SAND2013-10602P

Building to Grid Integration Research

Sandia National Laboratories
December 13, 2013

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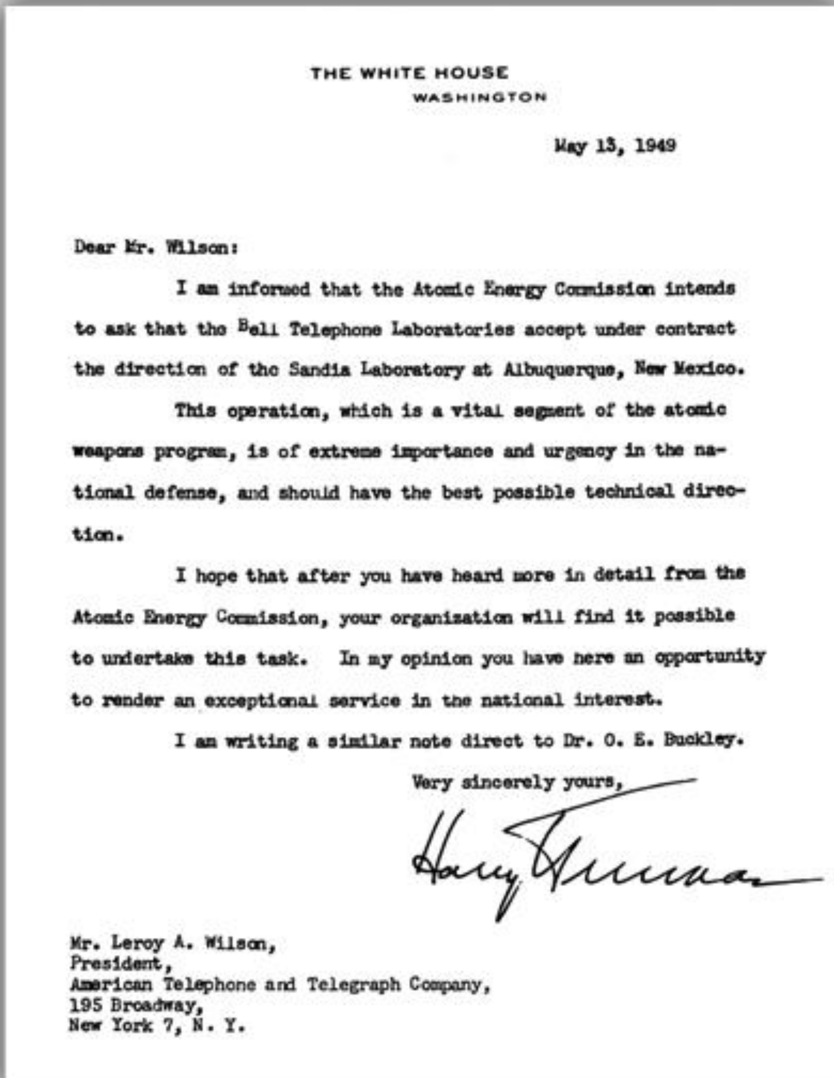
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Agenda

- **Sandia National Laboratories**
- Core team & capabilities
- Net positive buildings
- On going building related research
- Next steps

Sandia's History


THE WHITE HOUSE
WASHINGTON

May 13, 1949

Dear Mr. Wilson:

I am informed that the Atomic Energy Commission intends to ask that the Bell Telephone Laboratories accept under contract the direction of the Sandia Laboratory at Albuquerque, New Mexico.

This operation, which is a vital segment of the atomic weapons program, is of extreme importance and urgency in the national defense, and should have the best possible technical direction.

I hope that after you have heard more in detail from the Atomic Energy Commission, your organization will find it possible to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

I am writing a similar note direct to Dr. O. E. Buckley.

Very sincerely yours,

Harry Truman

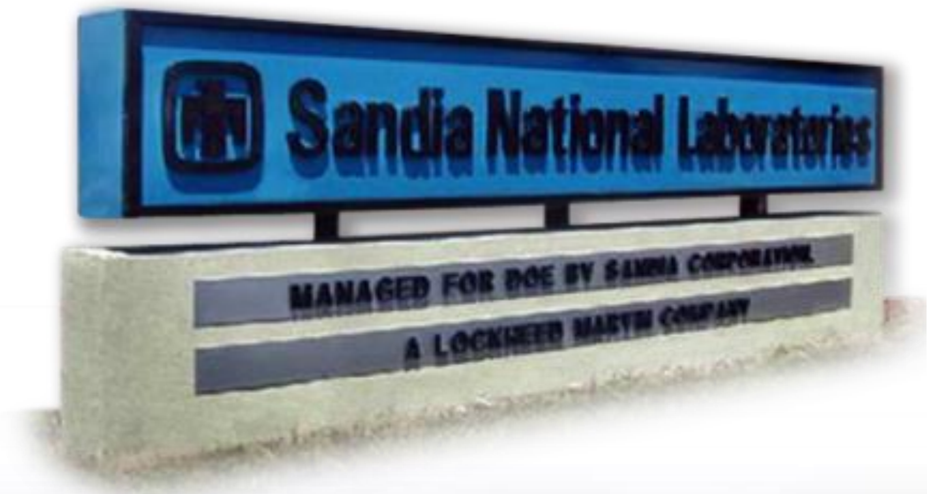
Mr. Leroy A. Wilson,
President,
American Telephone and Telegraph Company,
195 Broadway,
New York 7, N. Y.

Sandia is a Multidisciplinary National Security Laboratory

- **Sandia develops technologies to:**
  - Sustain and modernize the nuclear deterrent,
  - Prevent the spread of weapons of mass destruction,
  - Protect the national infrastructure,
  - Defend the national against terrorist threats,
  - Provide new capabilities to the armed forces, and
  - Ensure the stability of the nation’s energy and water supplies.

Sandia’s science, technology, and engineering help ensure that the nation maintains technological superiority and preparedness, which are critical to national defense, homeland security, and the nation’s economic well-being.

Sandia's Governance Structure



Sandia Corporation

- AT&T: 1949–1993
- Martin Marietta: 1993–1995
- Lockheed Martin: 1995–present

Government-owned contractor-operated

Federally funded research and development center

Sandia's Sites

Albuquerque, New Mexico

Carlsbad, New Mexico

Tonopah, Nevada

Livermore, California

Amarillo, Texas

Kauai, Hawaii

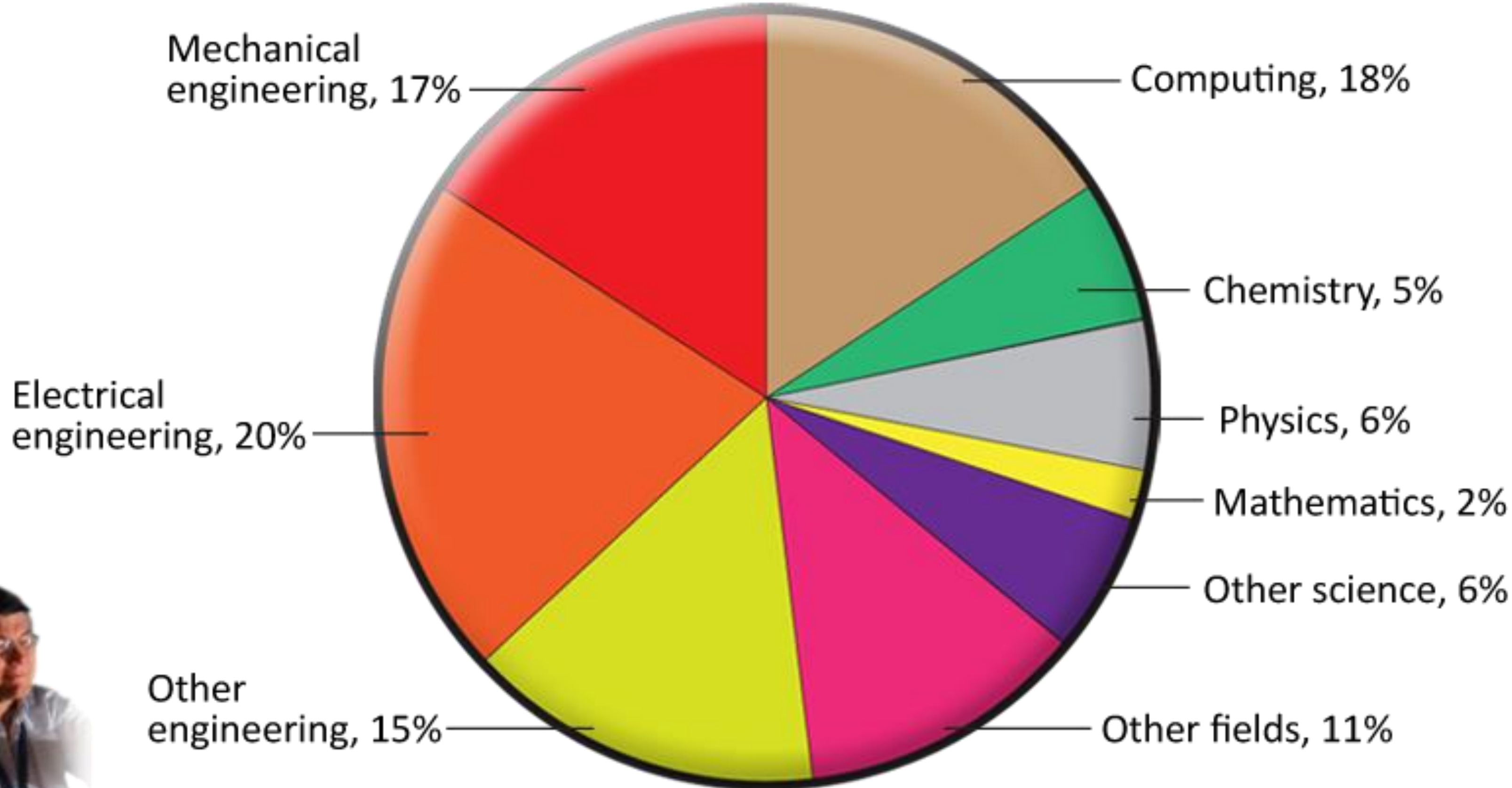
Our Workforce

~170 Purdue alumni

- **Onsite workforce: 11,711**
- **Regular employees: 9,238**
- **Gross payroll: ~$981M**

Data for FY12 through end of September

Research & Development staff(4,682) by discipline



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Core R&D Team

Steve Glover
SNL Manager

Charlie Hanley
SNL Manager

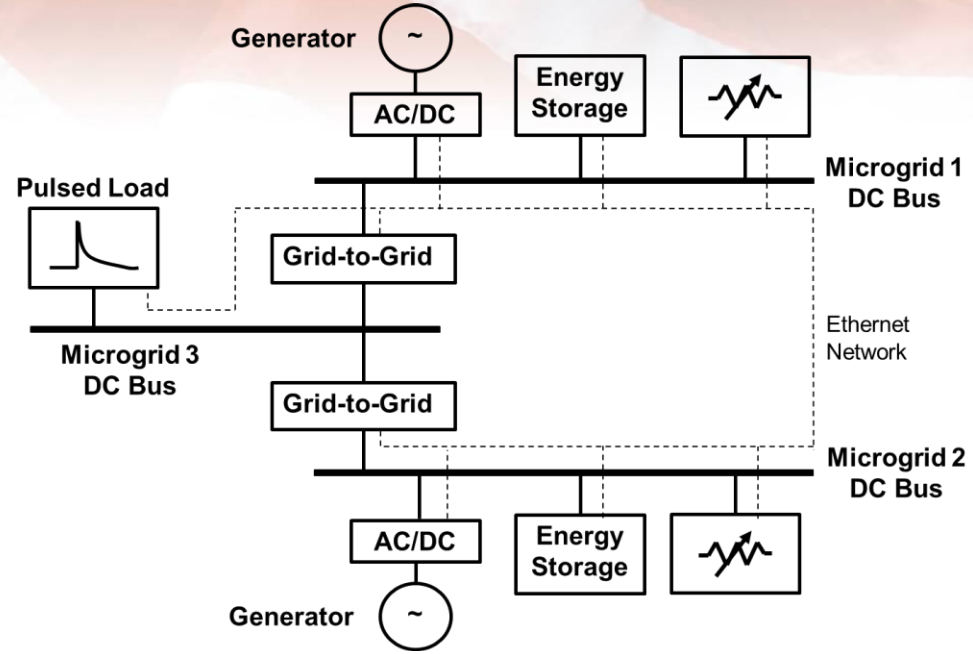
Jason Neely
Hdw, Mod, Sim

David Wilson
Nonlinear Controls

Marvin Cook
Informatics

Tony Lentine
Communications

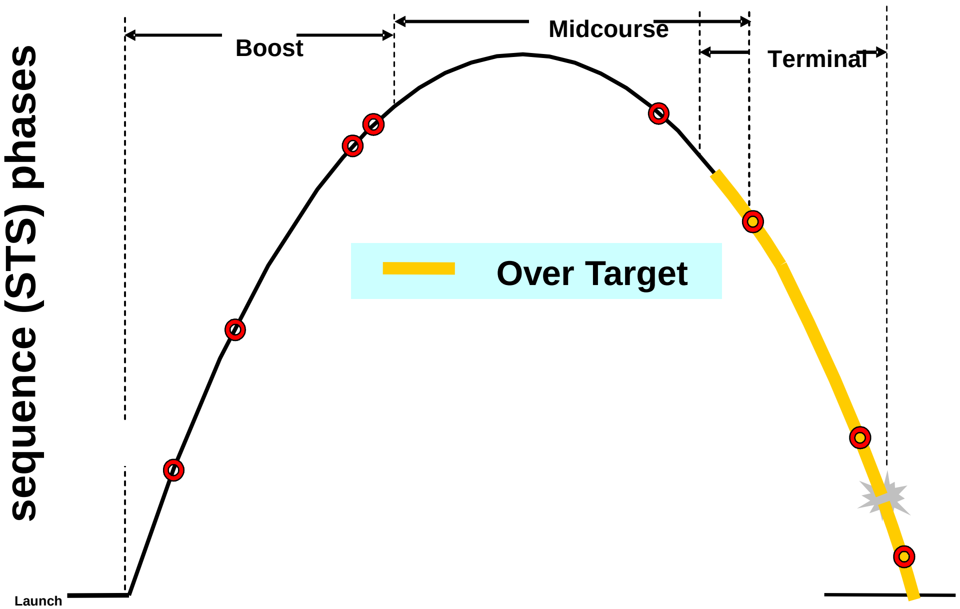
Rush Robinett IV
Prof. Mech. Eng., MTU



- Hamiltonian based nonlinear distributed control
- Agents
- Informatics for energy management and adaptive behavior
- Communication theory
- Experimental capabilities
- Power electronics and systems
- Wind, Water, and Solar energy sources

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

Sandia National Laboratories

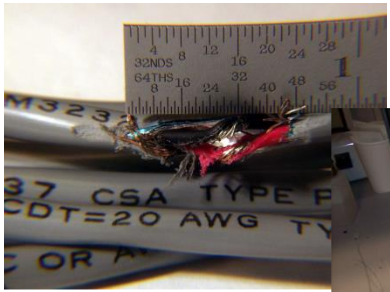
Electrical and Radiation Sciences Customers, Organization, and Facilities

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**

World class accelerator technology development & high heat flux research

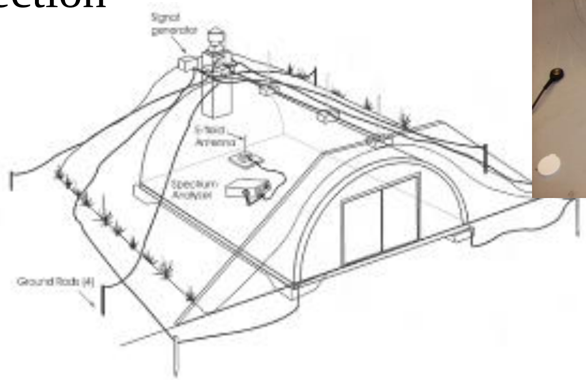
EMP coupling into facilities



ASTRONICS CORPORATION

Power systems
All Electric Warship

Lightning protection



Sago mine, 2006

Water Power Program

UNIQUE CAPABILITIES

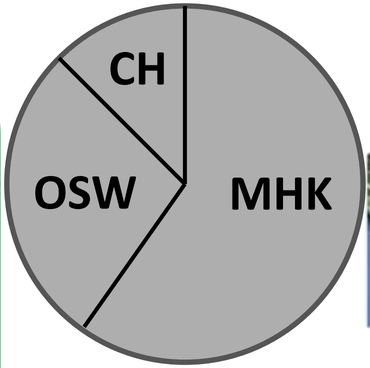
- SEAWOLF laboratory/field oscillatory-flow sediment transport testing
- Sandia Lake Facility – TRL 6 appropriate for wave testing
- MHK-capable environmental circulation and performance code (SNL-EFDC)

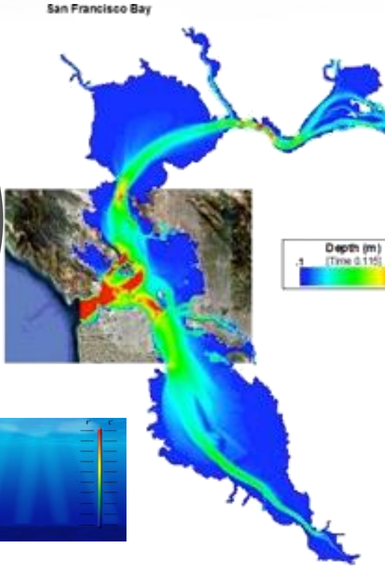
COLLABORATIVE PROJECTS

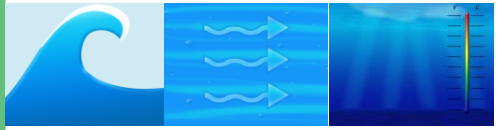
- Technical Industry FOA Support
  - Ocean Renewable Power Company, Ocean Power Technologies, Snohomish PUD
- SNL-EFDC Technology Transfer to
  - Free Flow Power, NOAA, FERC, BOEM, Verdant, ORPC

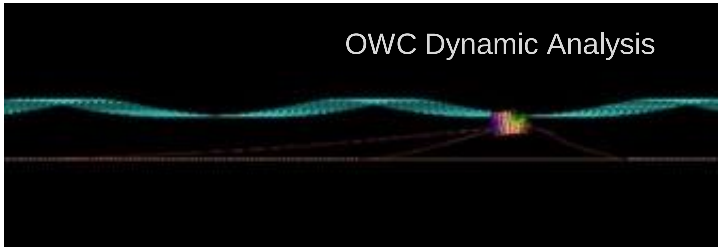
IMPACT EXAMPLES

- 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









Wind Program

UNIQUE CAPABILITIES

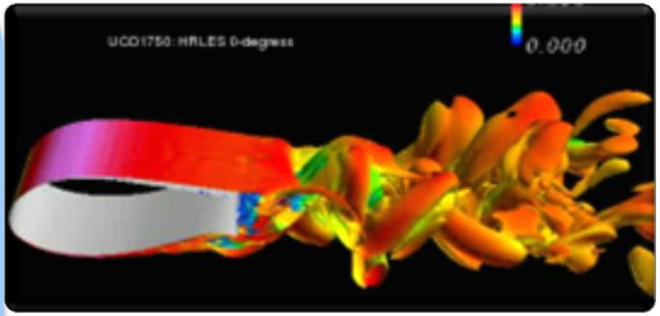
- Wind-turbine blade design and modeling, and wind system reliability
- Test facilities for scaled blade testing and turbine-to-turbine interaction studies (SWIFT test site, Lubbock, TX)

COLLABORITIVE 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

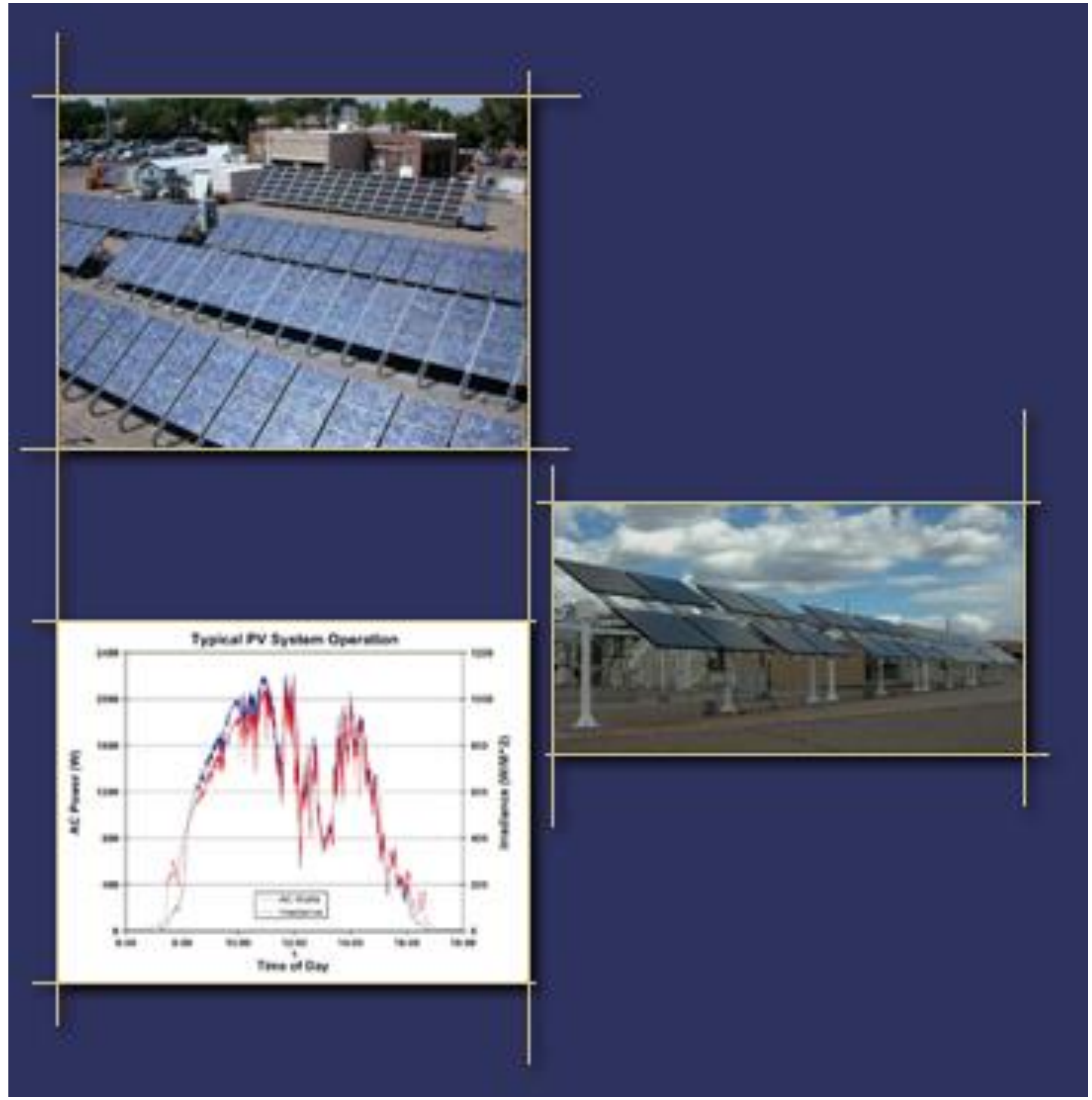
IMPACT EXAMPLES

- 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



Solar Program

- **Solar collection**
- **Energy storage**
- **Power distribution**
- **Standards and policies**



General Capabilities

- **Controls**
  - **Exergy based**
  - **Optimization**
  - **Multi-level**
  - **Deliberative and adaptive**
- **Hardware**
  - **Components ➡ systems ➡ networked systems**
  - **Emulation capabilities**
- **Energy sources**
  - **Deterministic**
  - **Stochastic**
  - **Solar, wind, hydrokinetic**
- **Storage**
  - **Design and optimization**

Sandia National Laboratories

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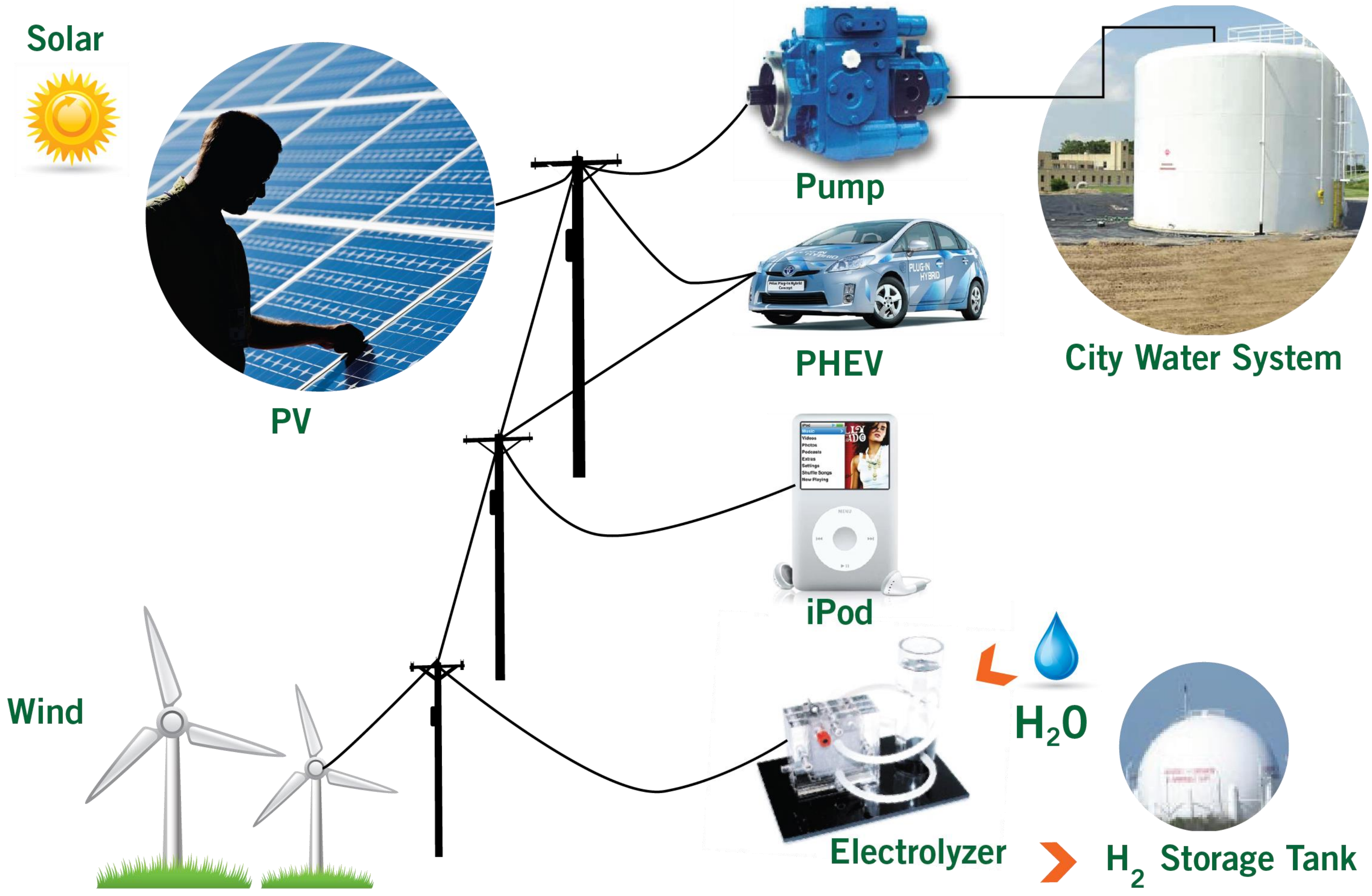
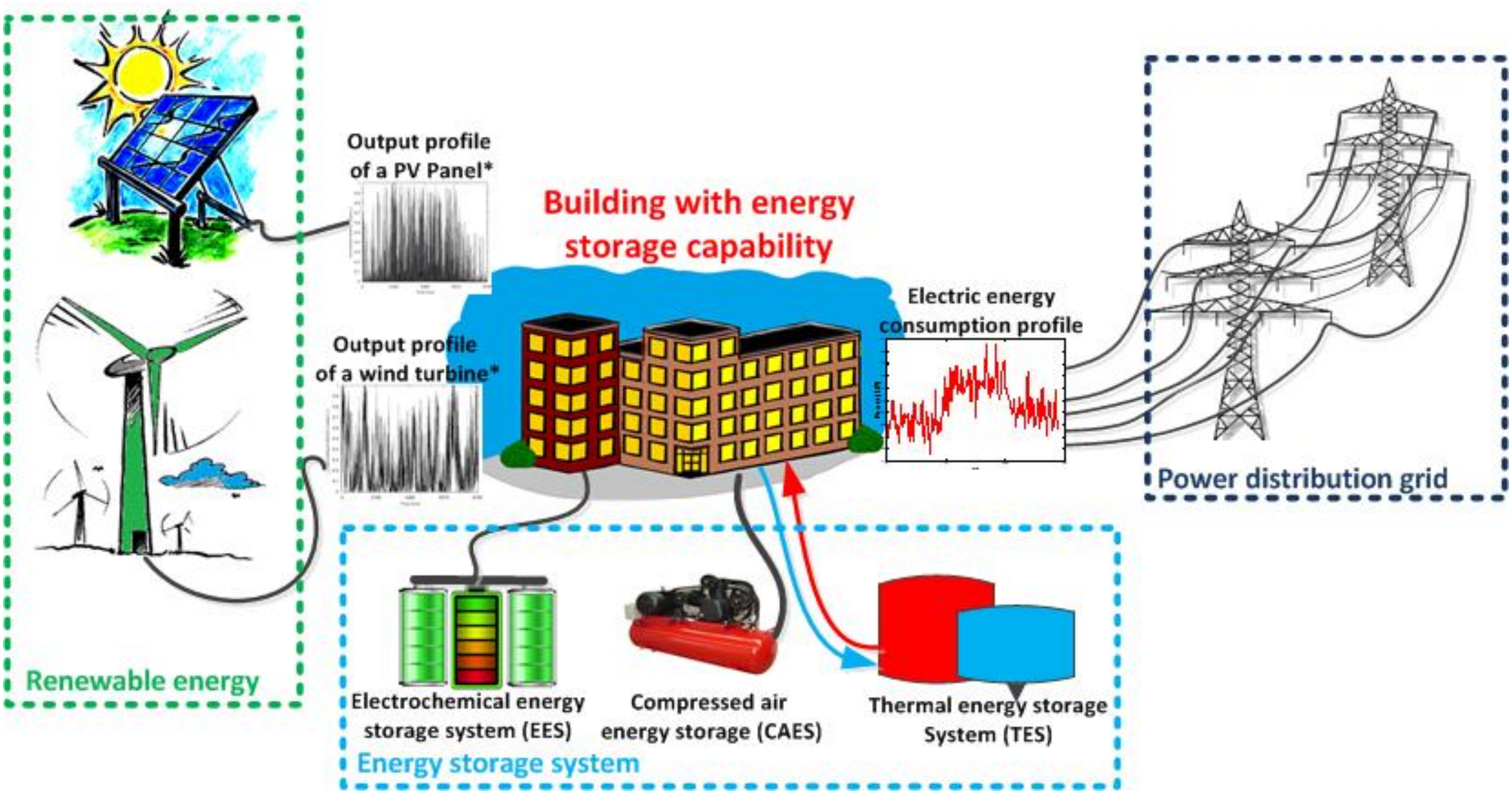
Importance of energy storage

Energy Storage and Dispatchable Loads



Net-Positive Buildings (Nμs): Building-Grid Integration with Energy Storage Options



Michigan Tech

* Image source for output profiles: D. Haeseldonckx, et al, Renewable and Sustainable Energy Reviews, 2008

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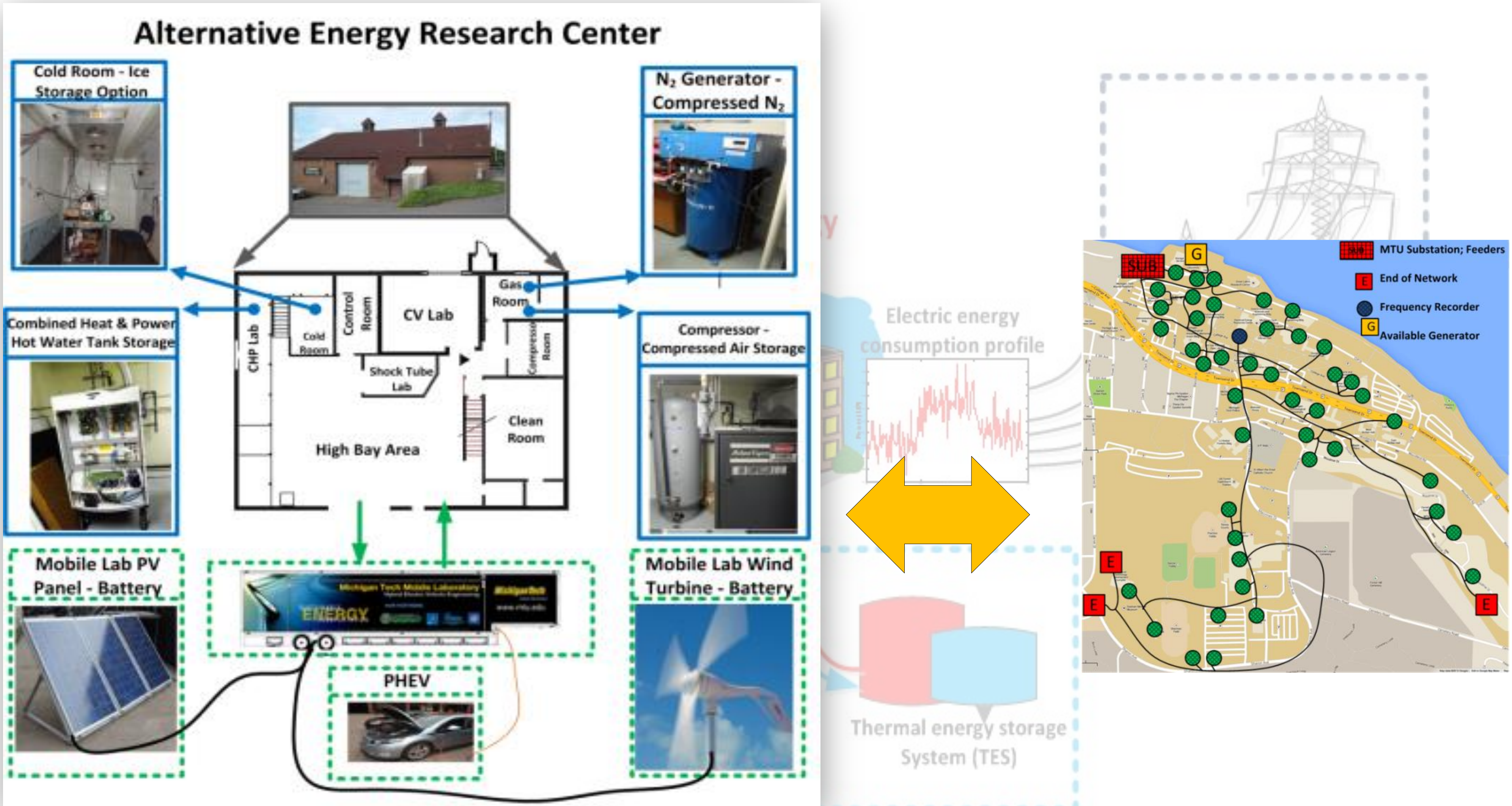
Net-Positive Buildings (Nμs): MTU Campus

Nμs Buildings and Testbed



Motivation

Buildings are scalable thermodynamic systems which offer a large existing energy storage potential.

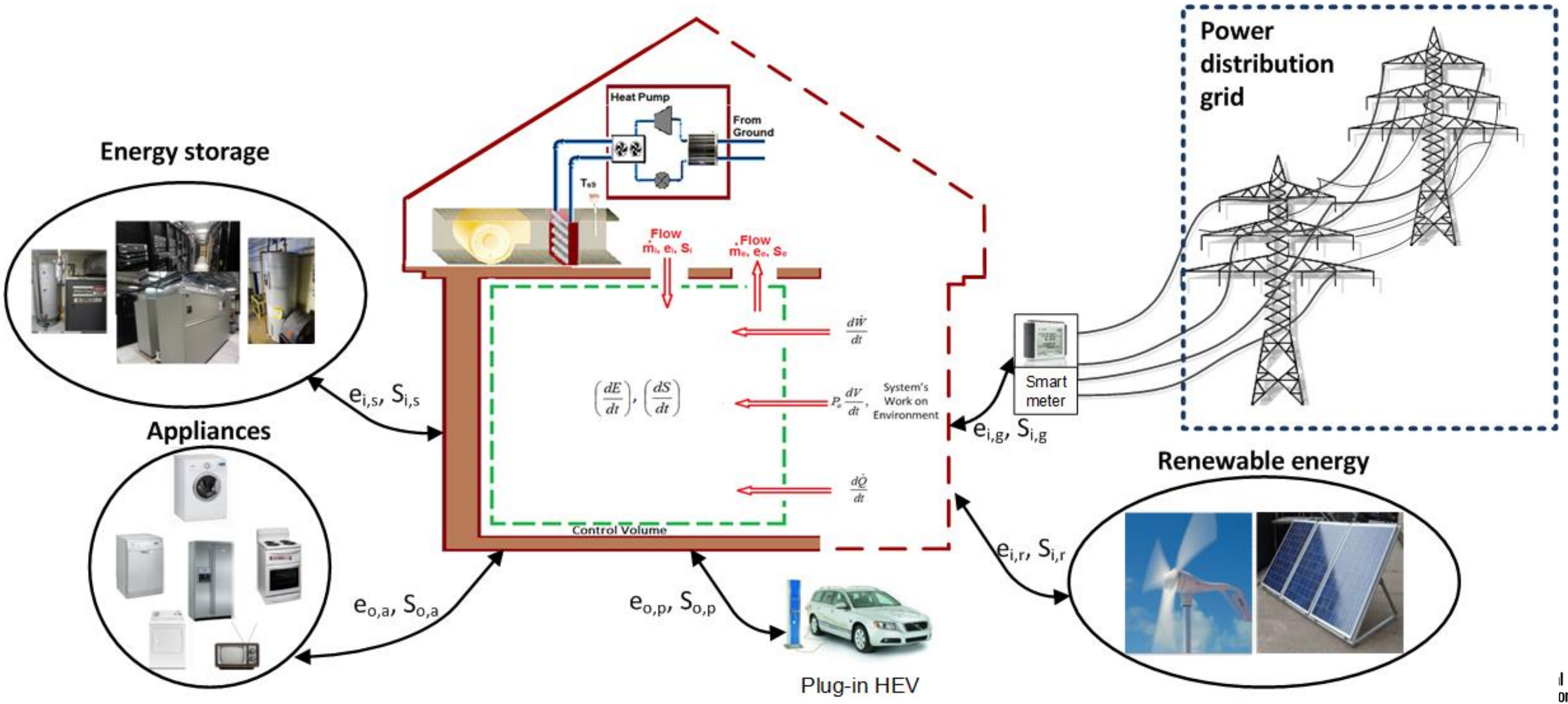
Goal

Stable, energy-optimal Networked Microgrid, through full utilization of building energy storage capacity

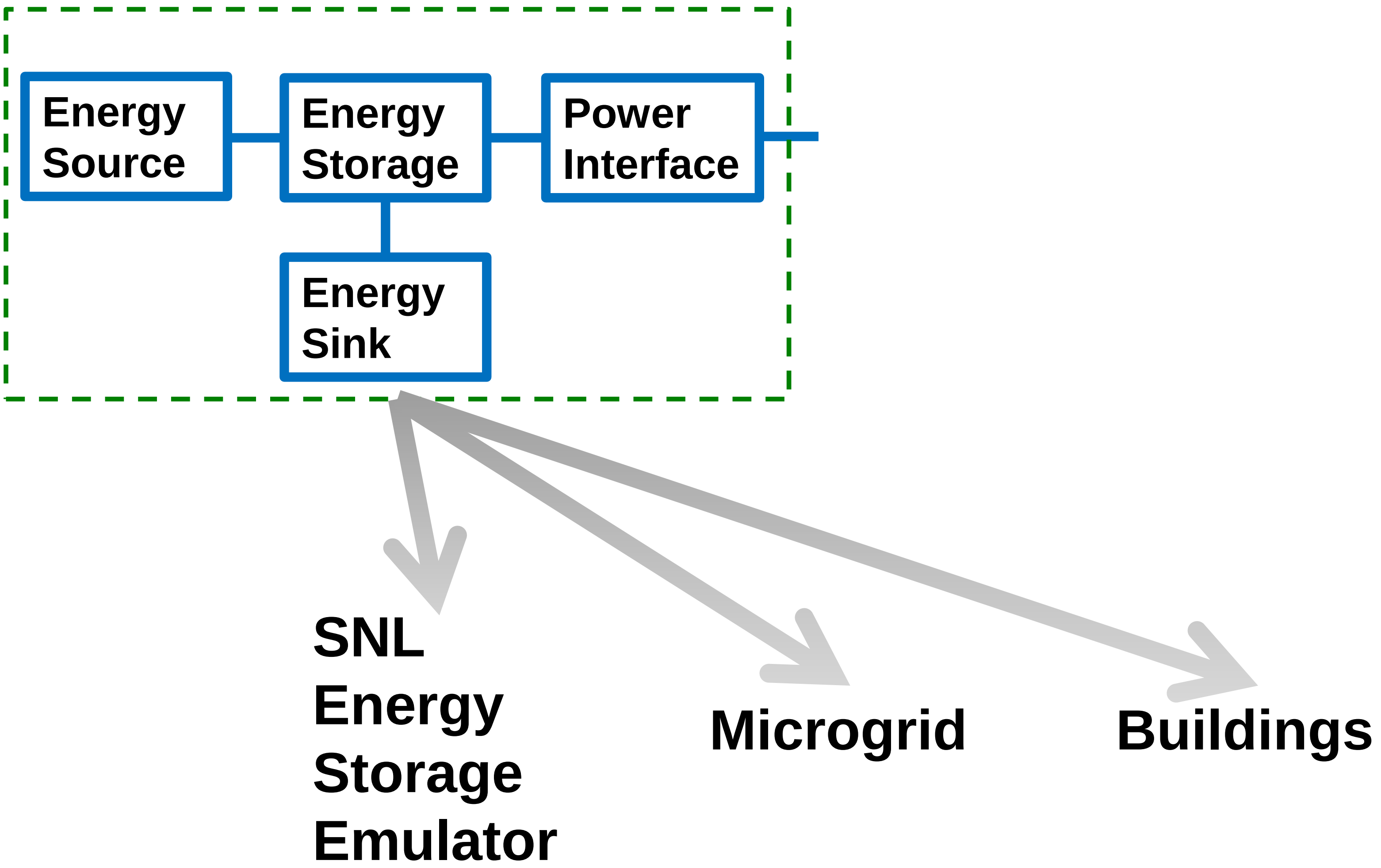
Proposed solution:

Exergy-based building-grid energy management – utilizing buildings with varying-scale storage systems

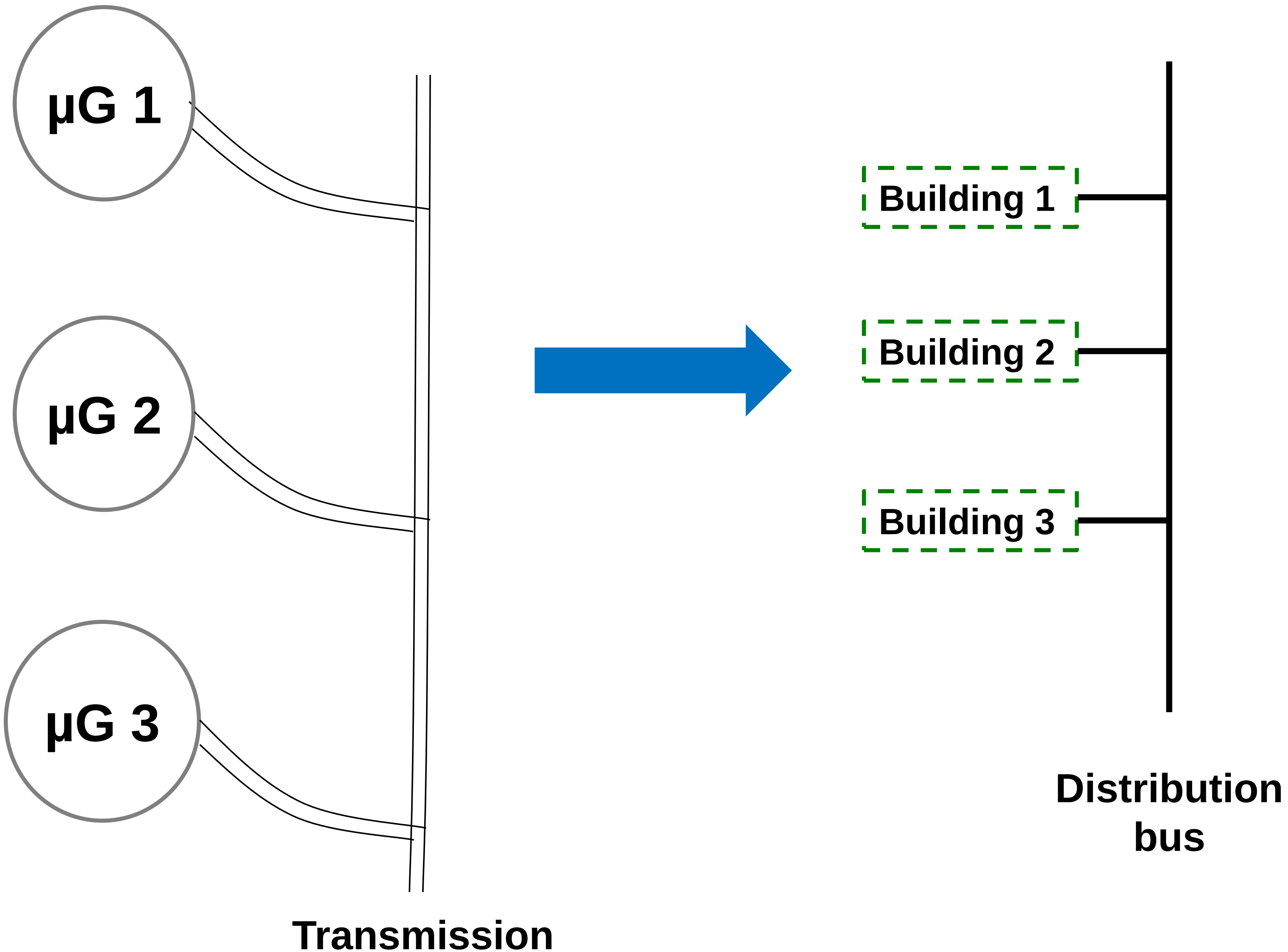
A universal power flow control to enable maximum building-grid energy saving



Net Positive Buildings have a Familiar Structure



Neighborhoods of Net Positive Buildings are Networked Microgrids



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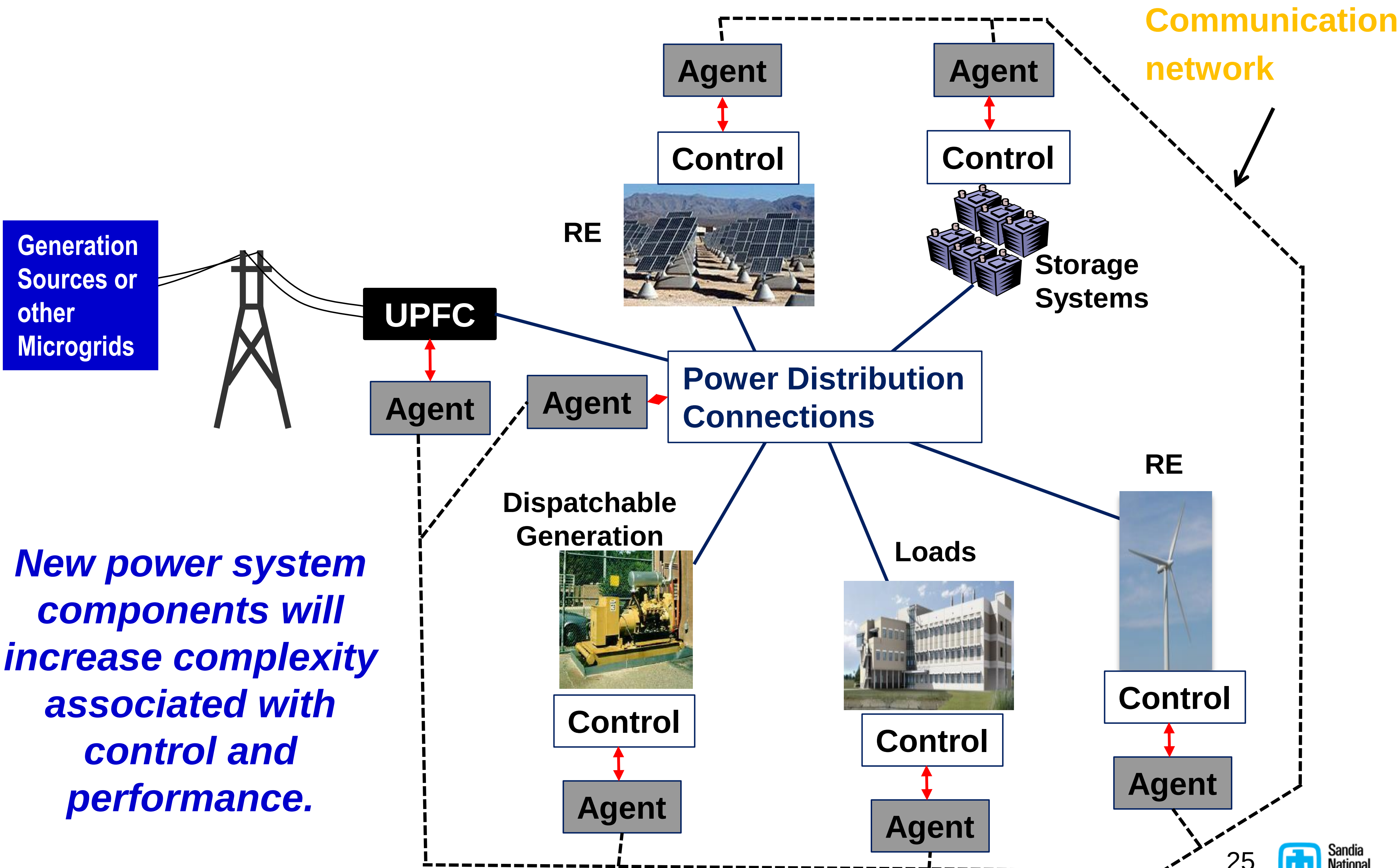
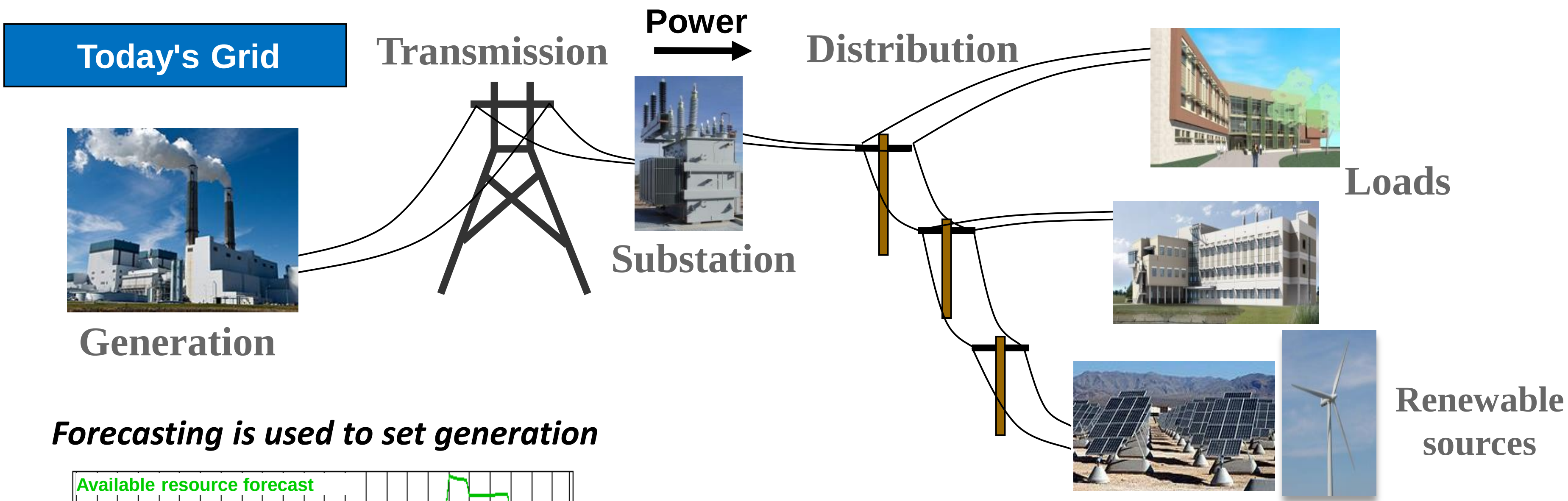
The Basic SSM Test Bed Structure Enables a Flexible Research Platform

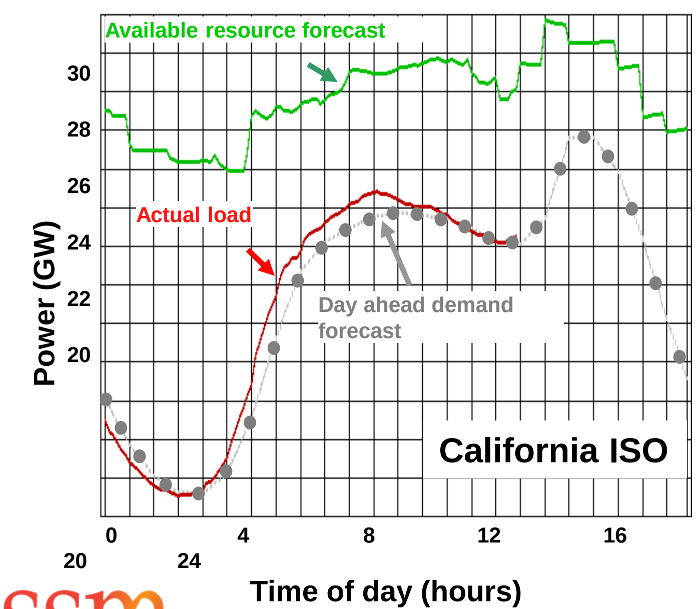


New power system components will increase complexity associated with control and performance.

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



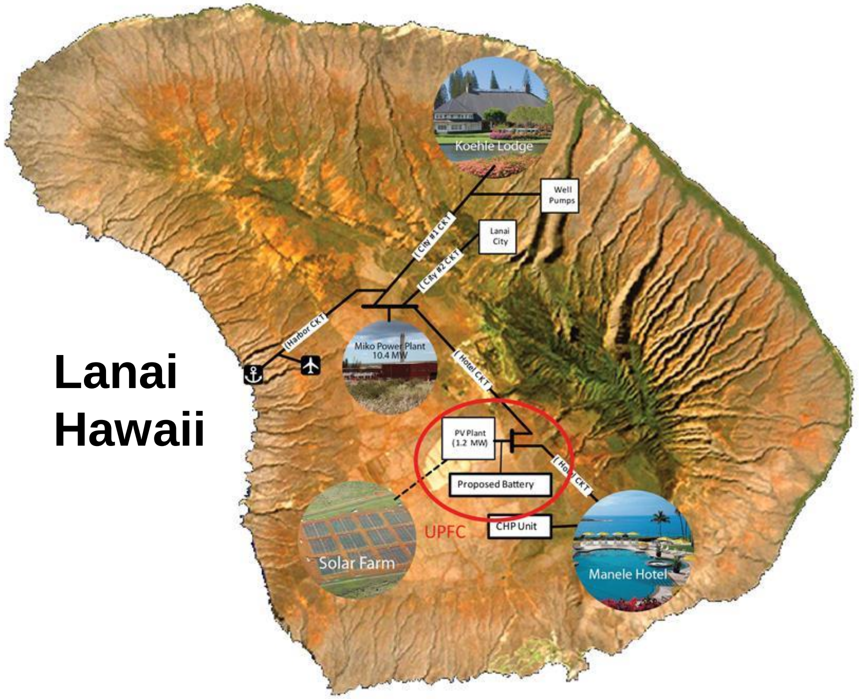
Forecasting is used to set generation

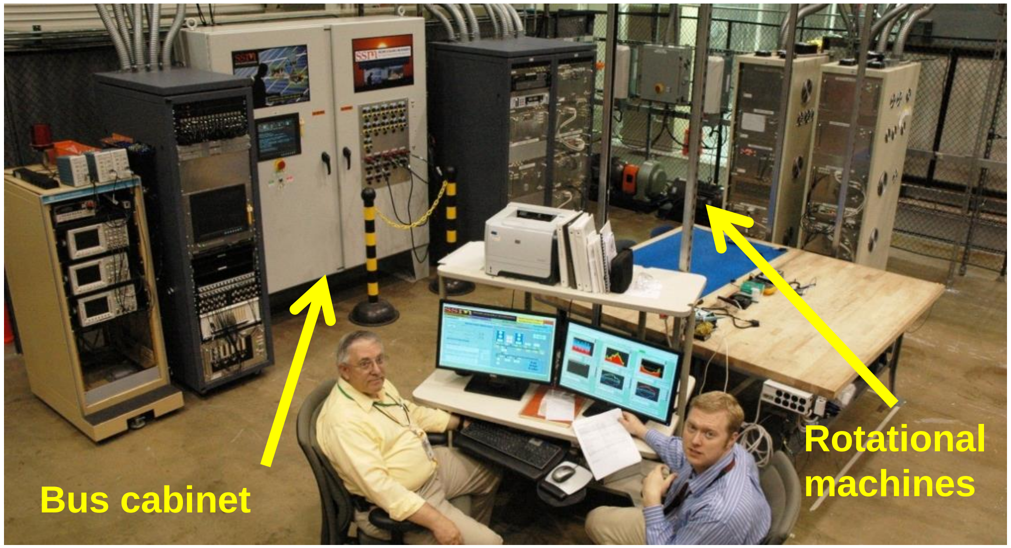


- Centralized generation
- Excess generation & fuel storage
- Fixed infrastructure
- Demand forecasting
- Essentially open loop control with human in the loop
- Limited ability to support renewable sources
- Limited ability to support disruptions
- Smart grid initiatives

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

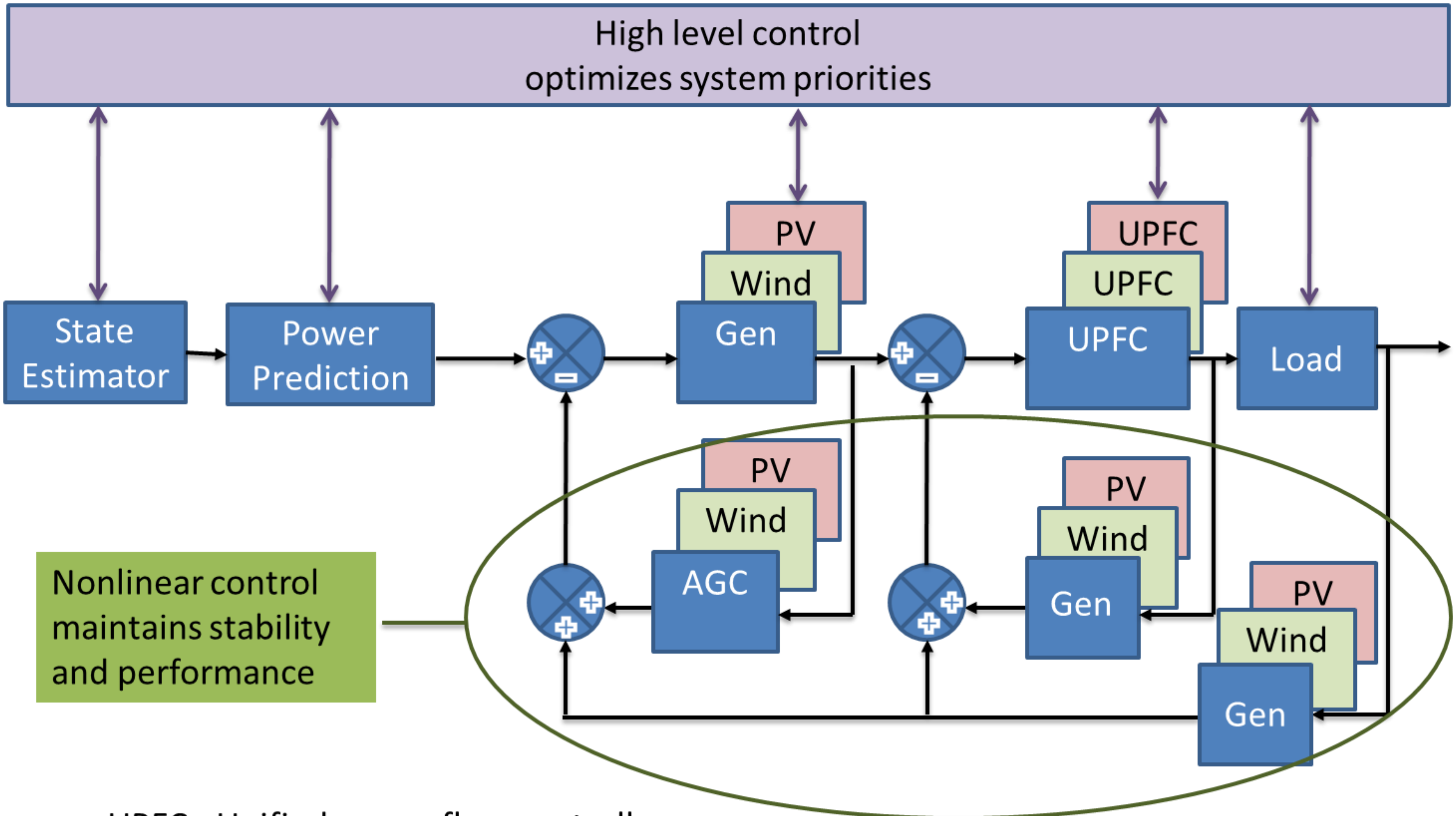
- Ground breaking nonlinear control theory, informatics, and innovation.
- Tools are being developed for networked microgrids spanning from conventional to 100% stochastic generation.
- Potential impact:
  - **Unlimited use of renewable sources**
  - **Lower-cost provisioning at a given level of renewables**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





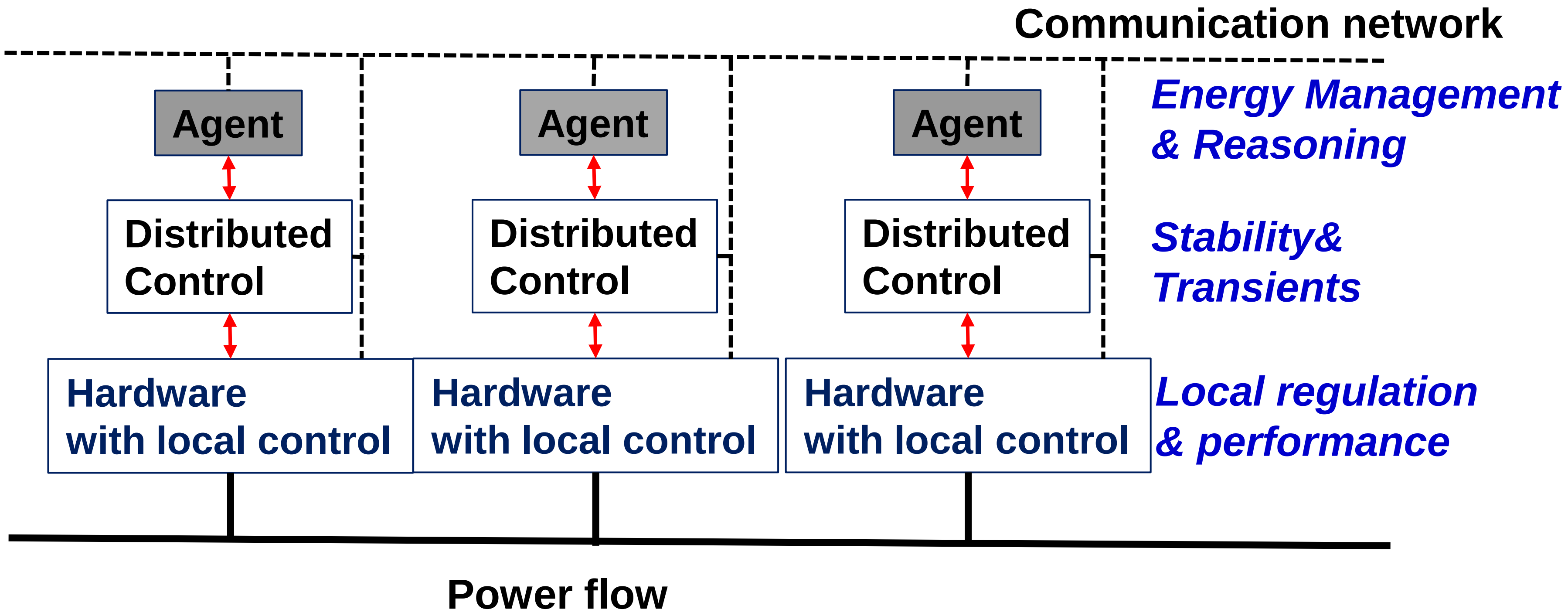
SSM test bed

Tiered Control Structure Enables Prioritization and System Adaptability



UPFC - Unified power flow controllers

Our Basic Control Structure adds Capability and Supports Flexibility



Accomplishments: 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

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

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

A method for optimizing microgrids through the use of Hamiltonians

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

$$c = \int H dt$$

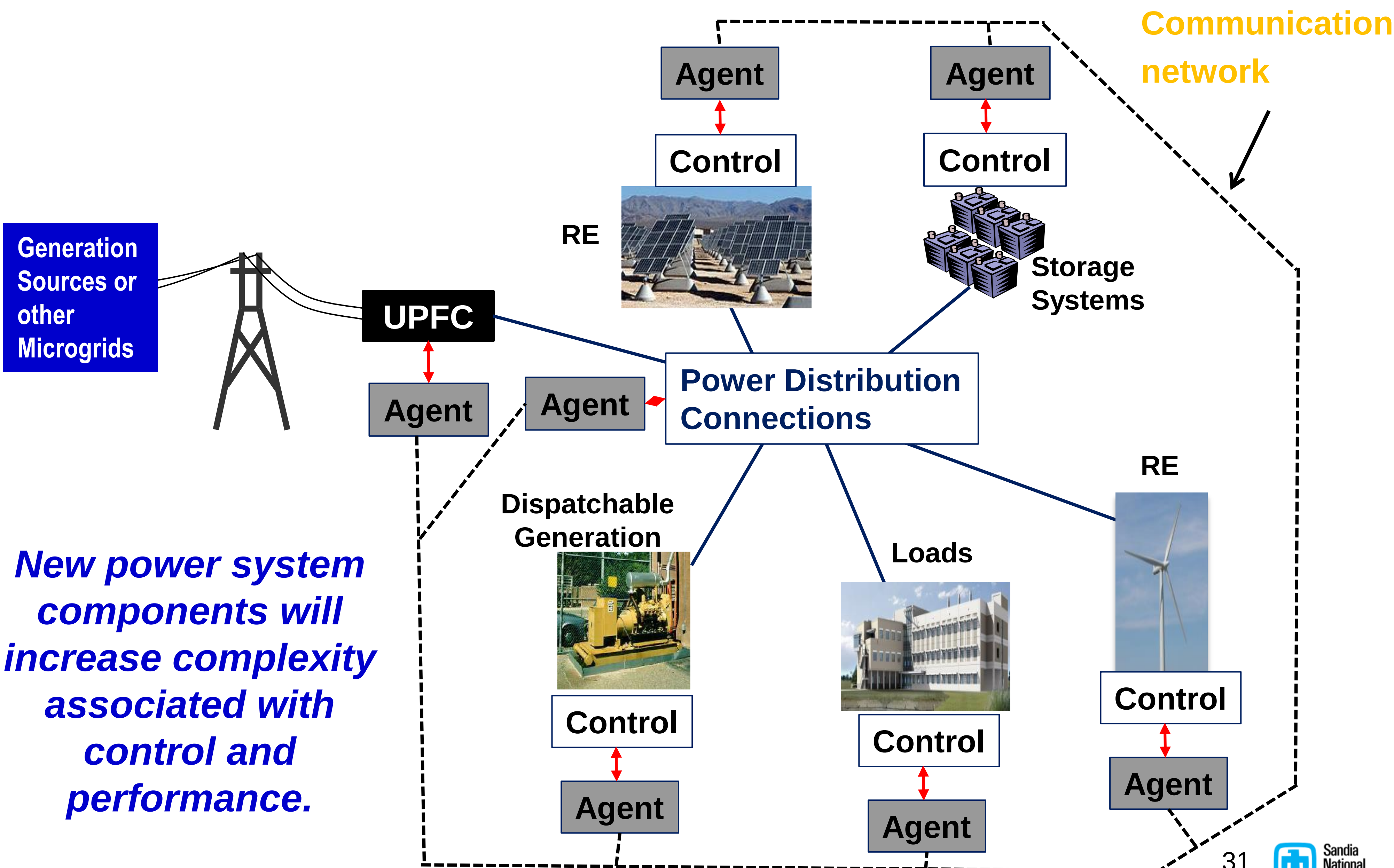
Uniqueness of Fisher Information Equivalency

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

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

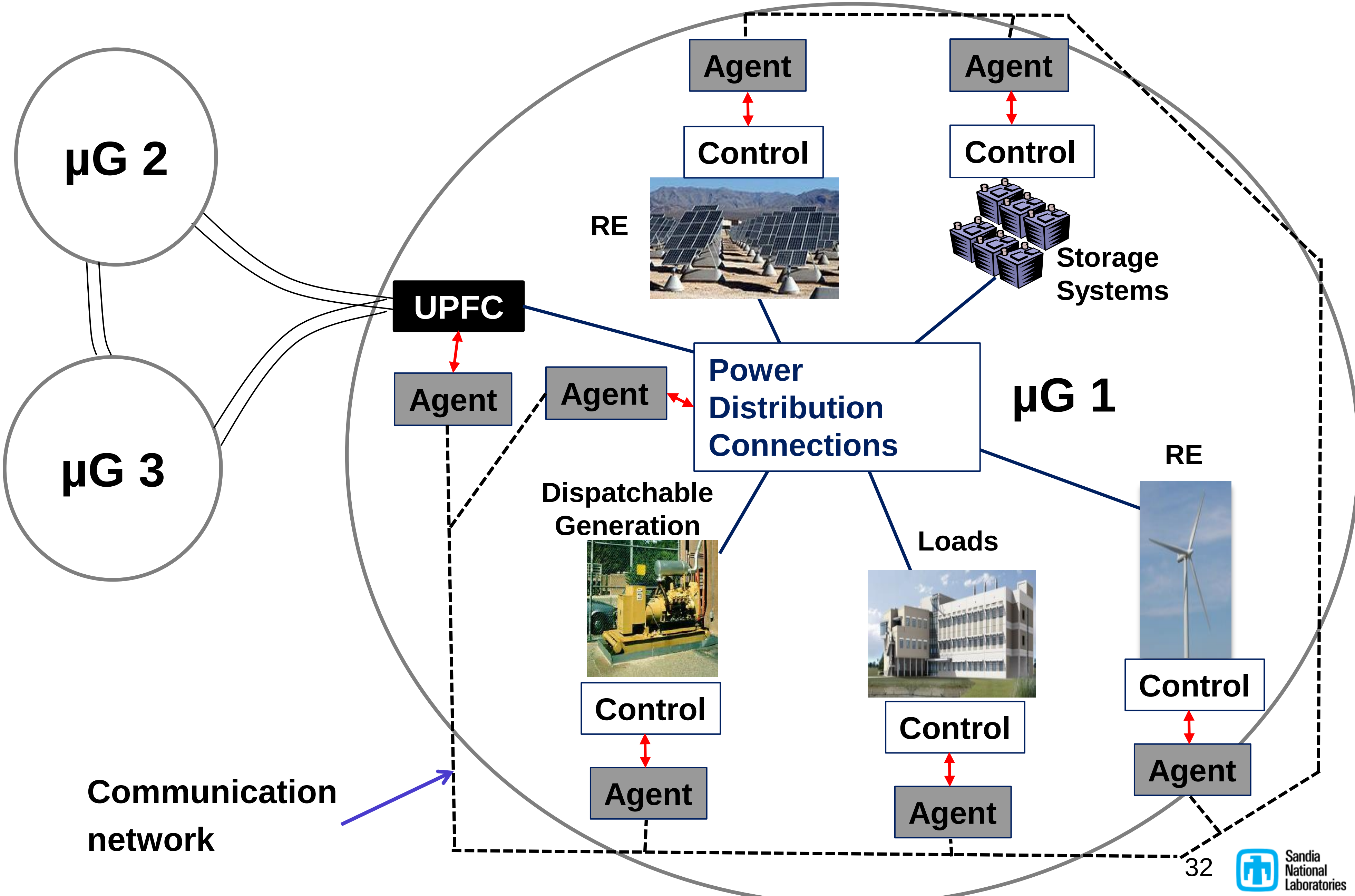
Sandia National Laboratories

The Basic SSM Test Bed Structure Enables a Flexible Research Platform



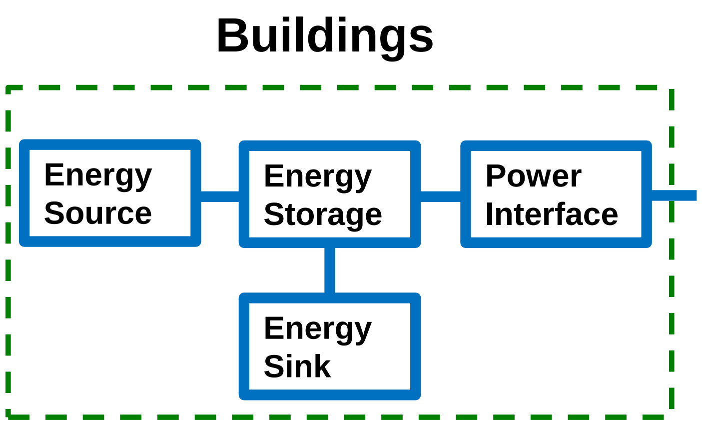
New power system components will increase complexity associated with control and performance.

These Microgrids will be Building Blocks for Large Networks



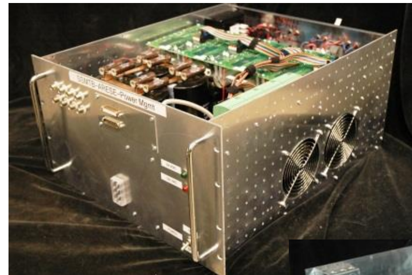
Research that Should be Integrated for Buildings

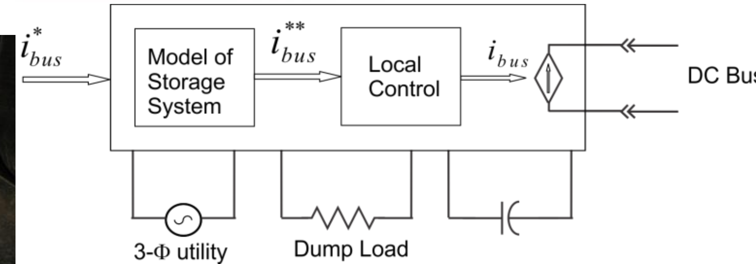
- **Secure Scalable Microgrids**
  - Networked, adaptive, multi-level control
- **Building controls**
  - PV integration
- **Exergy control**
  - Holistic design process
- **Advanced inverters**
  - Functionality, standards
- **Advanced generation**
  - High efficiency
- **Navy power systems**
  - Controls, energy storage
- **Industry projects through MTU**
  - Appliances, homes, trucks



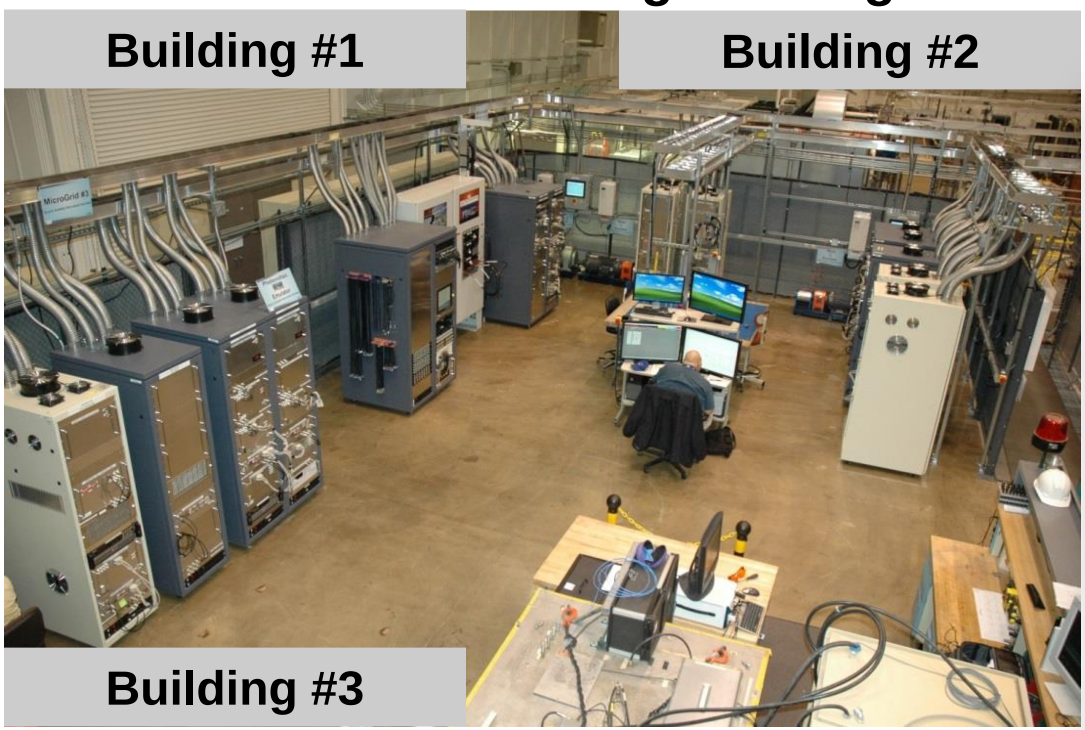
Platforms for Supporting Building Research

SNL - Component hardware with building type structure

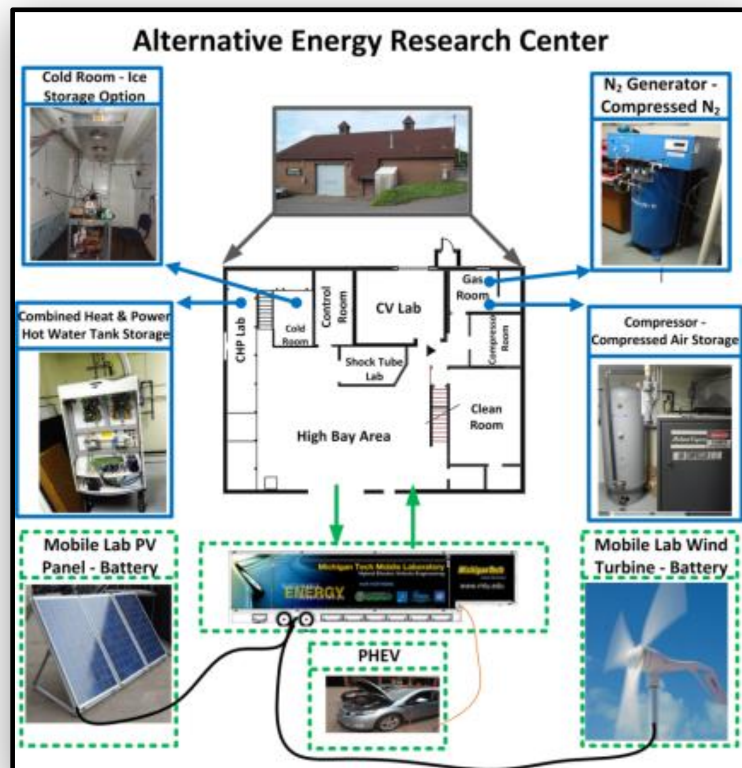




SNL - Networked buildings/microgrids



MTU research center



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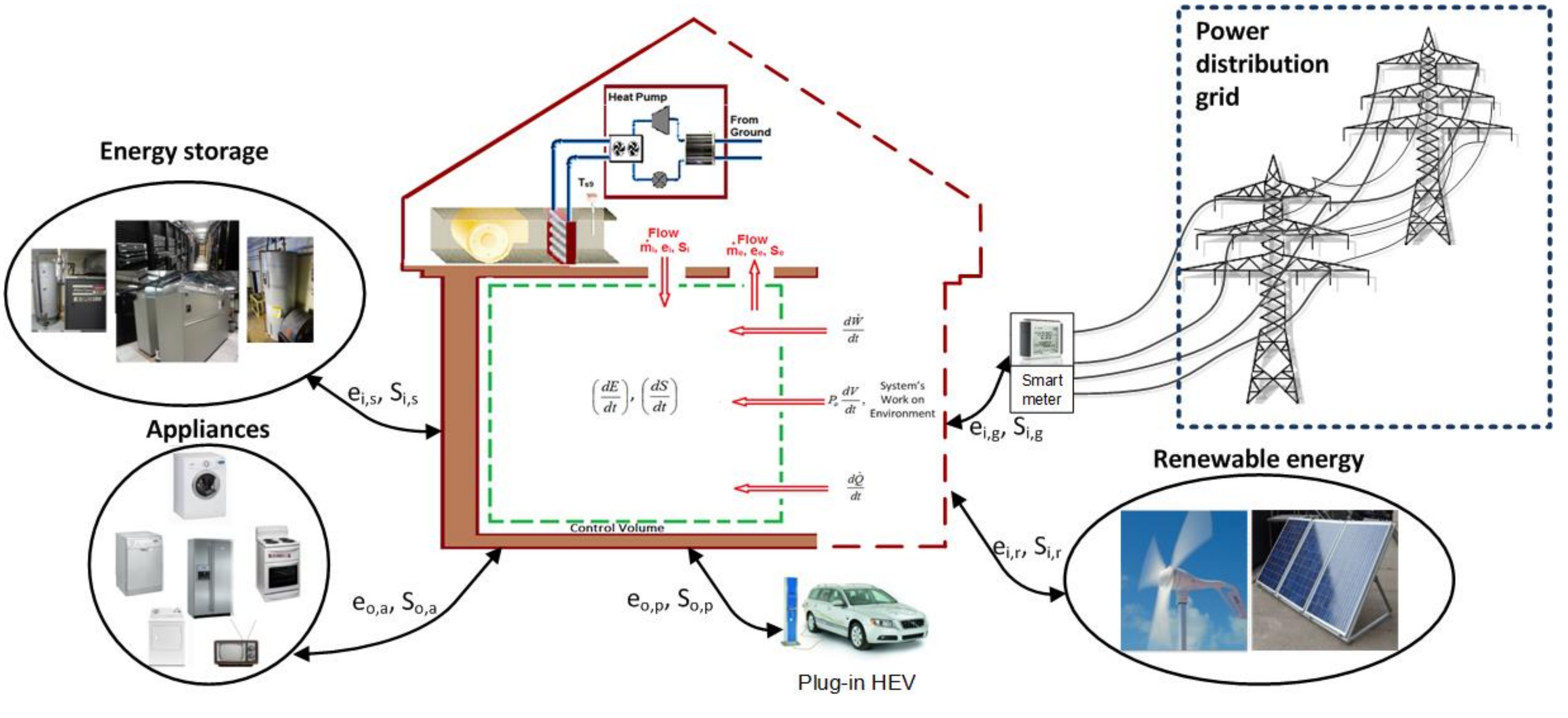
Propose to Create a Holistic approach to Building Design and Controls

Exergy-based building-grid energy management – utilizing buildings with varying-scale storage systems



Our Vision is:

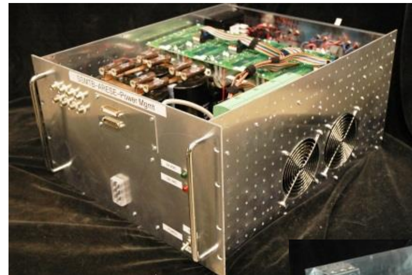
Net positive buildings that reliably and resiliently provide energy to tenants in an optimally efficient manner.

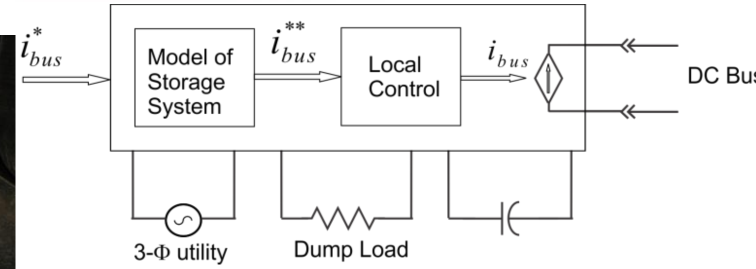
Advantages to net positive buildings:

- Critical loads are maintained
- Increased efficiency to tenants
- Revenue stream from grid connection through provision of ancillary services
    - Volt-var support, frequency support, peak power shaving, arbitrage, power quality, stability, etc
- Reliability and resiliency
- Excess generation capacity
- Energy storage

Platforms for Supporting Building Research

SNL - Component hardware with building type structure





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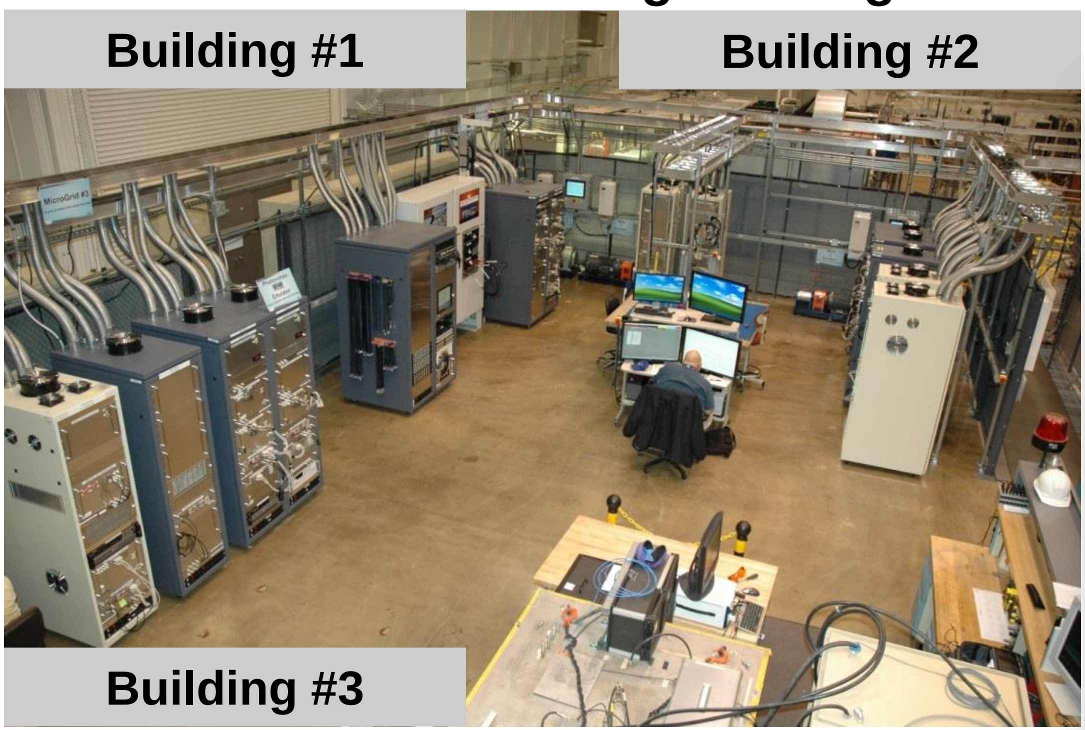
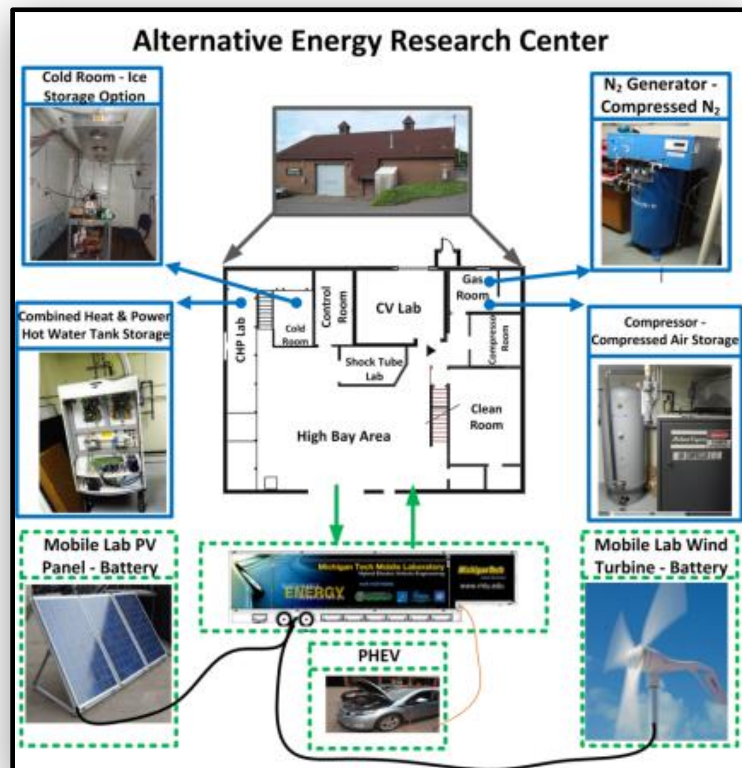


MTU research center



Sandia National Laboratories

Proposed Stages

- **Stage I:**
  - **Energy storage and exergy flow analysis, simulation, and test bed modification to AC and DC systems including instrumentation, estimated cost: *$1,000,000***
- **Stage II:**
  - **AERB – grid optimization (illustrate building-storage-grid promises), estimated cost: *$500,000***
- **Stage III:**
  - **Building storage identification and implementation on MTU campus microgrid, estimated cost: *$0.2-1M* depending on the required storage**
- **Stage IV:**
  - **Exergy Campus MicroGrid, estimated cost: *highly depends on analysis results from stages I-III.***

BACK UP

Hamiltonian Based Controls

David Wilson

Water Power and Controls Technologies

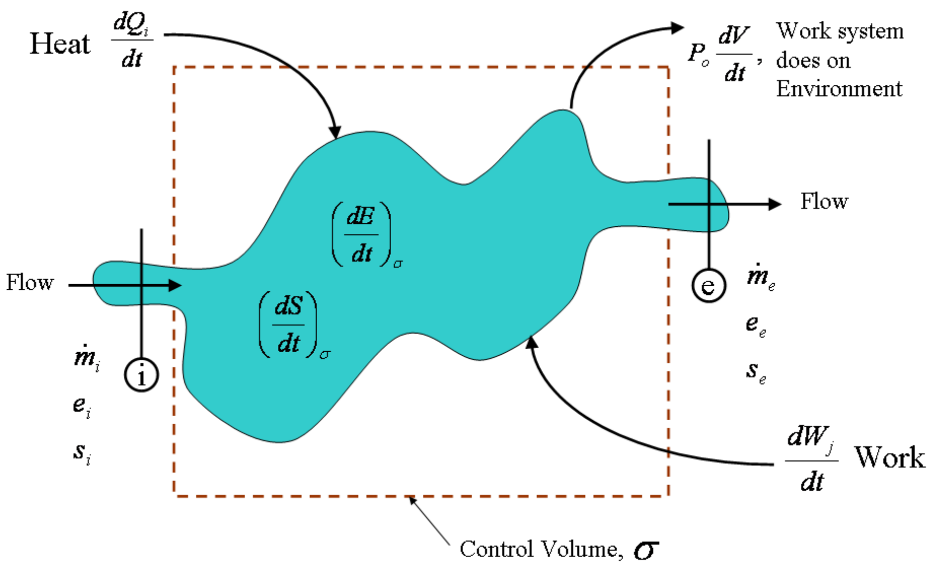
Sandia National Laboratories

Albuquerque, NM 87185

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

Unifying Theory: Nonequilibrium Thermodynamics



- **Energy rate equation**

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

- **Entropy rate equation**

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

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

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

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

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

Unifying Theory: Hamiltonian Mechanics

- **Hamiltonian Mechanics**
  - Lagrangian: $L = T(\underline{q},\dot{\underline{q}},t) - V(\underline{q},t)$
    - t – Time Explicitly
    - $\underline{q}$ – N Dimensional Generalized Coordinate Vector
    - $\dot{\underline{q}}$ – N Dimensional Generalized Velocity Vector
  - Hamiltonian: $H \equiv \sum_{j=1}^{N} \frac{\partial L}{\partial \dot{q}_i} \dot{q}_i - L(\underline{q},\dot{\underline{q}},t) = H(\underline{q},\dot{\underline{q}},t)$
  - Hamilton's canonical equations of motion:
    $\dot{q}_j = \frac{\partial H}{\partial p_j}, \; \dot{p}_j = -\frac{\partial H}{\partial q_j} + Q_j$
  - For most natural systems: $\frac{\partial L}{\partial t} = 0$
  - **Power flow equation: (work/energy)** $\dot{H}(\underline{q},\dot{\underline{q}}) = \sum_{j=1}^{N} Q_j \dot{q}_j$

- **Hamiltonian is stored exergy since potential and kinetic energies are available work; Exergy rate relationship:**

$$\dot{H} = \sum_k Q_k \dot{q}_k = \underline{F}_{NC} \cdot \dot{\underline{q}}$$

$$\dot{\Xi} = \dot{W} - T_o \dot{S}_i = \sum_{j=1}^{N} Q_j \dot{q}_j - \sum_{l=N+1}^{M+N} Q_l \dot{q}_l = \underline{F}_{NC} \cdot \dot{\underline{q}}$$

a) $\dot{W}$ – Power flowing in (N generators)
b) $T_o\dot{S}_i$ – Power Dissipation (M Dissipators)
c) $\dot{S}_i = \sum_k F_k \dot{X}_k = \frac{1}{T_o}\sum_k Q_k \dot{q}_k \geq 0$ (Assuming Local Equilibrium)
d) Assumptions applied to exergy rate equation:

$$\dot{Q}_i \cong 0, \quad 1 - \frac{T_o}{T_j} \cong 0, \quad p_o\dot{V} = 0, \quad \sum_k \dot{m}_k \zeta_k^{FLOW} = 0$$

e) A conservative system is equivalent to a reversible system when:

$$\dot{H} = 0 \;\; and \;\; \dot{S}_e = 0 \;\; then \;\; \dot{S}_i = 0 \;\; and \;\; \dot{W} = 0$$

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

Unifying Theory: Sorting Power Terms

Fundamental Stability Lemma for Hamiltonian Systems:

- The link between: "Lyapunov optimal"; the "Hamiltonian"; and Exergy/Entropy thermodynamics is defined as

$$\dot{\Xi} = \dot{V} = \dot{H} = \dot{W} - T_o\dot{S}_i = \sum_{j=1}^{N} Q_j\dot{q}_j - \sum_{l=N+1}^{M+N} Q_l\dot{q}_l$$

- Subject to the following necessary and sufficient conditions:

$T_o\dot{S}_i \geq 0$ Positive semi-definite, always true

$\dot{W} \geq 0$ Positive semi-definite – Exergy pumped into system

Bounded between Lyapunov Stability and Chetaev Instability Theorems

- **Corollary 1:** $For\ \left(T_o\dot{S}_i\right)_{ave} = 0\ \ and\ \ \left(\dot{W}\right)_{ave} = 0\ then\ \ \dot{V} = 0$
  the Hamiltonian system is neutrally stable, conservative & reversible
- **Corollary 2:** $For\ \left(T_o\dot{S}_i\right)_{ave} = 0\ \ and\ \ \left(\dot{W}\right)_{ave} > 0\ then\ \ \dot{V} > 0$
  the Hamiltonian system is unstable
- **Corollary 3:** $For\ \left(T_o\dot{S}_i\right)_{ave} > 0\ \ and\ \ \left(\dot{W}\right)_{ave} = 0\ then\ \ \dot{V} < 0$
  the Hamiltonian system is asymptotically stable and a passive system in the general sense (passivity controllers)
- **Corollary 4: Given** *apriori* $\left(T_o\dot{S}_i\right)_{ave} > 0\ \ and\ \ \left(\dot{W}\right)_{ave} > 0\ then$
  Hamiltonian is further subdivided into:
  - **4.1** $For\ \left(T_o\dot{S}_i\right)_{ave} > \left(\dot{W}\right)_{ave}\ \ with\ \ \dot{V} < 0 \Leftrightarrow asymptotic\ \ stability$
  - **4.2** $For\ \left(T_o\dot{S}_i\right)_{ave} = \left(\dot{W}\right)_{ave}\ \ with\ \ \dot{V} = 0 \Leftrightarrow neutral\ \ stability$
  - **4.3** $For\ \left(T_o\dot{S}_i\right)_{ave} < \left(\dot{W}\right)_{ave}\ \ with\ \ \dot{V} > 0 \Leftrightarrow unstable\ \ system$

Unique contribution to nonlinear control technical community

Unifying Theory:
Fisher Information Theory and Quantum Mechanics

- **Fisher information:** $I = 4\int \dot{q}^2(x)dx$

  $q^2(x) = p(x)$ "real amplitude" function of PDF
- **Interpreted as "mean kinetic energy" purposes of this discussion:**

  $$I = 4\int \dot{q}^2 dt = 4\int \frac{2}{m} T dt$$

  where: $T = \frac{1}{2} m\dot{q}^2$
- **Formalized further through bound Fisher information as:**

  $$J = 8\int [\bar{v} + \bar{v}_c]dt; \bar{v} = \sum_{i=1}^{N} \frac{1}{m_i} v_i; \bar{v}_c = \sum_{i=1}^{N} \frac{1}{m_i} v_{c_i}$$
- **Fisher Lagrangian defined as**

  $$I - J = 8\int \bar{T} - (\bar{v} + \bar{v}_c)dt = 8\int \bar{L}dt$$
- **The derivation of the equations of motion informs us about the physical infrastructure (robots, sensors, etc.) versus the information driven collective**

- **Physical and information exergies general result:**

  $$\dot{I} - \dot{J} = 8[\bar{T} - (\bar{v} + \bar{v}_c)]$$
- **This provides constraint on information flow and disordering rate since:**

  $$\dot{I} - \dot{J} \le 0 \quad \text{as} \quad t \to \infty \quad [*]$$
- **Fisher Hamiltonian provides "Fisher Information Equivalency:"**

  $$I + J = 8\int [\bar{T} + (\bar{v} + \bar{v}_c)]dt = 8\int \bar{H}dt$$
- **This relationship provides direct connection between stability of, performance of, and information flow within the collective**
- **Ideal optimization functional (keeps track of order of system and disordering rate of collective)**

[*] B.R. Frieden, Physics from Fisher Information: A Unification, Cambridge University press, 1999

From a communications point of view, Fisher Information is a measure of how well the receiver can estimate the message from the sender where as Shannon information/entropy is a measure of the sender's transmission efficiency over a communications channel.

Unifying Theory:
Static and Dynamic Stability

The Energy Storage Surface is

$$H = T + V = E$$

A system is statically stable if

$$H(\dot{x}, x) > 0 \text{ for } V(x) > 0 \; \forall x \neq x_e, \dot{x} \neq \dot{x}_e$$

$$H(\dot{x}_e, x_e) = 0$$

Statically unstable if

$$V(x) < 0 \; \forall x \neq x_e, V(x_e) = 0$$

And Neutrally stable if

$$V(x) = 0 \quad \forall x$$

The time derivative of the energy storage surface defines the power flow into, dissipated within, and stored in the system

A system is dynamically stable if

$$\dot{H}_{AVE} = \frac{1}{\tau_c} \int_o^{\tau_c} \dot{H} dt < 0$$

dynamically unstable if

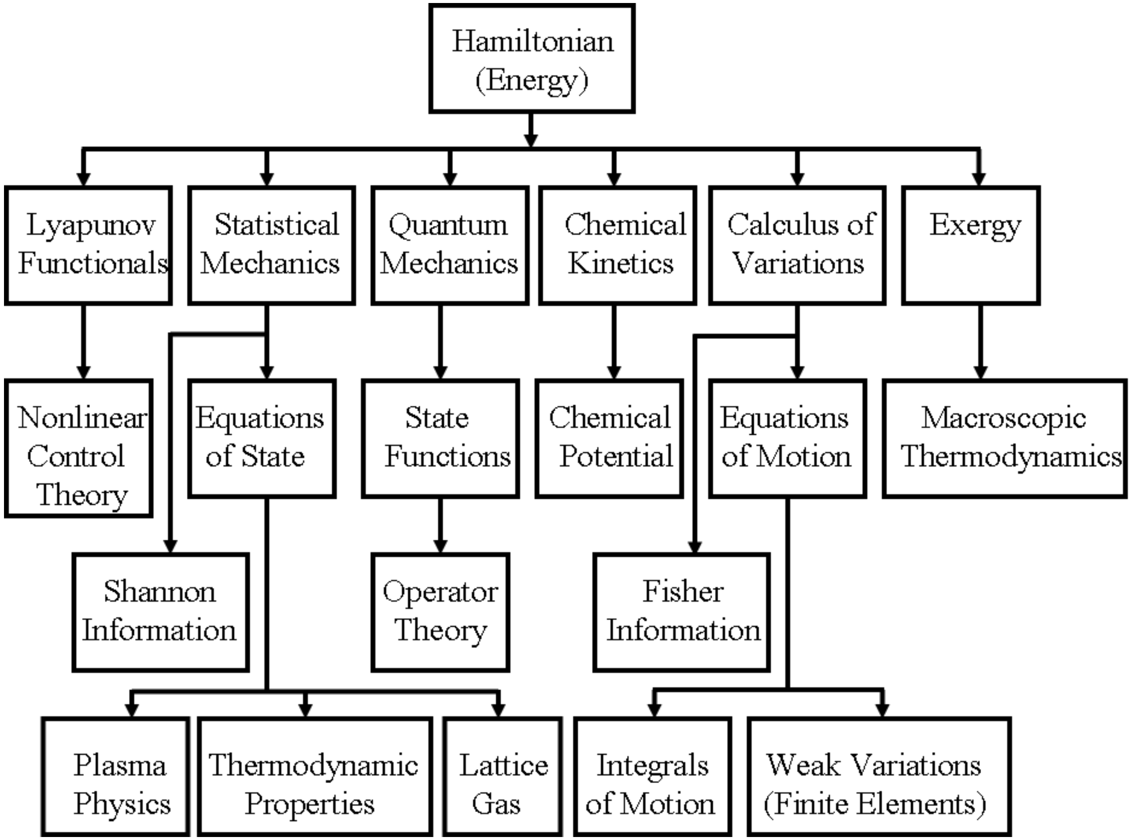
$$\dot{H}_{AVE} = \frac{1}{\tau_c} \int_o^{\tau_c} \dot{H} dt > 0$$

and dynamically neutral stable if (Limit Cycle)

$$\dot{H}_{AVE} = \frac{1}{\tau_c} \oint_{\tau_c} \dot{H} dt = 0$$

The goal of applying static and dynamic stability to the microgrid is to answer the following question: "How do you design the storage infrastructure to ensure the desired limit cycle behavior and parameter switching ensures reconfigurability and adaptivity?"

Unifying Theory:
Evolved to Collectives – Physical/Information Exergies



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

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***

HSSPFC key pieces accomplished on GC/LDRD

- 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

Nonlinear Control Design
HSSPFC Energy Storage DC Microgrid Example

- **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**

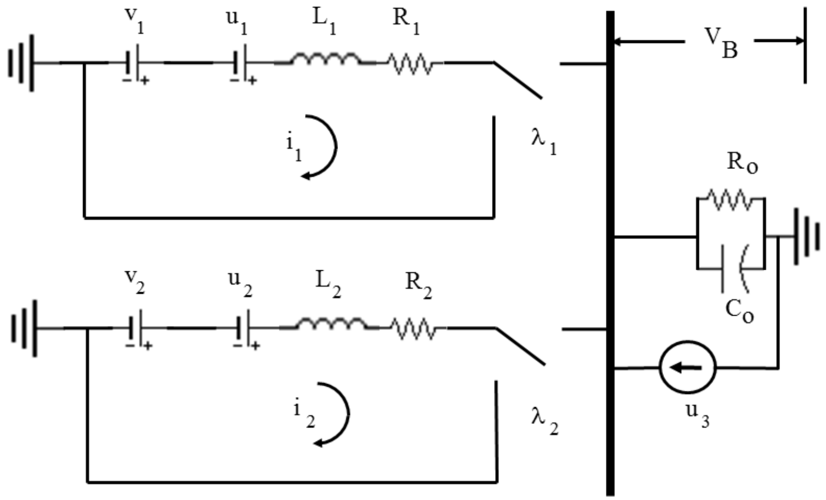
DC Bus Microgrid Model
2 Boost Converter with Voltage Sources

- **Circuit equations for 2 boost converters and DC bus:**

$$L_1 \frac{di_1}{dt} = -R_1 i_1 - \lambda_1 v_B + v_1 + u_1$$

$$L_2 \frac{di_2}{dt} = -R_2 i_2 - \lambda_2 v_B + v_2 + u_2$$

$$C_0 \frac{dv_B}{dt} = \lambda_1 i_1 + \lambda_2 i_2 - \frac{1}{R_0} v_B + u_3$$



- **Matrix form:**

$$\begin{bmatrix} L_1 & 0 & 0 \\ 0 & L_2 & 0 \\ 0 & 0 & C_0 \end{bmatrix} \begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{Bmatrix} = \begin{bmatrix} -R_1 & 0 & -\lambda_1 \\ 0 & -R_2 & -\lambda_2 \\ \lambda_1 & \lambda_2 & -\frac{1}{R_0} \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \\ x_3 \end{Bmatrix} + \begin{Bmatrix} v_1 \\ v_2 \\ 0 \end{Bmatrix} + \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \end{Bmatrix}$$

- **compactly:**

$$M\dot{x} = Rx + v + u = \left[\bar{R} + \tilde{R}\right]x + v + u$$

Note: u1,u2, u3 are what generate specs (power, energy, frequency)

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Duty Cycle Commands and Reference Set Points

- Several options in general can be selected:
  i. distributed decentralized
  ii. dynamic optimization (cost functions, w/ constraints, nonlinear)
  iii. distributed decentralized with constant bias
  iv. dynamic programming optimization

- For this example, duty cycle commands obtained through distributed decentralized option from steady-state solution with u=0
- Real-time potential and scalable to collective of microgrids

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HSSPFC Controller Design
Static Stability Condition

- **Error state defined along with reference state vector:**

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

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

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

$$u_{ref} = -\left[\bar{R} + \tilde{R}\right]x_{ref} - v$$

- **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**

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HSSPFC Controller Design
Dynamic Stability Condition

- **The Hamiltonian time derivative or power flow becomes:**

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

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

- **Where** $\tilde{x}^T \tilde{R} \tilde{x} = 0$ **skew-symmetric property**

- **Next select PI controller as:** $u = u_{ref} - \Delta u$

- **Which leads to** $\Delta u = -K_P \tilde{x} - K_I \int \tilde{x}\,dt$

$$\dot{H} = \tilde{x}^T \left[\overline{R} - K_P \right] \tilde{x} < 0,$$

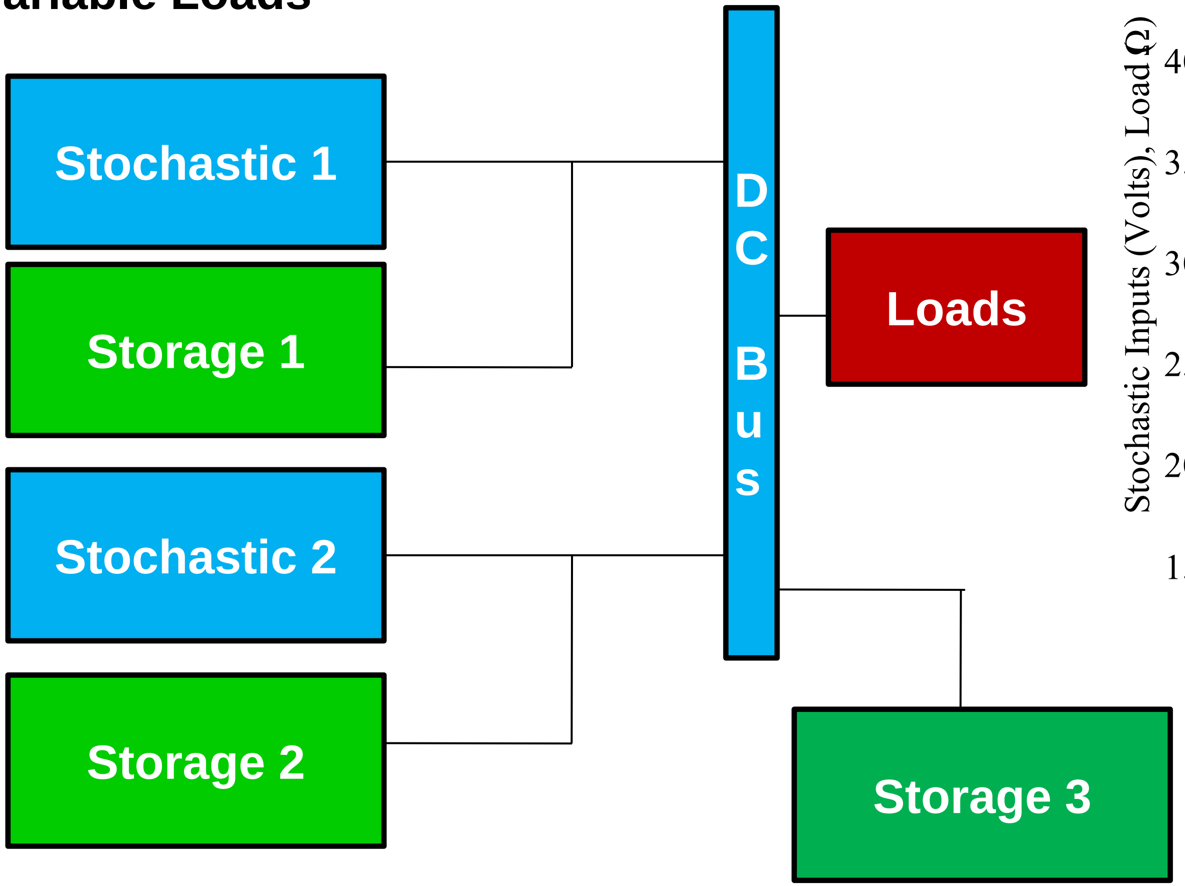
$$-\tilde{x}^T \left[K_P - \overline{R} \right] \tilde{x} < 0$$

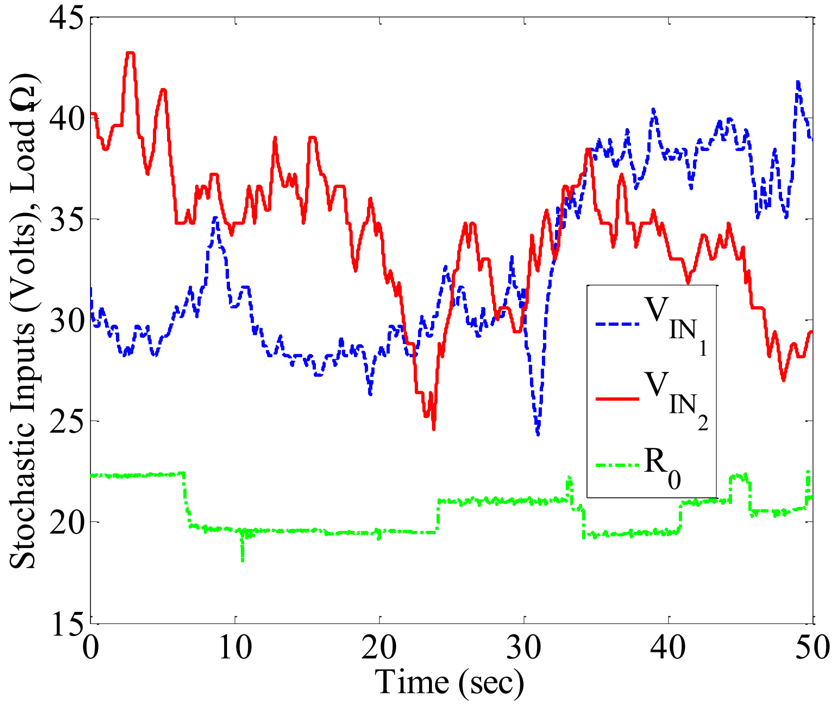
Dynamic Stability Condition

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

HSSPFC Implementation Scenario 2A

- 2 Variable Generators
- 3 Energy Storage
- Variable Loads





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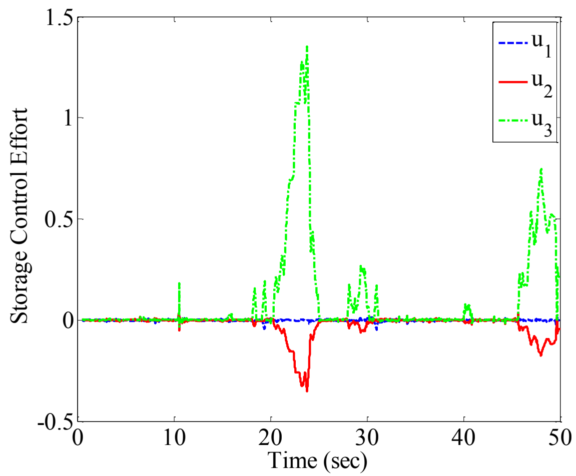
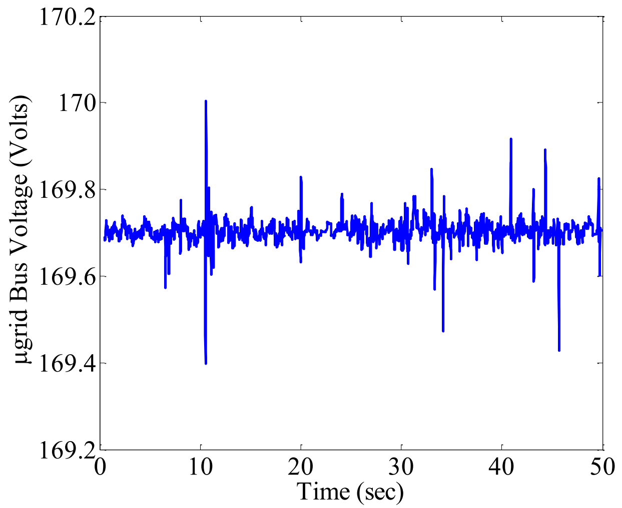
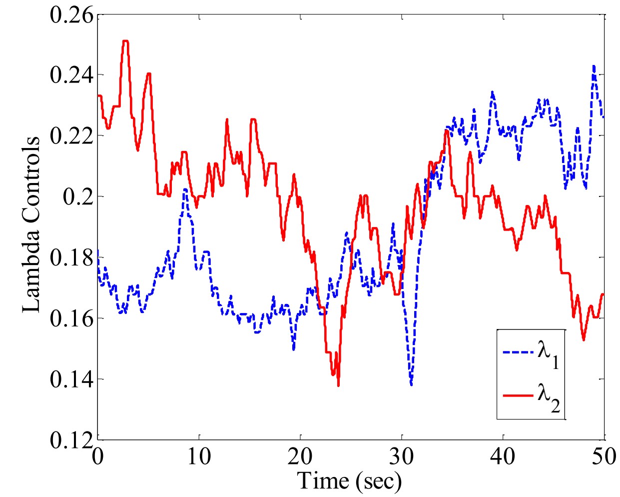
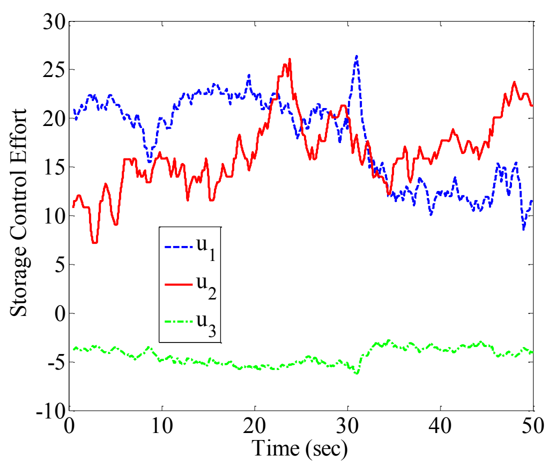
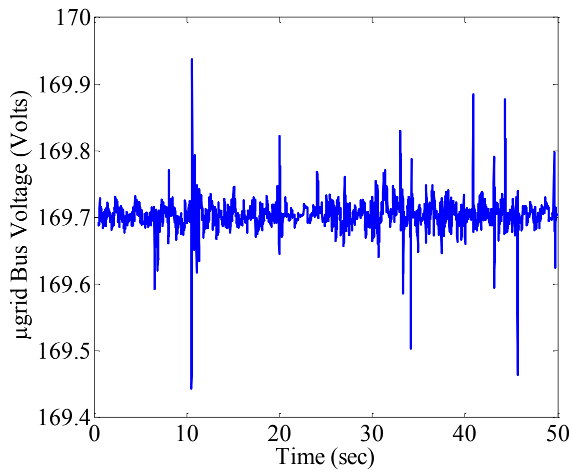
HSSPFC Results Contrasting Duty Cycle (Information Flow) vs Energy Storage Demands





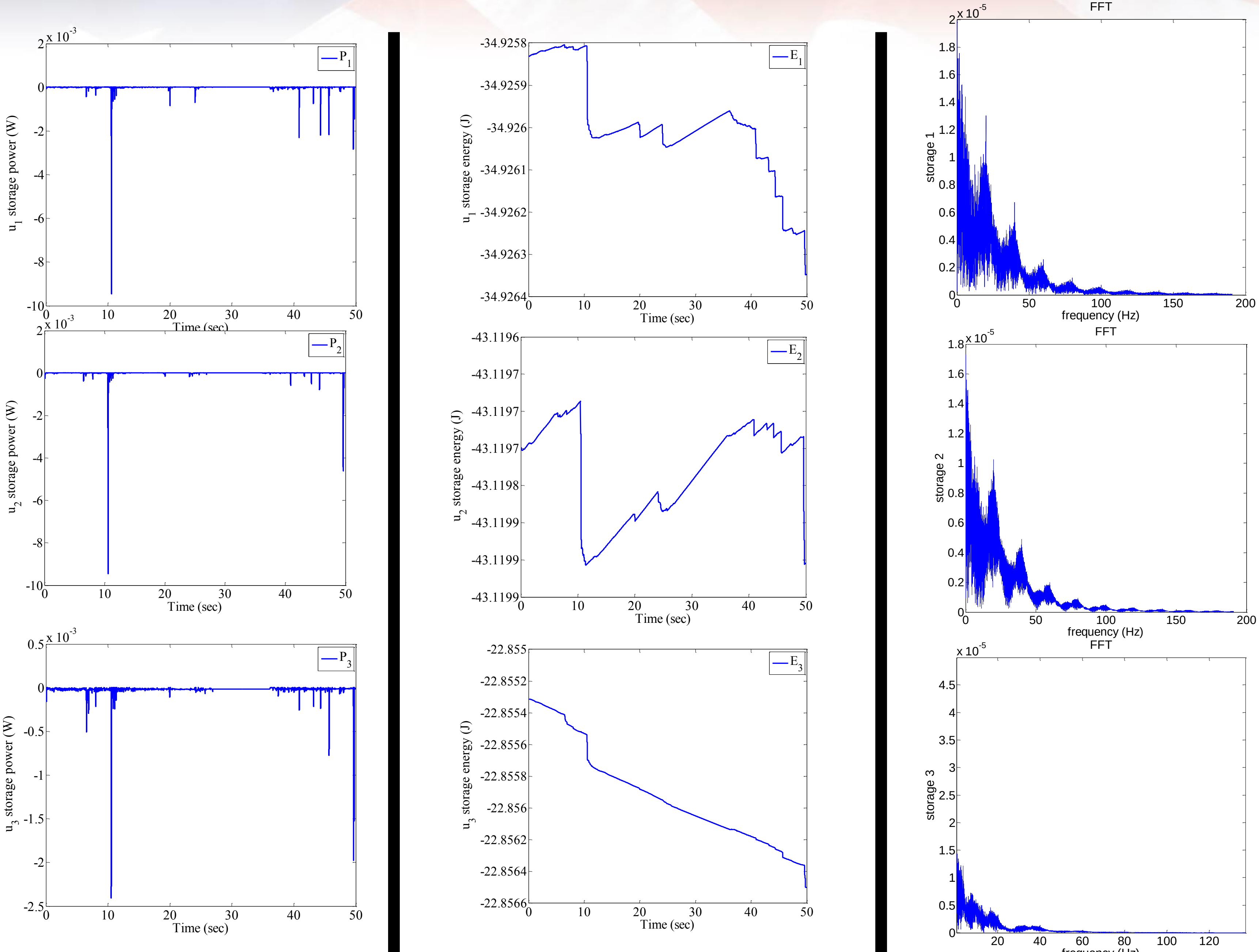






Lambda_1 = 0.2937 constant
Lambda_2 = 0.2935 constant

Example Energy Storage Requirements Scenario 2



DC Boost 1

DC Boost 2

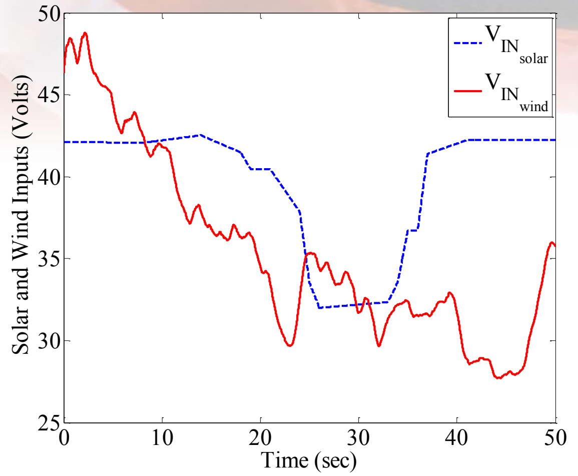
DC Bus

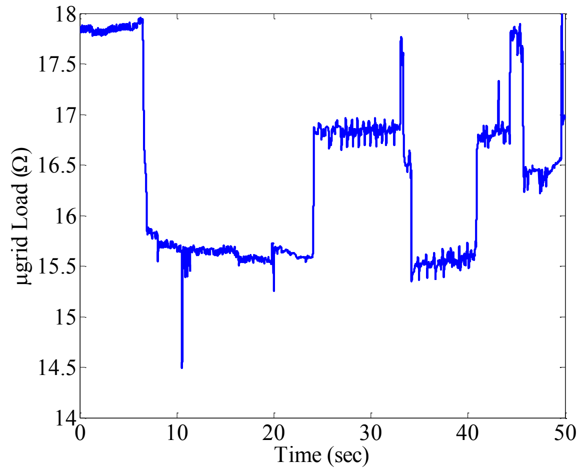
Power Requirements | Energy Requirements | Frequency Response

(requirements displayed for each channel - along the row)

Real-Time Validation

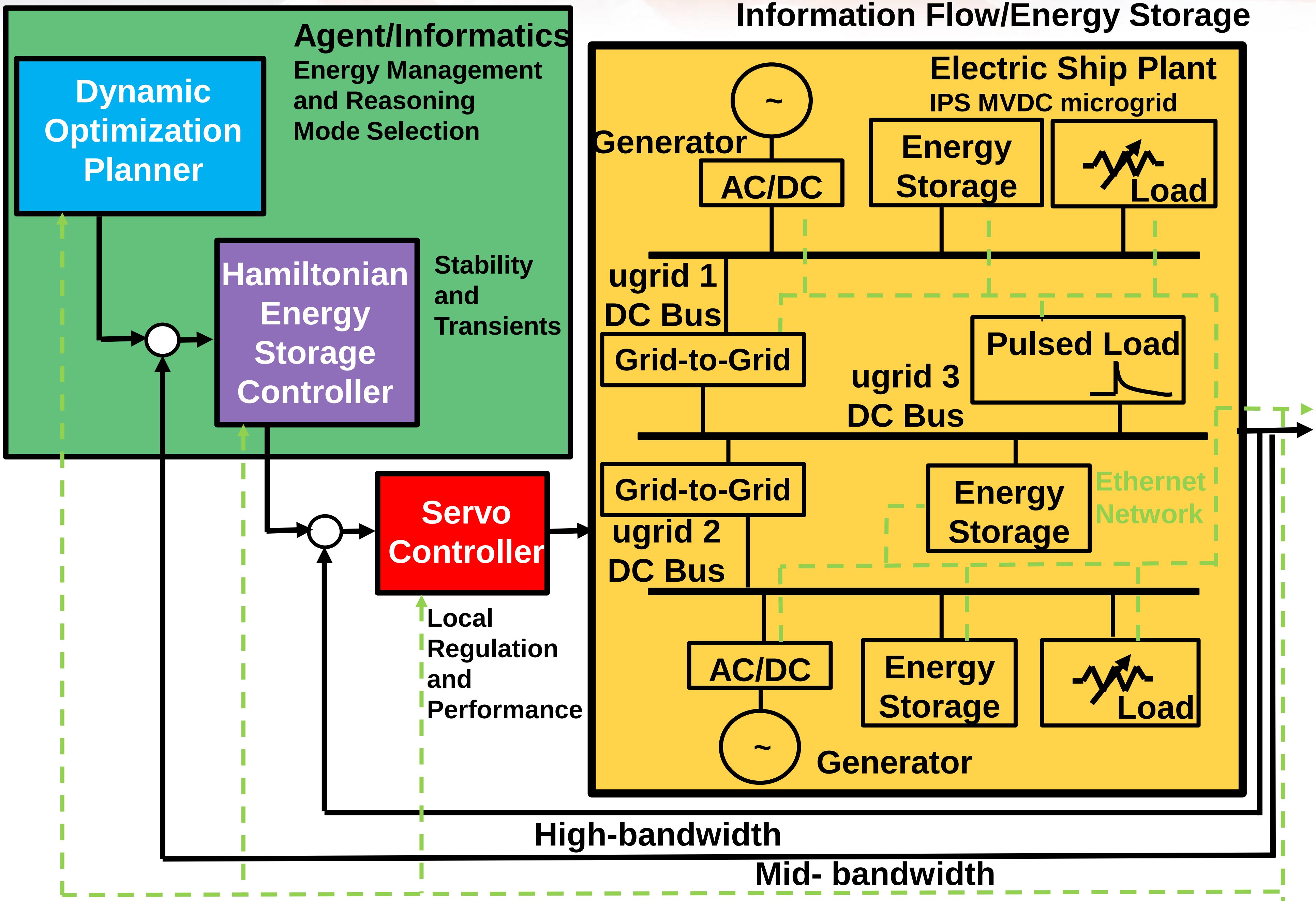
- **Variable Sources and Loads**
- **Trade-offs (information flow vs energy storage)**
  - **0% energy storage (zero controls) baseline high computational requirements on duty cycle (information flow)**
  - **100% energy storage (require high dimension), however information flow is low**
  - **Compromise 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**





Auto Pilot/ Auto Commander

Tertiary Level Control Design
Information Flow/Energy Storage



Informatics

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Agile Energy Systems

Objective:

- **Develop energy systems that reconfigurable in terms of interconnections and optimization strategies.**

Necessary Steps:

1. **Develop advanced control techniques (distributed and suitable for dynamic configurations)**
2. **Develop optimization strategies for the energy system management**
3. **Ensure that sensor data is made available to drive control decisions**
4. **Develop advanced modeling/simulation and test bed capabilities**
5. **Refine tools/capabilities based on experimentation**
6. **Continue maturation towards field deployment**

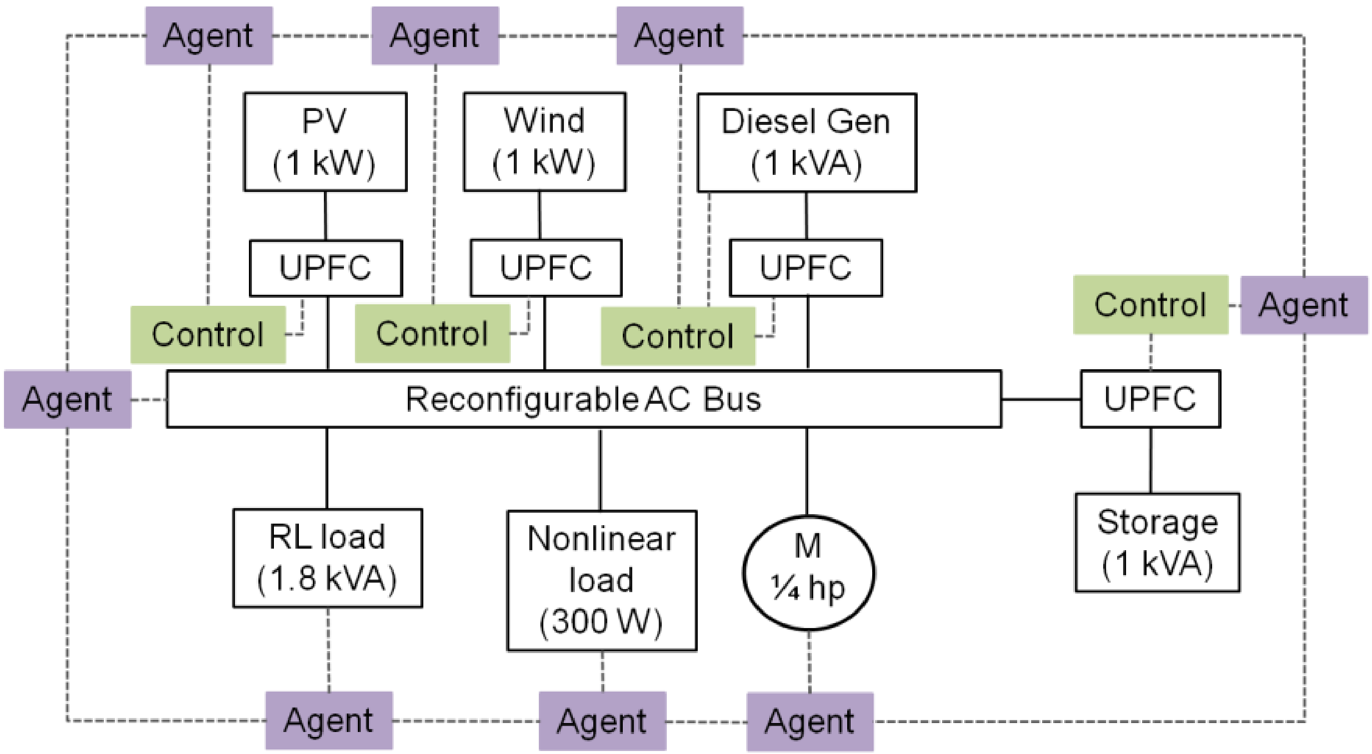
SNL Agent Architecture

- **Over two decades of software development (includes energy systems, border patrol, cyber security, life cycle analysis, and robotic swarms)**
- **Framework for designing and implementing collaborative agents with automated reasoning and self awareness**
- **Supports behavior policies and role assignment that may change during operations**
- **Input driven reasoning engine that can schedule and execute actions while monitoring feedback**
- **Supports human command and control with digital signatures**

Informatics and Agents

Background

- Human in the control loop approaches introduce response delays and rely heavily on training and experience.
- Centralized control approaches that are automated based on measurements and response rules introduce single point of failure.



Automated Reasoning Approaches

- Simple rule based representations in which the agent recognizes state and reacts (reflexive)
- Case Based with templates of general goals and tasks that are specialized based on the state
- Planning/scheduling with execution monitoring
- Expert system
- Cost Functions
- Optimizations that encompass multiple approaches

Considerations for Automated Reasoning

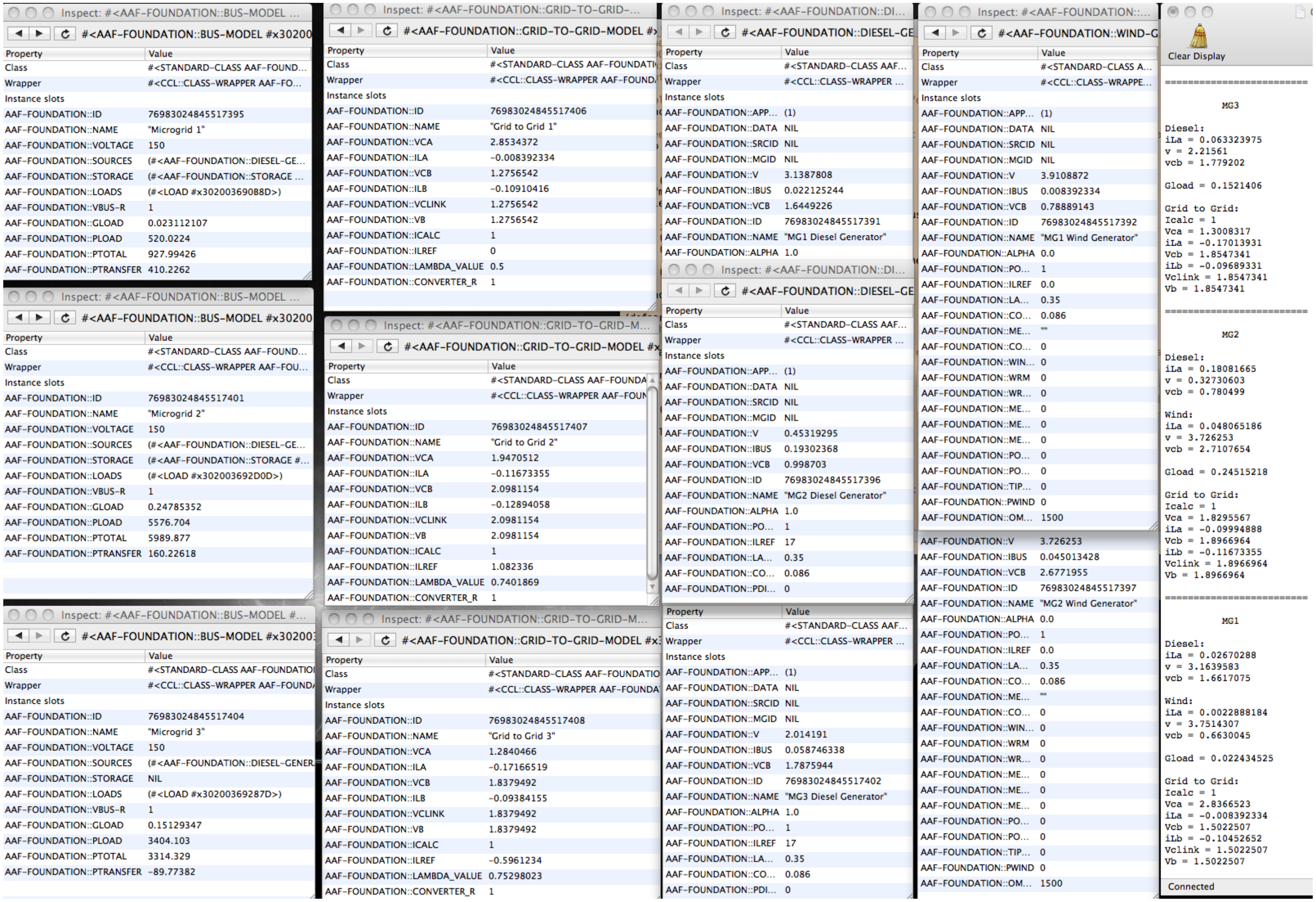
- **What are the constraints?**
  - Fuel Usage
  - Price of energy production
  - Price of wear and tear on components (storage thrashing)
  - Prioritization of loads or thresh holds for safe operation
  - Time to make the best decision and how long that decision is valid for (planning horizon)
  - Carbon dioxide emissions
- **Is forecasting available and with what measure of confidence?**
- **Are there key scenarios and problems that require automation?**

Energy System Optimization

- Apply dynamic optimization techniques to increase power efficiency, reliability, and quality
- Design energy system to provide appropriate inputs (current and voltage measurements)
- Distribute agent responsibilities to manage energy system components
- Use measurements to update system models and drive the optimization engine
- Choose appropriate actions based on the optimization results
- Monitor system state over time and adjust as needed

Energy System Models

- **Object Oriented software representations of energy system components**
- **Supports situated awareness (sense-decide-act)**



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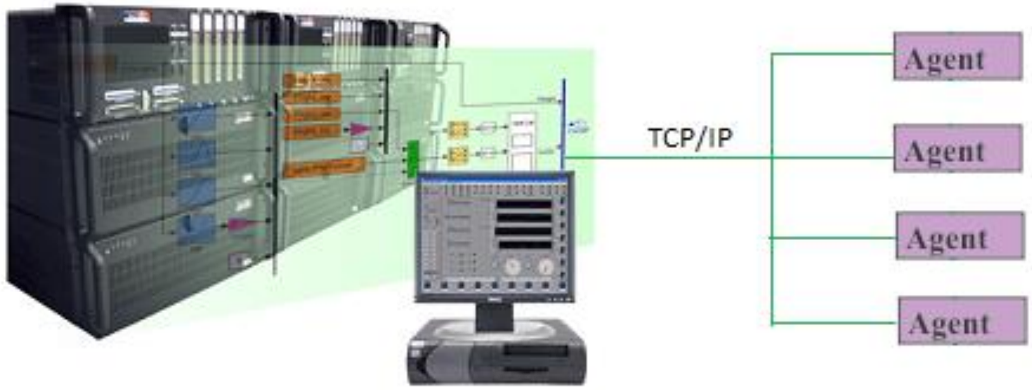
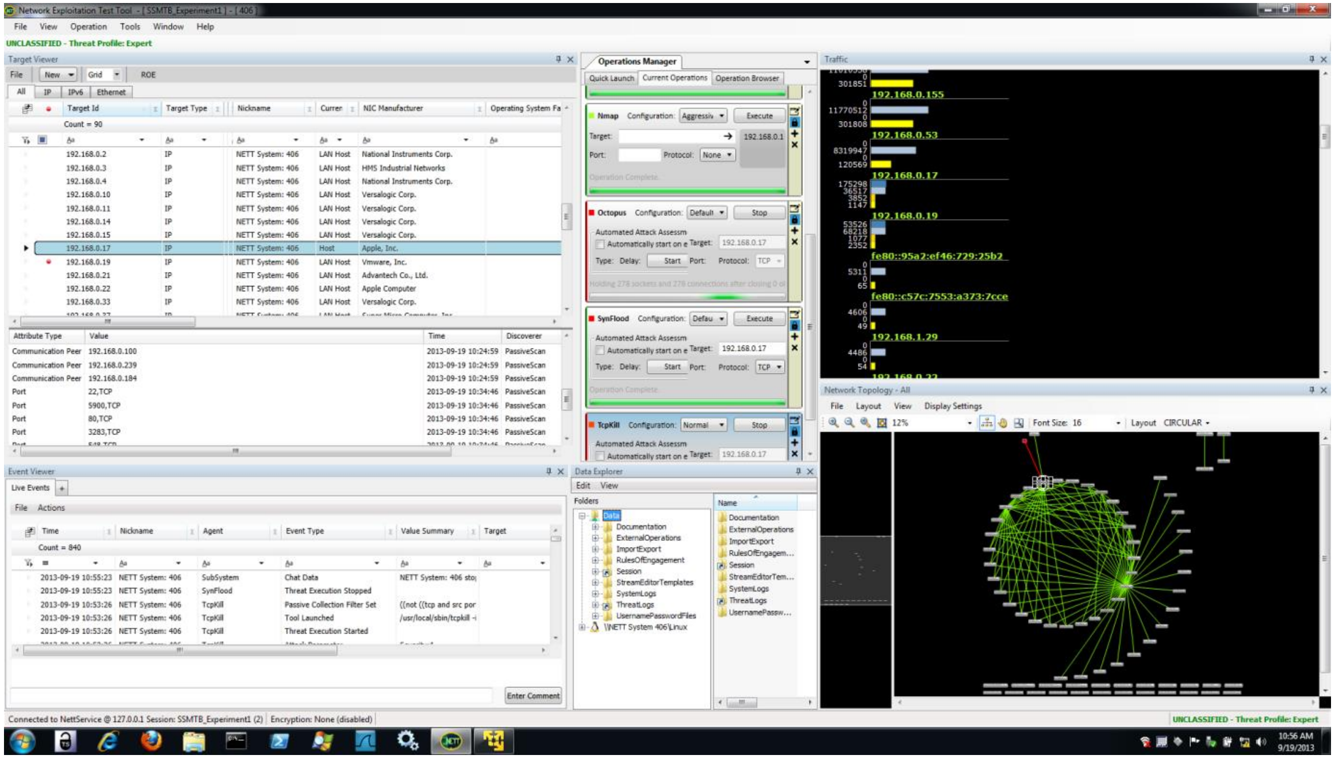
Real Time Simulation with Agent Controls

- Models of SSMTB hardware have been developed and validated
- OpalRT platform runs models real time
- Models have been extended to support TCP/IP communications
- Agents communicate with models to receive data measurements and send control updates
- Allows analysis in simulation prior to physical experimentation



Cyber Security

- **Performed research on energy system vulnerabilities, including specific focus on the SNL agent architecture**
- **Applied Army's Network Exploitation Test and Evaluation Tool for initial cyber security analysis**



Informatics Expertise

- Software Agent Architectures
  - Designing and implementing rational software agents for various problem domains
- Communications
  - Information representation, TCP/IP protocols, # bits and frequency
  - Interoperability standards (adopt, reconcile, create)
- Dynamic Optimization
  - Mature optimization capabilities that have been applied to various problem domains
  - Broad expertise with day ahead and real time stochastic optimization of distributed storage
- Scalability
  - Robotic swarm algorithms and optimization scale techniques
- Security
  - Multiple SNL departments with experience analyzing and defining secure grid control architectures

Hardware Testbed

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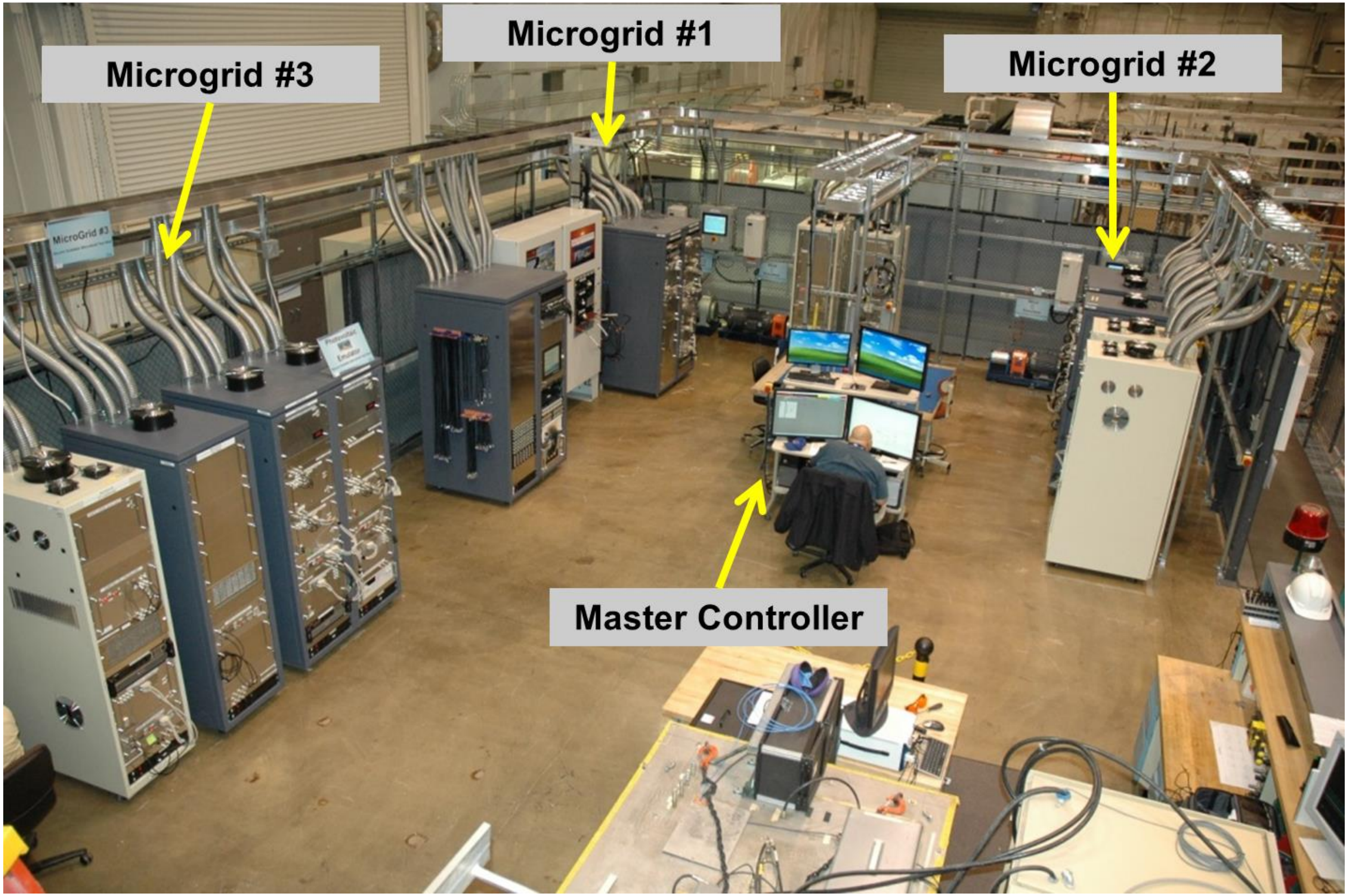
Secure Scalable Microgrid Testbed

- Hardware Testbed includes components representing generation, loads, energy storage and transmission/transfer
- Component building blocks enable a variety of system configurations



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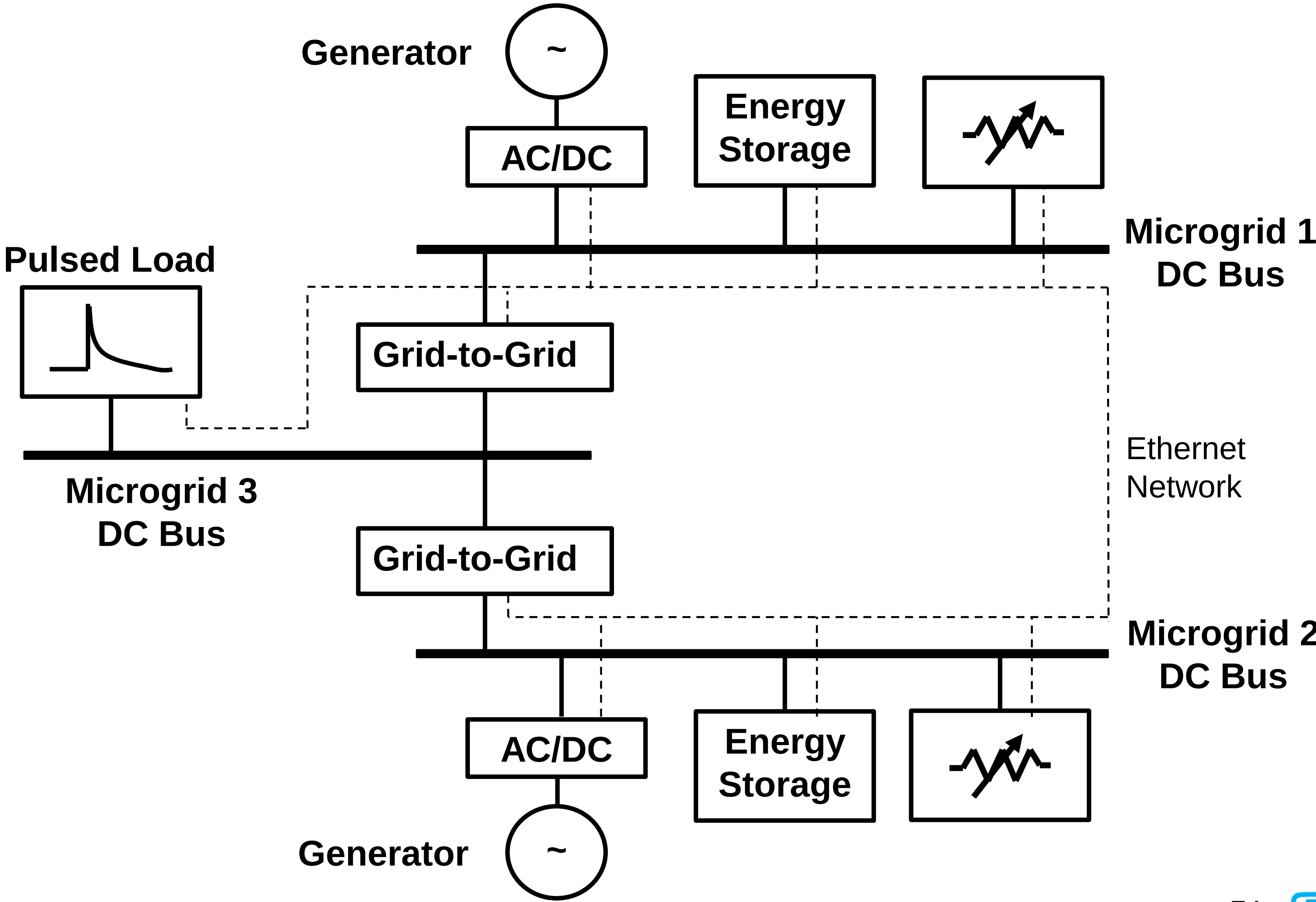
Hardware Testbed Components May be Used to Mimic an Electric Ship Configuration



SSM Test bed Includes a Controllable Buss Enabling Adaptive Topologies

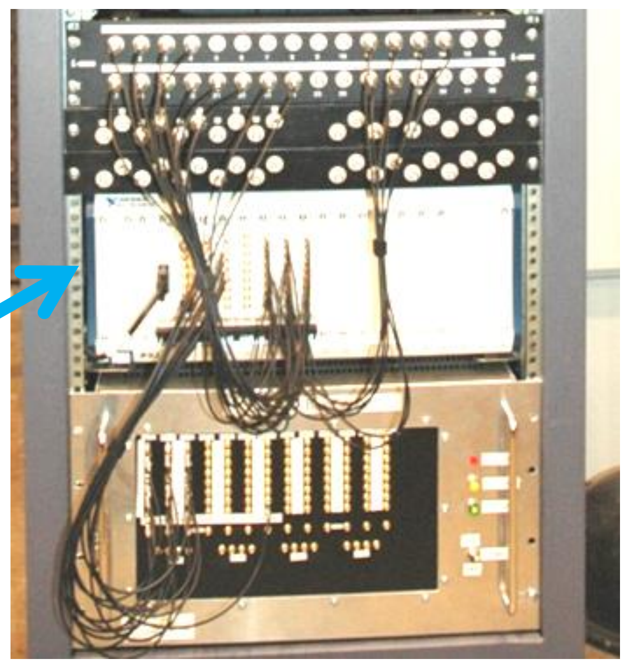
208 V, 3-φ or 240 V, 1-φ buss with controllable semiconductor contactors

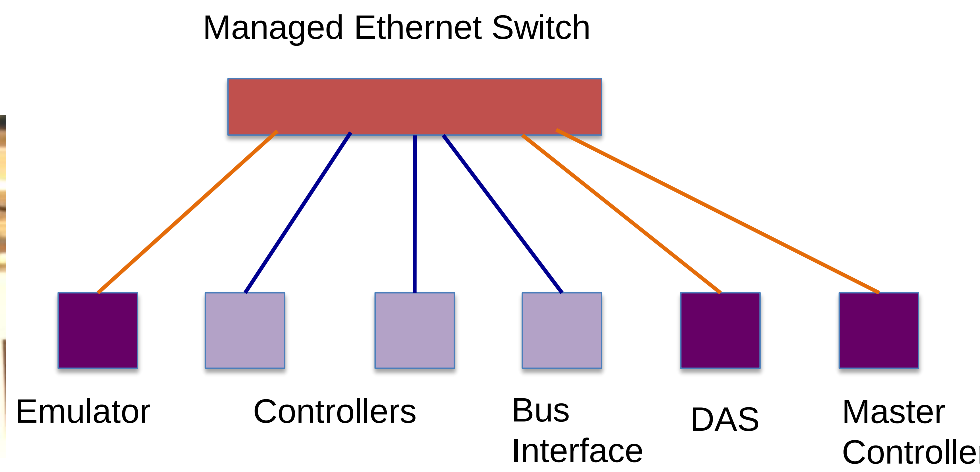
Eleven 25 Arms connections

400 V DC buss with controllable semiconductor contactors

Thirteen 25 A connections

SSM Testbed communication networks manage information flow

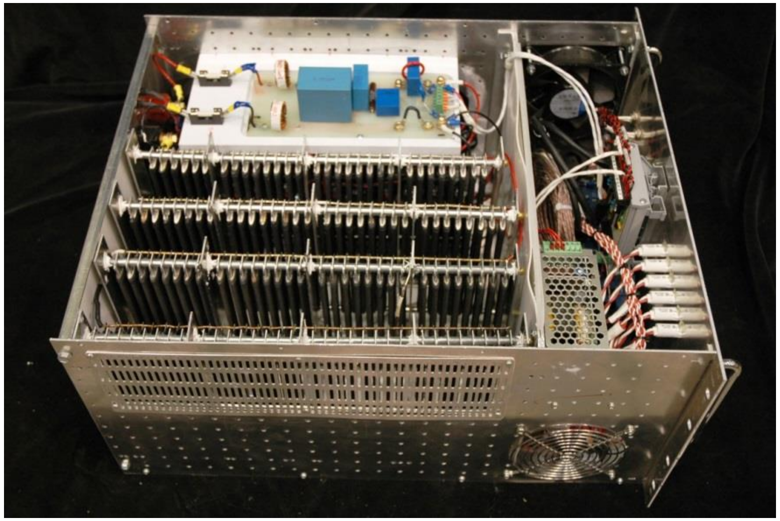


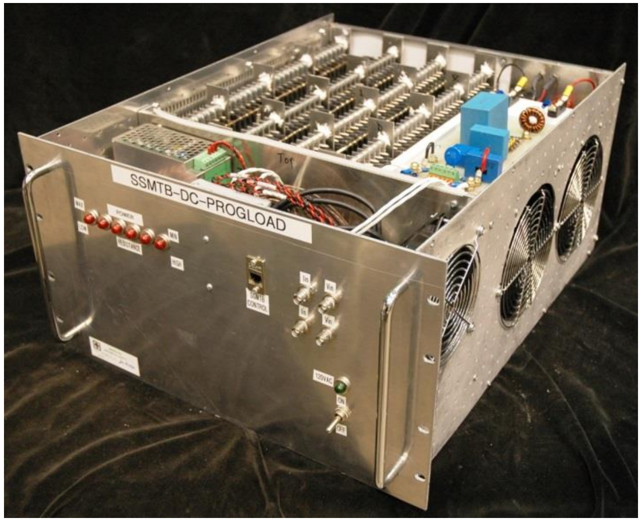


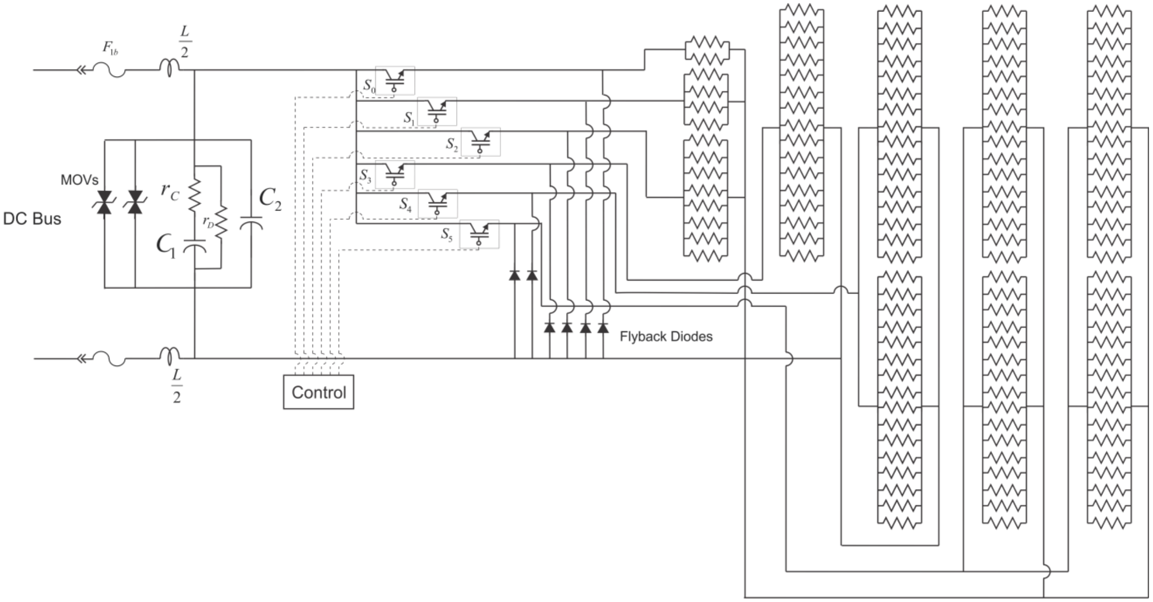
- GB Ethernet Communication
  - Control network
  - Timing network
  - Allows for hierarchical control
- 30 MHz Data Acquisition
  - 2 TB hard drive
  - 48 channels installed

Testbed Includes Several Power Electronic Components

- **Programmable Resistive Load**

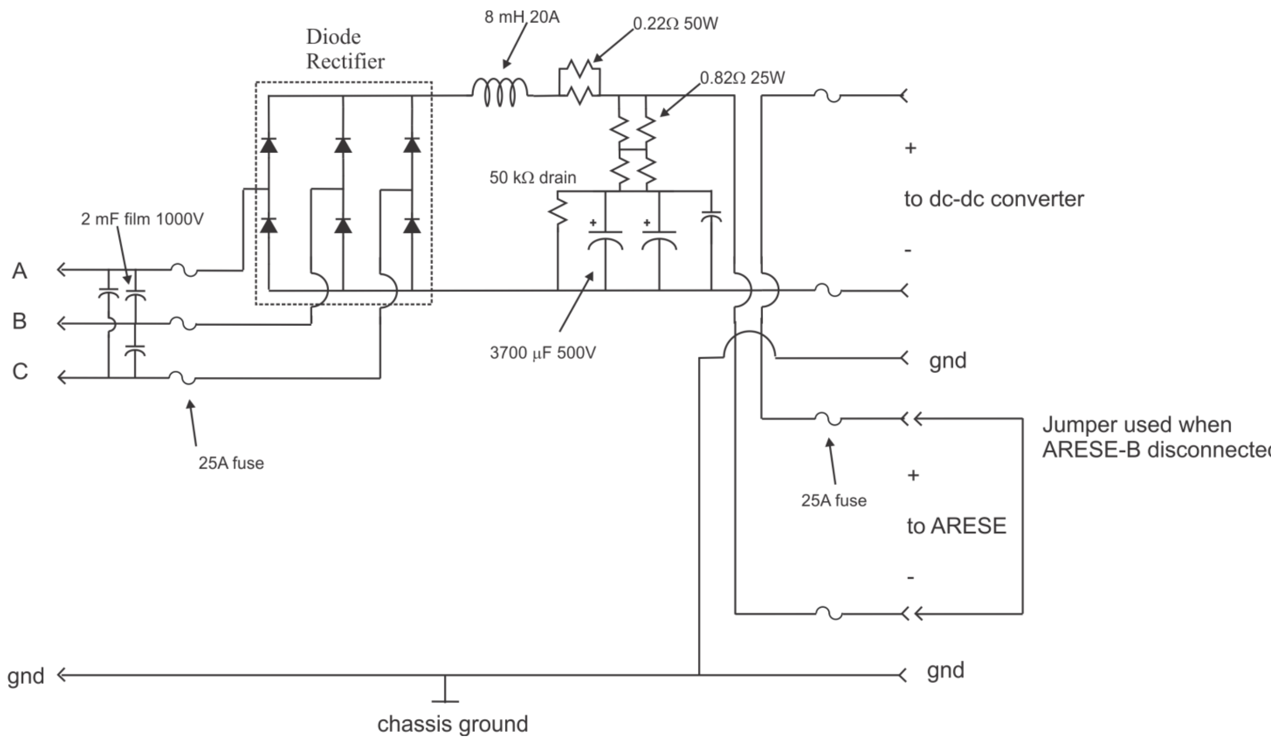






Testbed Includes Several Power Electronic Components

- **Rectifier with LC Output Filter**



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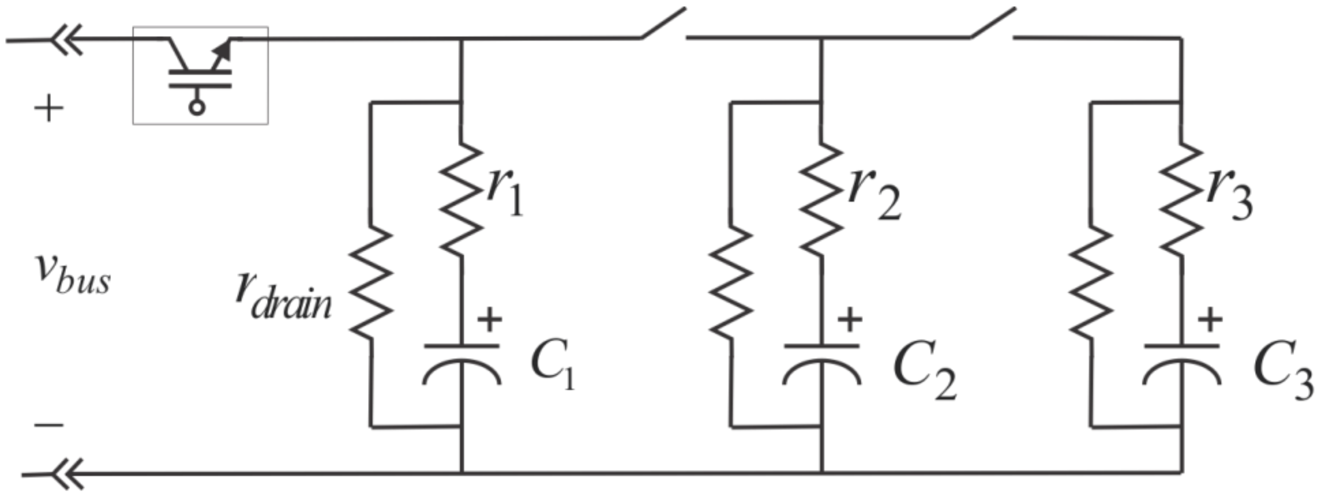
Testbed Includes Several Power Electronic Components

- **Proposed Pulsed Load**
  - **Parallel connected RC networks allow the pulse to be adjusted**

$$\max i_{pulse} = \frac{v_{bus}}{r_1 \parallel r_2 \parallel r_3}$$

$$E_{pulse} = \frac{1}{2}\left(C_1 + C_2 + C_3\right)v_{bus}^2$$



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Emulators Mimic Dynamics of Diesel, Wind or Other Rotational Generators

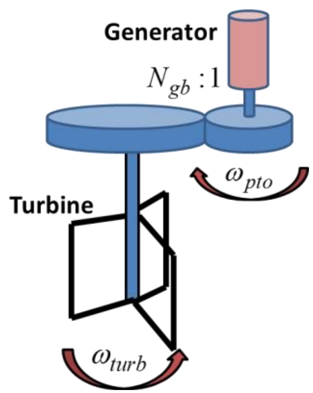
- Dynamic models are created for generators emulated using a commercial motor drive

River Turbine

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

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

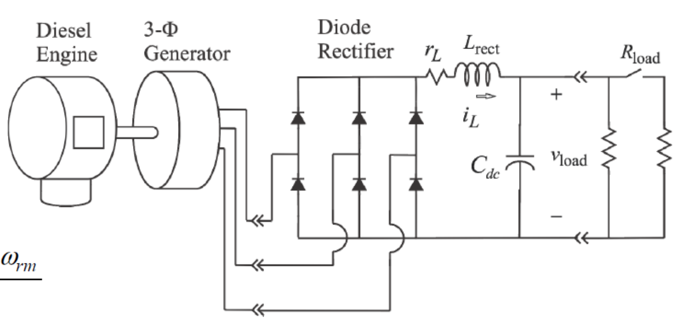
$$\frac{d}{dt}\omega_{pto} = \frac{(1/N_{gb})T_{turb} - T_{pto} - (1/N_{gb}^2)B_{gb}\omega_{pto}}{(1/N_{gb}^2)J_{turb} + J_{pto}}$$

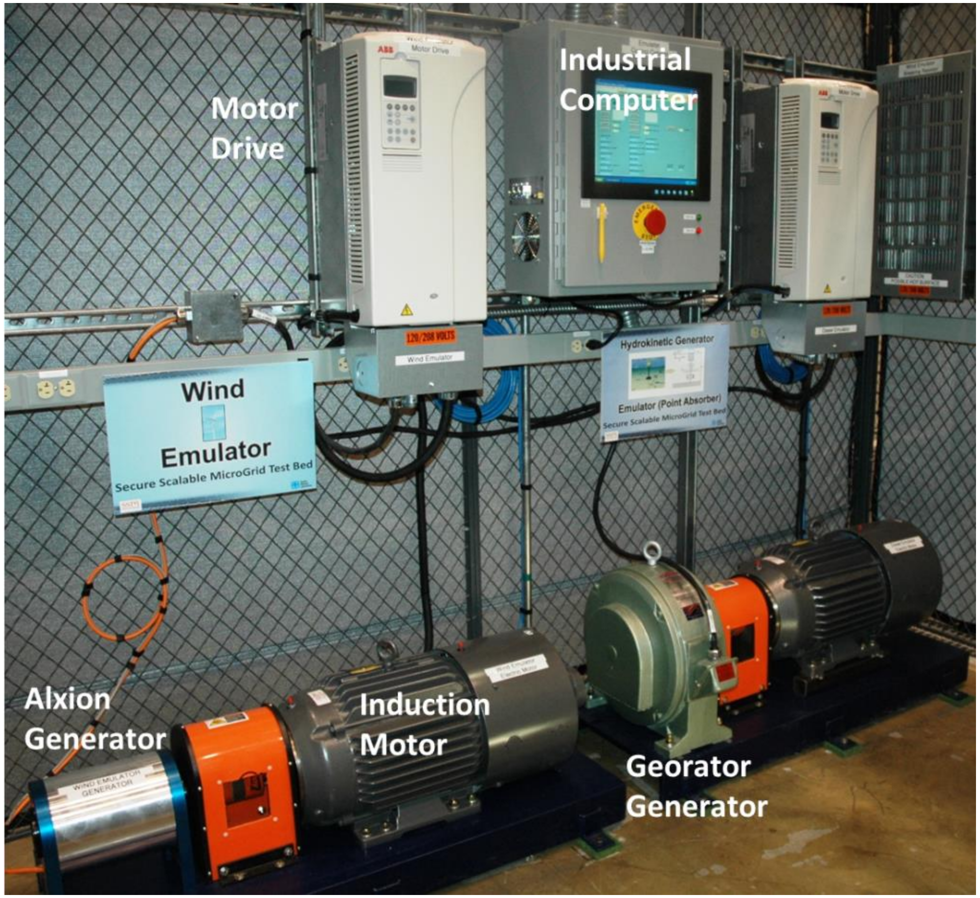


Diesel Engine

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

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

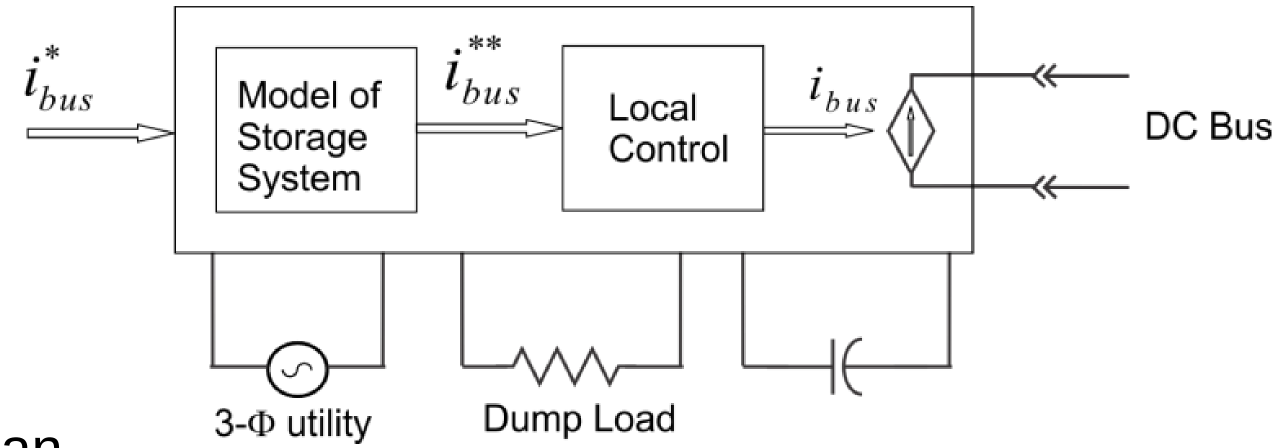




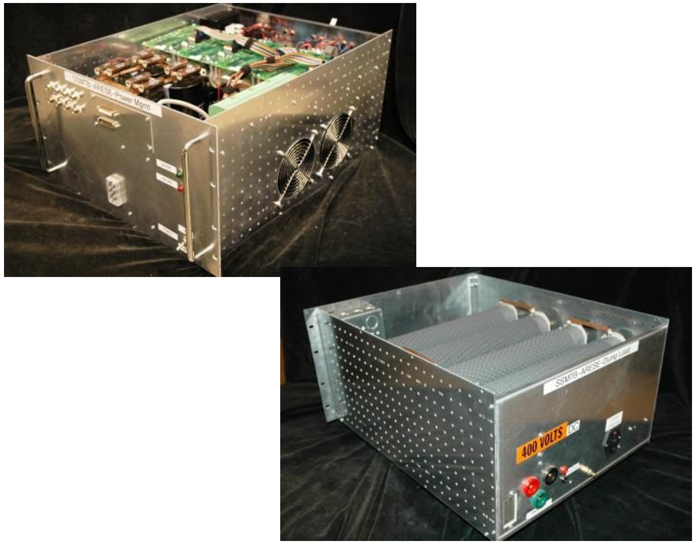
SSM Testbed Includes Energy Storage Emulation

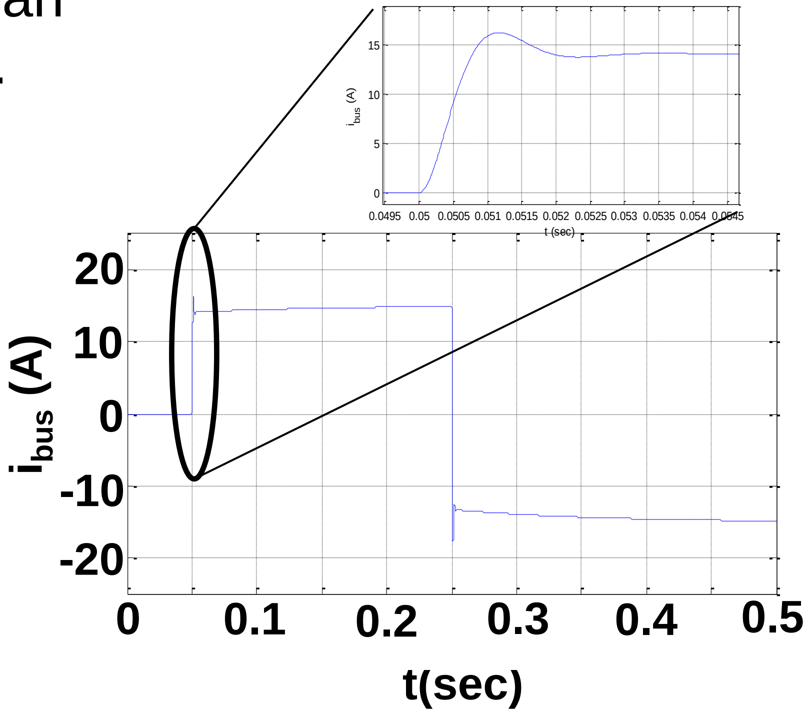
Energy storage can change from experiment to experiment

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



Higher level control systems can set storage reference points.

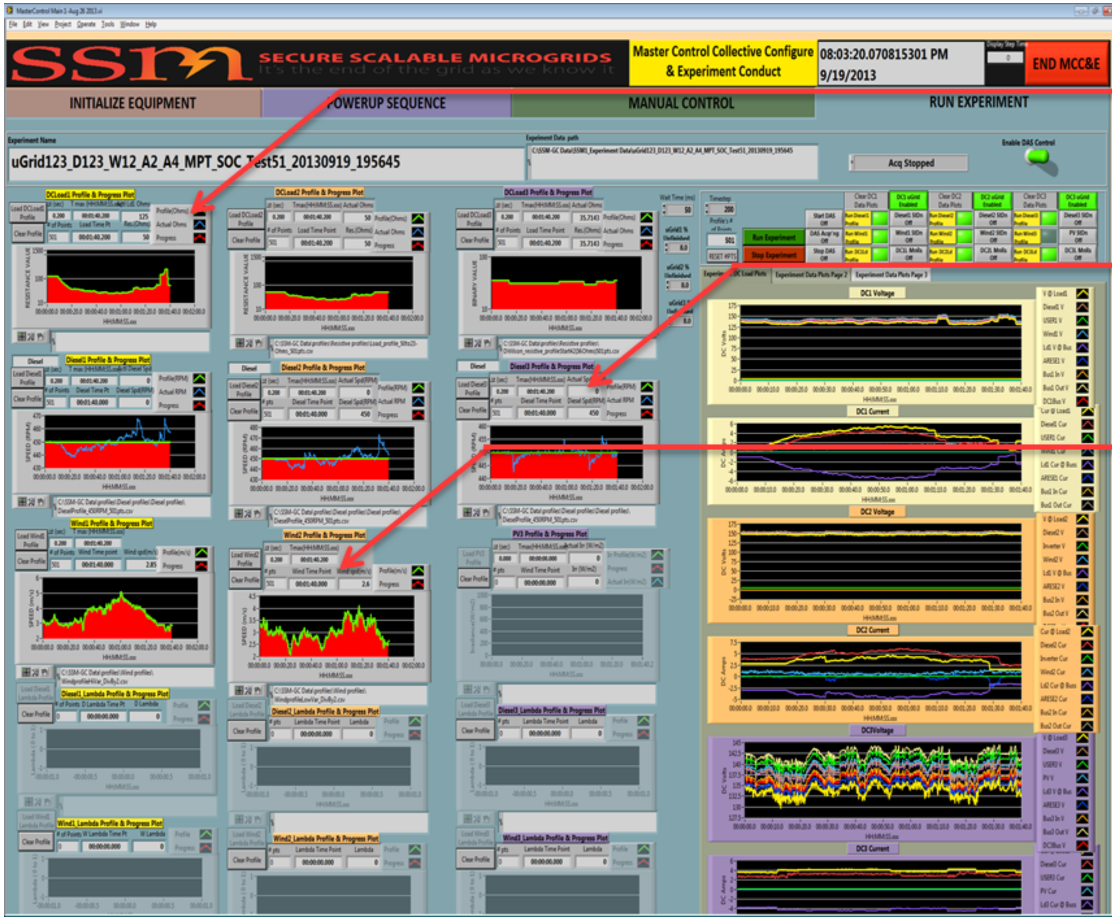




$$BW \approx \frac{0.35}{T_{rise}} \approx 583\,\mathrm{Hz}$$

Testbed Enables Automated "Batch-run" Experiments for Apples-to-Apples Control Comparison

- Same experiment described by load and generation profiles may be repeated with changes to control approach and performance evaluated



Microgrid 1 Load (Ω)

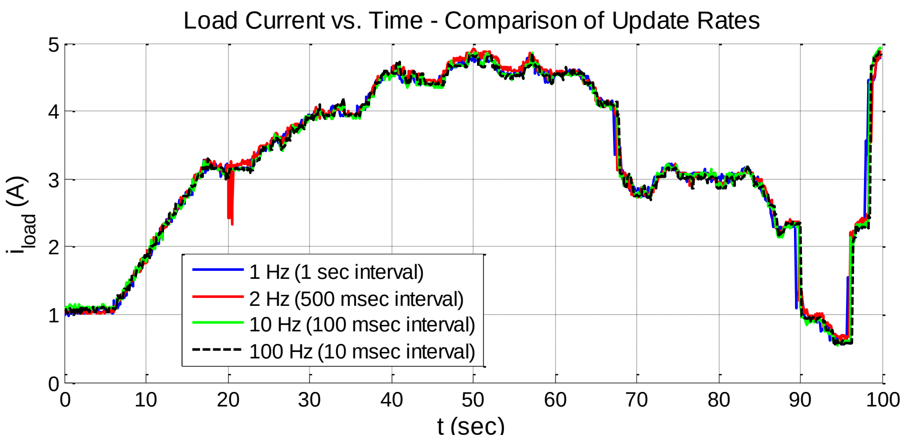
Microgrid 3 Diesel Engine speed (RPM)

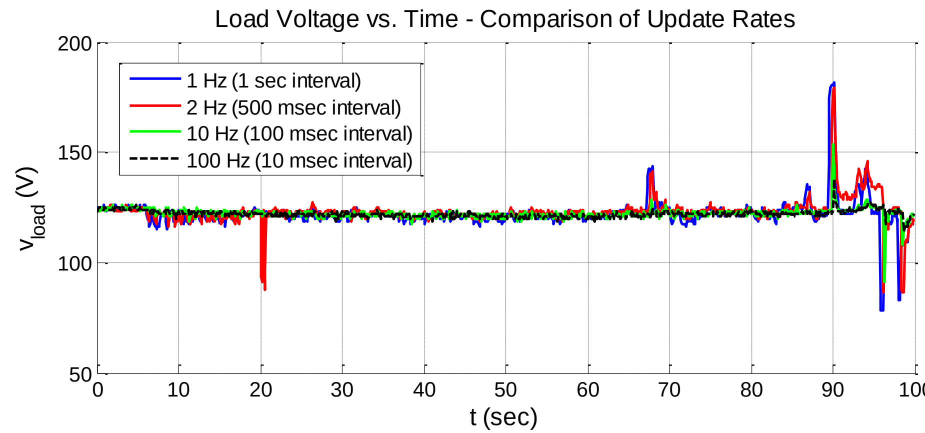
Microgrid 2 Wind speed (m/sec)

Realtime bus voltage and current plotting

Testbed Enables Automated "Batch-run" Experiments for Apples-to-Apples Control Comparison

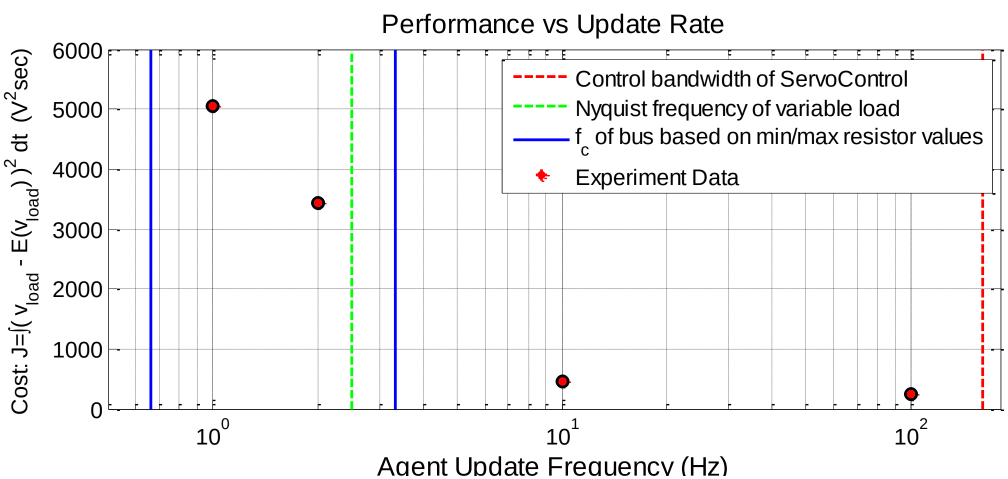
- **Example:**
  - **Effect of Informatic Control Update Rate on Cost**

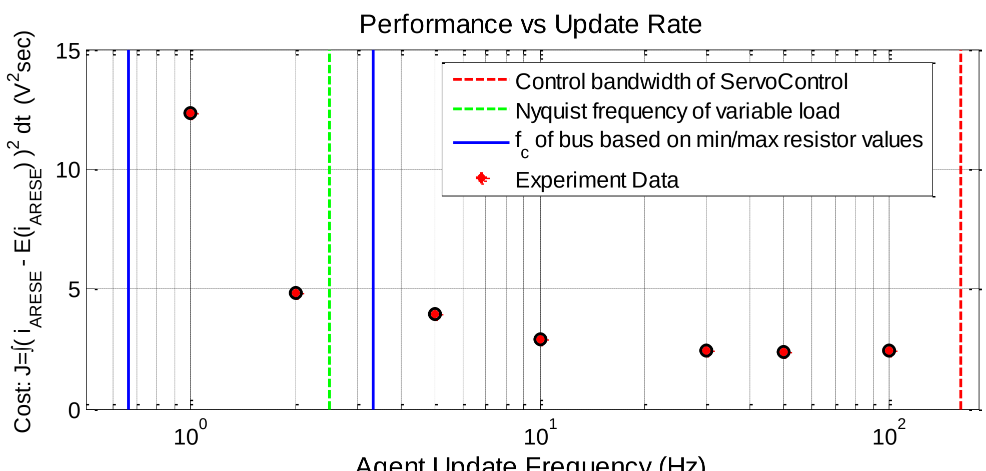




$$J_v(t_f) = \int_{t_0}^{t_f} \left(v_{load}(\tau) - \hat{v}_{load}(\tau)\right)^2 d\tau$$

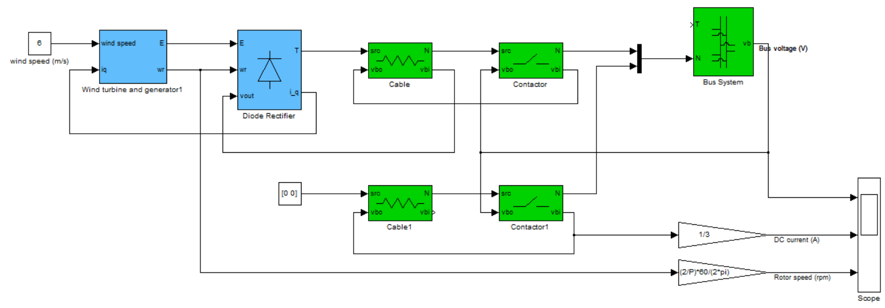
$$J_i(t_f) = \int_{t_0}^{t_f} \left(i_{ES}(\tau) - \hat{i}_{ES}(\tau)\right)^2 d\tau$$

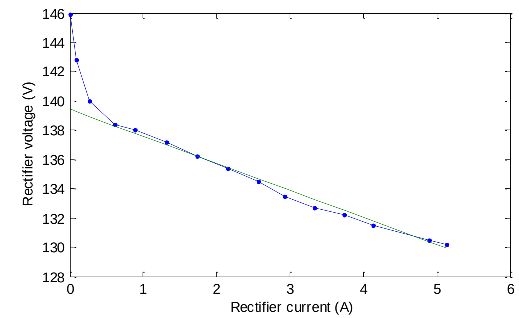




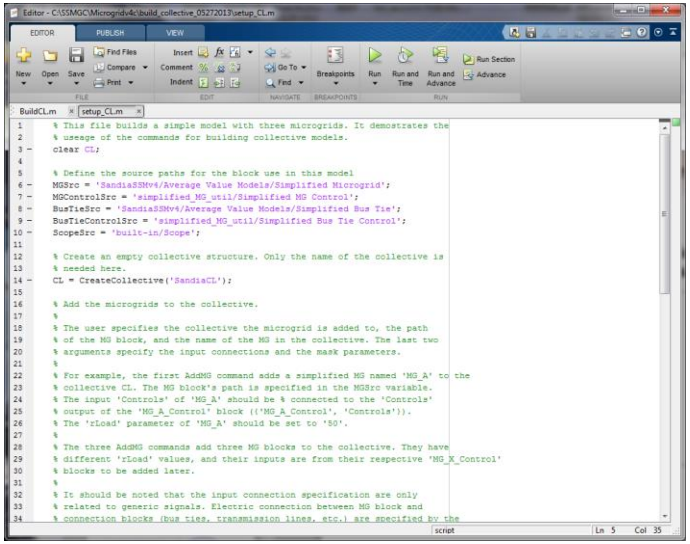
All Hardware Components are Represented in a Matlab/Simulink Library

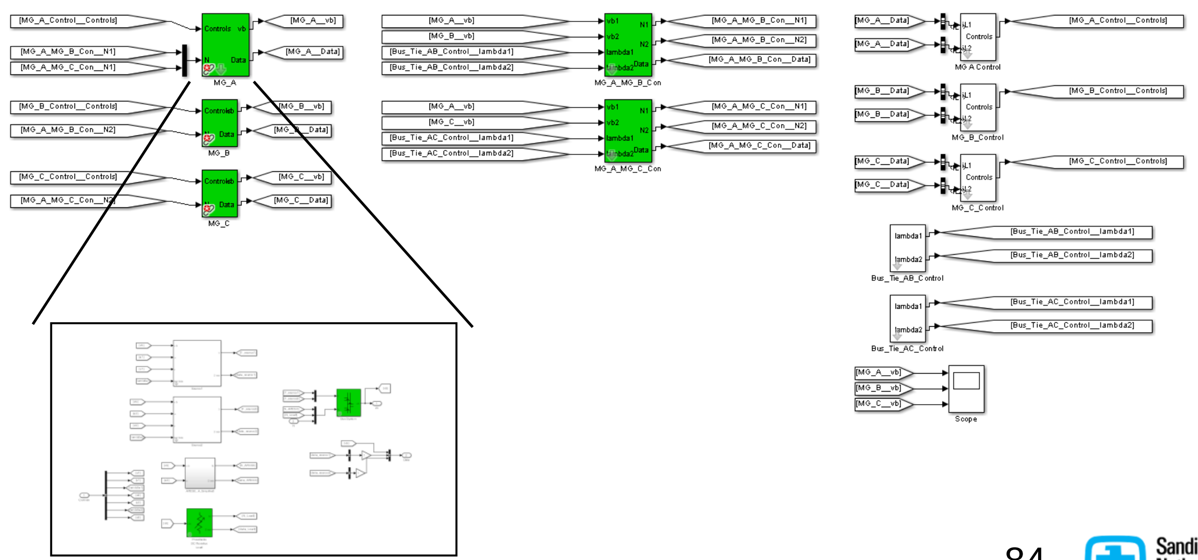
- **System components are modeled and calibrated to lab hardware**





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





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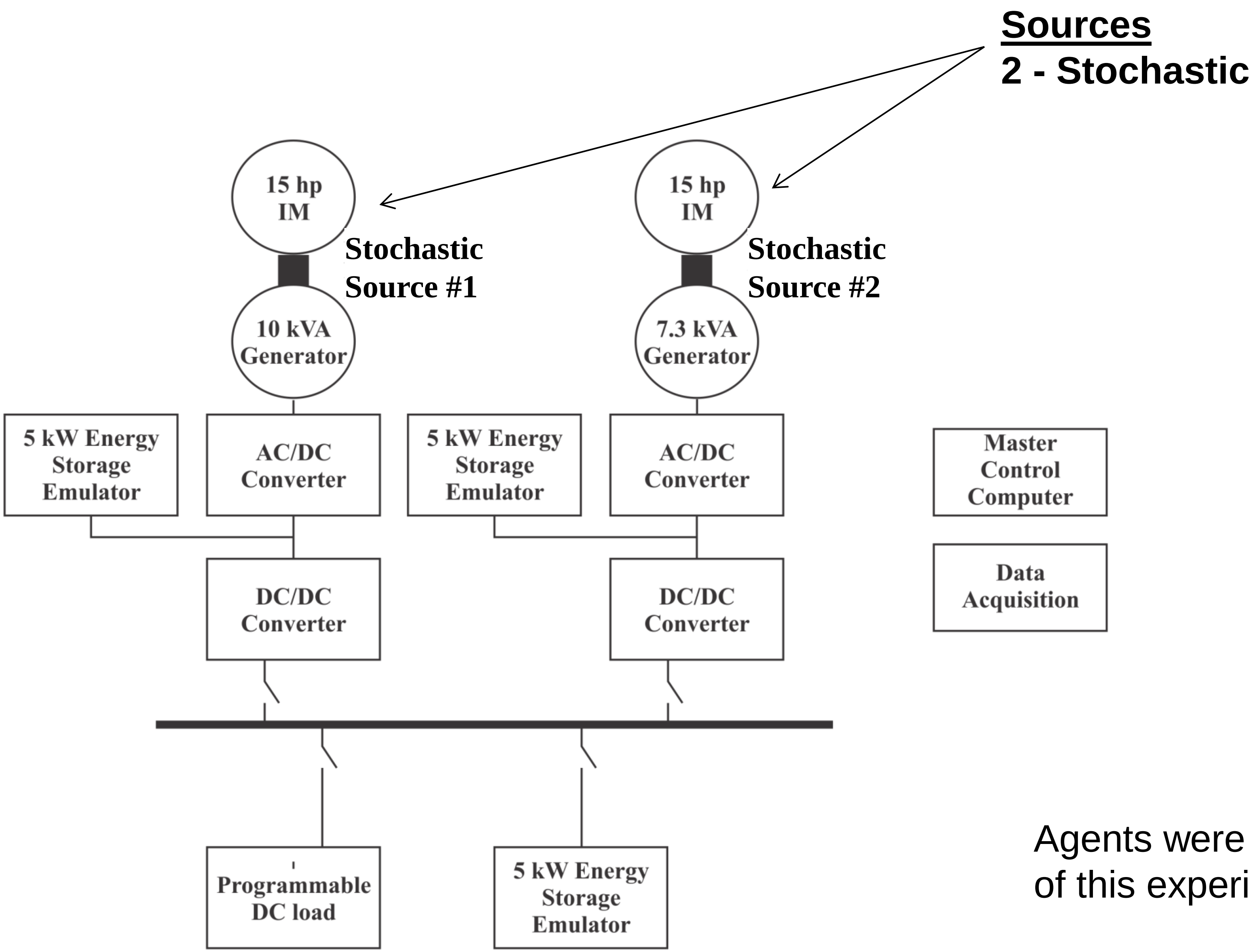
Demonstrated Performance with 100% Stochastic Generation and Load is Enabled Through Controls and Storage

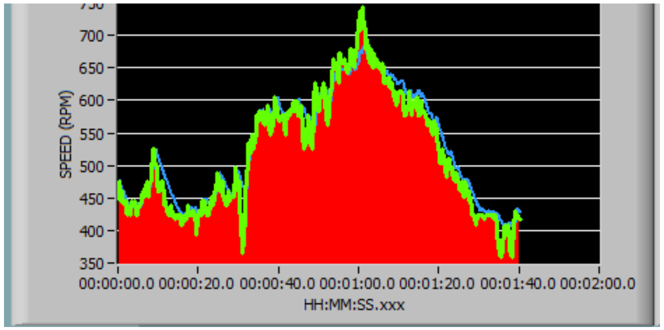


Agents were not part of this experiment.

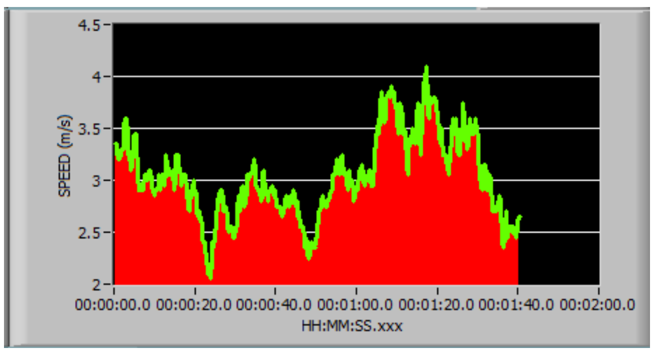
Hamiltonian Based Control Approach with Full State Control – Reduces Bus Voltage Transients

Source and load profiles

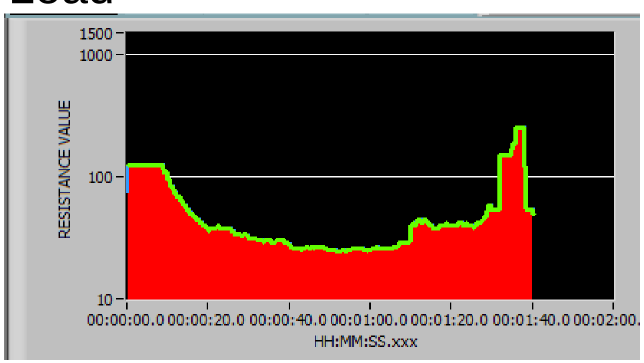
Stochastic source #1



Stochastic source # 2

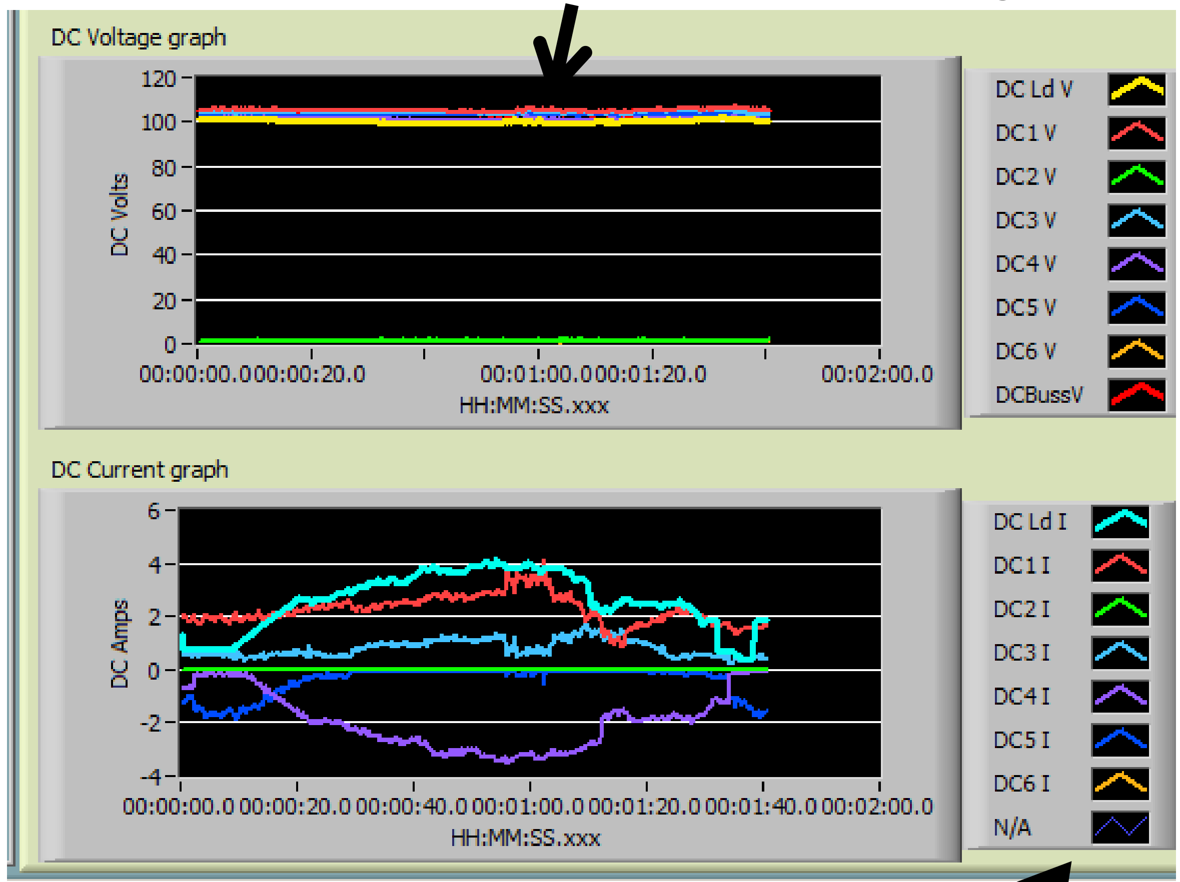


Load



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

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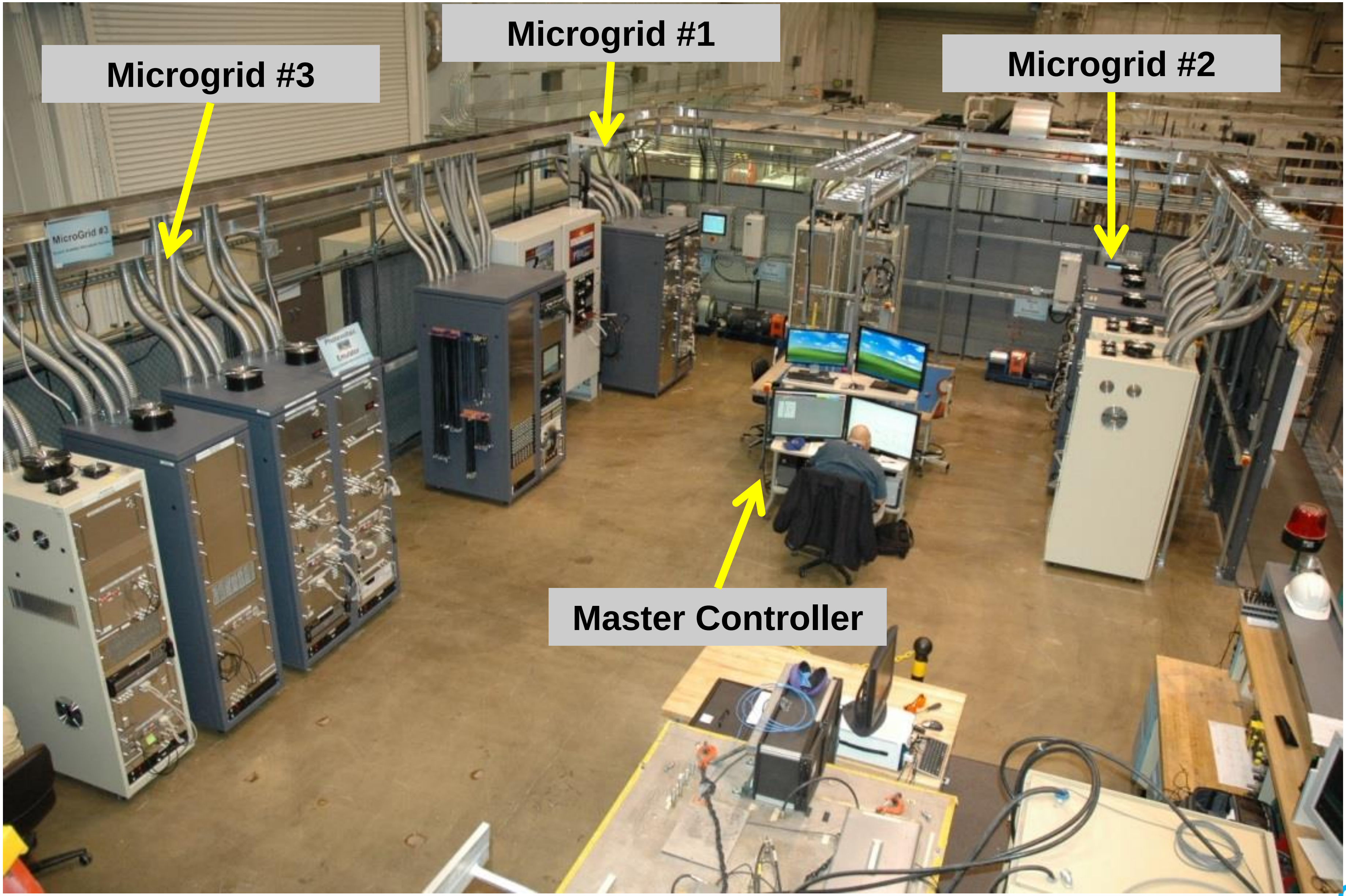
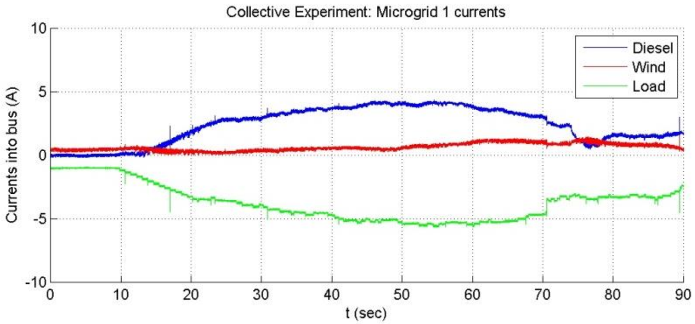
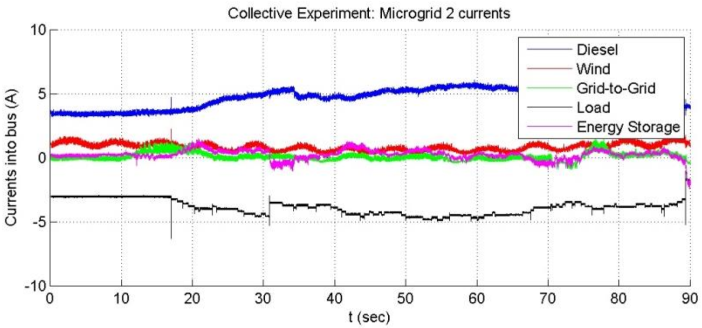
Networked Microgrids can add to Power System Reliability and Resiliency

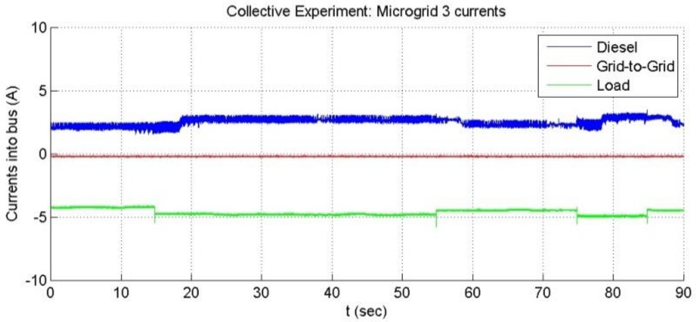


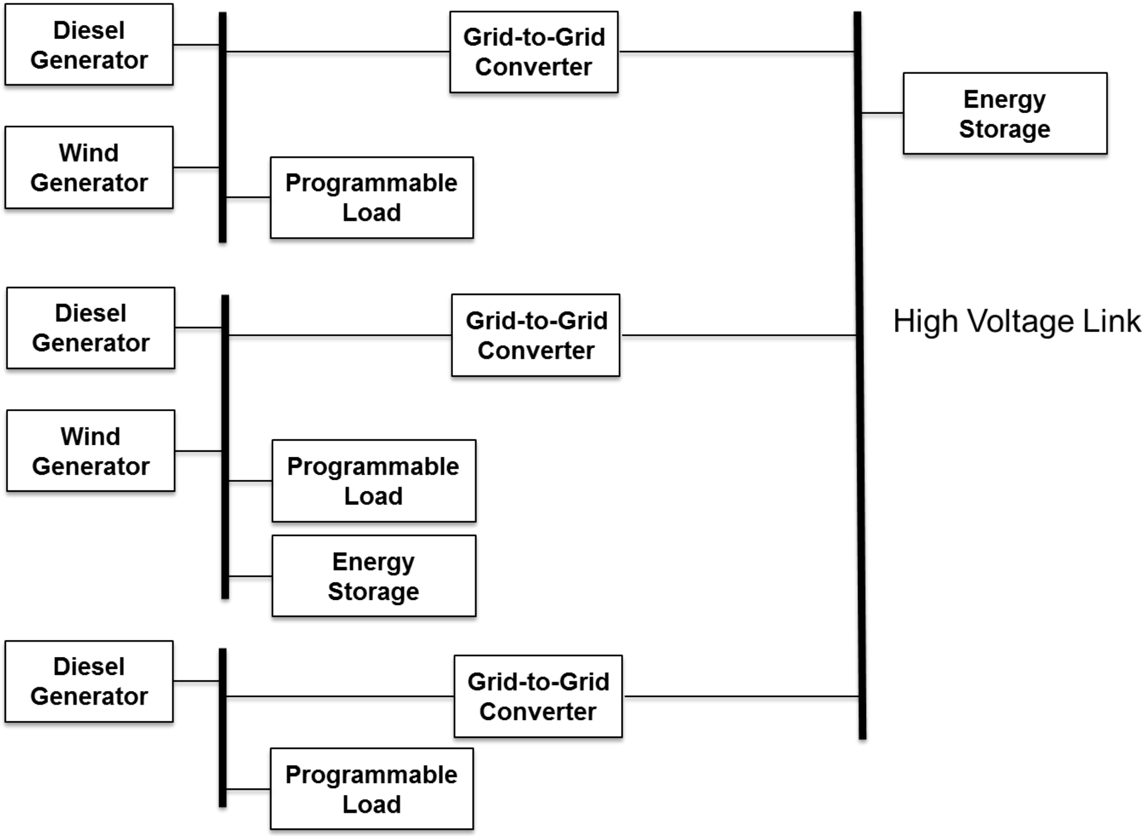
SSM Testbed Allows Study of Microgrid Collectives

- **Centralized data acquisition allows plotting/analysis in Matlab**









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8:00	30 min	SSM test bed and capabilities	Jason Neely	Offsite attendees will attend this portion of agenda via teleconference / web meeting
8:30	30 min	Project plan and objectives	Dave Wilson	
9:00	60 min	Round table project discussion	All	
10:00	60 min	SSM test bed tour	All	
11:00		Adjourn/Departure		

Project Plan and Objectives
&
Roundtable Discussion

David Wilson

Water Power and Controls Technologies

Sandia National Laboratories

Albuquerque, NM 87185

Sandia National Laboratories

PMS 320 & Sandia Project Goal / Scope

The goal of this project is to deliver innovative technologies that enable advanced power and energy storage systems that result in discriminating future naval warship capabilities.

Focus will be on control, design, and analysis techniques evolved from the Sandia National Laboratories Secure Scalable Microgrid research.

Control design and analysis high-level steps

- Identify Point-of-Departure reference IPS MVDC warship scenario
- Critical input profiles (generators)
- High power load profiles (railguns, etc.)
- Necessary dynamic microgrid components
- HSSPFC control design and analysis
- Optimization scenarios
- Determine energy storage requirements
- Validate: real-time simulator, SSM testbed

PMS 320 & Sandia Project High Level Plan

- **Create base line power system configuration**
  - **Obtain reference power system diagrams from NAVSEA with generation profiles**
  - **Obtain reference nonlinear and pulsed load specifications from NAVSEA with load profiles**
  - **Obtain reference conventional load specifications and profiles from NAVSEA**
  - **Obtain performance constraints from NAVSEA**
  - **Define the base line microgrid test bed configuration utilizing reference systems and existing test bed components**
  - **Identify critical scenarios based on NAVSEA input**
- **Create a simulation of the base line system from existing SSMTB models, simulations, and a new pulsed load**
  - **Create an average value model of the base line system**
  - **Create a reduced order model of the base line system Evaluate the FY14 plan and update**
  - **Update the FY14 plan based on the baseline system definition and NAVSEA**
- **Create a new load for the microgrid test bed based on the reference nonlinear and pulsed load descriptions**
  - **Design the hardware and software**
  - **Purchase hardware**
  - **Assemble load**
  - **Commission load**

PMS 320 & Sandia Project High Level Plan (continued)

- **Develop an advanced control approach for systems with pulsed loads targeting transient reduction and power balance**
  - **Hamiltonian based control design and analysis**
  - **Deliberative agent design**
  - **System control and storage optimization based on performance constraints and critical scenarios**

- **Experimental validation and control design refinement (will be updated following critical scenario definitions)**
  - **Safety review**
  - **Potential scenario: System with pulsed load but no storage**
  - **Potential scenario: System with pulsed load and with storage optimized for the load**
  - **Project management**
  - **Midproject report**
  - **Final report**

Project is planned to end in September of 2014. The Schedule is being revised to meet this date.

Original Schedule

Task	Date
Create base line power system configuration	
Obtain reference power system diagrams from NAVSEA with generation profiles	5/1/2013
Obtain reference nonlinear and pulsed load specifications from NAVSEA with load profiles	5/1/2013
Obtain reference conventional load specifications and profiles from NAVSEA	5/1/2013
Obtain performance constraints from NAVSEA	6/1/2013
Define the base line microgrid test bed configuration utilizing reference systems and existing test bed components	8/1/2013
Identify critical scenarios based on NAVSEA input	10/1/2013
Create a simulation of the base line system from existing SSMTB models, simulations, and a new pulsed load	
Create an average value model of the base line system	10/1/2013
Create a reduced order model of the base line system	11/1/2013
Evaluate the FY14 plan and update	
Update the FY14 plan based on the baseline system definition and NAVSEA	11/1/2013
Create a new load for the microgrid test bed based on the reference nonlinear and pulsed load descriptions	
Design the hardware and software	12/1/2013
Purchase hardware	3/1/2014
Assemble load	3/1/2014
Commission load	4/1/2014
Develop an advanced control approach for systems with pulsed loads targeting transient reduction and power balance	
Hamiltonian based control design and analysis	6/1/2014
Deliberative agent design	6/1/2014
System control and storage optimization based on performance constraints and critical scenarios	9/1/2014
Experimental validation and control design refinement (will be updated following critical scenario definitions)	
Safety review	4/1/2014
Potential scenario: System with pulsed load but no storage	7/1/2014
Potential scenario: System with pulsed load and with storage optimized for the load	9/1/2014
Project management	
Project management	9/20/2014
Midproject report	10/1/2014
Final report	9/20/2014

	2013										2014								
	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
MONTHLY TOTALS	9.91	12.63	4.47	14.02	23.52	31.25	36.43	70.64	51.68	45.87	28.55	53.08	63.84	34.48	77.62	53.04	35.47	35.47	17.90

- **Anticipated project start date of March 2013**
- **Planned project end date of September 2014**
- **Duration of 19 months**

Condensed Schedule & Monthly Spend Plan

Task	Date	2013 Oct	Nov	Dec	2014 Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
Create base line power system configuration													
Obtain reference power system diagrams from NAVSEA	5/1/2013												
Obtain reference nonlinear and pulsed load specifications	5/1/2013												
Obtain reference conventional load specifications and pro	5/1/2013												
Obtain performance constraints from NAVSEA	6/1/2013												
Define the base line microgrid test bed configuration utiliz	8/1/2013												
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Create a new load for the microgrid test bed based on the reference nonlinear and pulsed load descriptions													
Design the hardware and software	12/1/2013												
Purchase hardware	3/1/2014												
Assemble load	3/1/2014												
Commission load	4/1/2014												
Develop an advanced control approach for systems with pulsed loads targeting transient reduction and power balance													
Hamiltonian based control design and analysis	6/1/2014												
Deliberative agent design	6/1/2014												
System control and storage optimization based on perfor	9/1/2014												
Experimental validation and control design refinement (will be updated following critical scenario definitions)													
Safety review	4/1/2014												
Potential scenario: System with pulsed load but no stora	7/1/2014												
Potential scenario: System with pulsed load and with sto	9/1/2014												
Project management													
Project management	9/20/2014												
Midproject report	10/1/2014												
Final report	9/20/2014												

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
MONTHLY TOTALS ($k)	18.07	8.93	26.30	30.25	51.13	119.78	74.74	52.76	98.33	130.66	70.95	17.90

- **Contract start date of Sept / Oct 2013**
- **Effective start date of Dec. 2013**
- **Planned project end date of September 2014**
- **Effective duration of 10 months**

Proposed Schedule & Monthly Spend Plan

Task	Date
Create base line power system configuration	
Obtain reference power system diagrams from NAVSEA	5/1/2013
Obtain reference nonlinear and pulsed load specifications	5/1/2013
Obtain reference conventional load specifications and pro	5/1/2013
Obtain performance constraints from NAVSEA	6/1/2013
Define the base line microgrid test bed configuration utiliz	8/1/2013
Identify critical scenarios based on NAVSEA input	10/1/2013
Create a simulation of the base line system from existing SSMTB models, simulations, and a new pulsed load	
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Create a new load for the microgrid test bed based on the reference nonlinear and pulsed load descriptions	
Design the hardware and software	12/1/2013
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Develop an advanced control approach for systems with pulsed loads targeting transient reduction and power balance	
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Potential scenario: System with pulsed load and with sto	9/1/2014
Project management	
Project management	9/20/2014
Midproject report	10/1/2014
Final report	9/20/2014

	2013 Oct	2013 Nov	2013 Dec	2014 Jan	2014 Feb	2014 Mar	2014 Apr	2014 May	2014 Jun	2014 Jul	2014 Aug	2014 Sept	2014 Oct	2014 Nov	2014 Dec	Jan
MONTHLY TOTALS ($k)	19.82	8.93	35.80	70.13	68.11	51.68	45.87	28.55	53.08	63.84	34.48	77.62	53.04	35.47	35.47	17.90

- **Contract start date of Sept / Oct 2013**
- **Effective start date of Dec. 2013**
- **Proposed project end date of Jan 2015**
- **Effective duration of 14 months**

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Deliverables

- Safety review
- Monthly status reports by the 10th of each month
- Attend the next US & UK project agreement meeting
- Mid-project report
- Final report

Risks - Technical

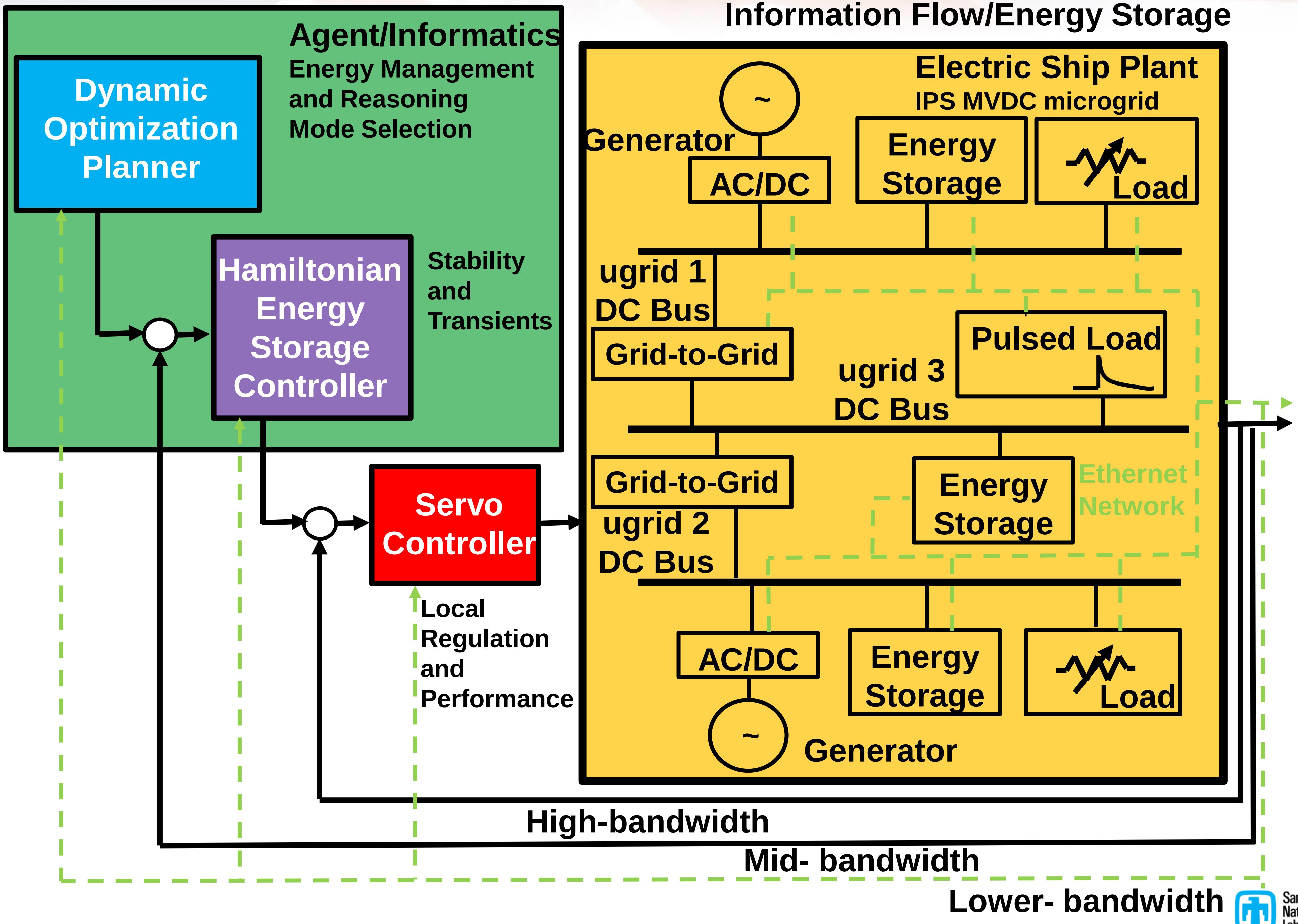
- **Assuring that the test bed configuration is consistent with the NAVSEA view of future advanced power systems**
  - **Request decision on the proposed architecture.**
- **Assuring that the proposed pulsed load is representative of the NAVSEA predictions**
  - **Request review of the proposed load.**
- **Control and system energy storage is found to be insufficient for mitigating system transients during pulsed load operation.**
  - **Alternative control and energy storage structures will be considered and proposed**
  - **An unstable control design for power systems has been conceptually developed, this is similar to fighter plane control concepts**
- **Hybrid power system design may be optimal for Navy systems**
  - **This work will**

Risks - Programmatic

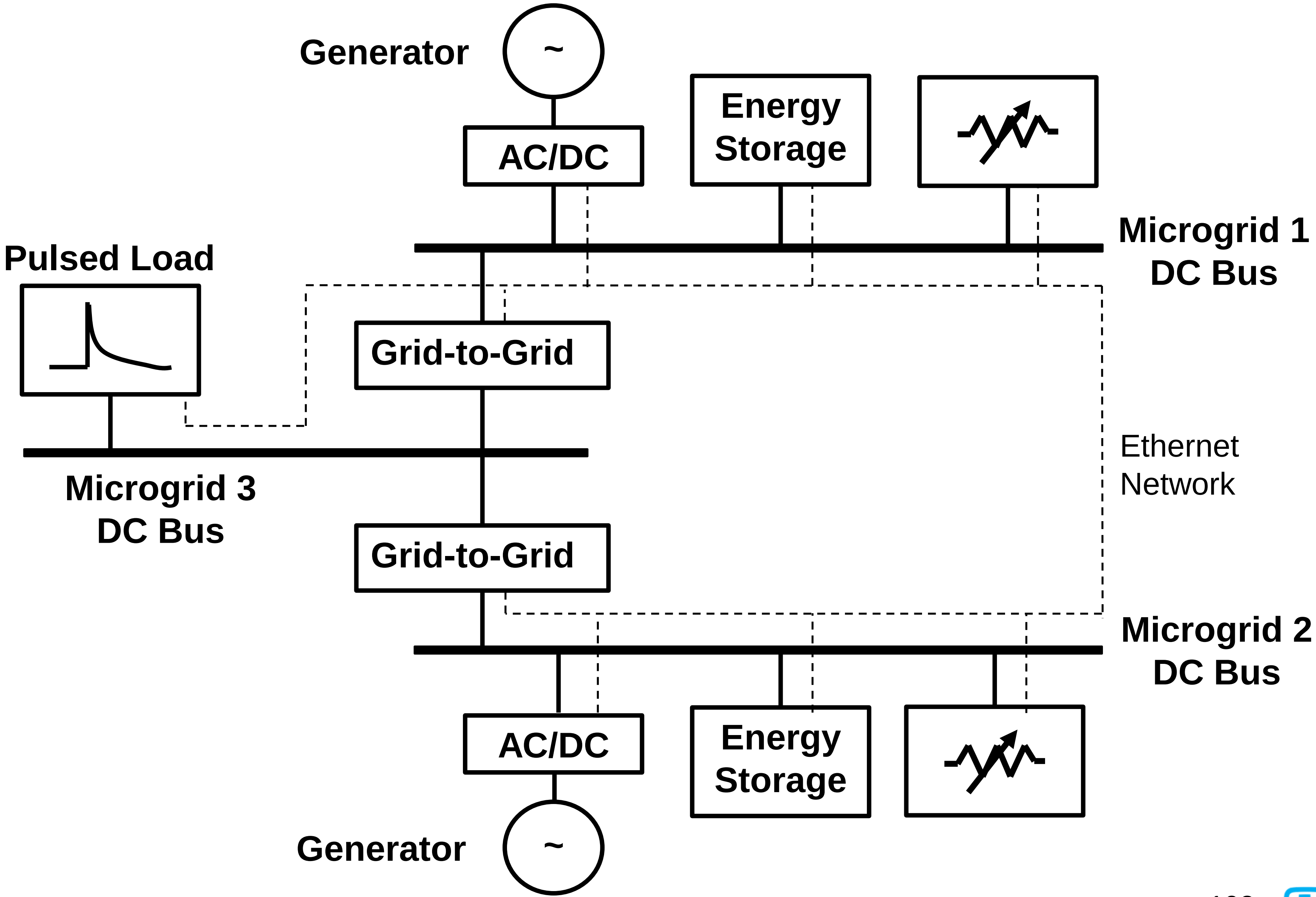
- **Late start to the project**
  - **Schedule and resources will be revised once the base line power system architecture and pulsed load are determined acceptable.**
- **Working with restricted information**
  - **Engage with NAVSEA to ensure document markings are correct.**
- **Technologies are not advanced at a rate that is suitable for NAVSEA application needs.**
  - **Schedules and applications will be discussed early to identify any potential gaps.**
  - **Need to identify the NAVSEA point of contact and horizon for movement to application**
    - » **Assumptions: Dr. Timothy McCoy and ten plus years**

Auto Pilot/ Auto Commander

Tertiary Level Control Design
Information Flow/Energy Storage



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



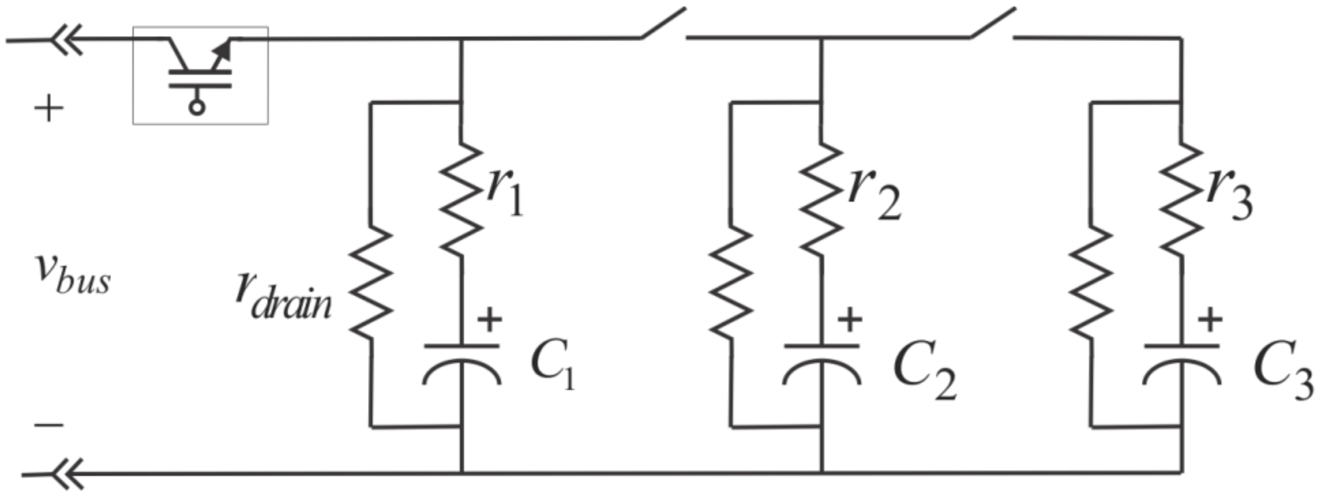
Similar to: Milestone I Decision Advanced Electric Power and Propulsion Project, page A-2

Testbed Includes Several Power Electronic Components

- **Proposed Pulsed Load**
  - **Parallel connected RC networks allow the pulse to be adjusted**

$$\max i_{pulse} = \frac{v_{bus}}{r_1 \| r_2 \| r_3}$$

$$E_{pulse} = \frac{1}{2}\left(C_1 + C_2 + C_3\right) v_{bus}^2$$

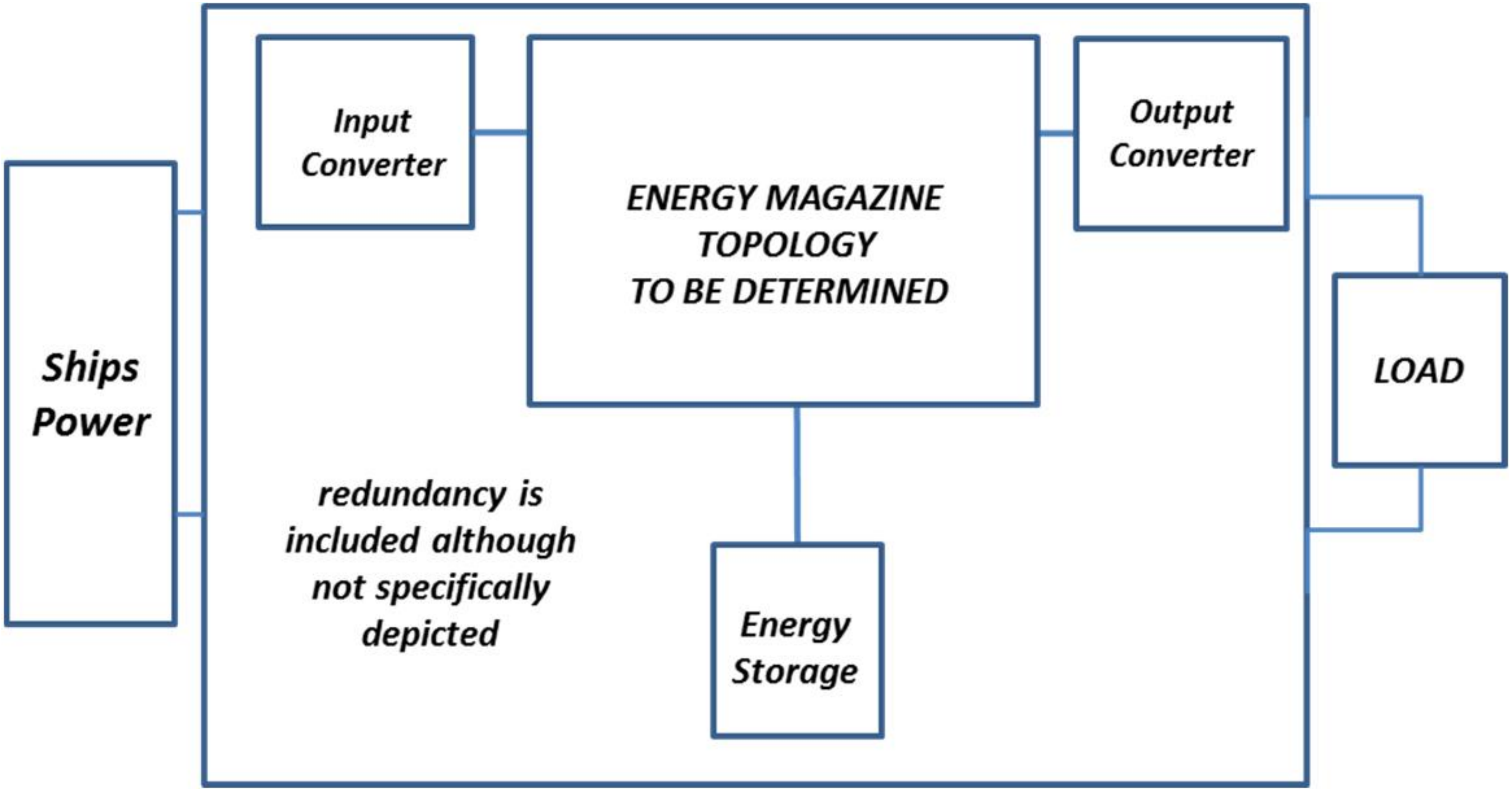


Round table questions

- How does the project feed into the larger program?
- How will research move into application?
  - Can we engage with key people early?
- Are there others outside this immediate group that we should be reaching out to?
- Discuss the power system definition
  - Desired architecture
  - Desired load profile
- Control problem / scenario
- Identify required and desired reporting
  - Monthly by the 10th.
- Publications and conferences (may be funding limited)
- When do you want the UK markings on documents and slides?
  - UNCLASSIFIED//REL TO USA,GBR//AEP3 Project Arrangement
- Others ?

Round table discussions
Energy Magazine – Design Optimization Options

- **Map technology to …**



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BACK UP

Auto Pilot/ Auto Commander

- **Control design architecture with 3-levels of control embedded with respective information updates**
- **Modes of operation**
- **Unstable Controller**
- **AC/DC hybrids**