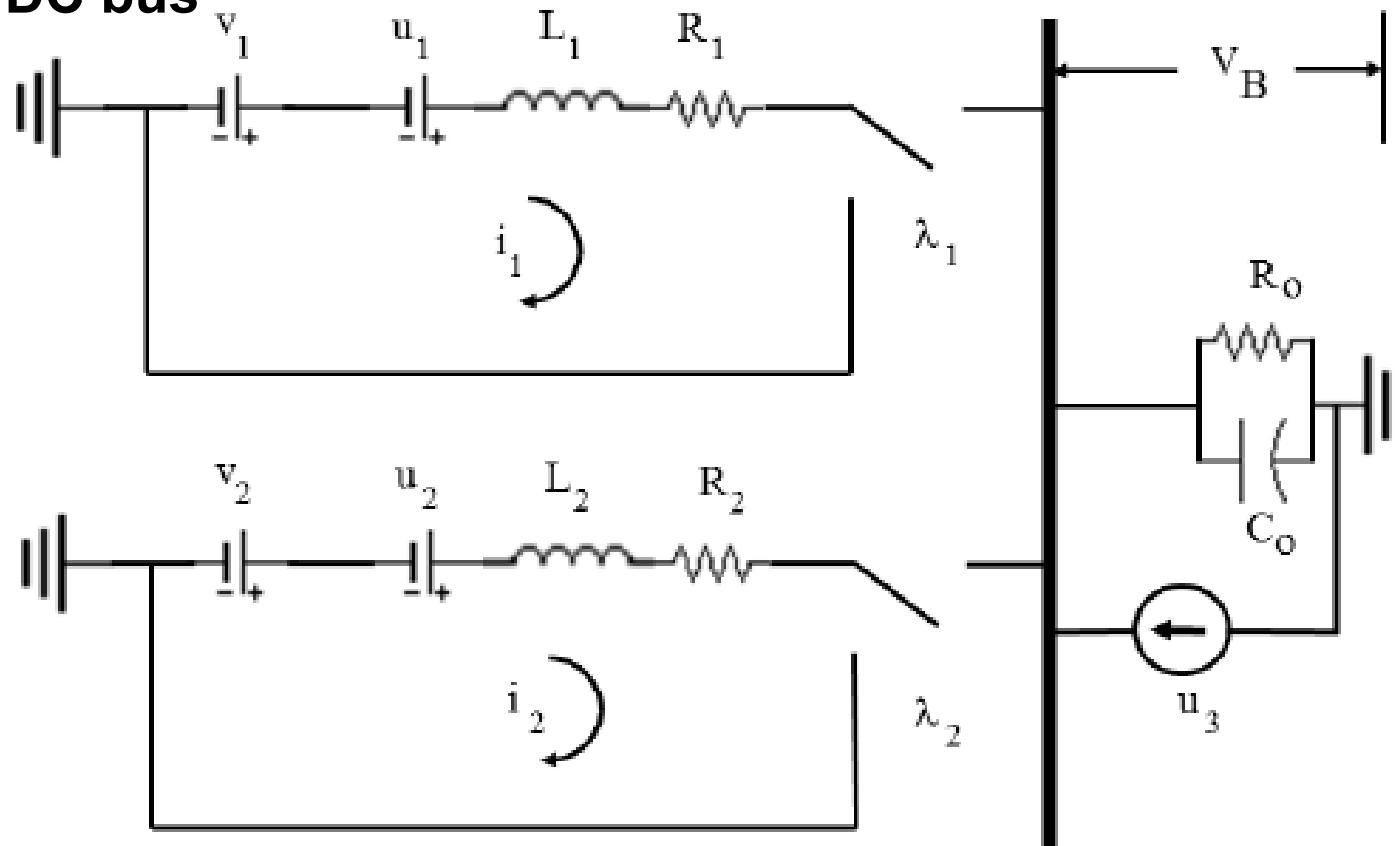
Currents into bus (A)

A Single DC Microgrid Configuration with Two Stochastic Sources Studied



A Simplified Circuit Model is Used for HSSPFC Control Development

- Supports representation of multiple boost converters on a single DC bus



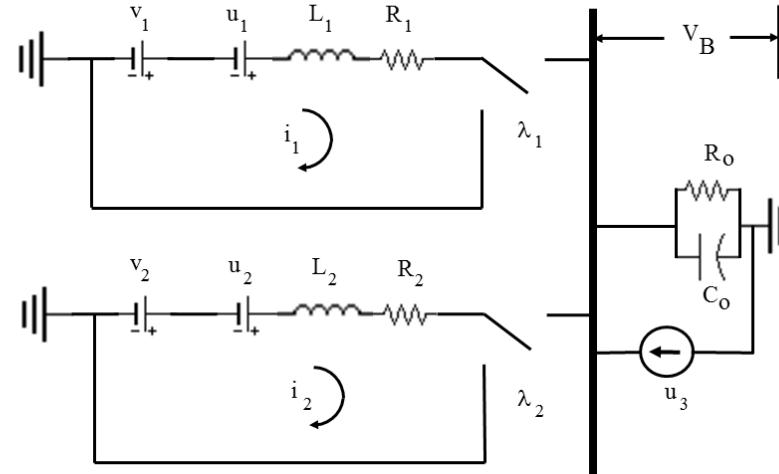
DC Microgrid Model: 2 Boost Converters with Voltage Sources

- Circuit equations for 2 boost converters and DC bus:

$$L_1 \frac{di_{L_1}}{dt} = -R_1 i_{L_1} - \lambda_1 v_{bus} + v_1 + u_1$$

$$L_2 \frac{di_{L_2}}{dt} = -R_2 i_{L_2} - \lambda_2 v_{bus} + v_2 + u_2$$

$$C_t \frac{dv_{bus}}{dt} = \lambda_1 i_{L_1} + \lambda_2 i_{L_2} - G_L v_{bus} + u_3$$



Note: u_1 , u_2 , u_3 are what generate specs (power, energy, frequency)

- Represented in matrix form as:

$$\begin{bmatrix} L_1 & 0 & 0 \\ 0 & L_2 & 0 \\ 0 & 0 & C_t \end{bmatrix} \begin{Bmatrix} \dot{i}_{L_1} \\ \dot{i}_{L_2} \\ \dot{v}_{bus} \end{Bmatrix} = \begin{bmatrix} -R_{L_1} & 0 & -\lambda_1 \\ 0 & -R_{L_2} & -\lambda_2 \\ \lambda_1 & \lambda_2 & -G_L \end{bmatrix} \begin{Bmatrix} i_{L_1} \\ i_{L_2} \\ v_{bus} \end{Bmatrix} + \begin{Bmatrix} v_1 \\ v_2 \\ 0 \end{Bmatrix} + \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \end{Bmatrix}$$

- or compactly as:

$$\dot{Mx} = Rx + v + u = [\bar{A}(R_{load}) + \tilde{A}(\lambda)]x + v + u$$

Where R matrix is written as a diagonal matrix $\bar{A}(R_{load})$ and a skew-symmetric, $\tilde{A}(\lambda)$

HSSPFC Controller is Designed for Energy Storage

- Error state defined along with reference state vector:

$$e = \tilde{x} = x_{ref} - x$$

$$M\dot{x}_{ref} = [\bar{R} + \tilde{R}]x_{ref} + v + u_{ref}$$

- Assume reference state vector is constant and reference control becomes:

$$u_{ref} = -[\bar{R} + \tilde{R}]x_{ref} - v \quad (1)$$

- Next step define the Hamiltonian as:

$$H = \frac{1}{2} \tilde{x}^T M \tilde{x} + \frac{1}{2} \left(\int \tilde{x} dt \right)^T K_I \left(\int \tilde{x} dt \right)$$

Static stability condition

- About $\tilde{x} = 0$
- With $K_I > 0$ and positive definite controller gain matrix

HSSPFC Controller is Designed for Energy Storage

- The Hamiltonian time derivative or power flow becomes:

$$\dot{H} = \tilde{x}^T \dot{M} \tilde{x} = \tilde{x}^T [M \dot{x}_{ref} - M \dot{x}] + \tilde{x}^T K_I \int \tilde{x} dt$$

$$\dot{H} = \tilde{x}^T \bar{R} \tilde{x} + \tilde{x}^T \Delta u + \tilde{x}^T K_I \int \tilde{x} dt$$

- where

$$\tilde{x}^T \bar{R} \tilde{x} = 0$$

- and

$$\Delta u = u_{ref} - u$$

HSSPFC Controller is Designed for Energy Storage

- Next step, select a PI controller as:

$$\begin{aligned}\Delta u &= -K_P \tilde{x} - K_I \int \tilde{x} dt \\ u &= u_{ref} - \Delta u\end{aligned}\tag{2}$$

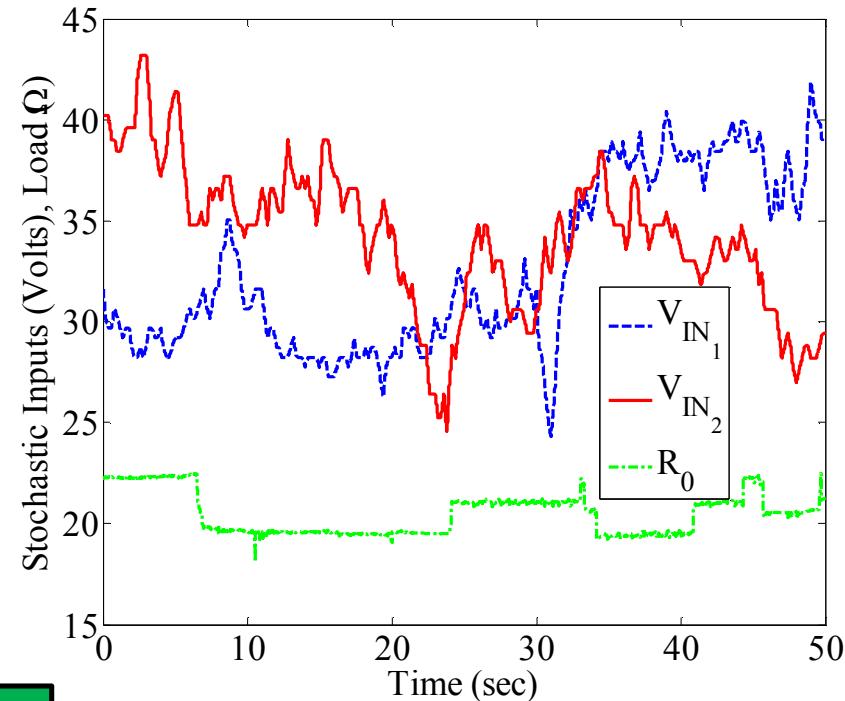
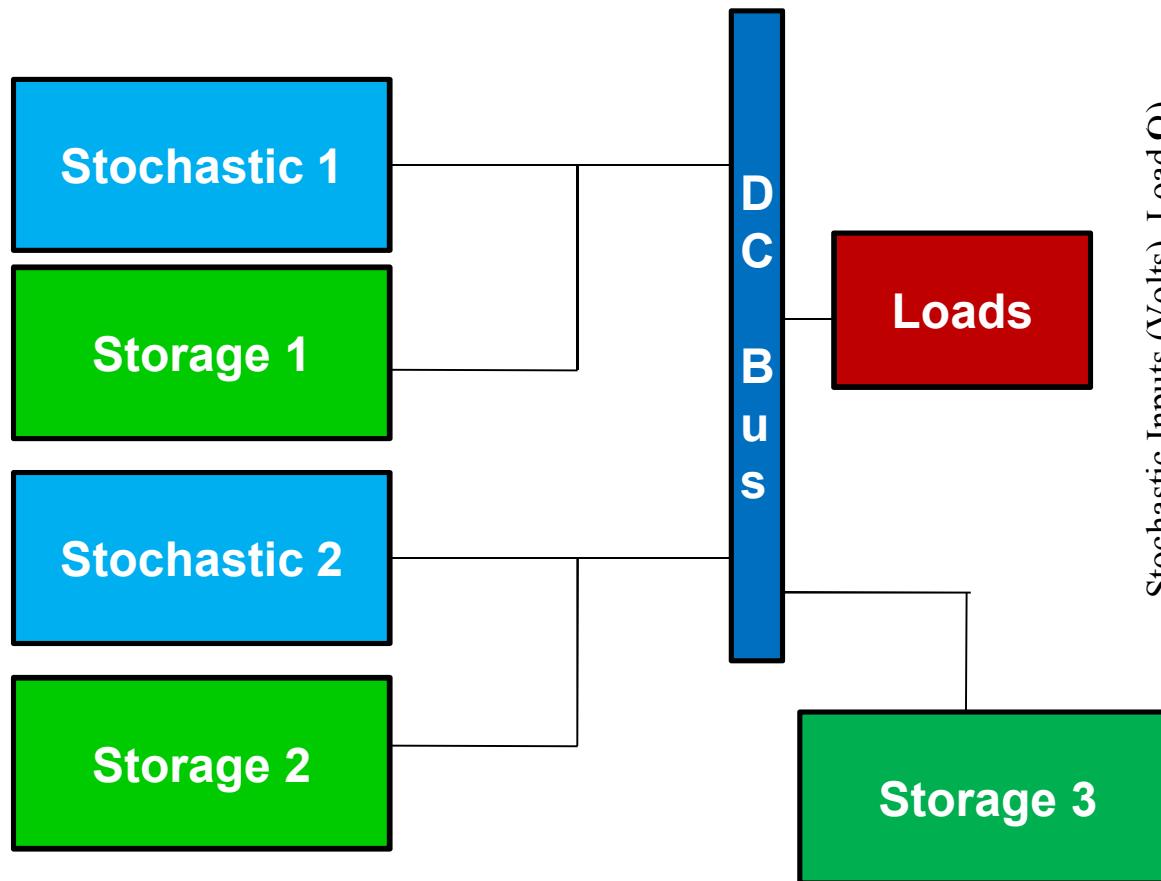
- Substitute and simplify leads to:

$$\begin{aligned}\dot{H} &= \tilde{x}^T [\bar{R} - K_P] \tilde{x} < 0, \\ -\tilde{x}^T [K_P - \bar{R}] \tilde{x} &< 0\end{aligned}$$

Dynamic stability condition

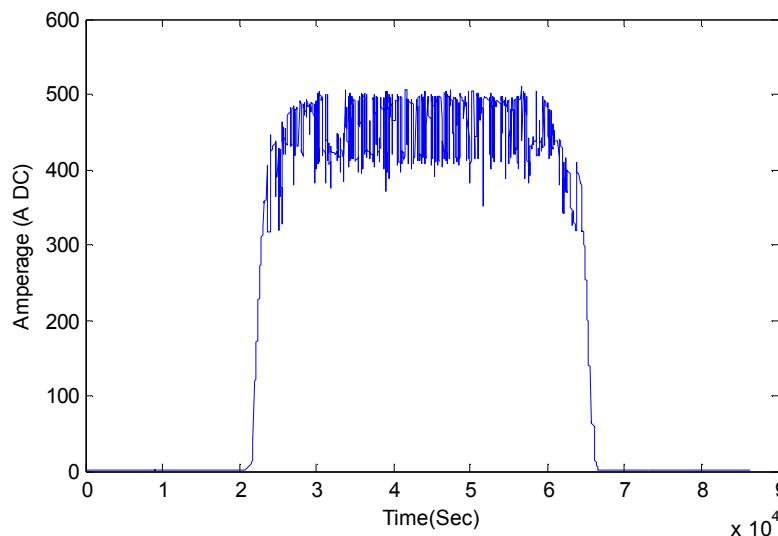
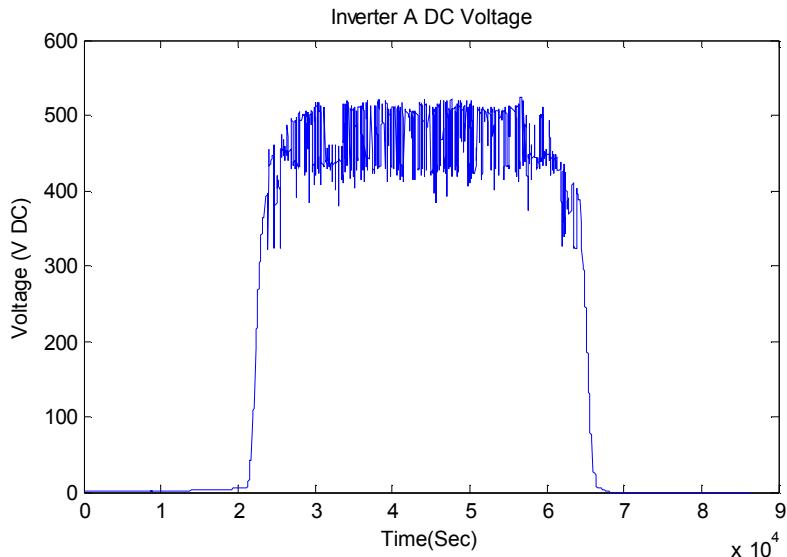
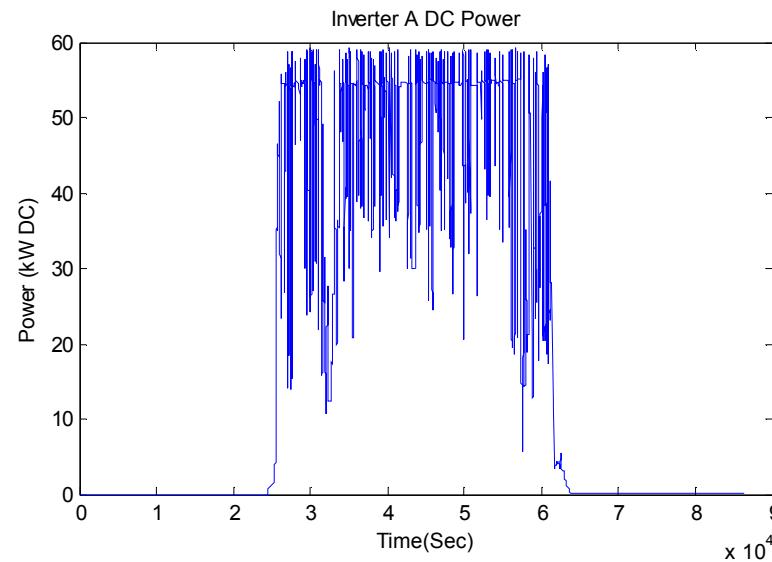
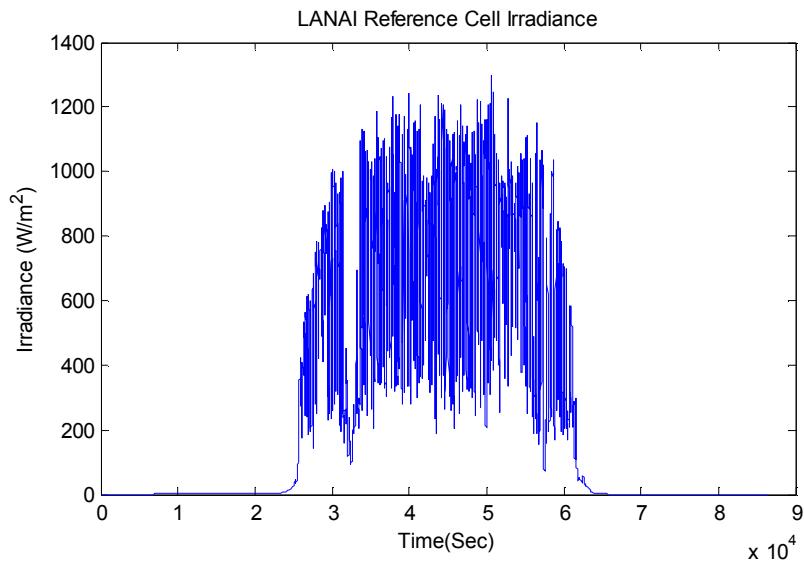
- With $K_P > 0$ positive definite controller gain matrix

HSSPFC Implementation Scenario



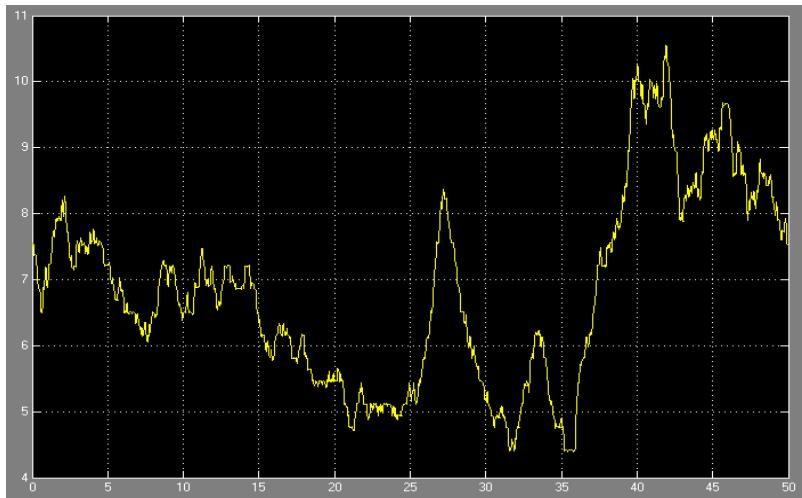
- 2 Variable Generators
- 3 Energy Storage
- Variable Loads

PV Data Lanai, Hawaii Microgrid System

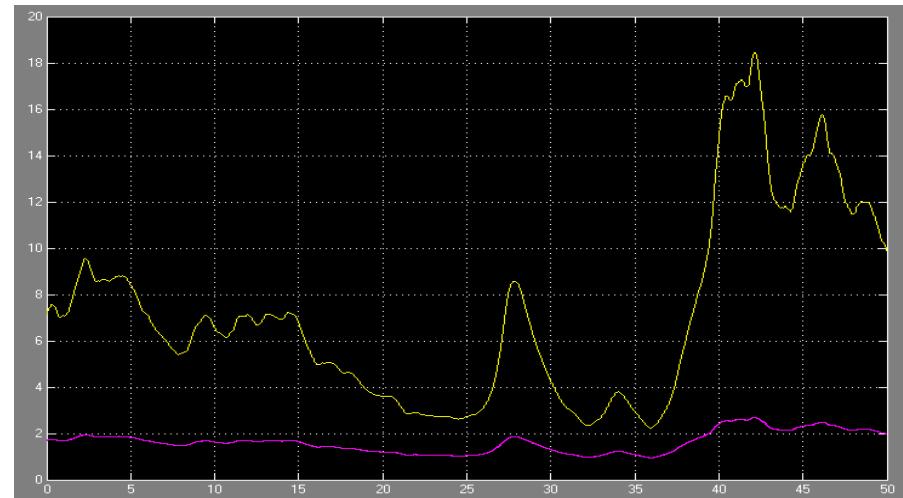


Variable Speed Wind Turbine Utilizing Bushland, Texas Test Site Data

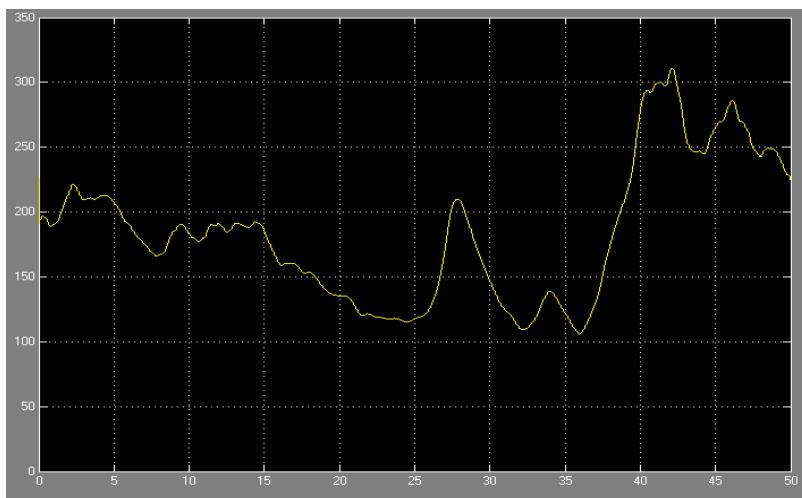
Wind Speed (m/s) *data from Bushland test site*



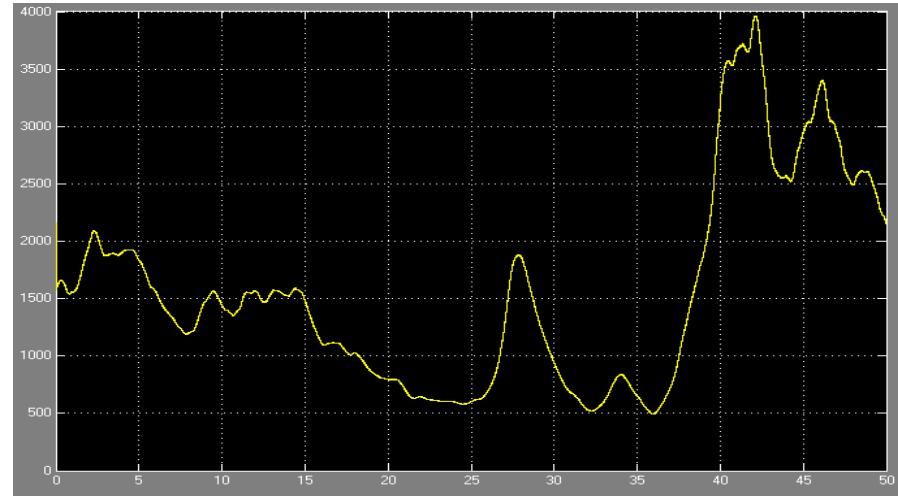
d and q axis currents (Amps)



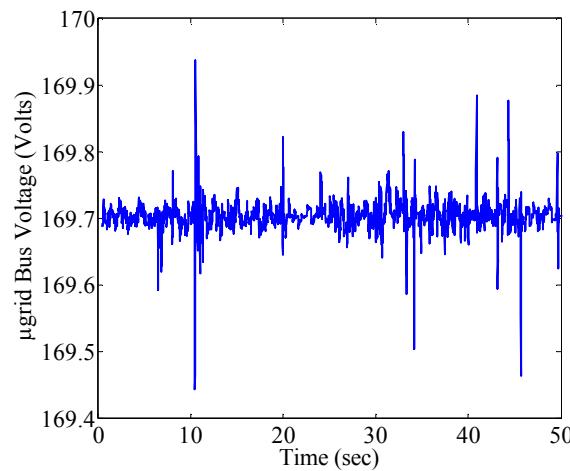
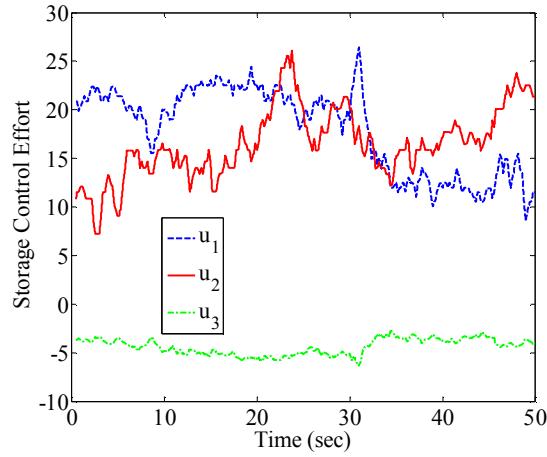
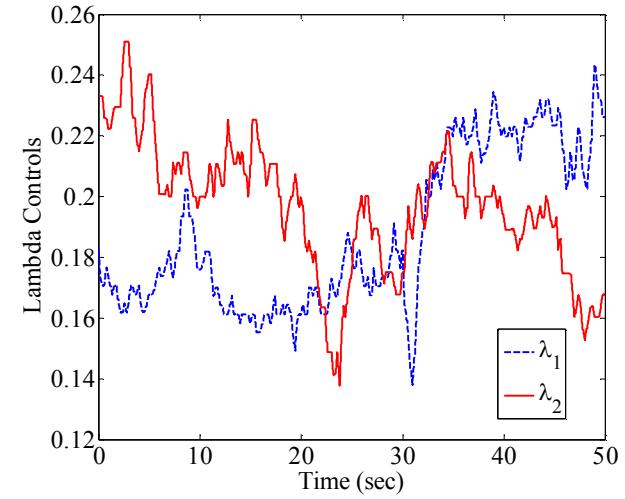
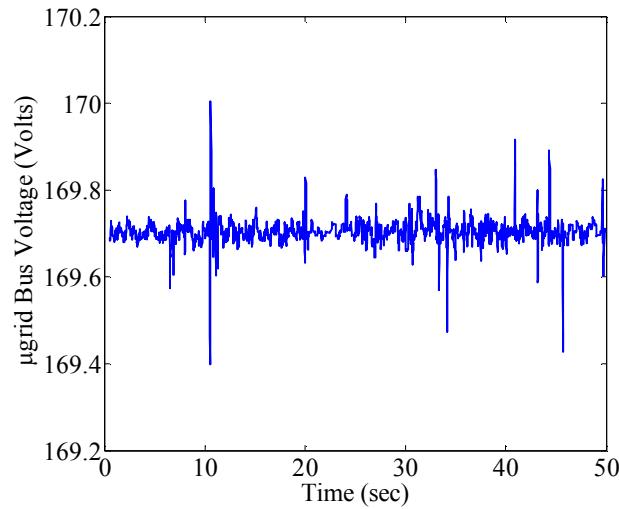
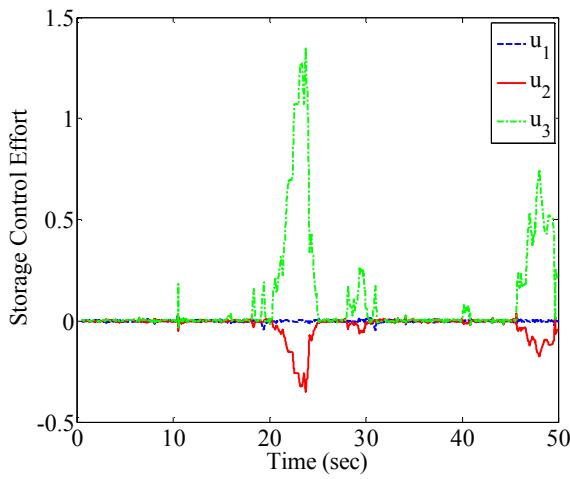
Rotor speed (RPM)



Real Power Out (W)



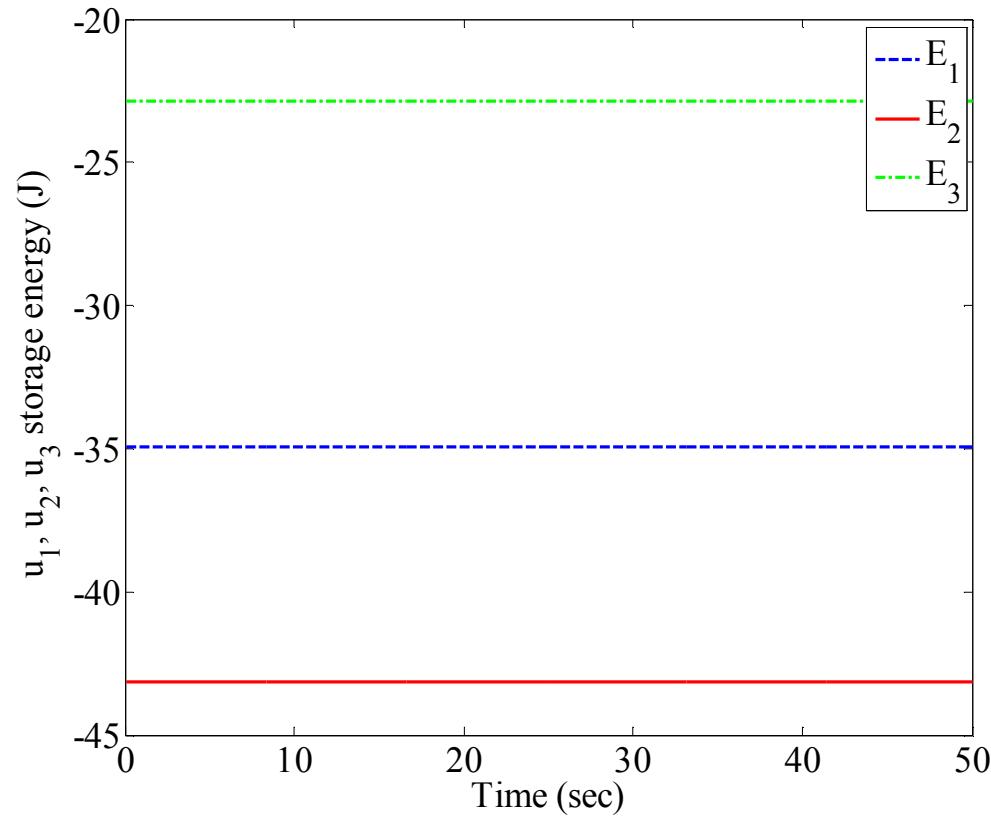
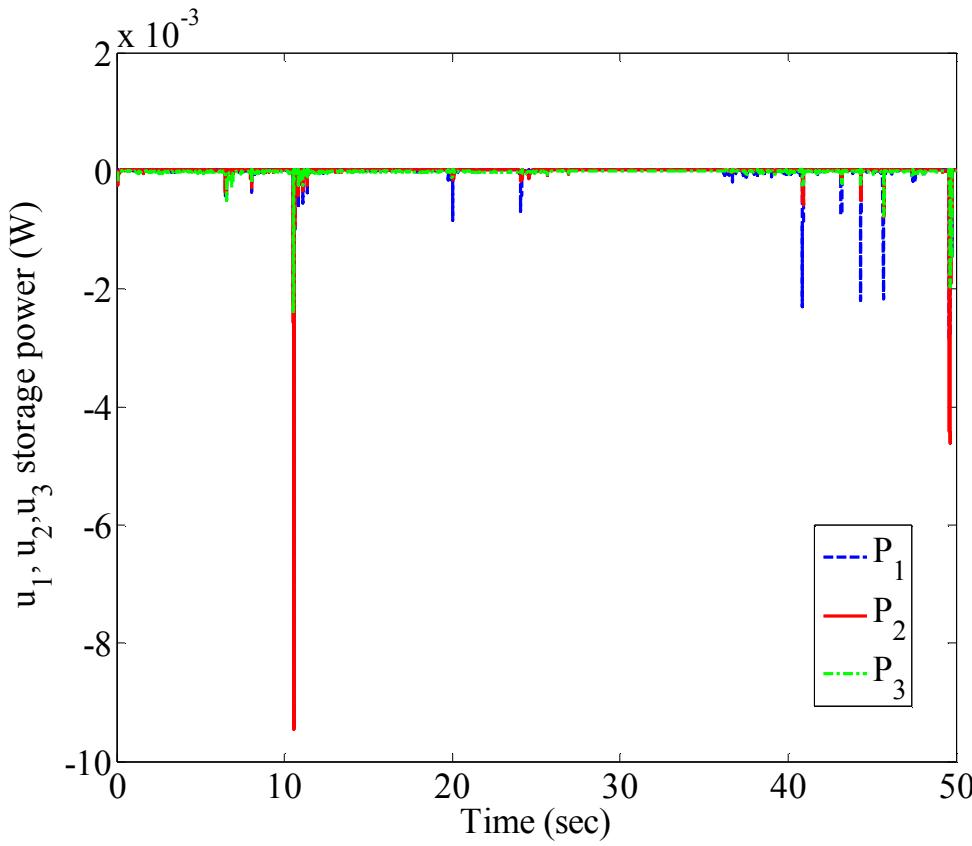
HSSPFC Results Contrasting Duty Cycle (Information Flow) vs Energy Storage Demands



Lambda_1 = 0.2937 constant
Lambda_2 = 0.2935 constant

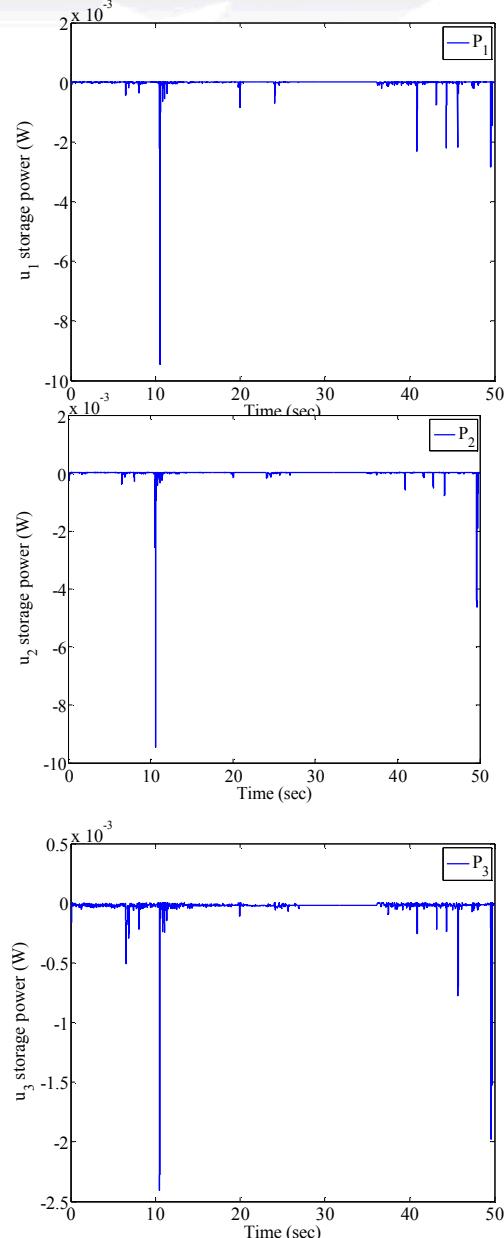
Energy Storage Requirements Scenario

- Power Requirements
- Energy Requirements
- Frequency Response Requirements (see next chart for individual channels)

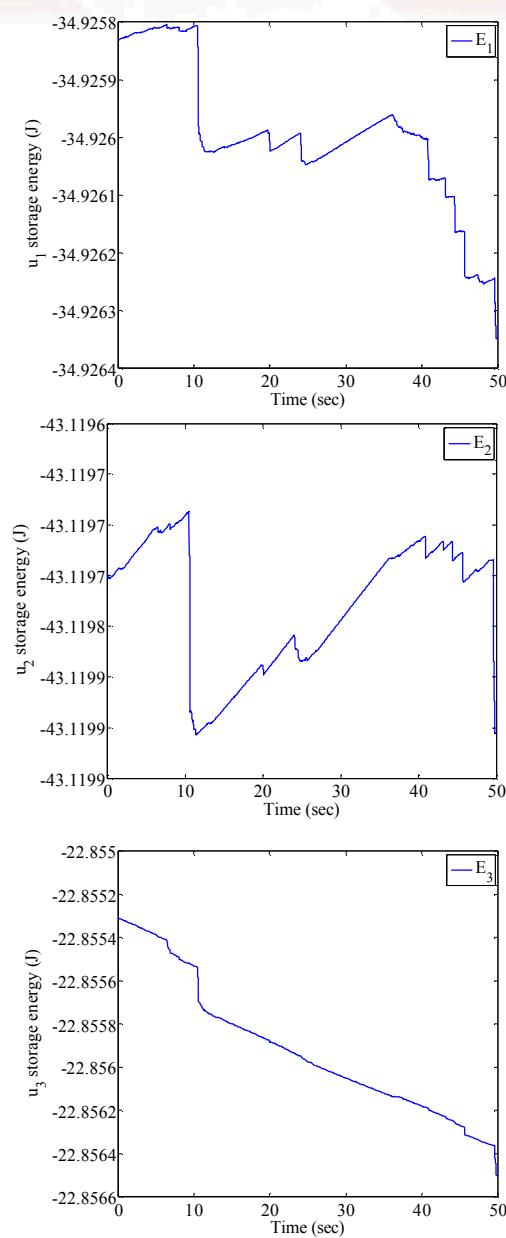


Specifications for the microgrid and/or UPFC based on:
(Power, Energy, Frequency PSDs)

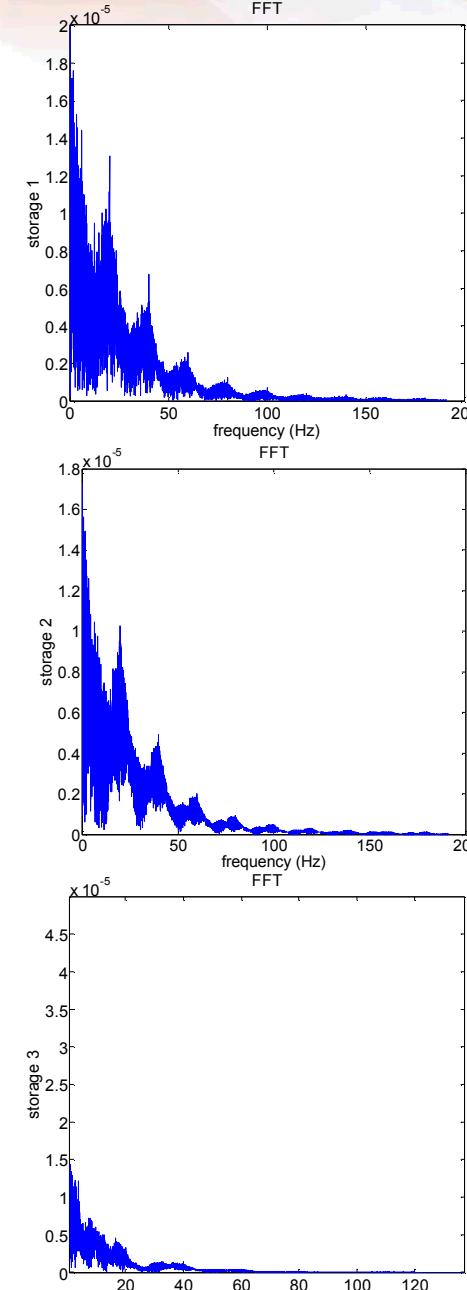
Example Energy Storage Requirements Scenario



Power Requirements
(requirements displayed for each channel - along the row)



Energy Requirements
(requirements displayed for each channel - along the row)



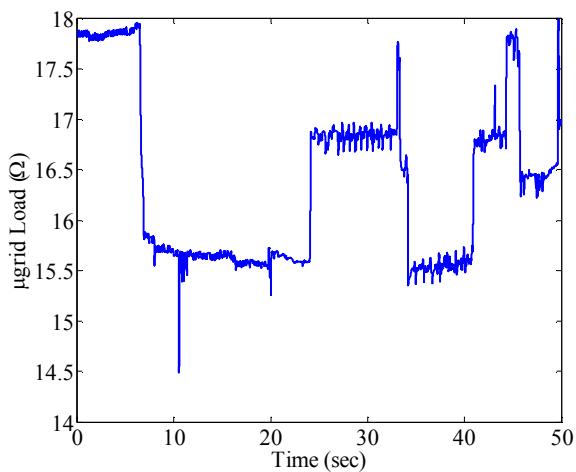
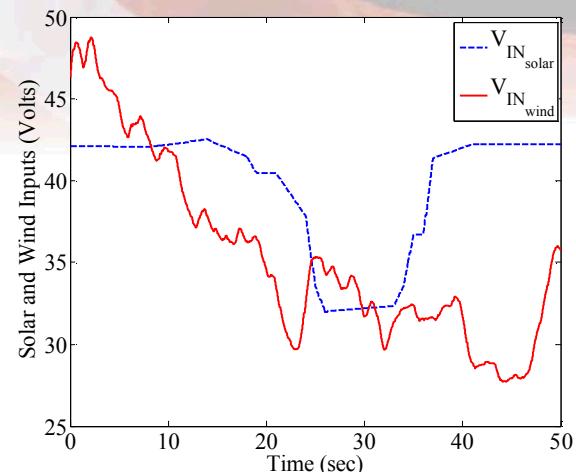
DC Boost 1

DC Boost 2

DC Bus

Real-Time Validation

- **Variable Sources and Loads**
- **Trade-offs (information flow vs energy storage)**
 - **0% energy storage (zero controls)** **baseline high computational requirements** **on duty cycle (information flow)**
 - **100% energy storage (require high dimension), however information flow is low**
 - **Compromise determined from trade-offs**
- **Opal-RT real-time digital simulator** utilized to prototype scenarios and packet protocols required for real time
- Handle high computational requirements
- Interface with agent-based control
- Interlace algorithms between low and high level priorities
- Interface with SSM testbed hardware



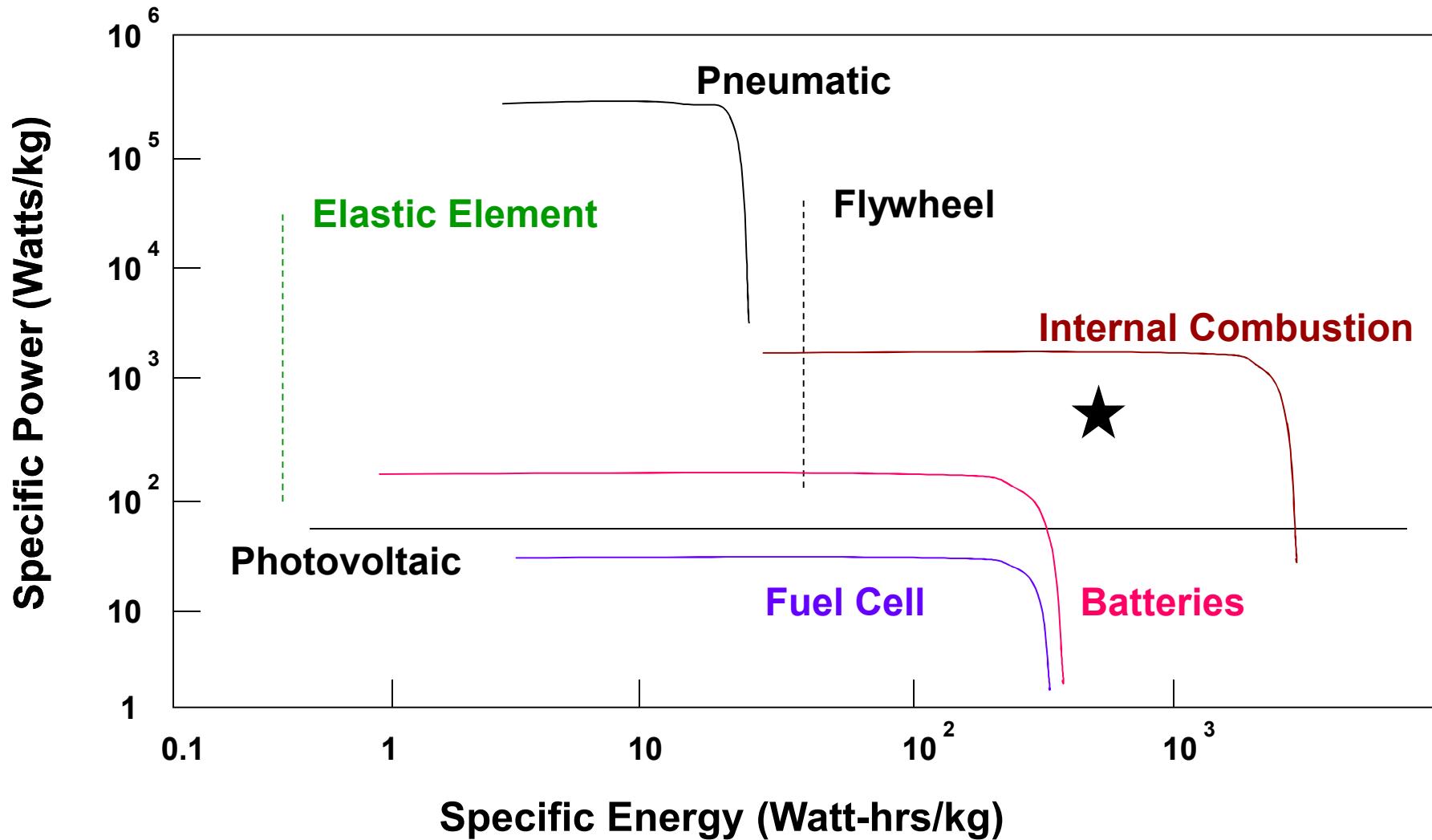
Energy Storage

- We are characterizing various energy storage modalities to enable us to optimize the choice of the montage for particular microgrid use scenarios
- There are many varying competing needs
- There are many energy storage modalities

Strengths, Weaknesses, and Roles of Various Energy Storage Devices Summary

- A bewildering array of energy storage devices are available for microgrid energy and power management; batteries, capacitors, flywheels, hydro, gas
- Each modality has strengths and weaknesses in cost, energy density, life, frequency response, efficiency, power, discharge time, etc.
- There is no single “best” energy storage device, even for well posed use scenarios
 - *Frequency regulation, peaking, and diurnal storage are all needed for a microgrid*
- Optimization of the *montage* of energy storage devices *to the microgrid use scenario* is key

Impedance/Capacity Mismatch (Duty Cycle) Ragone Plot



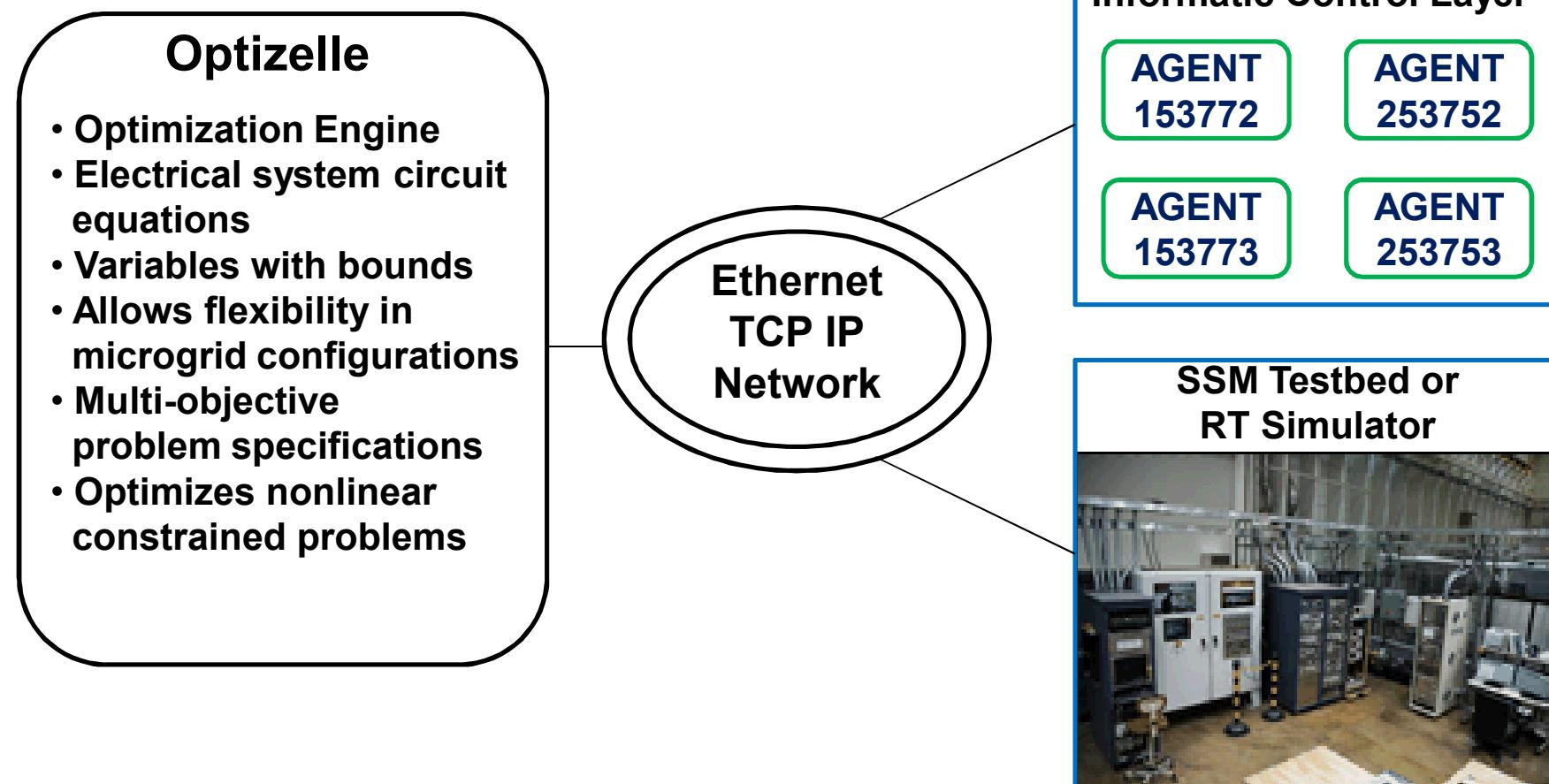
Performance comparison of various energy-storing devices

Optizelle uses a Model-Based Formulation

- **Guidance (duty cycle, set-points) algorithm utilizes single DC microgrid model**
 - 1) steady-state solution
 - 2) dynamic optimization formulation
- **General formulations identified for the following microgrid configurations:**
 - Single DC microgrid: Multiple boost converters on single DC bus
 - Multiple DC microgrid: Multiple boost converters on multiple DC buses connected by multiple DC transmission lines
 - Multiple AC microgrid: Multiple three phase inverters on multiple AC buses connected by multiple DC transmission lines
- **Concrete optimization codes developed using Optizelle for above formulations**

A Dynamic Optimizer/Planner Computes Optimal Operating Points

- SSM Testbed controllers send periodic measurements to the Informatic Control Layer
- The Informatic Control Layer sends optimization parameters to Optizelle based on measurements and system objectives
- Optizelle returns optimal reference points that are used by the Informatic Control Layers to drive low level controllers



Single DC Microgrid Optimization Problem is Defined

$$\begin{array}{ll}\min & \frac{w_1}{2} \|\dot{\lambda}\|^2 + \frac{w_2}{2} \|u\|^2 + \frac{w_3}{2} i^T \text{Diag}(R)i + \frac{w_4}{2} (x^T u)^2 \\ \text{st} & M\dot{x} = [\bar{R} + \tilde{R}(\lambda)]x + v + u \quad \text{Circuit equations,} \\ & x = \begin{bmatrix} i \\ v_B \end{bmatrix} \quad \text{Definition of } x, \\ & x = x_0 + \Delta t \dot{x} \quad \} \quad \text{Discretization,} \\ & \lambda = \lambda_0 + \Delta t \dot{\lambda} \quad \} \\ & i_{\min} \leq i \leq i_{\max} \quad \} \\ & u_{\min} \leq u \leq u_{\max} \quad \} \\ & \lambda_{\min} \leq \lambda \leq \lambda_{\max} \quad \} \end{array}$$

where

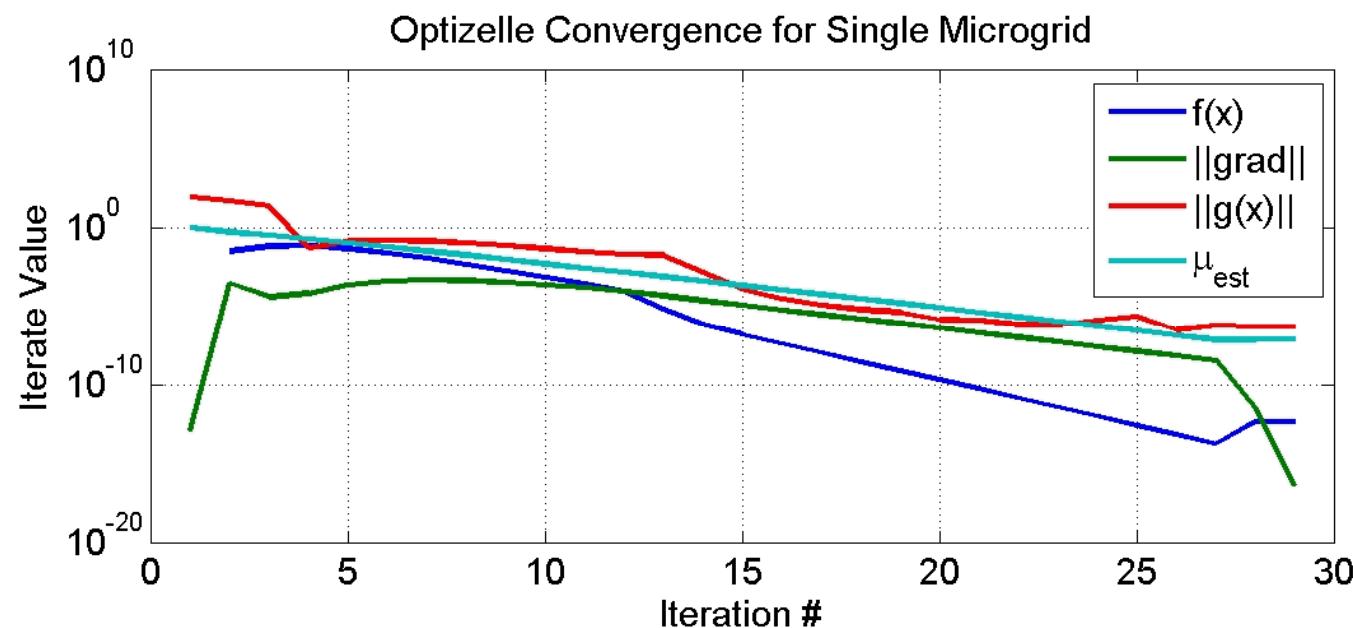
$$\bar{R} = \begin{bmatrix} -R_1 & & & & \\ & \ddots & & & \\ & & -R_d & & \\ & & & -1/R_o & \end{bmatrix}, \quad \tilde{R}(\lambda) = \begin{bmatrix} -\lambda_1 & & & \\ & \ddots & & \\ & & -\lambda_d & \\ \lambda_1 & \cdots & | & \lambda_d \end{bmatrix}$$

Optizelle Numerical Convergence Single Microgrid Results

Iter	f(x)	grad	dx	g(x)	mu_est
1	0.00e+00	1.29e-13	---	9.20e+01	1.00e+00
2	3.25e-02	3.12e-04	2.60e+02	5.29e+01	5.61e-01
3	7.30e-02	4.33e-05	8.50e+01	2.51e+01	3.33e-01
...					
27	1.90e-14	3.73e-09	3.05e+00	6.53e-07	7.66e-08
28	4.90e-13	3.64e-12	2.72e+01	5.37e-07	7.65e-08
29	4.91e-13	4.29e-17	9.11e-01	5.36e-07	7.65e-08

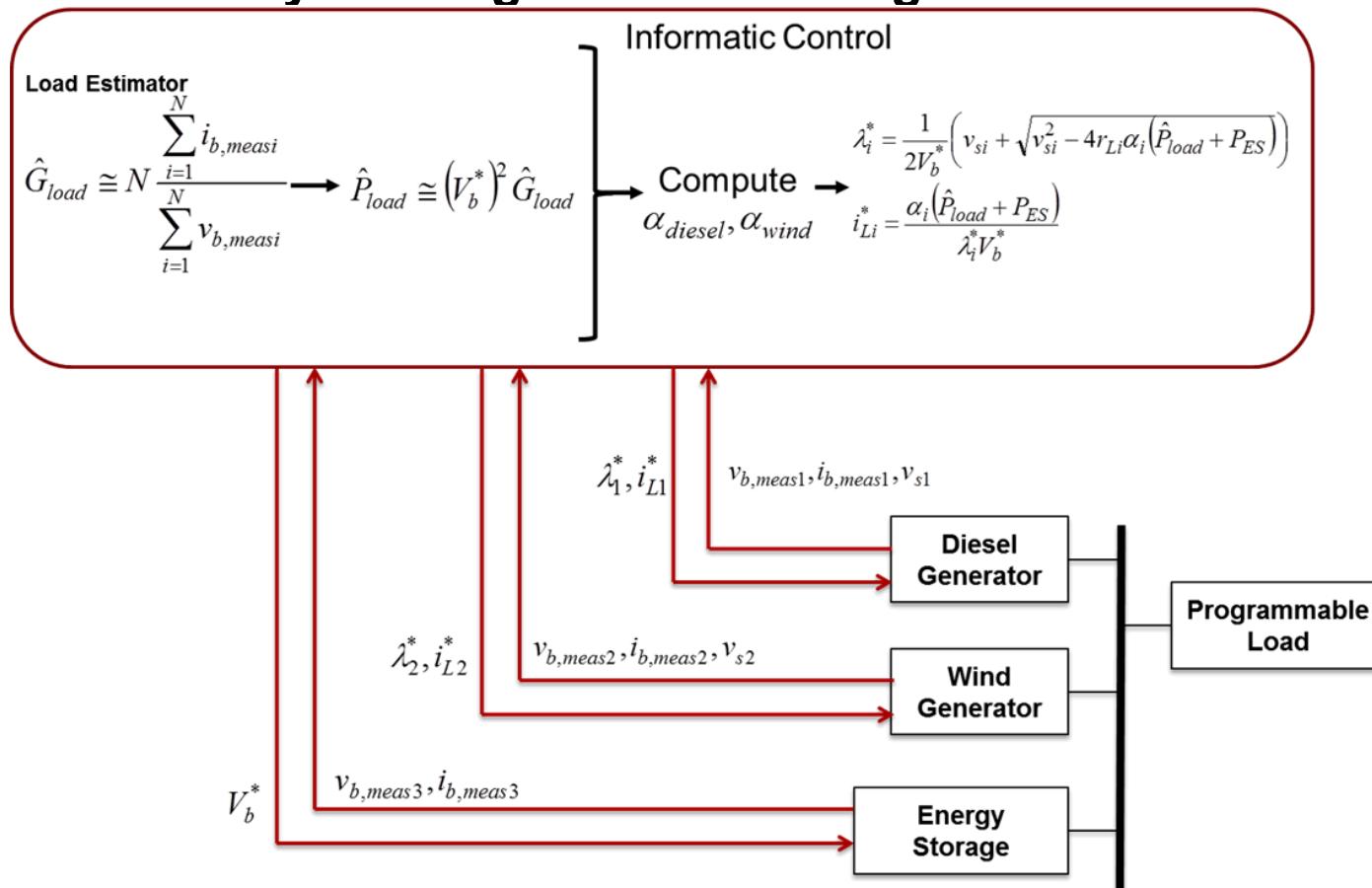
*Convergence time is affected by optimization input parameters

Optizelle NL MPC Optimizer Single DC Microgrid Convergence

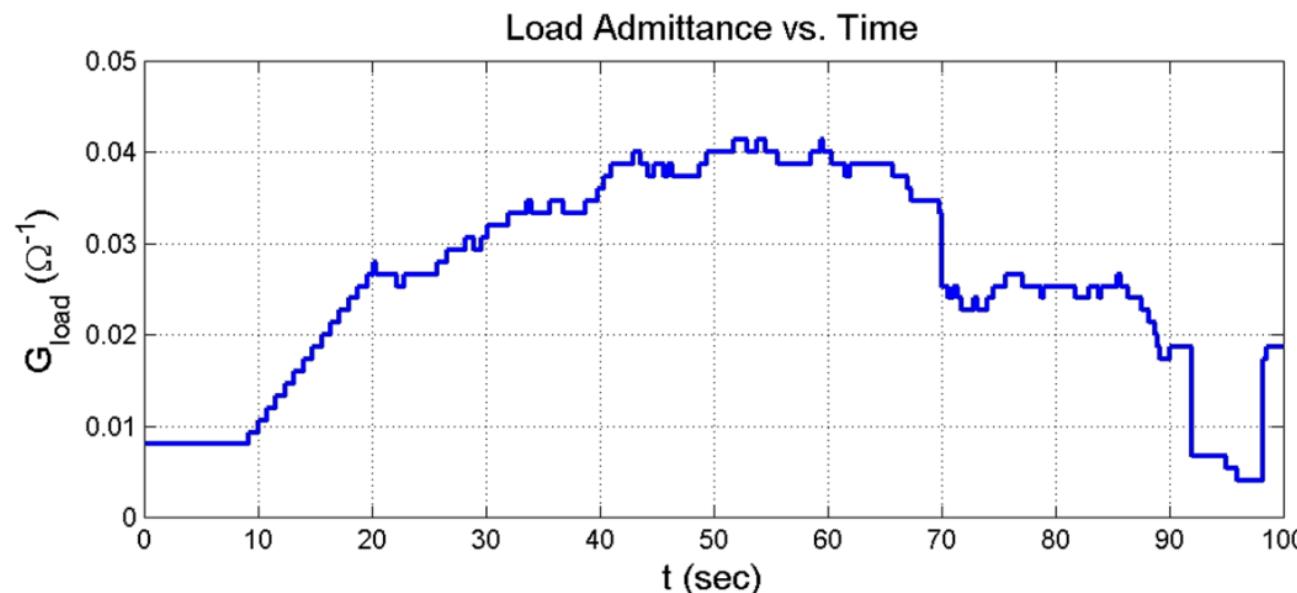
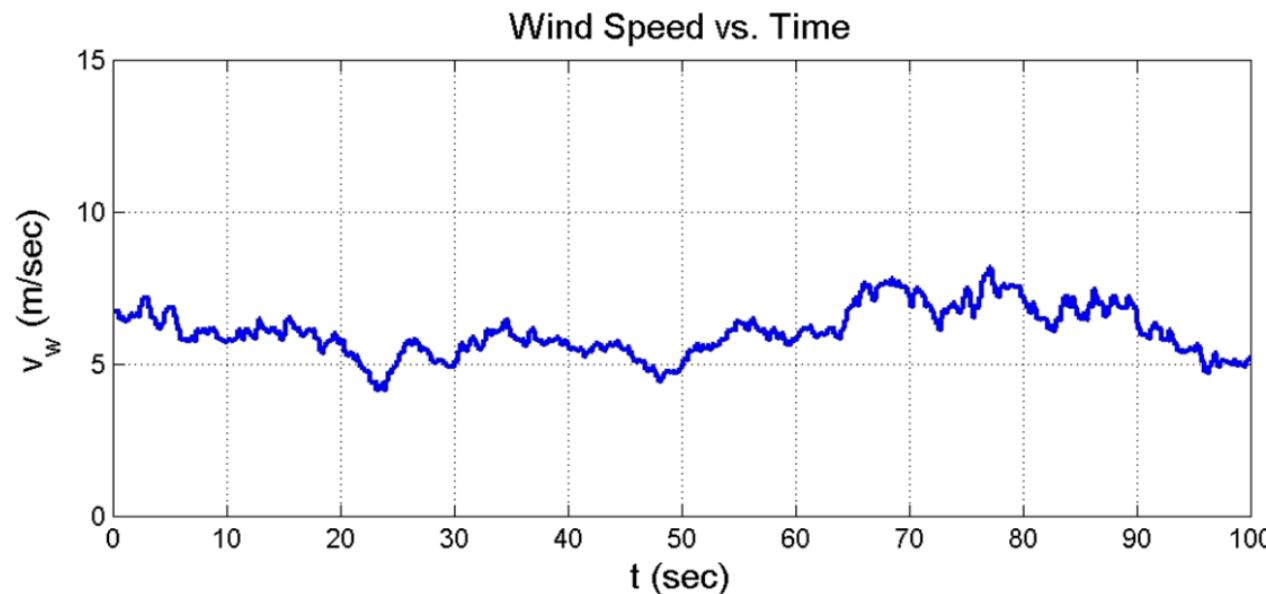


Trade-off between Information Flow and Energy Storage was Investigated

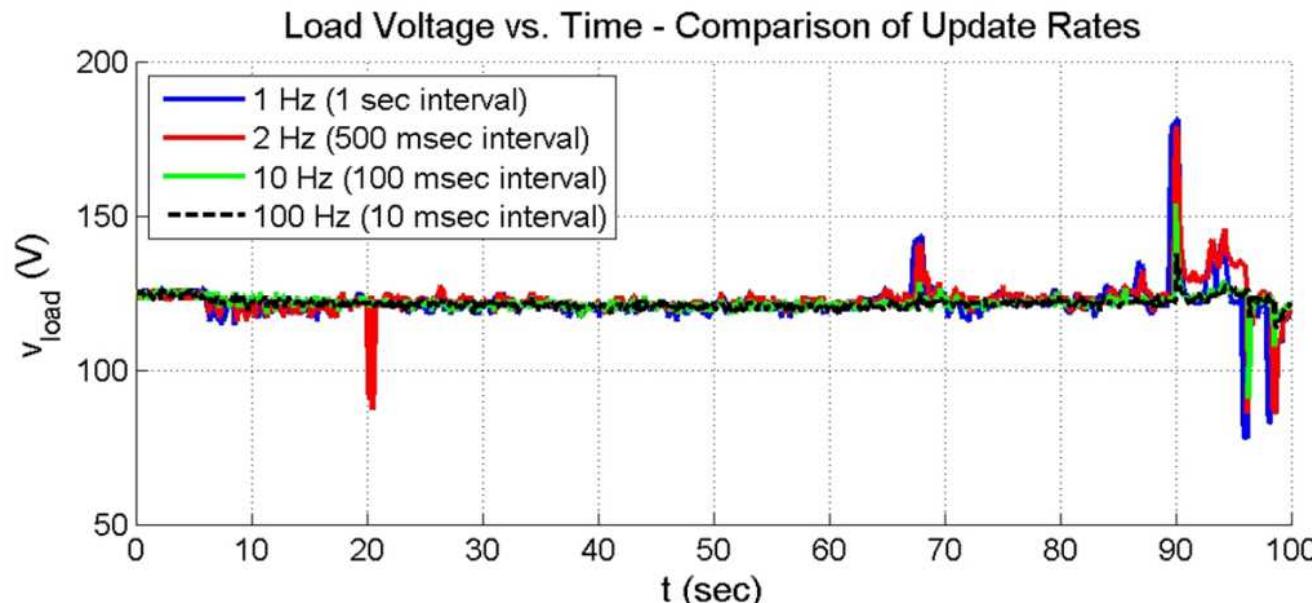
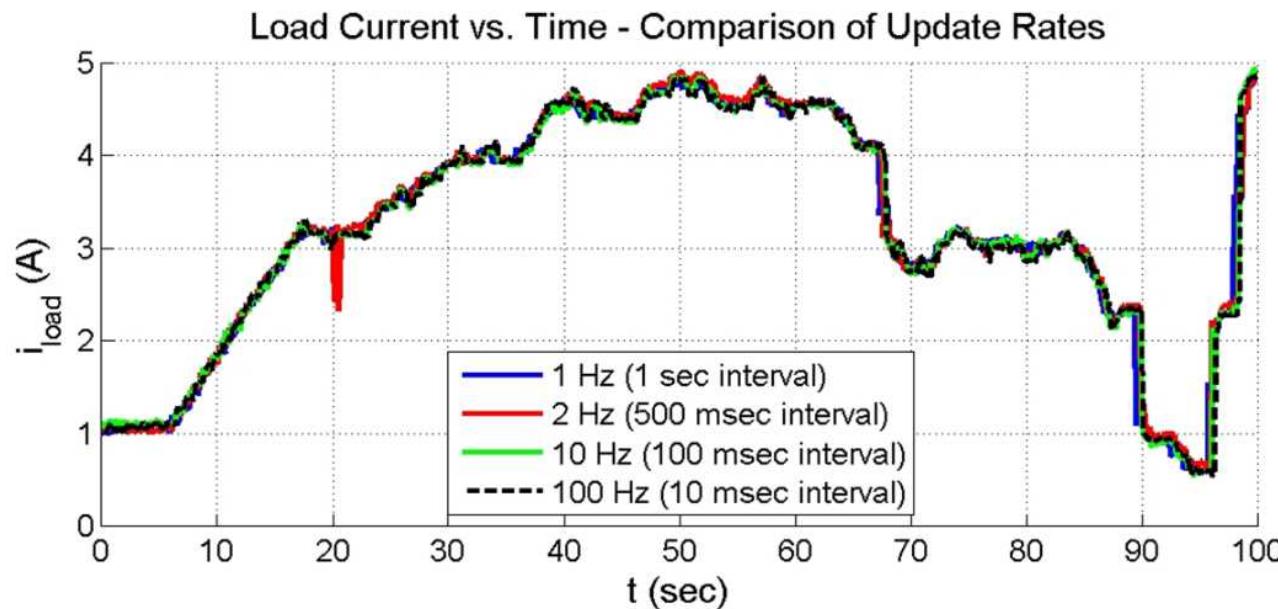
- Informatic control layer consolidates output current information from all sources and applies a filter to estimate load resistance
- Updates to duty cycles, reference currents, and energy storage reference inputs
- Without energy storage, system relies heavily on timely updates from Informatic control layer to regulate bus voltage



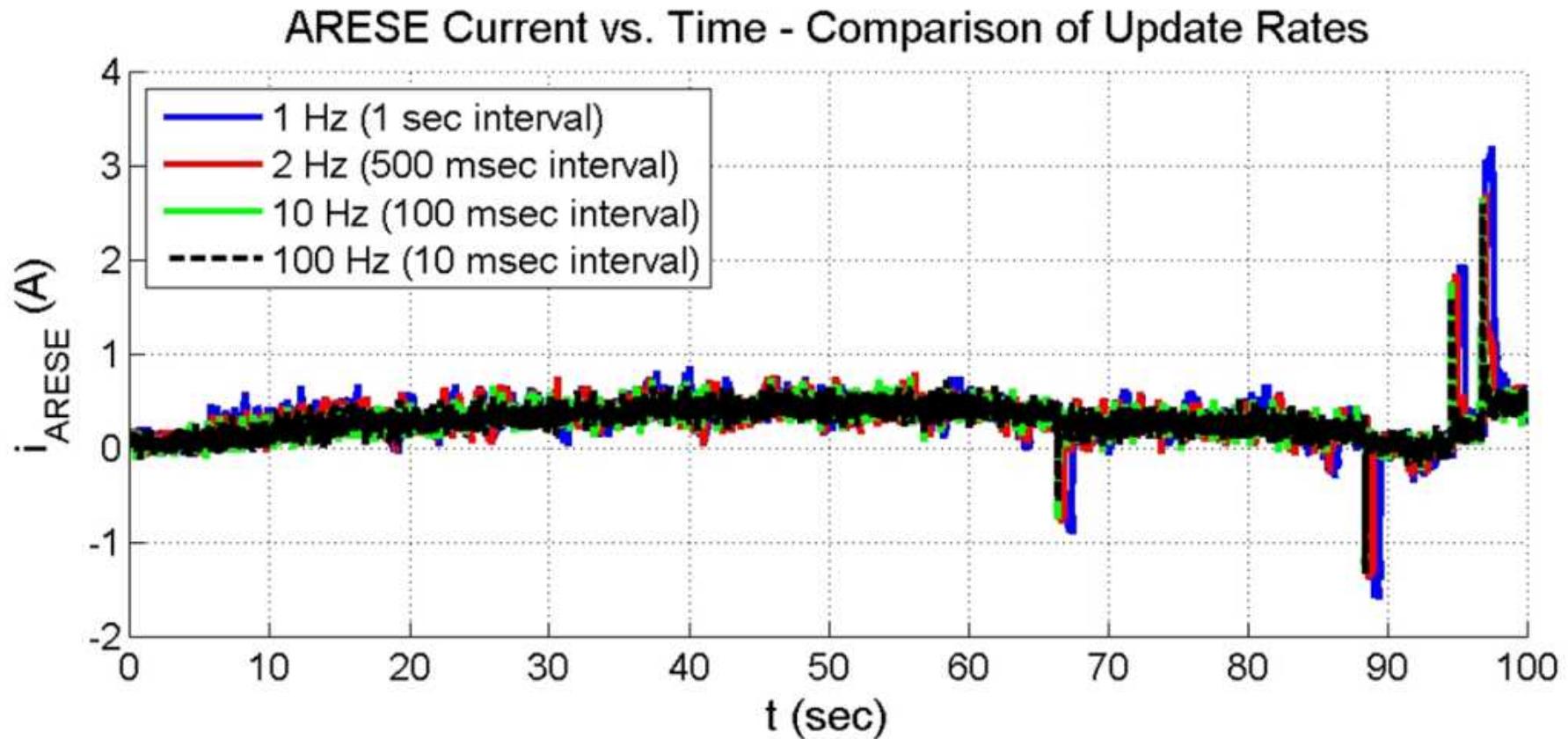
Communication Rate Without Energy Storage Experiment: Input Profiles



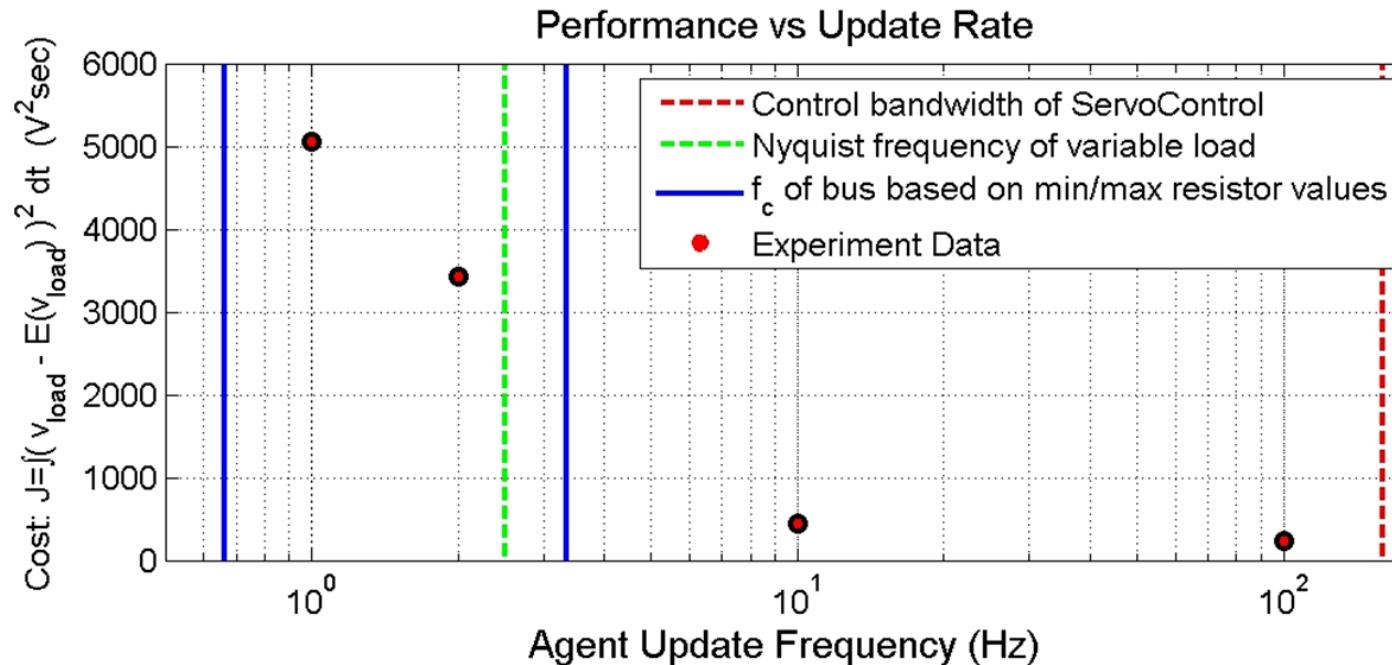
Communication Rate Affects System Performance



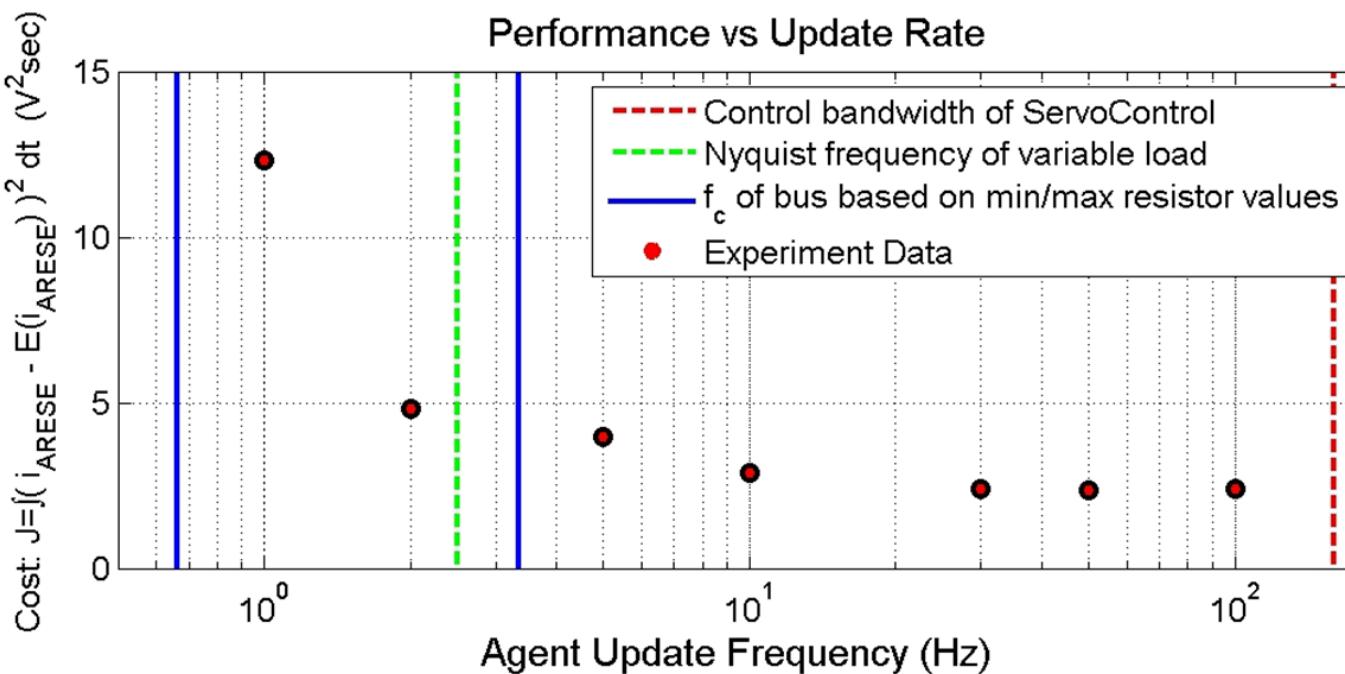
Communication Rate Affects Energy Storage Control Effort



Cost Function Values are Evaluated

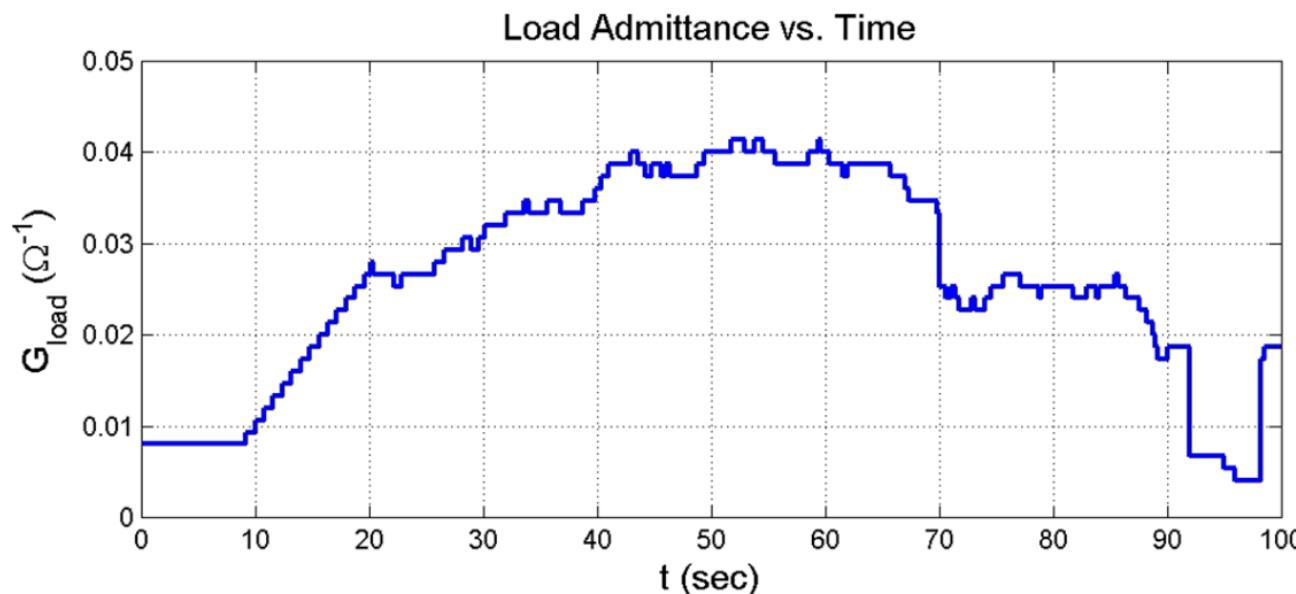
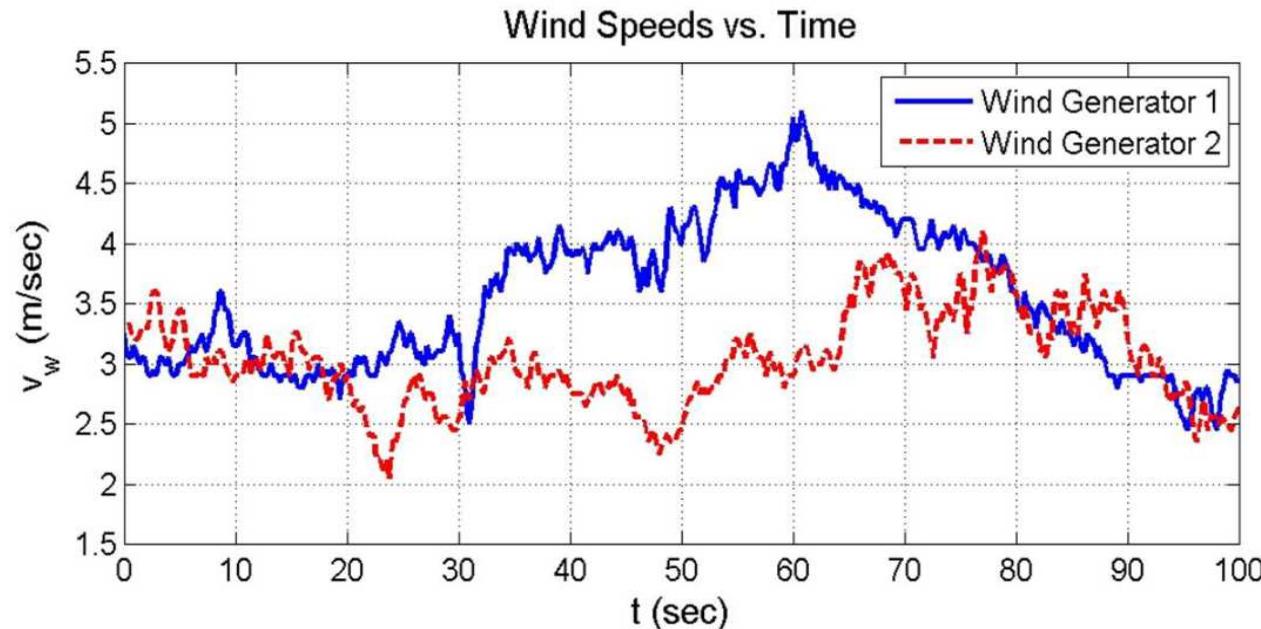


Without energy storage

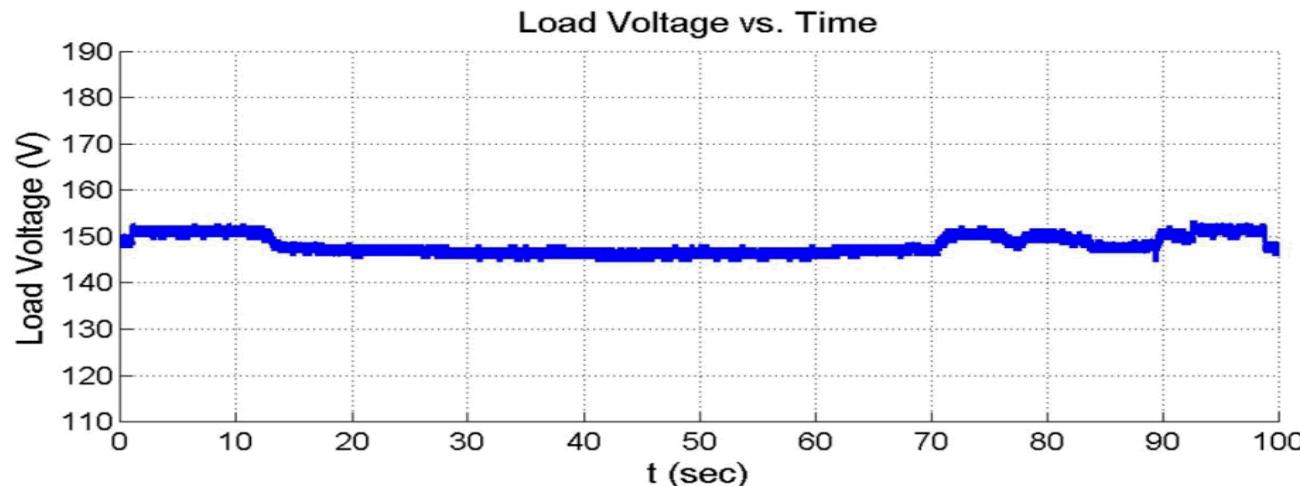
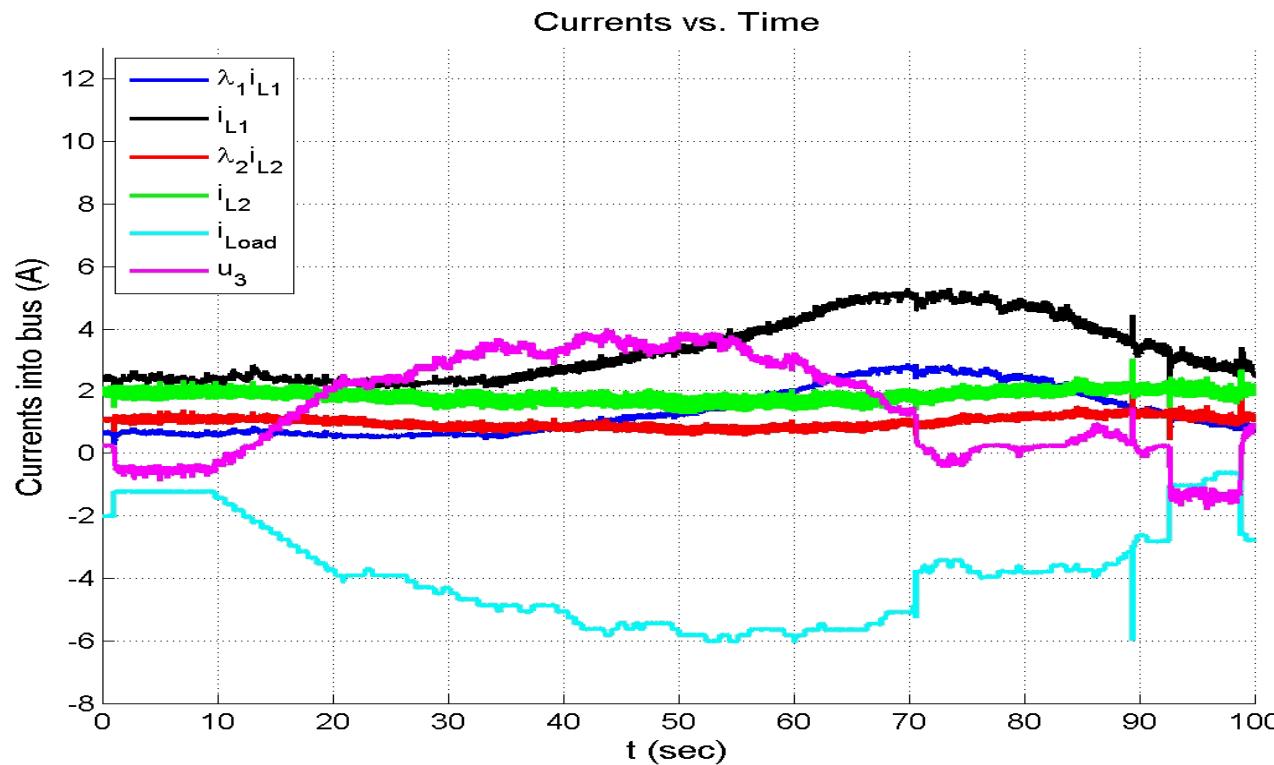


With energy storage

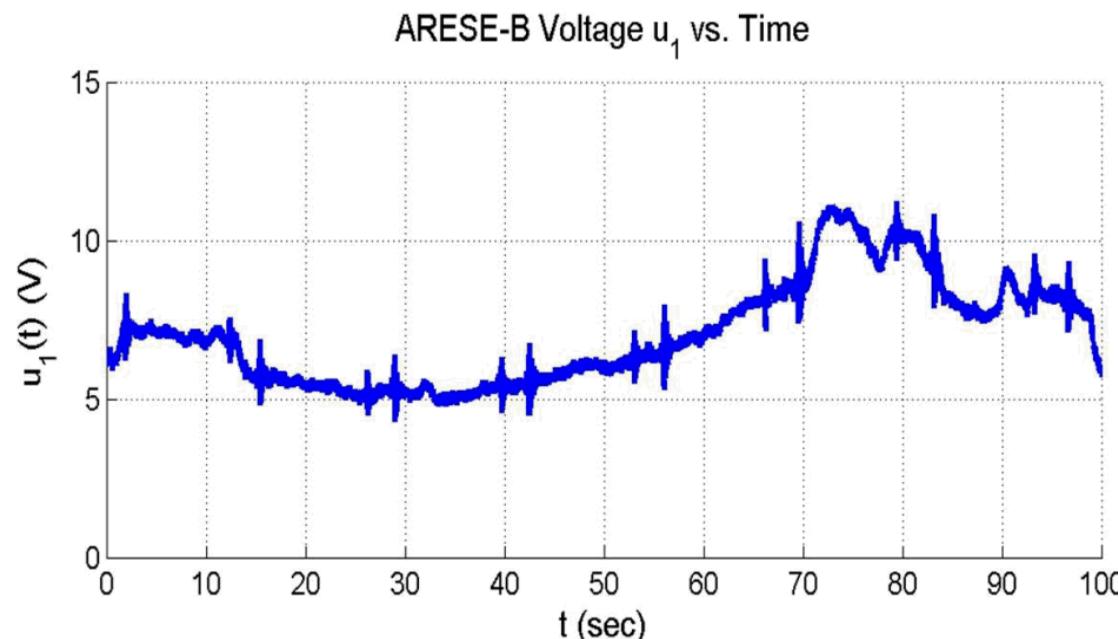
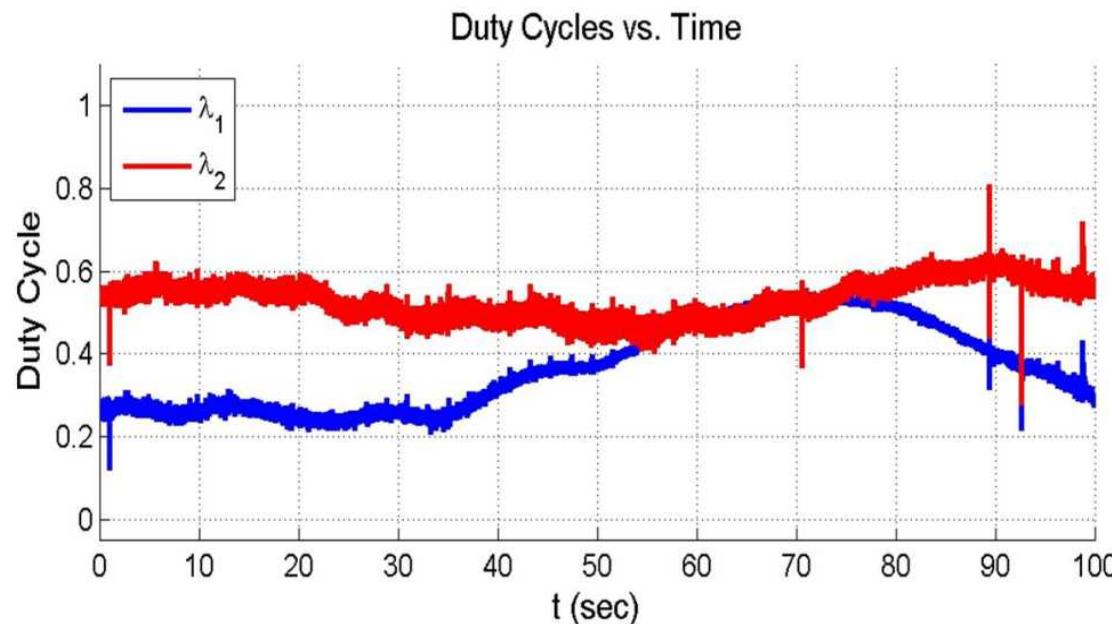
Experiment Input Profiles: Two Variable Wind Turbines and Variable Load



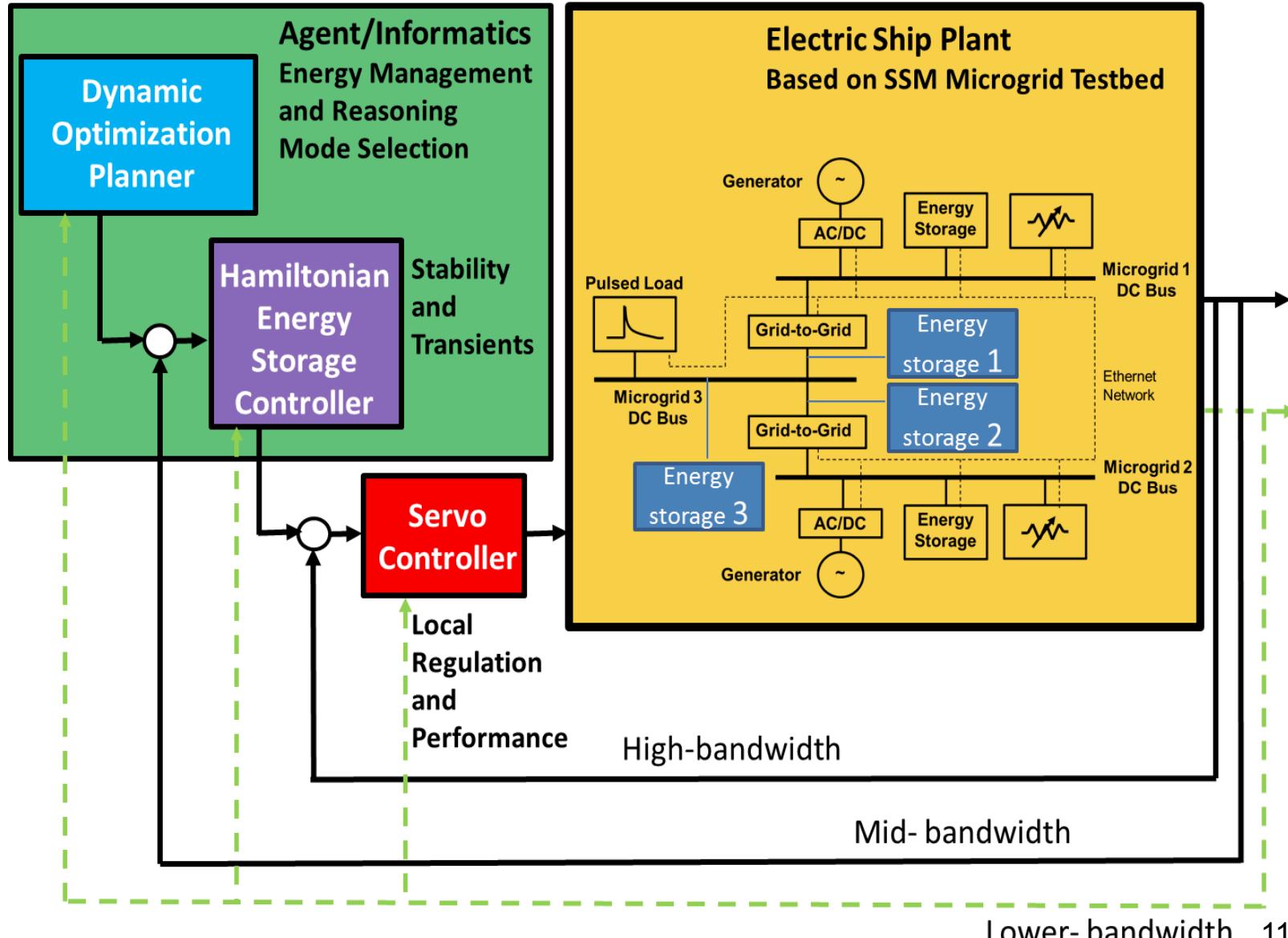
Two Variable Wind Turbine Variable Load Experimental Results (1)



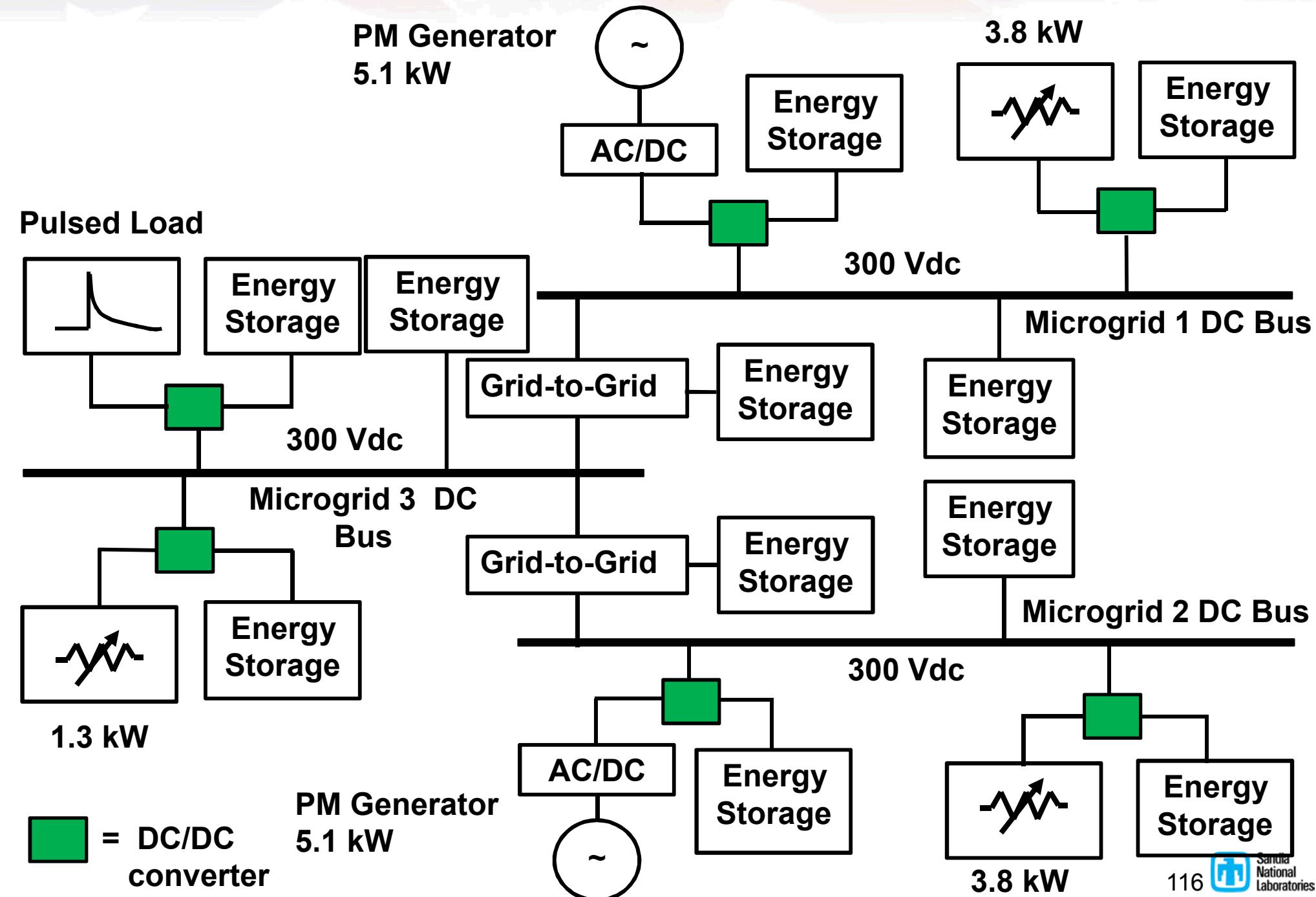
Two Variable Wind Turbine Variable Load Experimental Results (2)



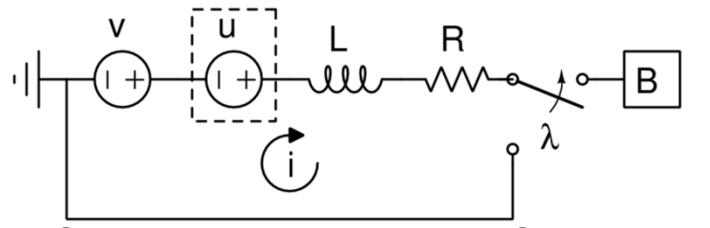
Multiple Microgrid System Represents a Navy Electric Ship Configuration



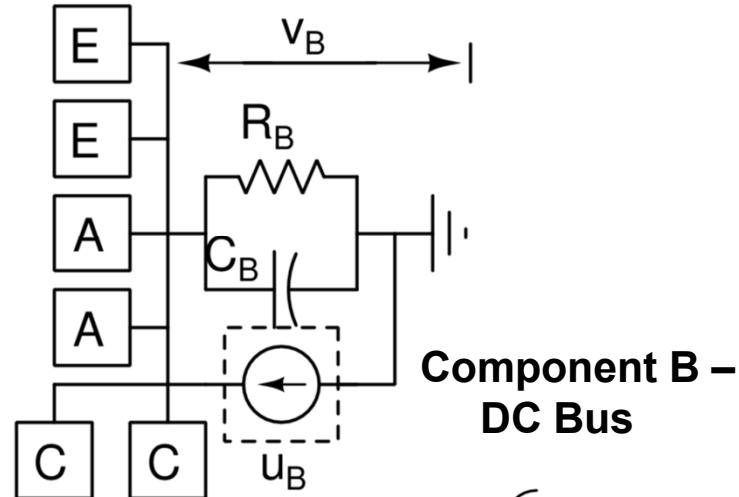
NAVSEA Fully Populated Energy Storage Space



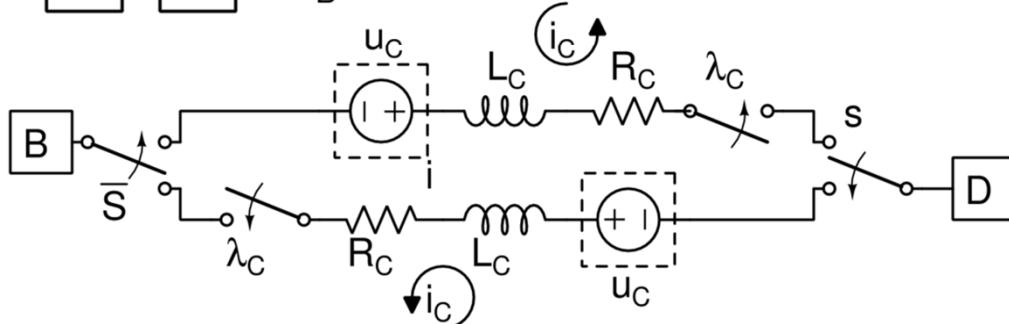
Optizelle Optimization Engine Topology Definition – Both Dynamic Optimizer and Offline Reference Trajectory Optimization



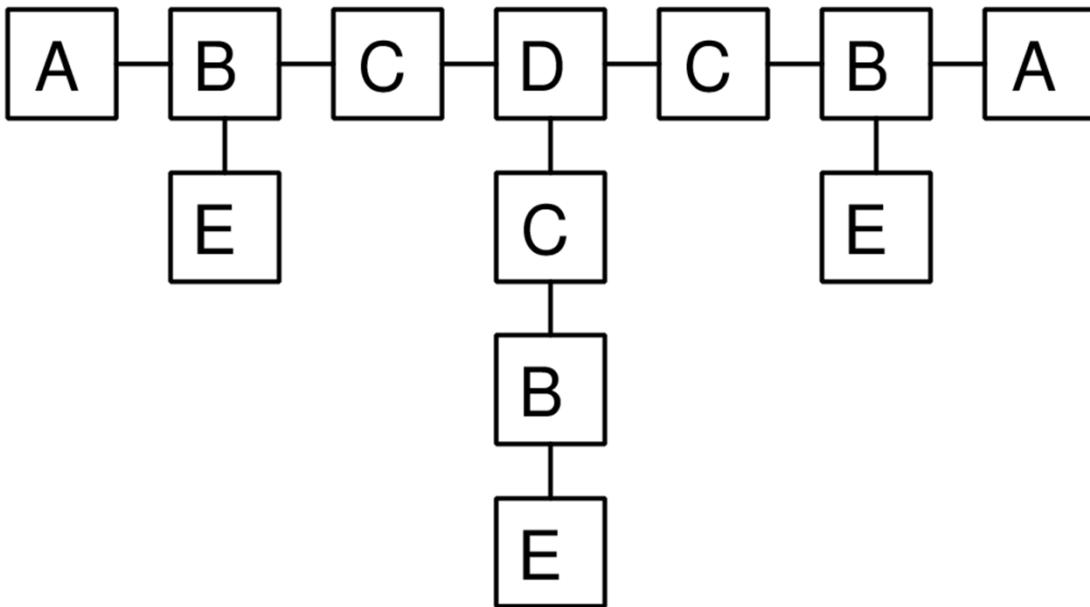
Component A – Boost Converter



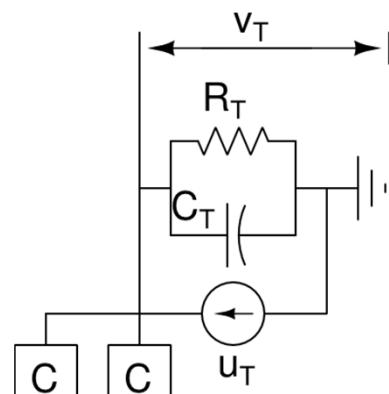
Component B – DC Bus



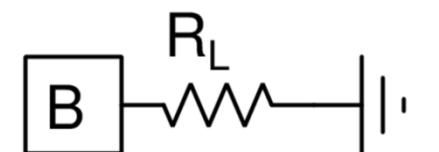
Component C – Connection between DC bus and DC transmission line



NAVSEA ship model – topology; dashed boxes allow energy storage to be added/subtracted in trade-off



Component D – DC transmission line

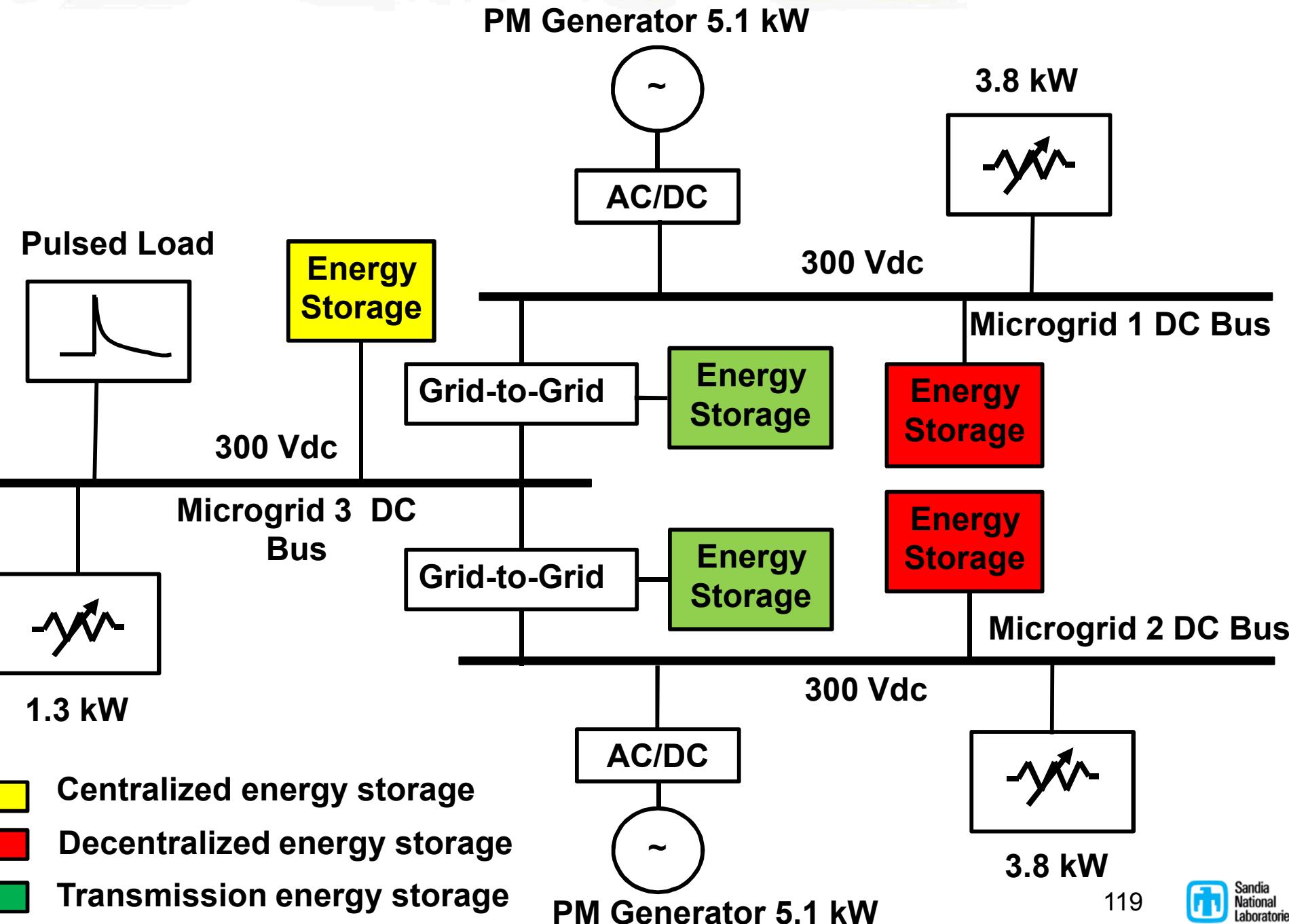


Component E – Additional load on bus

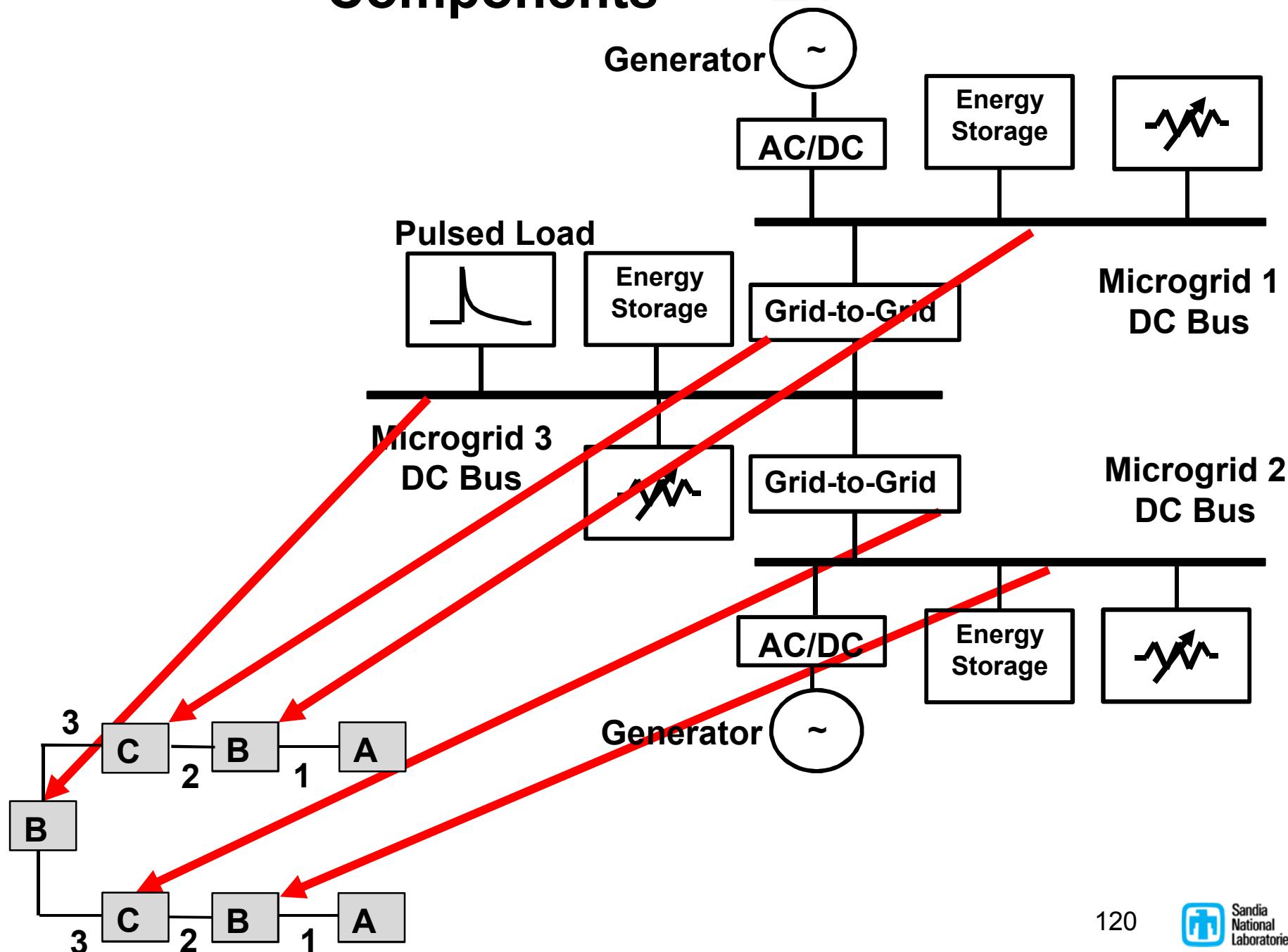
Multiple Optimization Metrics Problem Definition

- **Centralized vs Decentralized Energy Storage**
 - Centralized energy storage represents only energy storage (yellow) on the load bus microgrid
 - Decentralized energy storage represented as;
 - » Energy storage (light red) non-collocated on port/starboard microgrids
 - » Energy storage (light green) non-collocated on transmission devices between microgrids
 - » Combinations or sum of all non-collocated energy storage devices
- **Optimization Energy metrics specific interest;**
 - Boost converter duty cycles (held constant emphasizes energy storage solution vs generation)
 - Energy storage (in this scenario being manually configured and explored)
 - Parasitic losses (one way to measure/evaluate the advantage of one non-collocated configuration versus another or combinations thereof)
- **Focusing on quasi-steady state transient profile solutions for a single pulse load**

Optimization Scenario for Energy Storage Space



Mapping of Navy Ship Elements to Optizelle Components



Multiple DC Microgrid Optimization Formulation

Performance Index (PI):

$$\begin{aligned} PI_{multiple} = & \frac{w_1}{2} (\|\lambda - \lambda_0\|^2 + \|\lambda_C - \lambda_{C0}\|^2) \\ & + \frac{w_2}{2} (\|u\|^2 + \|u_B\|^2 + \|u_C\|^2 + \|u_T\|^2) \\ & + \frac{w_3}{2} (i^T \text{Diag}(R)i + i_C^T \text{Diag}(R_C)i_C) \\ & + \frac{w_4}{2} ((i^T u)^2 + (v_B^T u_B)^2 + (i_C^T u_C)^2 + (v_T^T u_T)^2) \end{aligned}$$

Subject to:

- Circuit equations
- Discretization equations
- Parameter bounds

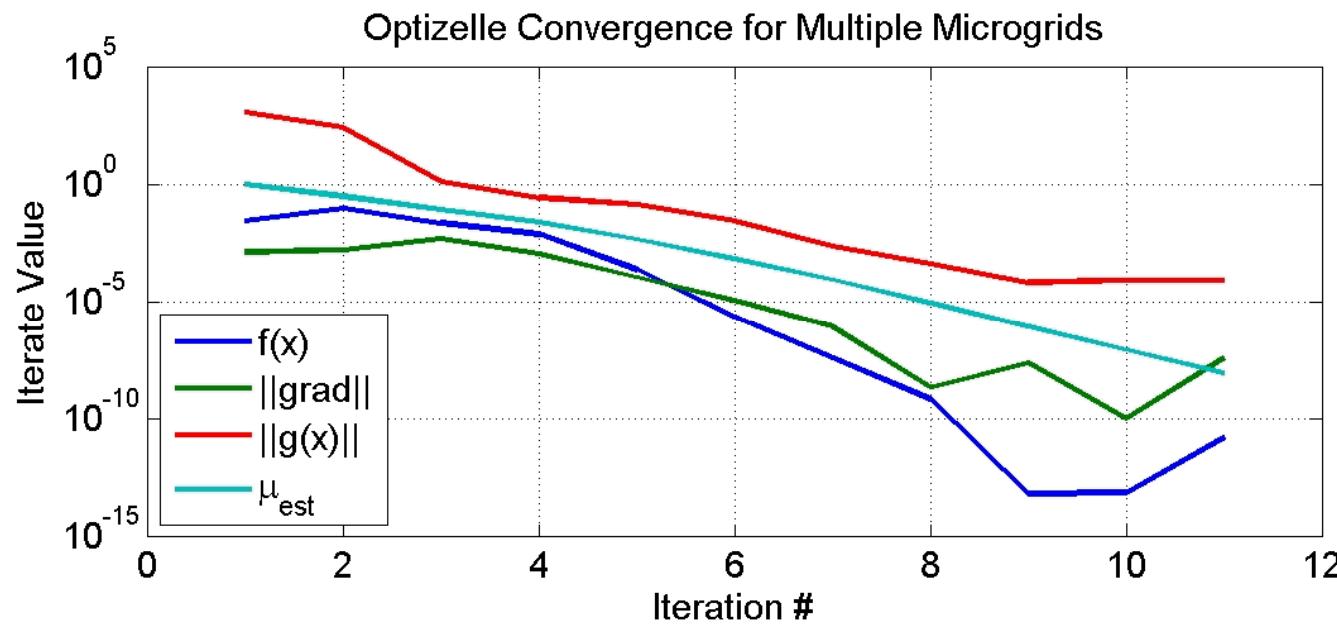
Can minimize PI wrt:

- Boost converter duty cycles (w1)
- Energy storage use (w2)
- Parasitic losses (w3)
- Power use (w4)

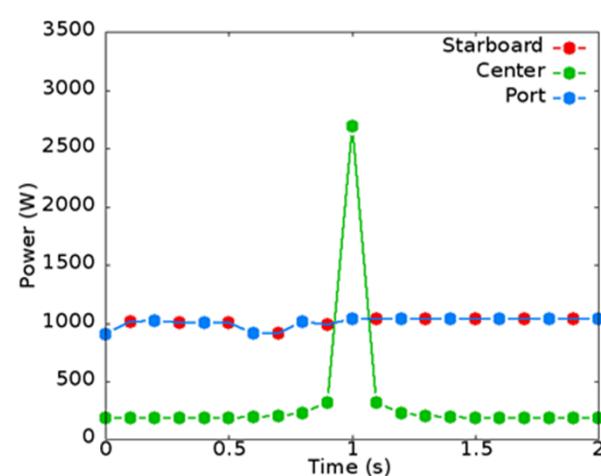
Optizelle Numerical Convergence Multiple Microgrid Results

Iter	f(x)	grad	dx	g(x)	mu_est
1	2.76e-02	1.38e-03	---	1.19e+03	1.00e+00
2	9.58e-02	1.62e-03	1.00e+03	2.74e+02	3.22e-01
3	2.43e-02	4.90e-03	2.00e+03	1.31e+00	8.51e-02
...					
9	6.44e-14	2.46e-08	5.13e+02	7.00e-05	8.92e-07
10	7.30e-14	1.01e-10	3.81e+02	8.42e-05	8.91e-08
11	1.59e-11	3.79e-08	3.95e+02	8.28e-05	8.91e-09

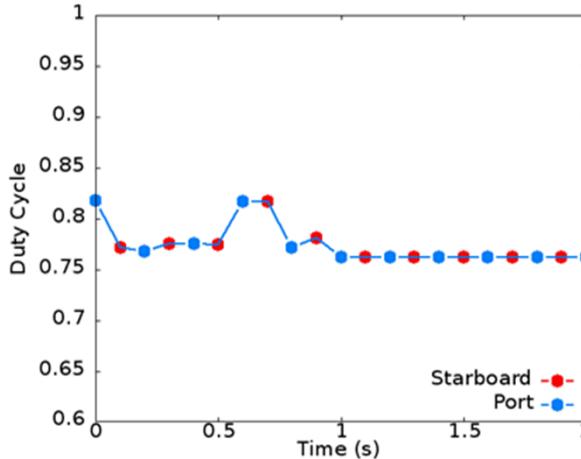
Optizelle NL MPC Optimizer Multiple DC Microgrid Convergence



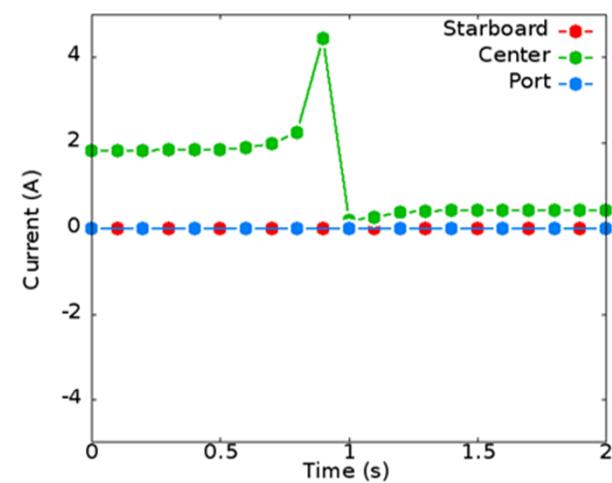
Centralized Energy Storage Solution Minimize Duty Cycles with Storage on the Load ugrid (center)



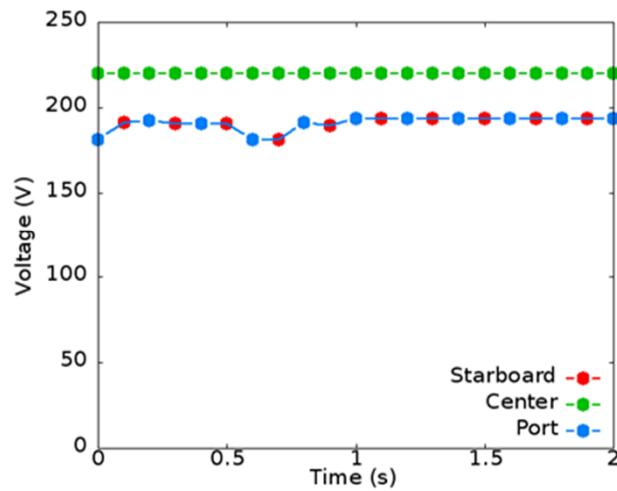
Power



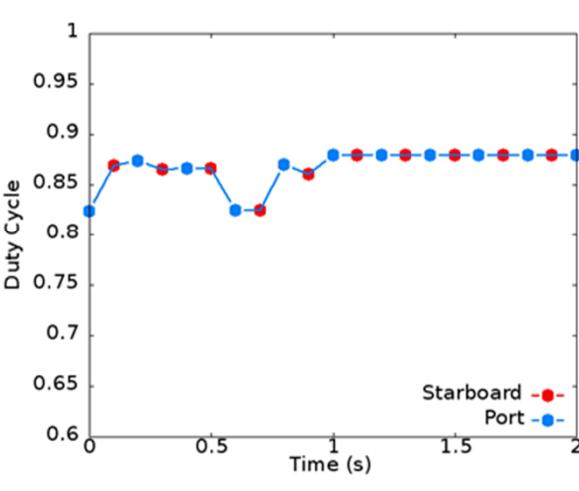
Boost Duty cycle



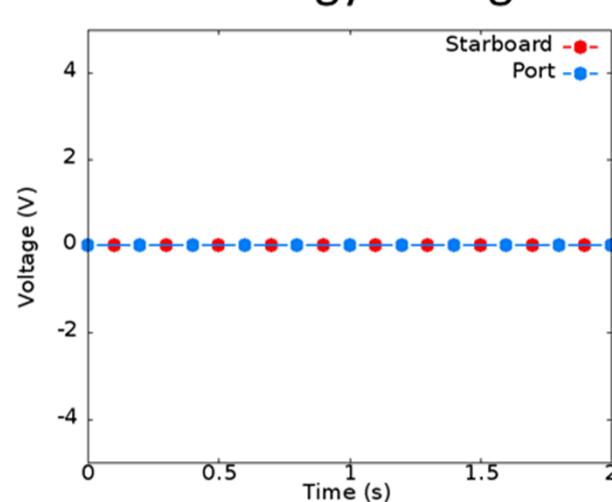
Bus Energy Storage



Bus Voltage

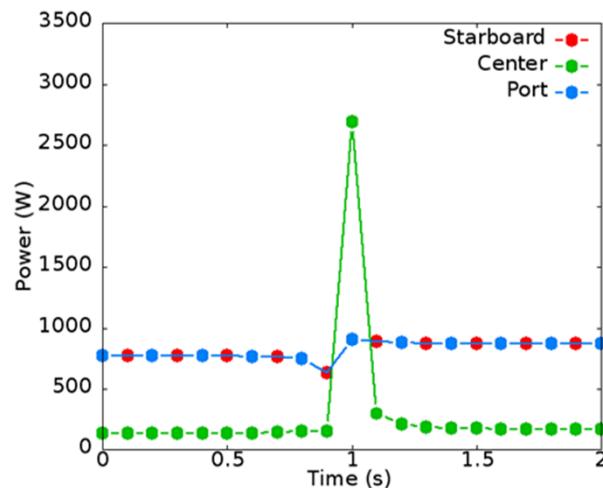


Grid-to-Grid Duty cycle

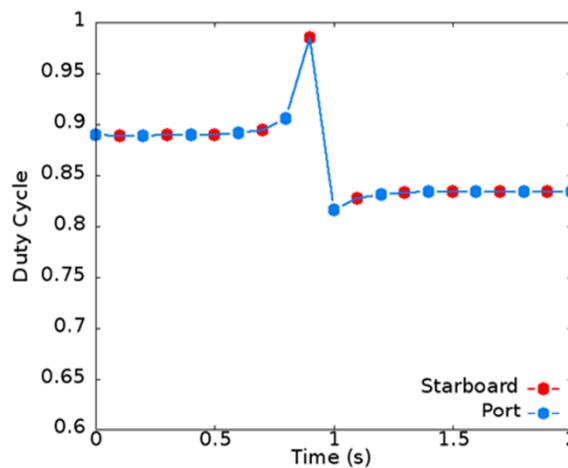


Grid-to-Grid Energy Storage

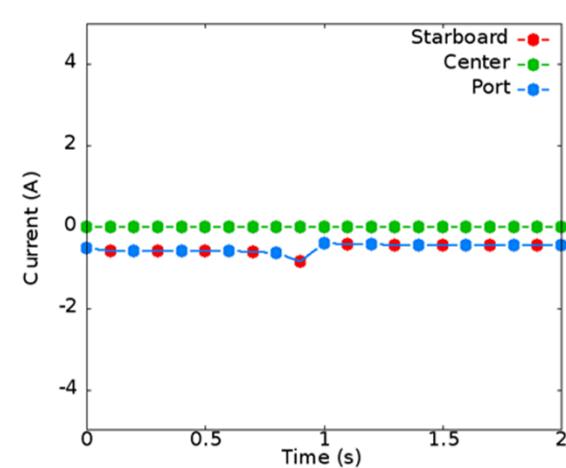
De-centralized Energy Storage Solution Minimize Duty Cycle with Storage on Port/Starboard ugrids (sides)



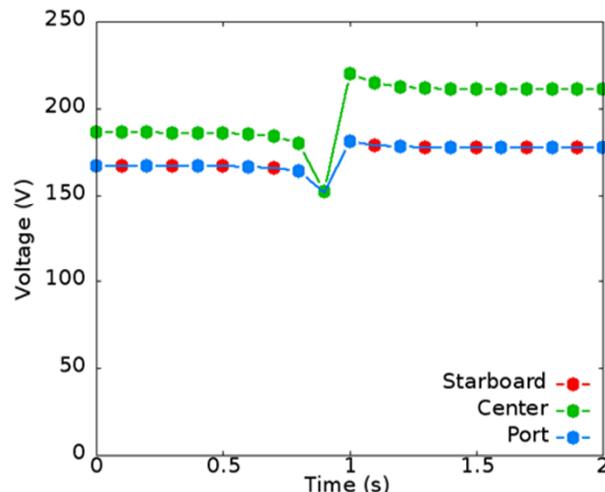
Power



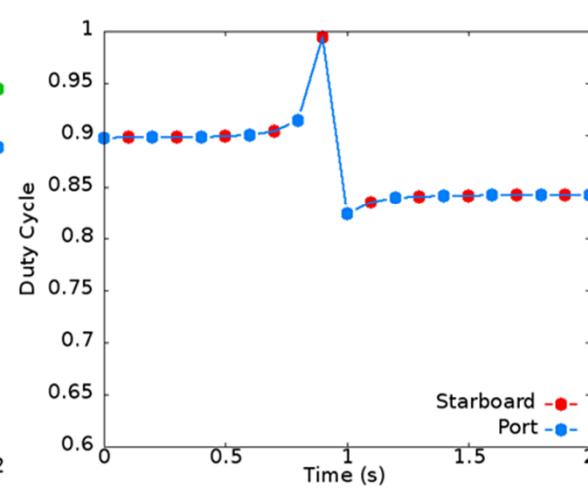
Boost Duty cycle



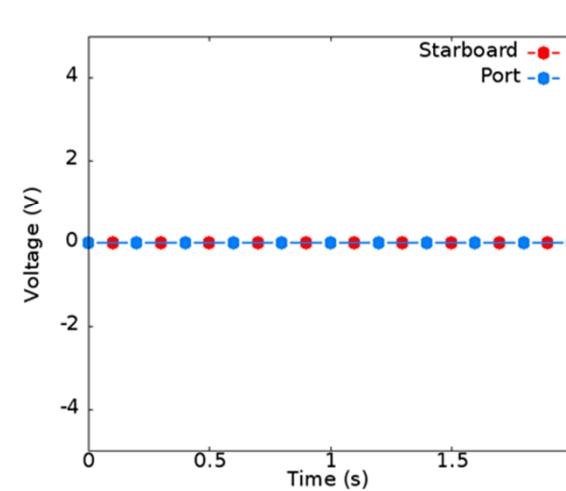
Bus Energy Storage



Bus Voltage

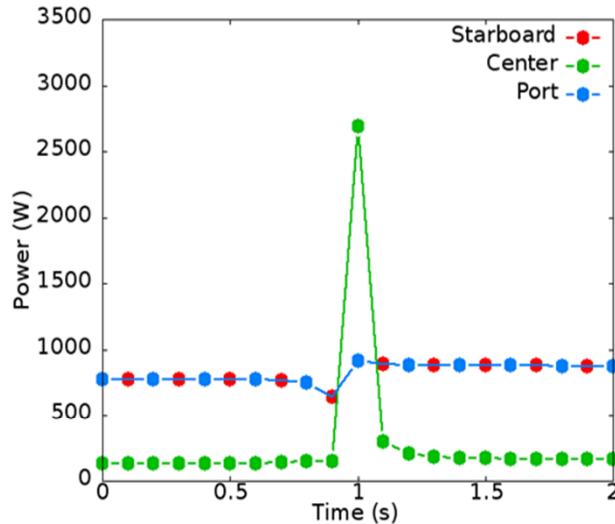


Grid-to-Grid Duty cycle

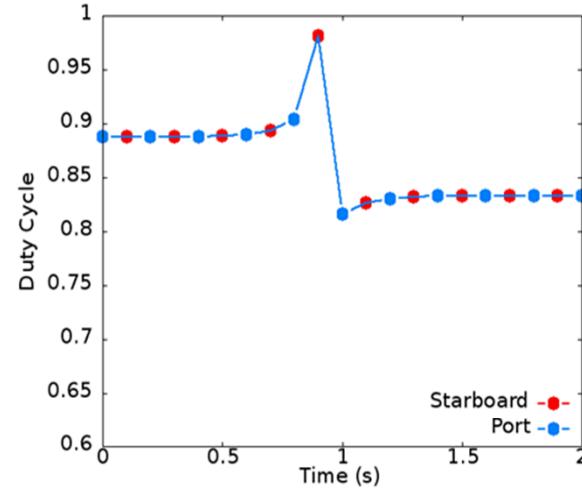


Grid-to-Grid Energy Storage

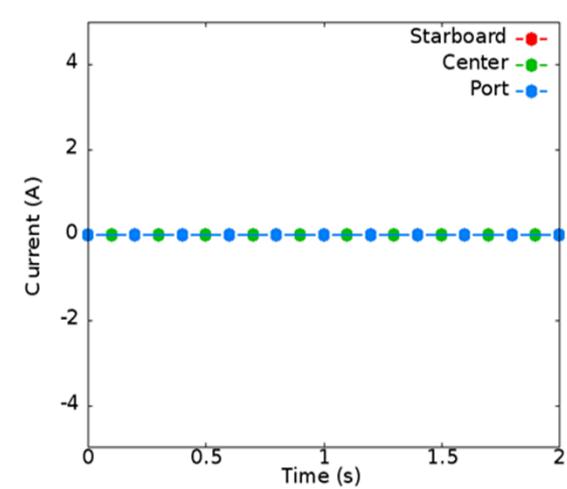
Minimize Duty Cycles with Storage on the Connectors Between Buses (De-centralized)



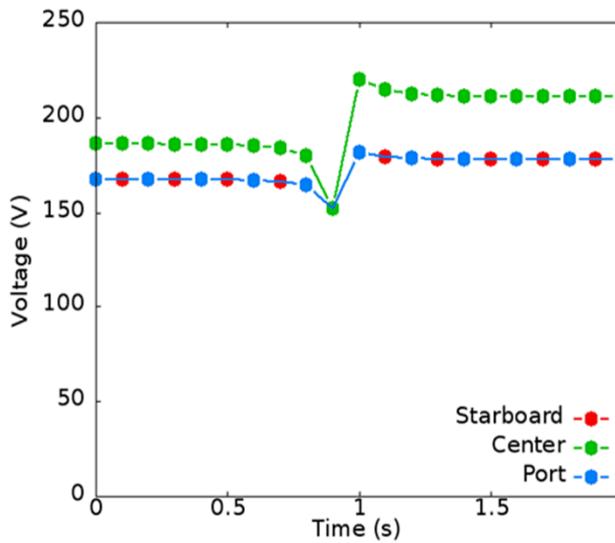
Power



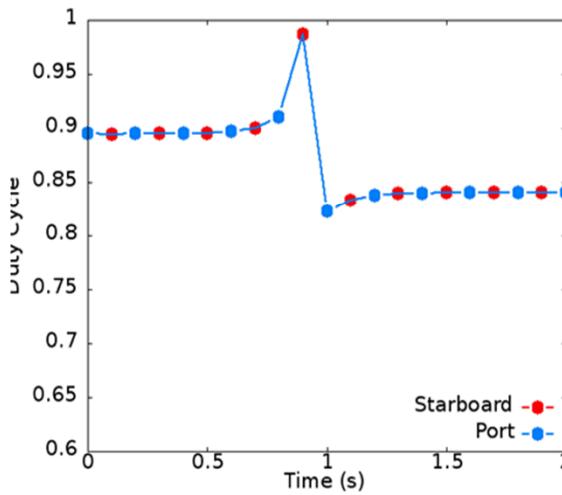
Boost Duty cycle



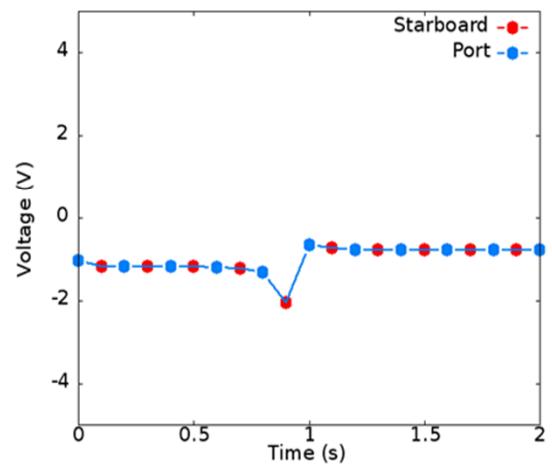
Bus Energy Storage



Bus Voltage



Grid-to-Grid Duty cycle



Grid-to-Grid Energy Storage

Summary and Conclusions

- A general method for design of nonlinear controllers for DC microgrid and multi-microgrid systems is presented
- An Optimizer/Planner, based on the Optizelle platform was developed for the system studies
- Optizelle framework specific to efficient NL MPC optimization
- Experimental results indicate a trade-off between rate of information flow, power quality and energy storage control effort
- Experimental/Numerical results for stochastic sources and loads demonstrated stable voltage regulation and provided energy storage specifications from SSM testbed ARESE (A/B) emulators
- The HSSPFC method utilized to combine microgrids into larger collective of microgrid systems, i.e. Navy electric ship application



Acknowledgments

- **Sandia National Laboratories** is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.
- **SNL GC/LDRD SSM Microgrid Work**
- **NAVSEA Naval Power Systems, Electric Ship PMS 320 Program**
- **Michigan Technological University**
 - Professor Gordon Parker (Optimization and Controls)
 - Professor Wayne Weaver (Power Engineering / Power Electronics)
 - Research Professor Steve Goldsmith (Agents / Informatics Framework)



Enabling Secure, Scalable Networked Microgrids with High Penetration Renewables and Pulsed Power Loads

IEEE MSC2015 Workshop
September 20, 2015

Steve Glover, David Wilson, Jason Neely, Marvin Cook
Sandia National Laboratories

Wayne Weaver, Gordon Parker, Rush Robinett
Michigan Tech



Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.



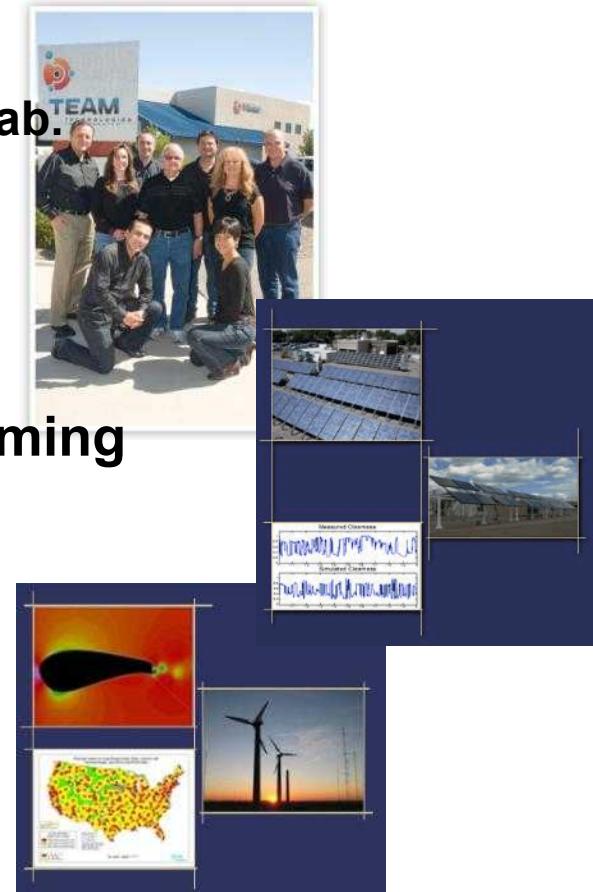
Agenda

- 8:00 Energy Surety Requirements for Microgrid Development
- 8:50 Break
- 9:05 Microgrid Modeling using MATLAB/Simulink: Components-to-Systems
- 10:05 Break
- 10:20 Microgrid Optimal Control and Optimization
- 11:20 Lunch
- 12:20 Microgrid Agent-Based Control for Mediating Generation, Storage, Loads, Cyber Security
- 1:20 Break
- 1:35 Microgrid Control and Performance Analysis
- 2:35 Break
- **2:50 Sandia National Lab's Secure Scalable Microgrid Testbed: Capabilities and Collaboration**
- 3:50 Wrap-up

Acknowledgements

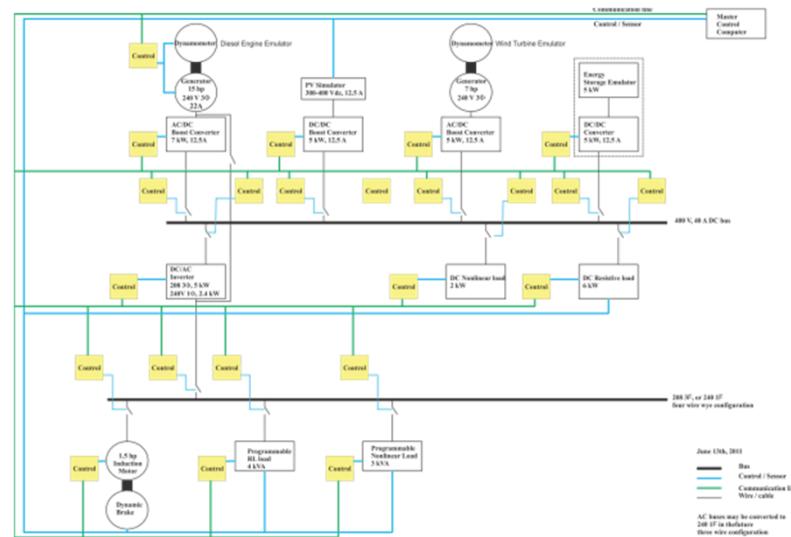
- **Modeling and Case Studies**
 - Dr. Oleg Wasyczuk, Purdue University
 - Dr. Benjamin Loop, PC Krause and Assoc.
- **Consulting, renewables data**
 - Sig Gonzalez, Distributed Energy Technologies Lab.
 - Joseph Williams, Wind Energy Technologies
- **Hardware Support, construction**
 - TEAM Technologies
- **Testbed Planning, Construction, and Programming**

• Forest White	• Ray Martinez
• Jason Finn	• Vanessa
• Mike Horry	• Romero
• Peter Foster	• Rory Schell
• Joe Rudys	• Mike Hileman
• Tom Ellis	• Mike Usher
• Sean Simpson	

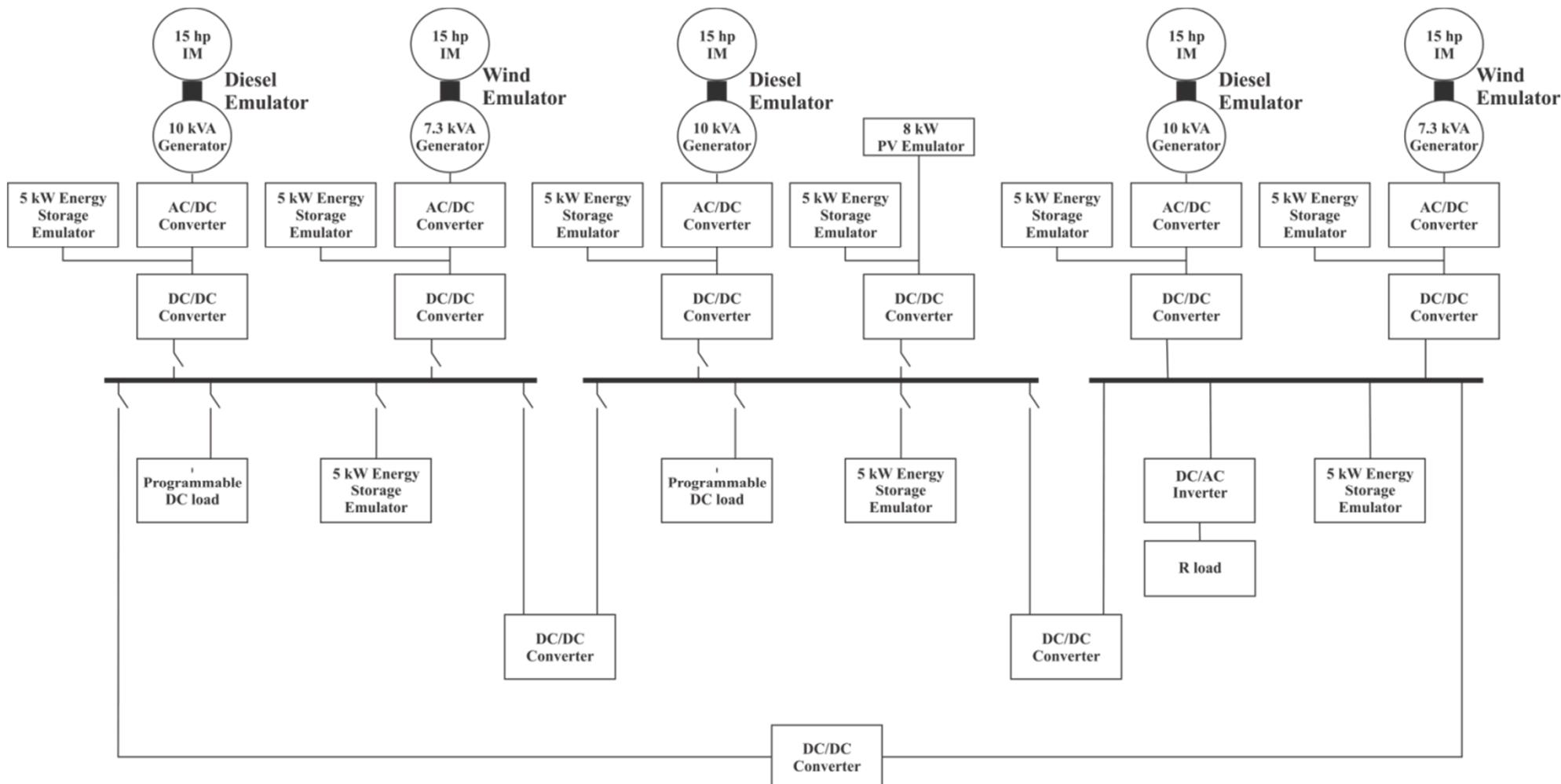


SSMGC Hardware Testbed

- **Hardware testing provides a bridge between simulation verification and implementation**
- **Hardware testing enables publication in “Power” Journals**
- **Testbed is based largely on custom hardware**
- **Why custom?**
 - **Knowledge of system assembly and control algorithms**
 - **Components and controls easily reconfigured**
 - **Allows for comprehensive Data Acquisition**
 - **Enables unique capabilities**
 - **Allows for testing in an *enclosed lab***



The SSM Consists of Three Interconnected Microgrids

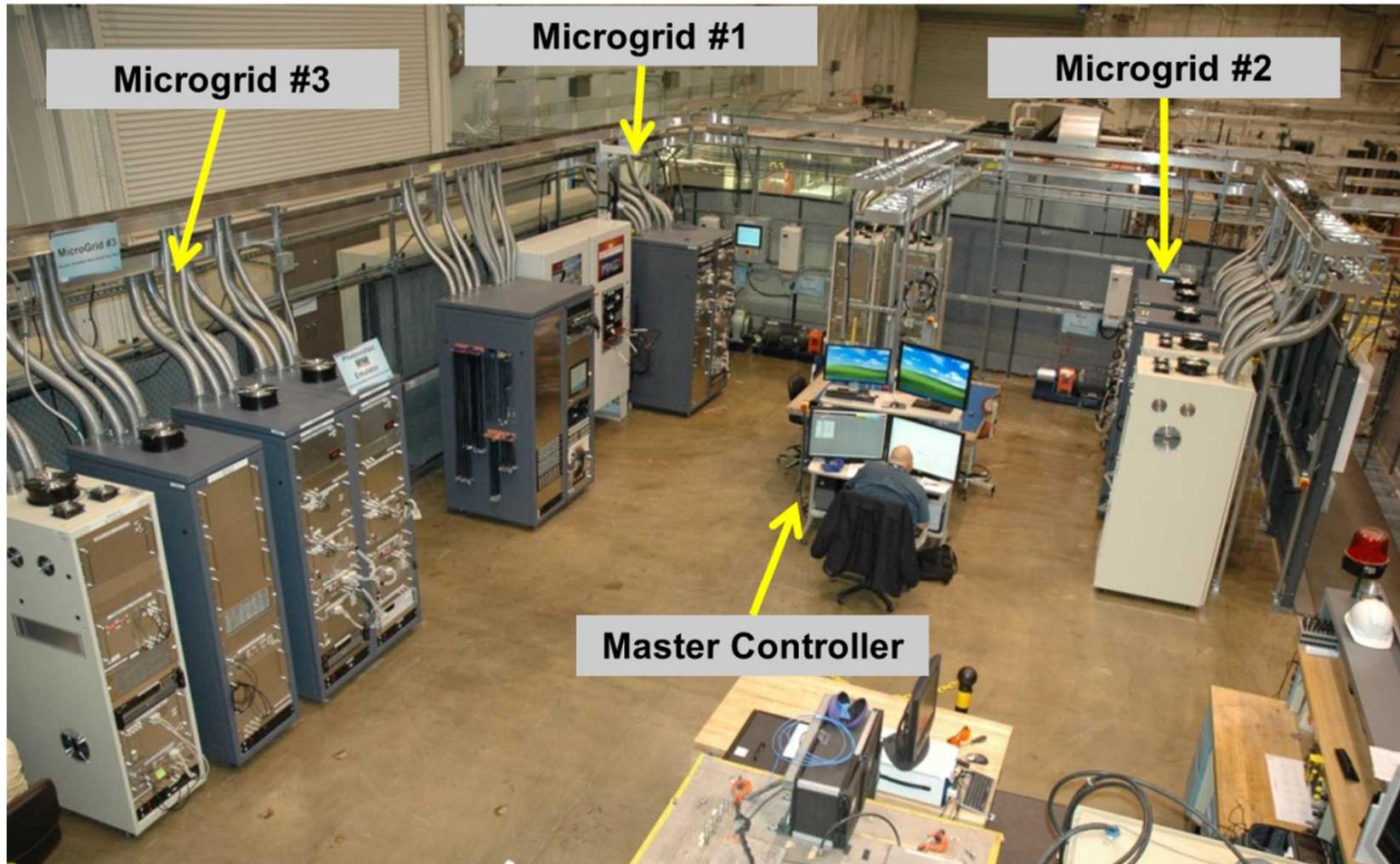


Master
Control
Computer

Data
Acquisition

Secure Scalable Microgrid (SSM) Testbed Enables Hardware Testing of HSSPFC

- 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



Emulators Enable a Variety of Sources Diesel, Wind or Other Rotational Generators

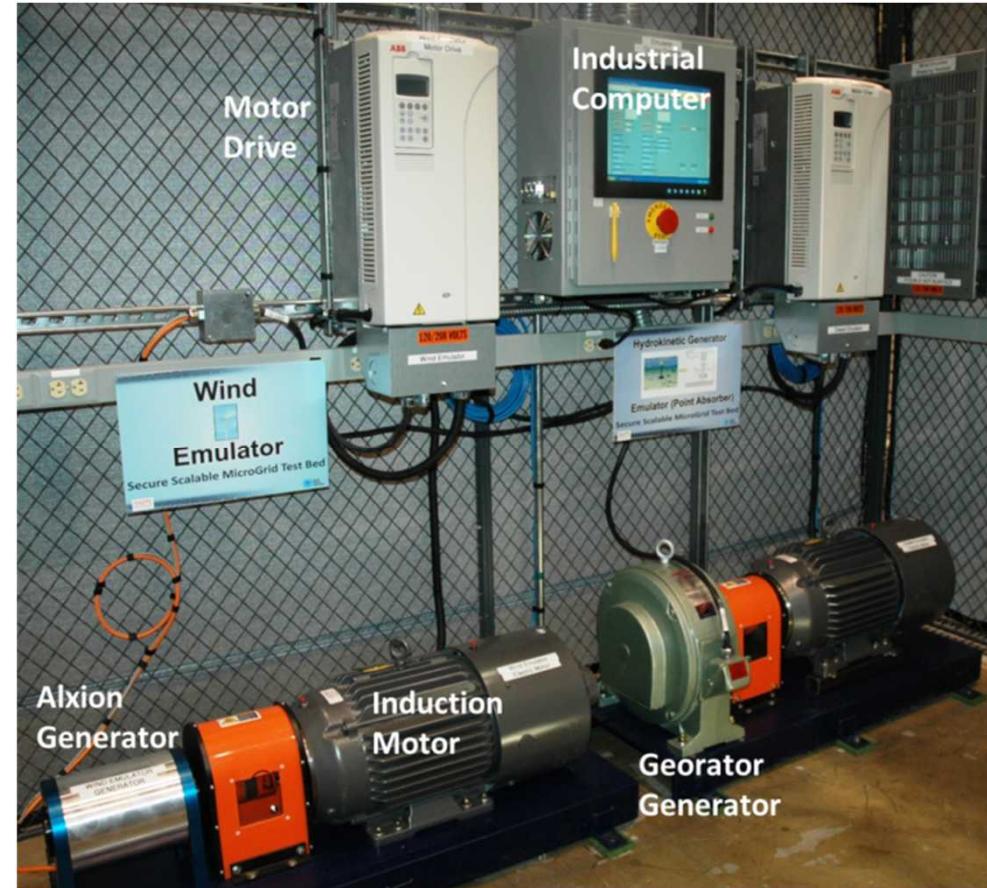
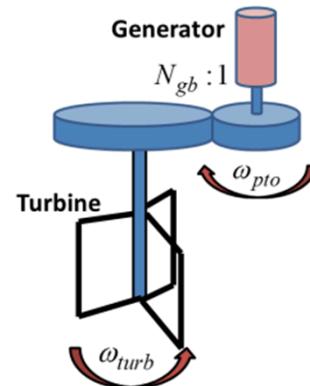
- Dynamic models are created for generators emulated using a commercial motor drive

River Turbine

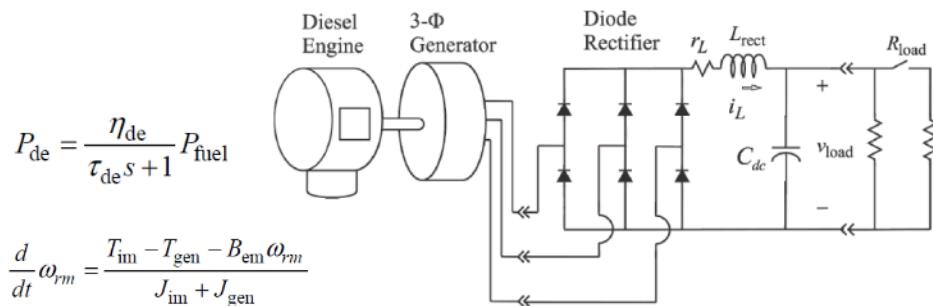
$$T_{turb} = \frac{P_{turb}}{\omega_{turb}} = \frac{C_p(\lambda) \rho_w A_r v_w^3}{2\omega_{turb}}$$

$$\frac{d}{dt} \omega_{turb} = \frac{T_{turb} - N_{gb} T_{pto} - B_{gb} \omega_{turb}}{J_{turb} + N_{gb}^2 J_{pto}}$$

$$\frac{d}{dt} \omega_{pto} = \frac{(1/N_{gb}) T_{turb} - T_{pto} - (1/N_{gb}^2) B_{gb} \omega_{pto}}{(1/N_{gb}^2) J_{turb} + J_{pto}}$$



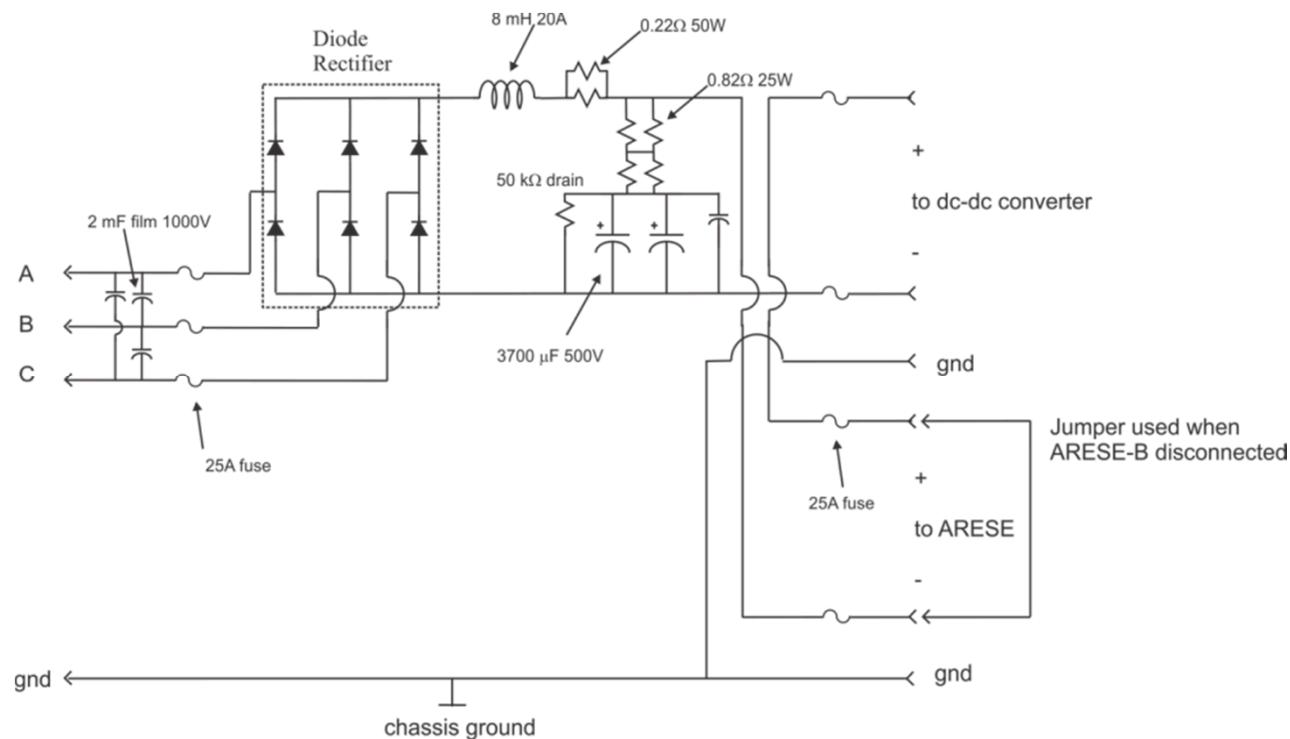
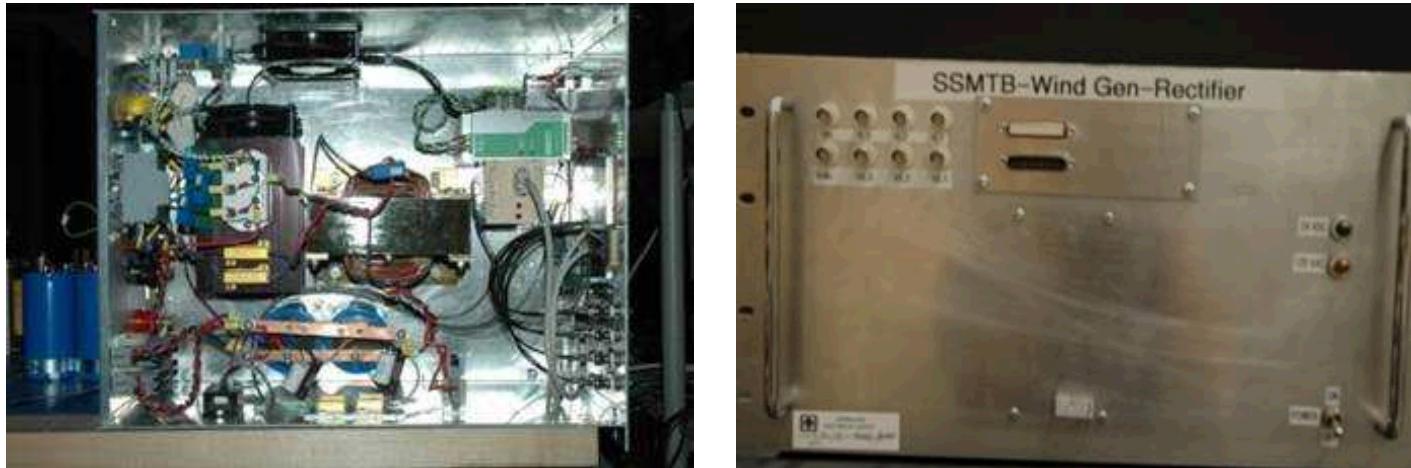
Diesel Engine



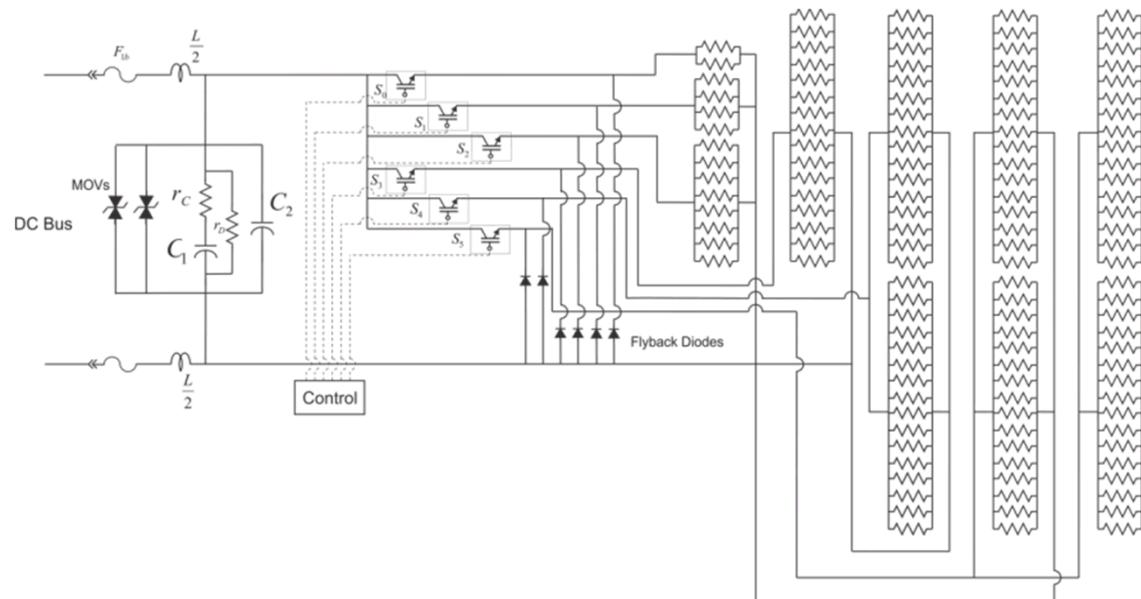
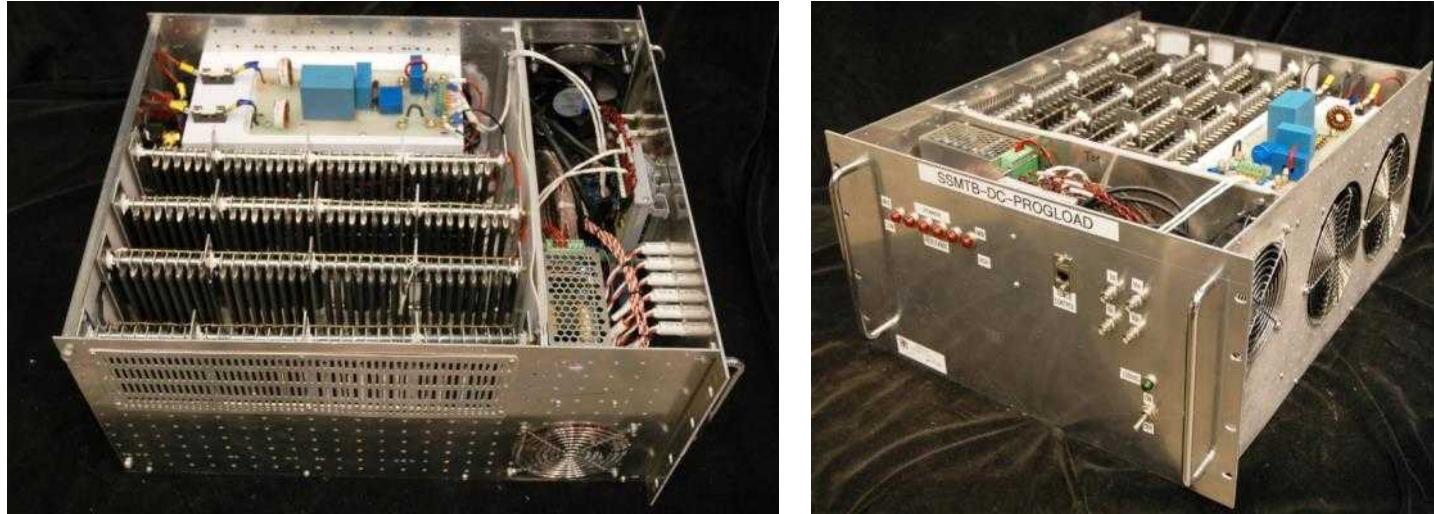
$$P_{de} = \frac{\eta_{de}}{\tau_{de} s + 1} P_{fuel}$$

$$\frac{d}{dt} \omega_{rm} = \frac{T_{im} - T_{gen} - B_{em} \omega_{rm}}{J_{im} + J_{gen}}$$

Rectifiers Convert Rotational Energy to DC



Programmable Loads Allow Stochastic and Deterministic Behavior



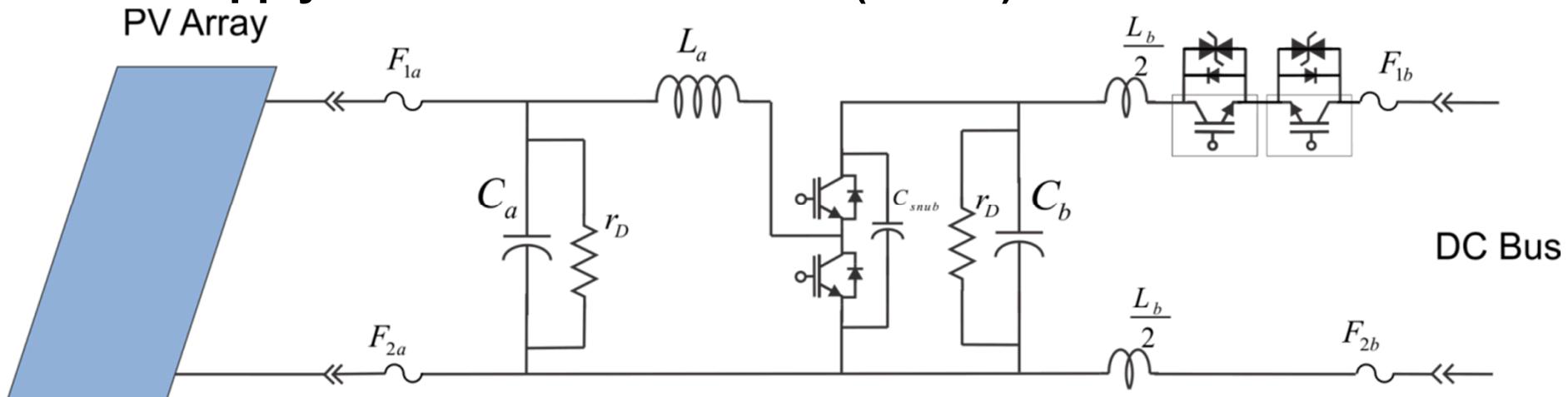
Photovoltaic Generator Connects to the Bus through a DC to DC Converter

- **Purpose**

- To emulate the behavior of a Photovoltaic array with pre-determined Insolation and Temperature schedules provided by Master Control Computer

- **Specifications**

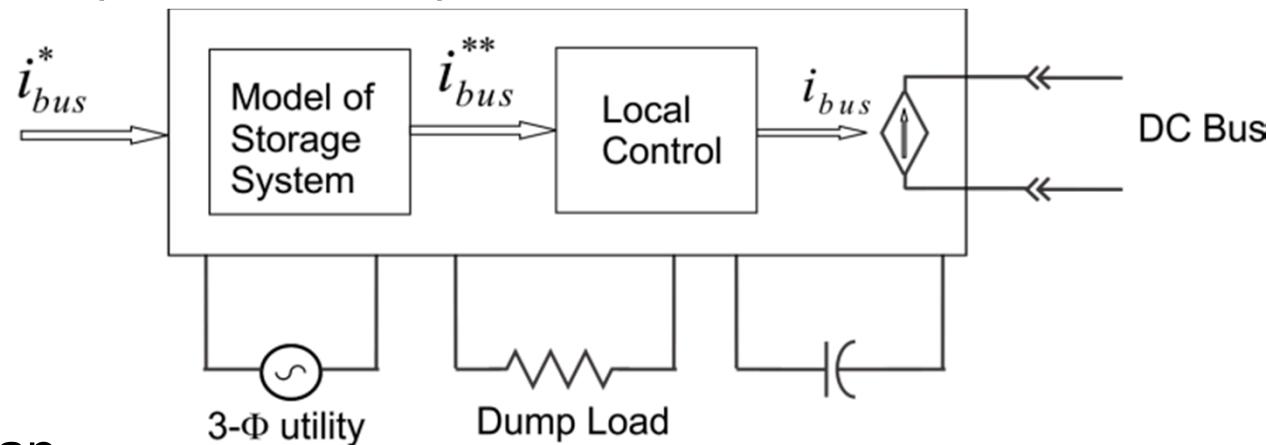
- **Supply a 400 VDC bus at 5 kW (12.5 A)**



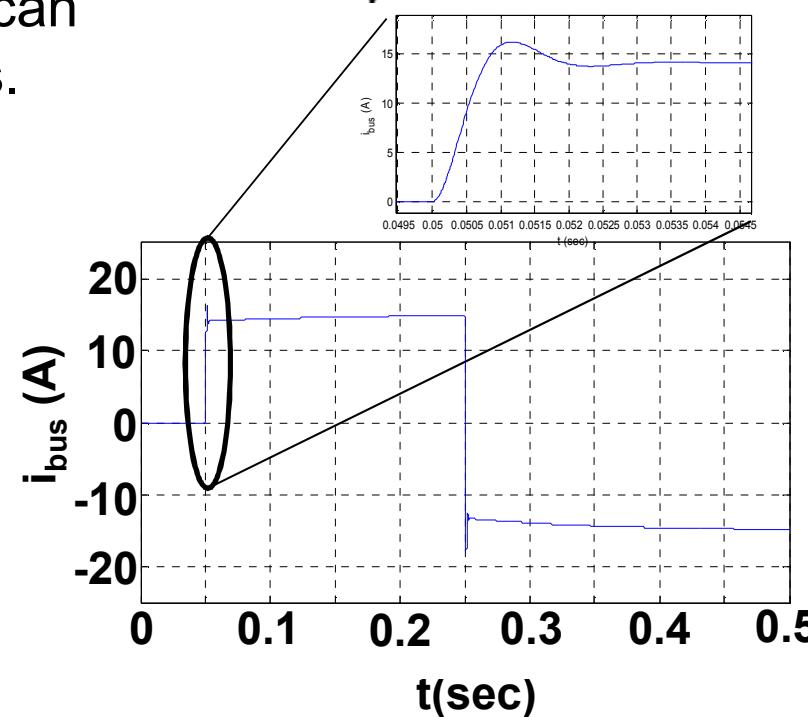
Energy Storage Emulation Allows Specification of Critical Parameters

Energy storage can change from experiment to experiment

- Bandwidth, 583 Hz max
- Peak power, 5 kW max
- Total energy storage
- Frequency response



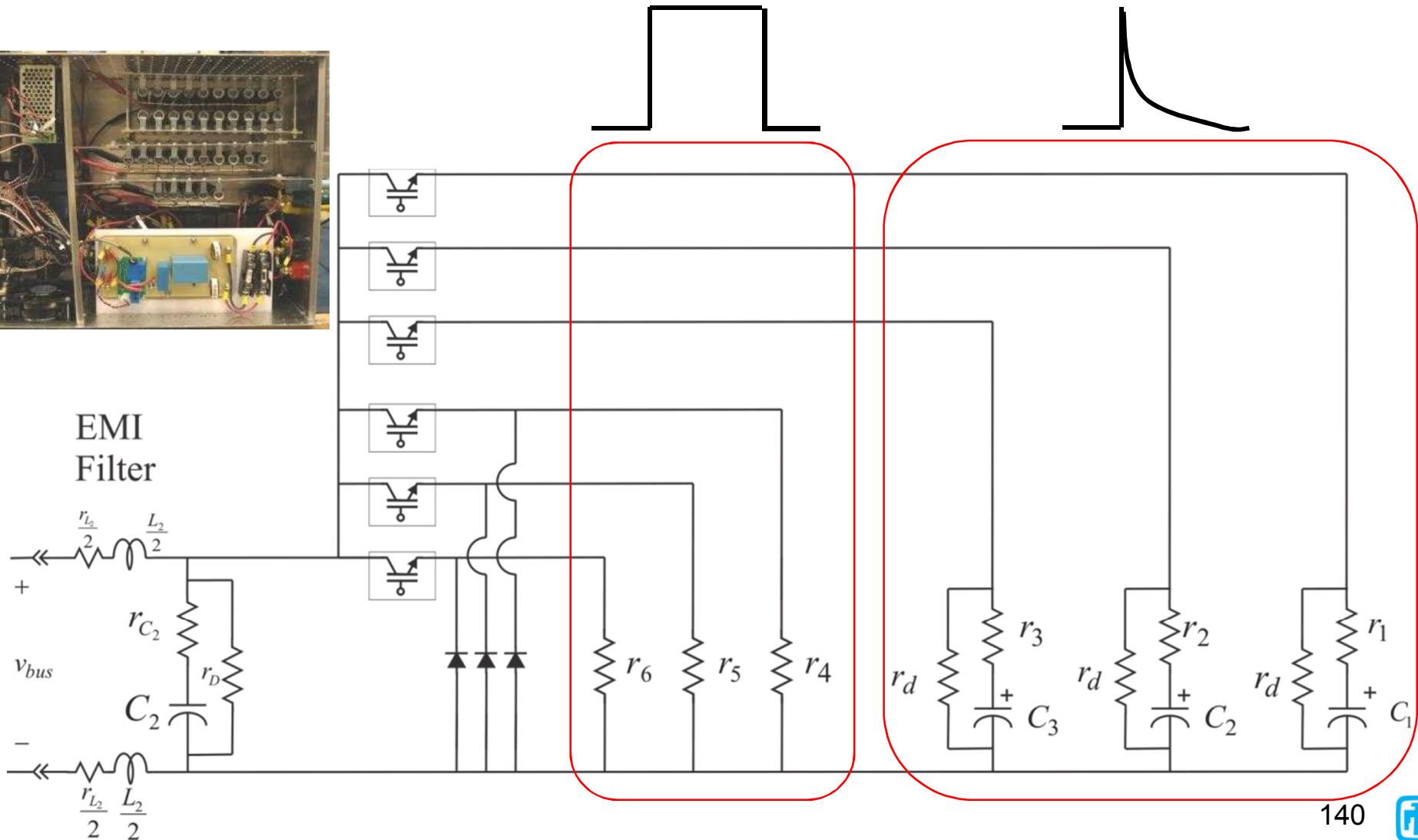
Higher level control systems can set storage reference points.



$$BW \approx \frac{0.35}{T_{rise}} \approx 583 \text{ Hz}$$

An Adjustable Pulsed Load is Programmable with both Resistive and RC Circuits

- Proposed Pulsed Load: two parallel circuits
 - Parallel connected RC networks allow the pulse to be adjusted (one shot)
 - Low valued resistor (timed on-off control)



A Controllable Buss is For Adaptive Topologies



400 V DC buss with
controllable
semiconductor contactors
Thirteen 25 A connections

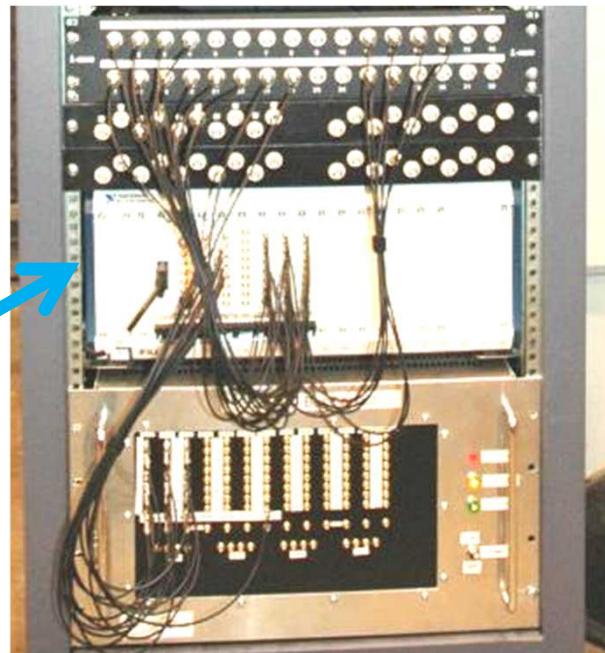
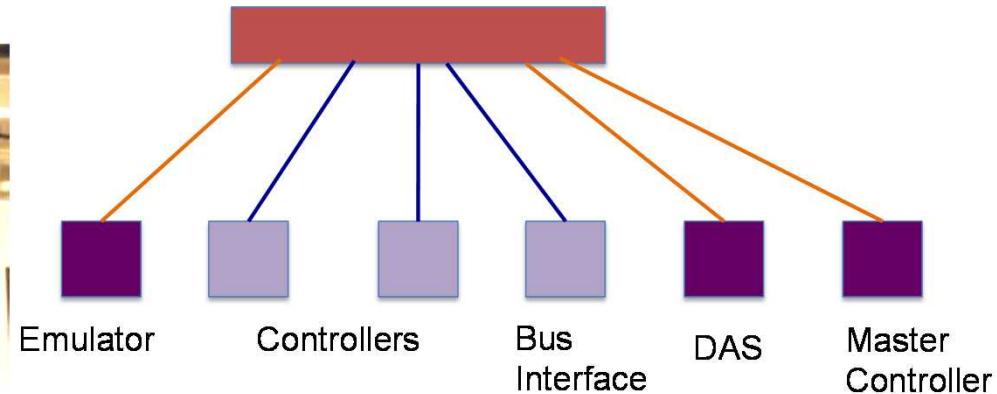
208 V, 3- φ or 240 V, 1- φ buss with
controllable semiconductor contactors
Eleven 25 Arms connections



Communication Networks Manage Information Flow



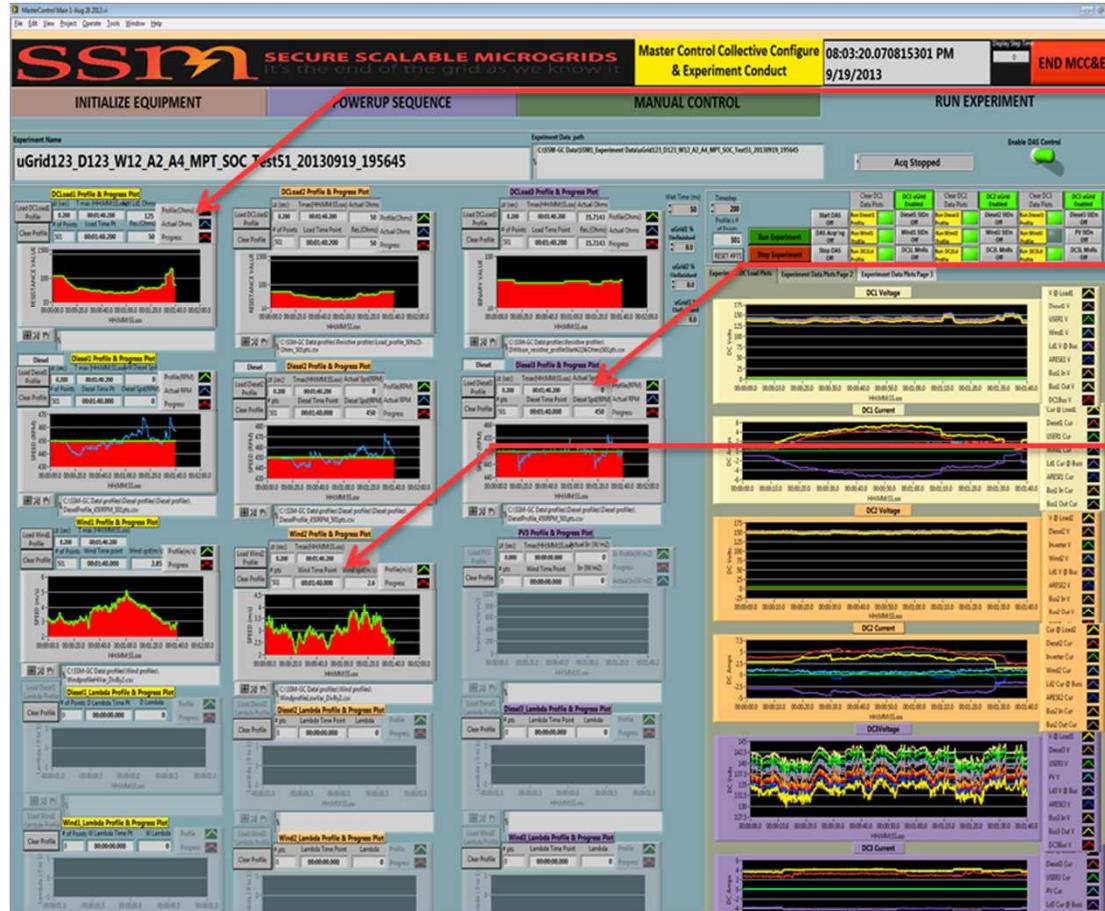
Managed Ethernet Switch



- GB Ethernet Communication
 - Control network
 - Timing network
 - Allows for hierarchical control
- 30 MHz Data Acquisition
 - 2 TB hard drive
 - 48 channels installed

Master Controller Coordinates HSSPFC Control Experiments

- Software User interface coordinates start and end for experimental runs and displays real-time performance data
- Allows specification of input profiles for each microgrid component
 - Same experiment described by load and generation profiles may be repeated with changes to control approach and performance evaluated



Microgrid 1 Load (Ω)

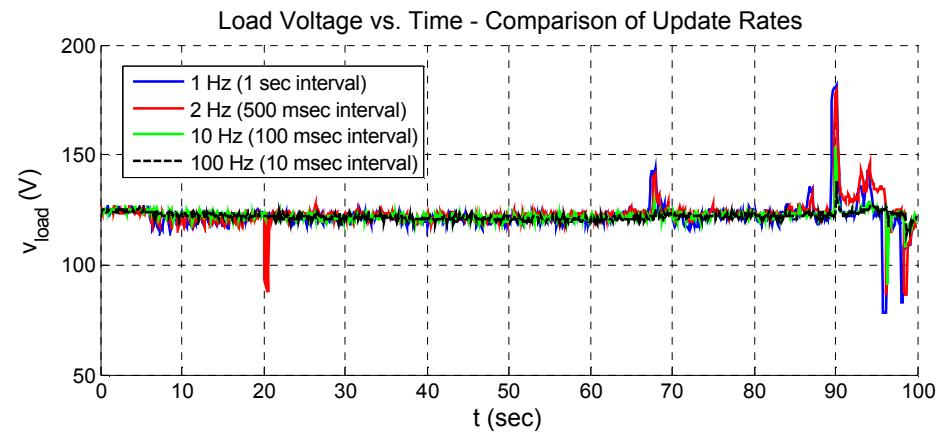
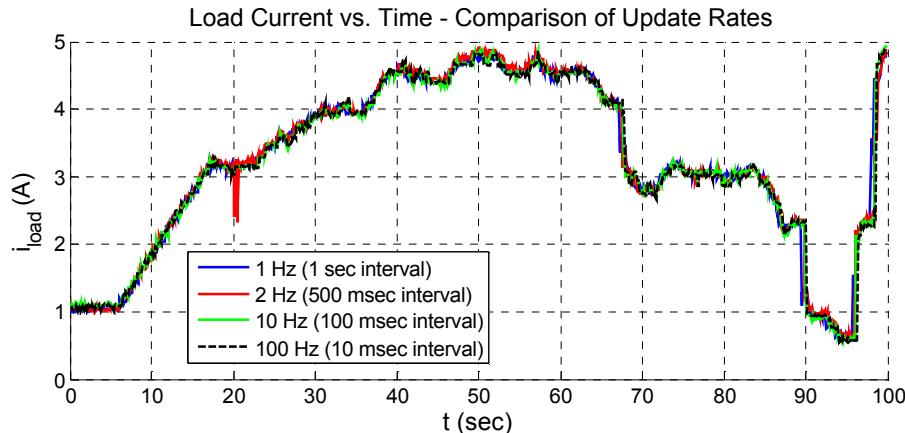
Microgrid 3 Diesel Engine speed (RPM)

Microgrid 2 Wind speed (m/sec)

Realtime bus voltage and current plotting

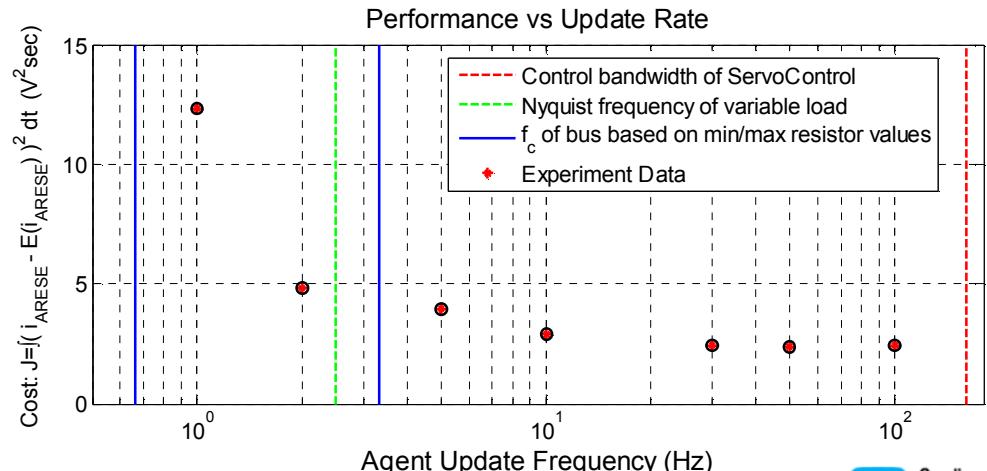
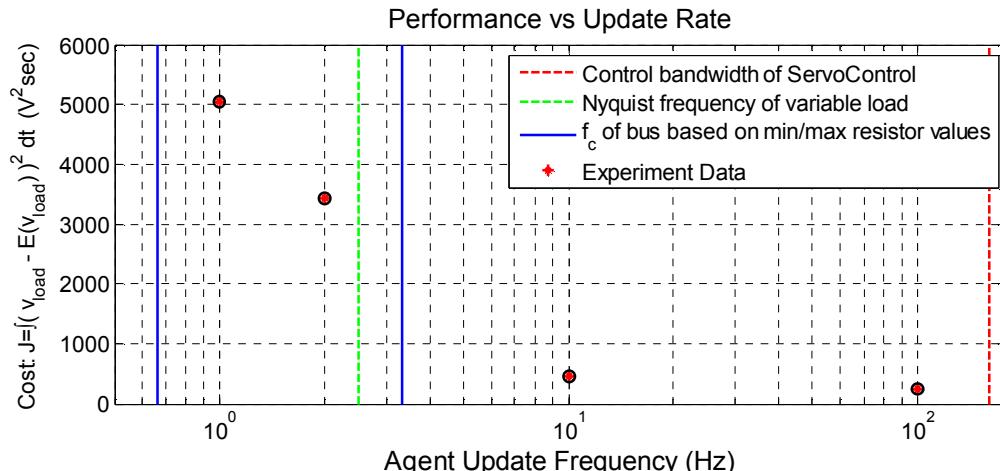
Automated “Batch-run” Experiments Enable Apples-to-Apples Control Comparison

- Example:
 - Effect of Informatic Control Update Rate on Cost



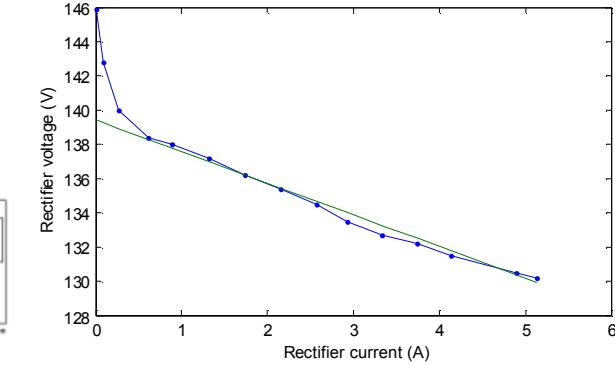
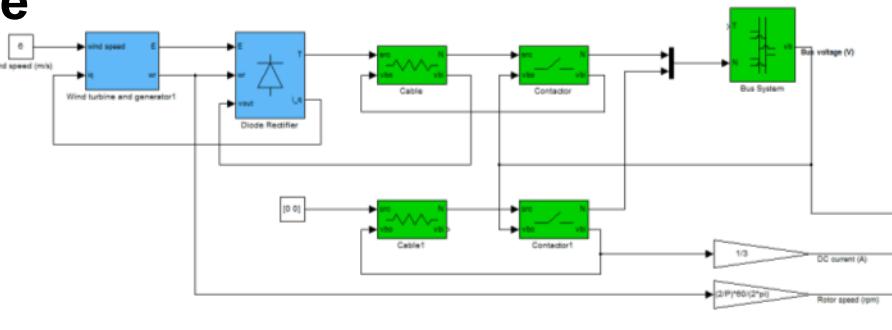
$$J_v(t_f) = \int_{t_0}^{t_f} (v_{load}(\tau) - \hat{v}_{load}(\tau))^2 d\tau$$

$$J_i(t_f) = \int_{t_0}^{t_f} (i_{ES}(\tau) - \hat{i}_{ES}(\tau))^2 d\tau$$



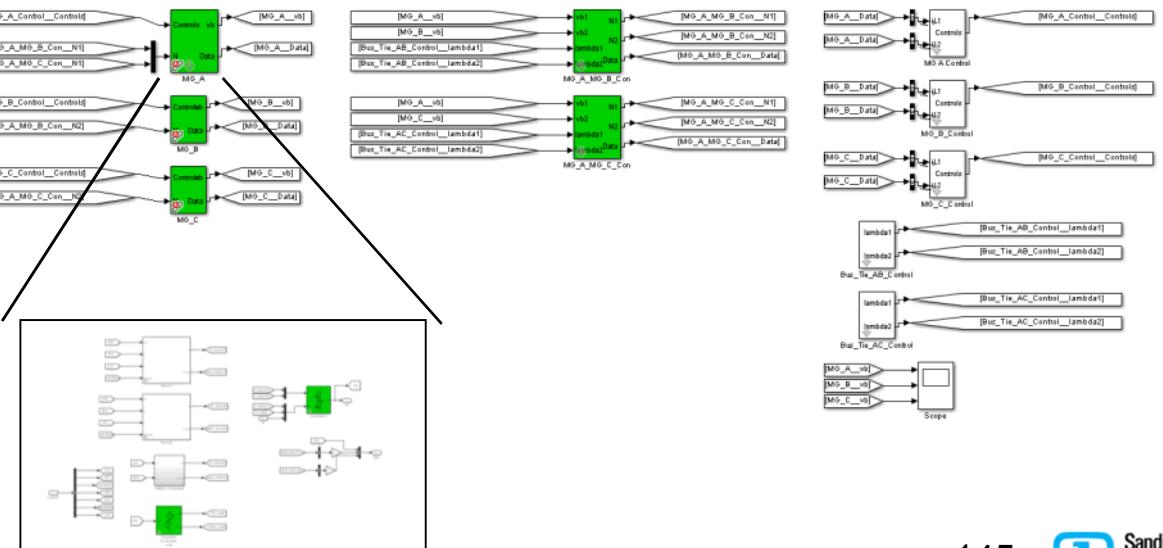
All Hardware Components are Represented in a Matlab/Simulink Library

- System components are modeled and calibrated to lab hardware



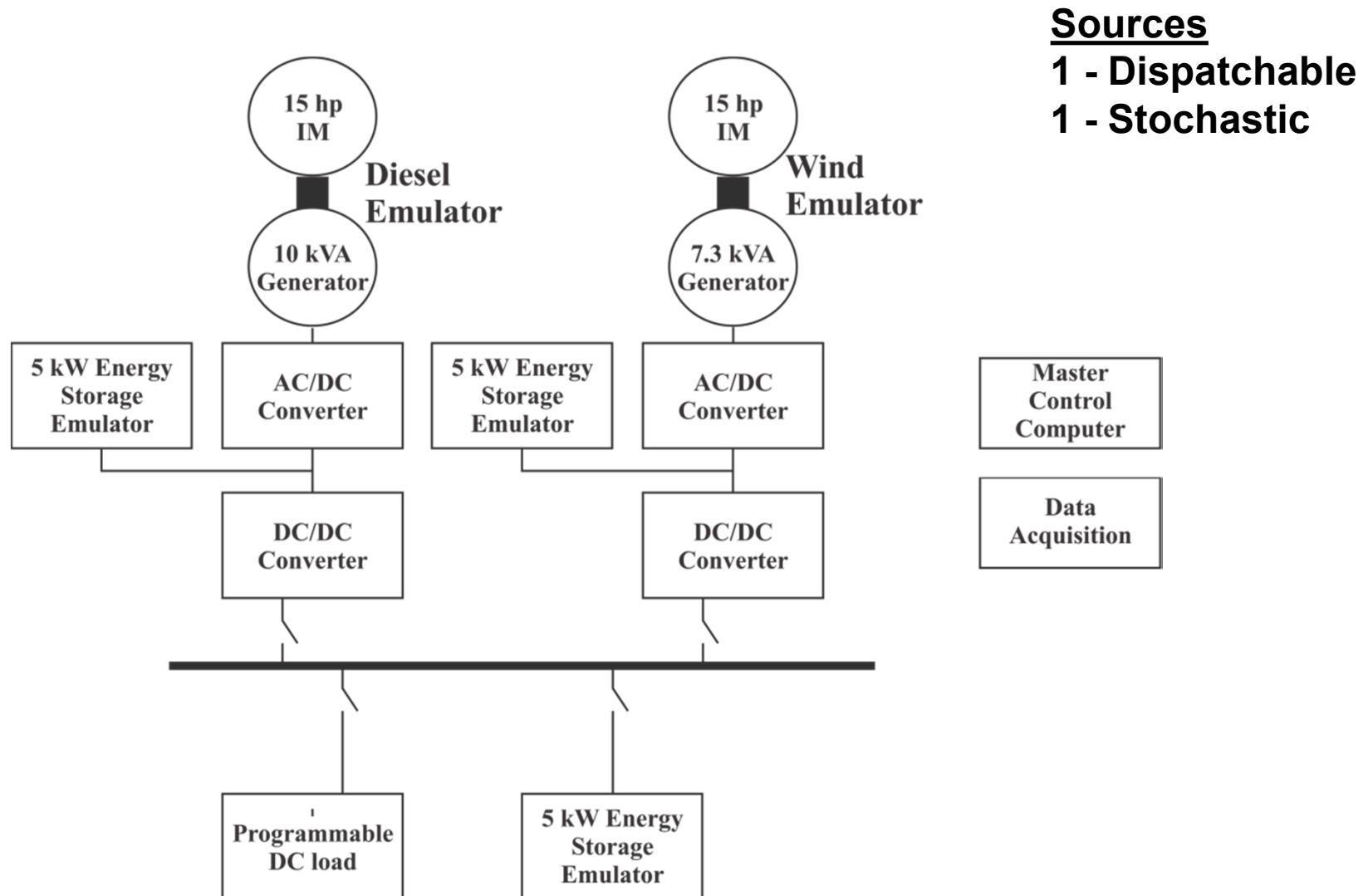
- Simulated microgrids matching lab hardware may be interconnected virtually using a simple Matlab script

```
1 % This file builds a simple model with three microgrids. It demonstrates the
2 % usage of the commands for building collective models.
3 % clear cl;
4 %
5 % Define the source paths for the block used in this model
6 % MGControl = 'simulink/MV/Average Value Model/Simplified Microgrid';
7 % MGControl = 'simulink/MV/Average Value Model/Simplified Bus Tie';
8 % BusTieControl = 'simulink/MV/Average Value Model/Simplified Bus Tie Control';
9 % BusTieControl = 'simulink/MV/Average Value Model/Simplified Bus Tie Control';
10 % BusTieControl = 'built-in/Scope';
11 %
12 % Create an empty collective structure. Only the name of the collective is
13 % needed here.
14 CL = CreateCollective('SandiaCL');
15 %
16 % Add the microgrids to the collective.
17 %
18 % The user specifies the microgrid the microgrid is added to, the path
19 % of the MG block, and the name of the MG in the collective. The last two
20 % arguments specify the input connections and the name parameters.
21 %
22 % For example, the first addMG command adds a simplified MG named 'MO_A' to the
23 % collective CL. The MG block's path is specified on the MGno variable.
24 % The input 'Control' of 'MO_A' should be connected to the 'Controls'-
25 % output of the 'MO_A_Control' block ('MO_A_Control', 'Controls').
26 % The 'cl' parameter of 'MO_A' should be set to 'cl'.
27 %
28 % The three addMG commands and three MG blocks to the collective. They have
29 % different 'cl'ad values, and their inputs are from their respective 'MO_X_Control'
30 % blocks to be added later.
31 %
32 % It should be noted that the input connection specification are only
33 % related to generic signals. Electric connection between MG block and
34 % connection blocks (bus tie, transmission lines, etc.) are specified by the
```



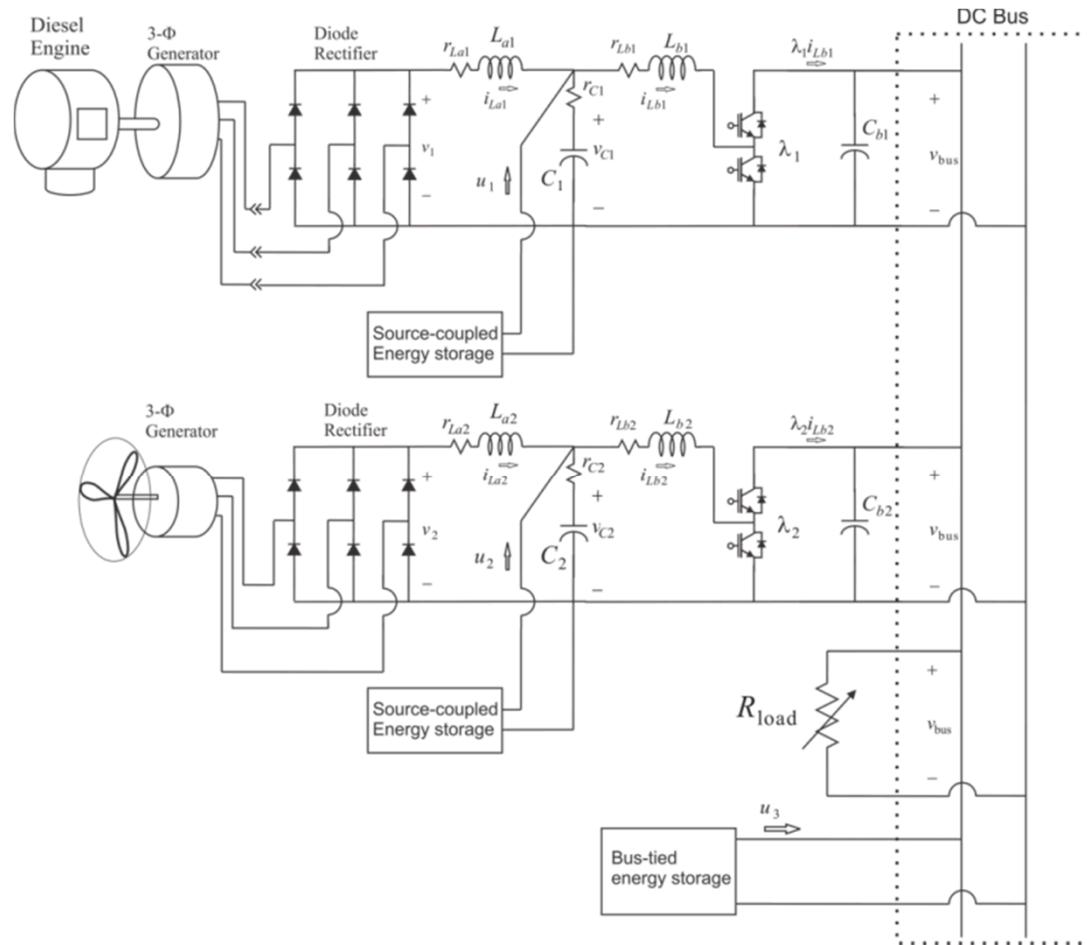
- Example of Droop Control versus Hamiltonian Control

SSM Test Bed Configuration



SSM Test Bed Configuration

Hardware realization



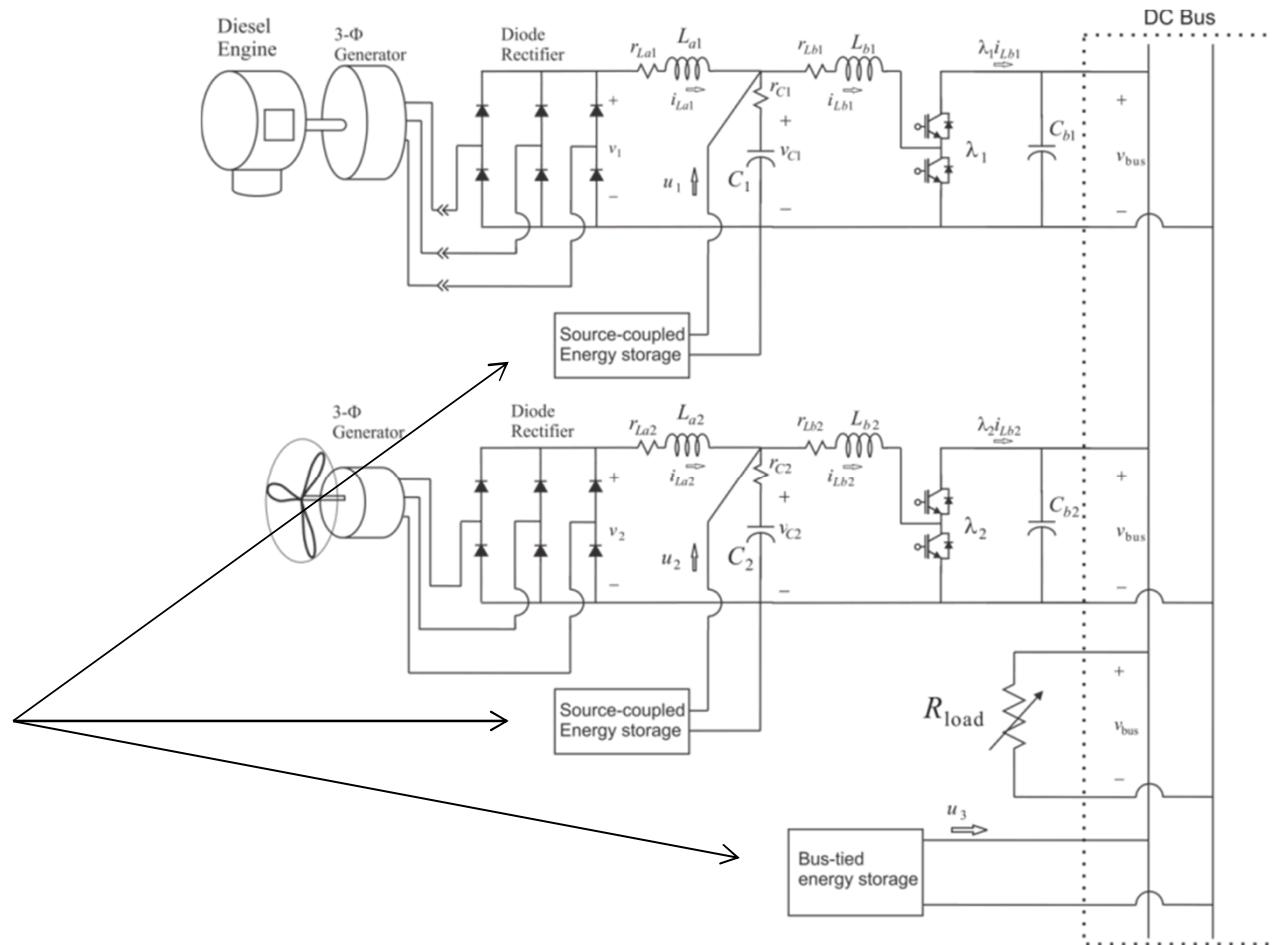
$$\begin{bmatrix} C_1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & L_{a1} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & L_{b1} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & C_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & L_{a2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & L_{b2} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & C_{b1} + C_{b2} \end{bmatrix} \begin{bmatrix} \dot{v}_{C1} \\ \dot{i}_{La1} \\ \dot{i}_{Lb1} \\ \dot{v}_{C2} \\ \dot{i}_{La2} \\ \dot{i}_{Lb2} \\ \dot{v}_{bus} \end{bmatrix} =$$

$$\begin{bmatrix} 0 & 1 & -1 & 0 & 0 & 0 & 0 \\ -1 & -(r_{La1} + r_{C1}) & r_{C1} & 0 & 0 & 0 & 0 \\ 1 & r_{C1} & -(r_{Lb1} + r_{C1}) & 0 & 0 & 0 & -\lambda_1 \\ 0 & 0 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & -1 & -(r_{La2} + r_{C2}) & r_{C2} & 0 \\ 0 & 0 & 0 & 1 & r_{C2} & -(r_{Lb2} + r_{C2}) & -\lambda_2 \\ 0 & 0 & \lambda_1 & 0 & 0 & \lambda_2 & -R_{load}^{-1} \end{bmatrix} \begin{bmatrix} v_{C1} \\ i_{La1} \\ i_{Lb1} \\ v_{C2} \\ i_{La2} \\ i_{Lb2} \\ v_{bus} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} + \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix}$$

SSM Test Bed Configuration

Hardware realization

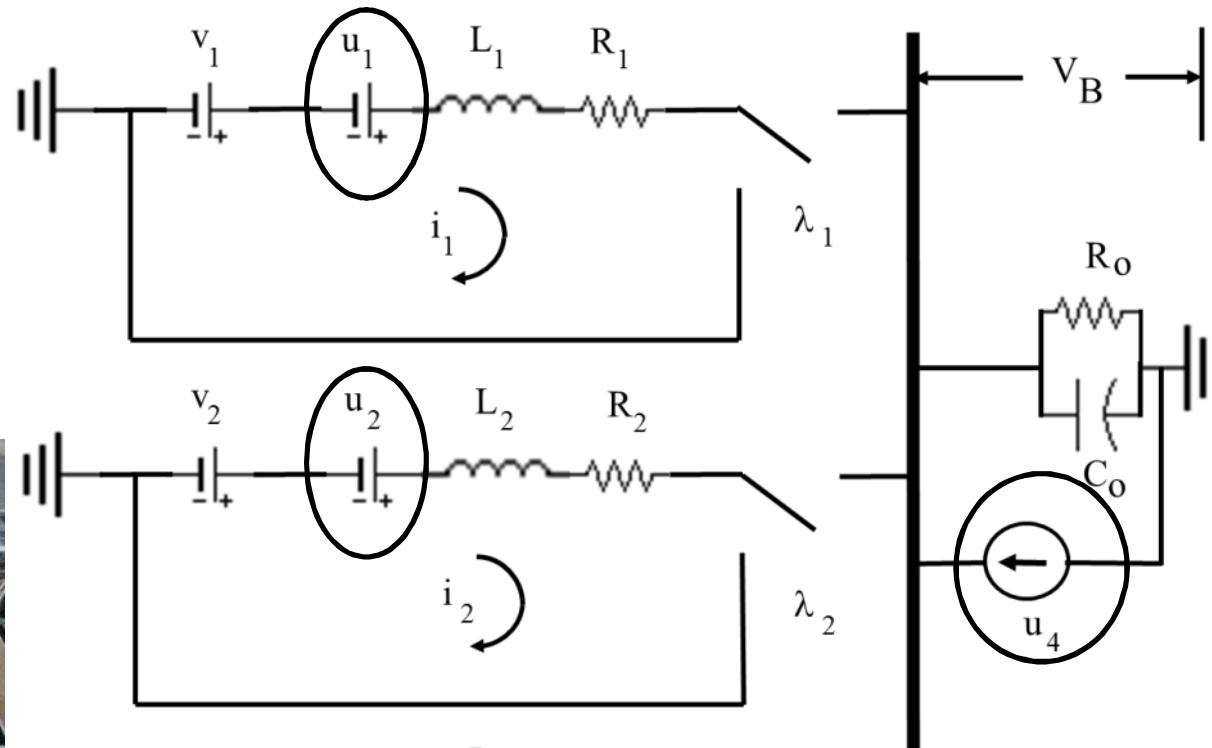
- ARESE
 - Arbitrary
 - Response
 - Energy
 - Storage
 - Emulator



SSM Test Bed Configuration

Reduced Model used for Hamiltonian Control

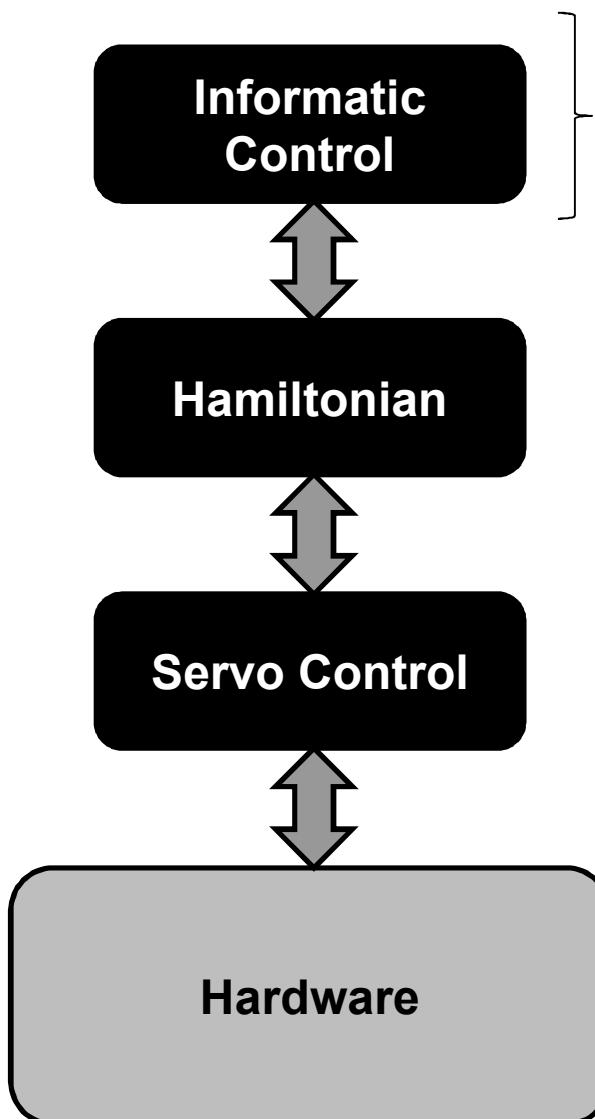
- ARESE
 - Arbitrary
 - Response
 - Energy
 - Storage
 - Emulator



$$\begin{bmatrix} L_{b1} & 0 & 0 \\ 0 & L_{b2} & 0 \\ 0 & 0 & C_{b1} + C_{b2} \end{bmatrix} \begin{bmatrix} \dot{i}_{Lb1} \\ \dot{i}_{Lb2} \\ \dot{v}_{bus} \end{bmatrix} = \begin{bmatrix} -r_{Lb1} & 0 & -\lambda_1 \\ 0 & -r_{Lb2} & -\lambda_2 \\ \lambda_1 & \lambda_2 & -R_{load}^{-1} \end{bmatrix} \begin{bmatrix} i_{Lb1} \\ i_{Lb2} \\ v_{bus} \end{bmatrix} + \begin{bmatrix} v_1 \\ v_2 \\ 0 \end{bmatrix} + \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix}$$

SSM Test Bed Configuration

Control Hierarchy



This was done offline using a Matlab script
To solve the following optimization problem
given the 100 second experiment information

$$\text{maximize } J = \lambda_2 I_{L2} V_{bus}$$
$$\mathbf{x}_{\text{ref}}, \lambda, \mathbf{u}_{\text{ref}}$$

subject to :

i. $V_{bus} = 100V$

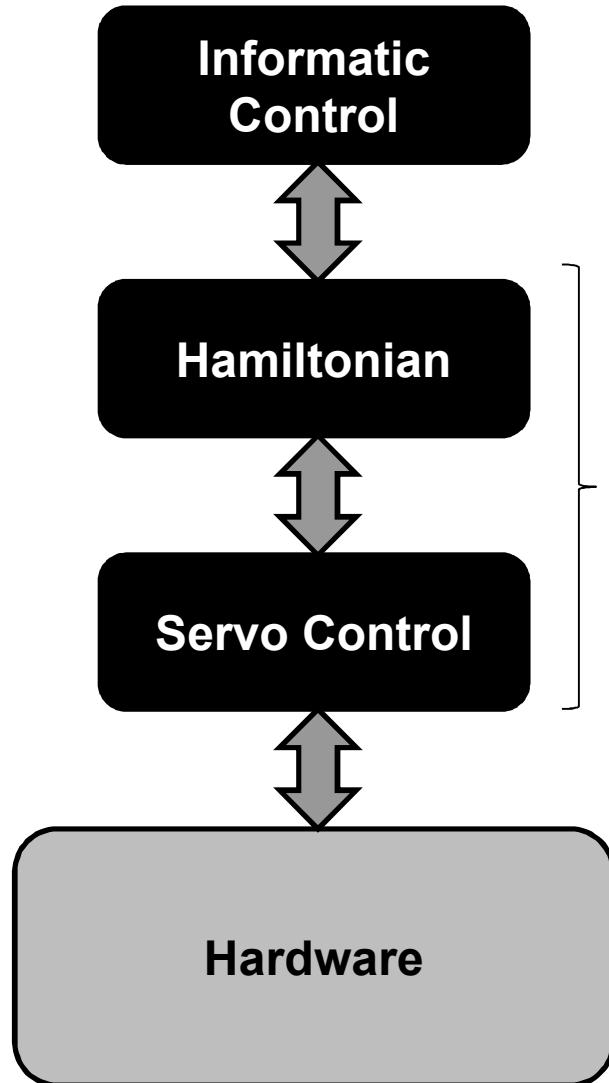
ii. $\lambda_1 I_{L1} V_{bus} > P_{d,\min}$

iii. $\lambda_1, \lambda_2 \in [0,1]$

iv. $\lambda_1 I_{L1} + \lambda_2 I_{L2} = V_{bus} \bar{G}_{load}$

SSM Test Bed Configuration

Control Hierarchy



These were done online the Versalogic Controller



Hamiltonian Control

$$\tilde{\mathbf{u}} = -\mathbf{K}_p \tilde{\mathbf{x}} - \mathbf{K}_i \int_0^t \tilde{\mathbf{x}} d\tau$$

$$\mathbf{u}^* = \mathbf{u}_{\text{ref}} + \tilde{\mathbf{u}}$$

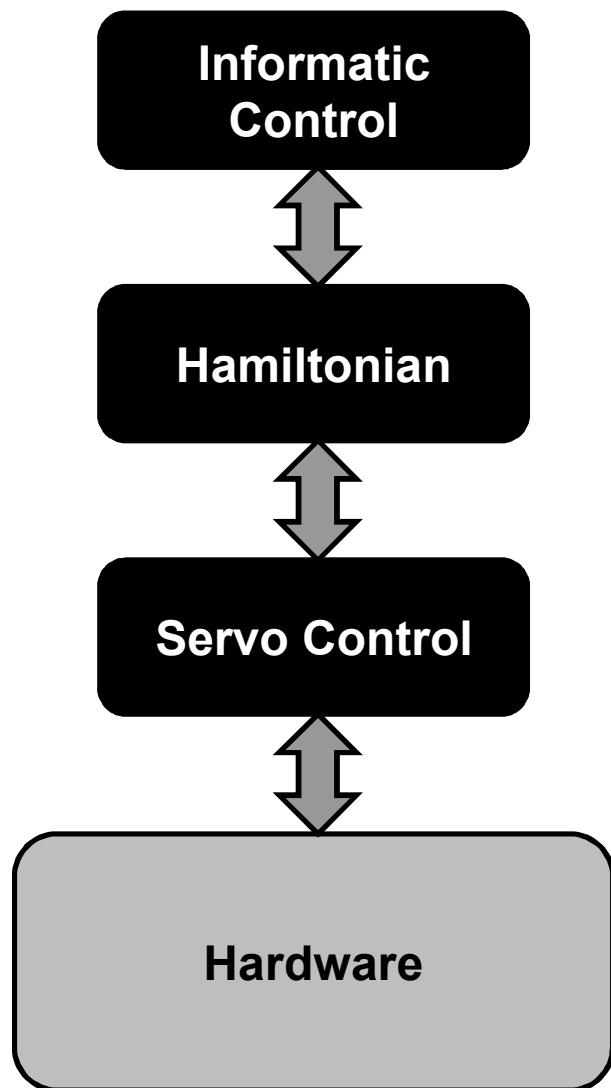
Servo Control

$$d_{ARESE} = f(x_{ARESE}, \mathbf{u}^*)$$

such that $\mathbf{u} \rightarrow \mathbf{u}^*$

SSM Test Bed Configuration

Control Hierarchy



Typical Time scales

10 msec – 100s of seconds

1msec-1sec

10 μ sec – 10 msec

Servo Control

Hardware

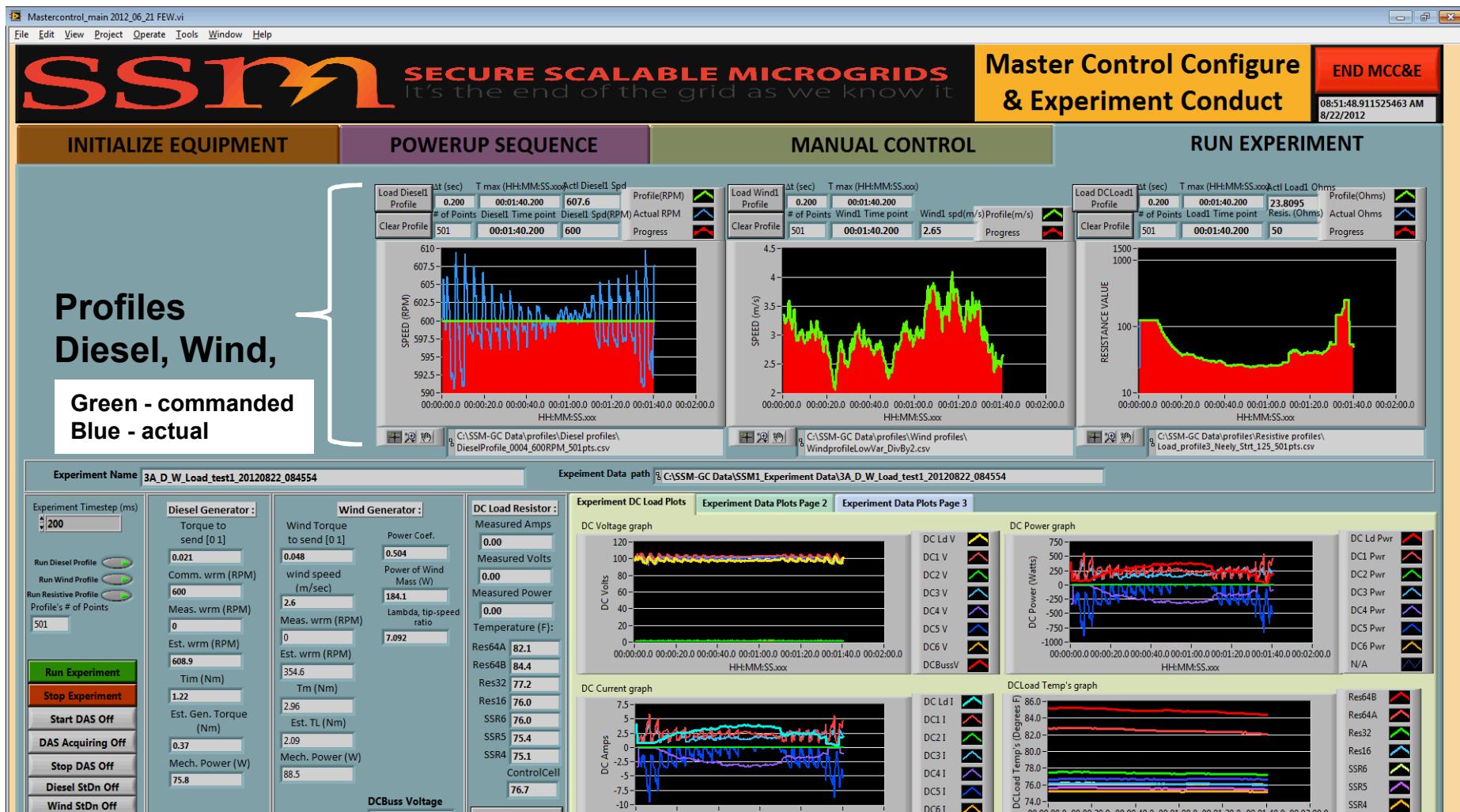
Time scales of our system

100 seconds

200 msec

100 μ sec

Conventional Control Approach with Droop (LWV) - Hardware Results

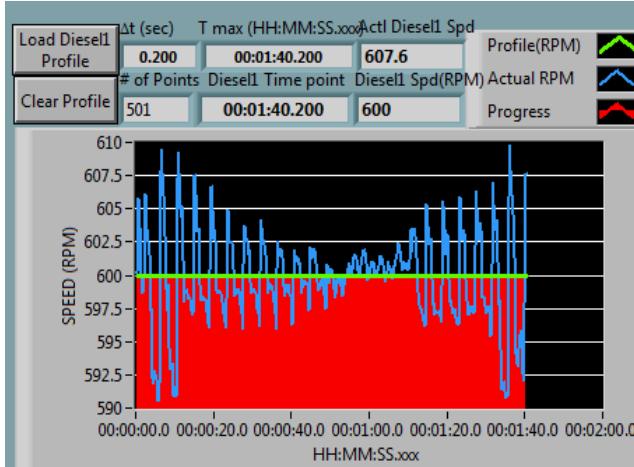


(LWV) Low variability wind speed profile

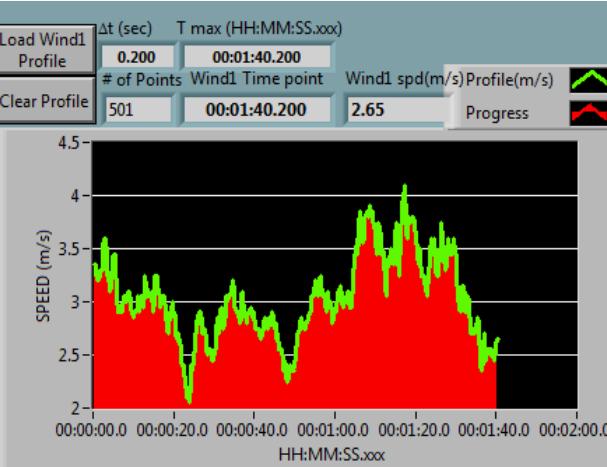
Conventional Control Approach with Droop (LVW) - Hardware Results

Source and load profiles

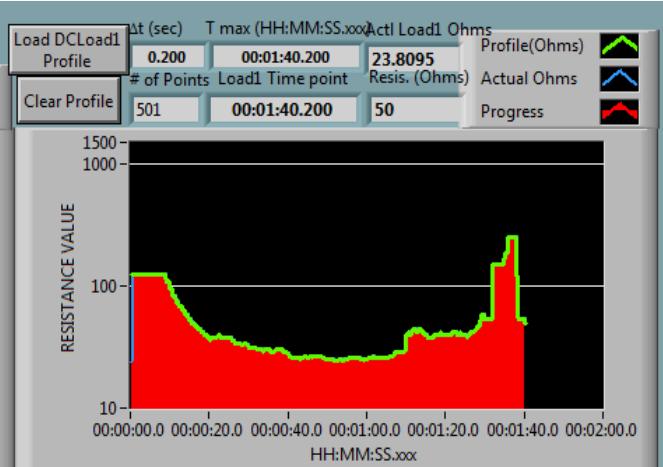
Diesel



Wind



Load



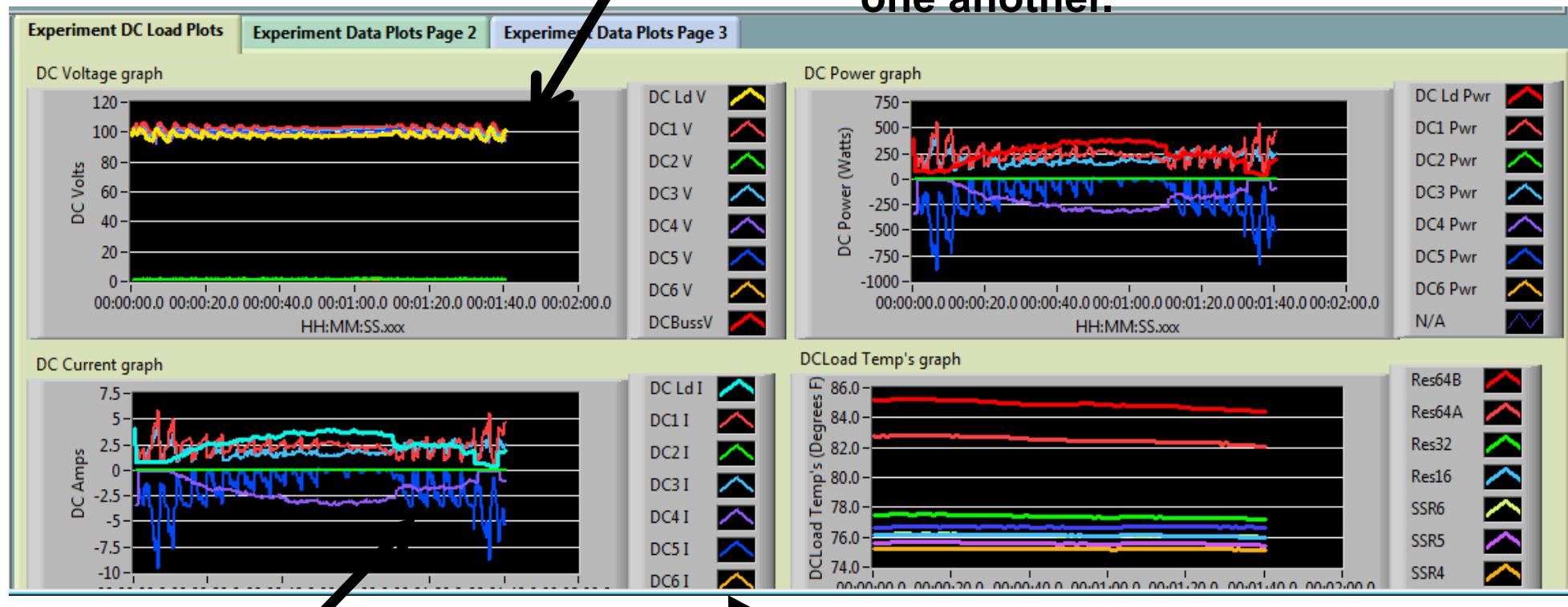
Green – commanded profile
Blue – actual profile
Red – indicates progress in time

Diesel engine speed is varying by ~1.5% due to perturbations in the system.

Conventional Control Approach with Droop (LVW) - Hardware Results Config. 1

Notice oscillations on the bus voltage.

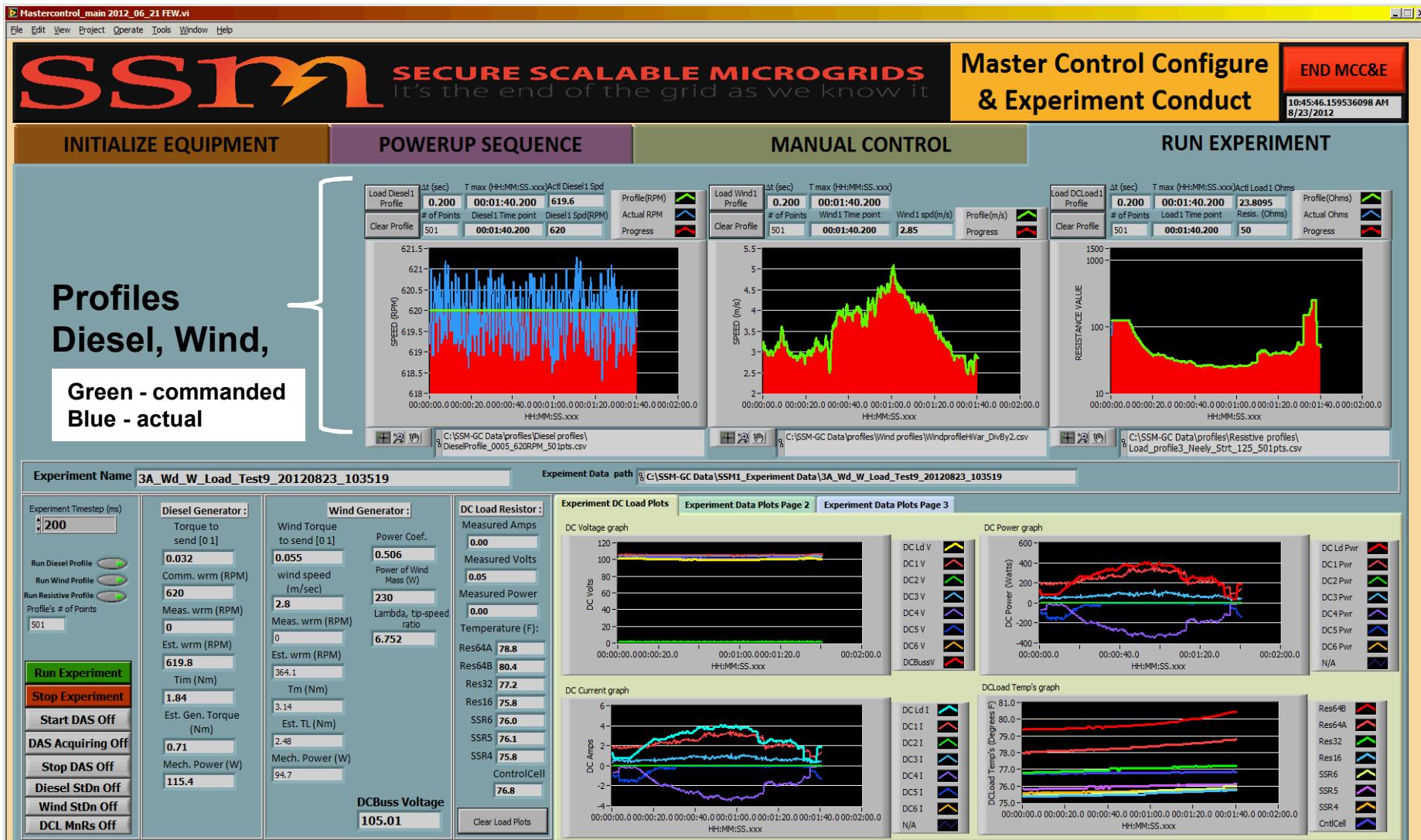
Oscillations indicate that the sources in the system are fighting one another.



Oscillations are also apparent in the source and load currents at the bus

Cyan – load current
Red – diesel current
Light blue – wind current
Purple – load current
Dark blue – Bus energy storage current

Hamiltonian Based Control Approach with Full State Control (HVW) - Hardware Results

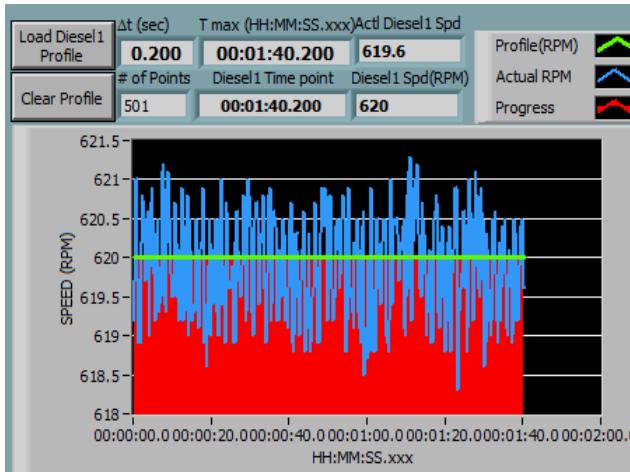


(HVW) High variability wind speed profile

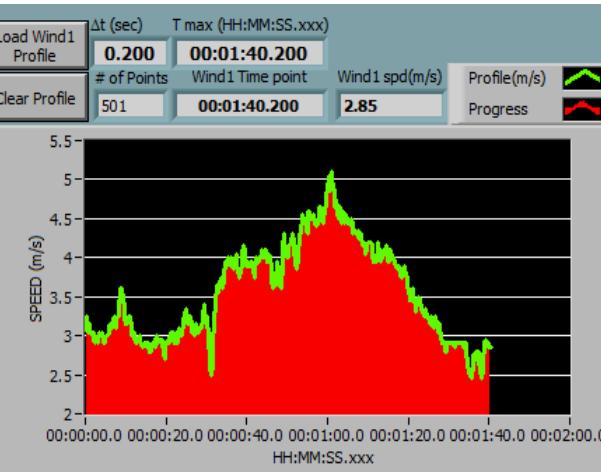
Hamiltonian Based Control Approach with Full State Control (HVW) - Hardware Results

Source and load profiles

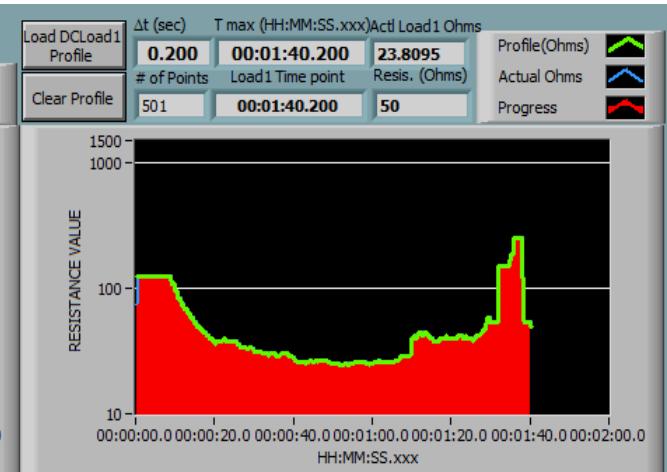
Diesel



Wind



Load



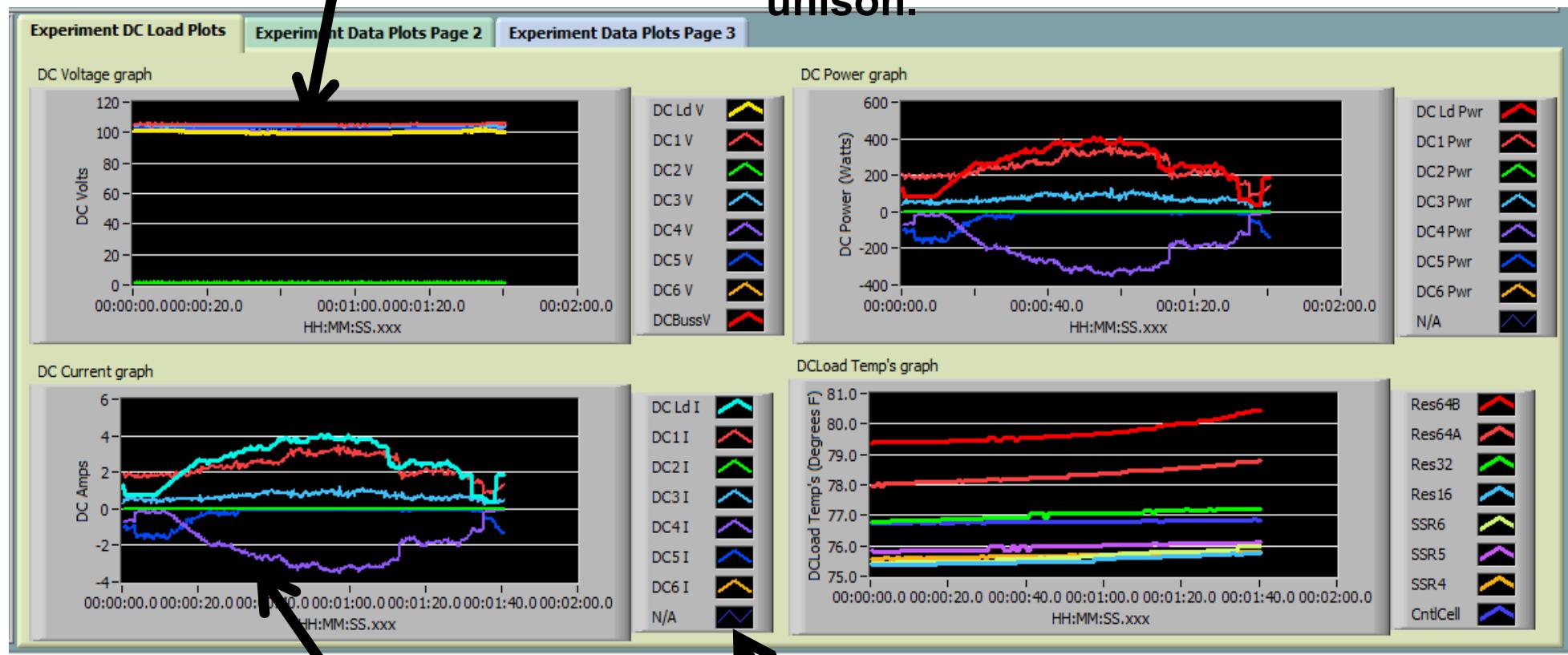
Green – commanded profile
Blue – actual profile
Red – indicates progress in time

Diesel engine speed is varying by ~0.28% due to perturbations in the system.

Hamiltonian Based Control Approach with Full State Control (HVW) - Hardware Results

Notice reduced oscillations on the bus voltage.

Lack of oscillations indicate that the sources in the system are working in unison.

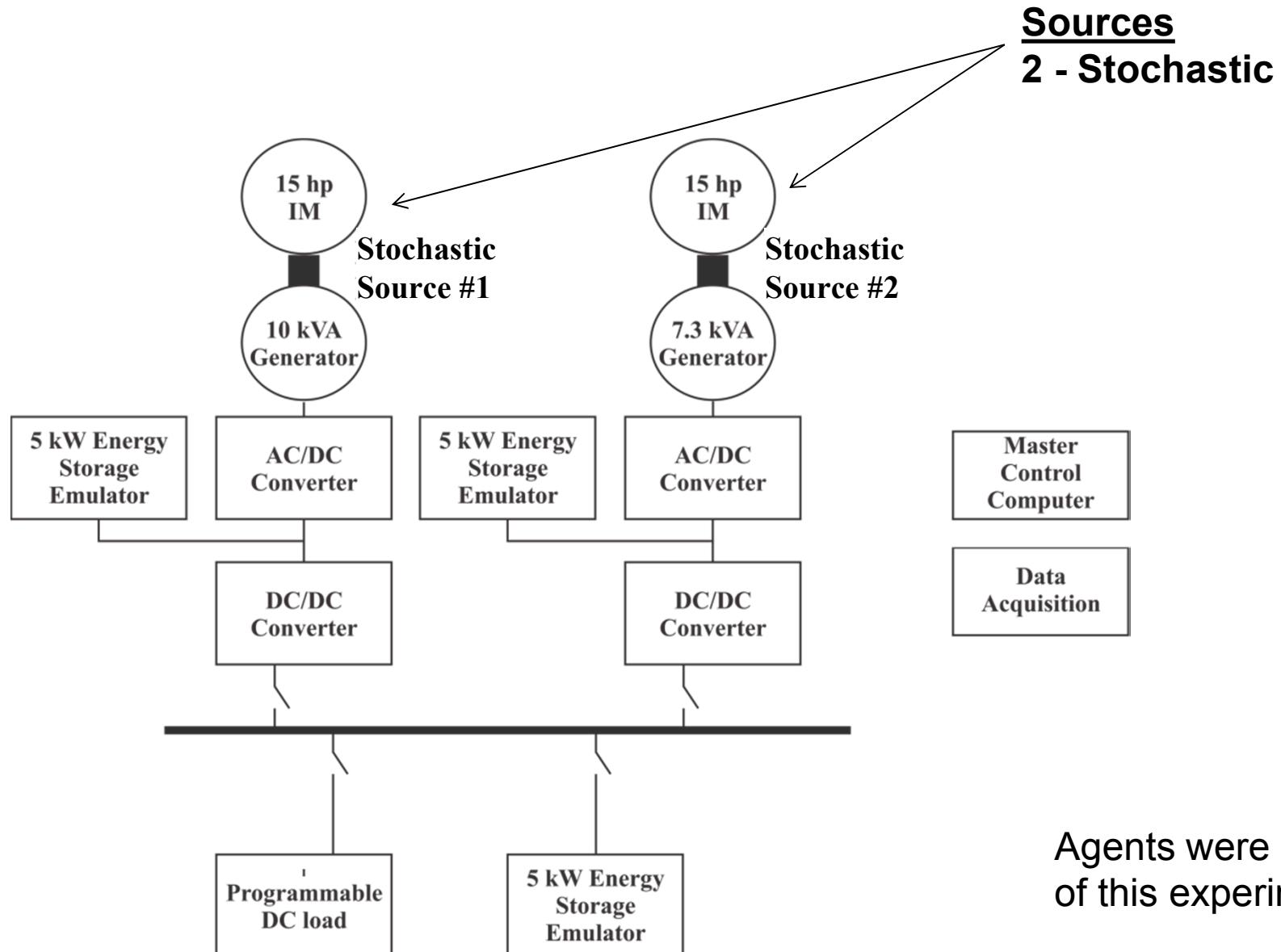


Oscillations are also not apparent in the source and load currents at the bus

Cyan – load current
Red – diesel current
Light blue – wind current
Purple – load current
Dark blue – Bus energy storage current

100% Stochastic Generation

Demonstrated Performance with 100% Stochastic Generation and Load is Enabled Through Controls and Storage

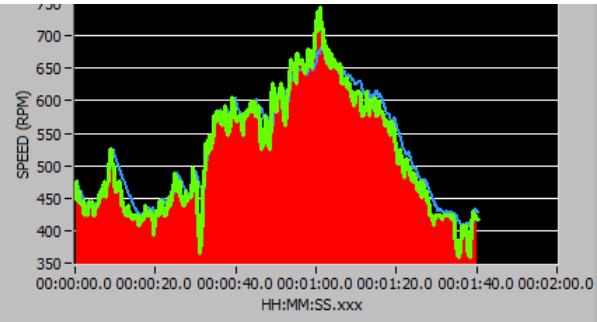


Agents were not part of this experiment.

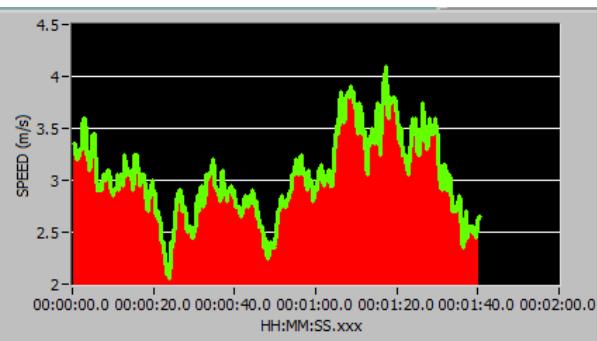
Hamiltonian Based Control Approach with Full State Control – Reduces Bus Voltage Transients

Source and load profiles

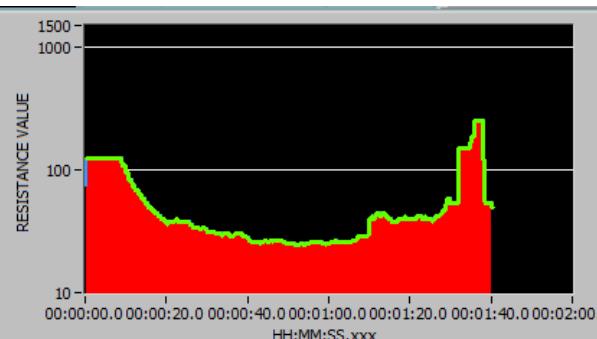
Stochastic source #1



Stochastic source # 2

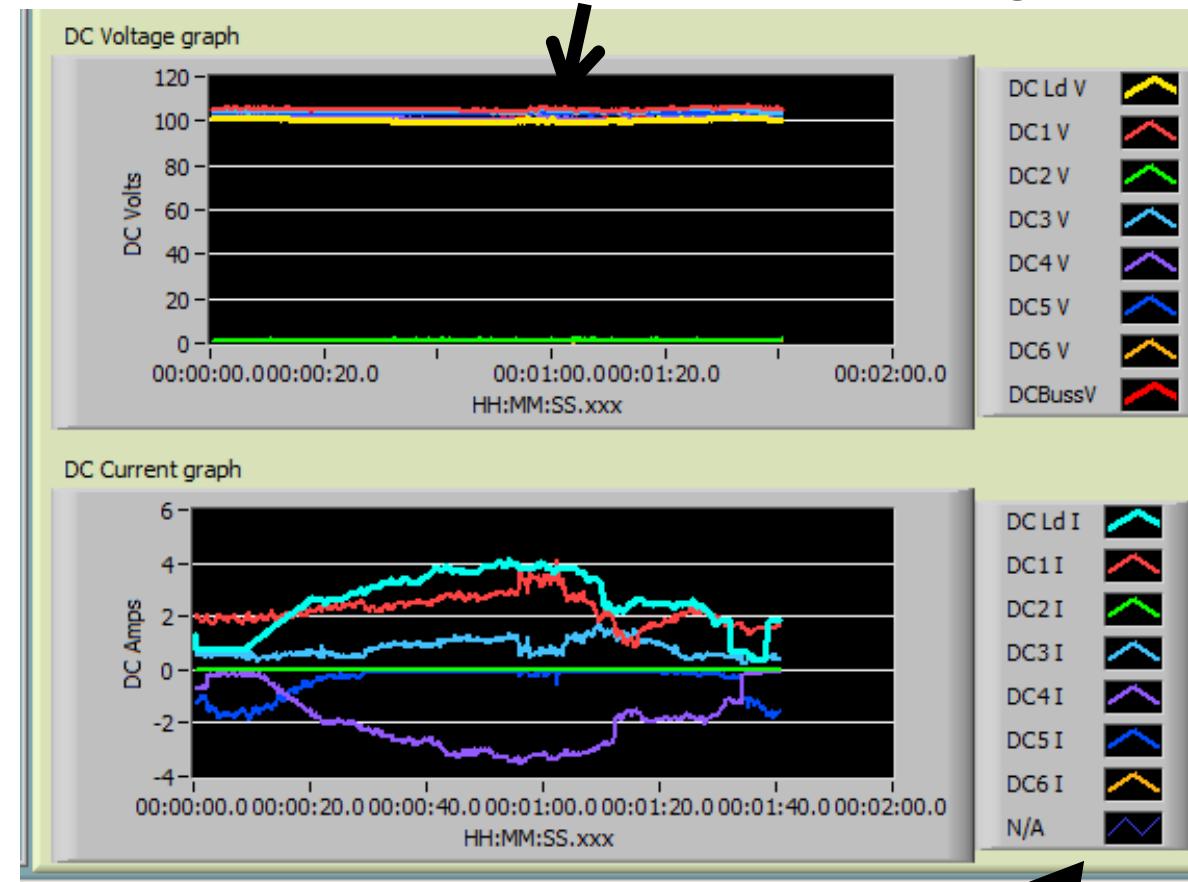


Load



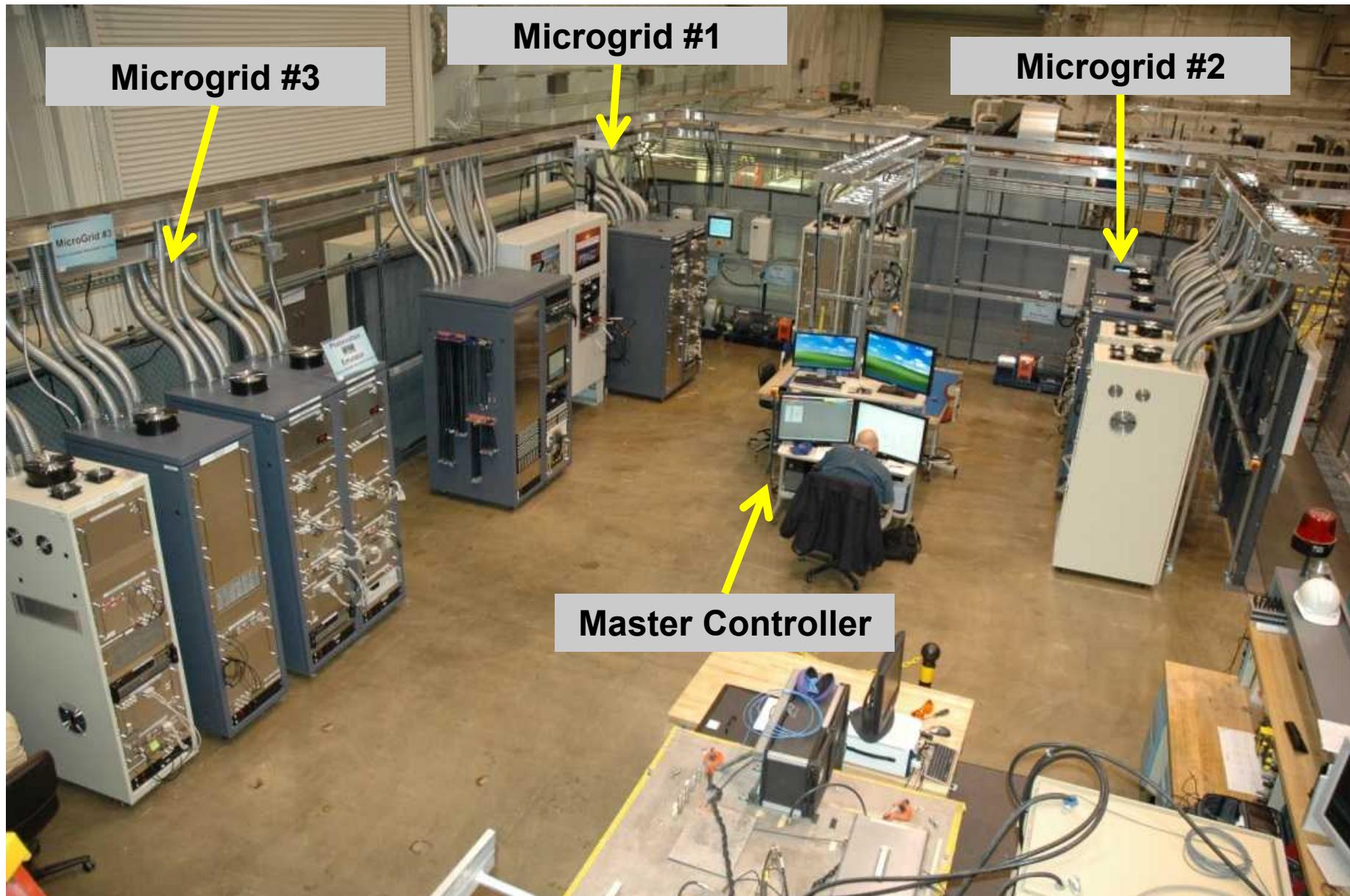
Green – commanded profile
Blue – actual profile
Red – indicates progress in time

Transients are not evident in the bus voltage



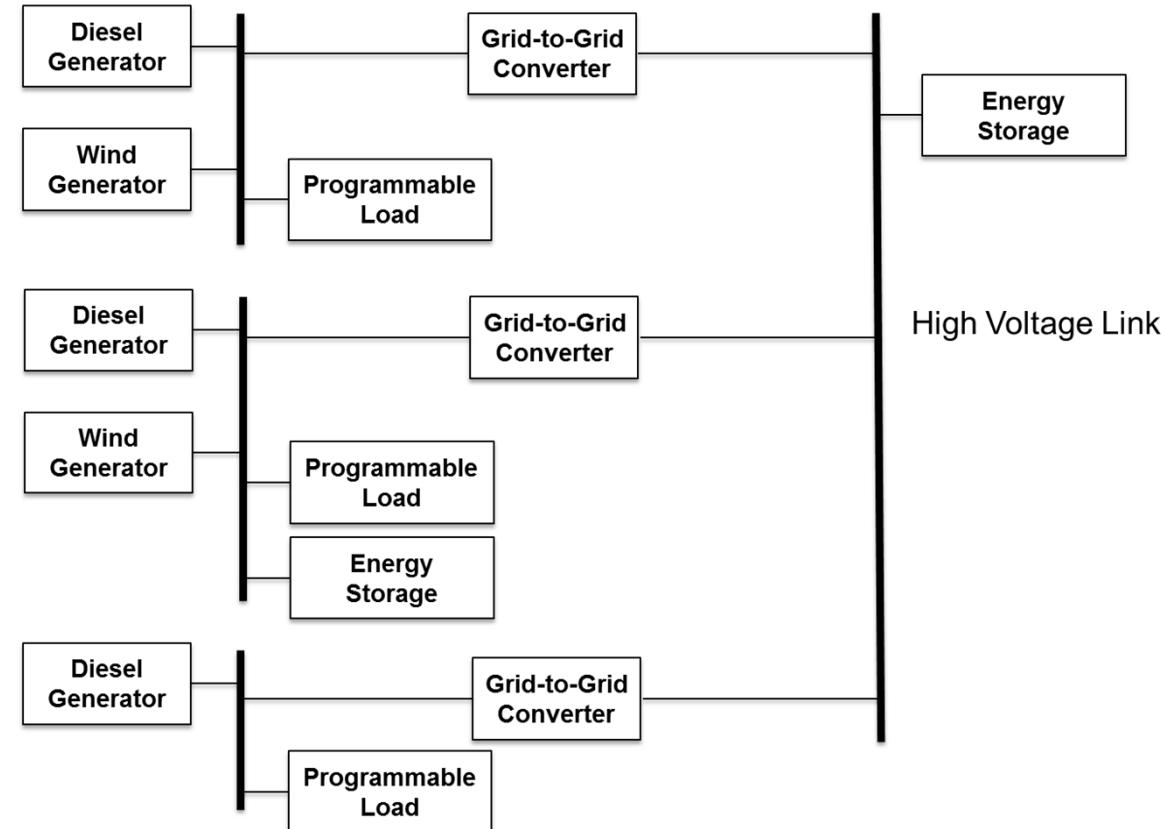
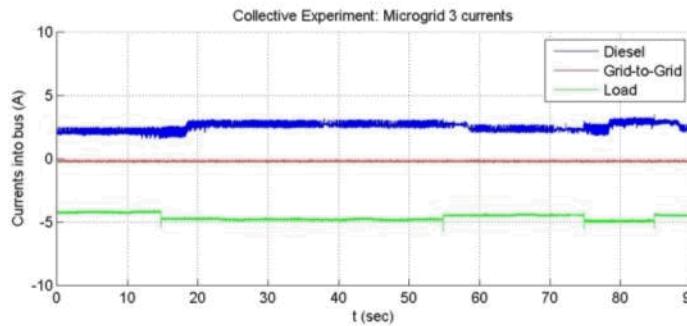
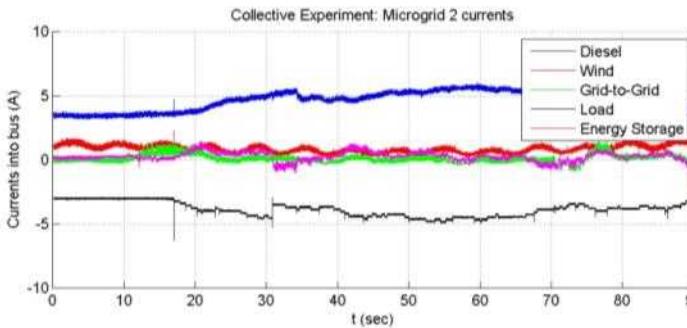
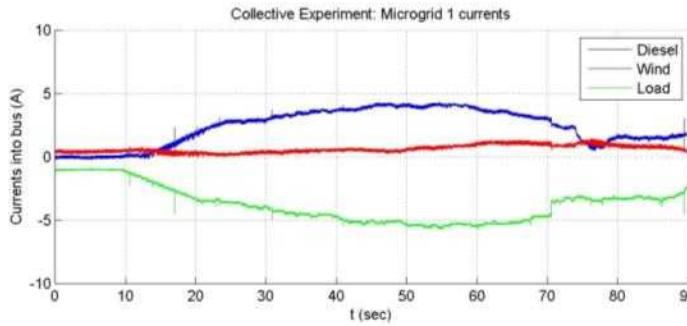
Cyan – load current
Red – stochastic source 1 current
Light blue – stochastic source 2 current
Purple – load current
Dark blue – Bus energy storage current

Networked Microgrids can add to Power System Reliability and Resiliency



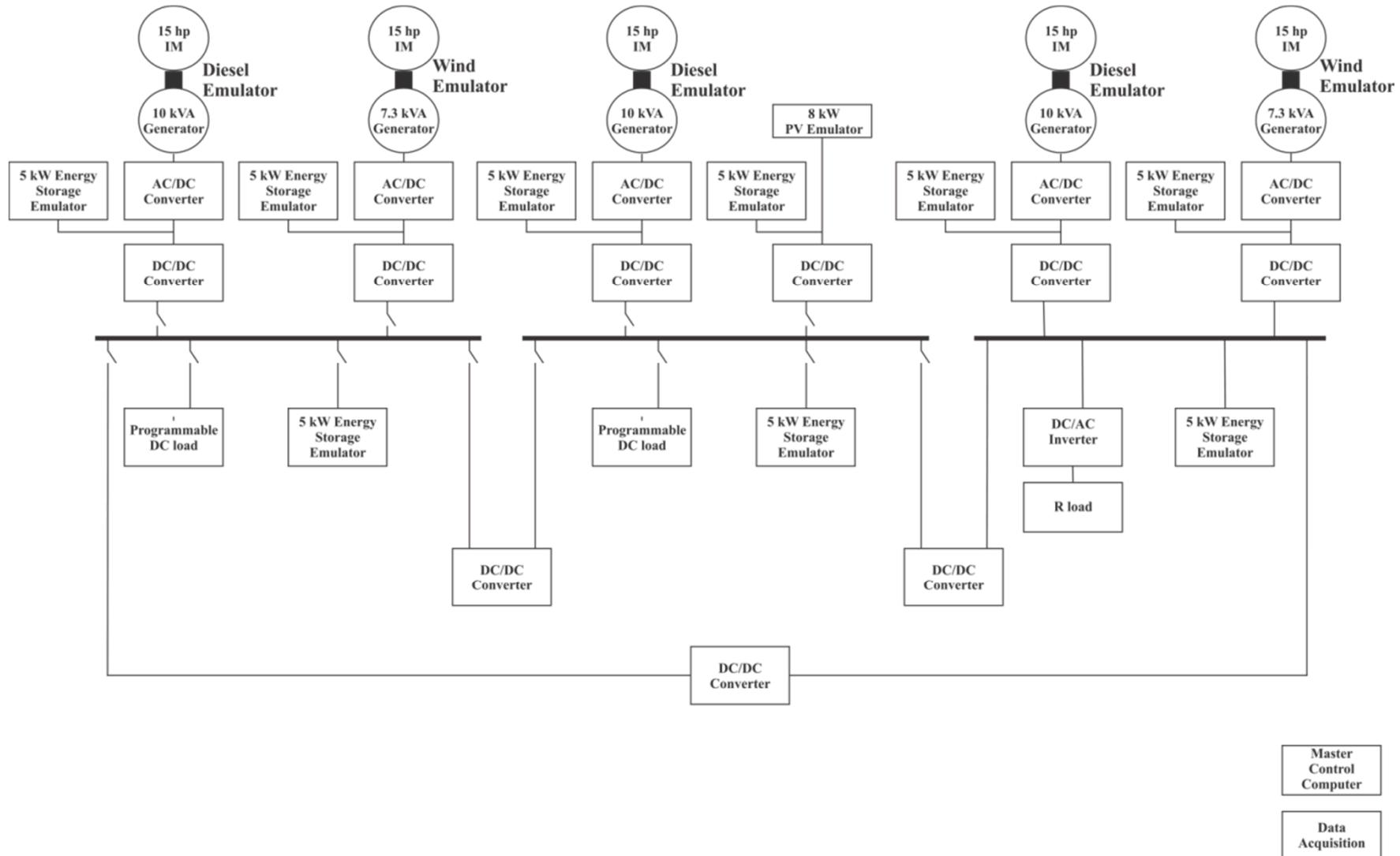
SSM Testbed Allows Study of Microgrid Collectives

- Centralized data acquisition allows plotting/analysis in Matlab

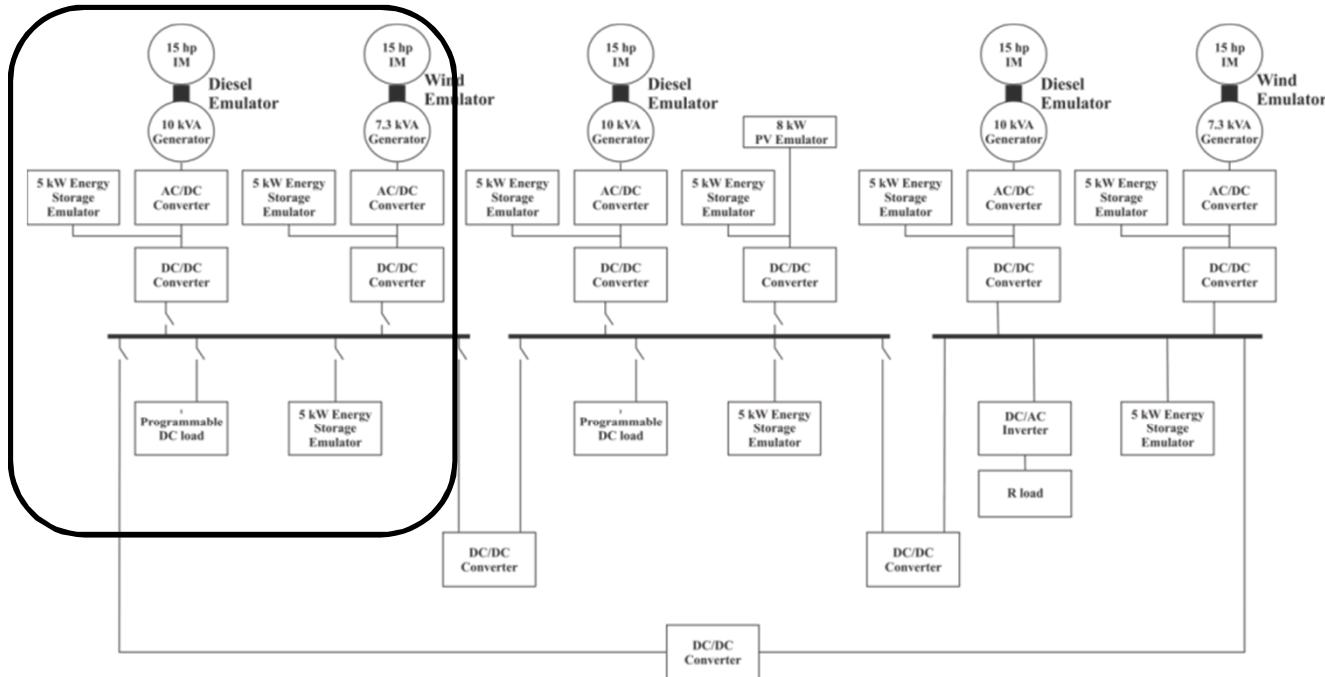


- **NETWORK EXAMPLE**

SSM Collective Configuration



MicroGrid 1 Layout

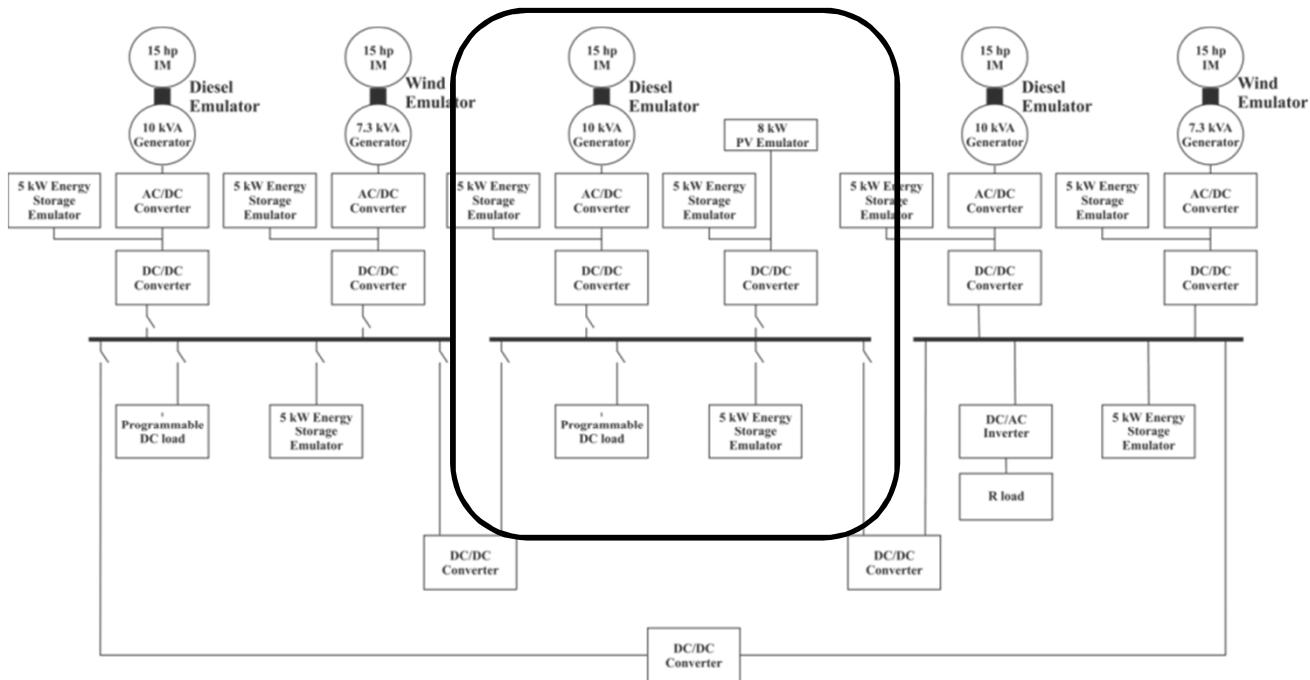


- Diesel Generator with storage
- Wind Generator with storage
- Bus-tied Energy storage
- Programmable Digital Resistor
- Presettable Digital Resistor
- Bus-to-Bus DC converter

Total Generation: 15.0 kW
Total Load: 13.4 kW
Energy Storage: +/- 15 kW

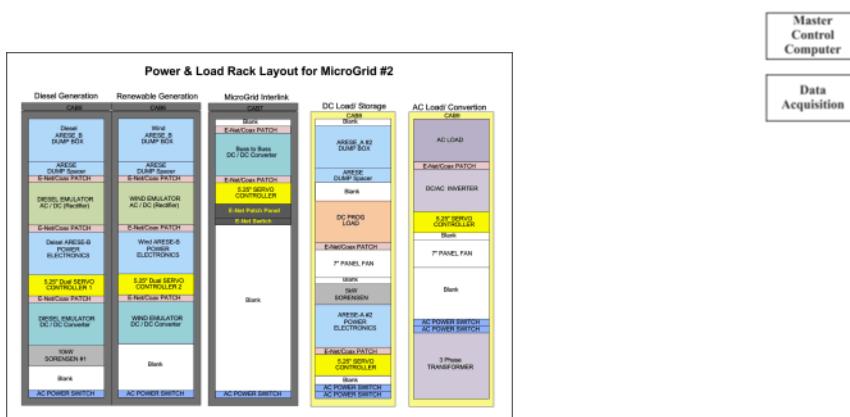


MicroGrid 2 Layout

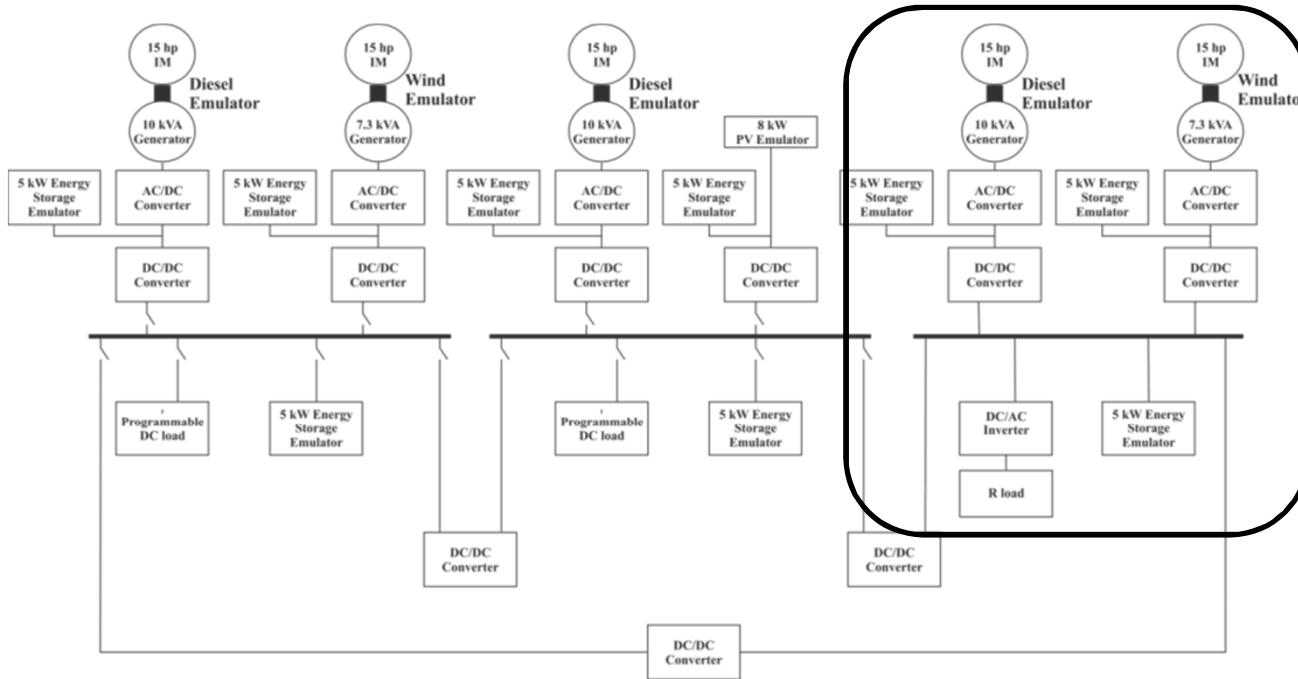


- Diesel Generator with storage
- Wind Generator with storage
- Bus-tied Energy storage
- Programmable Digital Resistor
- Inverter with 3-Φ load
- Bus-to-Bus DC converter

Total Generation: 15.0 kW
 Total Load: 10.4 kW
 Energy Storage: +/- 15 kW

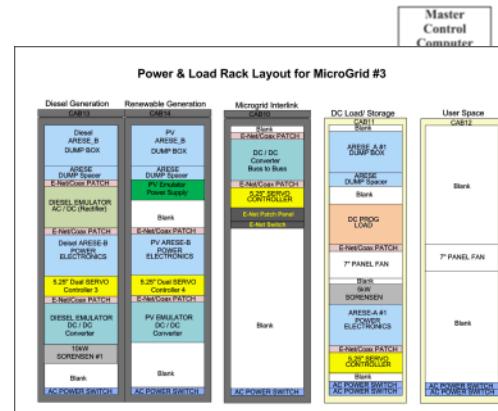


MicroGrid 3 Layout

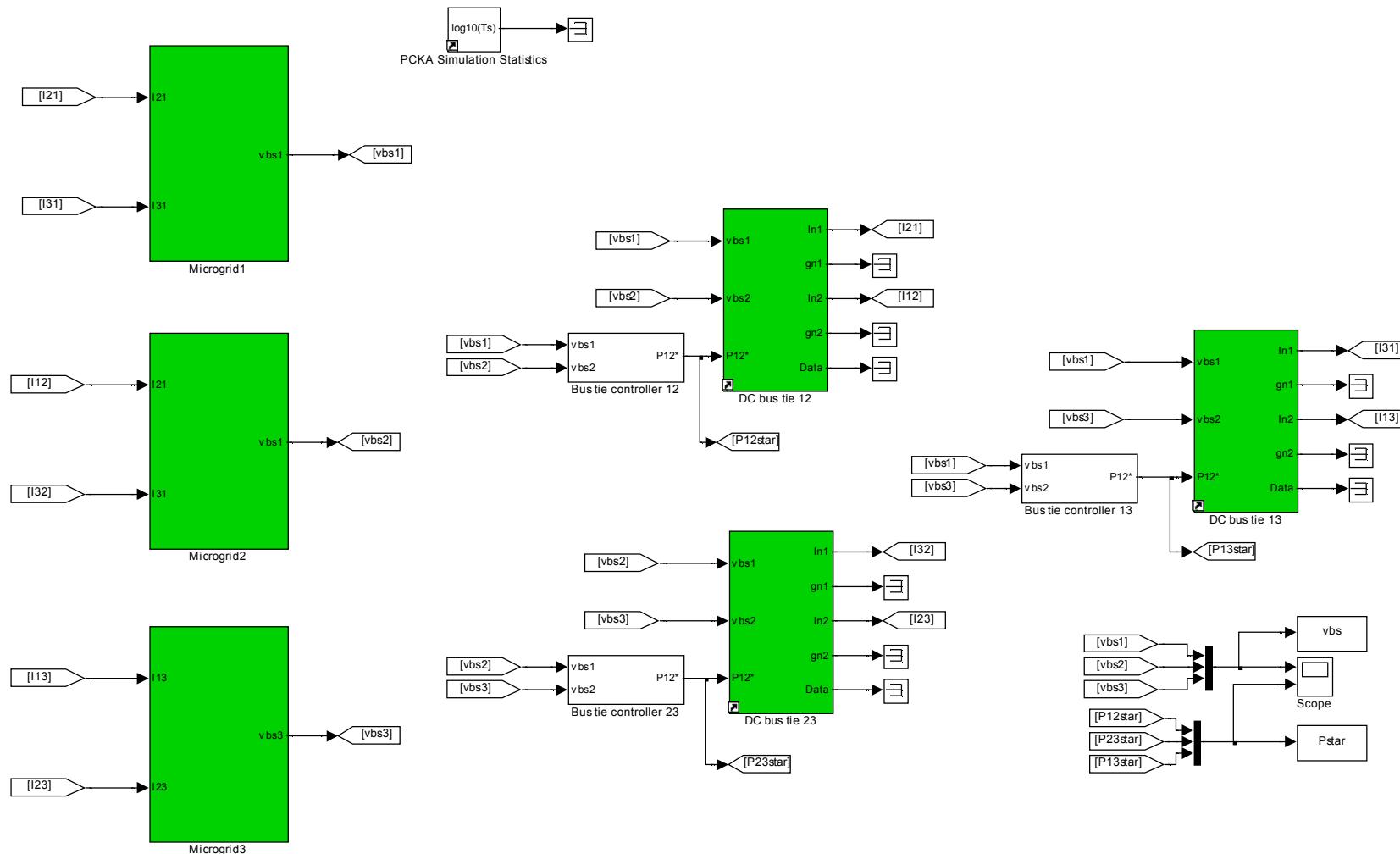


- Diesel Generator with storage
- PV Generator with storage
- Bus-tied Energy storage
- Programmable Digital Resistor
- Presettable Digital Resistor
- Bus-to-Bus DC converter

Total Generation: 15.0 kW
Total Load: 13.4 kW
Energy Storage: +/- 15 kW

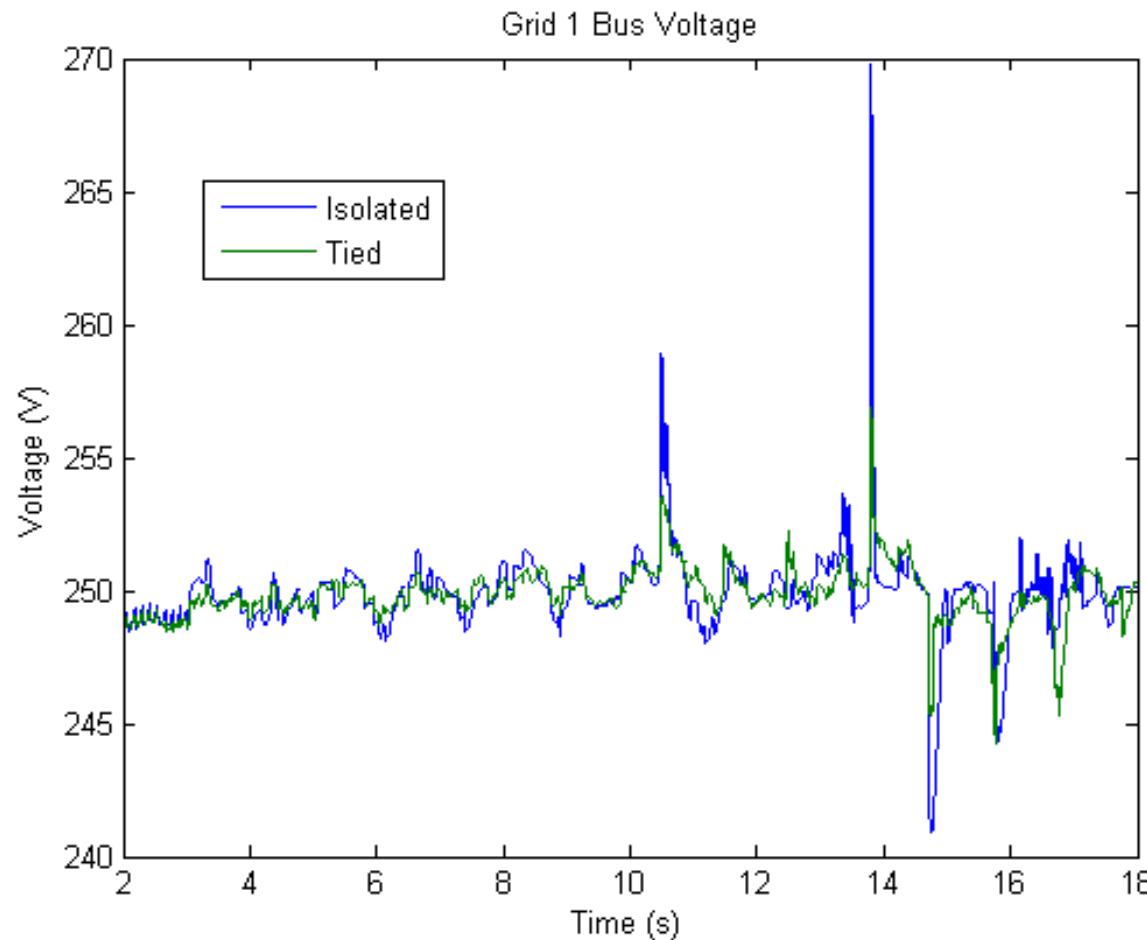


Three-Microgrid Collective Simulation



- Microgrid 1: Diesel with ARESE, Wind with ARESE, Resistive Load, Bus with ARESE
- Microgrid 2: Diesel with ARESE, Wind with ARESE, Resistive Load, Bus with ARESE
- Microgrid 3: Diesel with ARESE, PV with ARESE, Resistive Load, Bus with ARESE

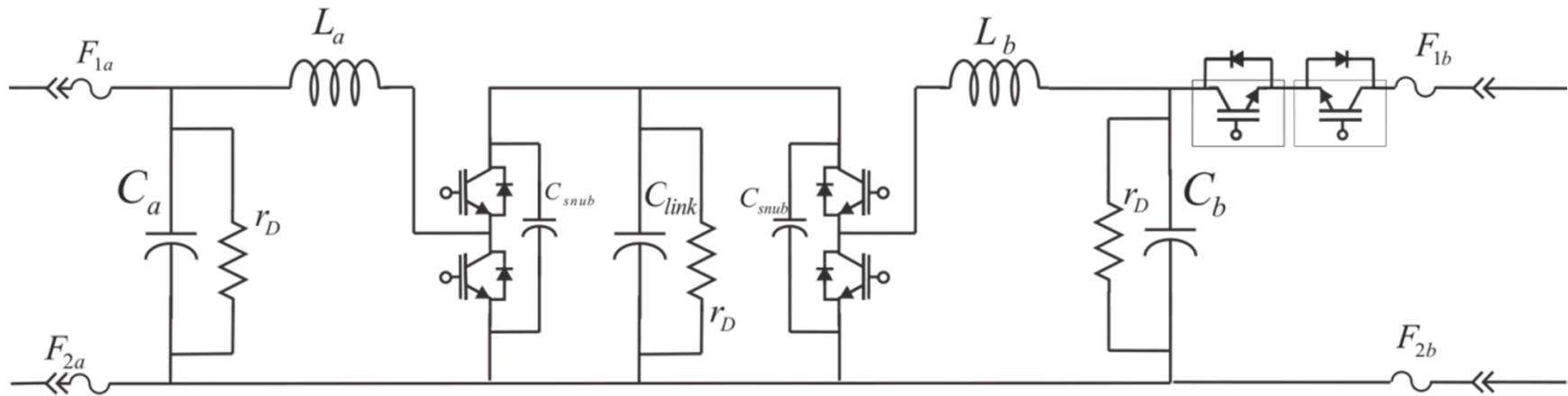
Microgrid #1 Bus Voltage



- Reduced bus voltage transients achieved by connecting grids
- Some external events cause transients otherwise not seen

Grid-to-Grid DC Tie Converter Controls Power Flow Between Microgrids

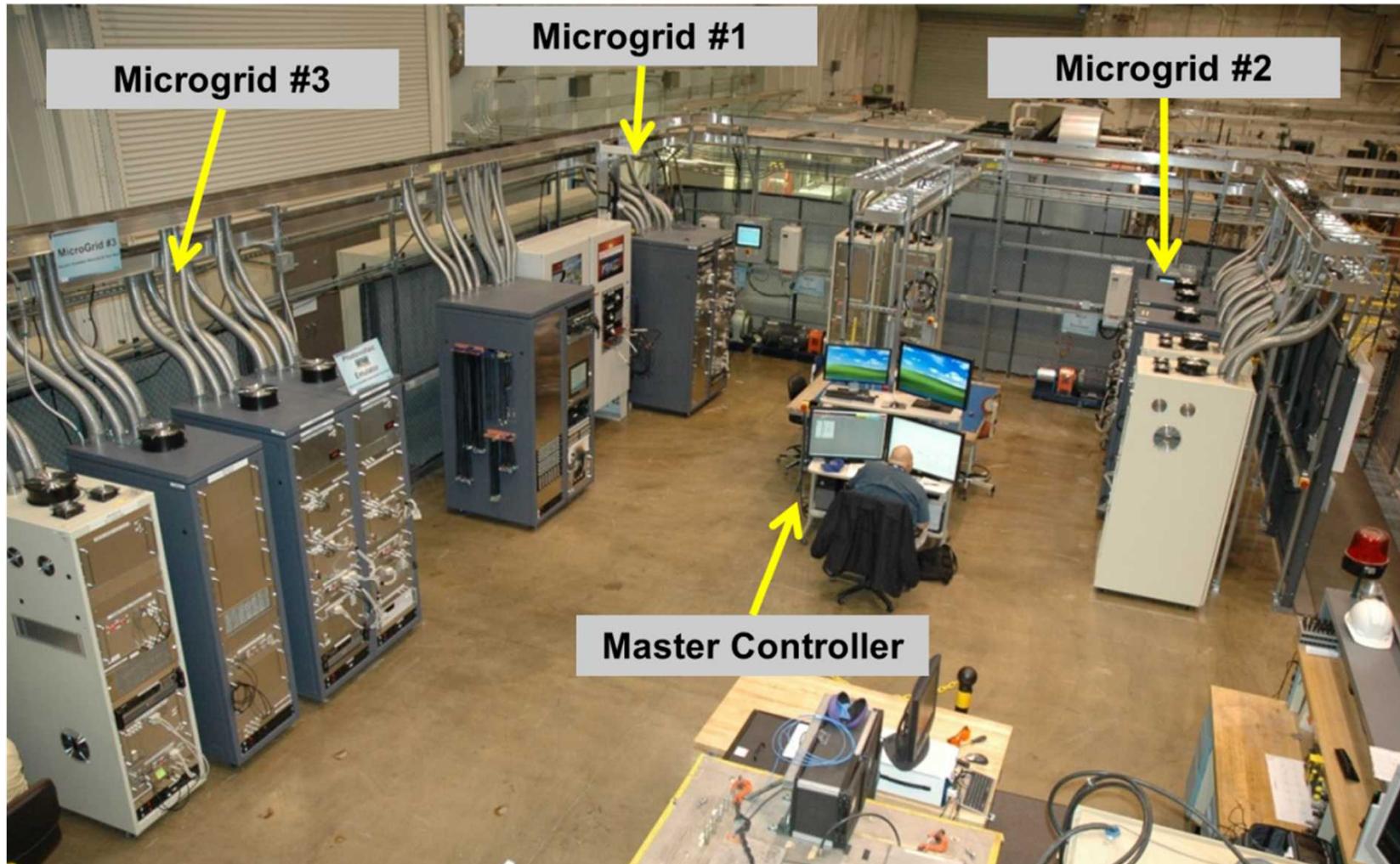
- Power flow is controlled between two MicroGrid buses
- DC link voltage is greater than the max of either bus voltage
- Bulk capacitance provides additional degree of control, allowing the absorption of approximately 3.25 kJ (15 kW surge for >200 msec)



EMALS Example

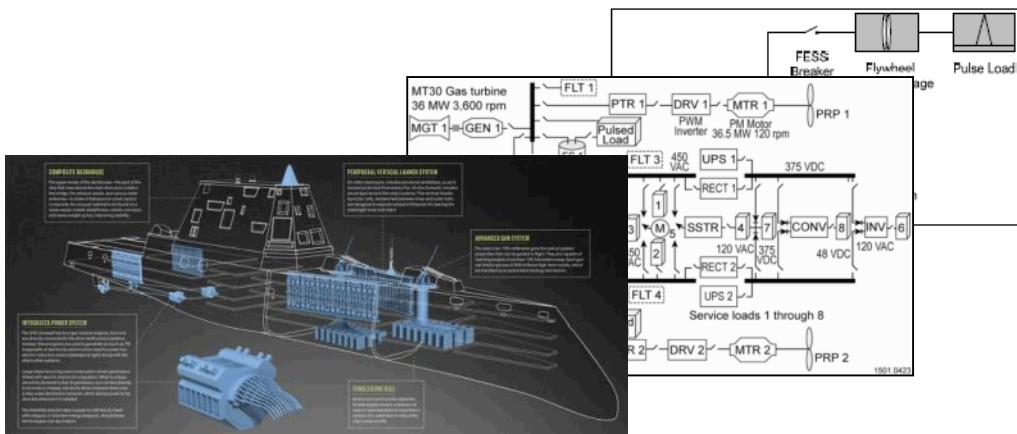
Secure Scalable Microgrid (SSM) Testbed Enables Hardware Testing of HSSPFC

- 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

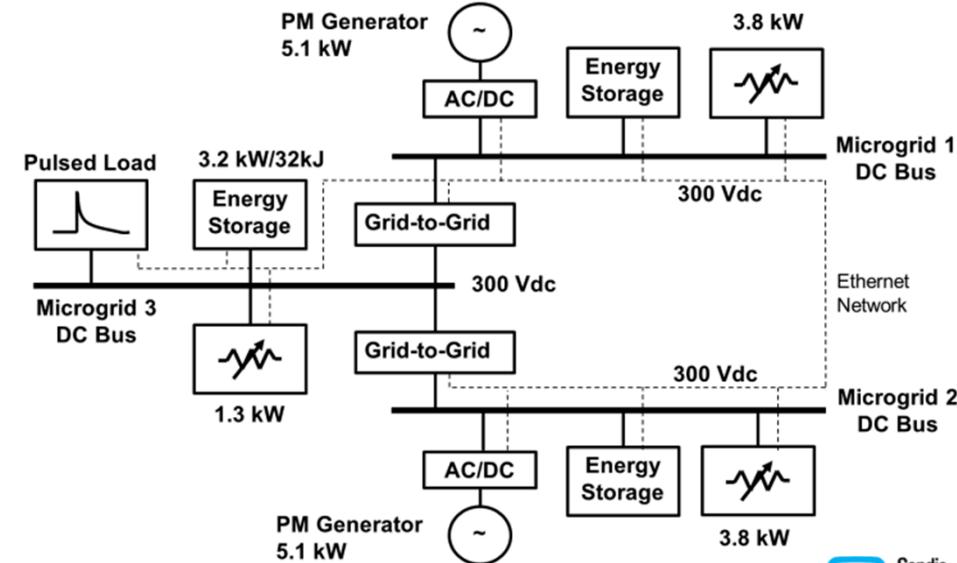
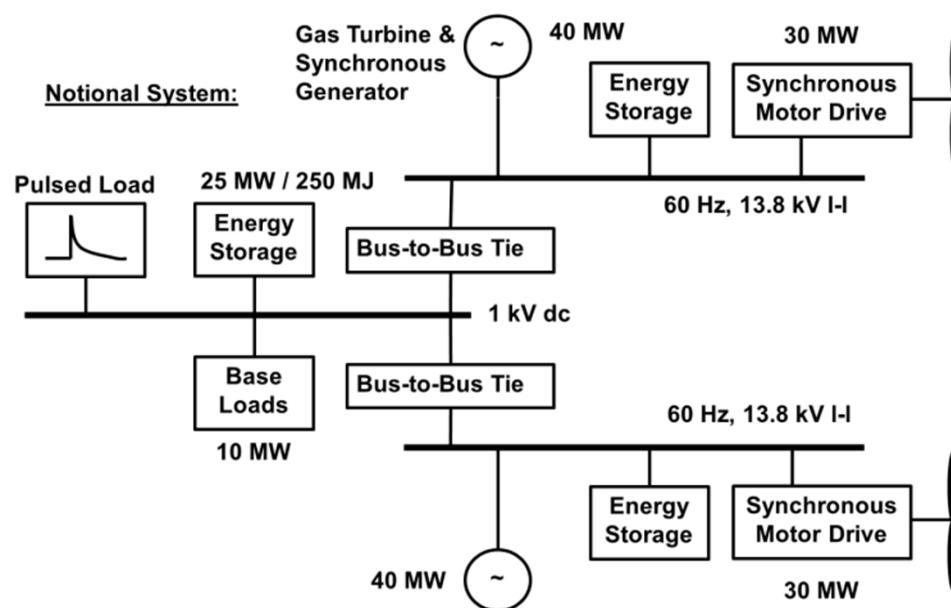
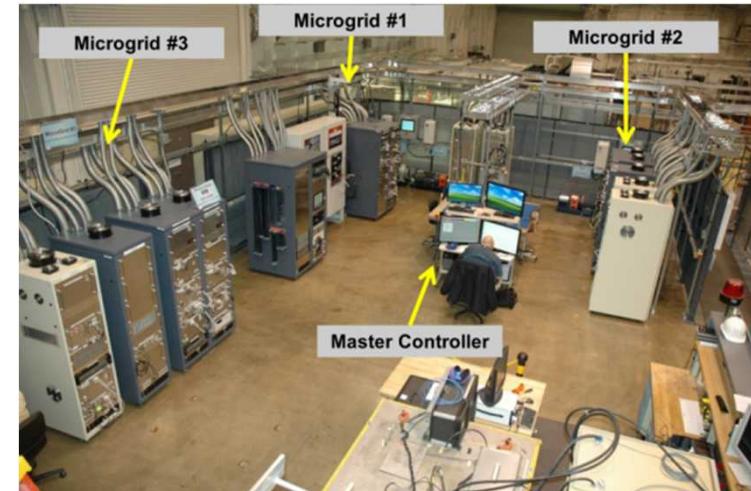


Hardware Testbed Components May be Used to Mimic an Electric Ship Configuration

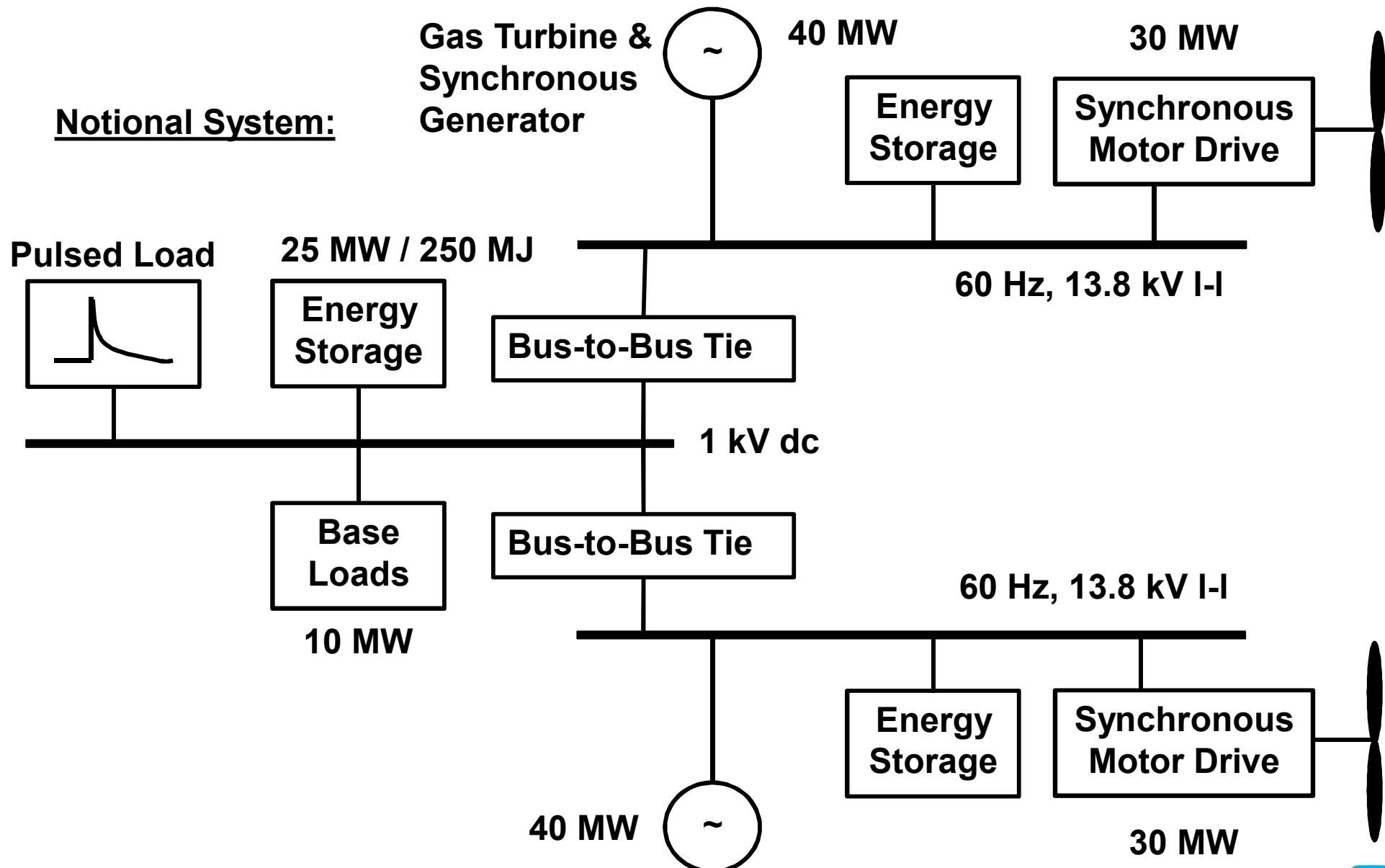
Candidate Notional System with 'Full Power' Components based on literature



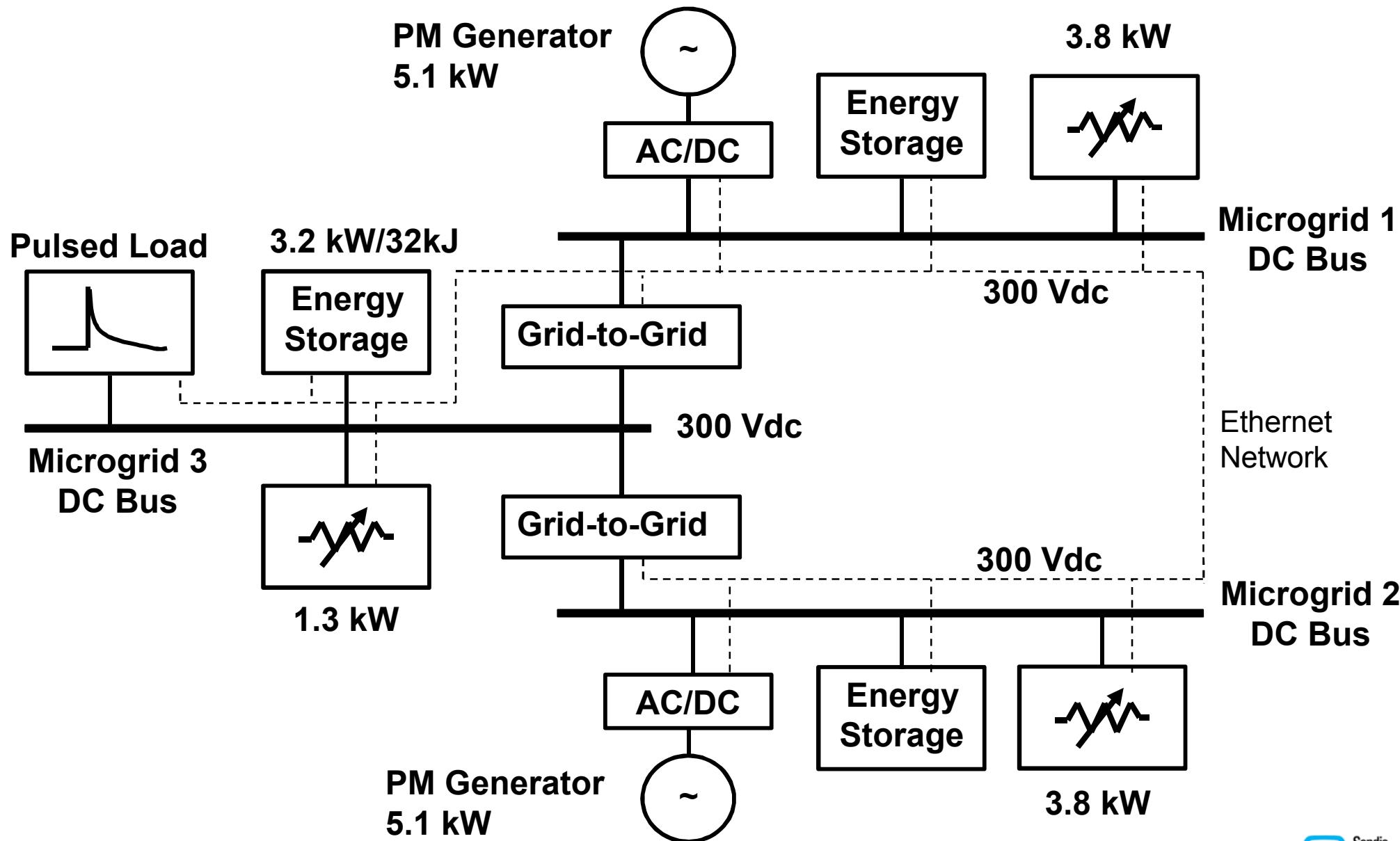
Testbed System with Per-Unit scaled parameters computed



Hardware Testbed Components May be Used to Mimic an Electric Ship Configuration



Hardware Testbed Components May be Used to Mimic an Electric Ship Configuration



Emulators Mimic Dynamics of Diesel, Wind or Other Rotational Generators

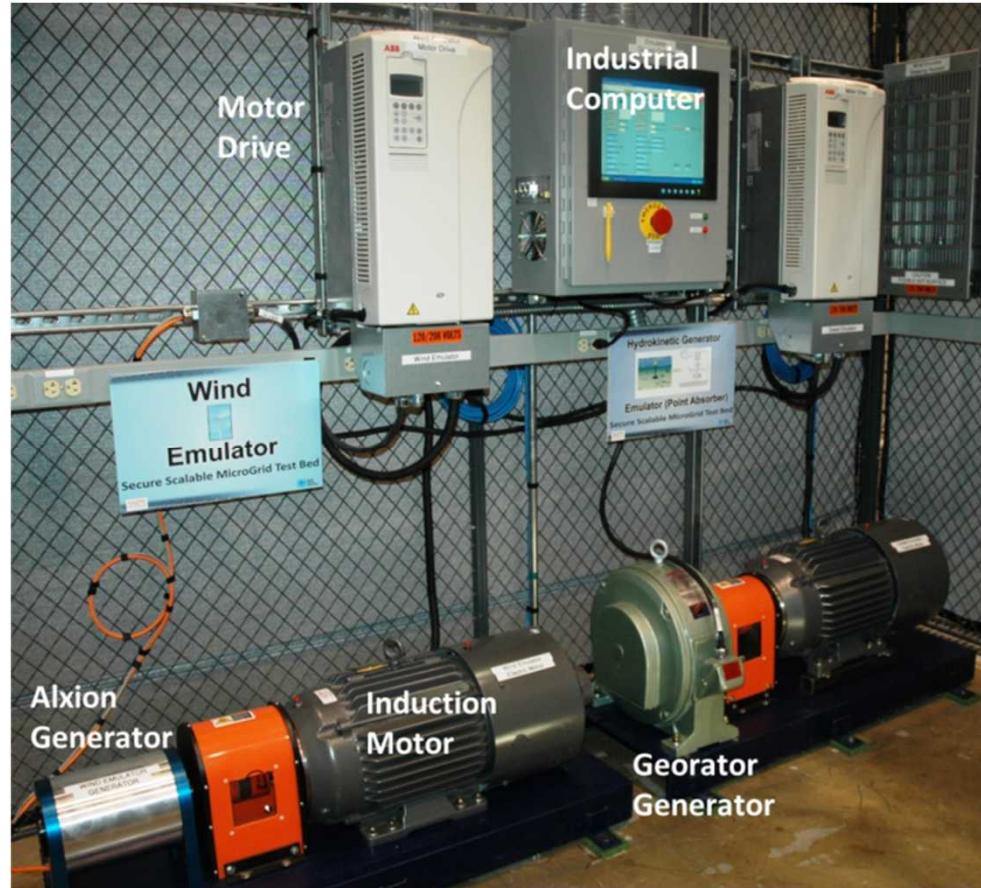
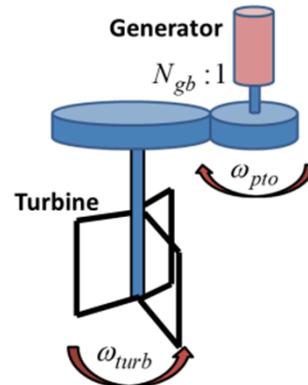
- Dynamic models are created for generators emulated using a commercial motor drive

River Turbine

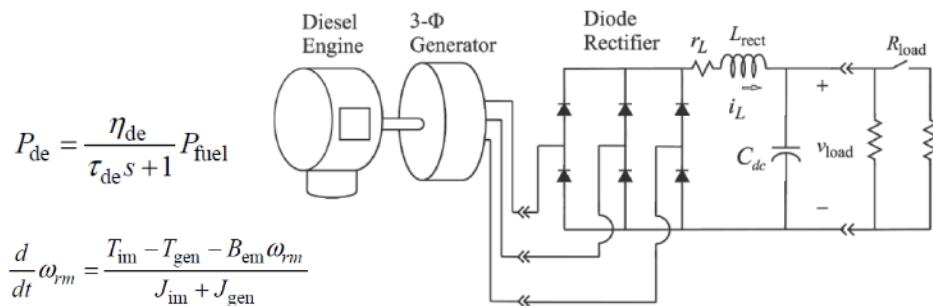
$$T_{turb} = \frac{P_{turb}}{\omega_{turb}} = \frac{C_p(\lambda) \rho_w A_r v_w^3}{2\omega_{turb}}$$

$$\frac{d}{dt} \omega_{turb} = \frac{T_{turb} - N_{gb} T_{pto} - B_{gb} \omega_{turb}}{J_{turb} + N_{gb}^2 J_{pto}}$$

$$\frac{d}{dt} \omega_{pto} = \frac{(1/N_{gb}) T_{turb} - T_{pto} - (1/N_{gb}^2) B_{gb} \omega_{pto}}{(1/N_{gb}^2) J_{turb} + J_{pto}}$$

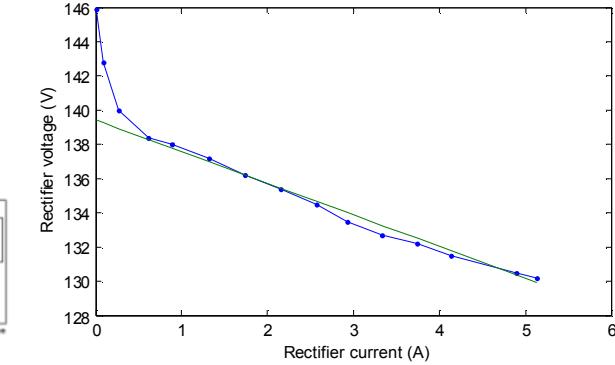
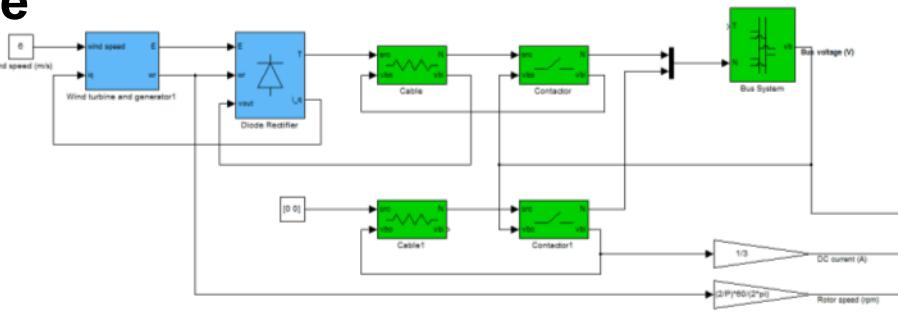


Diesel Engine

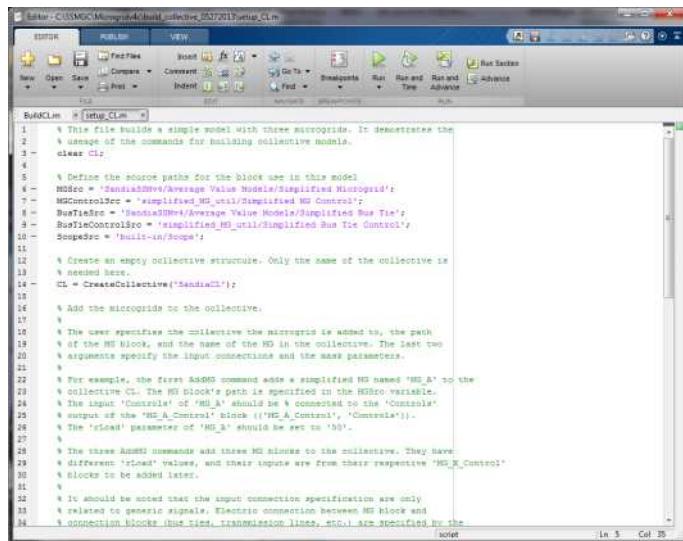


All Hardware Components are Represented in a Matlab/Simulink Library

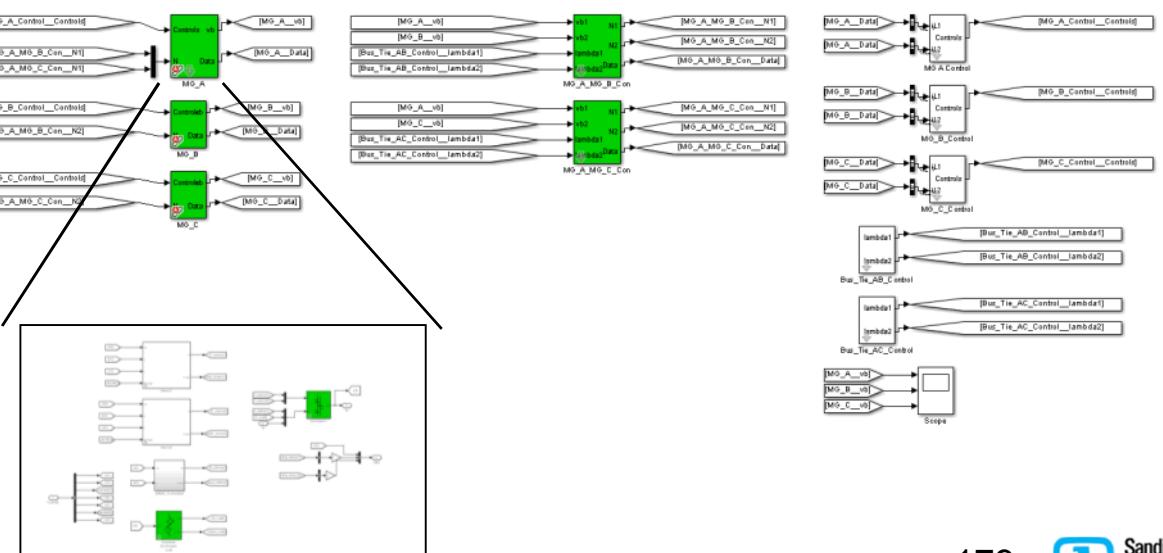
- System components are modeled and calibrated to lab hardware



- Simulated microgrids matching lab hardware may be interconnected virtually using a simple Matlab script



```
Editor - C:\SSMGC\Microgrid\Cloud\collective_057\setup_CLM.m
1 % This file builds a simple model with three microgrids. It demonstrates the
2 % usage of the command for building collective models.
3 % clear clc;
4 %
5 % Define the source paths for the block used in this model
6 % MOBlock = 'SimulinkBlocks/Average Value Model/Simplified Microgrid';
7 % MGControlBlock = 'SimulinkBlocks/Average Value Model/Simplified MG Control';
8 % BusTieControlBlock = 'SimulinkBlocks/Average Value Model/Simplified Bus Tie';
9 % BusTie = 'SimulinkBlocks/Average Value Model/Simplified Bus Tie Control';
10 % Scope = 'built-in Scope';
11 %
12 % Create an empty collective structure. Only the name of the collective is
13 % needed here.
14 CL = CreateCollective('SandiaCL');
15 %
16 % Add the microgrids to the collective;
17 %
18 % The user specifies the collective, the microgrid it's added to, the path
19 % of the MG block, and the name of the MG in the collective. The last two
20 % arguments specify the input connections and the name parameters.
21 %
22 % For example, the first addMG command adds a simplified MG named 'MO_A' to the
23 % collective CL. The MG block's path is specified on the MGBlock variable.
24 % The input 'Control' of 'MO_A' should be connected to the 'Controls'-
25 % output of the 'MO_A_Control' block ('MO_A_Control', 'Controls').
26 % The 'Control' parameter of 'MO_A' should be set to 'b0'.
27 %
28 % The three addMG commands and three MG blocks to the collective. They have
29 % different 'Control' values, and their inputs are from their respective 'MO_X_Control'
30 % blocks to be added later.
31 %
32 % It should be noted that the input connection specification are only
33 % related to generic signals. Electric connection between MG block and
34 % connection blocks (bus tie, transmission lines, etc.) are specified by the
35 % block's internal logic.
```



Hardware Testbed Components May be Used to Mimic an Electric Ship Configuration

- Testbed parameters are selected after first identifying components for a Notional System:

Component	Quantity	Power	Duration	Energy
Gas Turbine Generator	2	40 MW	steady	40 MJ (inertia)
Synchronous Motor	2	30 MW	steady	
Additional Base Loads	1	10 MW	steady	-
Energy Storage	3	25 MW	variable	250 MJ
Railgun Launcher	1	16 GW (40 MW)	10 millisec (4 sec charge)	160 MJ
E-Mag Aircraft launch	1	45 MW	2.7 sec	122 MJ
Free Electron Laser	1	20 MW	5 sec	100 MJ
Radar	1	10 GW	0.1 μ sec	1 kJ

Pulsed Loads

Hardware Testbed Components May be Used to Mimic an Electric Ship Configuration

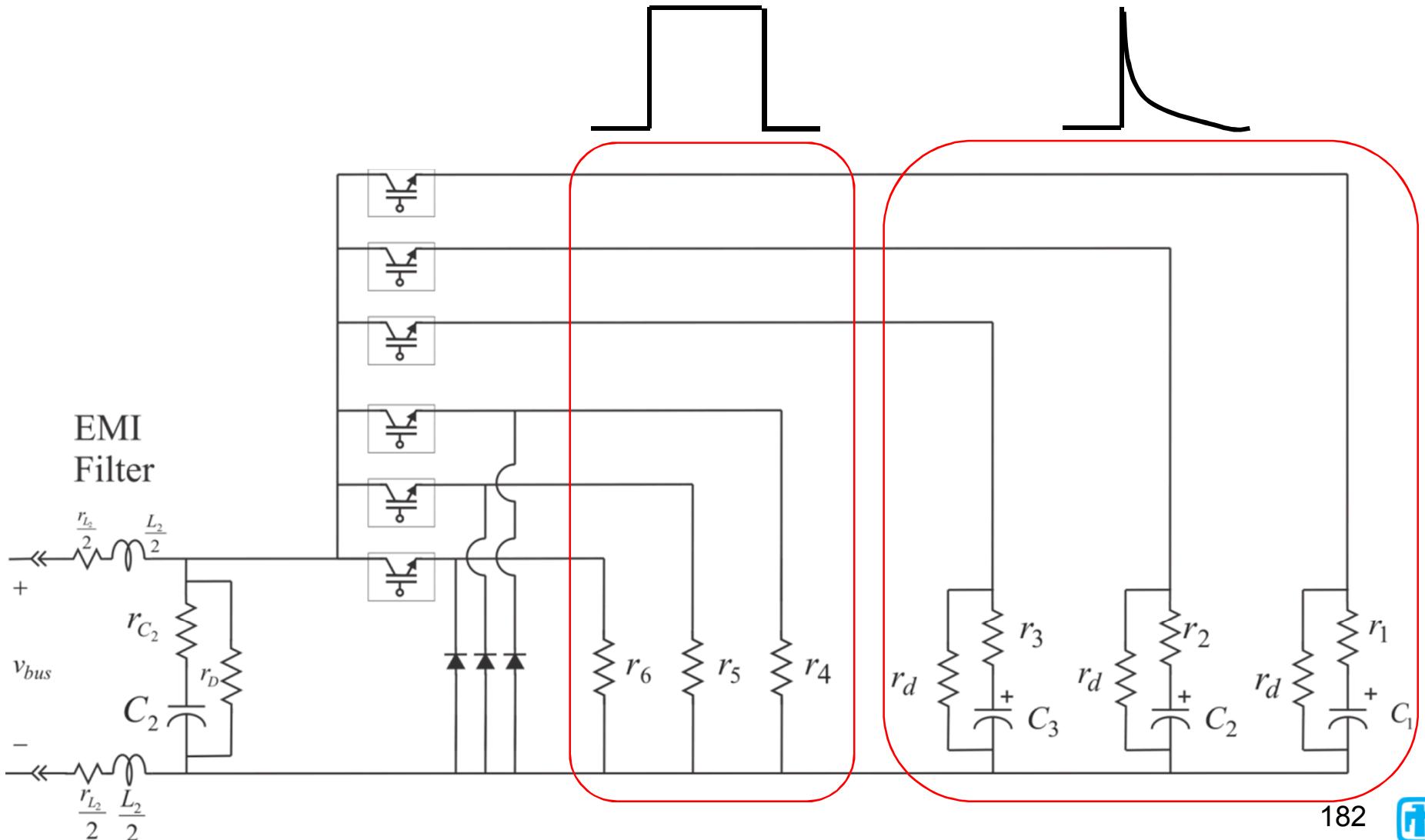
- Per Unit scaling (approx. 1/7850th) about a nominal 300 V dc bus voltage provides Testbed Component values:

Component	Quantity	Power	Duration	Energy
Georator PM Generator	2	5.1 kW	steady	5.1 kJ (inertia)
Digital Resistive Load 1&2	2	3.8 kW	steady	-
Digital Resistive Load 3	1	1.3 kW	steady	-
Energy Storage	3	3.2 kW	variable	32 kJ
Railgun Launcher	1	2 MW (5 kW)	10 millisec (4 sec charge)	20 kJ
E-Mag Aircraft launch	1	5.7 kW	2.7 sec	15.5 kJ
Free Electron Laser	1	2.5 kW	5 sec	12.5 kJ
Radar	1	1.25 MW	0.1 μ sec	0.1276 J

Pulsed Loads

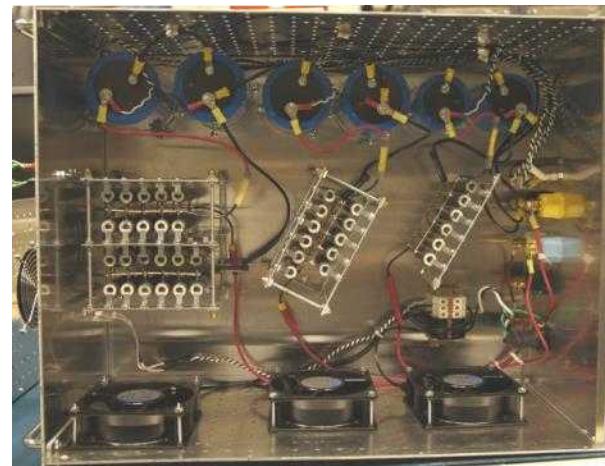
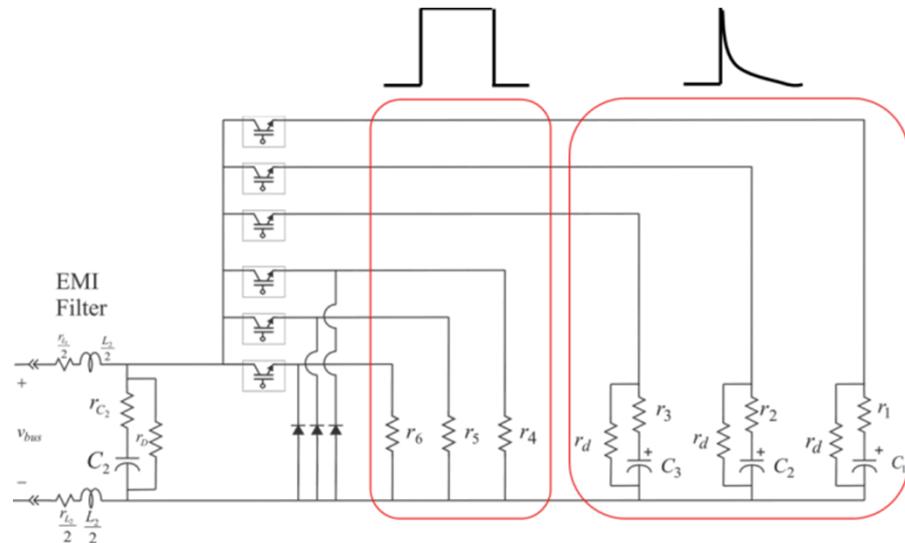
A New SSM Testbed Component was Developed: Adjustable Pulsed Load

- Proposed Pulsed Load: two parallel circuits
 - Parallel connected RC networks allow the pulse to be adjusted (one shot)
 - Low valued resistor (timed on-off control)



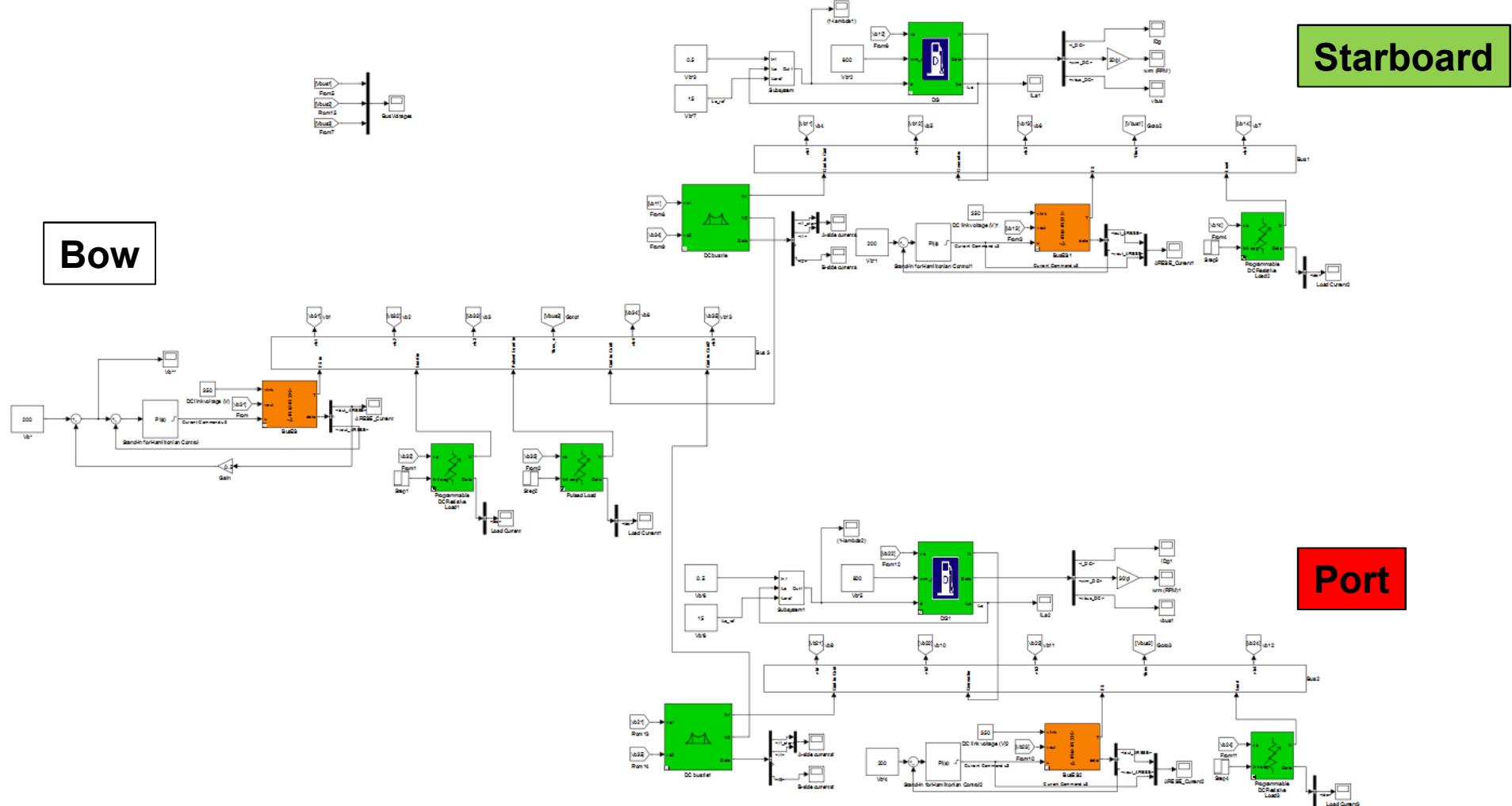
A New SSM Testbed Component was Developed: Adjustable Pulsed Load

- New Pulsed Load Design
 - Includes R (6.3 kW at 300V) and RC circuits



Electric Ship Configuration Model Allows Simulations of Electric Ship Dynamic Response

- Custom Simulink library was developed to model testbed hardware
- Source and load profiles used by Master Control Computer are same as those used by simulation



A Scenario is defined for EMALS Deployment

- Testbed parameters are selected after first identifying components for a Notional System:

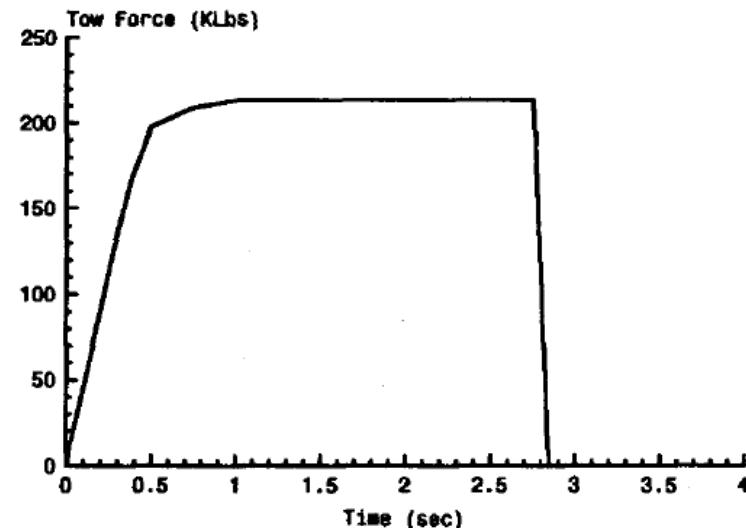
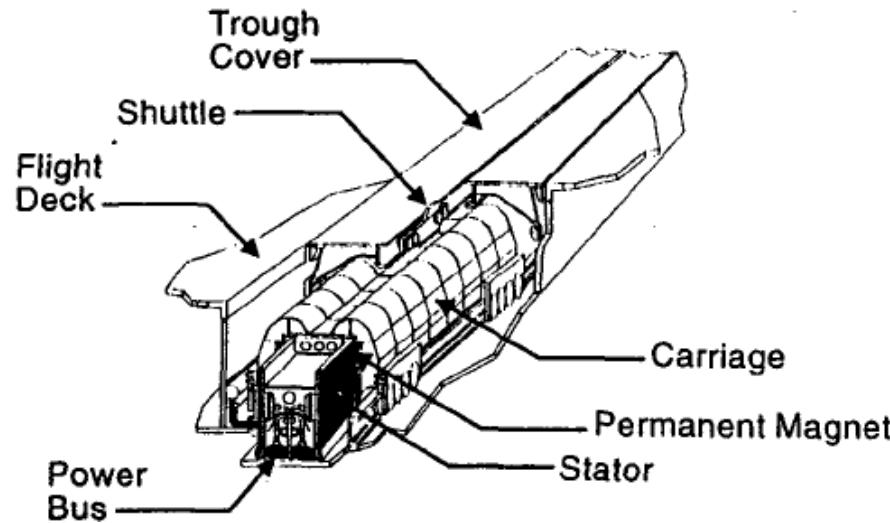
Component	Quantity	Power	Duration	Energy
Gas Turbine Generator	2	40 MW	steady	40 MJ (inertia)
Synchronous Motor	2	30 MW	steady	
Additional Base Loads	1	10 MW	steady	-
Energy Storage	3	25 MW	variable	250 MJ
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E-Mag Aircraft launch	1	45 MW	2.7 sec	122 MJ
Free Electron Laser	1	20 MW	5 sec	100 MJ
Radar	1	10 GW	0.1 μ sec	1 kJ

Pulsed Loads

A Scenario is defined for EMALS Deployment

- Electromagnetic Launch System characteristics are considered and modeled within the SSM Testbed

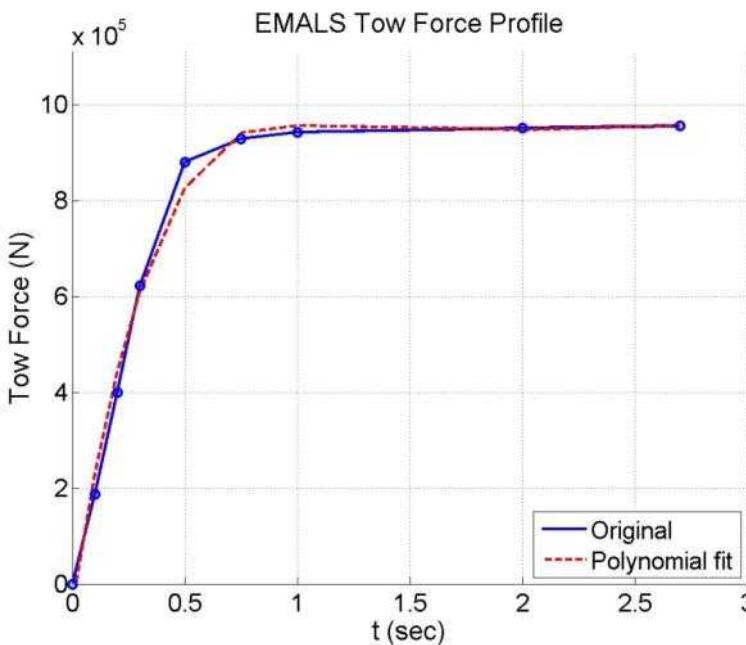
EMALS Launch Motor and tow force profile [1]



[1] Doyle, M.R.; Samuel, D.J.; Conway, T.; Klimowski, R.R., "Electromagnetic aircraft launch system-EMALS," *Magnetics, IEEE Transactions on* , vol.31, no.1, pp.528-533, Jan. 1995

A Scenario is defined for EMALS Deployment

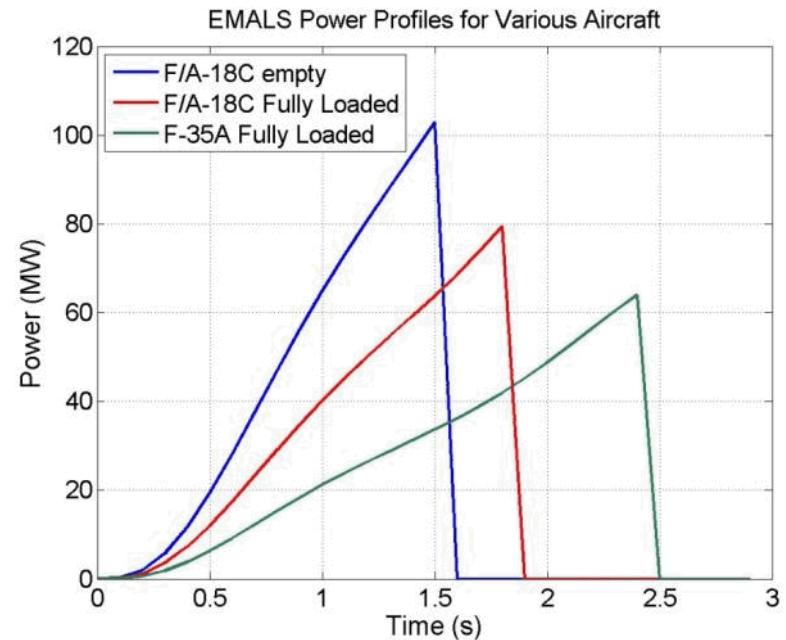
- Electromagnetic Launch System (EMALS) characteristics are considered and modeled to attain a power profile
 - The force profile is utilized within a dynamic simulation to define power as a function of time



Dynamic
Simulation

Parameters:

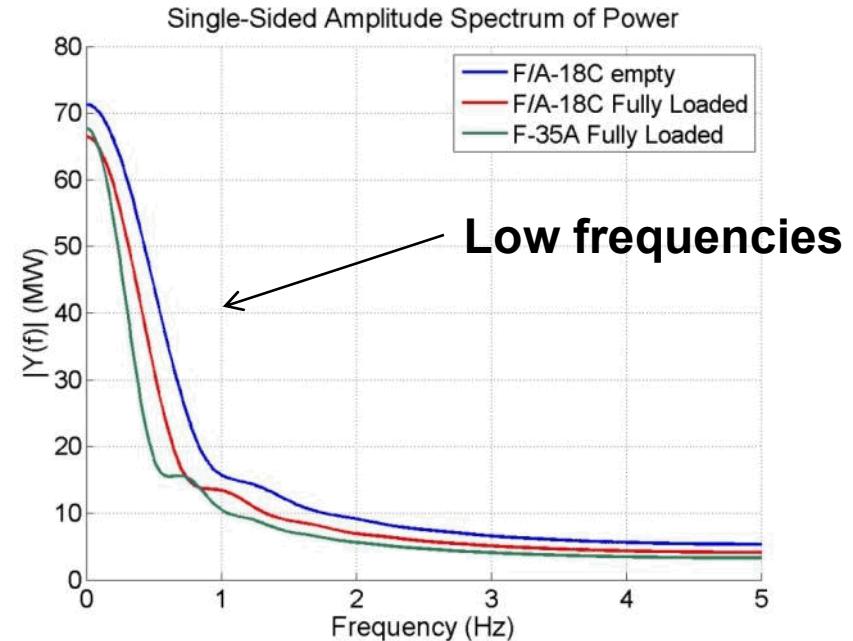
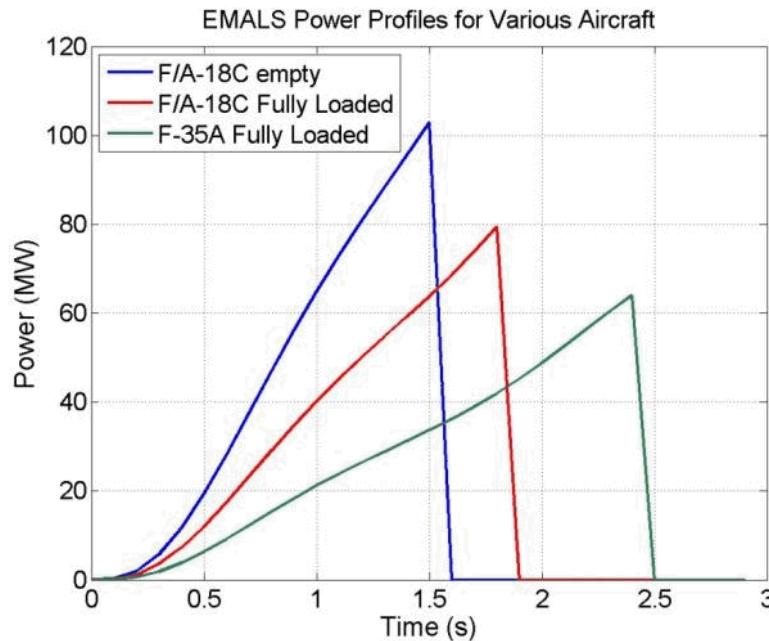
1. Mass
2. Deck length
3. Drag
4. Motor efficiency



[1] Doyle, M.R.; Samuel, D.J.; Conway, T.; Klimowski, R.R., "Electromagnetic aircraft launch system-EMALS," *Magnetics, IEEE Transactions on* , vol.31, no.1, pp.528-533, Jan. 1995

A Scenario is defined for EMALS Deployment

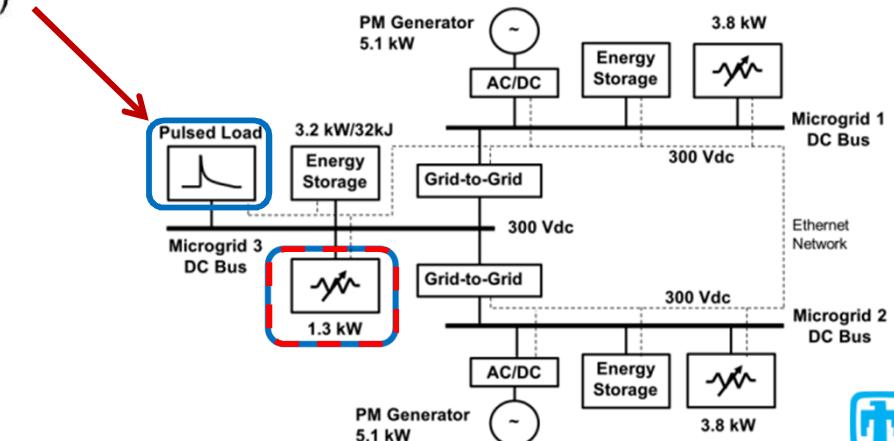
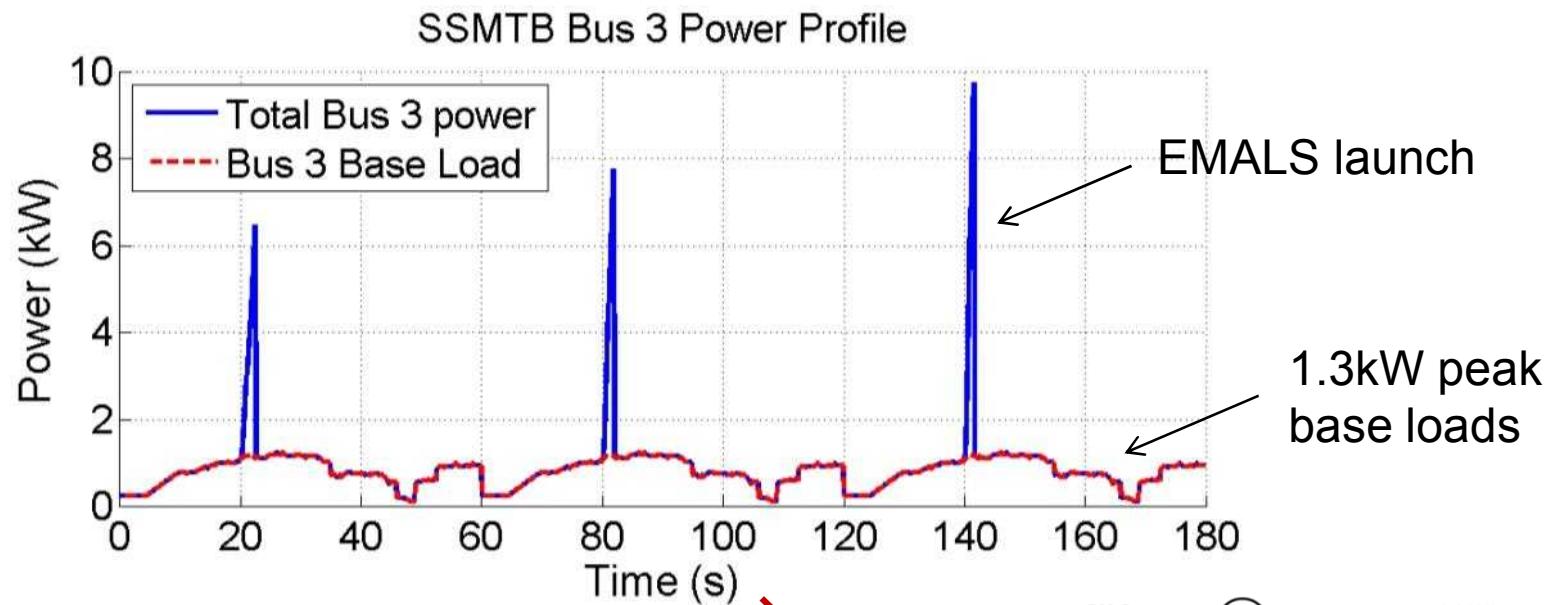
- Electromagnetic Launch System (EMALS) characteristics are considered and modeled to attain a power profile
 - Spectral Power Calculation indicates potential for excitation of electromechanical states on the ship power system



[1] Doyle, M.R.; Samuel, D.J.; Conway, T.; Klimowski, R.R., "Electromagnetic aircraft launch system-EMALS," *Magnetics, IEEE Transactions on* , vol.31, no.1, pp.528-533, Jan. 1995

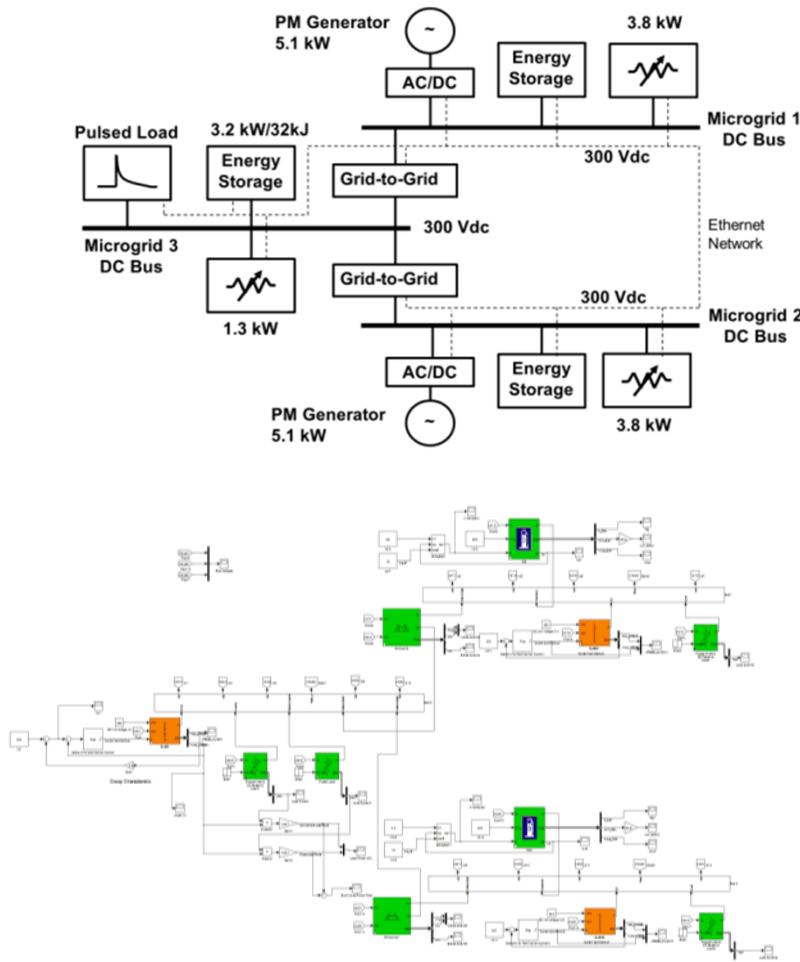
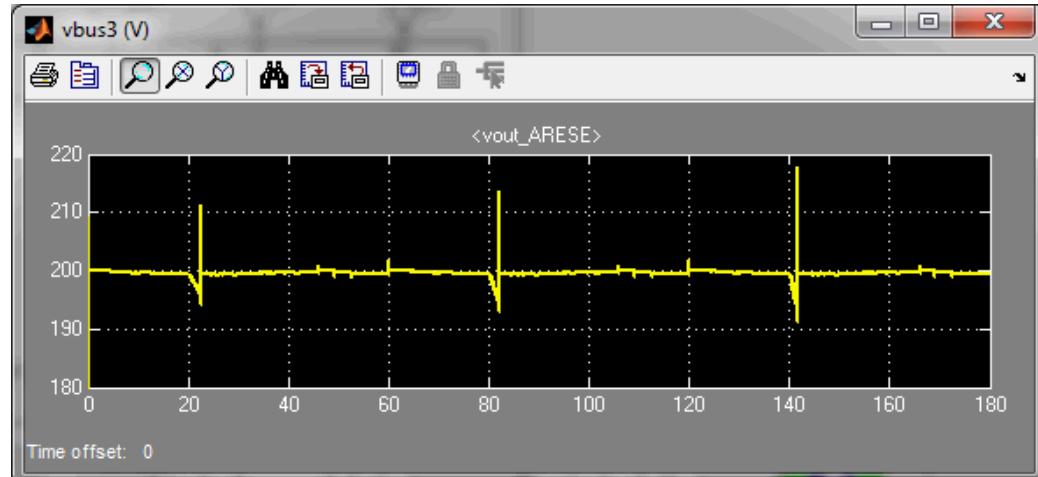
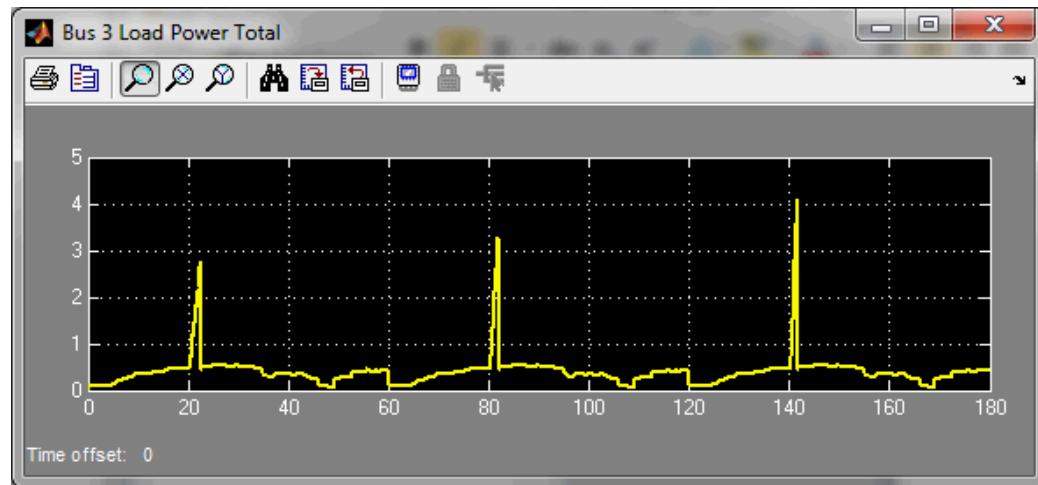
A Scenario is defined for EMALS Deployment

- Electromagnetic Launch System (EMALS) characteristics are considered and modeled to attain a power profile
 - Candidate Bus 3 power profile includes three launches over three minutes



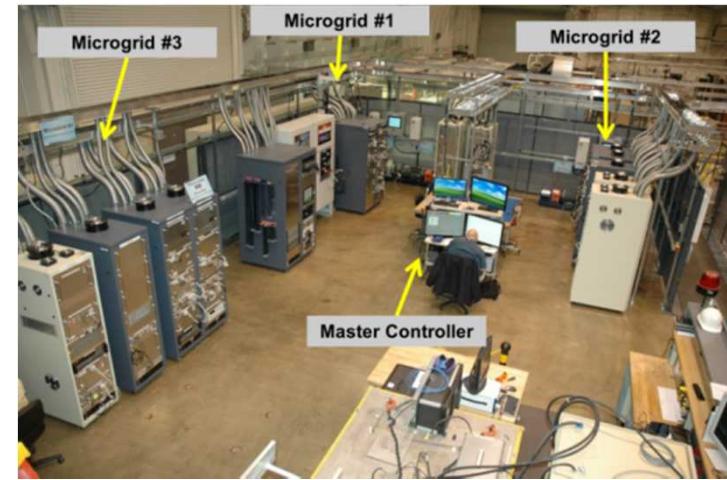
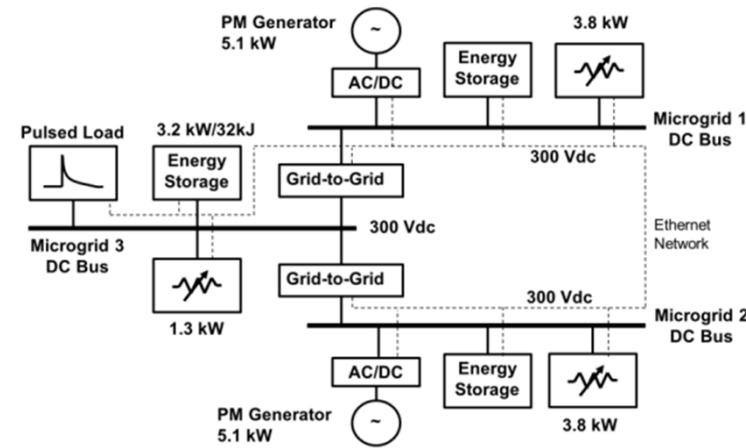
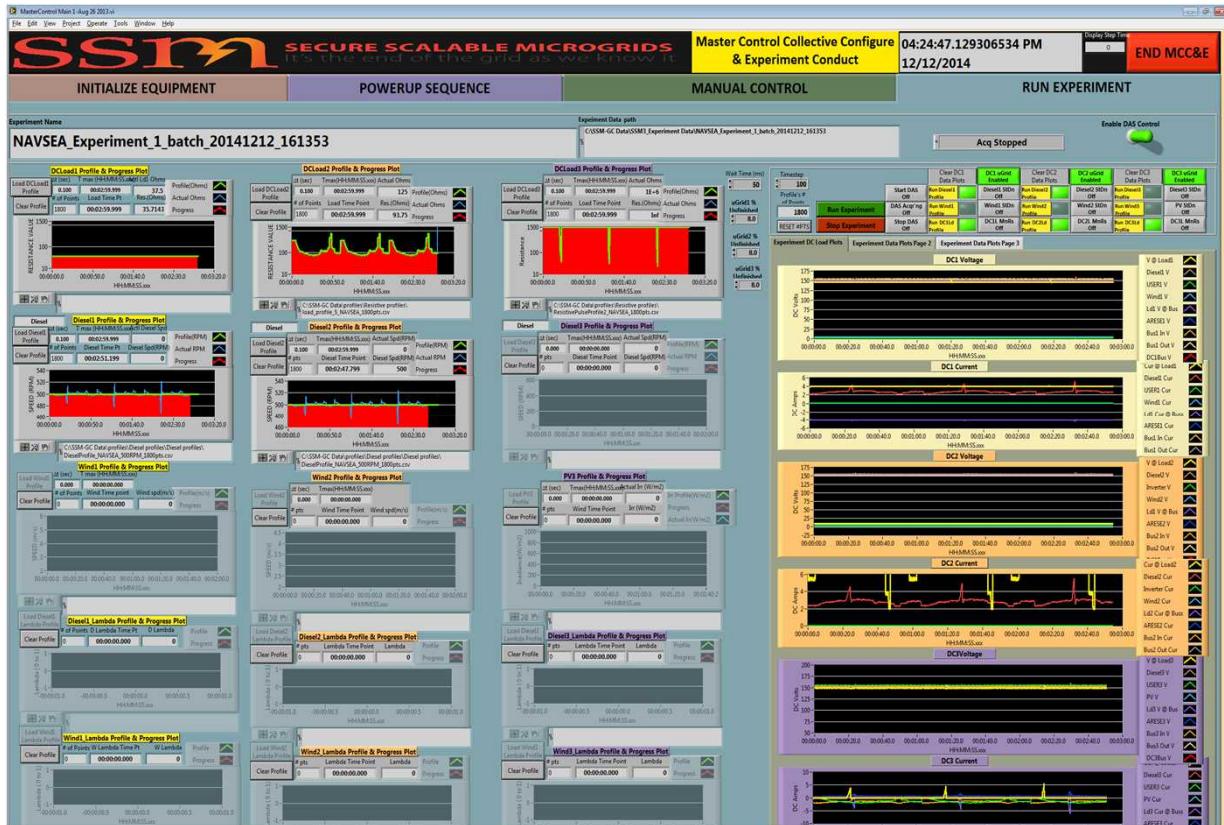
EMALS Scenario is Simulated

- Power Profiles are implemented using Simulink Model of Testbed



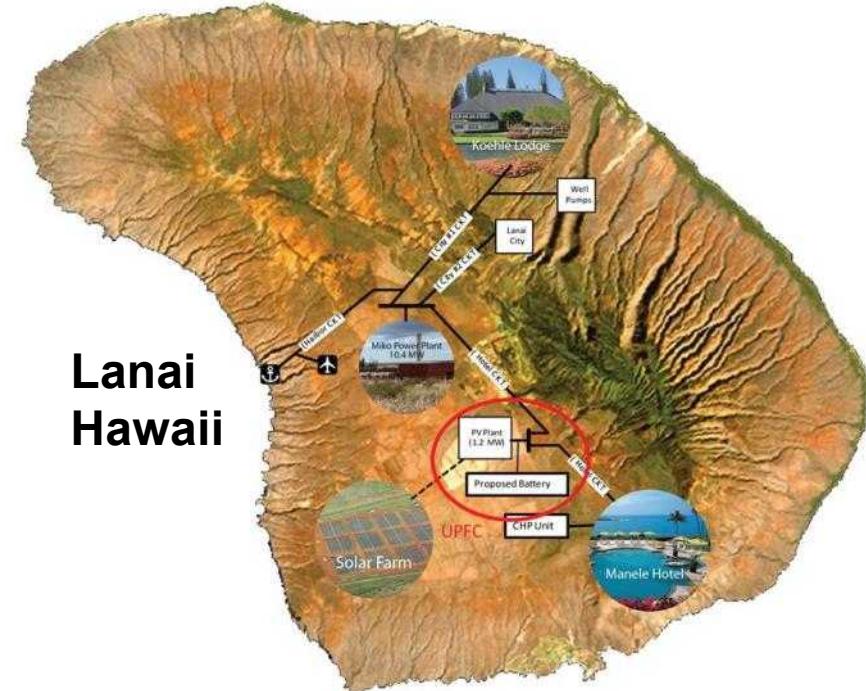
Hardware Experiments Incorporating EMALS Scenario are in Development

- Power Profiles are implemented using Hardware Testbed



Networked, Secure, Scalable Microgrids (SSM™) Enable High-Penetration Renewables and Improved Operations

- Ground breaking nonlinear control theory, informatics, and innovation.
- Tools are being developed for networked microgrids spanning from conventional to 100% stochastic generation.
- Potential impact:
 - **Unlimited use of renewable sources**
 - **Lower-cost provisioning at a given level of renewables**
 - **Reduction in centralized fossil fuel based sources**
 - **Self-healing, self-adapting architectures**
 - **Microgrids as building blocks for larger systems**



SSM test bed



**Thanks
For Your
Participation**

BACK UP

Energy Surety Requirements for Microgrid Development

- The Secure Scalable Microgrid (SSM) is a Sandia-developed grid architecture that separates away from unidirectional power and limited information flow and, rather, adopts closed-loop controls and an agent-based architecture with integrated communication networks. Adding a feedback component to the input signal establishes an intelligent power flow control and provides a basis for the integration of renewables and distributed power sources into the electrical power grid. This novel approach enables self-healing, self-adapting, self-organizing architecture and allows a trade-off between storage in the grid and information flow to control generation sources, power distribution, and loads.
- The SSM consists of a multilayer feedback control system. This new approach includes agent-based, closed loop architecture of the entire system with two main levels. The high-level layer, agent-based informatics architecture, regulates the mixture of energy resources, performs load leveling and prioritization and allows adaptive behavior. Basically, it chooses the network topology connecting the power generators, energy storage, and distribution/transmission lines in order to service the loads within the SSM while optimizing the SSM priorities.
- The low-level layer, distributed nonlinear control, ensures and maintains stability and transient performance of the network topology chosen by the high-level layer of the SSM. The interplay of these two levels is critical for the success of new control and informatics driven electric power grid. Specifically, the top-level layer must be effective and efficient in the selection process while the low level layer must guarantee stability and performance for non-linear systems.
- Incorporating agent-based, distributed, nonlinear control to maintain reliable energy distribution while minimizing the need for excessive storage or backup generation will be a revolutionary step towards extreme penetration of renewable energy sources into the U.S. energy infrastructure. The development of dynamic nonlinear source models, scalable agent-based architectures and multi-time-variant simulations will be key components to this solution.

- Introduce presenters
- Introduce university and lab
- Motivate
- Discuss topic areas
- Provide intro material for each area
- Kick off the workshop

Electrical Sciences core technical areas

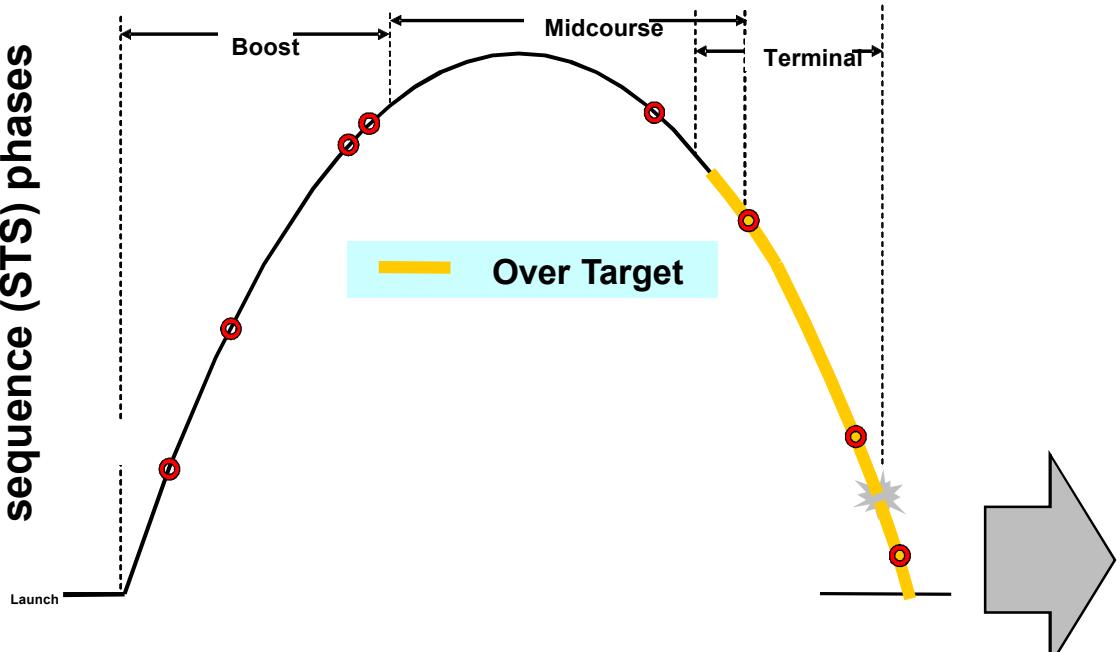
- **Linear electromagnetics**
 - Modeling, simulation & analysis of EM coupling/interactions in complex geometries,
 - *NW systems Qualification in normal and abnormal environments*
- **Plasma physics**
 - Electromagnetic kinetic (monte-carlo and PIC) modeling and simulation of EMP and gas and vacuum discharge physics supporting NW design, experiments, surveillance and *NW Systems Qualification in hostile environments*
- **High voltage sciences**
 - Physics of high voltage electrical breakdown, Lightning burn/blast through, electrostatic discharge supporting design, surveillance and *Qualification in normal and abnormal environments*
- ***Circuits and devices***
 - Analog, digital and RF circuit simulation & analysis supporting NW electrical systems design and surveillance. *NW circuit Qualification in hostile environments.*
 - Physics based device model development; device specific model extraction, V&V and calibration; supporting full lifecycle NW electrical systems
- **Power systems and electronics**
 - Design, development and modeling/simulation of power systems and microgrids, power electronics, advanced solid state switching and development of advanced control and optimization

System qualification/design support

Environment	<i>EM / Electrical</i> 1350	<i>Radiation</i>	<i>Thermal</i>	<i>Mechanical</i>
Normal	EMR ESD Nearby Lightning DeGauss		Climate	Shock Vibration Acceleration Aero
Hostile	EMP <i>SREMP</i> <i>SGEMP</i> TREE	<div style="display: flex; align-items: center;"> { <div style="display: flex; gap: 10px;"> Neutrons Gammas X-rays </div> </div>		Blast Shock
Abnormal	Lightning External Power		Jet-fuel, propellant fire	Shock Crush

Nuclear Weapons Stockpile Responsibilities Drive Deep Expertise in Grid-relevant Science and Engineering

All stockpile-to-target sequence (STS) phases



Physical Environments

- Weapon storage, transportation, maintenance, storage on delivery platform, launch and in-flight path
- Normal Environments (EMR, ESD, nearby lightning, degaussing)
- Abnormal Environments (lightning, exposure to power sources)
- Hostile Environments (nuclear weapon effects, directed energy weapons, high power microwaves)

System & Components



Grid-relevant Science and Engineering at Sandia

- Advanced power systems and AC/DC microgrids
- High voltage breakdown science & experiments
- Pulsed power components and systems development
- Electromagnetics theory/code development
- Electromagnetic experiments
- Systems engineering and integration

Other Capabilities include

E-beam supported wind tunnel and high heat flux research

Water Power Program

UNIQUE CAPABILITIES

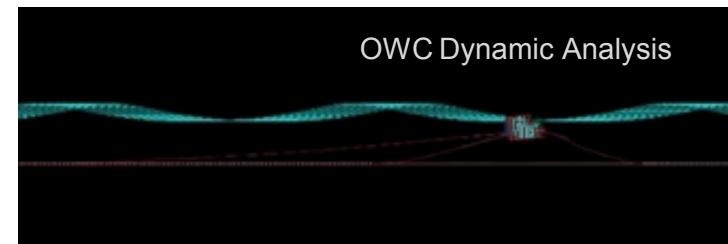
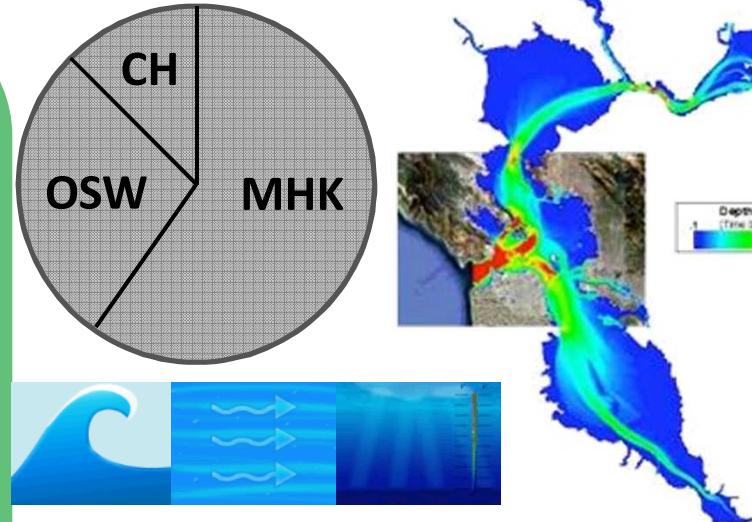
- SEAWOLF laboratory/field oscillatory-flow sediment transport testing
- Sandia Lake Facility – TRL 6 appropriate for wave testing
- MHK-capable environmental circulation and performance code (SNL-EFDC)

COLLABORATIVE PROJECTS

- Technical Industry FOA Support
 - Ocean Renewable Power Company, Ocean Power Technologies, Snohomish PUD
- SNL-EFDC Technology Transfer to
 - Free Flow Power, NOAA, FERC, BOEM, Verdant, ORPC

IMPACT EXAMPLES

- Leading the techno-economic report to be given to Congress this fall detailing how significant penetration will be possible and what steps need to be taken to ensure the growth of the WEC industry.
- Reference model generation and evaluation to set industry cost of electricity baselines and cost reduction pathways
- Renewable-appropriate composite structural materials and anti-biofouling coatings evaluation
- Fundamental code development for current and wave devices
- Water turbine acoustic signature prediction and measurement
- Large HAWT rotor blades, novel VAWT designs, and structural health monitoring for offshore wind devices.



Sandia Lake Facility

Wind Program

UNIQUE CAPABILITIES

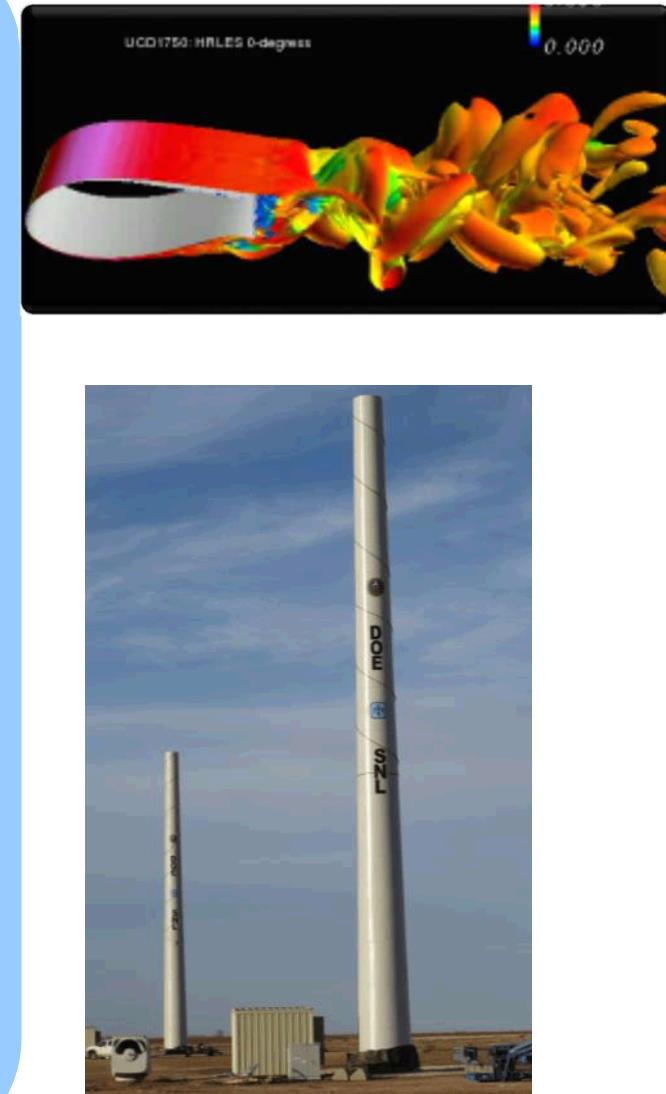
- Wind-turbine blade design and modeling, and wind system reliability
- Test facilities for scaled blade testing and turbine-to-turbine interaction studies (SWIFT test site, Lubbock, TX)

COLLABORATIVE PROJECTS

- GE, Vestas, Texas Tech University – complex wind flow; active controls; scaled wind farm testing
- MIT Lincoln Lab – wind turbine radar interference
- Montana State University – blade material testing
- NREL – systems engineering, wind farm planning, blade testing

IMPACT EXAMPLES

- The SWIFT facility being built at TTU will allow turbine and farm testing at approximately 1/20th of full scale cost
- Evaluation of methods for mitigating radar interference
- Reliability data base and analysis
- Development of tools for wind turbine design & modeling
- Blade testing and materials analysis to improve efficiency





Steven Glover, Manager, Sandia National Laboratories, Albuquerque, NM

- Dr. Glover obtained his B.S. and M.S. degrees in electrical engineering from the University of Missouri-Rolla, Rolla, Missouri, in 1995 and 1997, and the Ph.D. degree with research on modeling and stability analysis of power electronics based systems from Purdue University, West Lafayette, Indiana, in 2003. He was a Research Engineer for P.C. Krause and Associates from 1996 to 2001 where he created simulations, performed model validation, and provided support for integrated power systems. From 1997 to 1998 he served as an Associate Research Engineer with the University of Missouri-Rolla and then as a Research Engineer at Purdue University until 2003, pursuing interests in power electronics based systems. In May 2003 he joined Sandia National Laboratories, Albuquerque, NM, where he is the Manager of the Advanced Pulsed Power Systems Department which performs research spanning from materials to systems. Current research includes developing design and analysis techniques for
- Microgrids and renewable energy systems through the integration of informatics, nonlinear distributed control, communications, and hardware.

Rush D. Robinett III, Richard and Elizabeth Henes Professor, Mechanical Engineer, Michigan Tech

- Dr. Robinett has three degrees in Aerospace Engineering from Texas A&M University (B.S. - 1982, Ph.D. - 1987) and The University of Texas at Austin (M.S. - 1984). He has authored over 100 technical articles including three books and holds 8 patents. Rush began his career at Sandia National Laboratories in 1988 as a Member of the Technical Staff working on the Star Wars Program (Ballistic Missile Defense). In 1995, he was promoted to Distinguished Member of Technical Staff. In 1996, he was promoted to technical manager of the Intelligent Systems Sensors and Controls Department within the Robotics Center. In 2002, Rush was promoted to Deputy Director and Senior Manager of the Energy and Infrastructure Future Group where he is developing new opportunities in distributed, decentralized energy and transportation infrastructures with a focus on entropy and information metrics. Presently, he is professor at Michigan Technological University, ME-EM Department.

Wayne Weaver, Associate Professor Electrical Engineering, Michigan Tech

- Dr. Weaver's area of expertise is in the areas of power electronics and microgrids. His research focus is in distributed control methodologies in microgrids that enable robust and efficient distribution of energy resources. Prior to his current position he worked as a control system development engineer in the electric power generation group at Caterpillar Inc, and as a research associate at the U.S. Army Corp of Engineers - Construction Engineering Research Lab in the area of military microgrids.



Gordon G. Parker, John and Cathi Drake Professor of Mechanical Engineering, Michigan Tech

- Dr. Parker has been developing control strategies for electro-mechanical systems for the past 24 years. He and his graduate students recently developed a mobile microgrid research and education laboratory through a grant sponsored by the U.S. DOE. This will be used to compliment previous studies in electric vehicle / grid interaction. Navy logistics operations, diesel engine aftertreatment state estimation and wind turbine modeling and control are other active research areas. The research conducted by Dr. Parker and his students has resulted in more than 115 peer-reviewed articles and 40 graduate student theses. Prior to taking his current position at Michigan Tech he spent four years at Sandia National Laboratories in Albuquerque developing a variety of structural vibration control solutions including large-angle spacecraft reorientation.



Marvin Cook, R&D Software Engineer, Sandia National Laboratories, Albuquerque, NM

- Mr. Cook received a BS in Computer Science from the University of South Florida and MS in Computer Science from Johns Hopkins University in 1999 and 2000 respectively. He is a R&D software engineer for the Military & Energy Systems Analysis Department at Sandia National Laboratories. During his 13 years at Sandia, he has developed several multi-agent oriented systems with an emphasis on situated reasoning and cyber security. Currently, he is designing and implementing an agent oriented approach to achieve high penetration of renewables and microgrid connectivity.

***Steven Y. Goldsmith, Research Professor
Mechanical and Electrical Engineering, Michigan
Tech***

- Dr. Goldsmith is currently a Research Professor at Michigan Technological University with dual appointments in the Mechanical Engineering and Engineering Mechanics Department, and the Electrical and Computer Engineering Department. He is also a Senior Fellow at the Technological Leadership Institute at the University of Minnesota. Dr. Goldsmith spent 32 years with Sandia National Laboratories and retired as Distinguished Member of the Technical Staff in 2011. His current research efforts are focused on intelligent agent systems and technology, particularly the development of adaptive and multi-
- agent systems. His current projects involve the application of intelligent agents to "smart" electric grid controls, automated cyber defense, and complex energy systems management.



Jason Neely, R&D Electrical Engineer, Sandia National Laboratories, Albuquerque, NM

- Dr. Neely received BS and MS degrees in Electrical Engineering from the University of Missouri-Rolla (now the Missouri School of Science and Technology, Missouri S&T) in 1999 and 2001 respectively and a Ph.D in Electrical Engineering from Purdue University in 2010. Jason currently has 16 technical publications; Jason's interests include machine and drive systems, electrical generation, power electronics, and optimal control. Jason joined Sandia National Labs in Albuquerque, NM in 2001; he currently works in the Advanced Pulsed Power Systems Department.

David G. Wilson, R&D Control Engineer, Sandia National Laboratories, Albuquerque, NM

- Dr. Wilson has three degrees in Mechanical Engineering (BS, MS, PhD). He has authored over 50 technical articles that include three books. He is the R&D nonlinear controls lead for the Electrical Science and Experiments Department at Sandia National Labs. He has over 25 years of research and development engineering experience in energy systems, robotics, automation, and space and defense projects. His areas of research include nonlinear/adaptive control, distributed decentralized control, and exergy/entropy control for nonlinear dynamical systems. Currently he is developing nonlinear power flow control systems for critical energy surety microgrid systems. He is the current PI on the NAVSEA future electric ship nonlinear controls and power systems for advanced microgrid design project.

The Smart Grid is a Focus of Widespread Attention but Key Questions are Unanswered

Present R&D primarily addresses “incremental” changes to the grid.

- **Smart Grid:** an overlay of information technology to monitor status (smart meters..).
- Exploration of renewable energy source limits, not the means to significantly increase their penetration.
- Smart switches to reroute power during faults.

A smaller number of groups are exploring new microgrid architectures

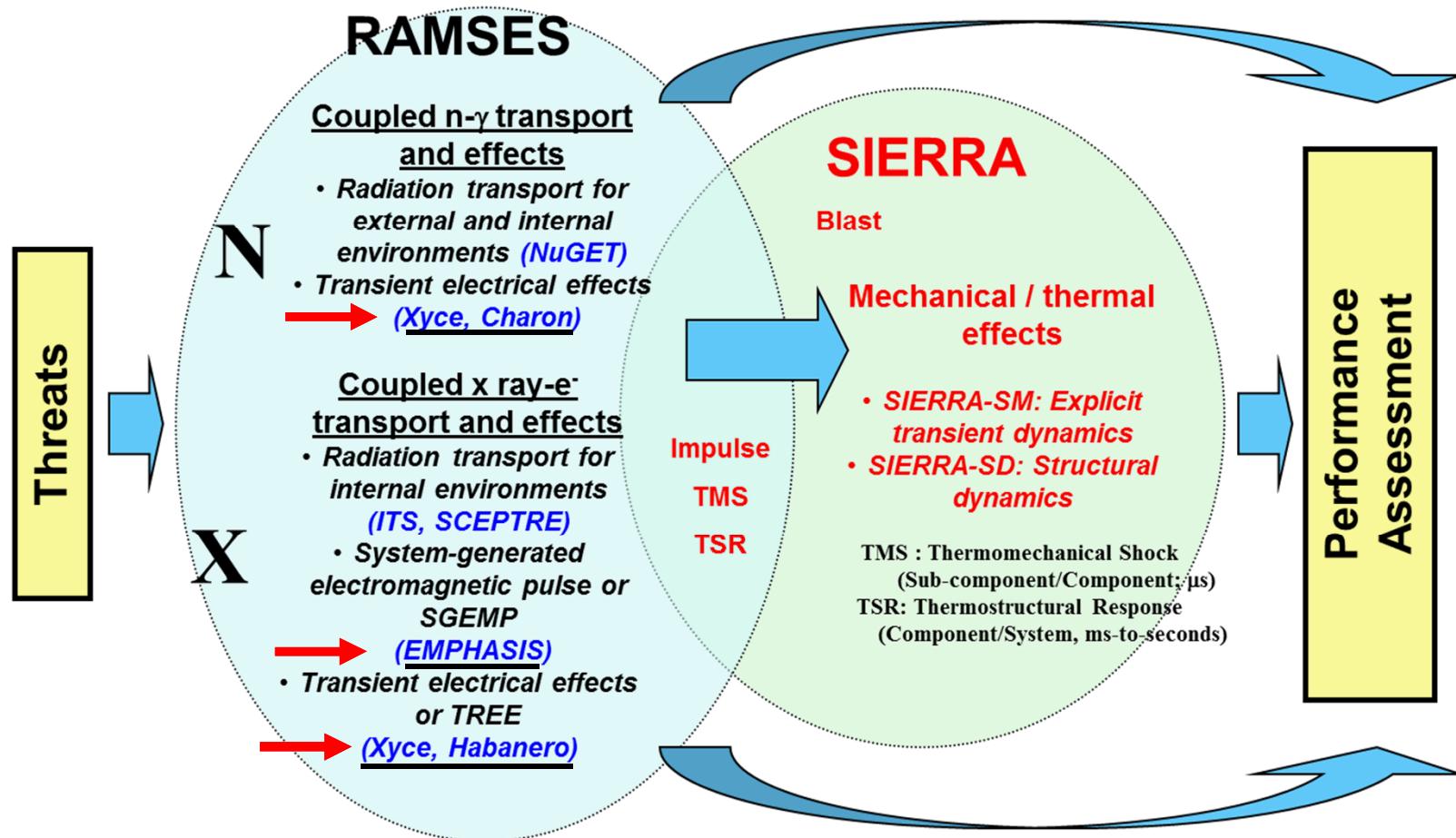
- This includes the Consortium for Electric Reliability Technology Solutions (CERTS), GE, NASA, EU Microgrid...

There is no clear definition of a microgrid, its attributes or how it would be managed and operated in the future.

- What are the constraints on the makeup and size of a microgrid?
- Can microgrids be coupled together? How would you control their interactions?
- How will a microgrid or collection of microgrids react to faults or major disruptions?
- How will they be controlled and their health monitored?

The RAMSES code suite consolidated into 1300, similar to the 1500 model for SIERRA

This is especially influential in Nuclear Survivability of Non-Nuclear Components



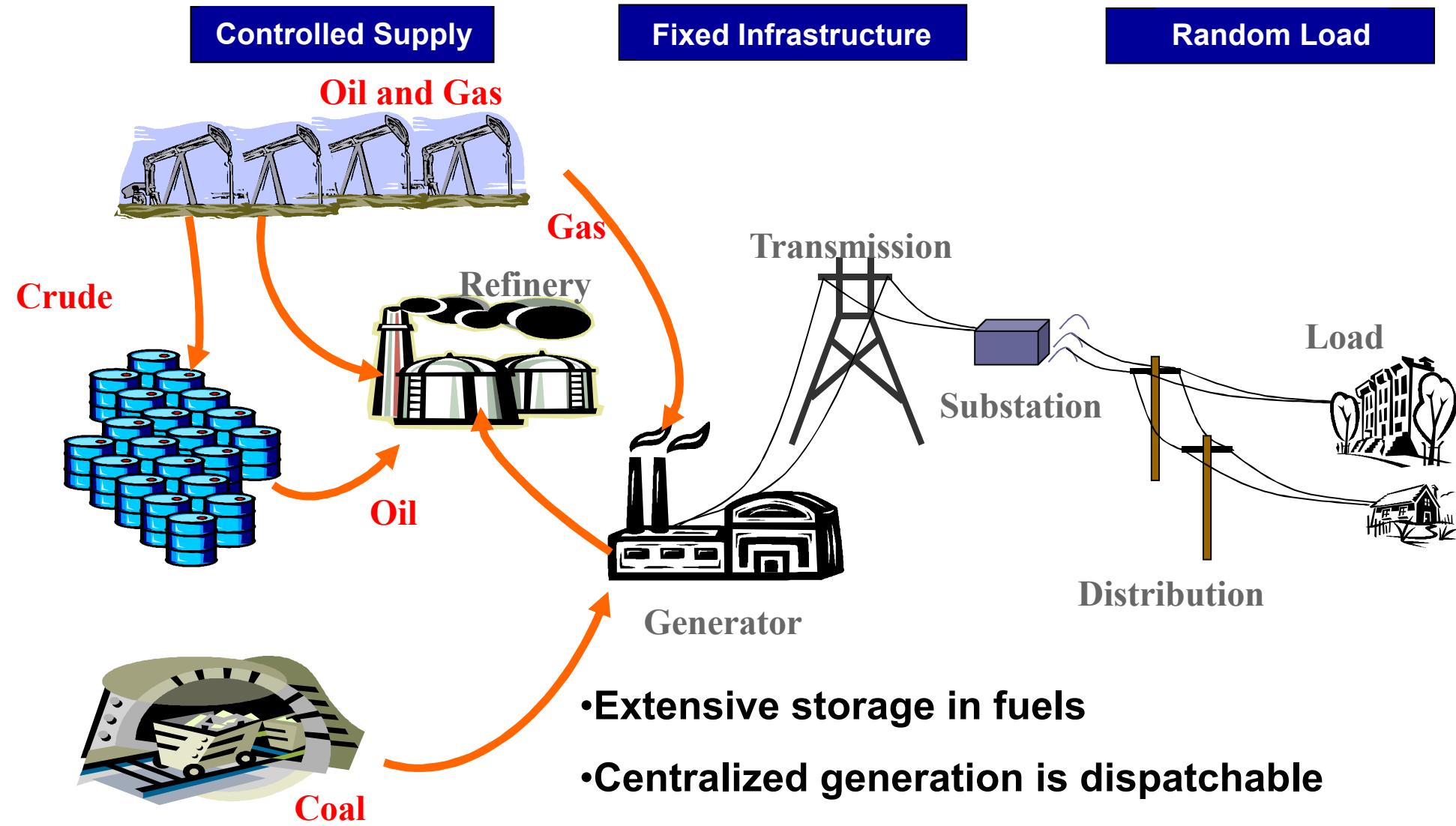
Xyce

CHARON

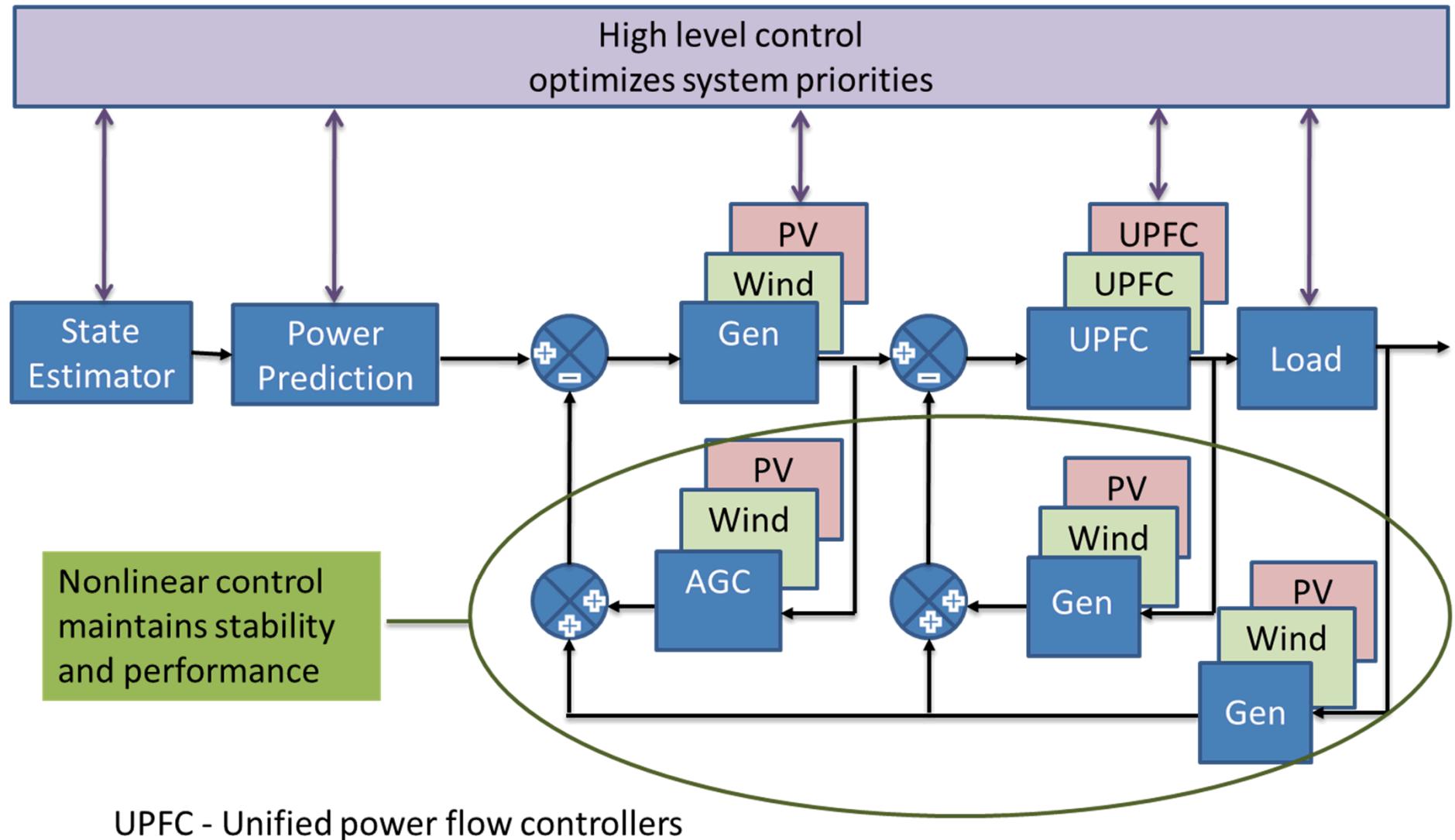
Habanero



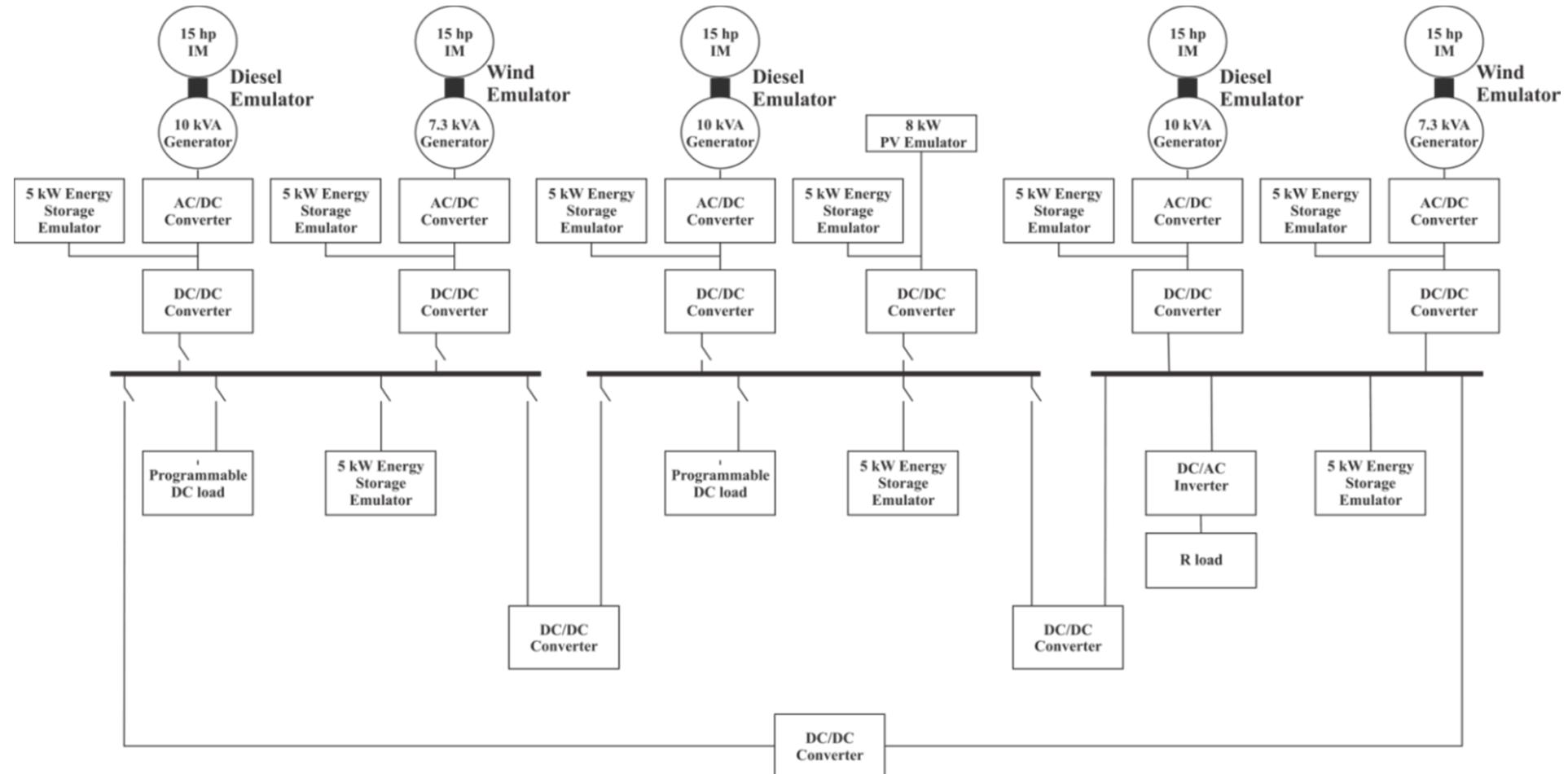
Today's Power Grid Is Unidirectional and Inflexible



Tiered Control Structure Enables Prioritization and System Adaptability



SSM collective structure



Master
Control
Computer

Data
Acquisition

SNL Grid Informatics Fulfill the tasks of the High Level Control

High level control will

- Monitor and predict the state of the system
- Negotiate and define power flow priorities
- Adapt the system to maintain performance and stability
- Heal the system when faults or failures occur

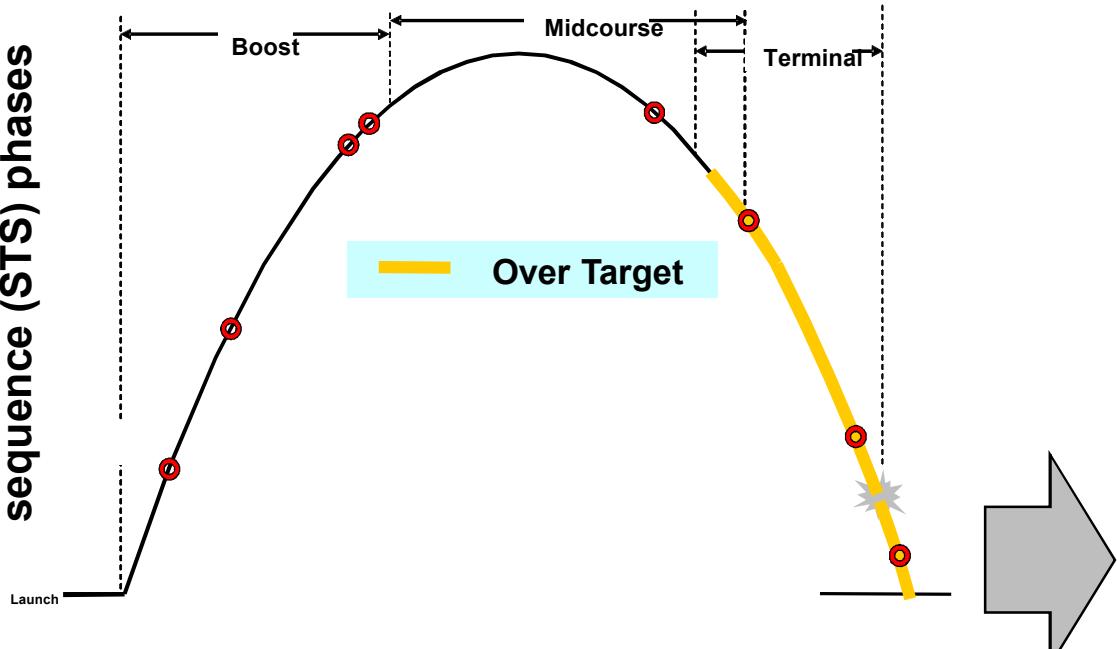
Agents are placed on each system component:

- Model physical properties of each component
- Communicate with other agents
- Prioritize / define component operation (source, storage, loads, etc)
- Can work collectively towards a common goal
- *Must run realtime*

Agents will be embedded and run real time.

Nuclear Weapons Stockpile Responsibilities Drive Deep Expertise in Grid-relevant Science and Engineering

All stockpile-to-target sequence (STS) phases



Physical Environments

- Weapon storage, transportation, maintenance, storage on delivery platform, launch and in-flight path
- Normal Environments (EMR, ESD, nearby lightning, degaussing)
- Abnormal Environments (lightning, exposure to power sources)
- Hostile Environments (nuclear weapon effects, directed energy weapons, high power microwaves)

System & Components



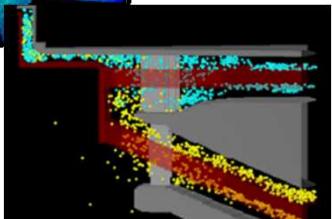
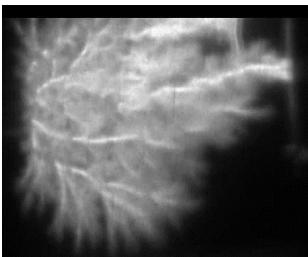
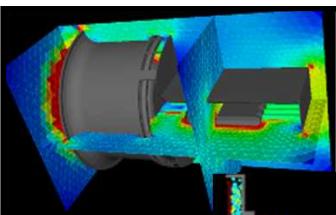
Grid-relevant Science and Engineering at Sandia

- Advanced power systems and AC/DC microgrids
- High voltage breakdown science & experiments
- Pulsed power components and systems development
- Electromagnetics theory/code development
- Electromagnetic experiments
- Systems engineering and integration

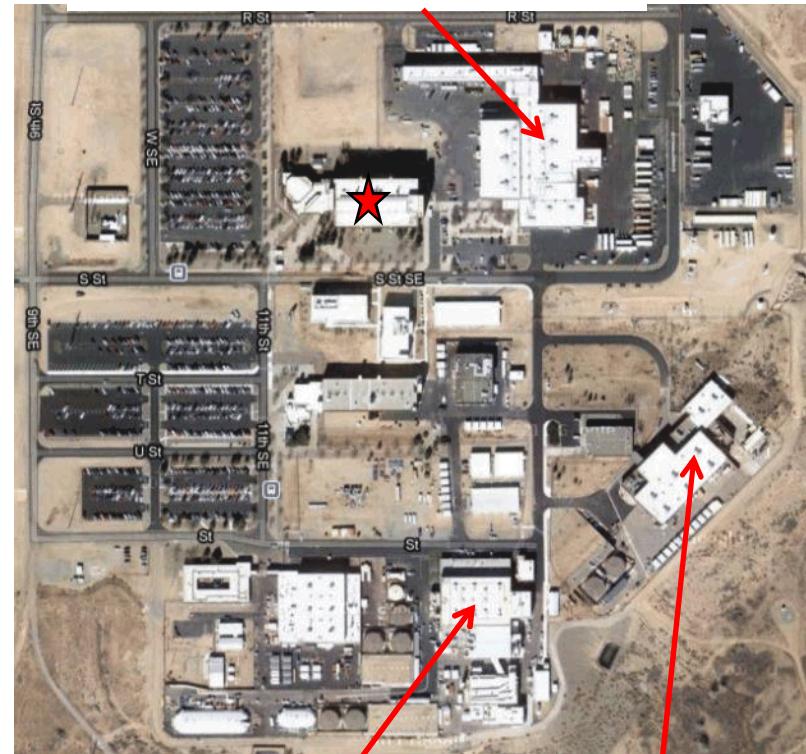
Pulsed Power and Radiation Sciences

Customers and Organization and Facilities

- National security activities for and in collaboration with:
 - Department of Energy (National Nuclear Security Administration, Office of Science, Office of Electricity)
 - Other federal agencies (DOD-Army/USAF/NRL, DOT-Federal Aviation Administration, DOL – Mine Safety and Health Admin.)
 - Non-federal entities
 - Industry (Goodyear, FMC, Inc., Lockheed Martin Technology Research)
 - Universities



HAWK
World's largest DC-like electron beam accelerator

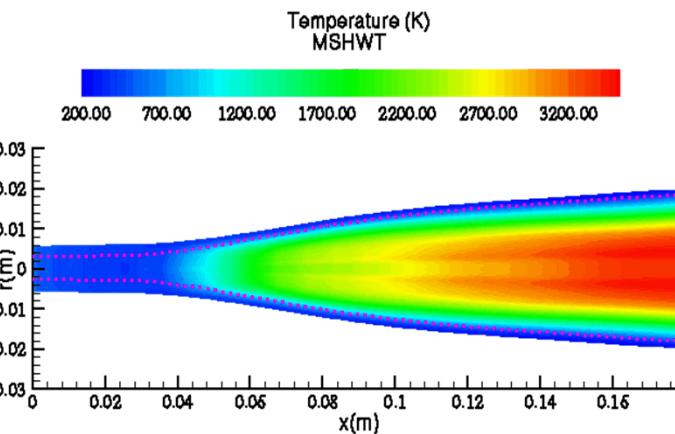
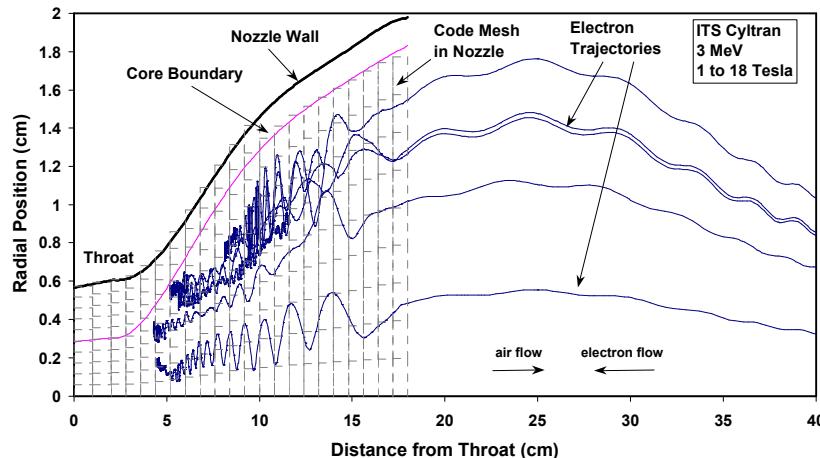


Z Machine (350 TW, 26 MA)
World's most powerful radiation source for fusion, dynamic materials and radiation effects sciences

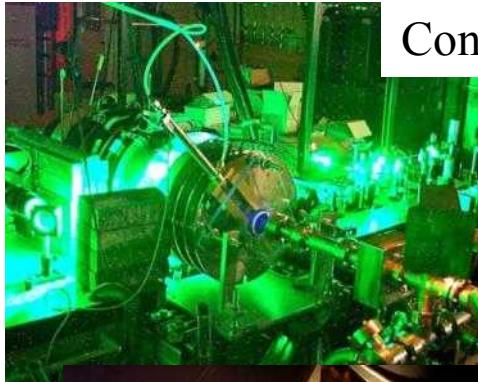
Hermes III
Flash x-ray source for nuclear weapons effects testing

Modeling, analysis, validation experiments, Complex system design & integration

Coupled electron/photon Monte Carlo transport codes for energy addition and CFD



Conduct of complex experiments



World's first large
aperture vacuum window



World class accelerator
technology development

Past Example of Solving Problems Based on Techniques Developed for the Nuclear Weapons Complex: Mine Safety

Sago Mine -Upshur County, West Virginia



In January 2006, twelve miners perished as the result of a methane gas explosion in an abandoned mine shaft.



Report of Investigation May 9, 2007 [1]

Root cause:

“Lightning was the most likely cause for this explosion with the energy transferring onto an abandoned pump cable ...providing an ignition source for the explosion.” [1]

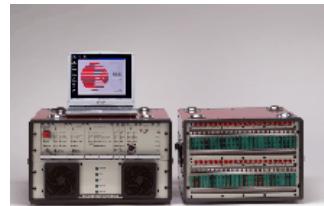
[1] R. Gates, et al., Fatal underground coal mine explosion, Mine Safety and Health Administration, Office of the Administrator, ID No. 46-08791, May 9, 2007.

In January 2006, twelve miners perished as the result of a methane gas explosion in an abandoned mine shaft.



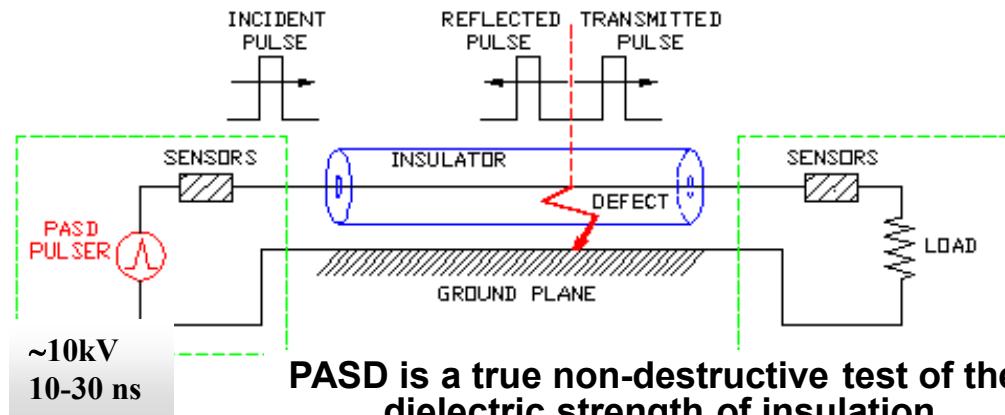
Sandia-developed techniques and diagnostics demonstrated a first-ever link between a mine explosion and indirect coupled lightning.

Wiring test bed developed for the evaluation of wiring diagnostics for commercial aircraft



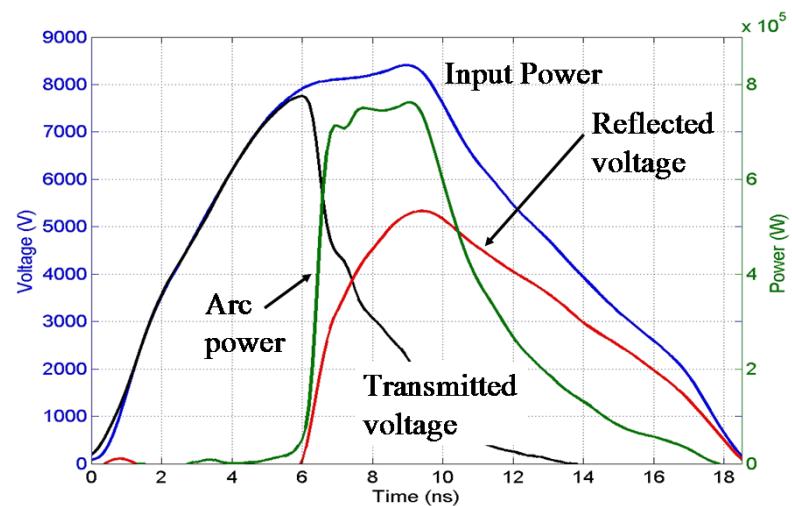
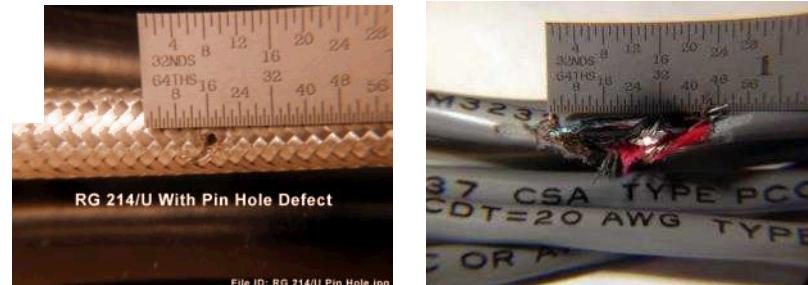
Another Example of Solving Problems Based on Techniques Developed for the NW Complex: Wiring Diagnostics

PASD can find and locate what no others can see – from pin-holes in the dielectric to crushed, but fully functional cables, waiting for a disaster to occur.



Commercialized by

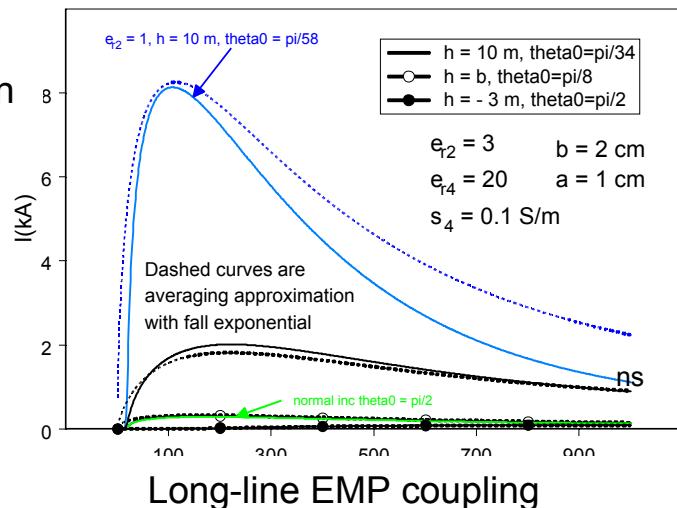
ASTRONICS
CORPORATION



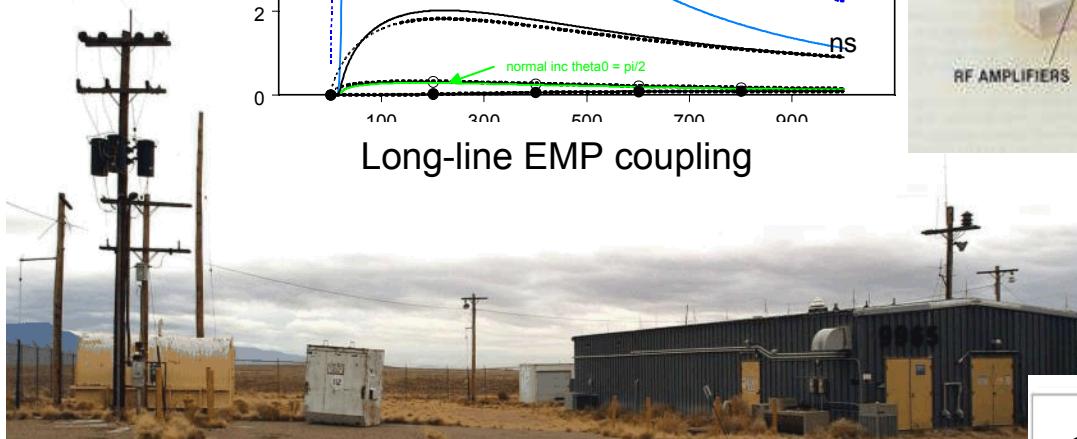
- Winner of Federal Laboratories Consortium Award for Interagency Partnering
- Winner R&D 100 Award from R&D magazine

Support to the Congressional Commission on the impact of Nuclear ElectroMagnetic Pulse energy on power systems

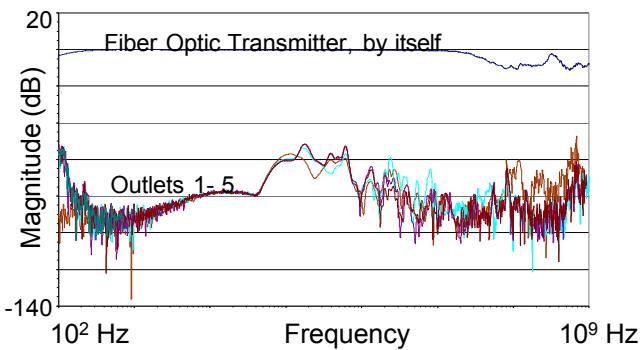
Warne / Chen



Long-line EMP coupling

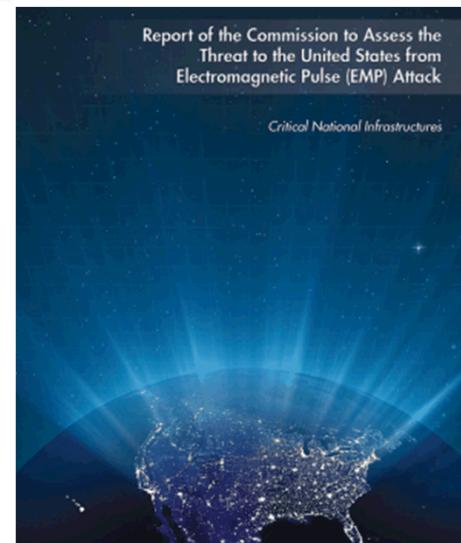
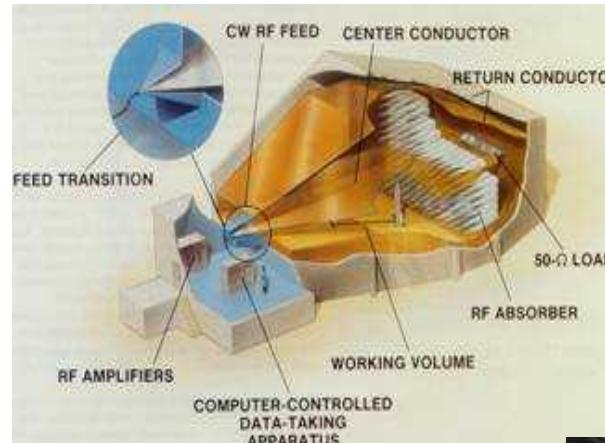


EMP coupling into facilities

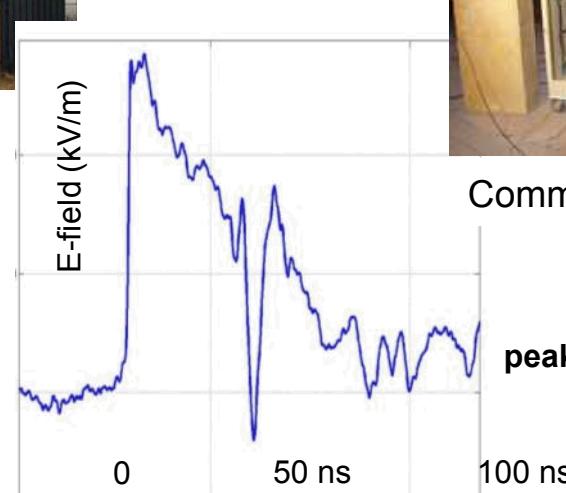


Typical EMES EMP waveform

Large scale TEM cell with full threat EMP capabilities

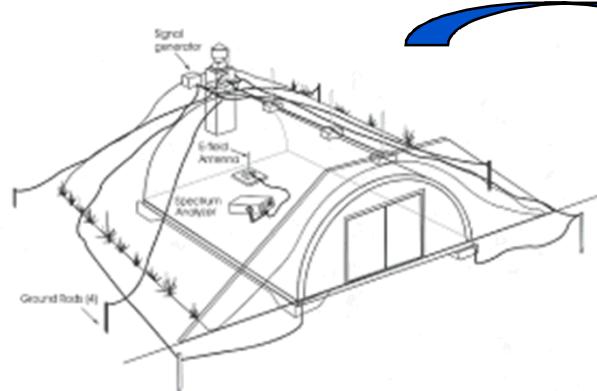


Communication Equipment

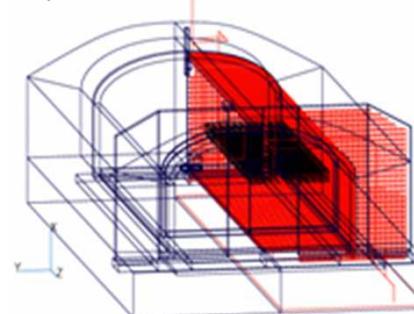


Rigorous Lightning Protection Developed for DOE Nuclear Weapons Facilities

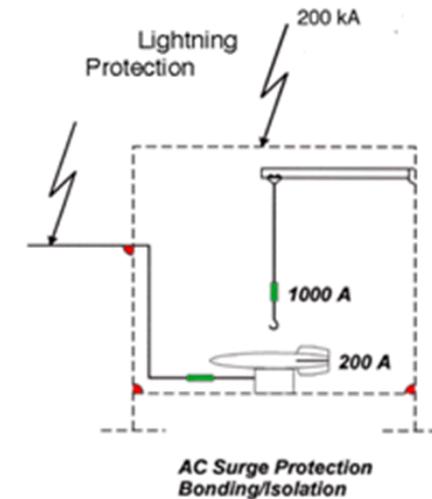
Lightning effects analysis, field transfer function measurements, engineered solutions for facility operations



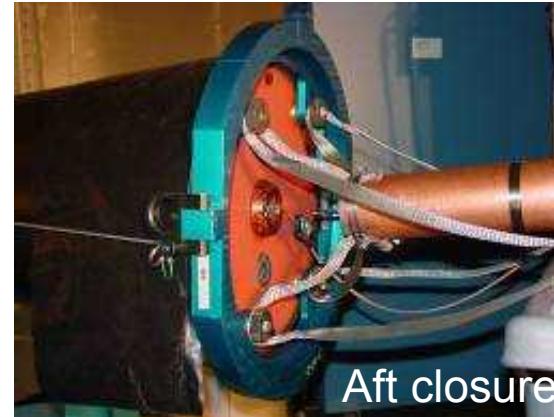
Field diagnostics/measurements



Modeling & analysis



High voltage standoff isolation



Aft closure

Weapons response to electrical static discharge

Backup Slides

A Path From Today's Grid To The Future (Smart) Grid

Today's Grid

Fossil

Fixed Infrastructure

Load

- Large spinning machines → Large inertia (matrix); dispatchable supply with storage
- Constant operating conditions → well-ordered state
- Well-known load profiles → excellent forecasting
$$[I]\dot{x} = f(x, u, t) ; [I]^{-1} \simeq [0] \rightarrow \dot{x} = [I]^{-1} f(x, u, t) \simeq 0 ; x(t) = x_0$$
$$G - L \geq 0 \ \forall t$$

Retain Today's Grid: Replace lost storage with serial or parallel additional energy storage

RE

Energy Storage Load

Fixed Infrastructure

Load

A Path From Today's Grid To The Future (Smart) Grid (cont.)

Future Grid:

1. **High penetration of renewables: loss of storage**
 - Loss of large spinning machines
 - Loss of dispatchable supplies
2. **Variable operating conditions → variable state $x(t)=?$**
3. **Stochastic load profiles → renewables as negative loads**
$$[I_F] \dot{x} = f_F(x, u, t) \rightarrow \dot{x}_F(t) = [I_F]^{-1} f_F(x, u, t)$$

$G - L \leq 0$ much of the time
4. **Problem Restated: How do we regain**
 - a) Well-ordered state $\rightarrow x(t) ?$
 - b) Well-known load profiles?
 - c) Dispatchable supply with energy storage?
 - d) Stability and performance?
 - e) An optimal grid?

A Path From Today's Grid To The Future (Smart) Grid (cont.)

Our Solution Approach:

1. A combination of feedback control and added energy storage
 - a) Requires a trade-off between information flow (control) and added energy storage while simultaneously minimizing both
 - b) Requires maximizing performance while ensuring stability
2. Develop a set of tools

The Details:

1. **Need consistent models (equations of motion)**
 1. MATLAB / Simulink
2. **Need a consistent metric for all energy supplies, energy storage, and dispatchable loads**
 - *Exergy: A measure of order*

A Path From Today's Grid To The Future (Smart) Grid (cont.)

3. Need to stabilize the grid and define stability boundaries (nonlinear)
 - » Hamiltonian Surface Shaping and Power Flow Control (HSSPFC)
 - » Measure of order
4. Need to span the space of solutions for optimization process

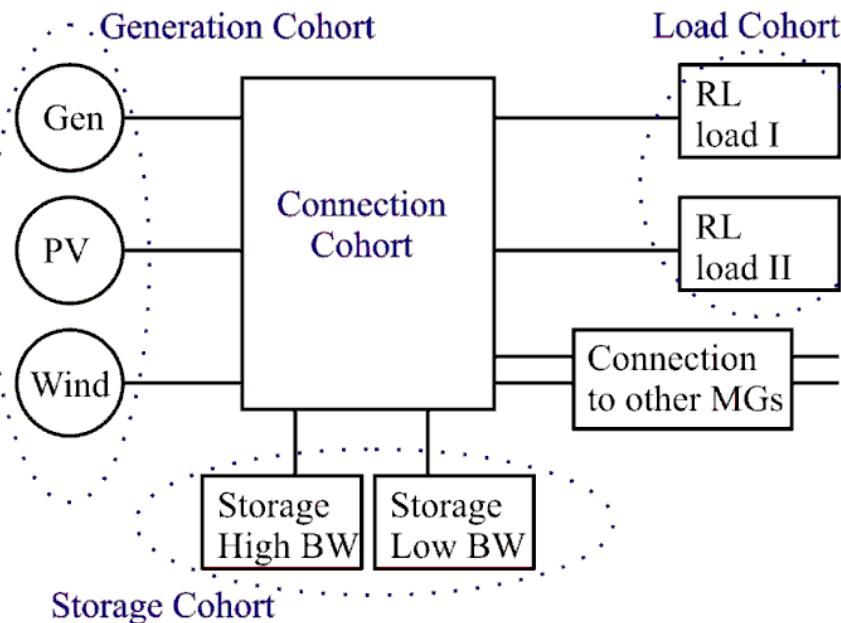


- 0% storage; under-actuated; limited state space ($G-L \leq 0 \ \forall t$)



- 100% storage; over-actuated; full state reachability ($G-L \geq 0 \ \forall t$)

Summary Nonlinear Power Flow Control Design Steps



1. Define Reduced Order Model (ROM)
2. Formulate K.E. and P.E.
3. Formulate Hamiltonian
4. Hamiltonian Rate (Power Flow)
5. Design nonlinear control laws
6. Determine static stability conditions
7. Determine dynamic stability conditions
8. Optimize control, controller gains
9. Perform Enterprising Optimization
10. Minimize information flow and energy storage

Microgrid and Collectives of
Microgrid Configurations



Nonlinear Control Design HSSPFC Energy Storage

- Feedback controller design for integration of renewable energy into DC bus microgrid
- Feedback controller decomposed into two parts:
 - Feedback guidance command for boost converter duty cycle
 - HSSPFC implements energy storage systems
- Duty cycle servo control fully coupled
- HSSPFC completely decoupled due to skew-symmetric form analogous to Spacecraft and Robotic systems
- Example: DC bus with 2 boost converters for investigation of 0%-100% energy storage evaluation, specifications, and requirements

Duty Cycle Commands

- Duty cycle commands are obtained from steady-state solution with $u=0$ as:

$$0 = -R_1 x_1 - \lambda_1 x_3 + v_1$$

$$0 = -R_2 x_2 - \lambda_2 x_3 + v_2$$

- Or in matrix form as:

$$0 = \lambda_1 x_1 + \lambda_2 x_2 - \frac{1}{R_0} x_3$$

- Leads to quadratic equation in duty cycles:

$$\left[\bar{R} + \tilde{R} \right] x + v = 0$$

$$R_0 x_{3_0} \left(\frac{1}{R_1} \lambda_1^2 + \frac{1}{R_2} \lambda_2^2 \right) - R_0 \left(\frac{v_1}{R_1} \lambda_1 + \frac{v_2}{R_2} \lambda_2 \right) + x_{3_0} = 0$$

HSSPFC for Energy Storage Design Observations

It is useful to discuss several observations about Equations (1) and (2):

$$u_{ref} = -[\bar{R} + \tilde{R}]x_{ref} - v \quad (1)$$

$$u = u_{ref} - \Delta u \quad (2)$$

- a) *Equation (1) is an equivalent guidance command that is fully coupled in the states and dependent upon the duty cycle commands. The duty cycle commands will be determined from an optimization routine (SQP, DP, etc.) when desired cost functions and constraints are included.*
- b) *For renewable energy sources, v will be time varying and possibly stochastic which leads to an under-actuated system, for 0% energy storage, u=0.*
- c) *For fossil energy sources, v will be dispatchable with excess capacity which leads to an over-actuated systems with 100% energy storage even with u=0.*
- d) *For u not equal to zero, microgrid with 100% transient renewable energy sources(PV and wind) will lead to requirements for energy storage systems (power, energy, frequency specs., etc.)*
- e) *Controller, u, is decoupled which simplifies design procedure*



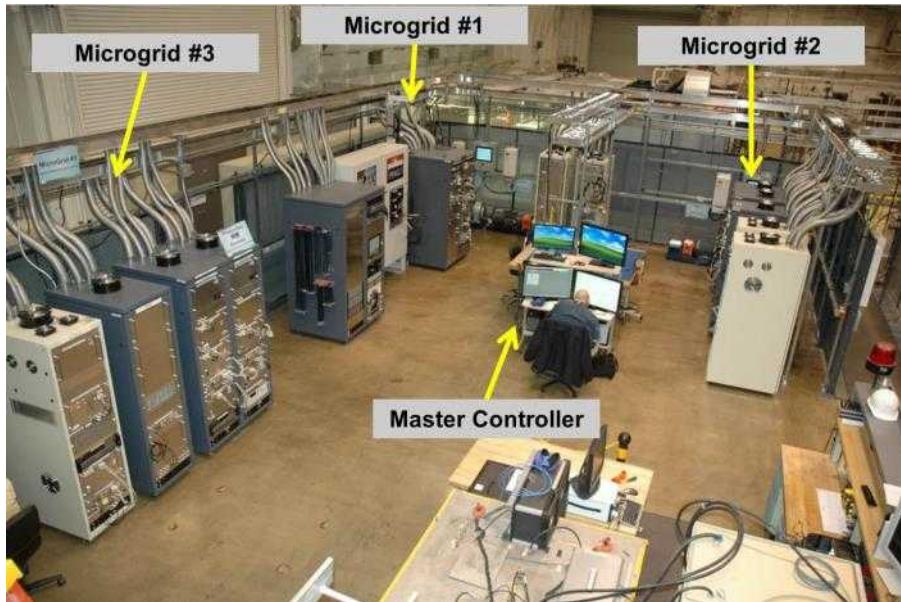
BACKUP

Sandia National Lab's Secure Scalable Microgrid Testbed: Capabilities and Collaboration

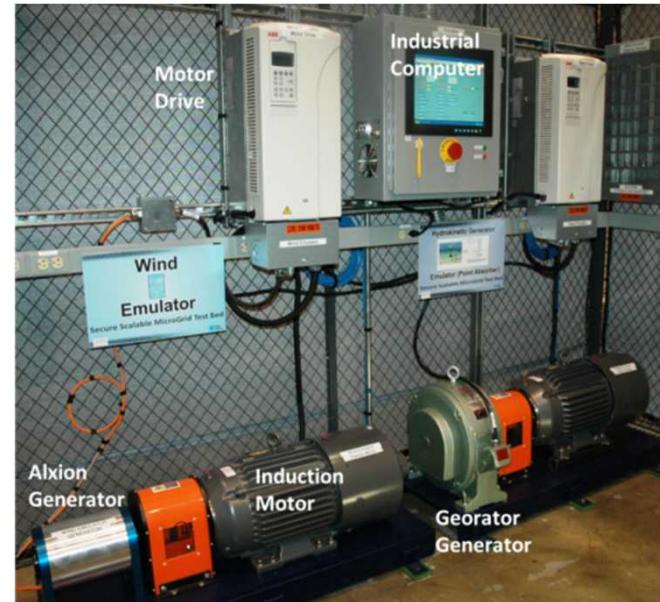
- Sandia National Laboratories is expanding their renewable energy research to develop new tools for the design and analysis of power systems with high penetration levels of stochastic renewable sources. A necessary step for this research is experimental validation, which has resulted in the development of a hardware testbed called the Secure Scalable Microgrid Testbed (SSMTB). Given a time-indexed load and weather profile that includes load resistances (Watts or Ω), wind speed (m/sec), wave crest (m), river currents (m/sec), solar irradiance (W/m²), etc.), the testbed can be used to repeat an experiment over and over using different control schemes but the same simulated test conditions. This is done from a central computer interface.

Secure Scalable Microgrid (SSM) Testbed Enables Hardware Testing of HSSPFC

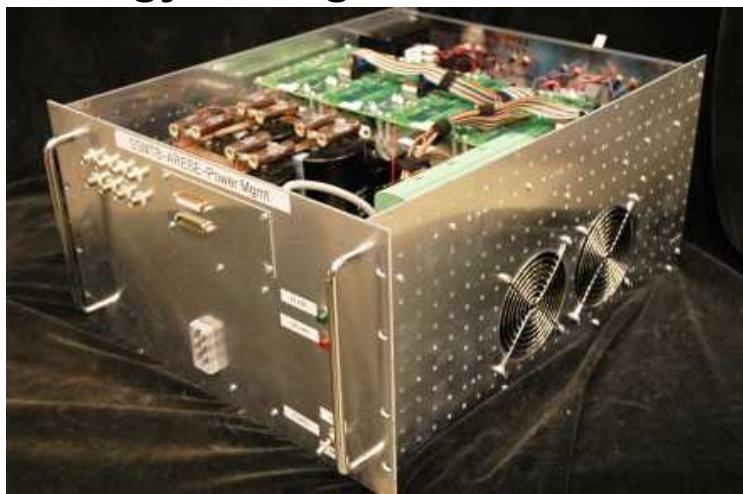
Multiple Microgrid Testbed



Mechanical Source Emulators



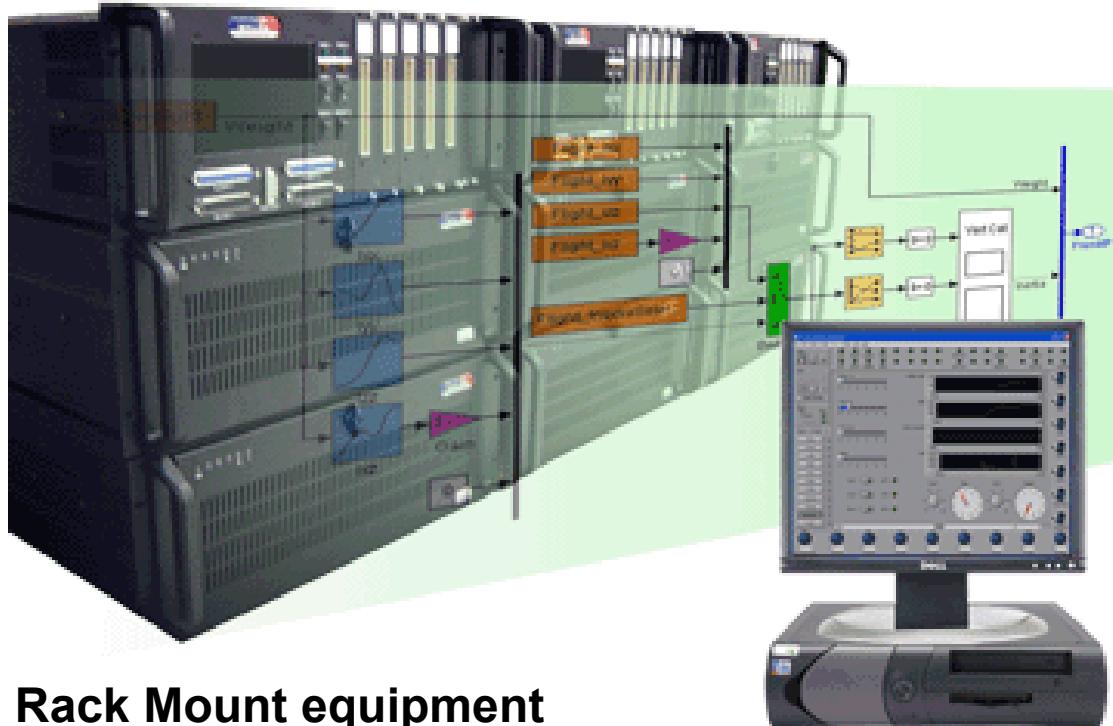
Energy Storage Emulators



High Power Digital Resistor – Load Bank



Rapid-Prototyping Environment for Real-Time Distributed Control Systems



Rack Mount equipment

Hybrid real-time digital simulator with I/F to real hardware (scaled, DETL, actual components), renewables I/F and PSCAD calibrated models

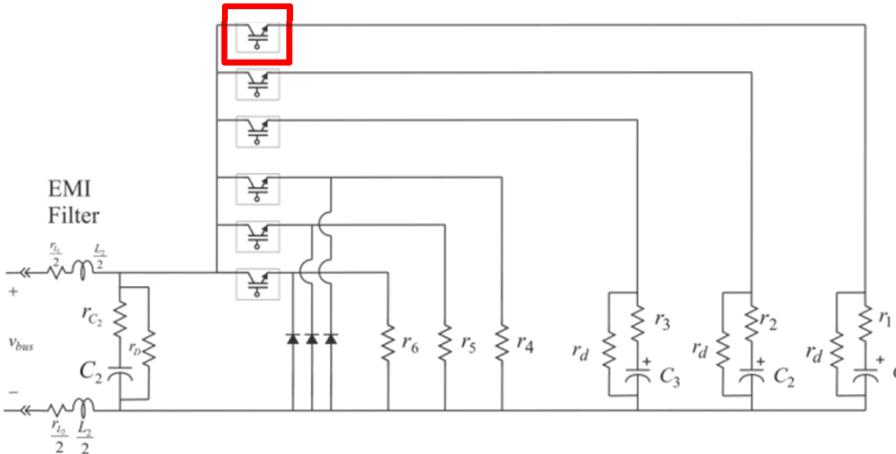
- Matlab/Simulink/RTW
- SimPower Systems Blockset
- xPC Target(s)
- Opel-RT RT-Lab (multi-node system)
- ARTEMIS, RT-Events, and HIL I/F capability



Pulsed Load Simulations

New SSM Testbed Component: Adjustable Pulsed Load

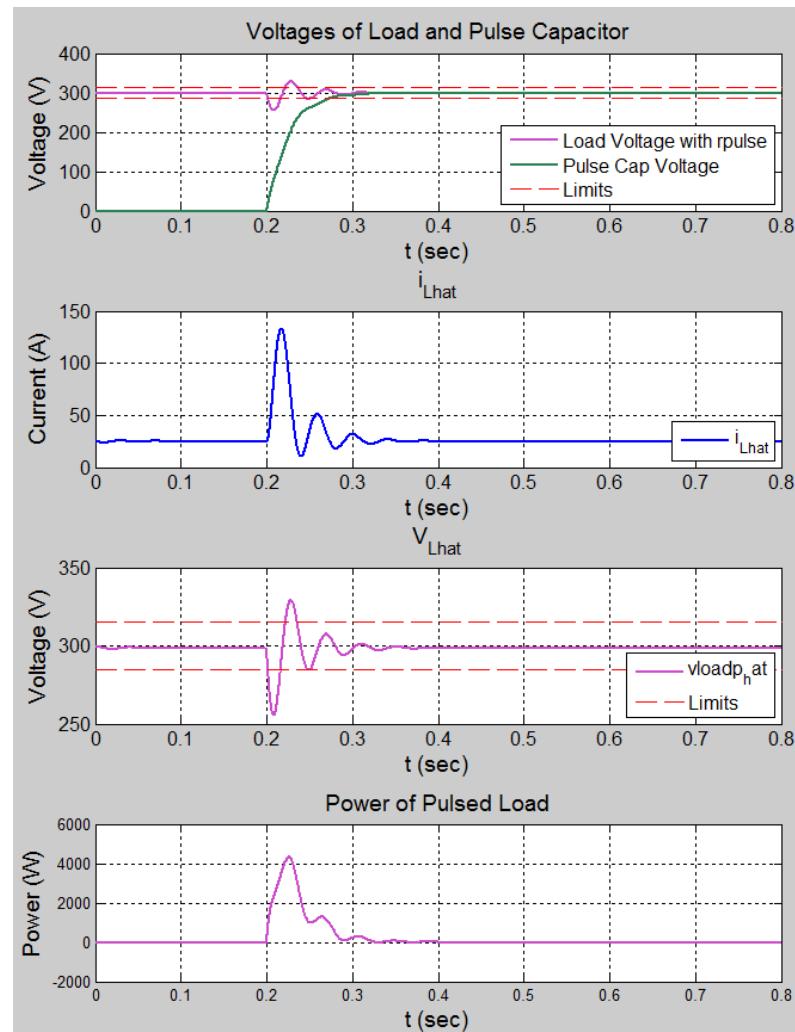
- Simulations were performed to gauge severity of pulsed load on boost converter uncontrolled response



Peak Load Power	= 4.34 kW
Load Energy	= 348.9 J
Peak Over Shoot	= 10.6 %
Peak Under Shoot	= 14.2 %

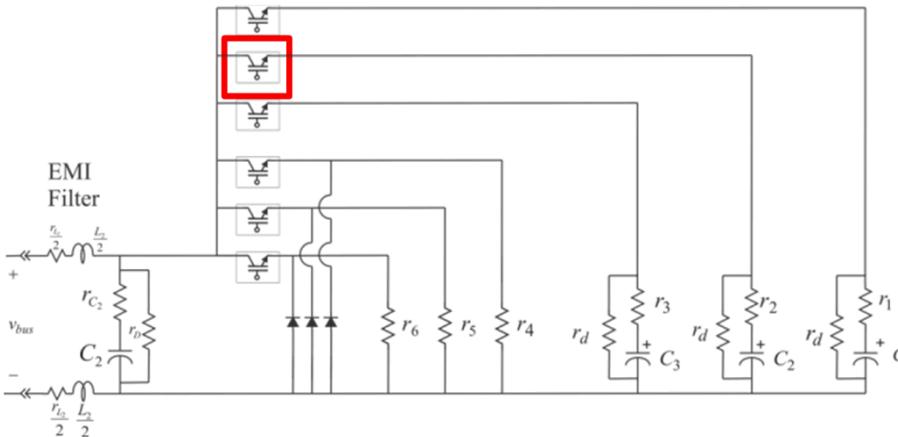
$$r_1 = 6 \Omega$$

$$C_1 = 4 \text{ mF}$$



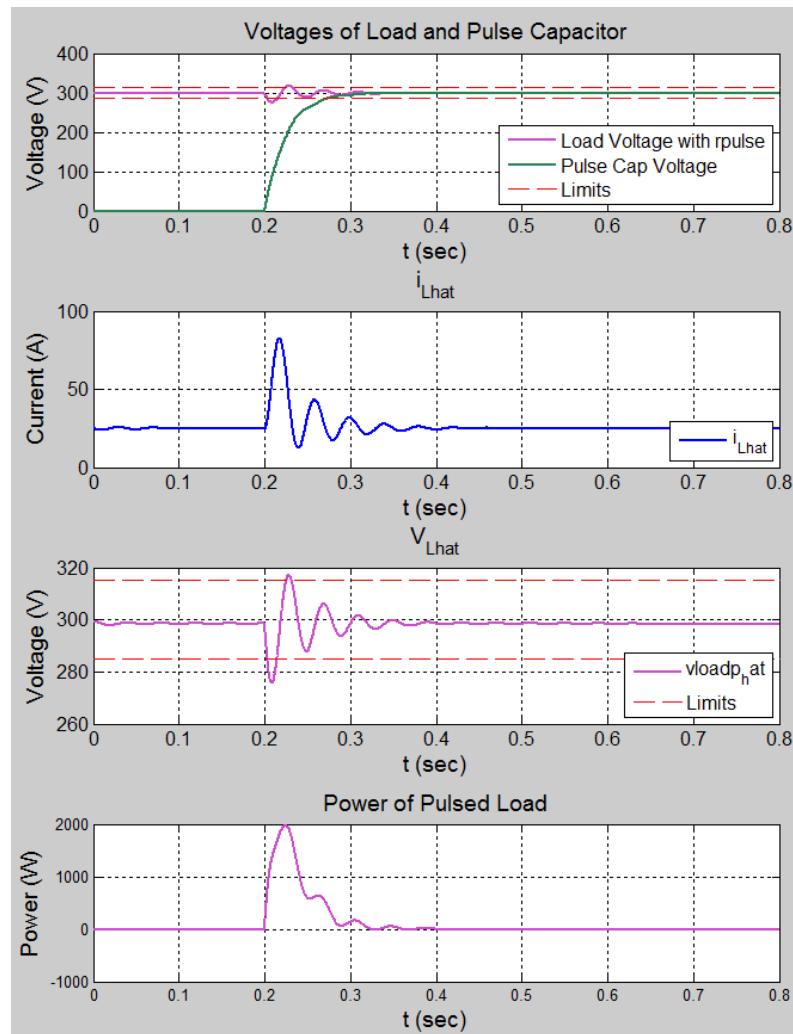
New SSM Testbed Component: Adjustable Pulsed Load

- Simulations were performed to gauge severity of pulsed load on boost converter uncontrolled response



$$r_2 = 12 \Omega$$

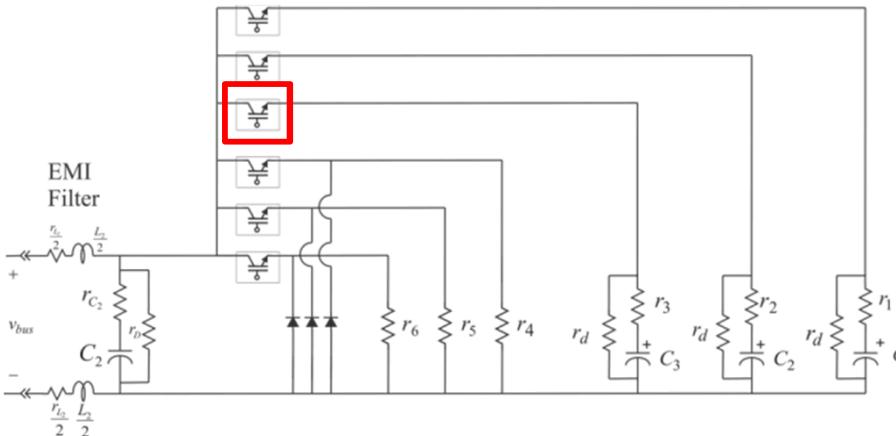
$$C_2 = 2 \text{ mF}$$



Peak Load Power	= 1.98 kW
Load Energy	= 176.2 J
Peak Over Shoot	= 6.4 %
Peak Under Shoot	= 7.6 %

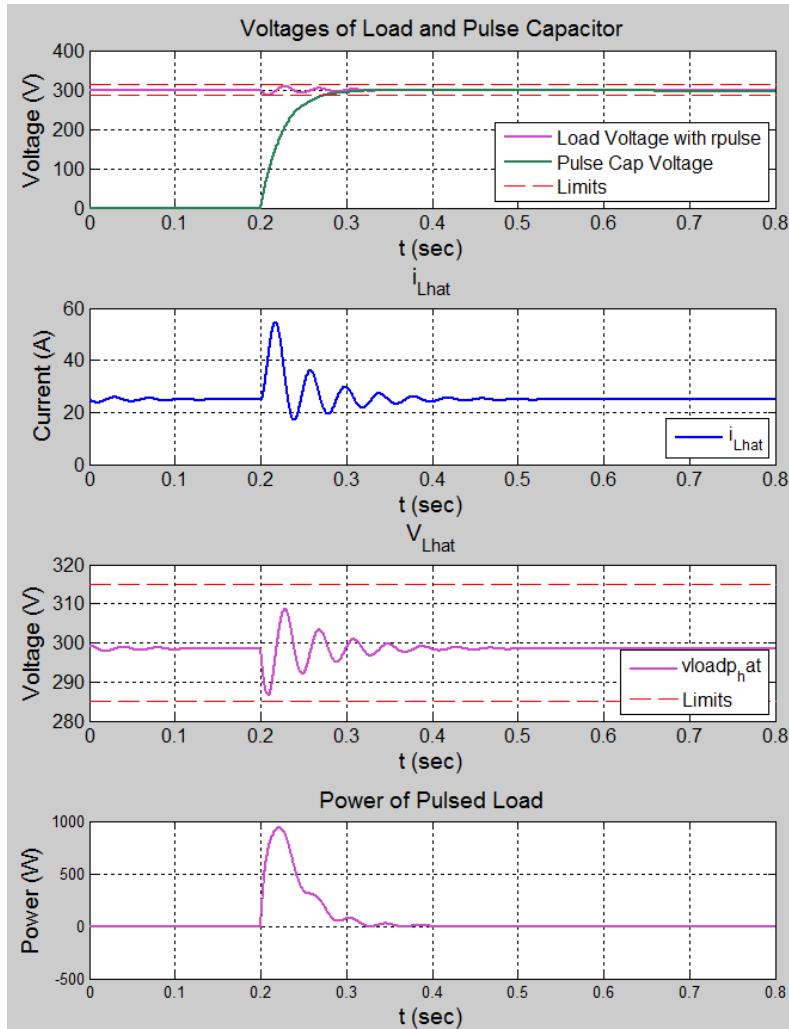
New SSM Testbed Component: Adjustable Pulsed Load

- Simulations were performed to gauge severity of pulsed load on boost converter uncontrolled response



$$r_3 = 24 \Omega$$

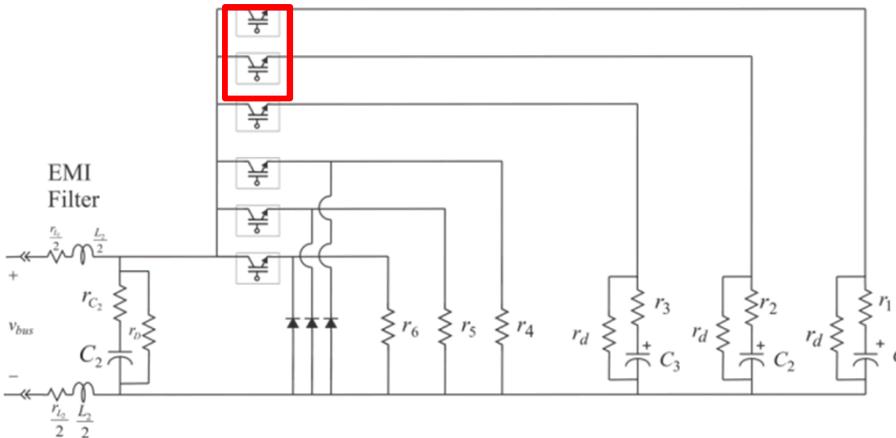
$$C_3 = 1 \text{ mF}$$



Peak Load Power	= .94 kW
Load Energy	= 88.8 J
Peak Over Shoot	= 3.5 %
Peak Under Shoot	= 3.9 %

New SSM Testbed Component: Adjustable Pulsed Load

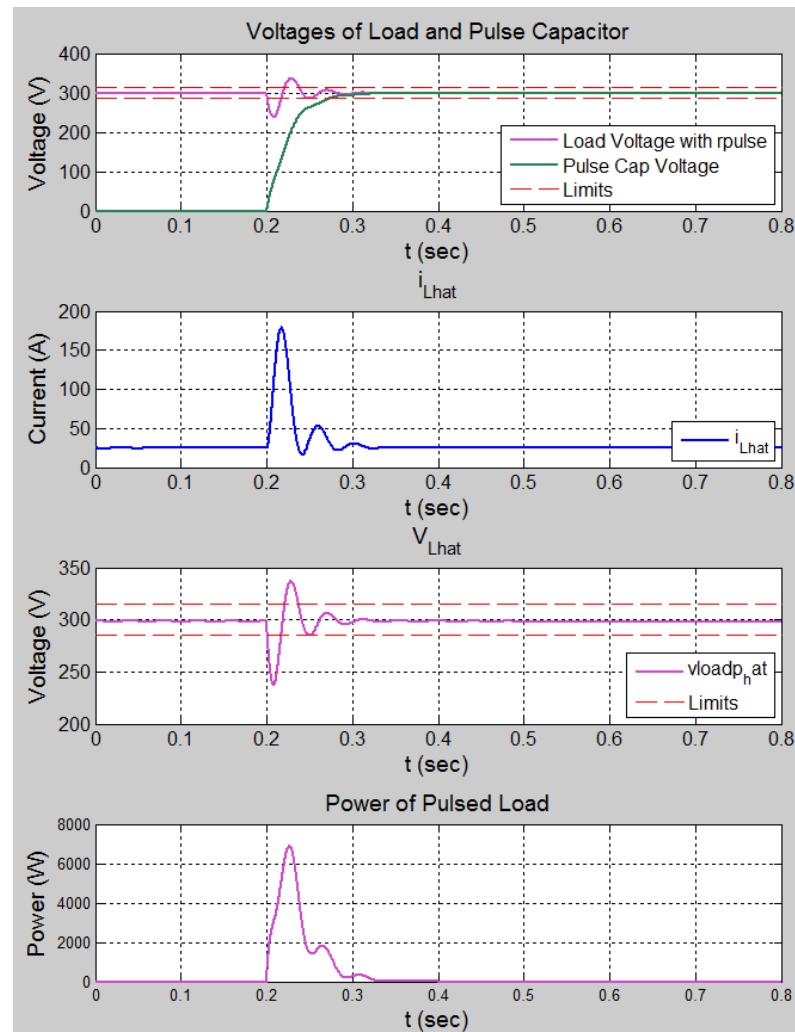
- Simulations were performed to gauge severity of pulsed load on boost converter uncontrolled response



Peak Load Power	= 6.90 kW
Load Energy	= 519.8 J
Peak Over Shoot	= 13.4 %
Peak Under Shoot	= 20.1 %

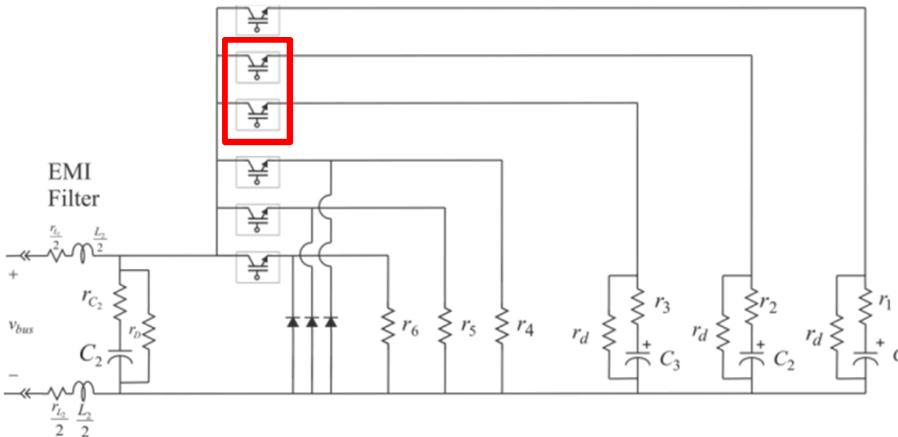
$$r_1 \parallel r_2 = 4 \Omega$$

$$C_1 \parallel C_2 = 6 \text{ mF}$$



New SSM Testbed Component: Adjustable Pulsed Load

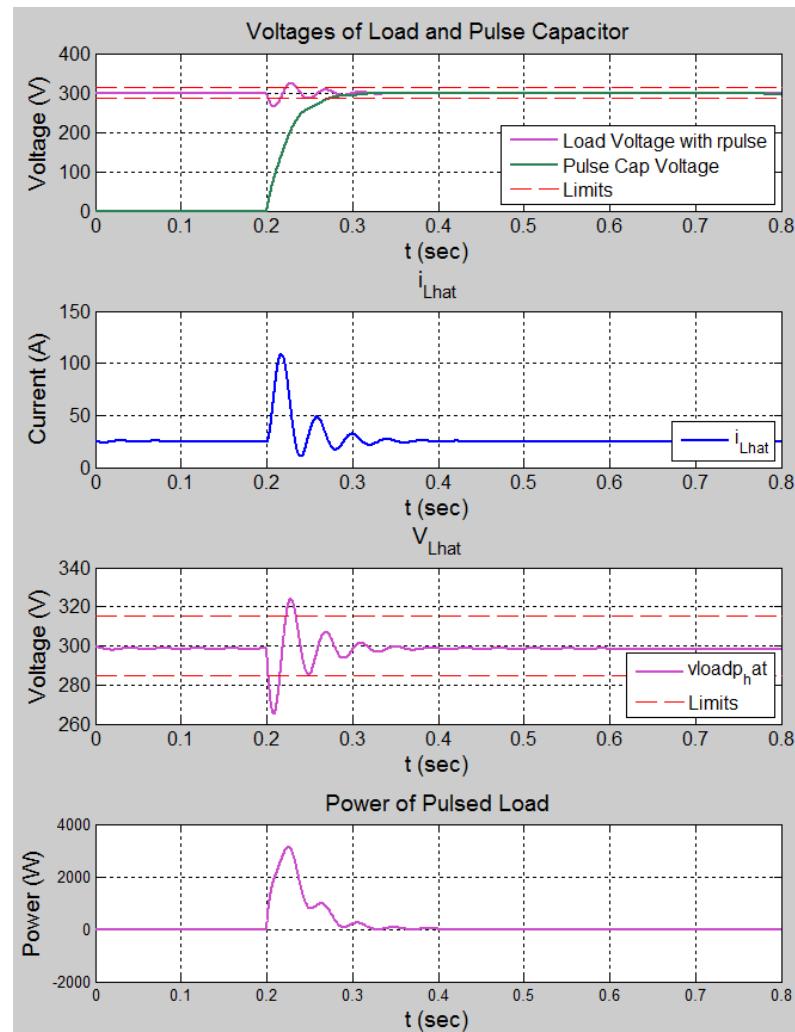
- Simulations were performed to gauge severity of pulsed load on boost converter uncontrolled response



$$r_2 \parallel r_3 = 8 \Omega$$

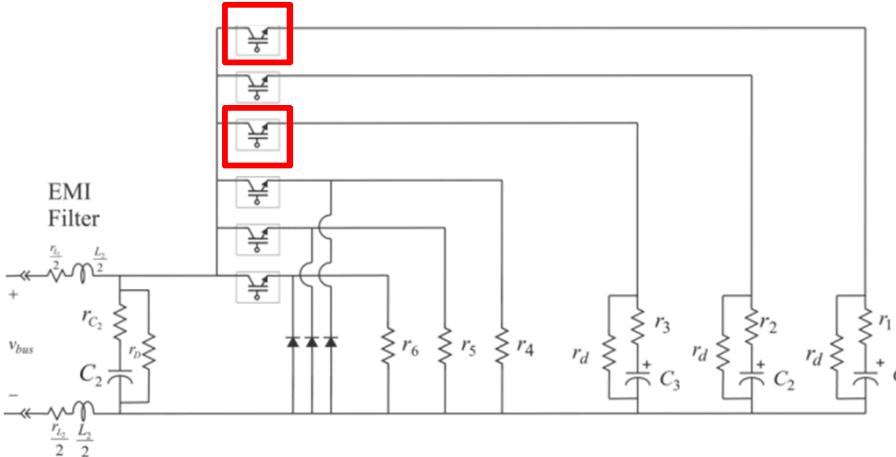
$$C_2 \parallel C_3 = 3 \text{ mF}$$

Peak Load Power	= 3.12 kW
Load Energy	= 263.3 J
Peak Over Shoot	= 8.7 %
Peak Under Shoot	= 11.0 %



New SSM Testbed Component: Adjustable Pulsed Load

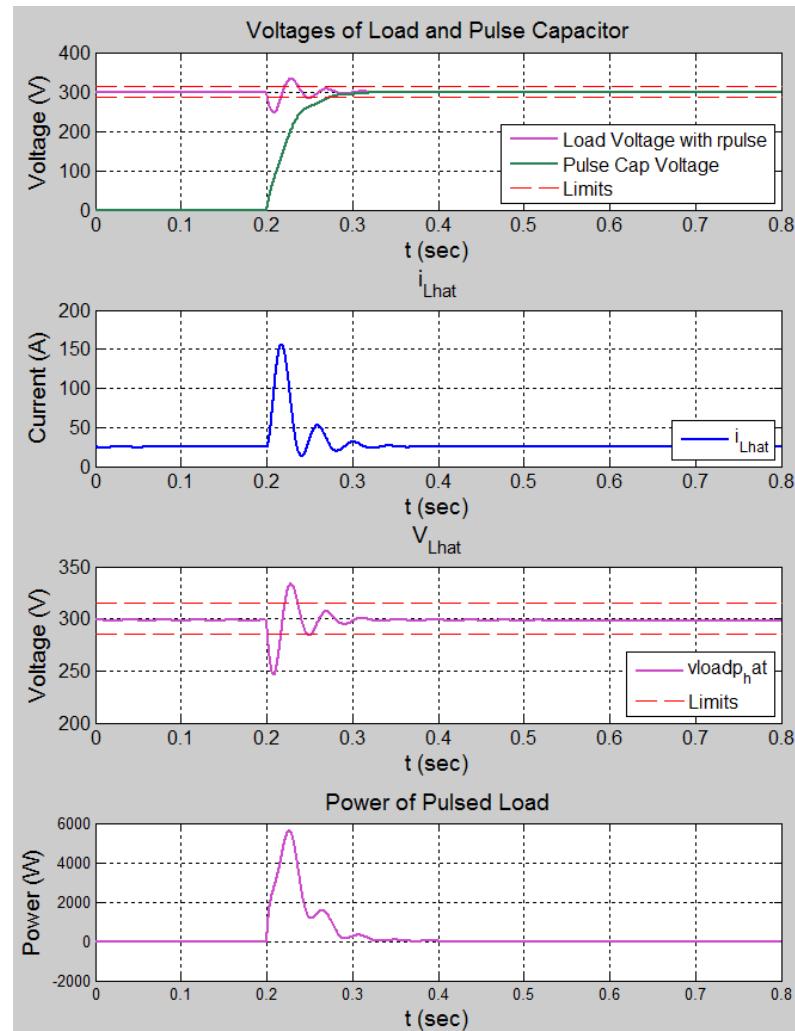
- Simulations were performed to gauge severity of pulsed load on boost converter uncontrolled response



Peak Load Power	= 5.61 kW
Load Energy	= 434.8 J
Peak Over Shoot	= 12.2 %
Peak Under Shoot	= 17.2 %

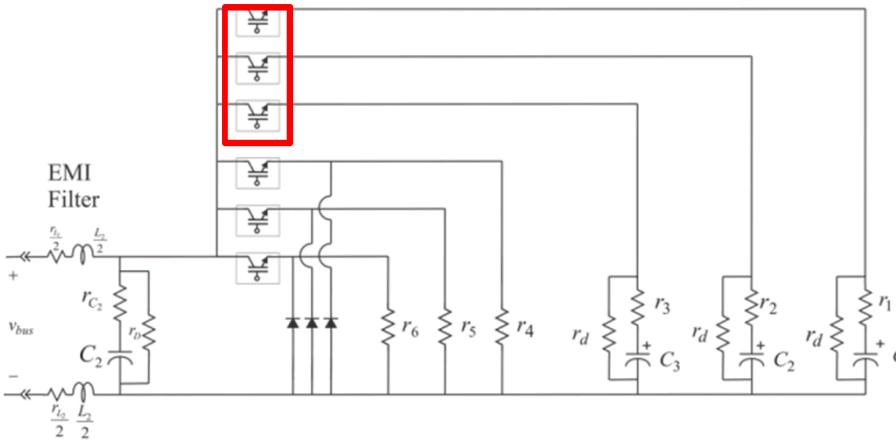
$$r_1 \parallel r_3 = 4.8 \Omega$$

$$C_1 \parallel C_3 = 5 \text{ mF}$$



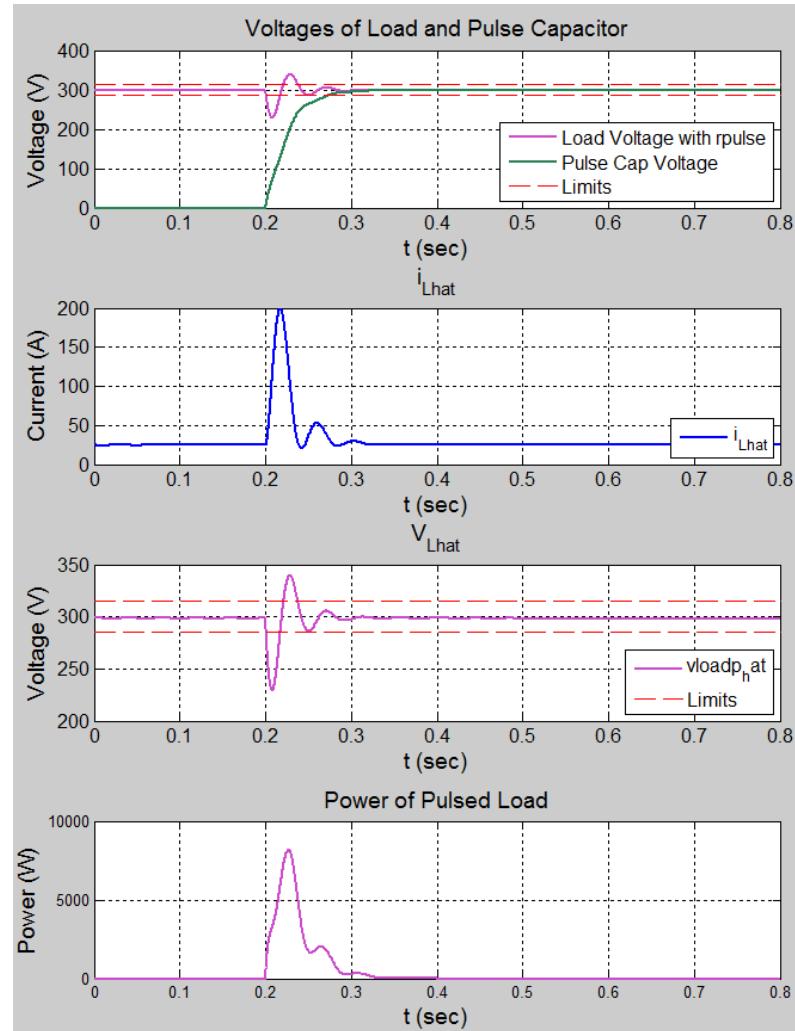
New SSM Testbed Component: Adjustable Pulsed Load

- Simulations were performed to gauge severity of pulsed load on boost converter uncontrolled response



$$r_1 \parallel r_2 \parallel r_3 = 3.43 \Omega$$

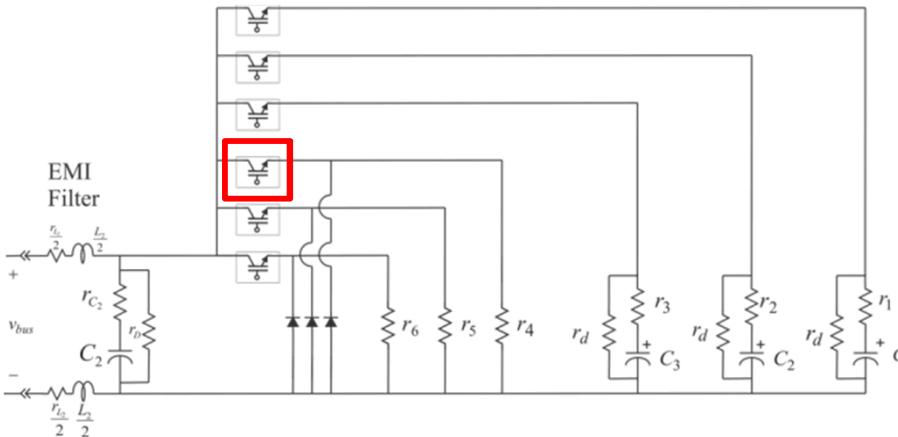
$$C_1 \parallel C_2 \parallel C_3 = 7 \text{ mF}$$



Peak Load Power	= 8.19 kW
Load Energy	= 604.6 J
Peak Over Shoot	= 14.4 %
Peak Under Shoot	= 22.7 %

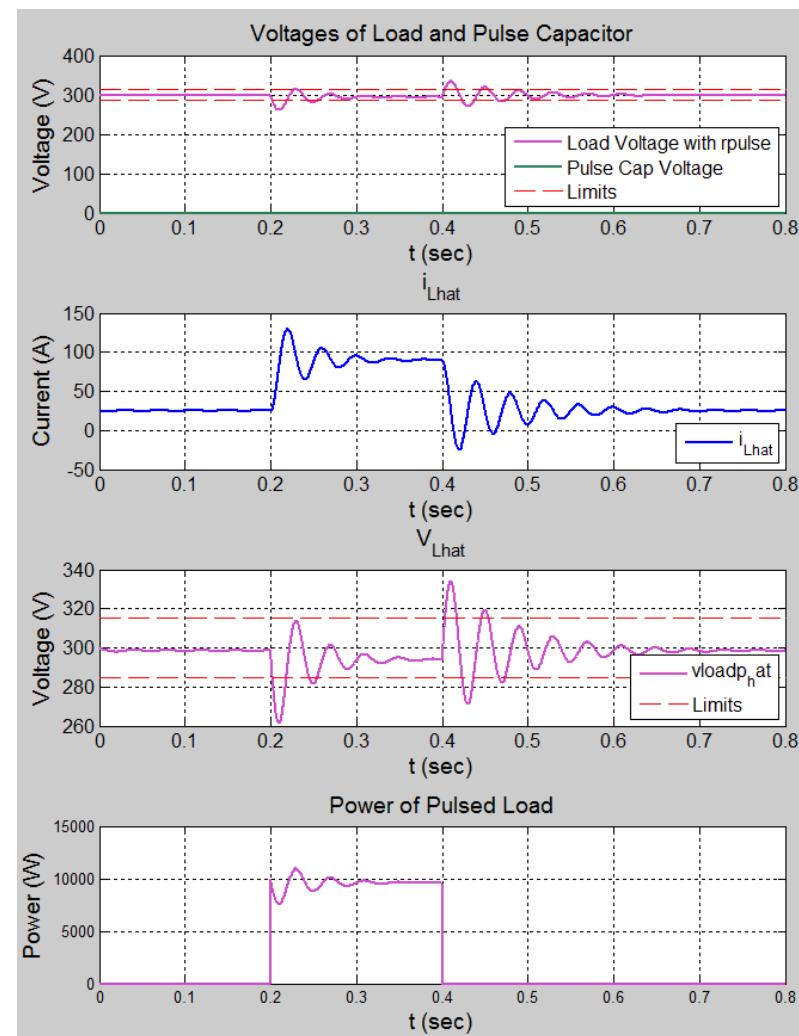
New SSM Testbed Component: Adjustable Pulsed Load

- Simulations were performed to gauge severity of pulsed load on boost converter uncontrolled response



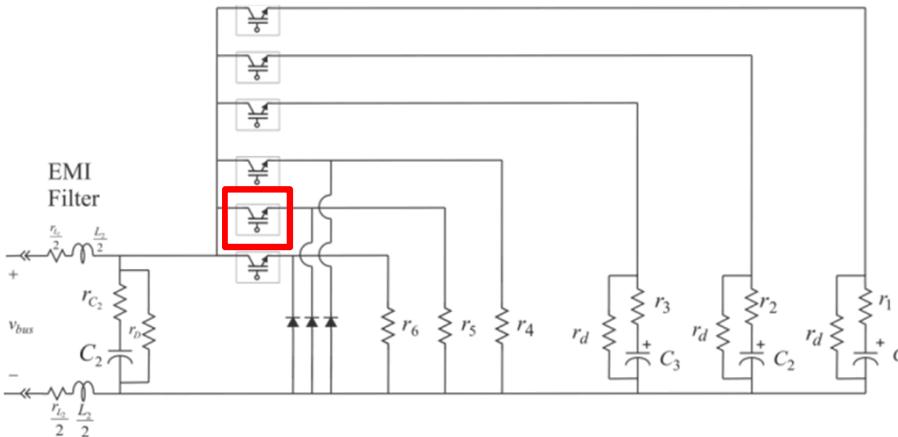
$$r_4 = 9 \Omega$$

Peak Load Power	= 10.94 kW
Load Energy	= 1903.6 J
Peak Over Shoot	= 12.4 %
Peak Under Shoot	= 12.0 %



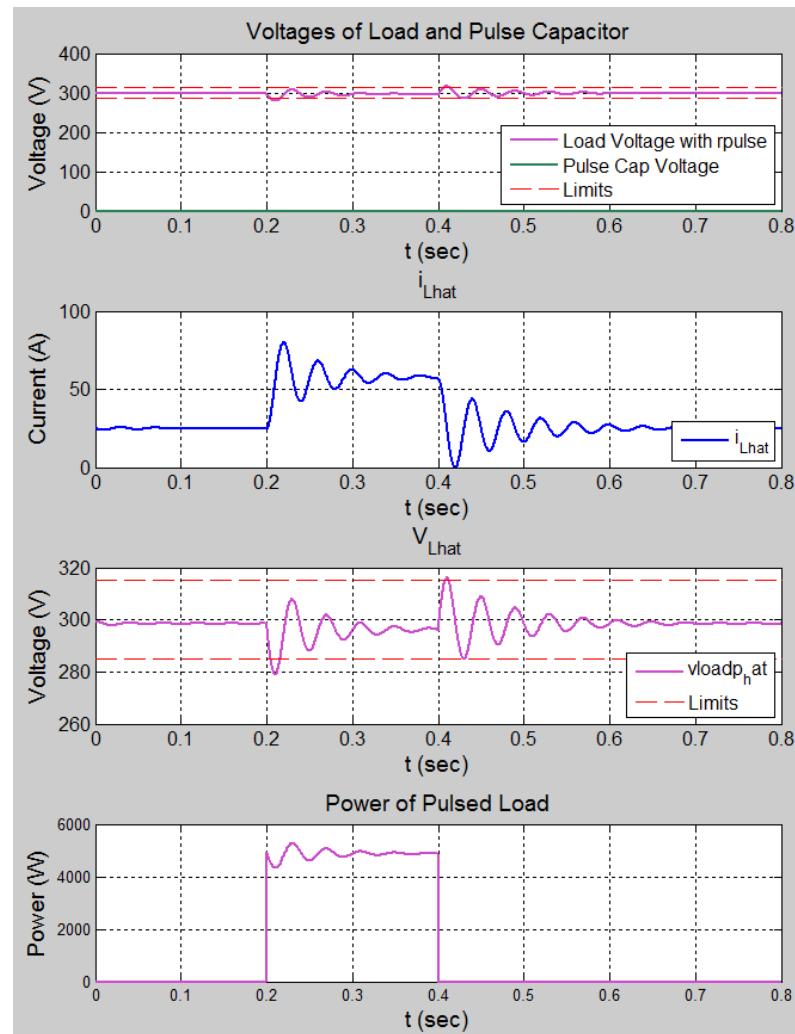
New SSM Testbed Component: Adjustable Pulsed Load

- Simulations were performed to gauge severity of pulsed load on boost converter uncontrolled response



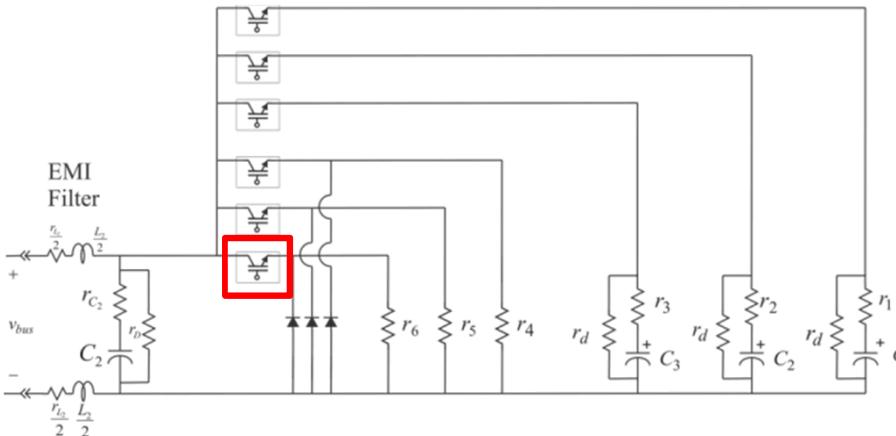
$$r_5 = 18 \Omega$$

Peak Load Power	= 5.27 kW
Load Energy	= 970.4 J
Peak Over Shoot	= 6.2 %
Peak Under Shoot	= 6.3 %



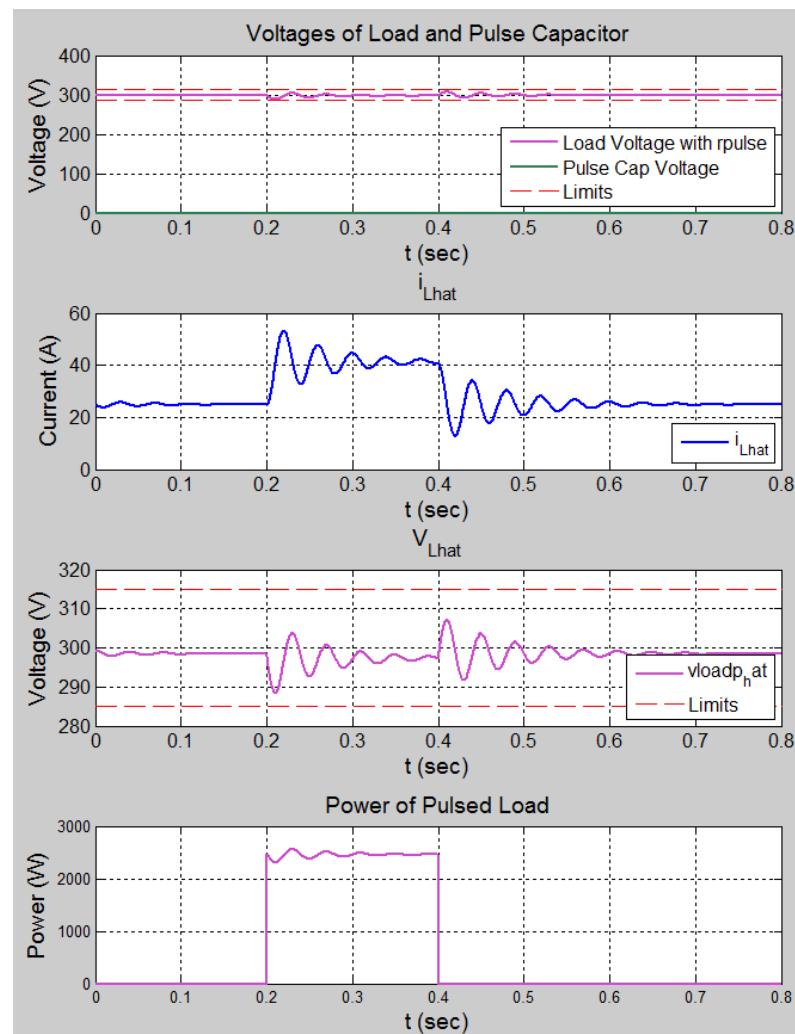
New SSM Testbed Component: Adjustable Pulsed Load

- Simulations were performed to gauge severity of pulsed load on boost converter uncontrolled response



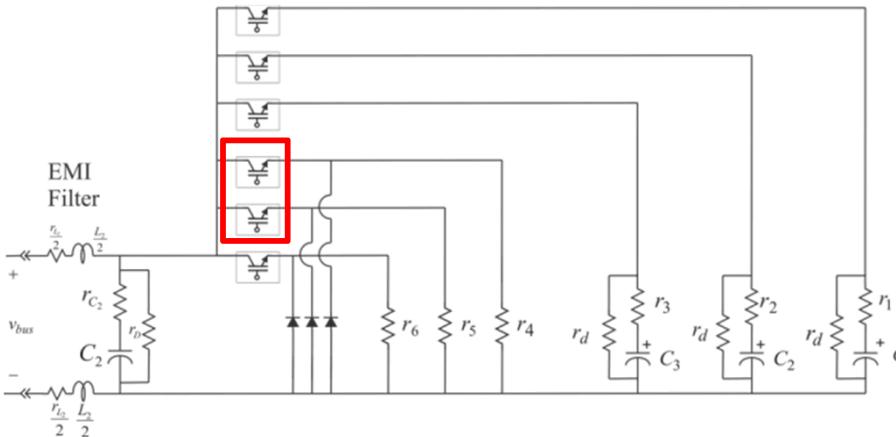
$$r_6 = 36 \Omega$$

Peak Load Power	= 2.56 kW
Load Energy	= 490.0 J
Peak Over Shoot	= 3.0 %
Peak Under Shoot	= 3.2 %



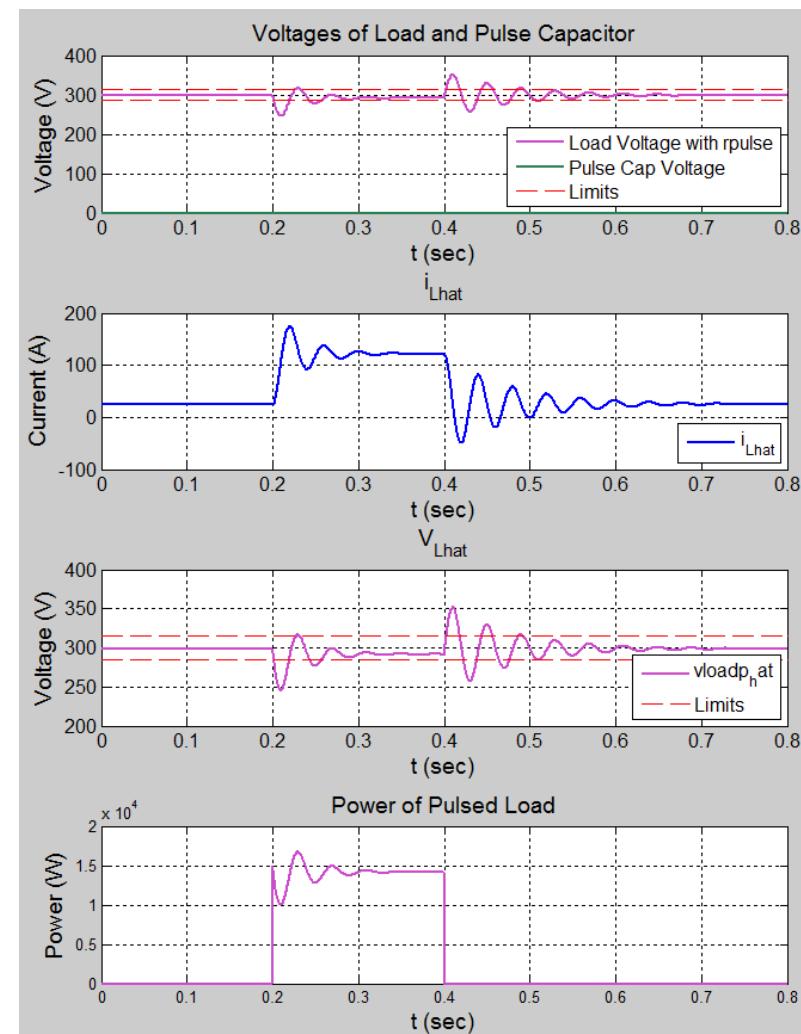
New SSM Testbed Component: Adjustable Pulsed Load

- Simulations were performed to gauge severity of pulsed load on boost converter uncontrolled response



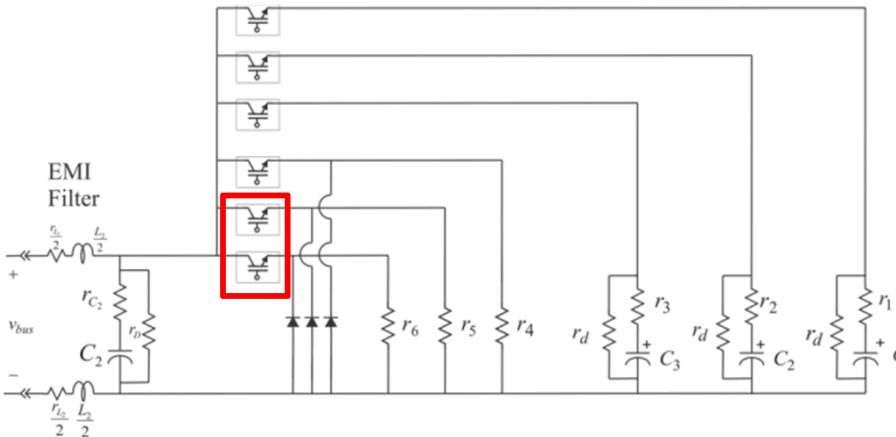
$$r_4 \parallel r_5 = 6 \Omega$$

Peak Load Power	= 16.7 kW
Load Energy	= 2801.6 J
Peak Over Shoot	= 18.6 %
Peak Under Shoot	= 17.2 %



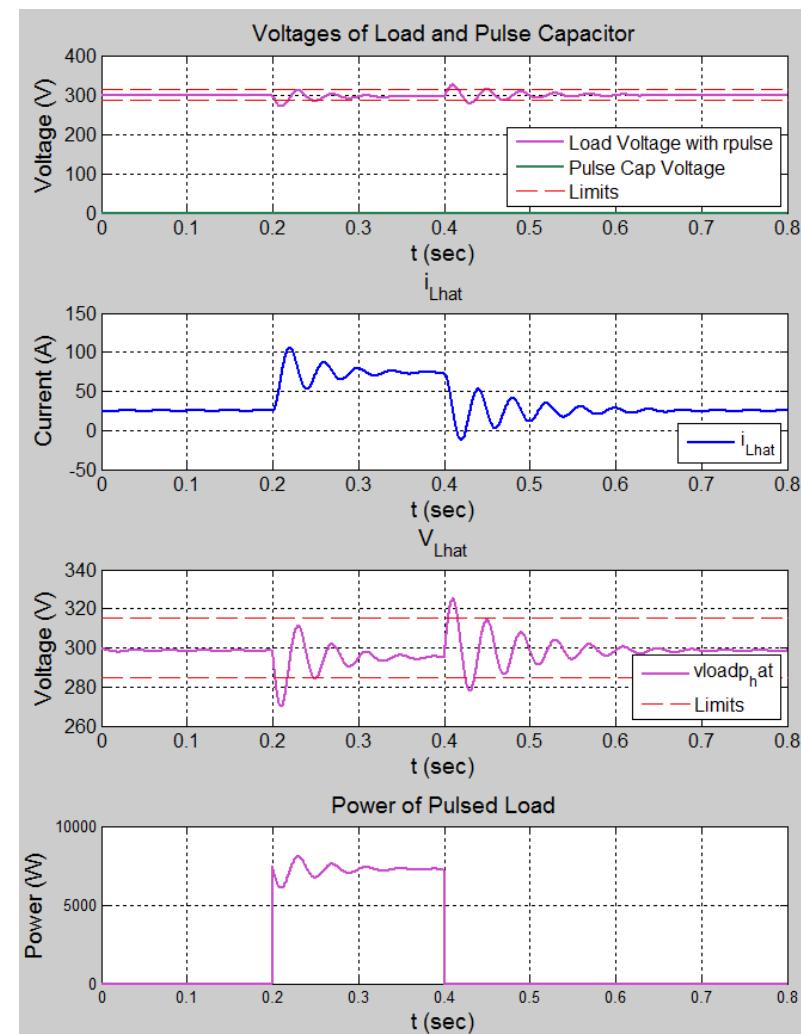
New SSM Testbed Component: Adjustable Pulsed Load

- Simulations were performed to gauge severity of pulsed load on boost converter uncontrolled response



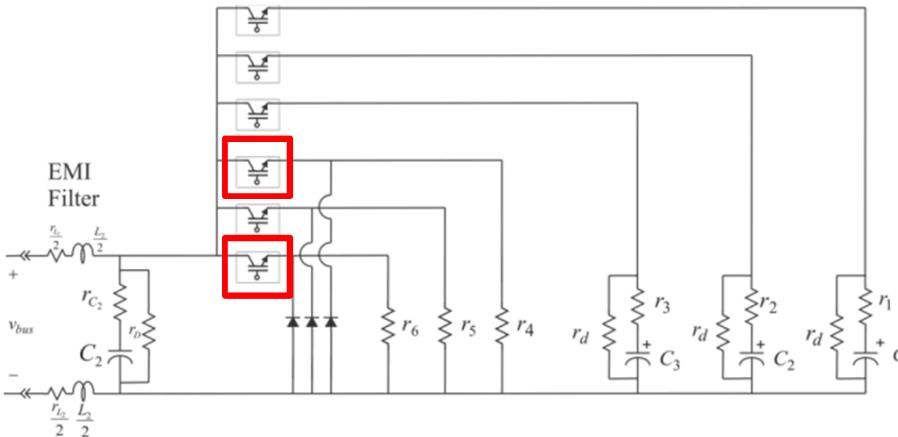
$$r_5 \parallel r_6 = 12 \Omega$$

Peak Load Power	= 8.07 kW
Load Energy	= 1442.5 J
Peak Over Shoot	= 9.3 %
Peak Under Shoot	= 9.3 %



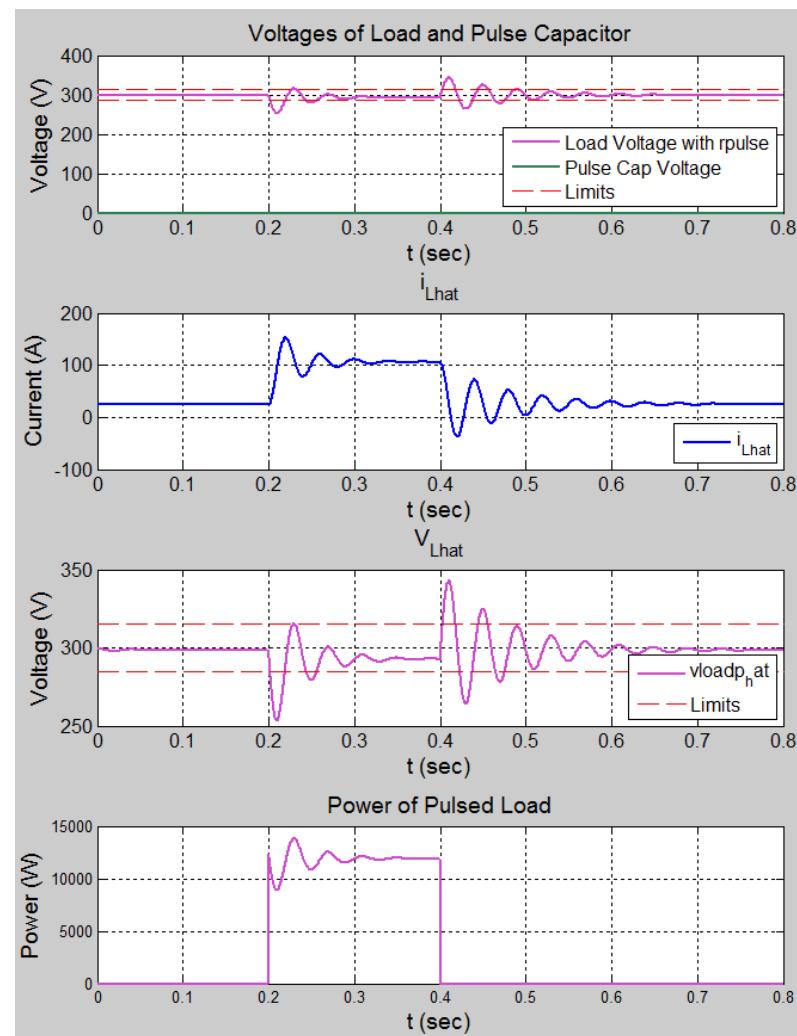
New SSM Testbed Component: Adjustable Pulsed Load

- Simulations were performed to gauge severity of pulsed load on boost converter uncontrolled response



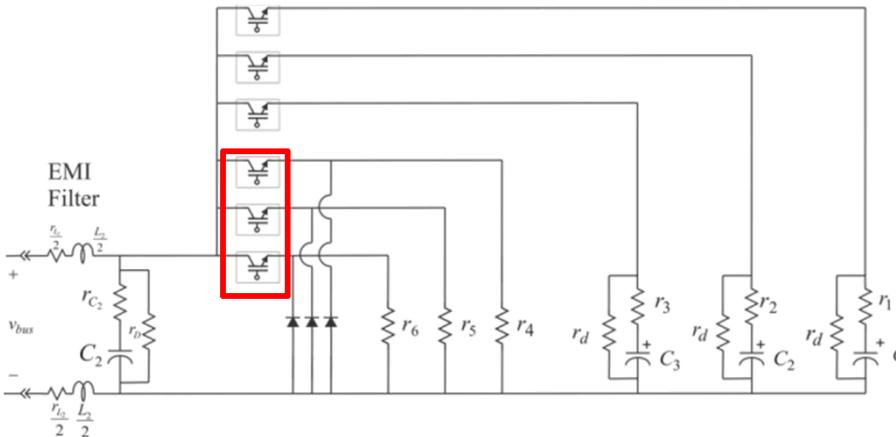
$$r_4 \parallel r_6 = 7.2 \Omega$$

Peak Load Power = 13.84 kW
 Load Energy = 2356.9 J
 Peak Over Shoot = 15.5 %
 Peak Under Shoot = 14.7 %



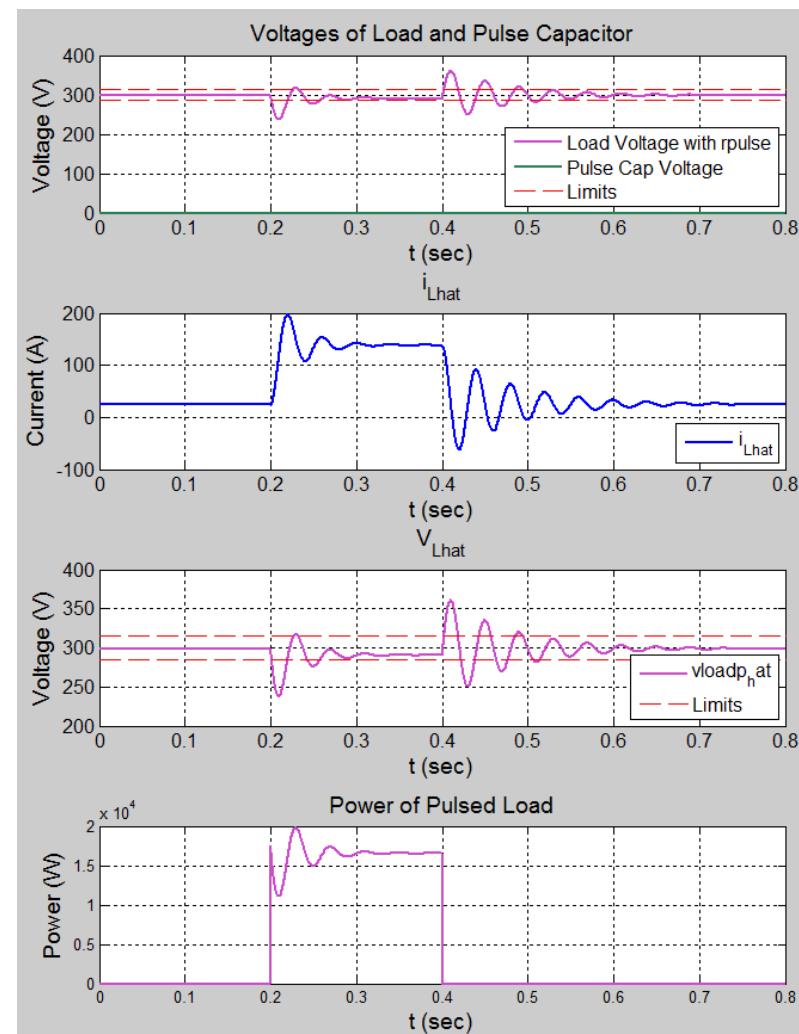
New SSM Testbed Component: Adjustable Pulsed Load

- Simulations were performed to gauge severity of pulsed load on boost converter uncontrolled response

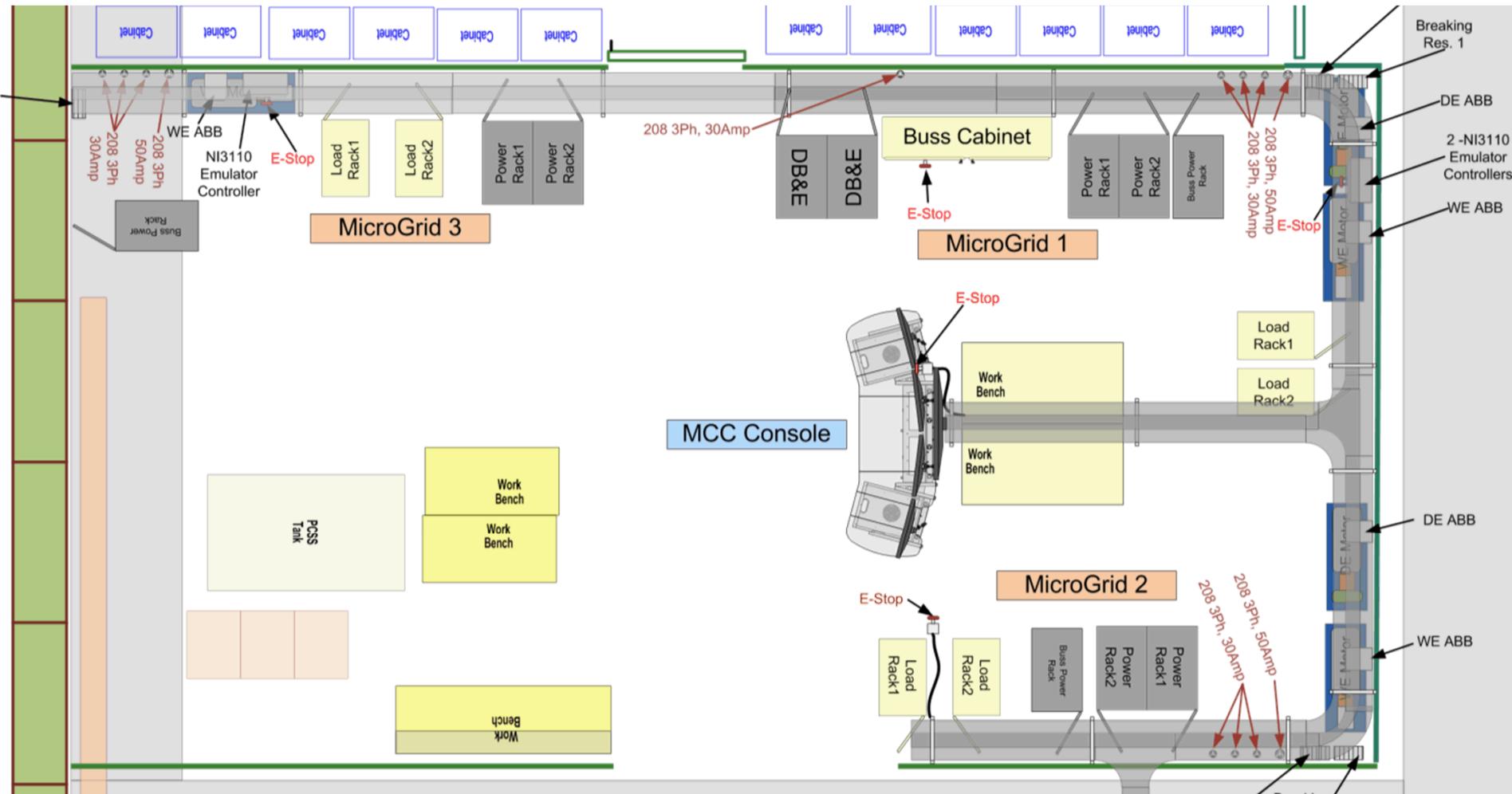


$$r_4 \parallel r_5 \parallel r_6 = 5.1 \Omega$$

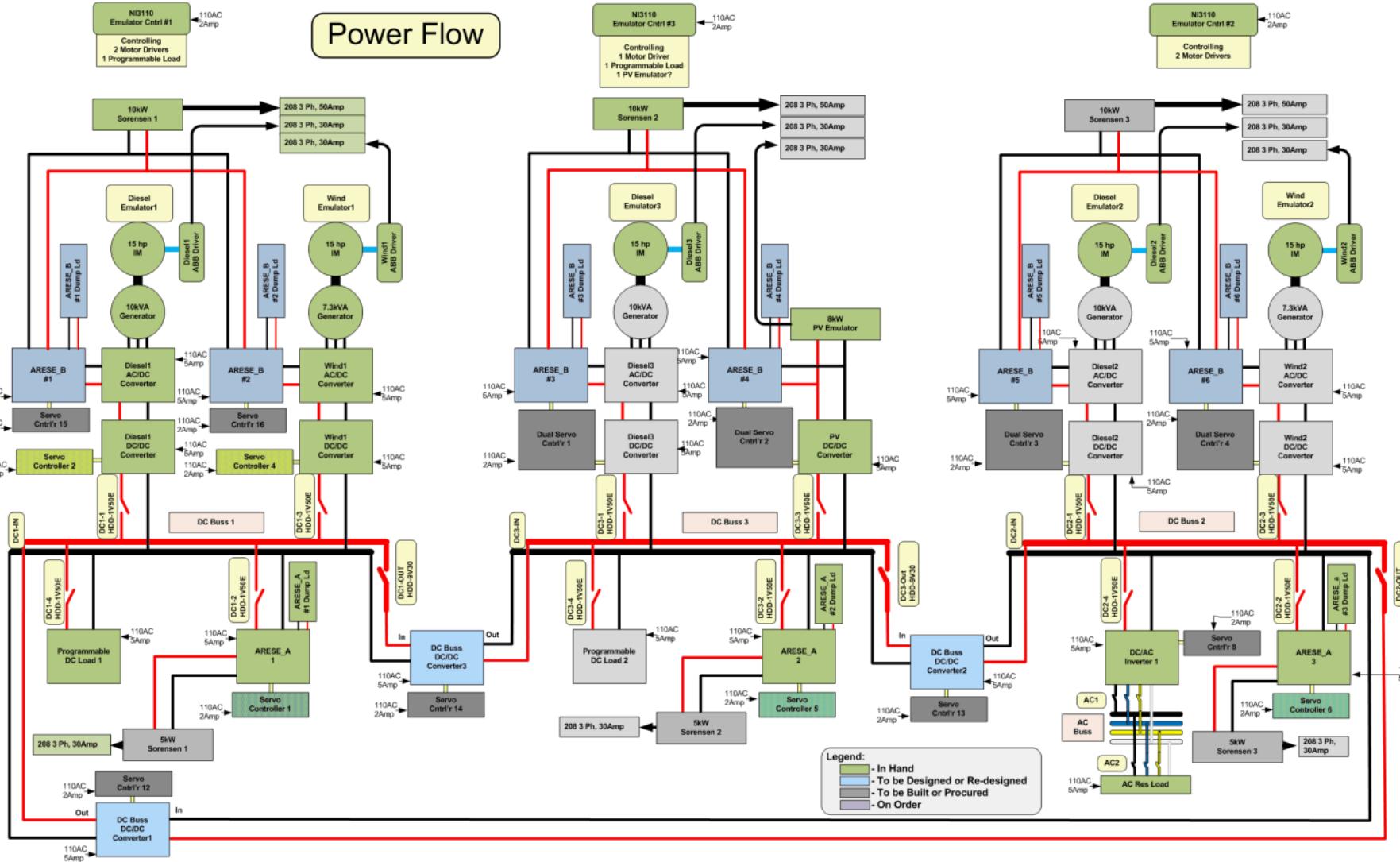
Peak Load Power = 19.79 kW
 Load Energy = 3263.3 J
 Peak Over Shoot = 21.8 %
 Peak Under Shoot = 19.8 %



MicroGrid Collective

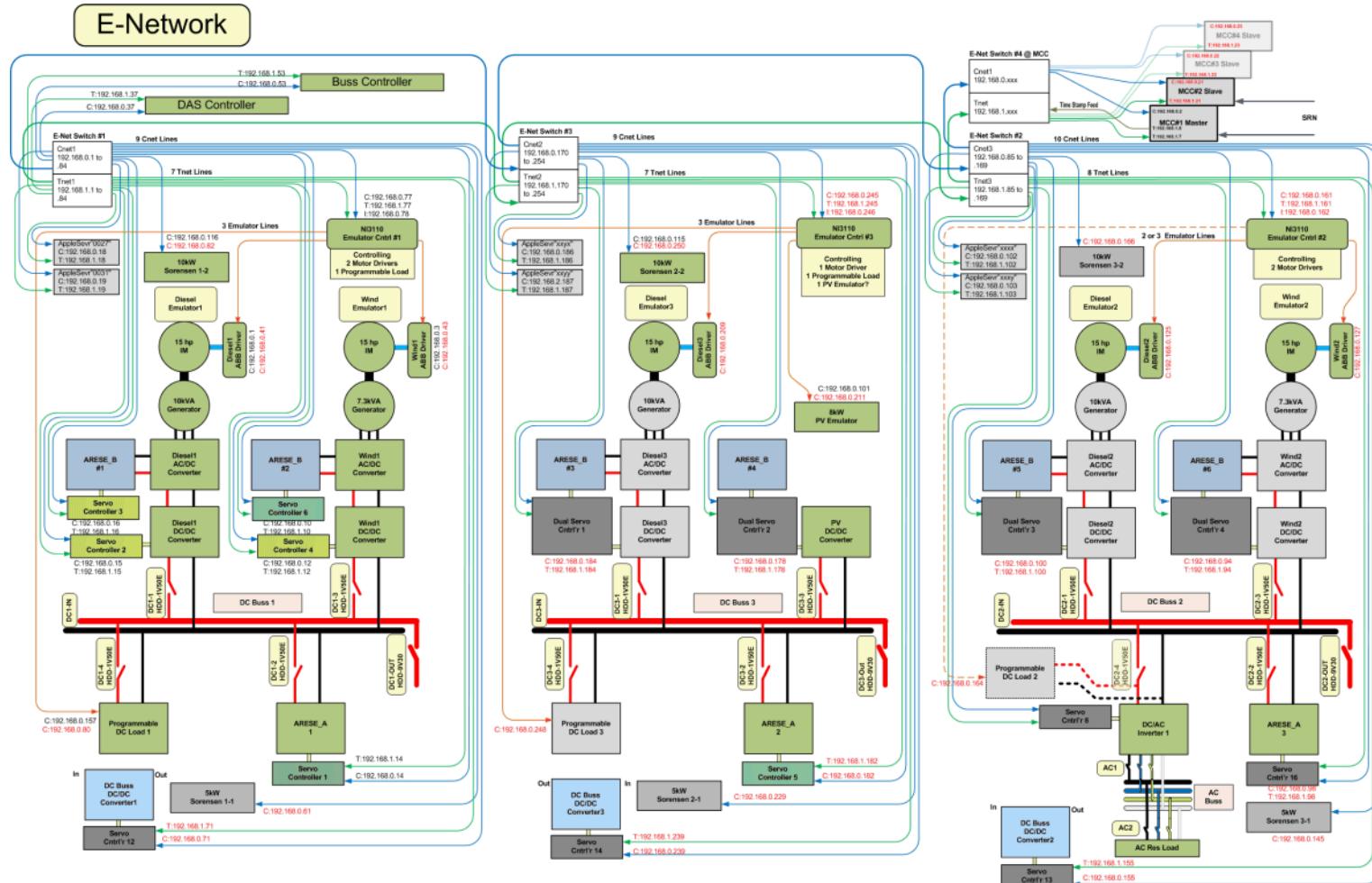


MicroGrid Collective: Power Flow

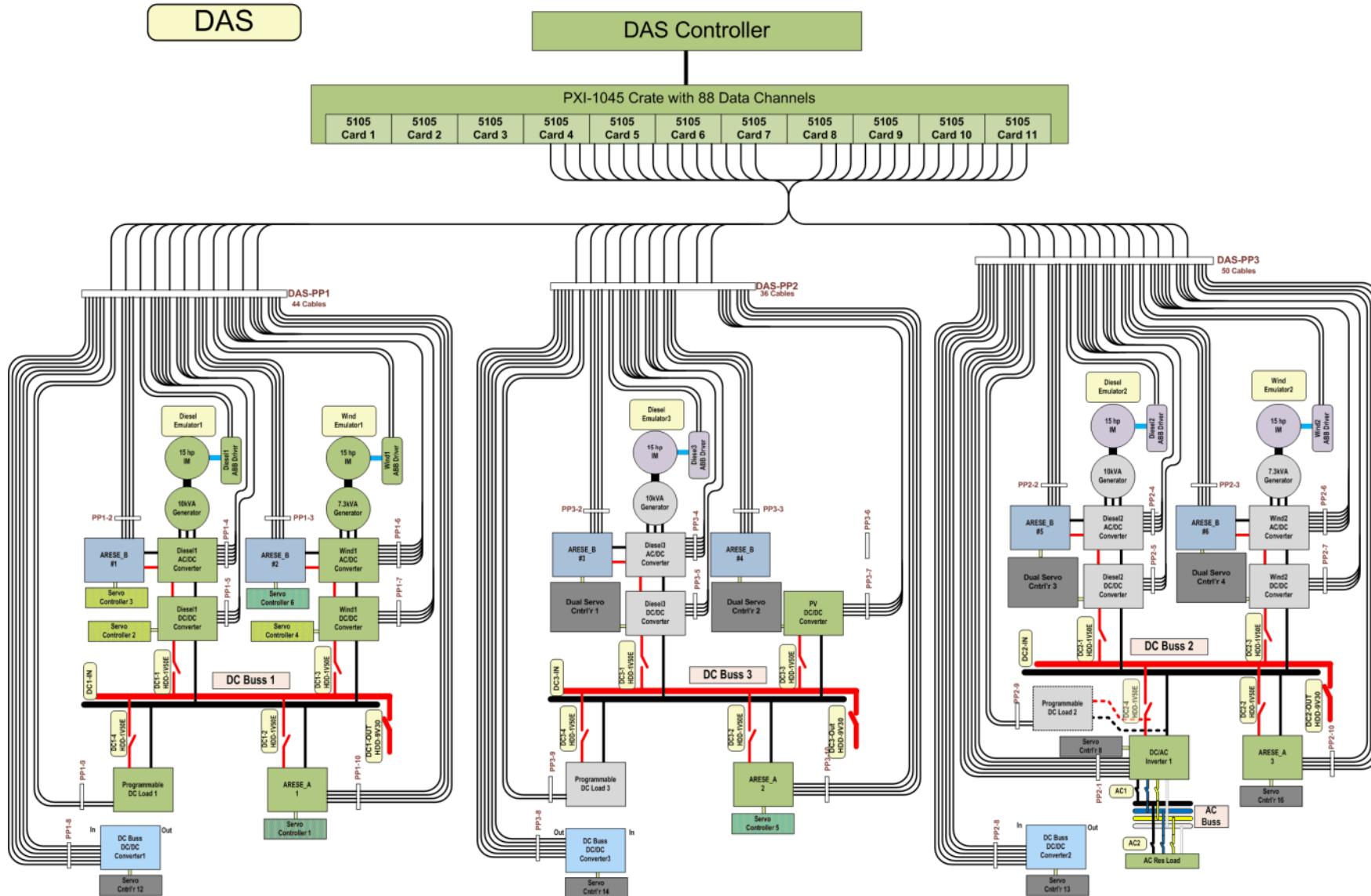


MicroGrid Collective: Network Architecture

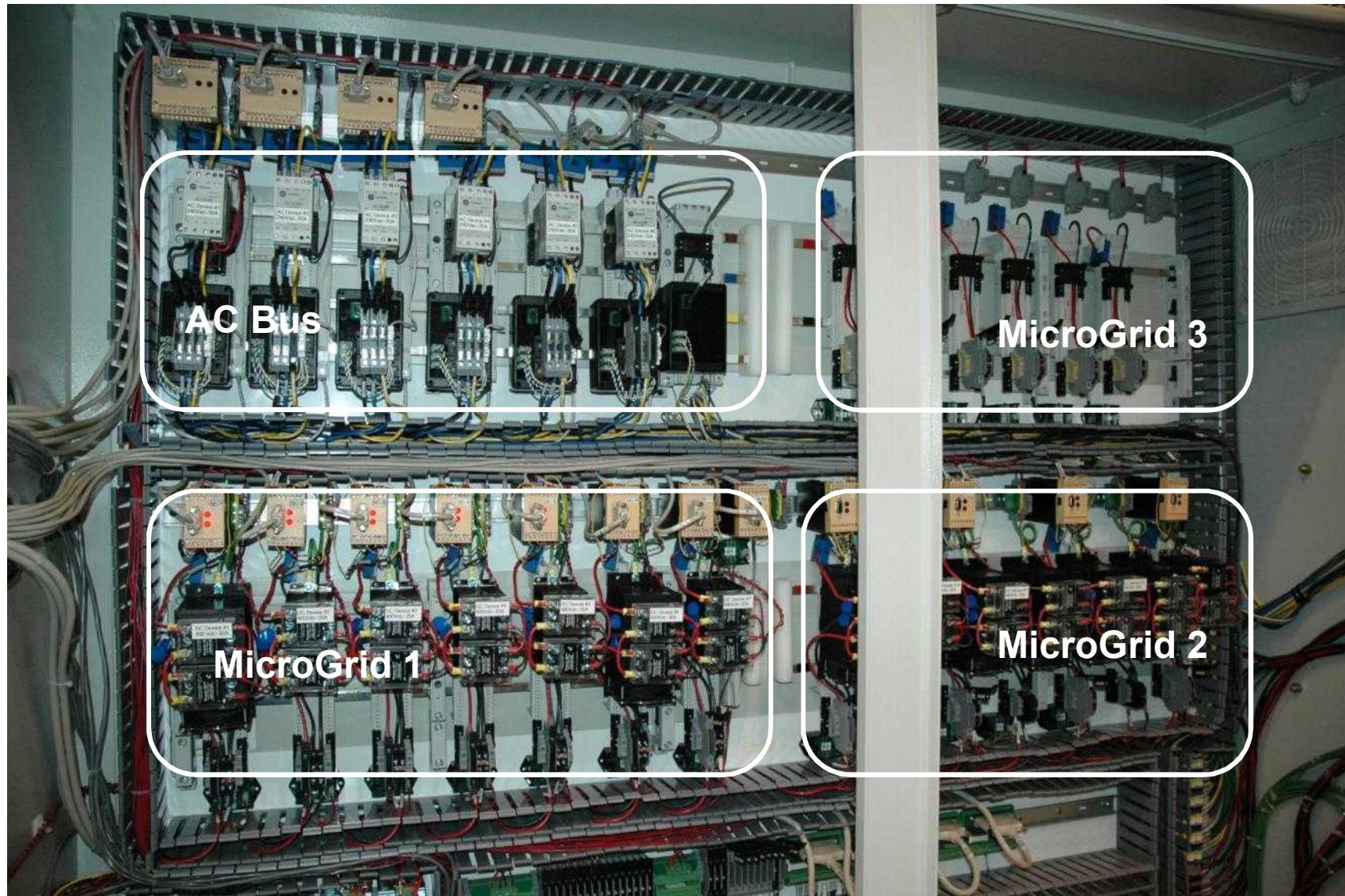
- Single network for broadcasting time-stamps (UDP)
- Single network realized in hardware for control
- Control sub-networks realized by partitioning Port numbers
- Information flow between grids controlled by grid-to-grid tie converters



MicroGrid Collective: Data Acquisition

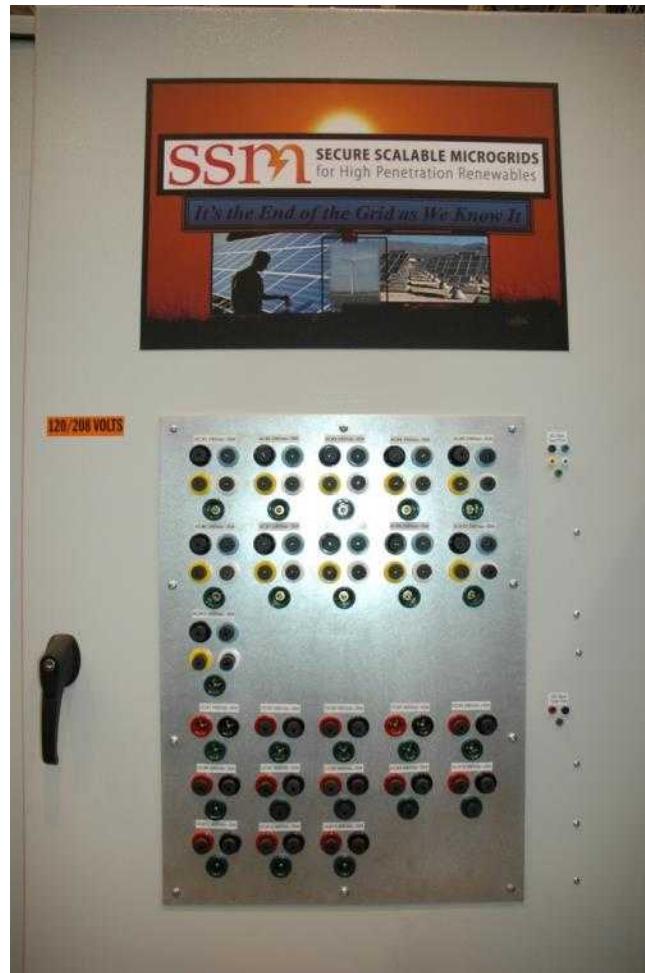


Bus System has been Modified

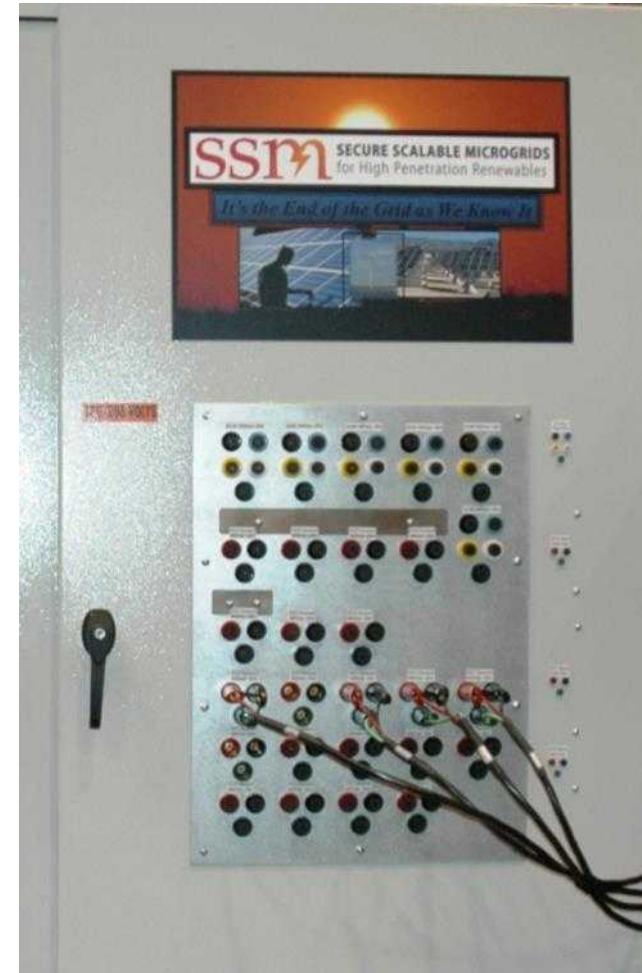


Bus System has been Modified

Previous Configuration

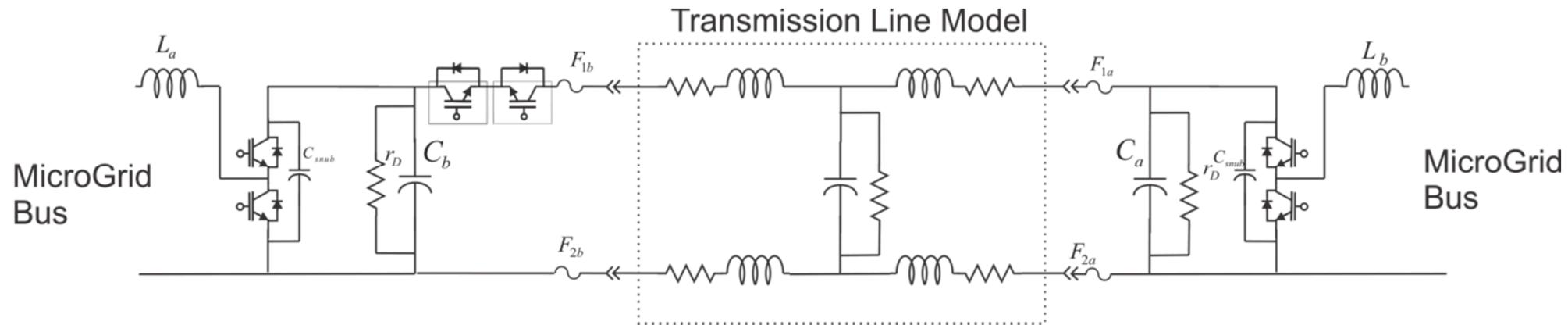


New Configuration



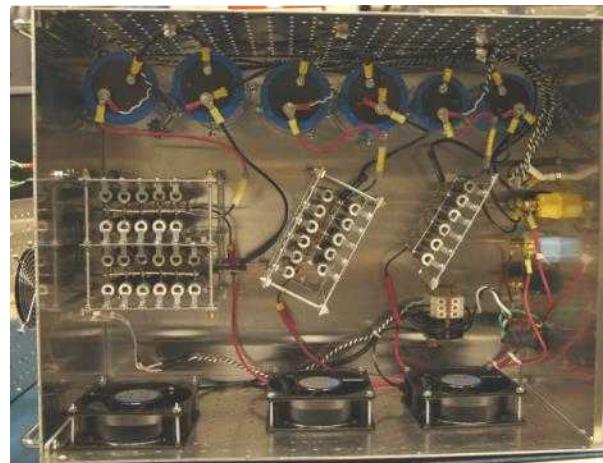
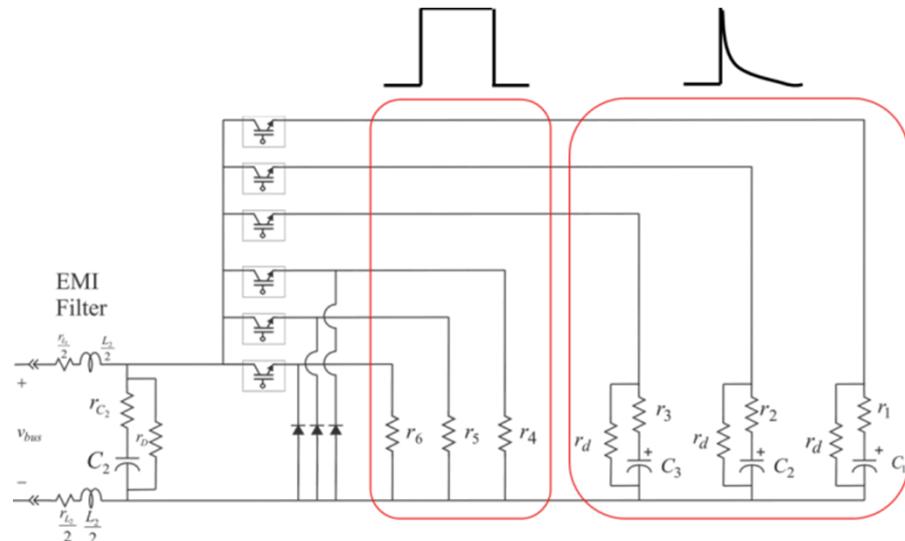
Transmission in Collective Microgrids

- Thus far, the transmission lines between microgrids have been modeled as ideal or resistive
- The transmission line between Microgrid Tie converters is modeled to include parasitic reactance and losses
- Additional dynamics are expected in the interaction between converters
- Development of a “Long line simulator” may be necessary in hardware



A New SSM Testbed Component was Developed: Adjustable Pulsed Load

- New Pulsed Load Design
 - Includes R (6.3 kW at 300V) and RC circuits



SSM Collective Configuration for FY13

- Each MicroGrid has one dispatchable and one Renewable source
- Conversion effort
 - Reconfigure bus cabinet
 - Bus bar reassignment
 - E-stop upgrade
 - Data Acquisition software updates
 - Network update
 - Upgrade the Infrastructure
 - Cable Trays
 - 208 AC power
 - 3 additional motor drives / generators
 - Build additional Power Electronics
 - 3 Rectifiers
 - 3 DC-DC boost converters
 - 3 Grid-to-Grid converters
 - 6 Energy Storage Emulators
 - 2 Programmable Digital Resistors
 - Build additional computer controls
 - 8 Versalogic-based control units (“Servo-boxes”)

