SAND2013-8615C

Secure and Scalable Microgrids

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Secure and Scalable Microgrids Grand Challenge

Sandia National Laboratories
Albuquerque, NM 87185

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.

Outline

- Overview of electrical science and electromagnetics activities and capabilities at Sandia
- DOE related microgrid activities
- Secure Scalable Microgrid Grand Challenge
- Q&A and discussion

Context and Discussion Goals

- **Sandia is a large multi-program national security laboratory**
  - A Department of Energy / National Nuclear Security Administration lab with a range of programs and sponsors
  - $2.4B annual budget; 10,000 employees (including over 1,700 PhDs)
- **Sandia has an active program in energy security and grid management**
  - Historically based in part on the need for high expertise on electromagnetic issues relating to safeguarding and certifying the nuclear stockpile.
- **Sandia has completed a strategic investment in novel microgrid controls**
  - One of a handful of "Grand Challenge" initiatives ongoing at Sandia
  - Several million dollars per year in dedicated research funding

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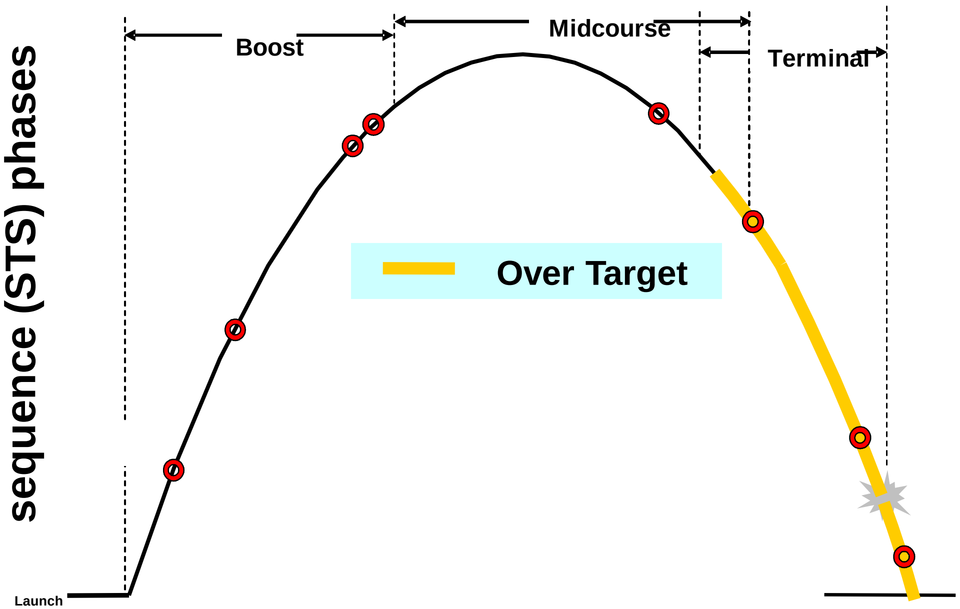
Nuclear Weapons Stockpile Responsibilities Drive Deep Expertise in Grid-relevant Science and Engineering

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

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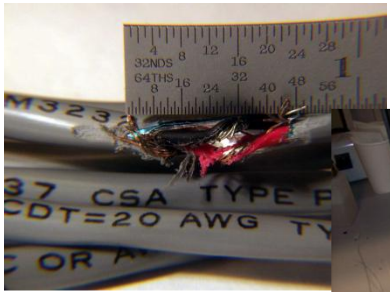
Electrical and Radiation Sciences
Customers and Organization and Facilities

National security activities for and in collaboration with:

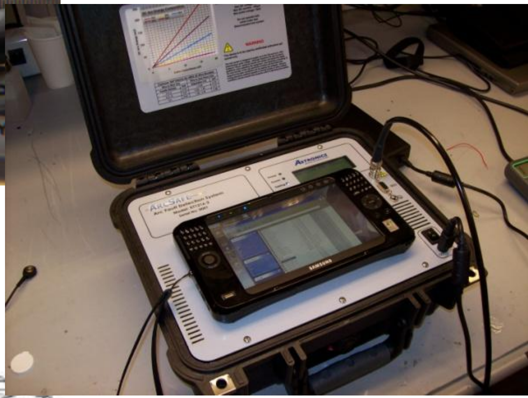
- **Department of Energy** (National Nuclear Security Administration, Office of Science, Office of Electricity)
- **Other federal agencies** (DOD-Army/USAF/NRL, DOT-Federal Aviation Administration, DOL – Mine Safety and Health Admin.)
- **Non-federal entities**
- **Industry** (Goodyear, FMC, Inc., Lockheed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

World class accelerator technology development & high heat flux research

EMP coupling into facilities

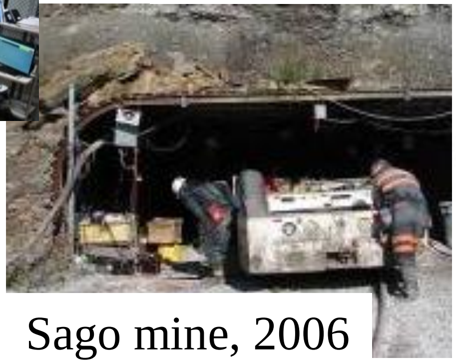


ASTRONICS CORPORATION

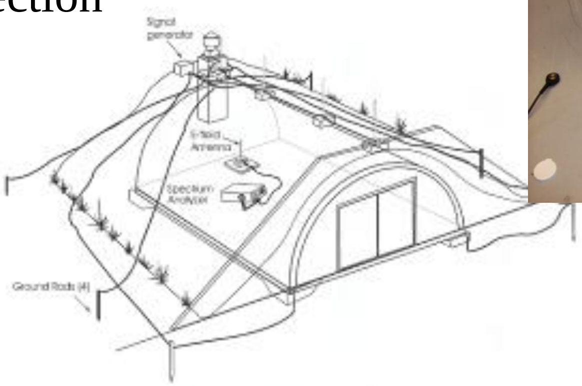


Power systems
All Electric Warship

Lightning protection



Sago mine, 2006



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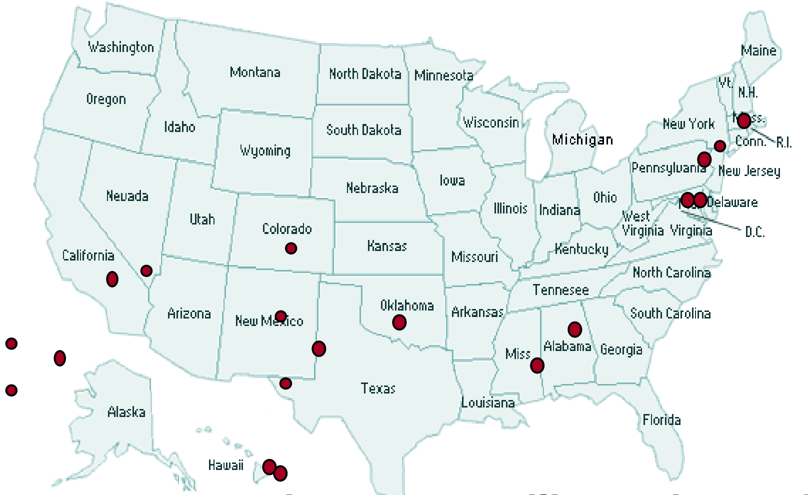
DOE/DoD Support for Advanced Energy Surety Microgrids (ESM) at Military Sites

Objective

To address current shortcomings of power reliability and security, Sandia is investigating advanced microgrid approaches to make distributed energy generation and storage resources more reliable, cost effective, and secure to improve overall critical mission assurance. Advanced microgrids can be designed to be equally applicable to military, industrial, and utility needs.



22 CONUS and OCONUS Military Site Designs

Funding Summary ($K)

	FY 09	FY10	FY11	FY12	FY13
DOE	700	1300	1500	800	500
DoD	200	500	500	600	500

Technical Scope

Sandia's microgrid research utilizes smart grid technologies to enable:

- **Distributed energy generation and storage to be operated both 'grid-tied and 'islanded',**
- **Energy demand/response to enhance overall cost effectiveness,**
- **Increased and enhanced use of renewables**
- **Secure cyber control,**
- **Improved energy reliability and resiliency, and**
- **Use DoD sites as initial test beds.**

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DOE and Utility R&D with Sandia ESM

Objective

Using lesson learned from military evaluations and implementations of advanced Energy Surety Microgrids (ESM), determine applicability of approach to commercial, industrial, and utility applications. Focus on providing higher energy reliability and resiliency to critical community and industrial infrastructure and operations for low probability but high consequence events (natural disasters, intentional events, or large accidents).

Projects

Past, Current, and Projected Projects include:

- NEDO research project with PNM
- Two Alaskan Villages - FY13
- Hoboken, NJ – currently underway
- NJ Transit Authority – currently underway
- NY City – FY14
- Metropolitan DC – FY 14
- Multiple small Mass. Communities – currently underway

Sandia Funding Summary ($K)

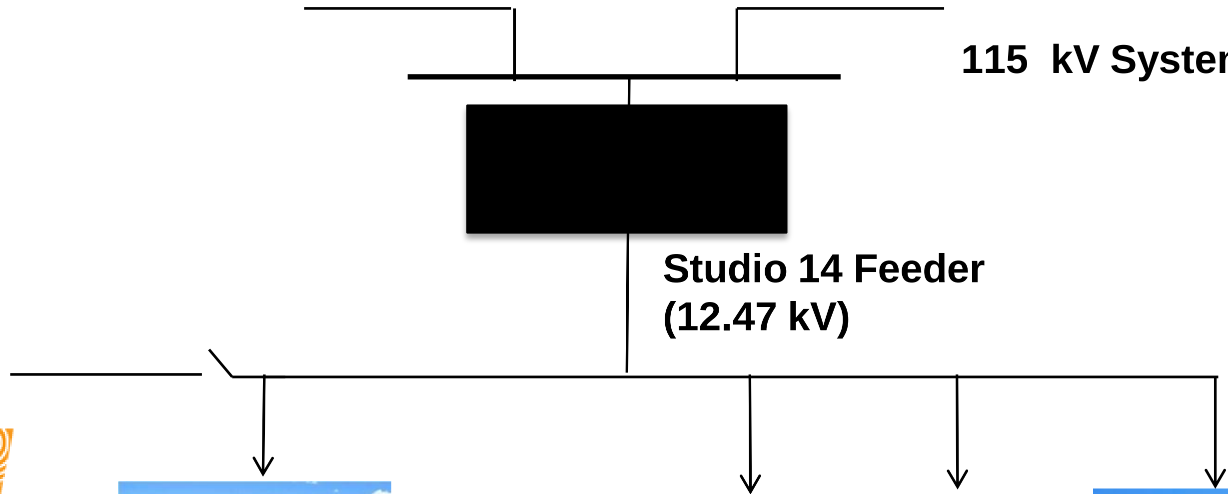
	FY 12	FY13	FY14 (Scheduled)
DOE	200	500	1300
Others		300	600

Technical Scope

Use Sandia's ESM approach developed to enhance energy safety, security, and reliability for military applications to civilian applications with a focus on:

- Providing energy resiliency using distributed generation to maintain critical community functions and operations for extended outages,
- Support demand/response of distributed community generation and storage to support local utility distribution system.

Example Community/Utility Coupled Microgrid Efforts



PNM Microgrid Project
- Large-scale PV (500 kW)
- Large-scale Storage
  - 250 kW 4 hr. energy battery
  - 500 kW, 40 min power battery
- Smart Grid / SCADA integration

NEDO Microgrid Project
- Energy storage (small)
- Gas Engine (240 kW)
- Fuel Cell (80 kW)
- PV (50 kW)
- Demand response?
  - 100 kW Dummy load
  - Electric Chiller/Thermal storage

Helping to accelerate Commercial Smart Grid Applications

- Overview of electrical science and electromagnetics activities and capabilities at Sandia
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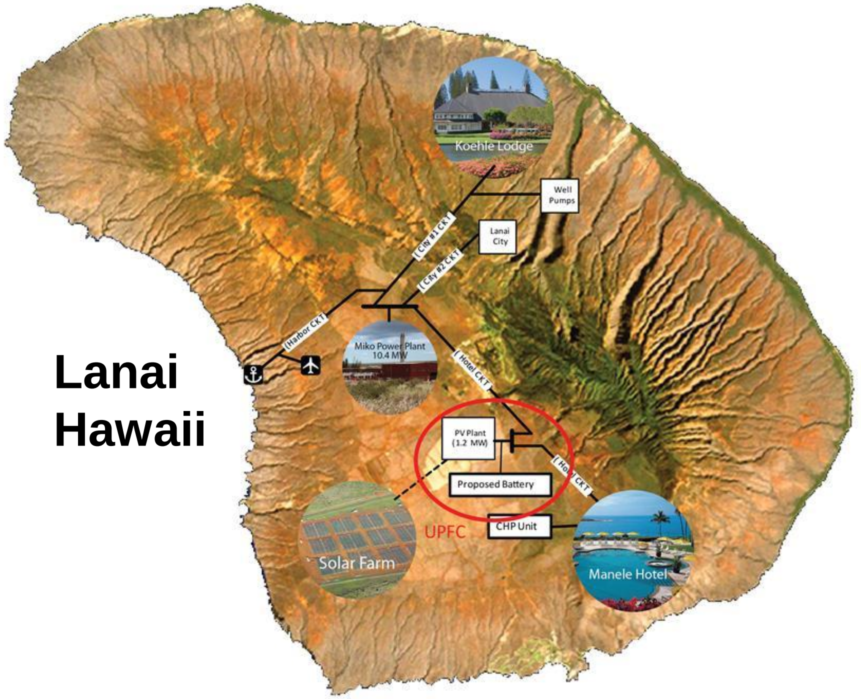
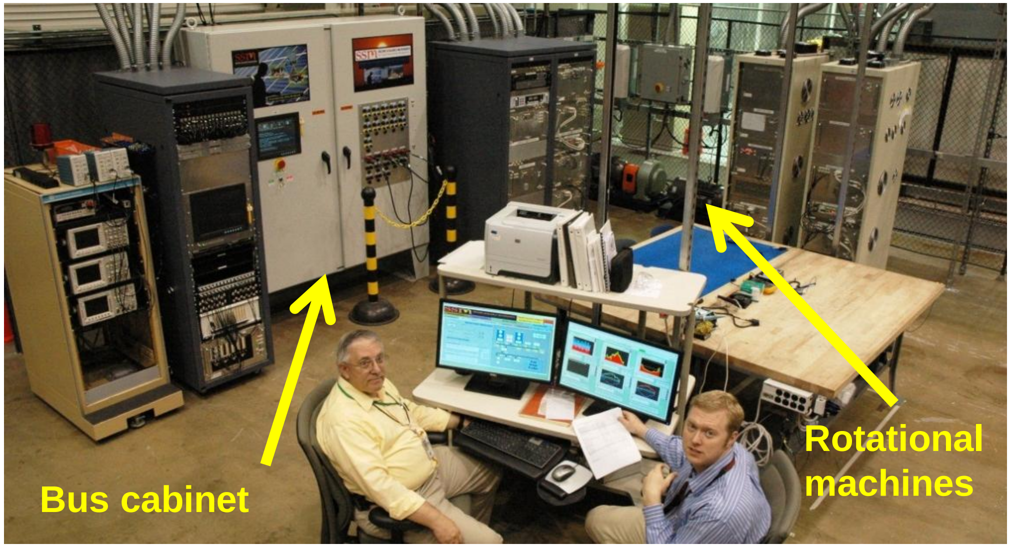
Networked, Secure, Scalable Microgrids (SSM™) Enable High-Penetration Renewables and Improved Operations

- 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**

Lanai Hawaii





SSM test bed

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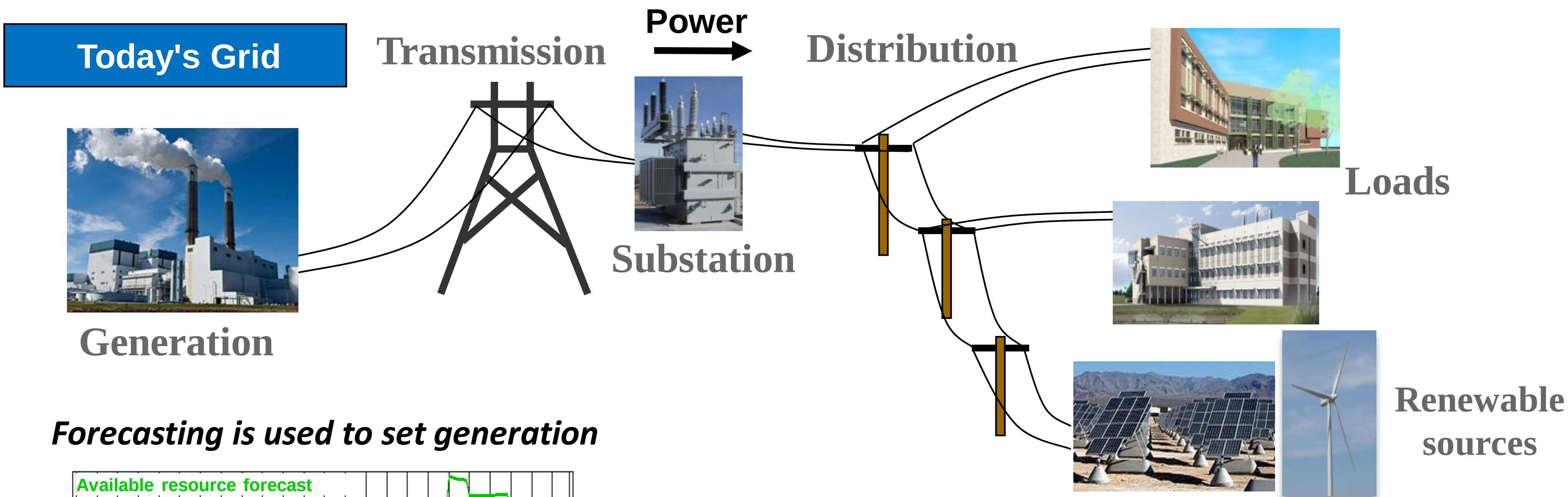
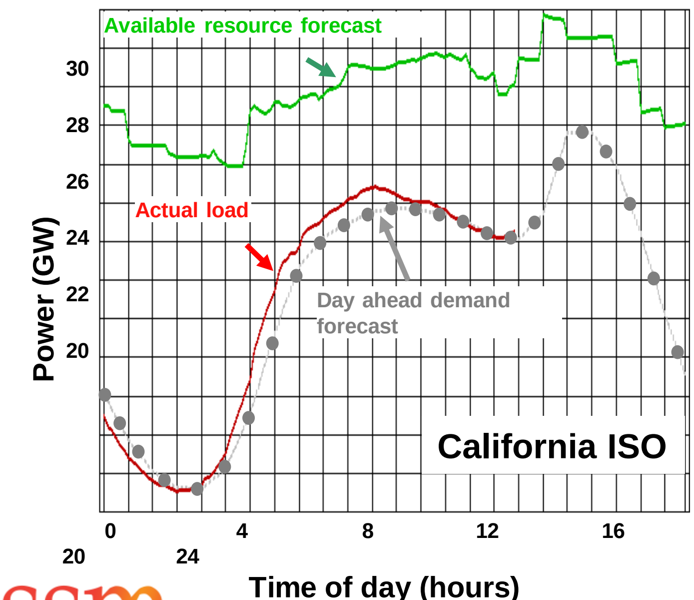
Current Grid will need to Evolve to Accommodate Different Energy Sources and Increase Reliability



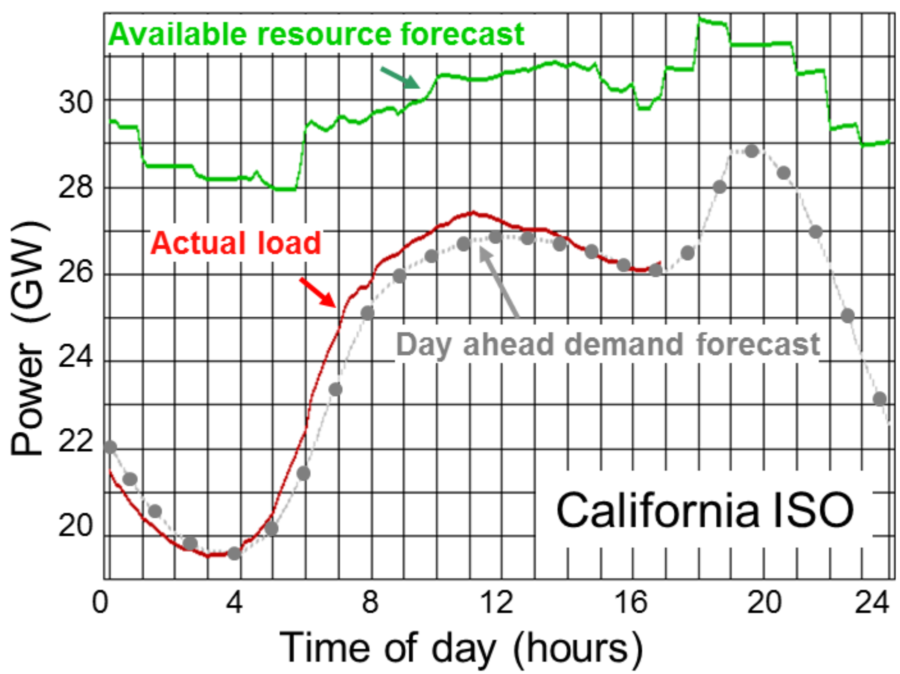
Forecasting is used to set generation



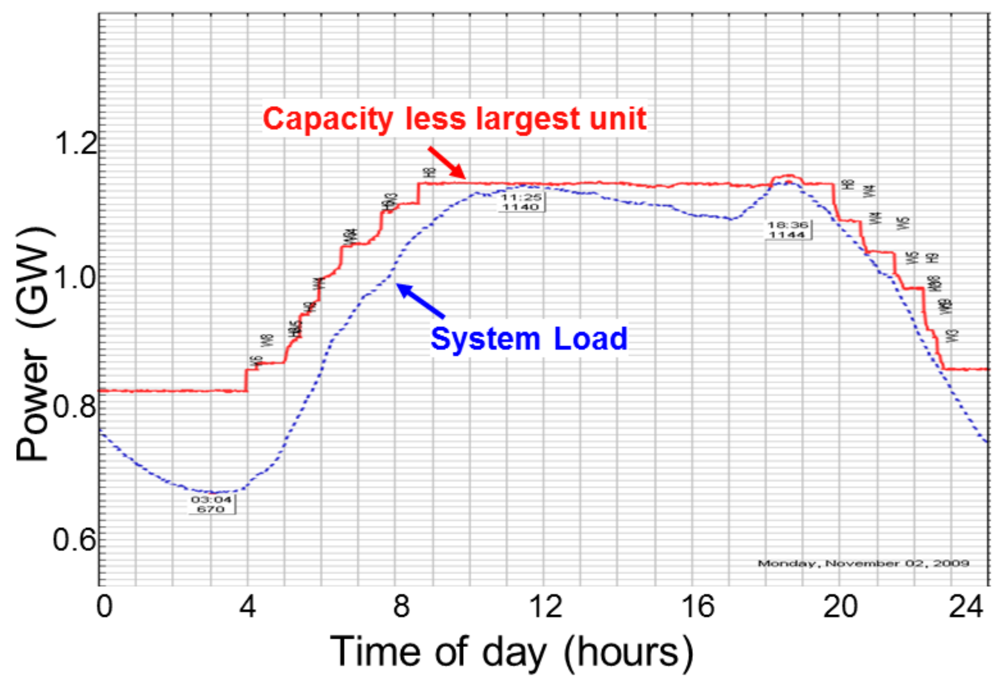
- Centralized generation
- Excess generation & fuel storage
- Fixed infrastructure
- Demand forecasting
- Essentially open loop control with human in the loop
- Limited ability to support renewable sources
- Limited ability to support disruptions
- Smart grid initiatives
- Desire for continued & increased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

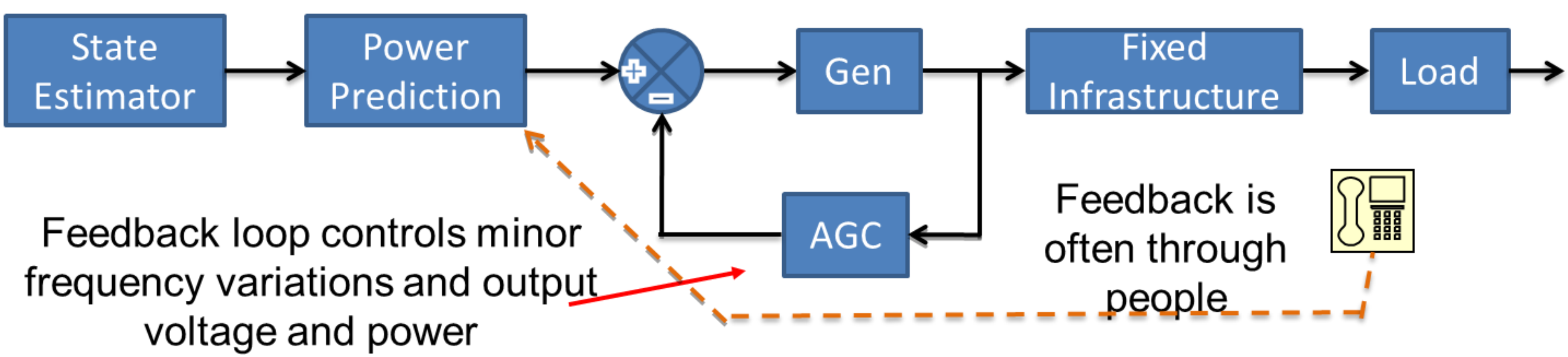
In Today's Grid Loads are Predictable and Generation is Dispatchable Allowing Essentially Open-loop Grid Control

Forecasting is used to set generation



Hawaiian Electric Co. daily load vs capacity





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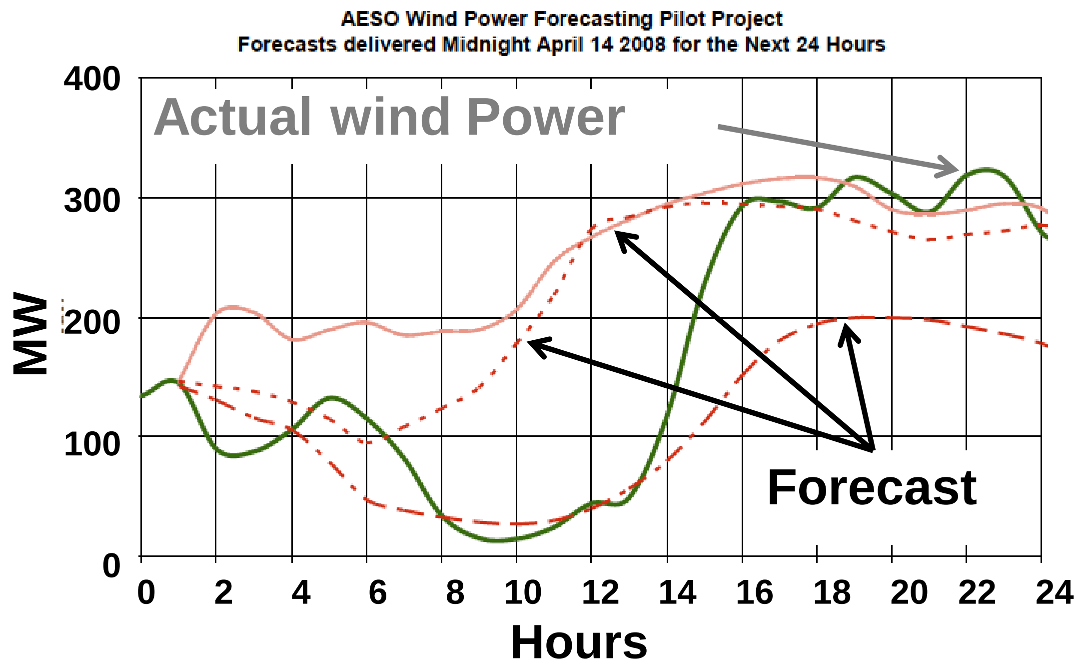
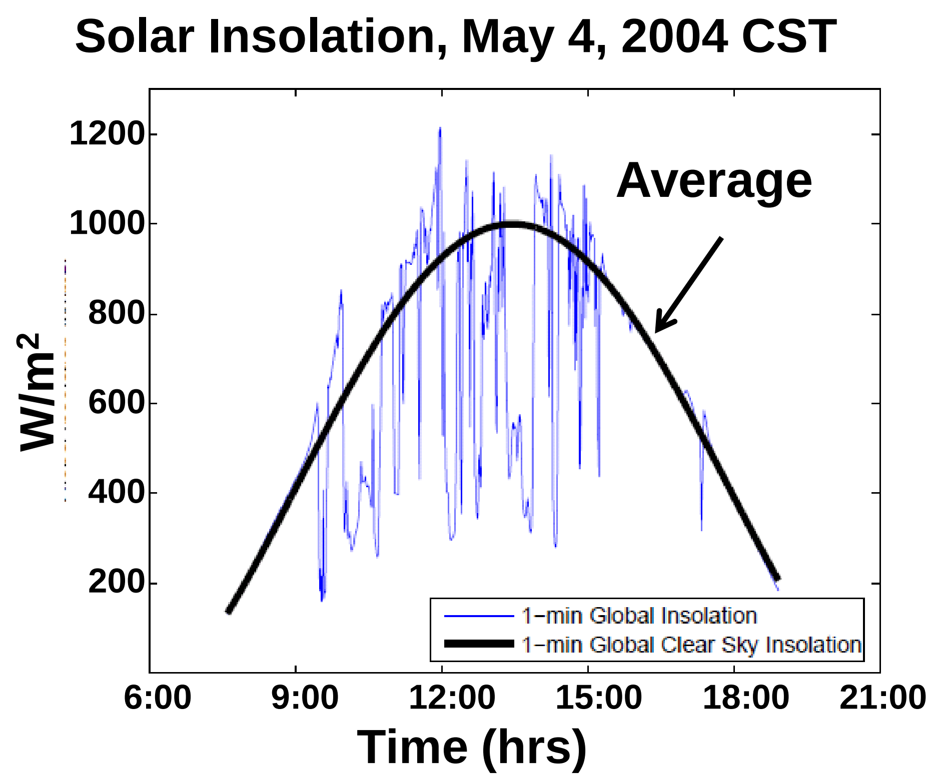
Stochastic Sources Complicate System Performance

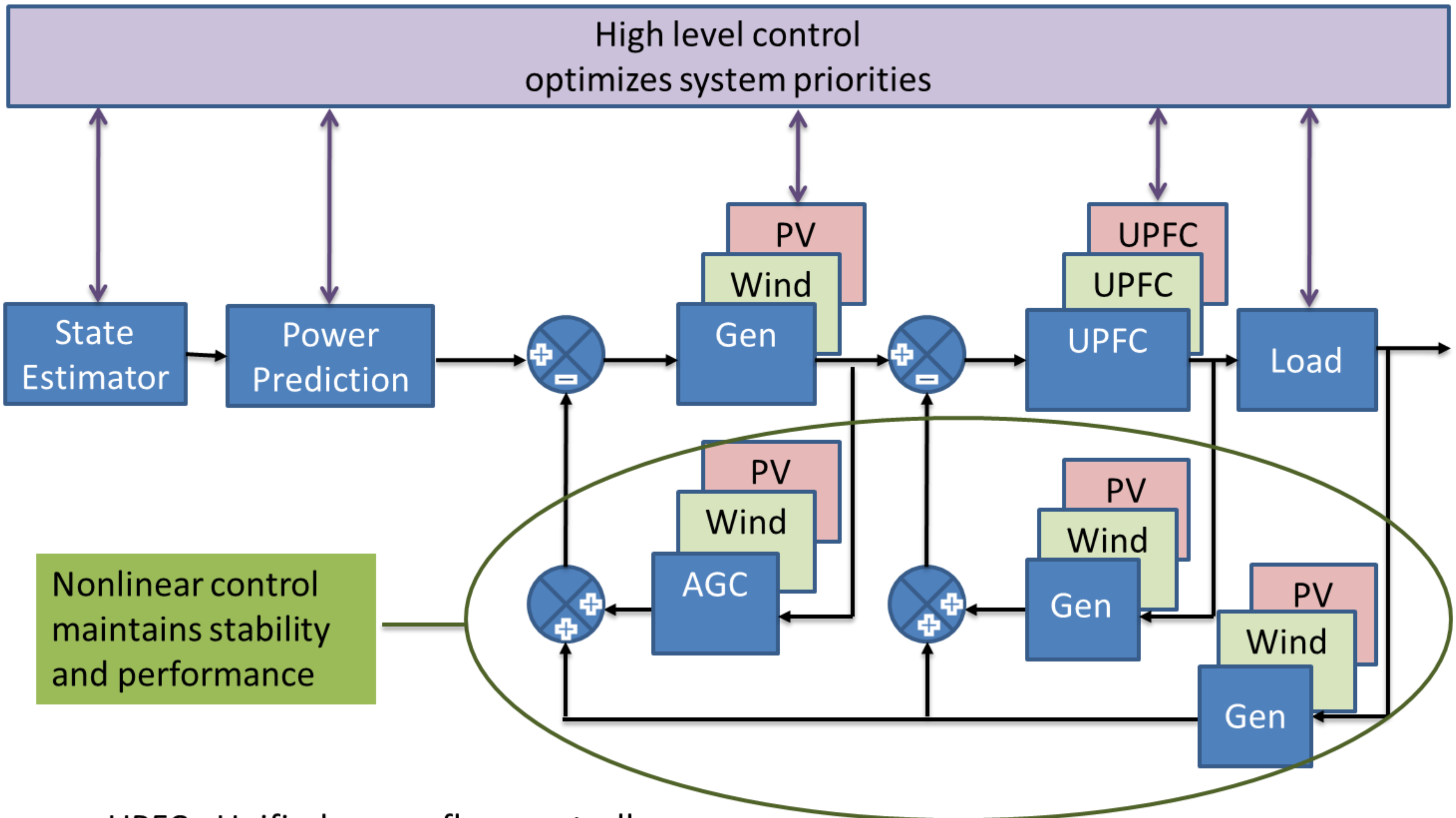
Wind power forecasting examples





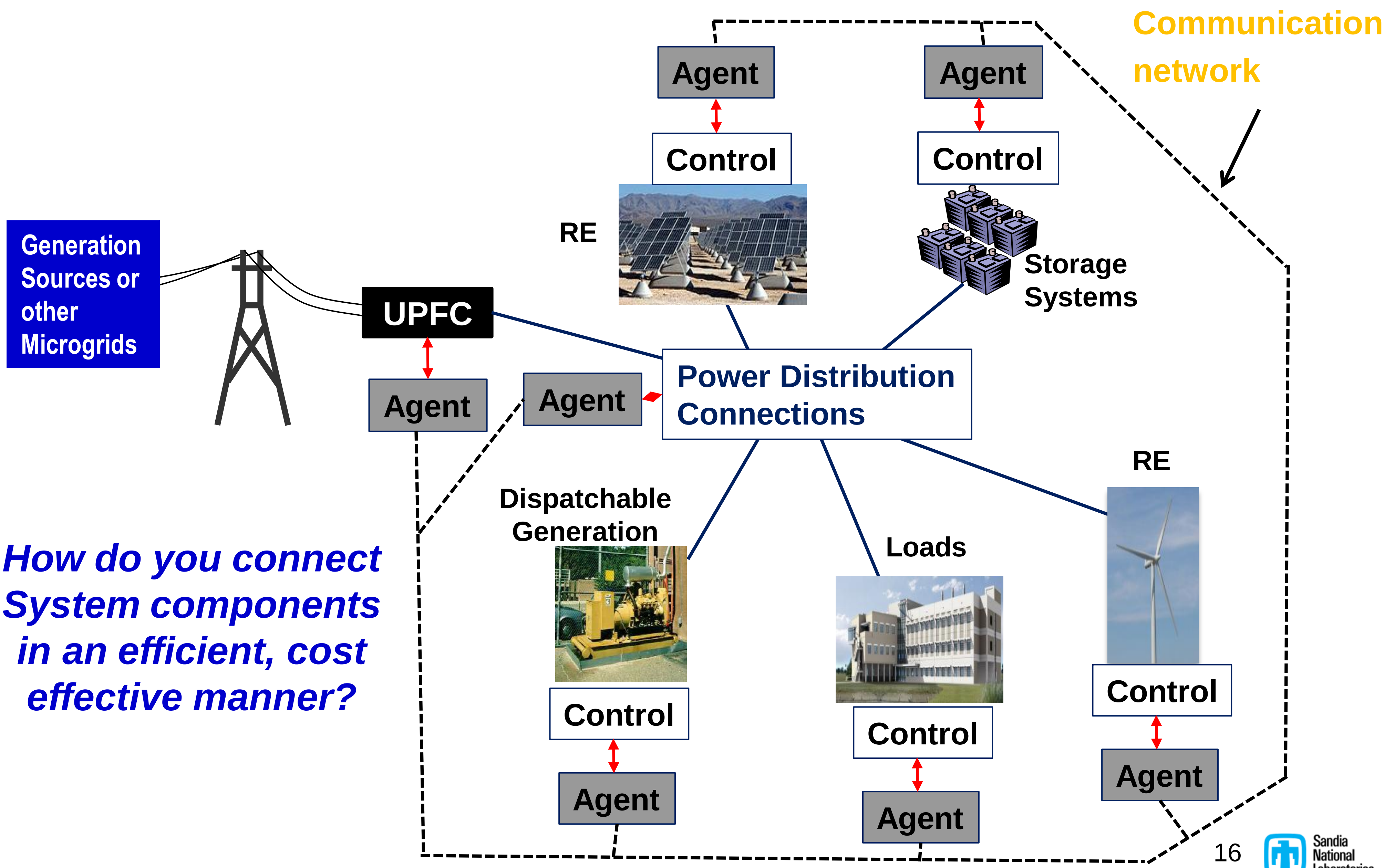
This is weather forecasting!

High Level Control Enables Prioritization and System Adaptability



UPFC - Unified power flow controllers

Future Grids will be Complex and Highly Interconnected



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

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**

$$c = \int H dt$$

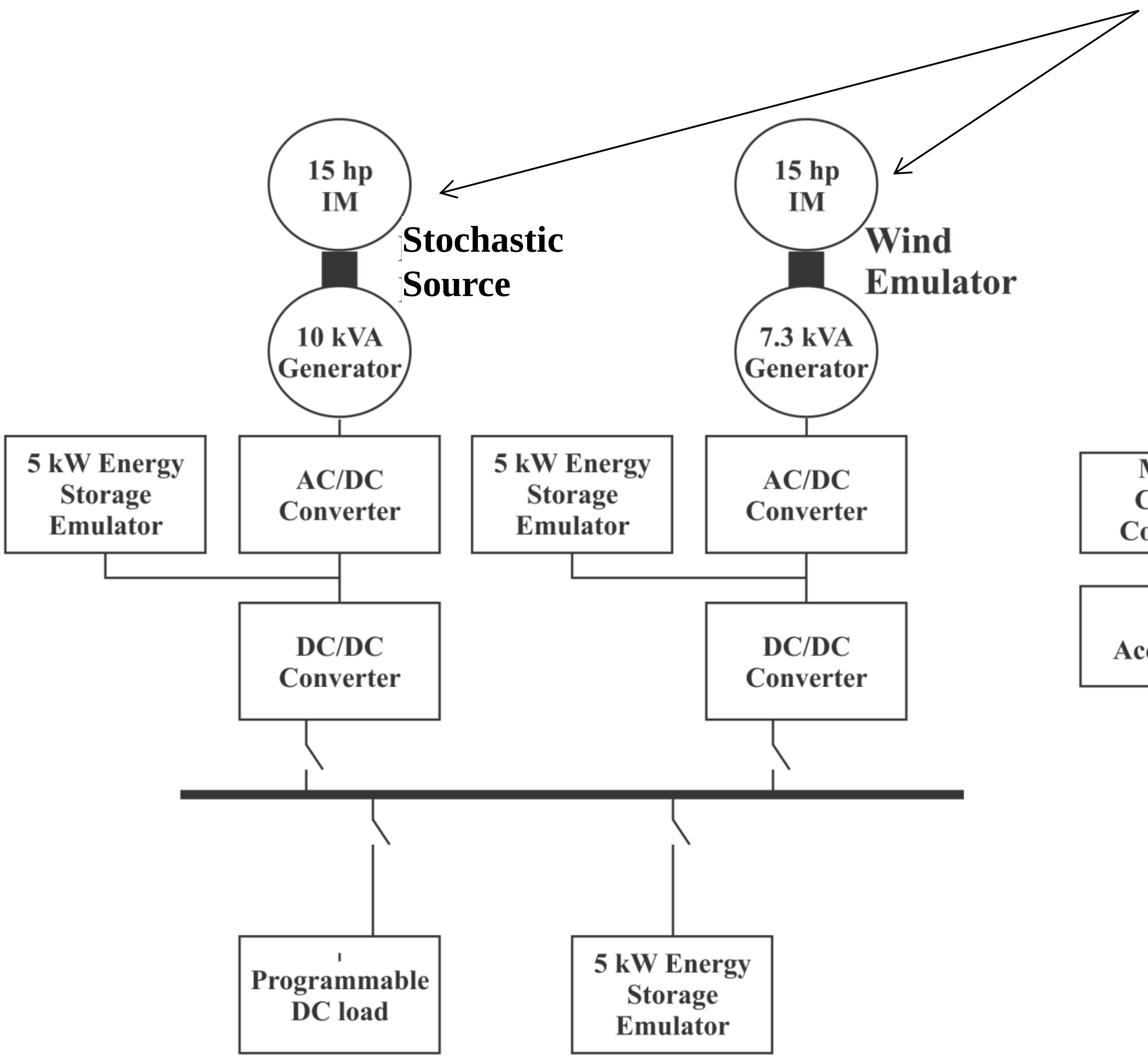
Uniqueness of Fisher Information Equivalency

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

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

SSM Test Bed Experiment

Sources
2 - Stochastic

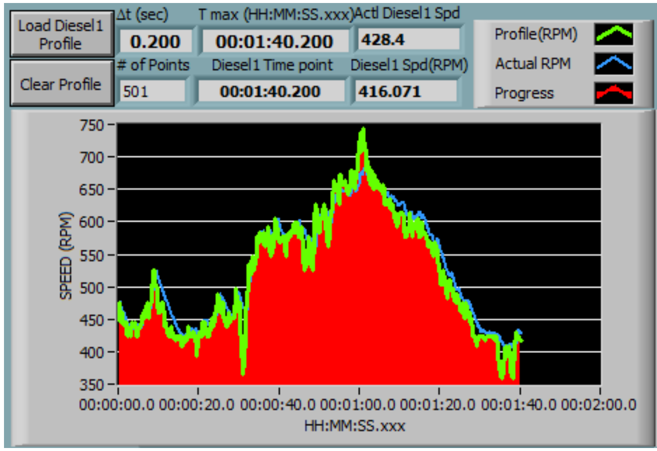


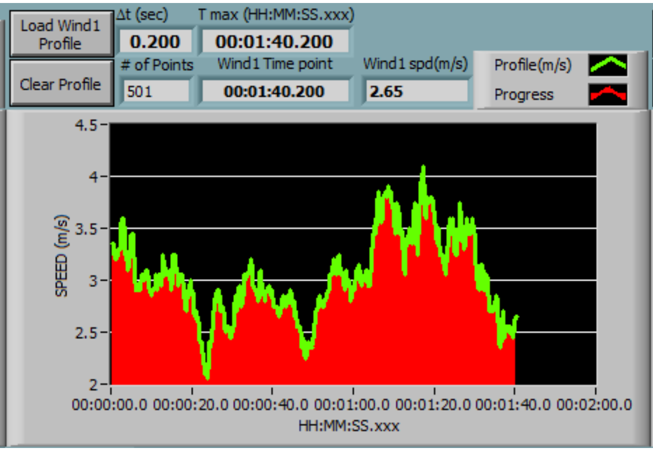
Agents were not part of this experiment.

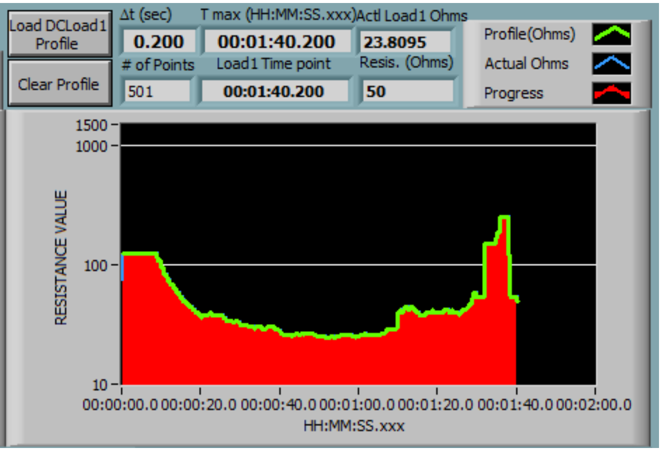
Hamiltonian Based Control Approach with Full State Control - Hardware Results

Source and load profiles

Diesel Generator speed   Wind speed   Load





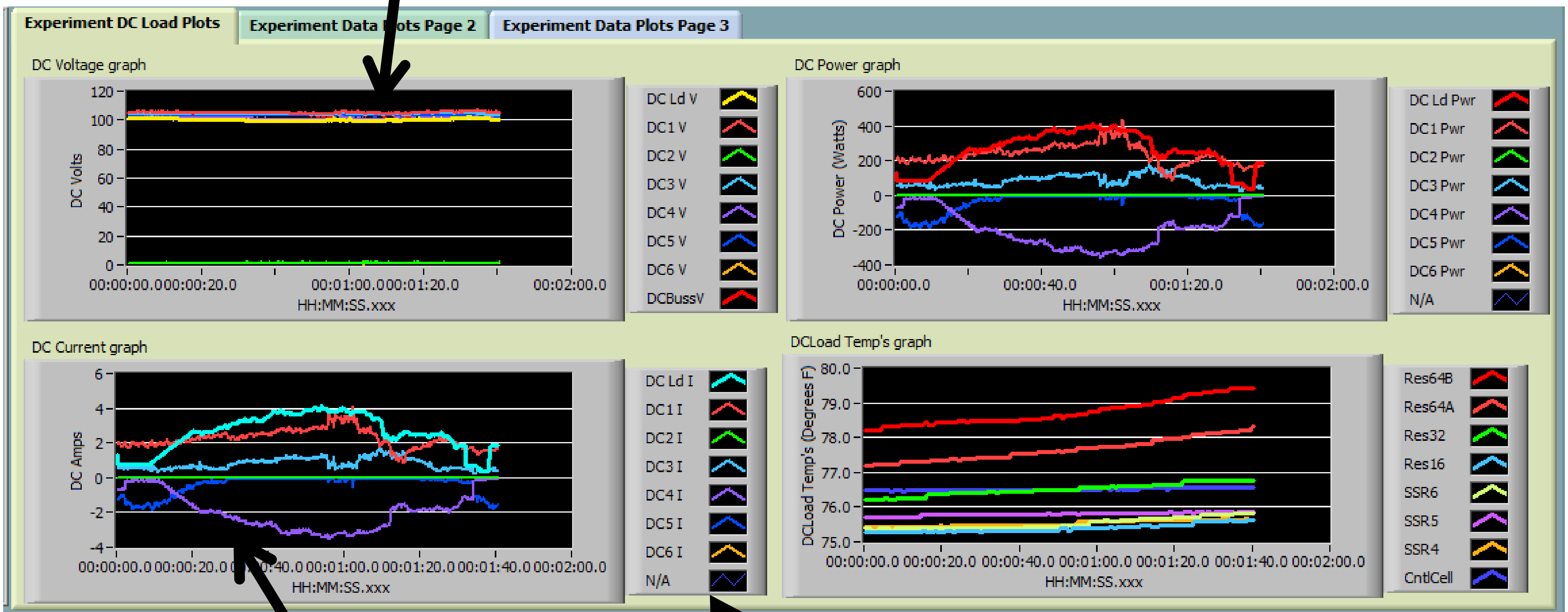


Green – commanded profile
Blue – actual profile
Red – indicates progress in time

Hamiltonian Based Control Approach with Full State Control - Hardware Results

Bus voltage regulation is does not oscillate

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

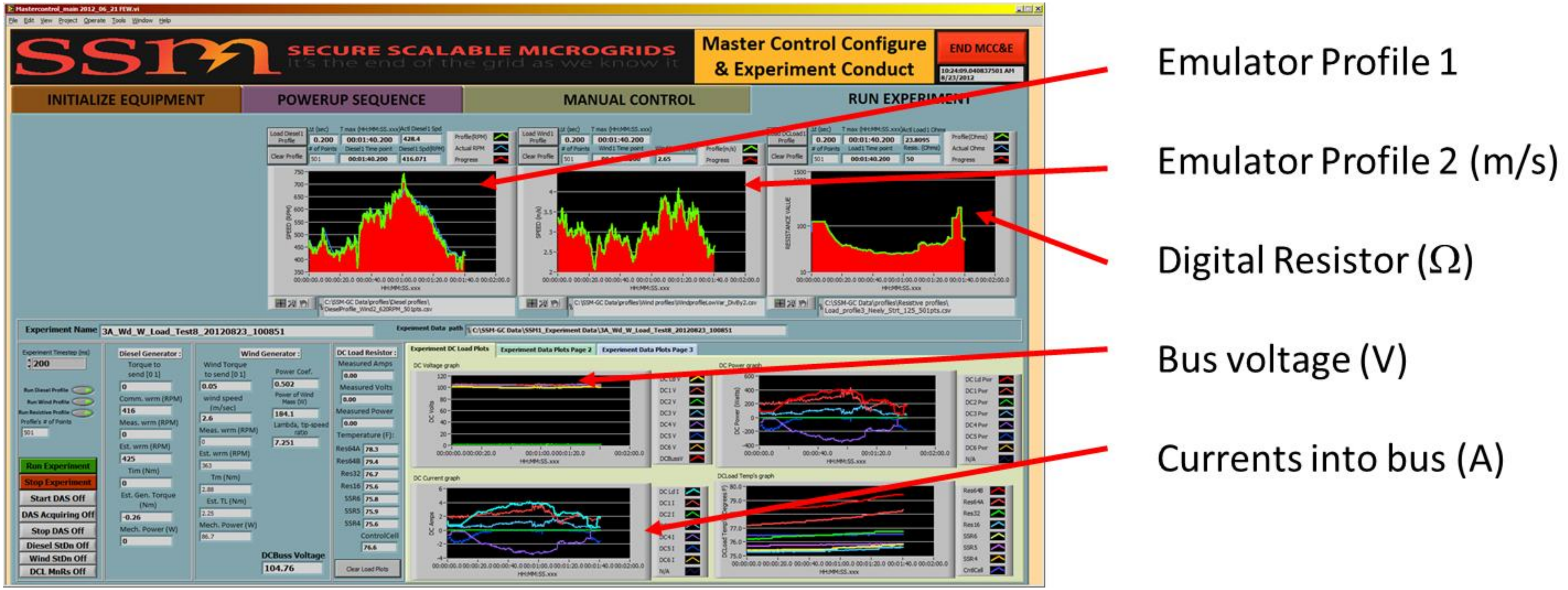


Source and load currents indicate system energy balances

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

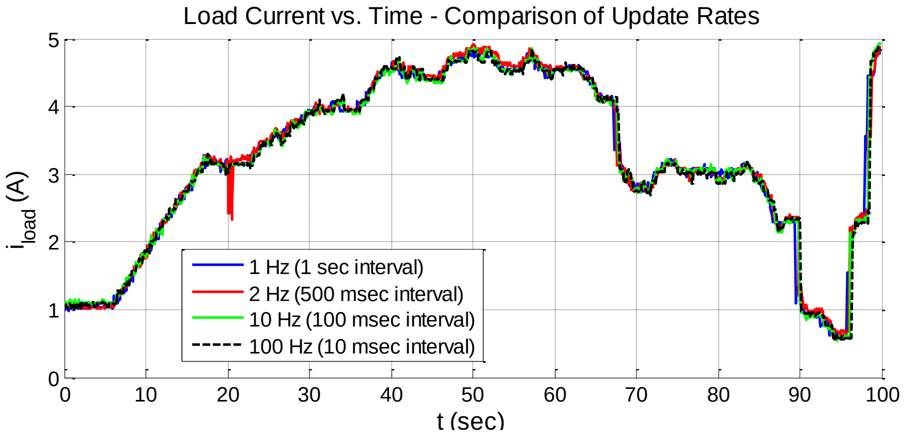
Testbed Enables Automated "Batch-run" Experiments for Apples-to-Apples Control Comparison

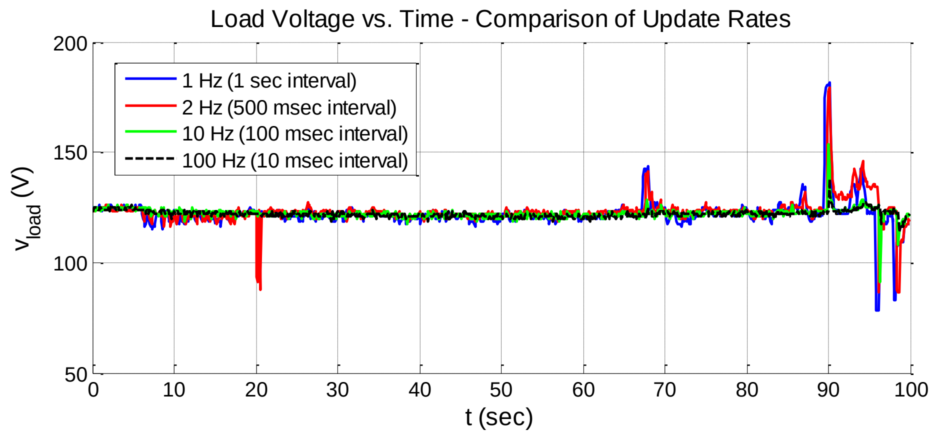
- **Same experiment described by load profile and "weather" may be repeated with changes to control approach and performance evaluated**



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

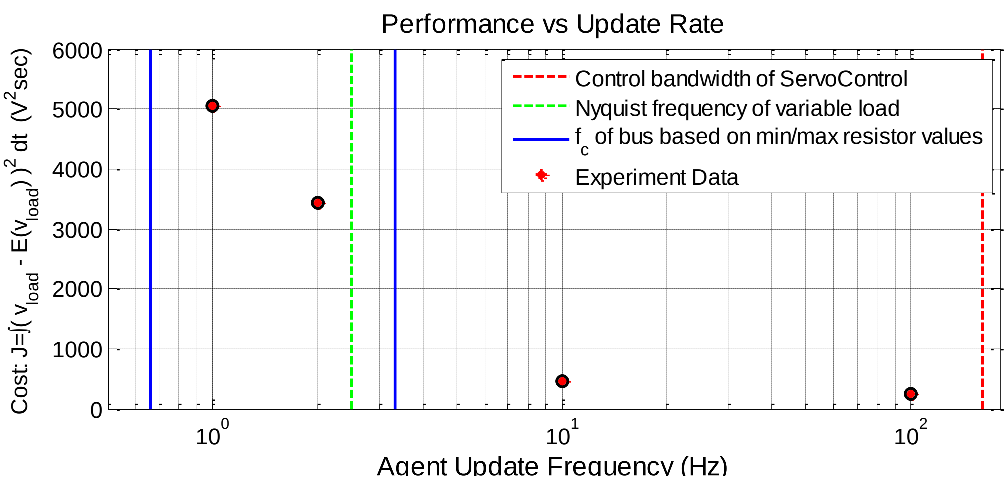
- **Example:**
  - **Effect of Informatic Control Update Rate on Cost**

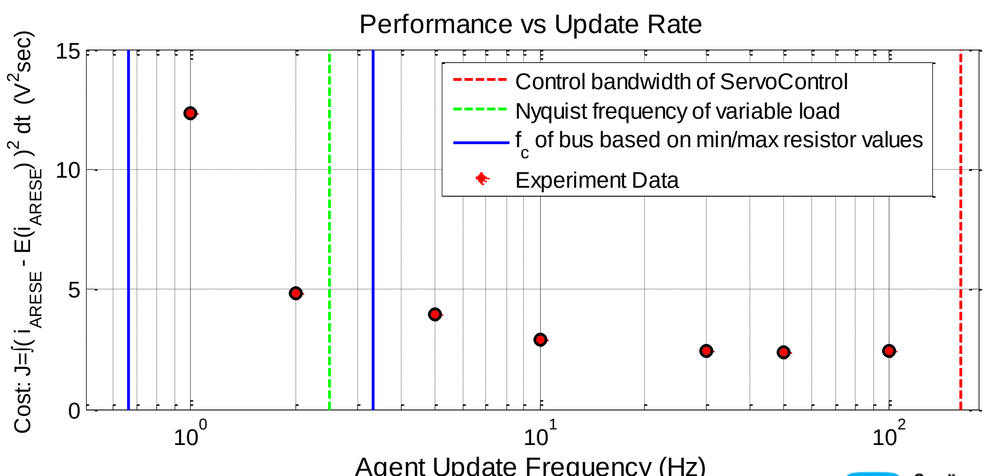




$$J_v(t_f)=\int_{t_0}^{t_f}\left(v_{load}(\tau)-\hat{v}_{load}(\tau)\right)^2 d\tau$$

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





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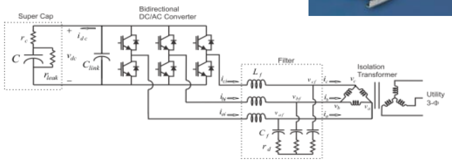
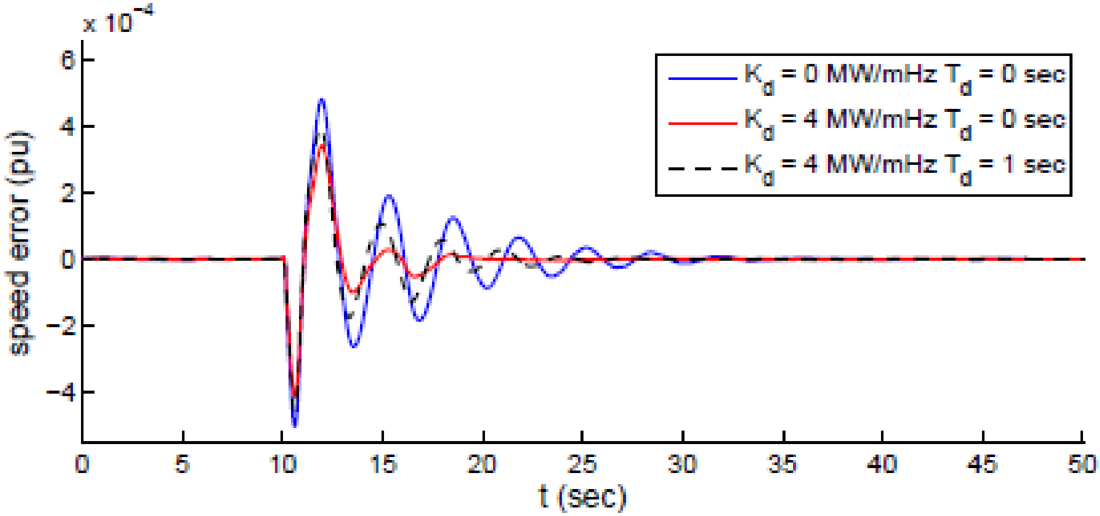
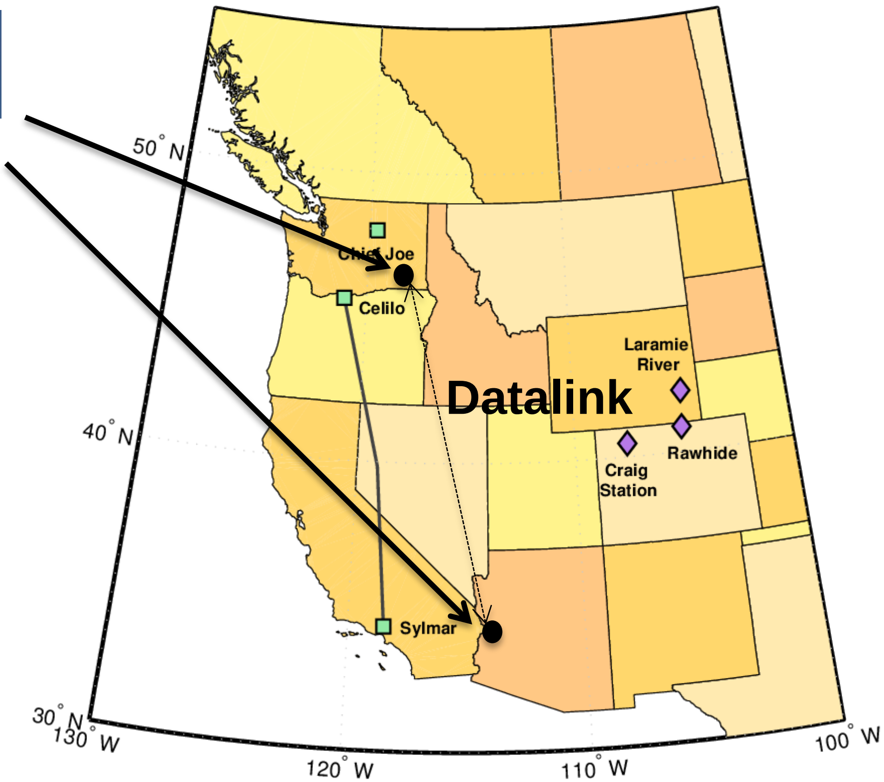
Energy Storage can Improve Grid Dynamics/Resiliency

- **Large generation and load complexes separated by long transmission lines can develop inter-area oscillations**
- **Networked energy storage complexes can improve damping of inter-area modes**

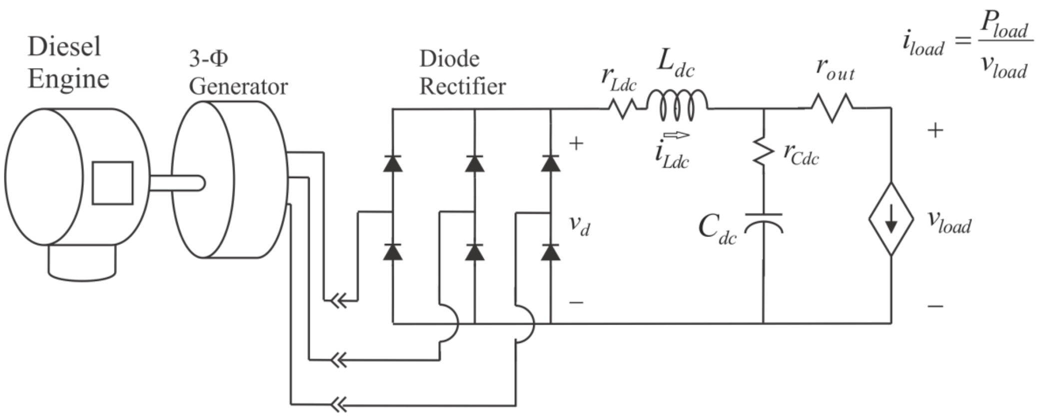


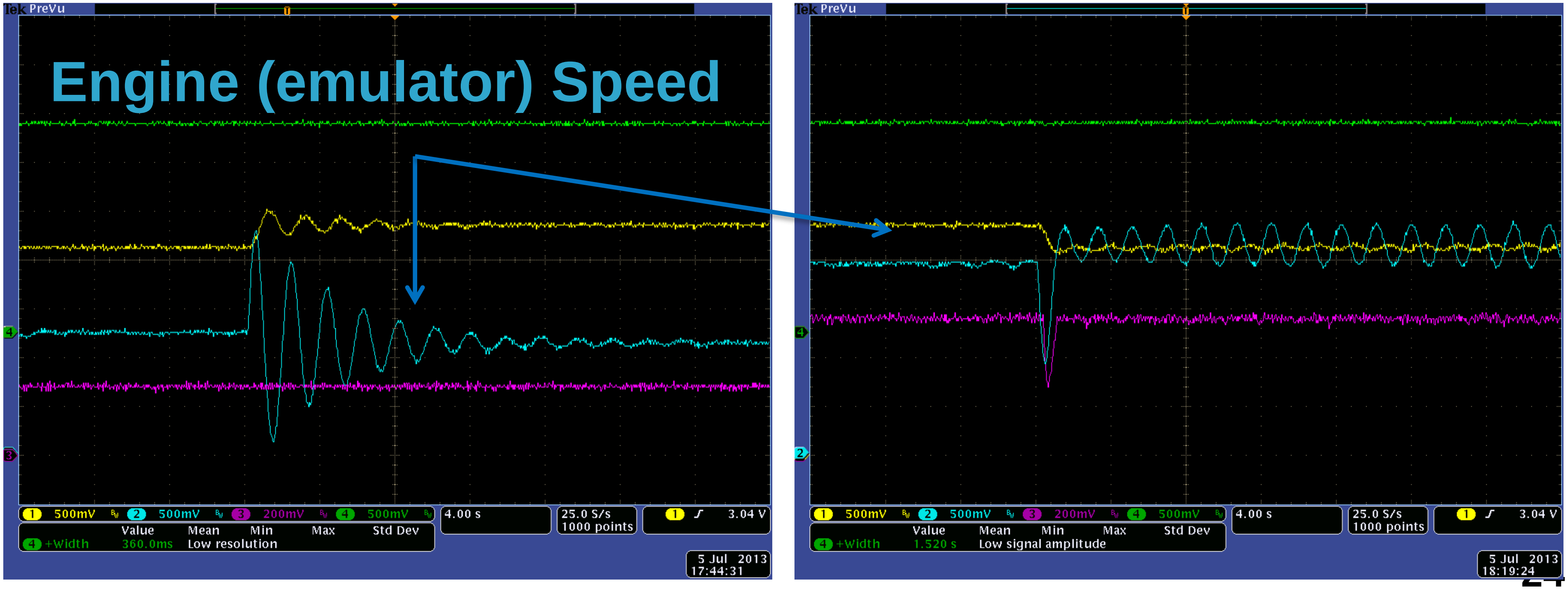




SSM Testbed Allows Study of Electromechanical Modes in Microgrids

- **Control Attributes Influence stability**
  - Constant current/power
  - Operating Point
  - Network Time Delays





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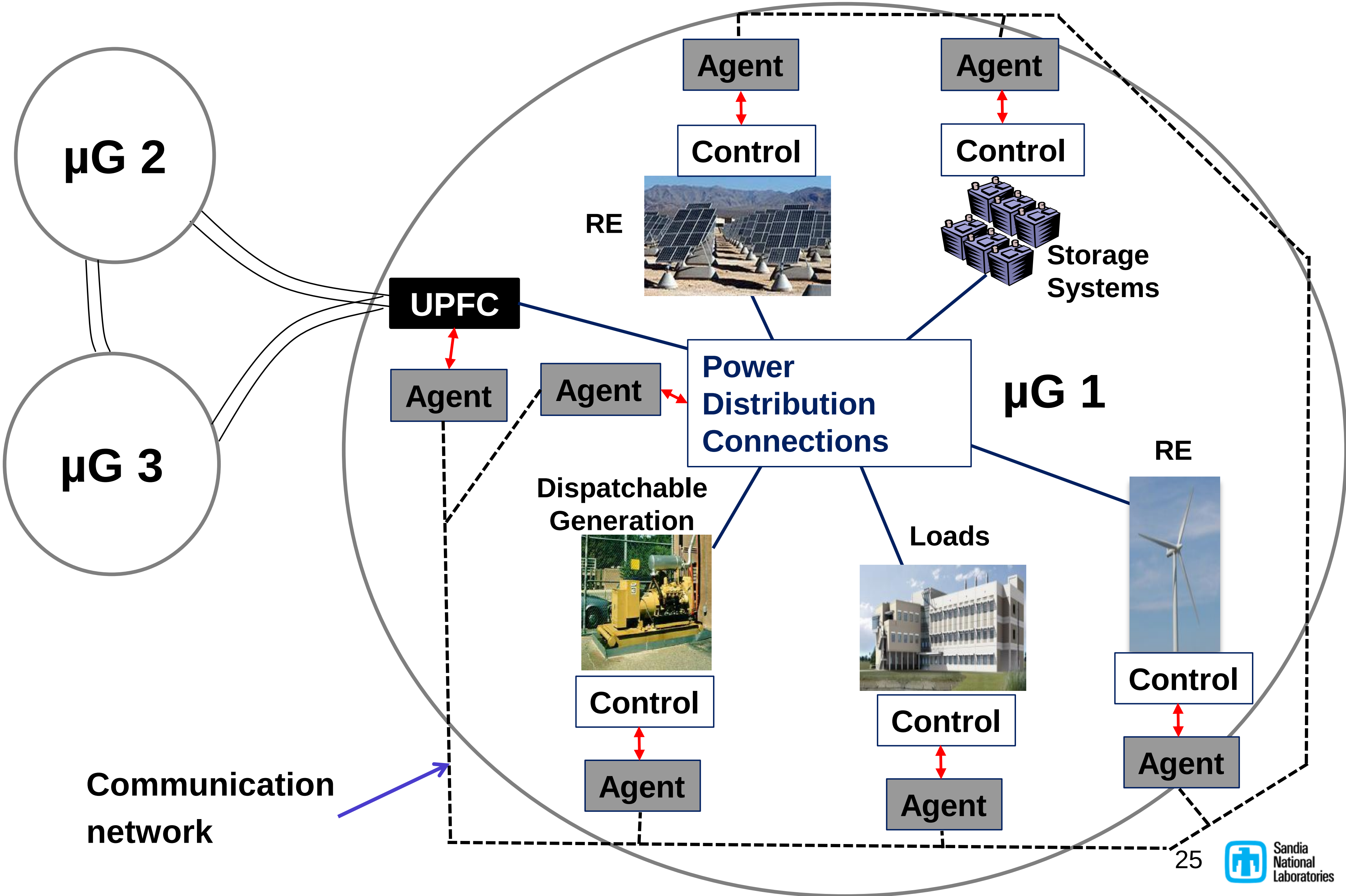
These Microgrids will be Building Blocks for Large Networks



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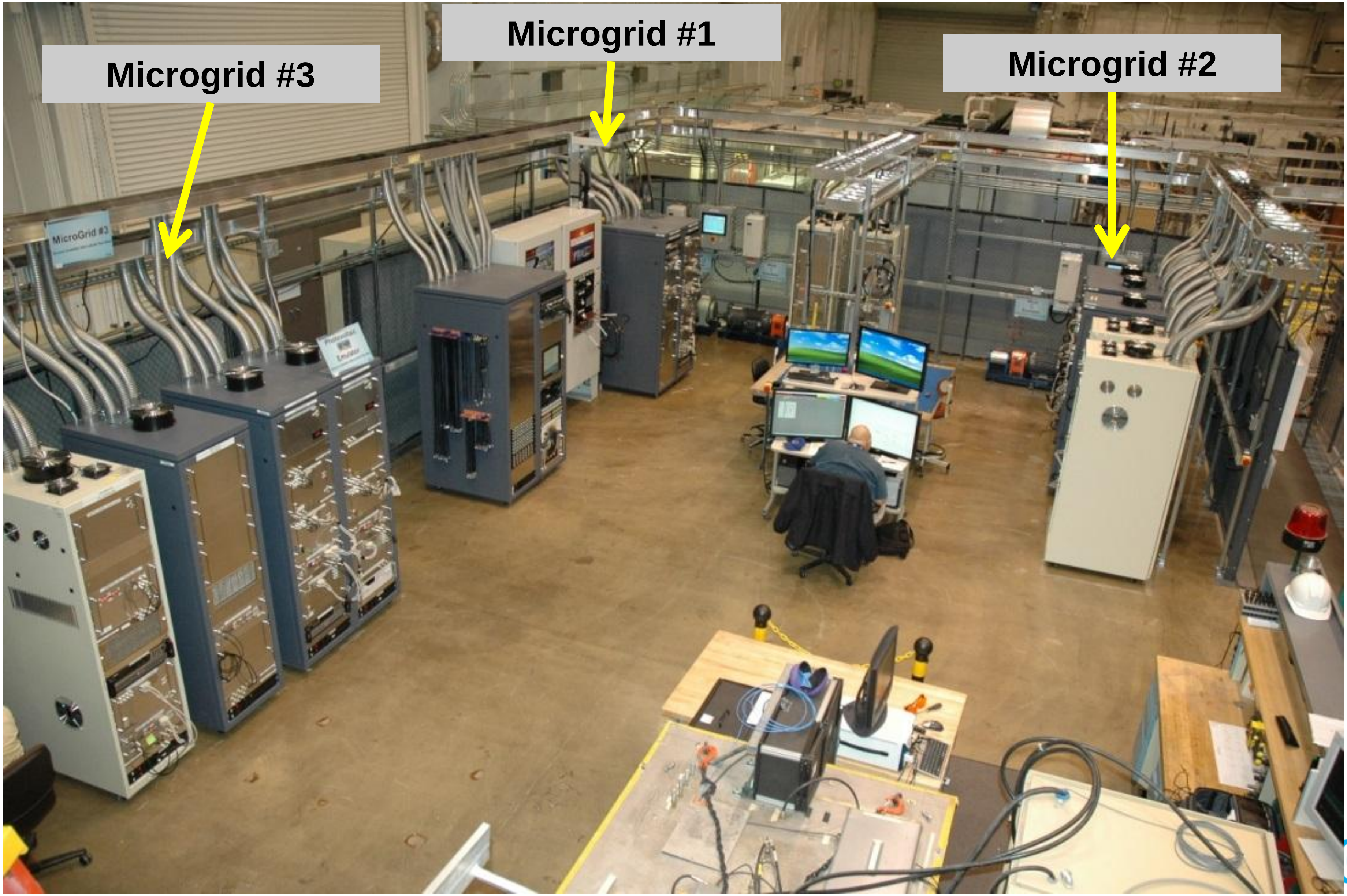

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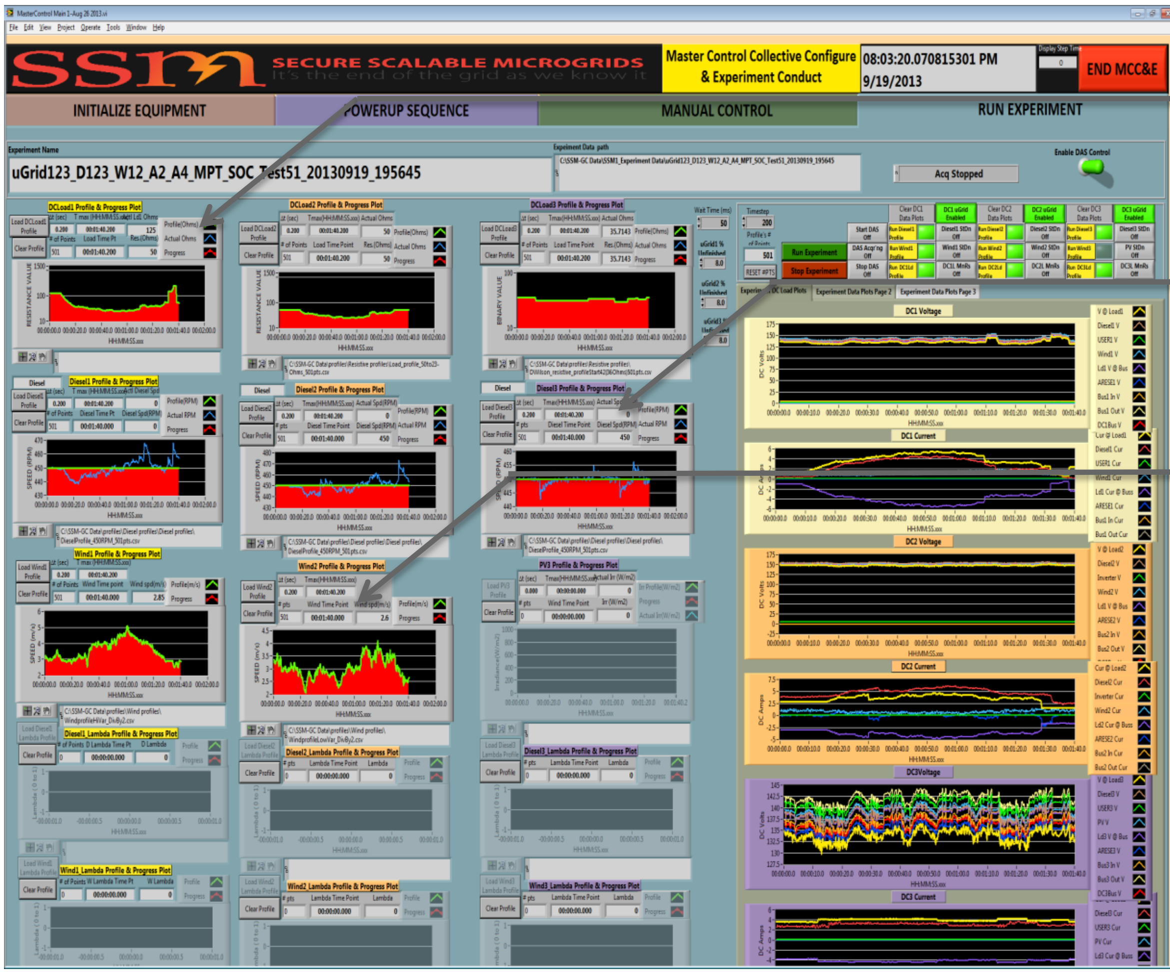
SSM Testbed Allows Study of Microgrid Collectives

- **Experiments on the microgrid collective may be coordinated from one control center**



Microgrid 1 Load (Ω)

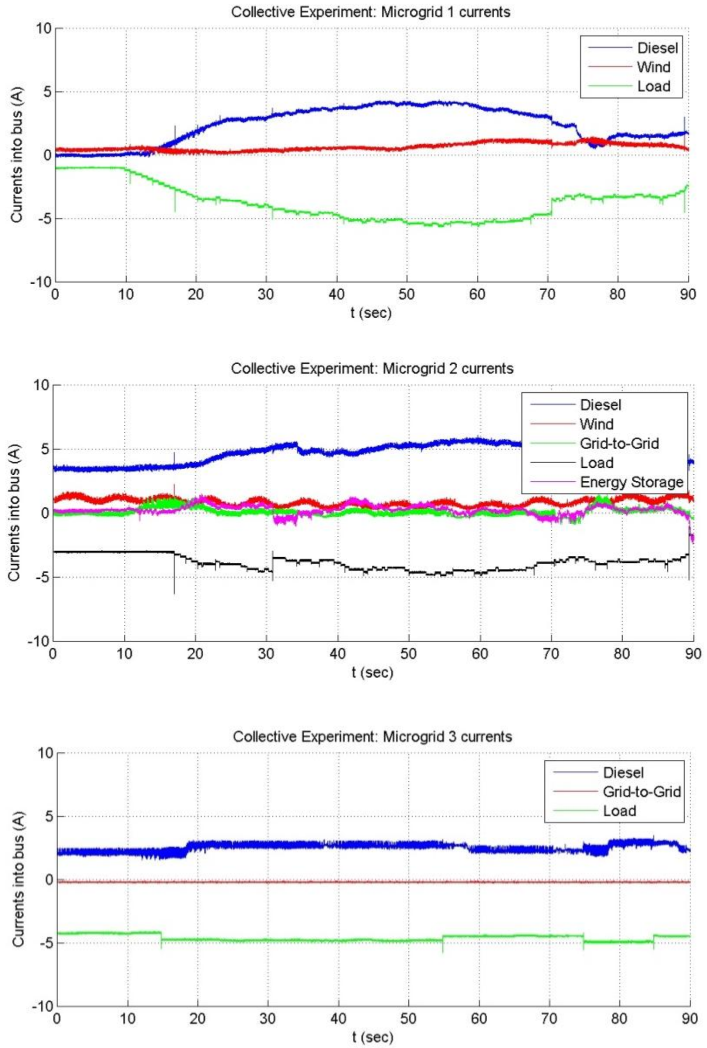
Microgrid 3 Diesel Engine speed (RPM)

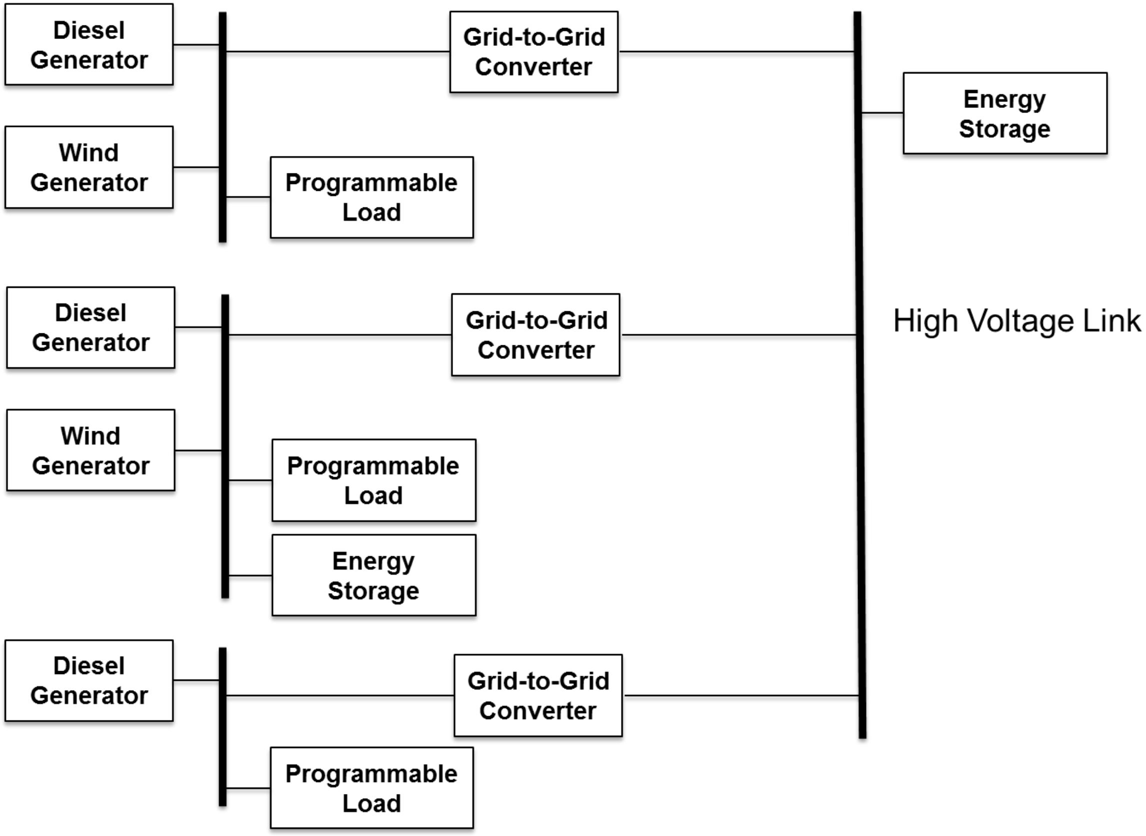
Microgrid 2 Wind speed (m/sec)

Realtime bus voltage and current plotting

SSM Testbed Allows Study of Microgrid Collectives

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





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SSM Status

- Hamiltonian based control design techniques have been experimentally validated with 100% stochastic generation
- Agent design advancements have demonstrated agent based partitioning of energy management set points
- Real time simulation capabilities have been demonstrated with the SSM models
- Distributed Hamiltonian based control design method for AC systems has been determined and can be structured like a DC system
- Army Network exploitation tool has been connected to the SSMGC communication network
  - Threat analysis continues
- Distributed Hamiltonian based control design method for networked DC systems is in progress
- Distributed Hamiltonian based control design method for networked AC systems is in progress
- Informatics based algorithms for collectives are under development

BACK UP

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:
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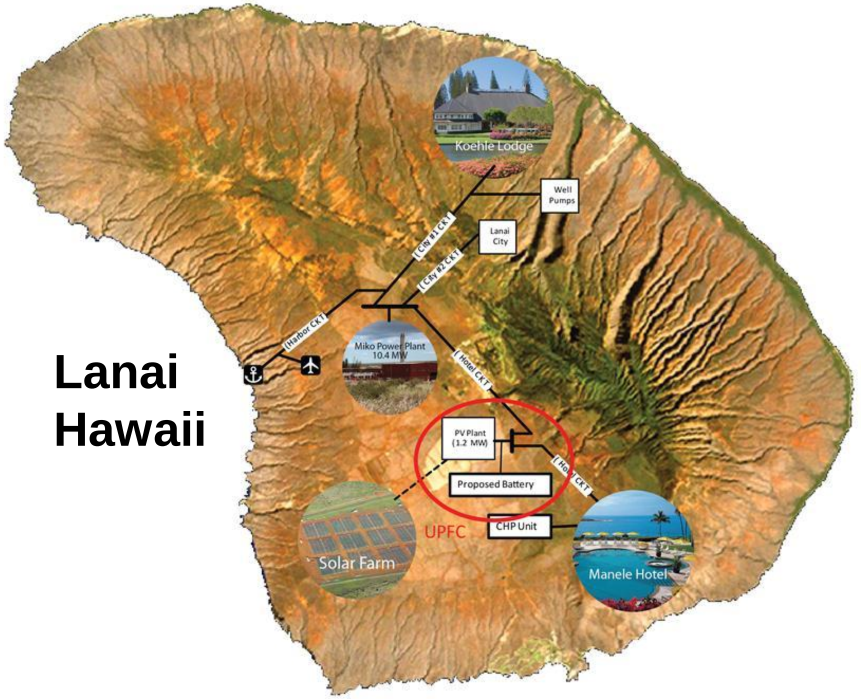
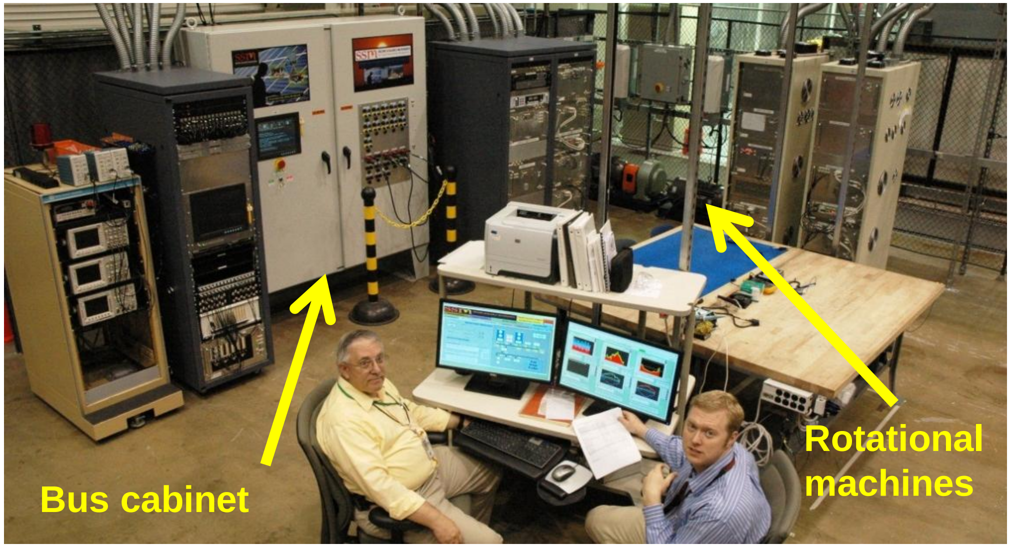
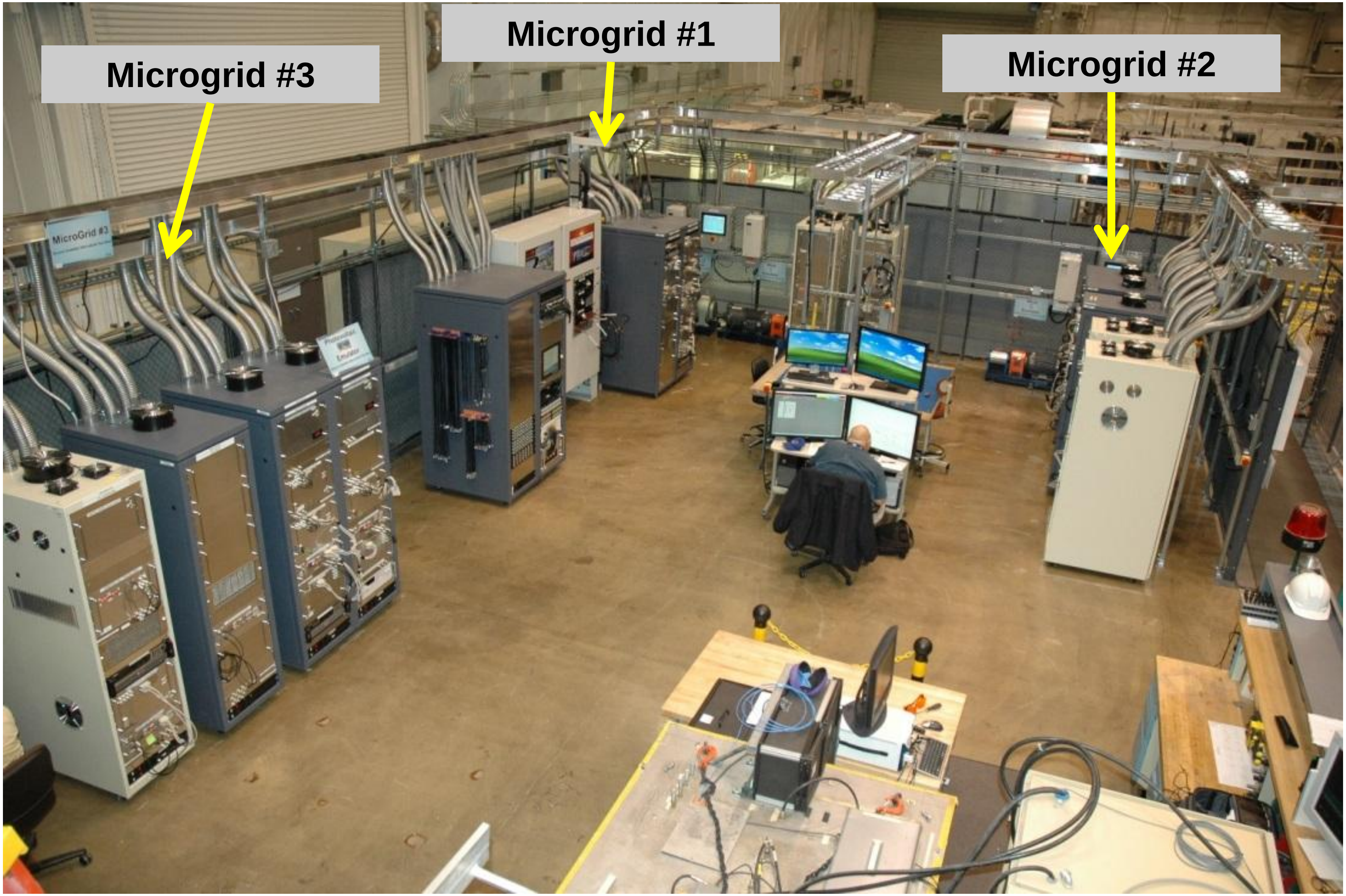
  - **Self-healing, self-adapting architectures**
  - **Microgrids as building blocks for larger systems**





SSM test bed

Discussion



Agent Based Controls

- Identified appropriate separation of agent based controls and servo level controls
- Demonstrating automated control of the SSMGC hardware by enacting protocols
- Agents interpret measured test bed points, exchange information, and appropriately adjust the boost converter settings and storage settings
- Performance results have been captured and will be published

Advancements in Microgrid Modeling and Simulation

- Purdue PCK delivered Matlab and Simulink models representing the SSMGC physical system
  - Simulates the dynamics of the SSMGC hardware
  - Supports easy construction of interconnected microgrids
- Opal RT simulation environment runs the SSMGC collective microgrid models
  - Supports real time evaluation of control algorithms
  - Supports investigation of the controls impact with increasing numbers of interconnected microgrids
- Michigan Tech University delivered Matlab and Simulink based simulation of agents controlling the SSMGC collective models
  - Set of general purpose Matlab and Simulink models for implementing and analyzing SSMGC test bed scenarios
  - Demonstrates several key points regarding agent control of microgrids
    - » Boost-mediated control agents that accomplish coordinated control of disparate PV arrays
    - » Cooperative adaptive PI control of wind turbines with varying wind speed excitation
    - » Adaptive PI scheme for PV and Wind sources
  - Provides functional abstractions for load and generation cohorts into a simple message passing specification

Sandia National Laboratories

Cyber Security for Microgrids

- Integration of the Army threat computer
  - Network exploitation tool connected to the SSMGC communication network
  - Ran passive and active scan attacks during preliminary control experiment runs
  - Relevant threats are being identified based on the control experiment
- University of Minnesota is analyzing threats against microgrid collectives in simulation
  - Developing a Matlab and Simulink simulation environment that incorporates malicious entities
  - Analyzes sophisticated threats not easily performed/feasible in the physical system
  - Validates previous work in identifying vulnerabilities in collective microgrid with network based controls

In Summary: We have a history of diverse impact on national security

- **US ground beef safety in response to 1993 Jack-in-the-box O157:H7 e-coli outbreak 1997**
  - **Radiation pasteurization technology and contingency planning for major US and foreign beef producers, process development and validation experiments.**
  - **High dose-rate irradiation of ground beef for sensory panel evaluation.**

- **Introduction of radiation processing technology into tire manufacturing 1997-98**
  - **Irradiation of green and cured elastomers to determine impact on wide range of properties and applications. Led to tailoring of compounds for targeted effects.**

- **Mach 8-12 US hypersonic ground test facility R&D. (US Army/USAF) 1998 - ongoing**
  - **Concepts and proof-of-principle technology demonstrations, physics validation experiments.**

- **Response to Hart building anthrax attack (US Postal Service) 2001**
  - **Electron beam irradiation efficacy, process reliability, impact on mail content including volatile organic chemical release, national irradiation facilities planning.**

- **Wiring diagnostics for the Aging US Aircraft Fleet (DOT/FAA, Industry) 2005-07**
  - **PASD - World's first effective aging wiring diagnostic for commercial aircraft fleet.**
  - ***2007 R&D 100 Award.***
  - ***2007 Federal Lab Consortium Interagency Partnering Award.***

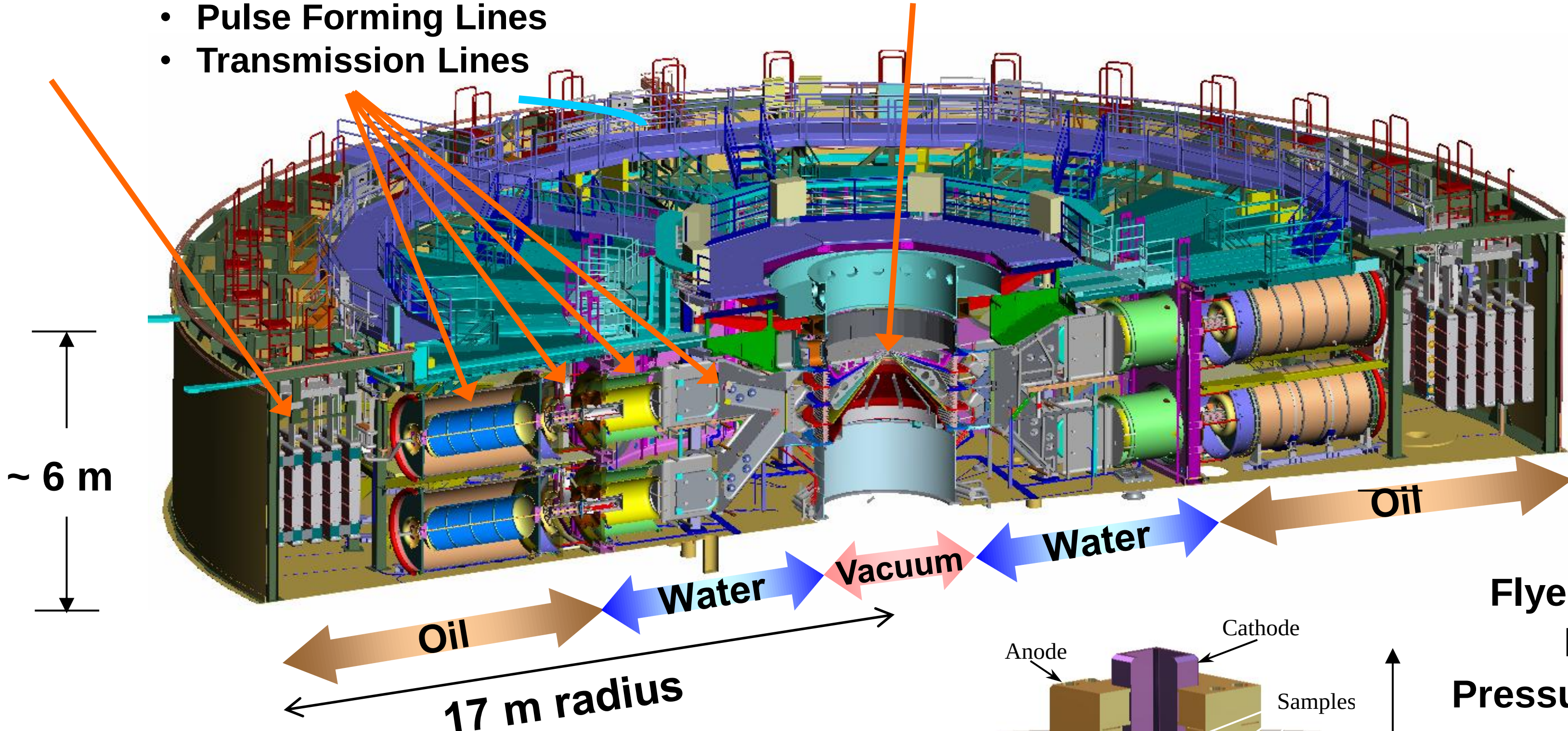
- **Sago Coal Mine accident investigation (DOL/Mine Safety & Health Administration) 2007**
  - **First-ever demonstrated link between a lightning ground strike and deep mine explosion. Led to changes in mine safety requirements.**

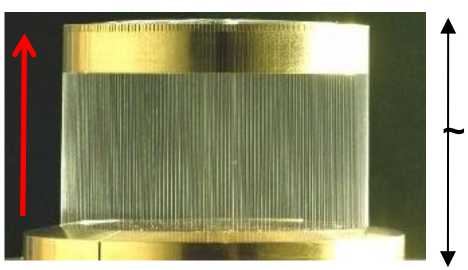
- ***Next: the Secure Scalable Microgrid***
  - ***Integration of informatics, nonlinear distributed control, communication, and hardware for the development of power system design and analysis tools.***

Z Represents the Core of Pulsed Power Sciences

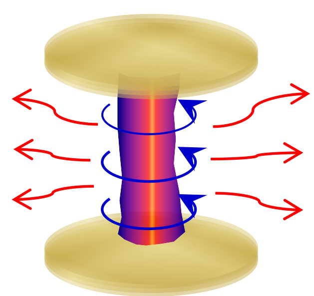
Pulse Forming Section:
- Intermediate Storage Capacitors
- Laser triggered gas switches
- Pulse Forming Lines
- Transmission Lines

Experiment
Load Region

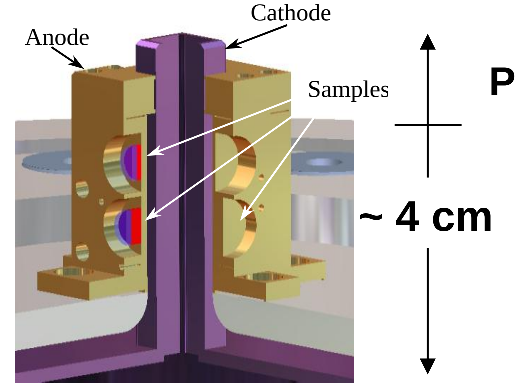




Wire-array z-pinch load
for radiation effects and inertial
confinement fusion

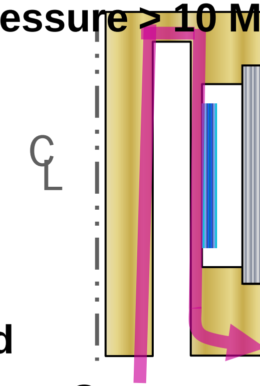


Implosion/stagnation
300 TW, 2 MJ x-ray



Magnetic compression load
for dynamic materials
experiments

Flyer plate > 40
km/sec
Pressure > 10 Mbar



22 MJ stored energy, 26 MA peak current, 100-600ns rise times

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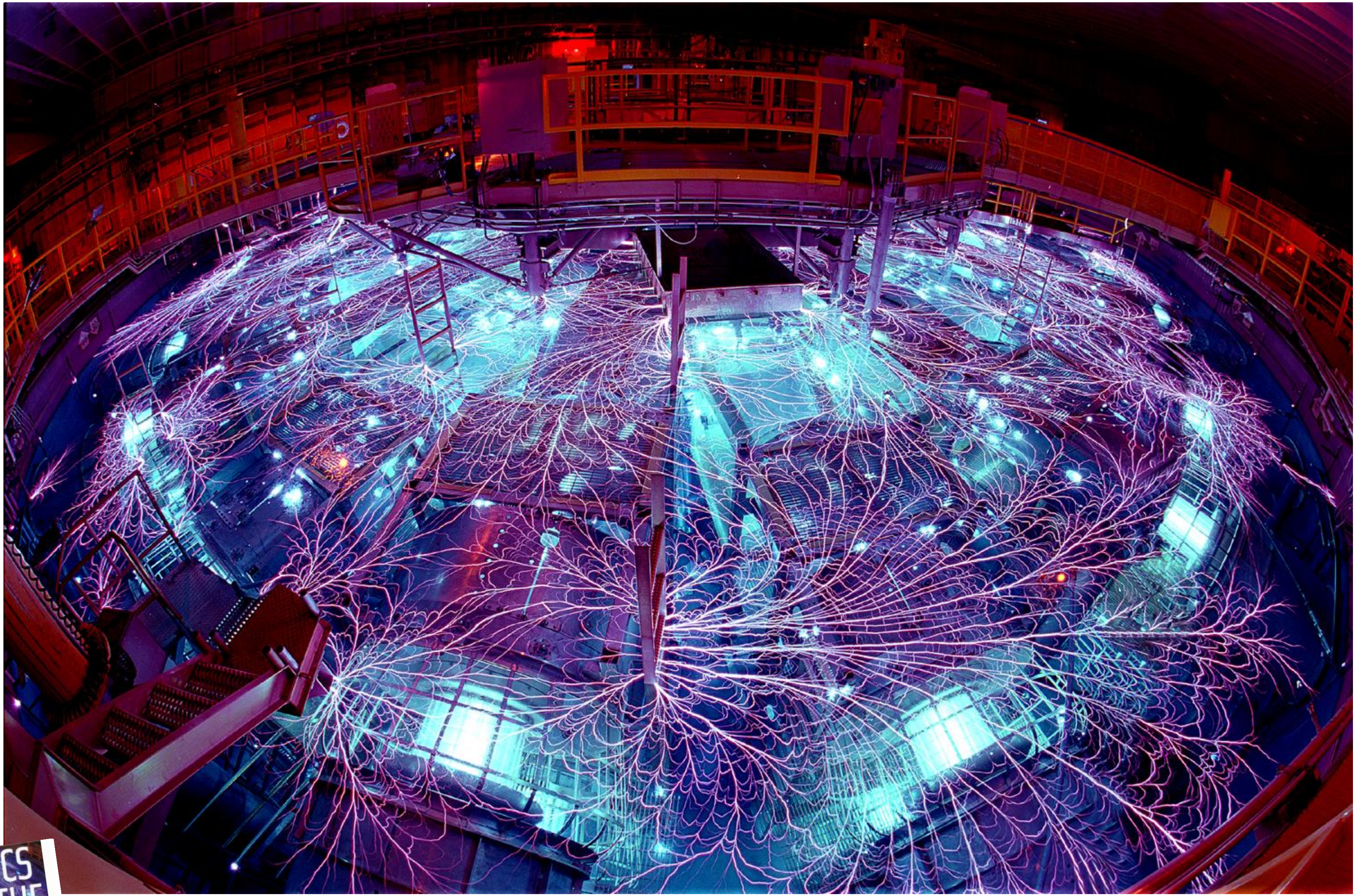
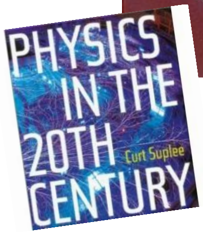
Z Machine in Operation





Arcing on the surface of the water and gas switch closure can be seen during operation of an older version of Z. These features disappear within a microsecond.

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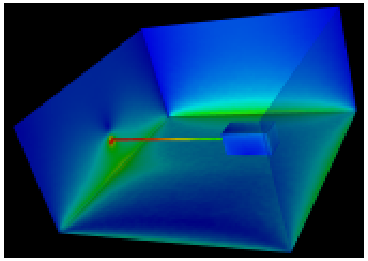
Unique Capabilities Support Other Federal Agencies and Industry

Example Partnerships:

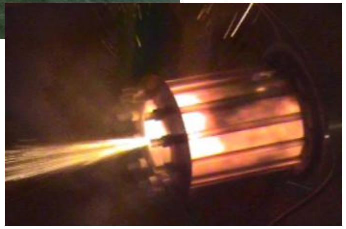
DOE-Nuclear National Security Administration, Office of Science, Office of Electricity
DOD-Army/USAF
DOT-Federal Aviation Administration
DOL – Mine Safety and Health Admin.
Lockheed Martin Technology Research
Electric Power Res. Institute
Naval Research lab
Boeing
FMC, Inc.
Goodyear









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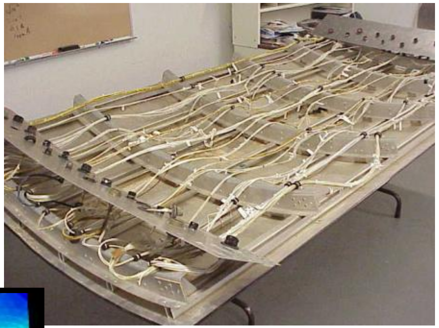
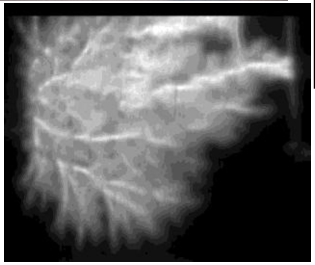
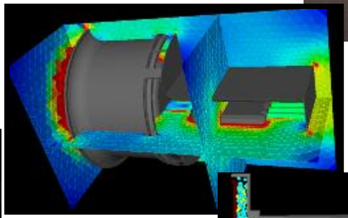
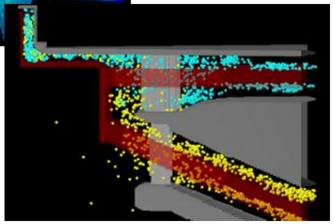
Integrated Science and Engineering Expertise is Required to Support our Mission Responsibilities

Theoretical, experimental, advanced development, systems engineering

- 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



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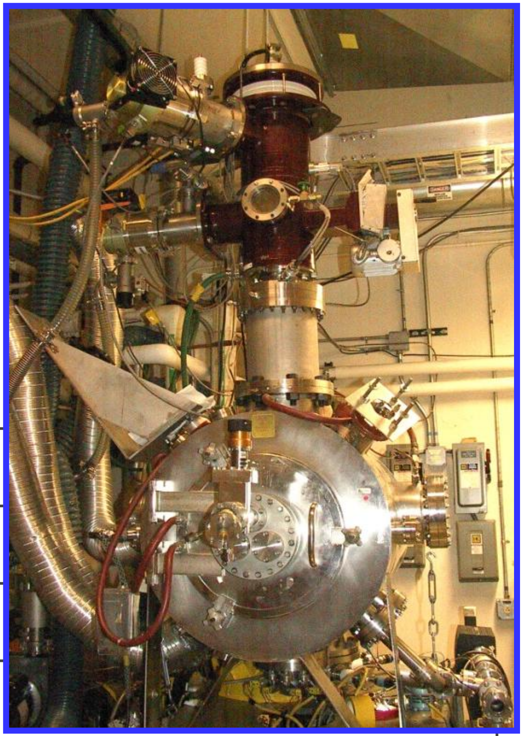
- e-beam testing gives complete access to the heated surface for optical, IR and pyrometry measurements
- low thermal conduction losses
- requires 10 mTorr or better vacuum
- RGA, OES and LIF possible
- Fiberscopes, borescopes

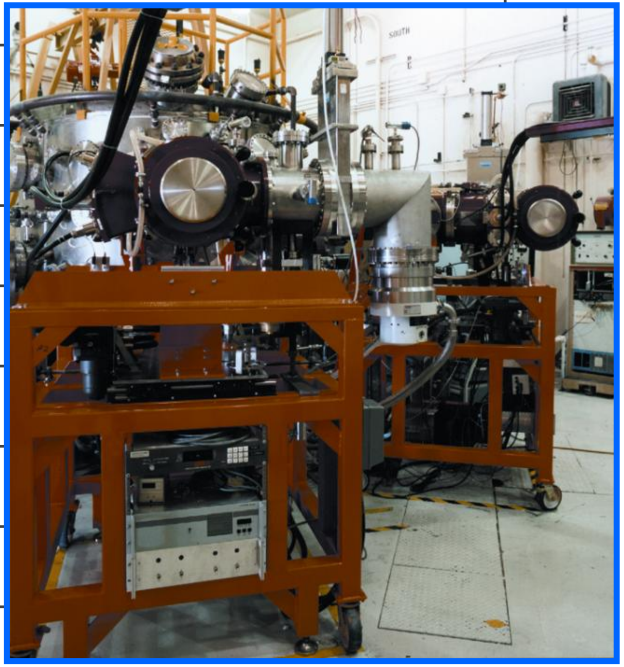


EB-60

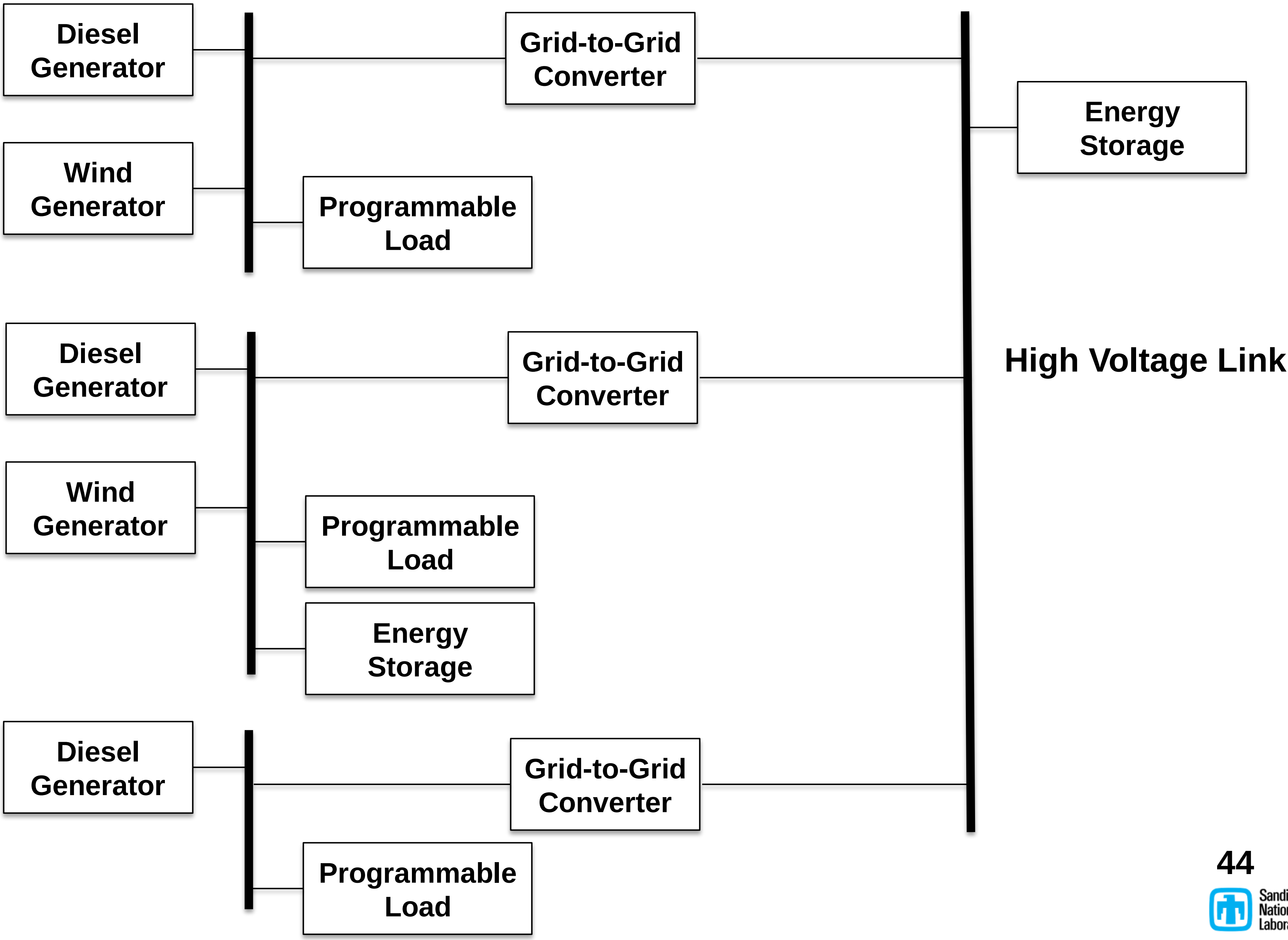
Beam power	60,000W (60kW)
Accelerating voltage	30,000V (30kV)
Beam current	2A
Beam spot	2mm FWHM at target plane
Target area	0.1-10,000mm^2
Pulse length	From 2ms to continuous
Chamber pressure	~6 x 10^{-4} Pa, cold-trapped diffusion pump
Gun pressure	~1 x 10^{-6} Pa, turbopump

EB-1200

Beam power	0-0.6MW(cw) each gun; 0-1.2MW(cw) total
Accelerating voltage	0-40,000V (40kV)
Beam current	0-15A each gun
Magnetic lenses	2 coils
Spot diameter at 600kW, 1.5m	12mm
Magnetic deflection	2 yokes(orthogonal)
Max raster frequency	10,000Hz (10kHz)
Max. angle beam deflection	±7°, 10kHz; ±30°, <200Hz
Max. heat flux (unrastered)	>1000MW/m^2
Max. heated area at 10kHz	370mm x 370mm at 1.5m
Heat flux at maximum area	8.7MW/m^2
Max. pressure in chamber	<3Pa
Cooling water consumption	2.2m^3/h



- So you have the original drawing



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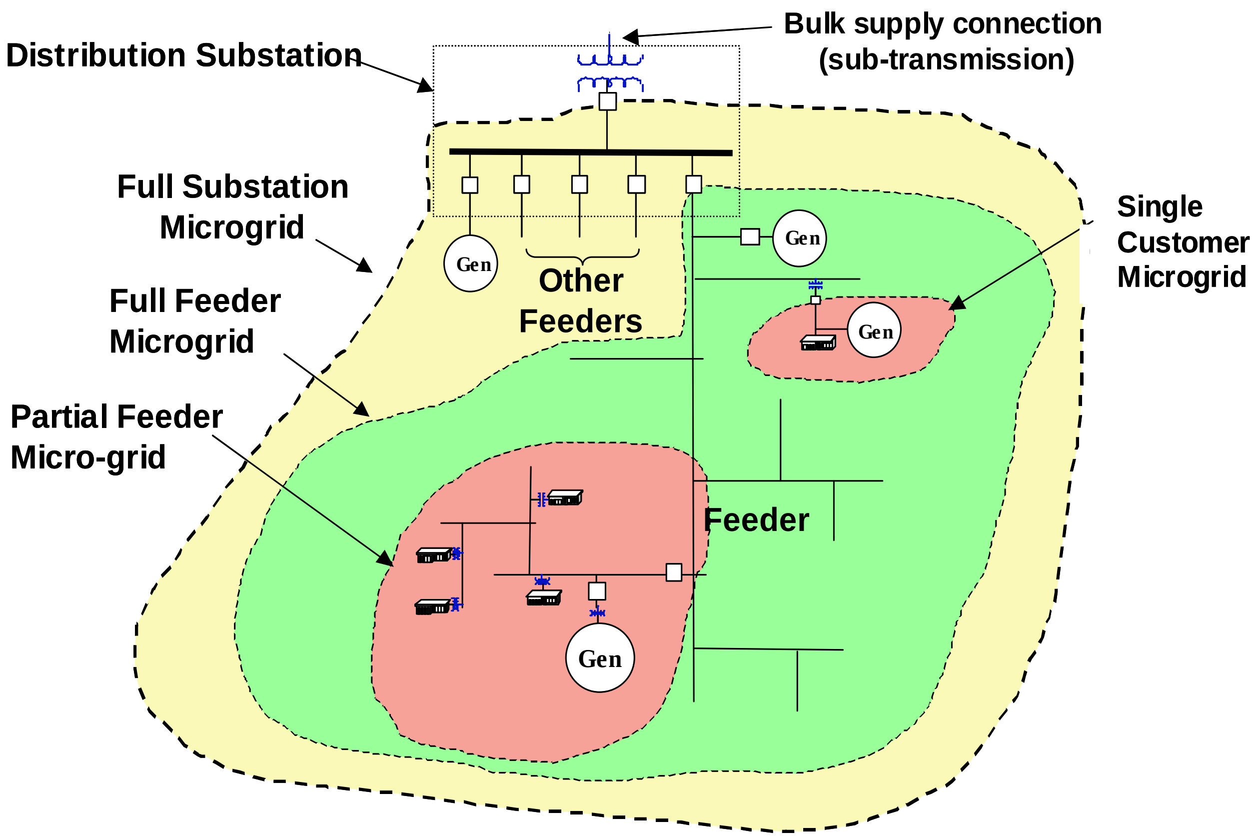
Sandia Advanced Microgrid R&D Program

- Design advanced microgrids to operate 'grid tied' and 'islanded'
- Support enhanced
  - Use of distributed energy and storage technologies
  - System resiliency
  - System reliability
  - System security and safety
  - Utility/military benefits
- Scalable implementation of Smart Grid technologies to assure mission performance



Advanced Microgrids – Supporting Use of Renewable, Distributed, and Smart Grid Technologies for Assured Mission Performance

Transformational R&D Approach

Reduce the "unacceptably high risk"* of mission impact from an extended electric grid outage by maintaining energy delivery

- **Develop and Demonstrate:**
  - **Secure microgrid generation & distribution**
  - **Cyber-security of electric grid**
  - **Smart Grid technologies & applications**
  - **Integration of distributed & intermittent renewable sources**
  - **Demand-side management**
  - **Improved energy system safety, security, reliability, resiliency, and cost-effectiveness**
- **Results in:**
  - **Technically sound, commercially viable, secure advanced microgrids with mixed generation including renewables**
  - **Advanced microgrids capable of operating grid tied of islanded**
  - **Template for mission critical asset energy security for a city, utility, or military base an by collecting the cost and performance data needed to accelerate technology**

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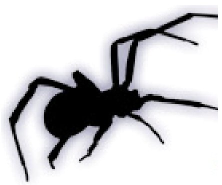
Example Sandia ESM Military Applications



TRANSITION

- Template for DoD-wide implementation
- CONOPS
- TTPs
- Training Plans
- DoD Adds Specs to GSA Schedule
- Transition to Commercial Sector
- Transition Cyber-Security to Federal Sector and Utilities

CAMP SMITH ENERGY ISLAND

- Entire Installation Smart Microgrid
- Islanded Installation
- High Penetration of Renewables
- Demand-Side Management
- Redundant Backup Power
- Makana Pahili Hurricane Exercise
- 4 MW
- Demo Mar 2014

FT CARSON ADVANCED MICROGRID

- Large Scale PV (50%)
- Vehicle-to-Grid
- Only Critical Assets
- CONUS Homeland Defense Demo
- 3MW
- Demo May 2013

PEARL HARBOR / HICKAM AFB CIRCUIT LEVEL DEMONSTRATION

- Renewables (20% PV)
- Storage – Flow battery
- Energy Management
- Peak Shaving
- 1 MW
- Demo Dec 2012

CYBER-SECURITY

Sandia National Laboratories' Energy Security Program

Energy Security Roles

$250M DOE Energy Research Program

Support DoD on energy system, physical, and cyber security

System integrator for the DOE/NNSA

DoD Installation Security Projects

Energy Security Focus

Operational Energy Systems
- **Electric Power Assurance (microgrid, renewables, nuclear, storage, control systems, cyber)**
- **Transportation Energy Assurance (combustion research, renewable fuels)**

Climate Change Science
- **Operational Impacts**
- **Assessments**

Nuclear Design & Fuel Cycle

Combustion Research Facility

Distributed Energy Technology Laboratory

Sandia's Electrical Sciences Group

SANDIA NATIONAL LABORATORIES
ELECTRICAL SCIENCES

1350
Electrical Sciences
Larry Schneider

Financial/Space: Robert Petro, 10616 manager
Financial support: Renee Sisneros, 10616
OAAs: Bev Rudys, Peggy Aragon

1352 Electromagnetic Theory
Bryan Oliver

- EMPHASIS Code Development
- SGEMP, EMP, EMR
- Electrical Breakdown
- NW System Qualification

11 SNL tech staff (9 PhD)*
1 Staff Aug
Total:12

1353 Electrical Science & Experiments
Steve Glover

- Electromagnetic Experiments
- NW System Qualification
- High Voltage Sciences
- WFO Programs

8 SNL tech staff (5 PhD)*
6 SNL technicians
7 Contractors
Total: 21

1355 Electrical Models & Simulation
Scott Hutchinson

- Xyce Code Development
- Charon Code Development
- Physics & Model Development
- Application Analysts

11 SNL tech staff (12 PhD)*
1 Staff Aug
1 Contractor
Total: 13

1356 Component & System Analysis
Steve Wix

- Device Model Development & Extraction
- Test & Characterization
- Mixed Signal Analysis

3 SNL tech staff (1 PhD)*
2 SNL technicians
2 Contractors
Total: 7

*Includes managers

Electrical Sciences Group Total:
42 SNL (34 tech staff (27 PhDs), 8 technicians)*
10 Contractors
2 Staff Aug
2 Admin
56 total

The technical area leads

Len Napolitano
Champion

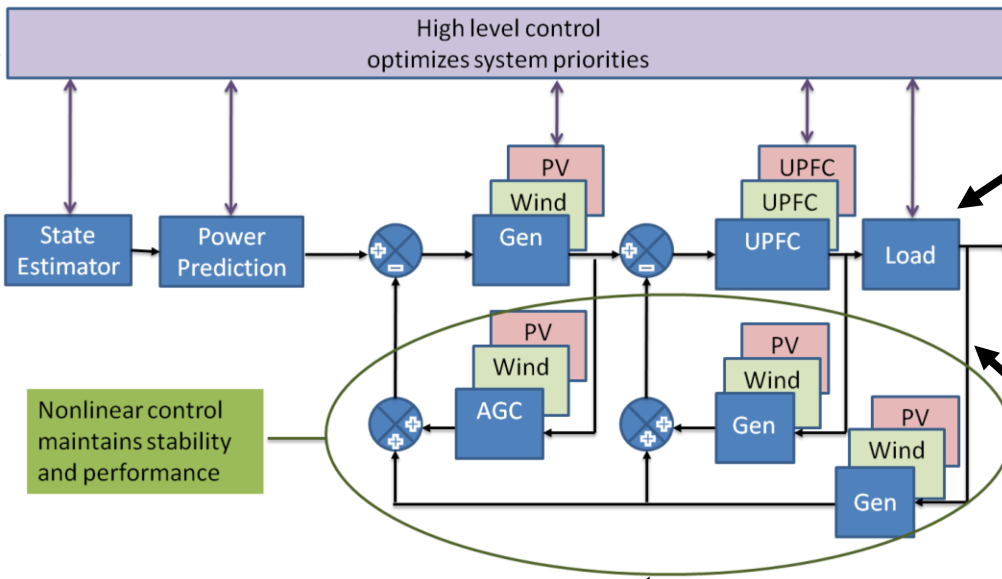
Larry Schneider
Project Manager

Steve Glover
Principal investigator

Ross Guttromson
Program Development

Jason Neely
Hardware, Modeling, & Simulation

Marvin Cook
Informatics

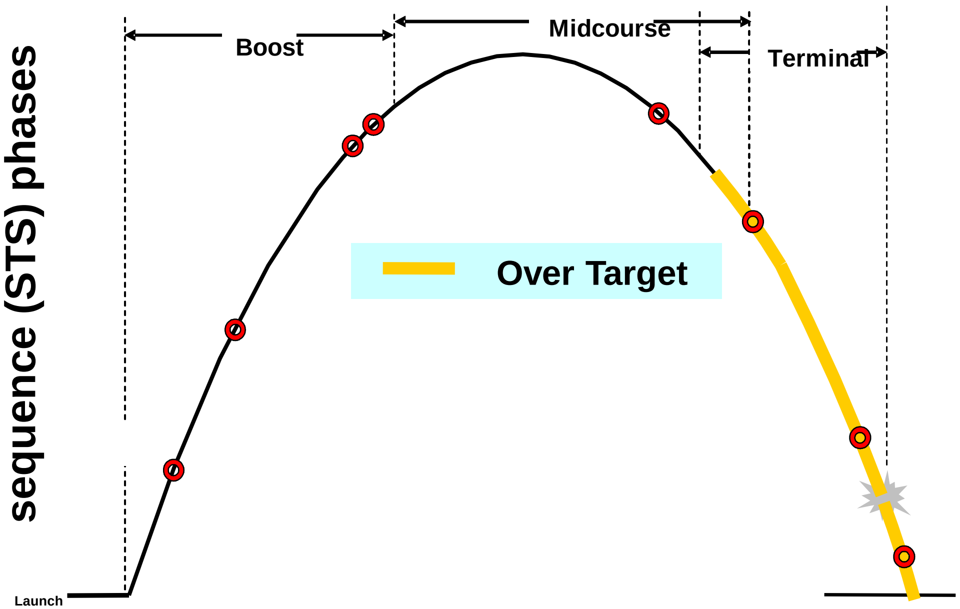


Tony Lentine
Communications

David Wilson
Nonlinear Controls

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

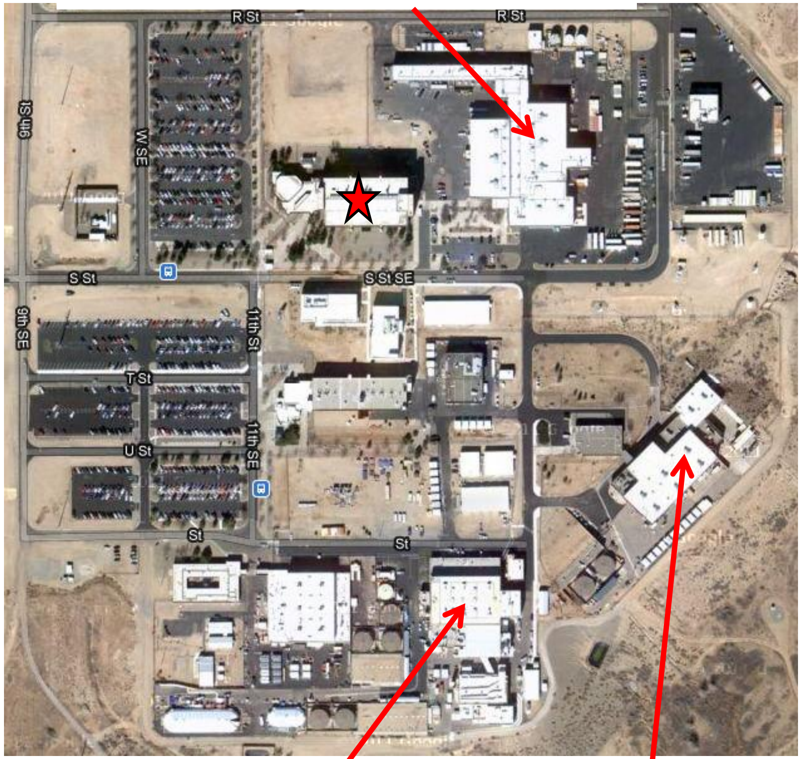
- Advanced power systems and AC/DC microgrids
- High voltage breakdown science & experiments
- Pulsed power components and systems development
- Electromagnetics theory/code development
- Electromagnetic experiments
- Systems engineering and integration

Sandia National Laboratories

Electrical and Radiation Sciences Customers and Organization and Facilities

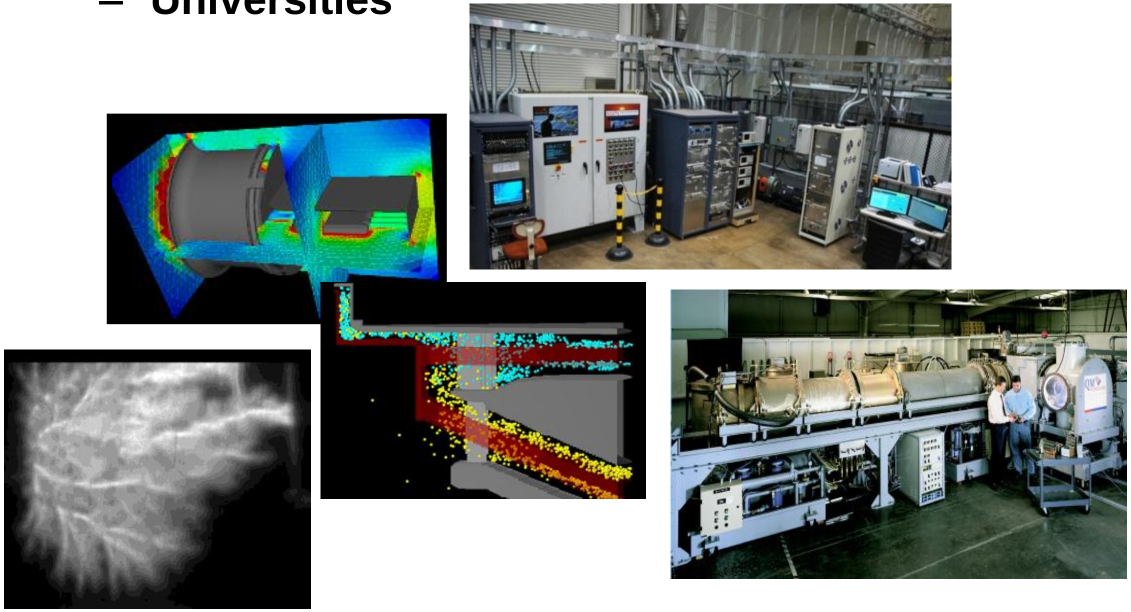
- **National security activities for and in collaboration with:**
  - **Department of Energy** (National Nuclear Security Administration, Office of Science, Office of Electricity)
  - **Other federal agencies** (DOD-Army/USAF/NRL, DOT-Federal Aviation Administration, DOL – Mine Safety and Health Admin.)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

HAWK
World's largest DC-like electron beam accelerator



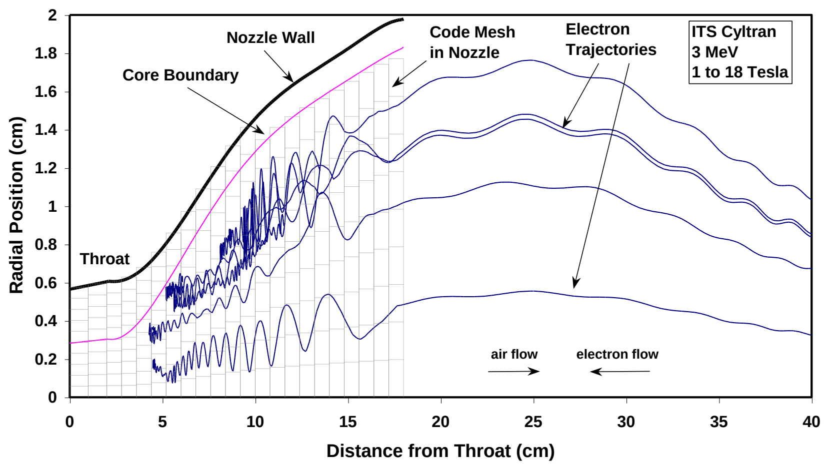
Z Machine (350 TW, 26 MA)
World's most powerful radiation source for fusion, dynamic materials and radiation effects sciences

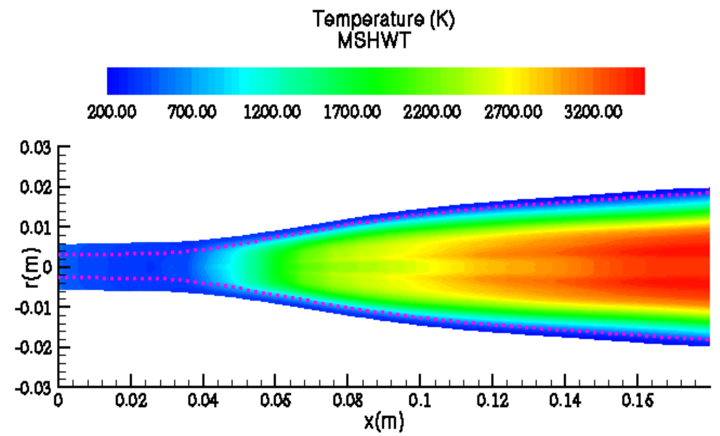
Hermes III
Flash x-ray source for nuclear weapons effects testing



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

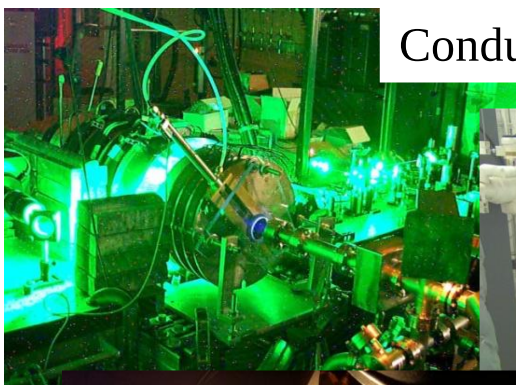
Coupled electron/photon Monte Carlo transport codes for energy addition and CFD





Conduct of complex experiments

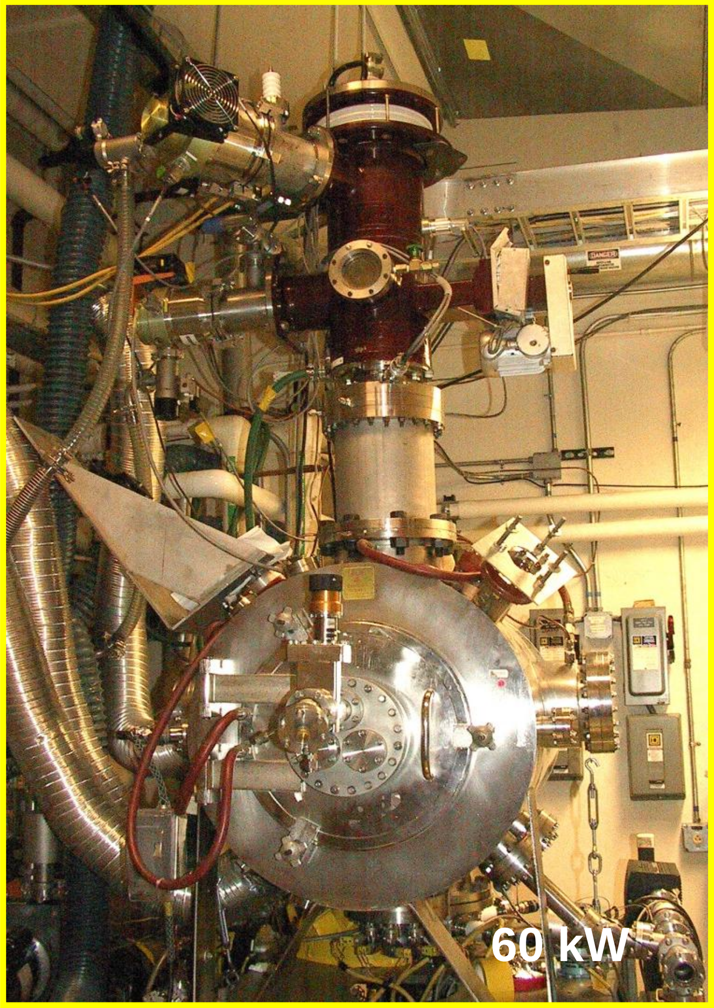
World class accelerator technology development



World's first large aperture vacuum window

Sandia National Laboratories

HHFF e-beams



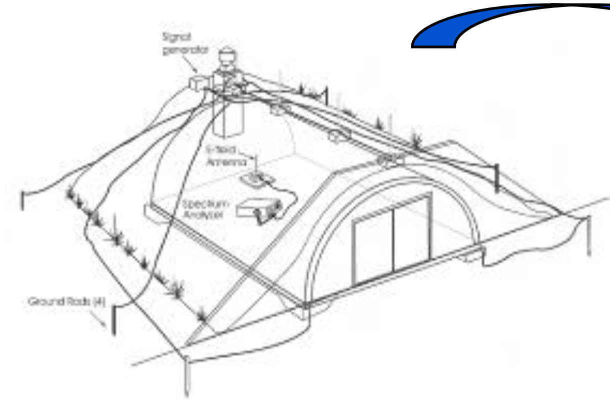
EB-1200

EB-60

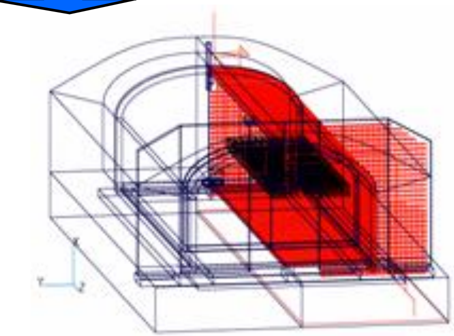
Sandia National Laboratories

Rigorous Lightning Protection Developed for DOE Nuclear Weapons Facilities

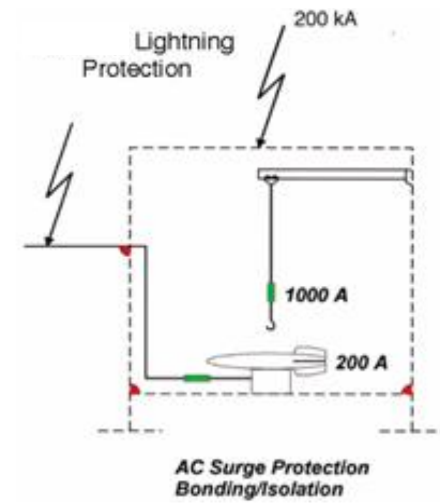
Lightning effects analysis, field transfer function measurements, engineered solutions for facility operations

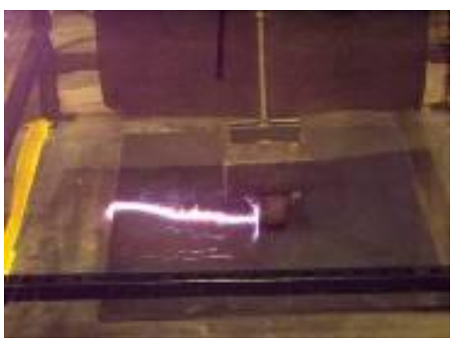


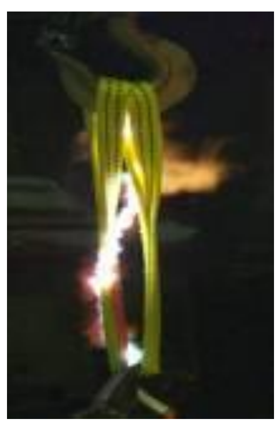
Field diagnostics/measurements



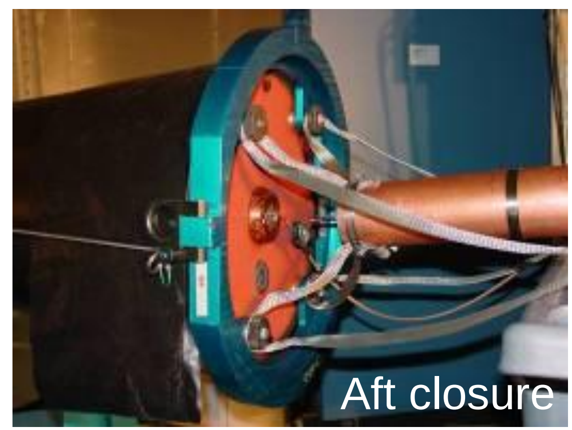
Modeling & analysis







High voltage standoff isolation



Weapons response to electrical static discharge

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.

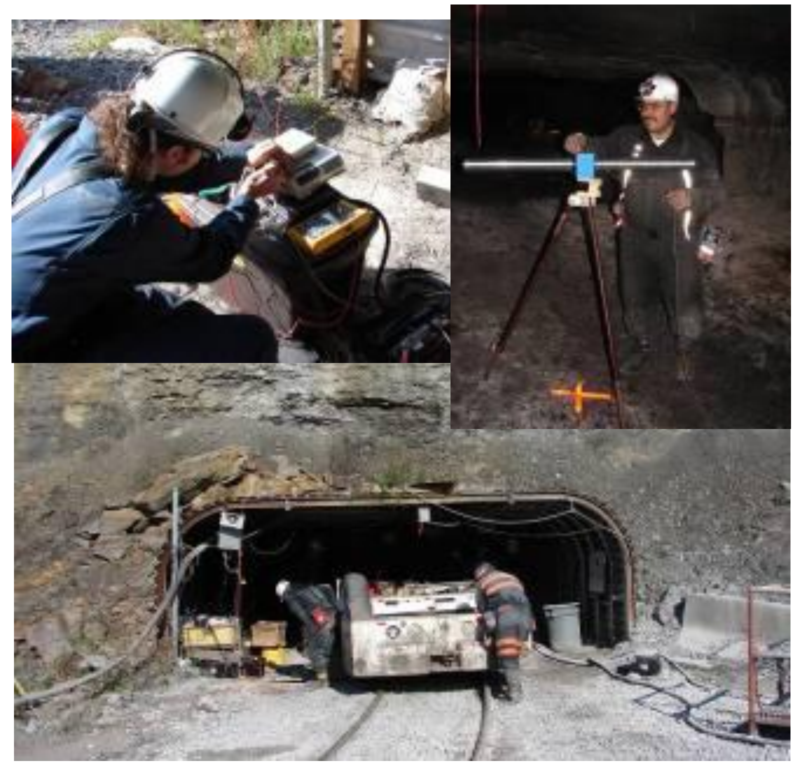
Report of Investigation
May 9, 2007 [1]

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.



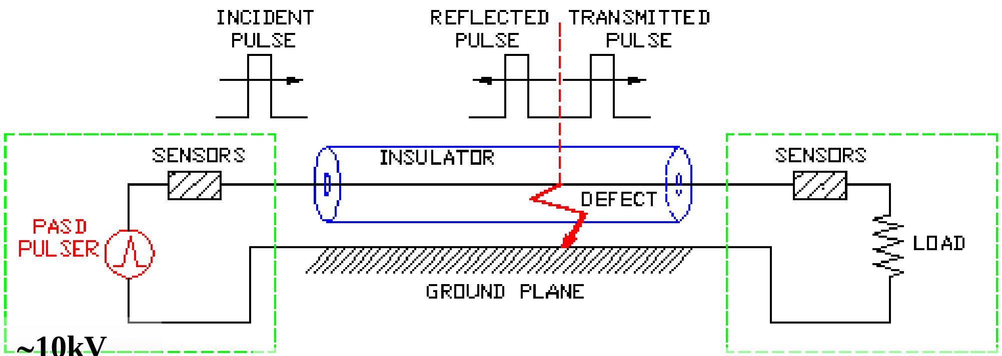
Sandia-developed techniques and diagnostics demonstrated a first-ever link between a mine explosion and indirect coupled lightning.

Sandia National Laboratories

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

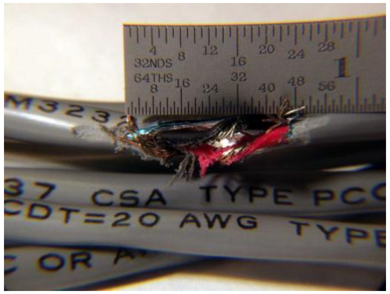
Another Example of Solving Problems Based on Techniques Developed for the NW Complex: Wiring Diagnostics

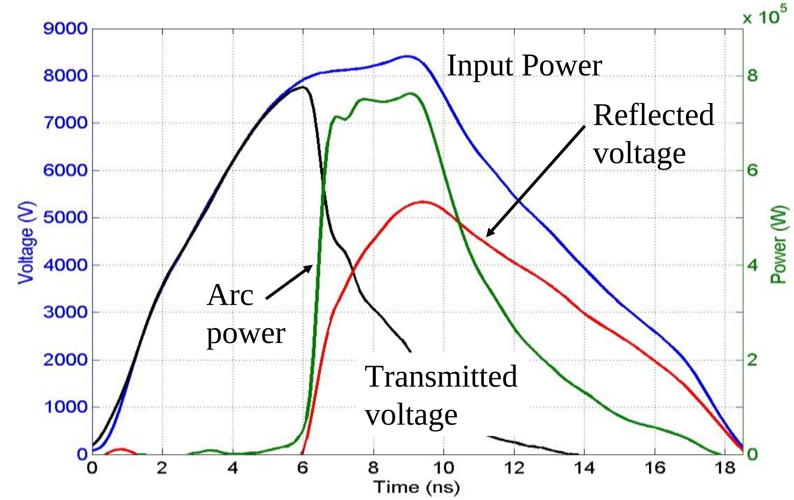
PASD can find and locate what no others can see – from pin-holes in the dielectric to crushed, but fully functional cables, waiting for a disaster to occur.



~10kV
10-30 ns

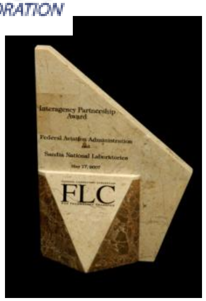
PASD is a true non-destructive test of the dielectric strength of insulation





Commercialized by

ASTRONICS CORPORATION

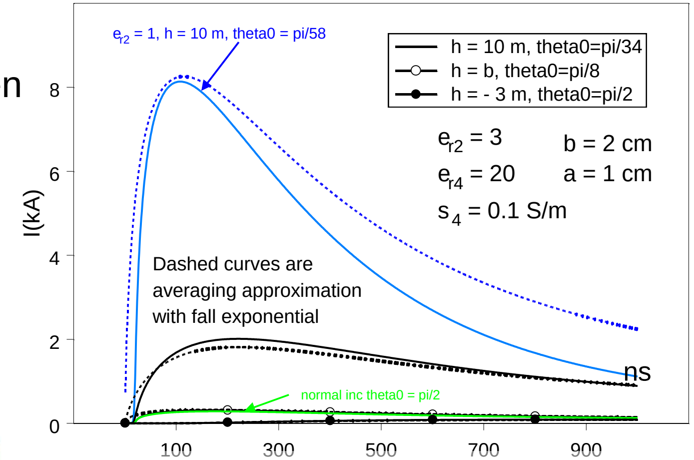


R&D 100

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

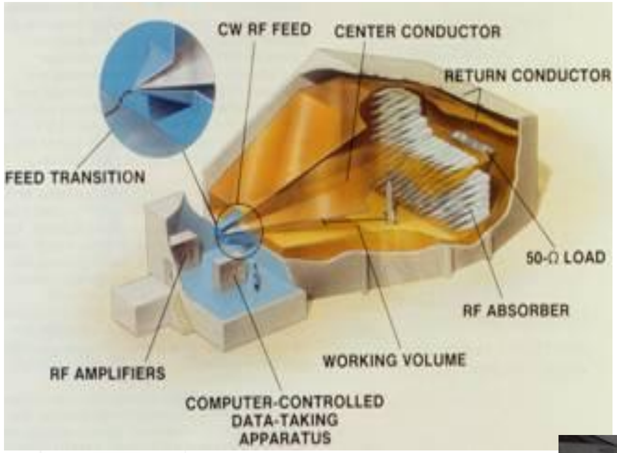
Support to the Congressional Commission on the impact of Nuclear ElectroMagnetic Pulse energy on power systems

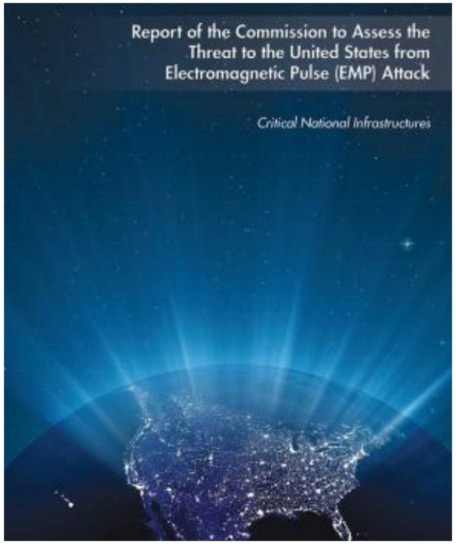
Warne / Chen

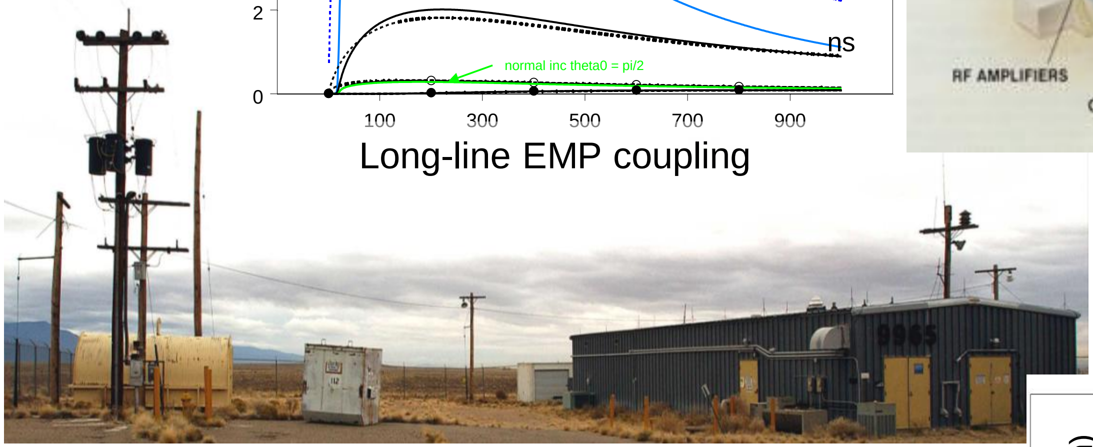


Long-line EMP coupling

Large scale TEM cell with full threat EMP capabilities

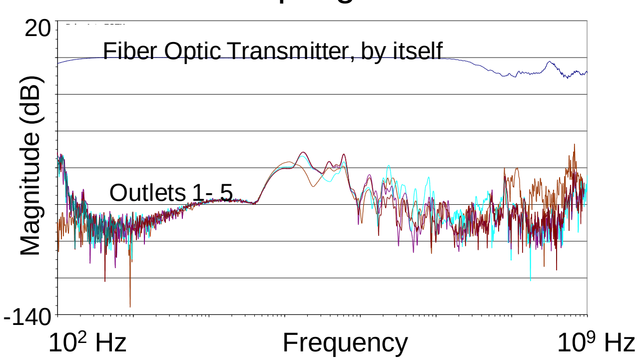




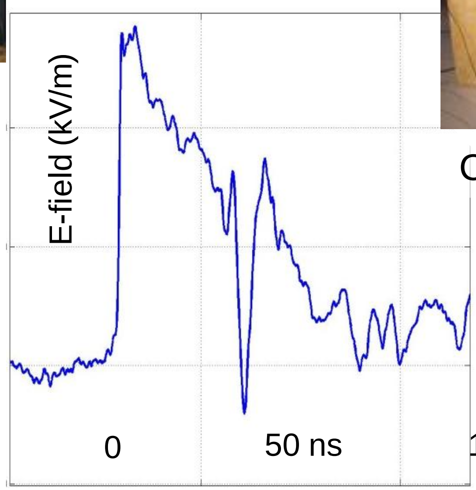


Communication Equipment

EMP coupling into facilities



Typical EMES EMP waveform



peak 30 – 250 kV/m

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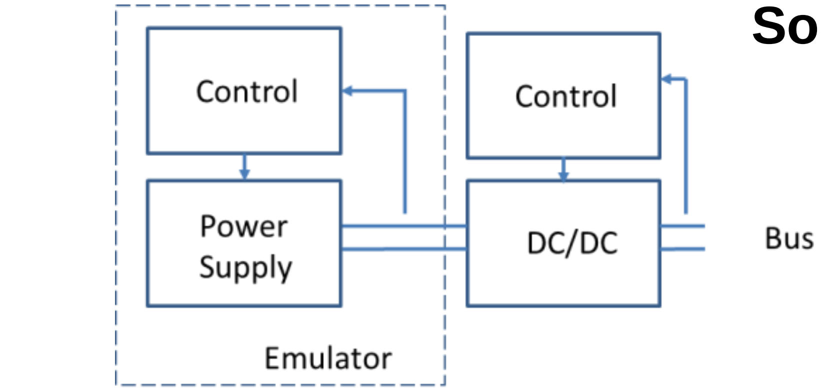
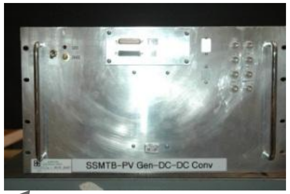
Infrastructure: Flexible SSM DC Testbed

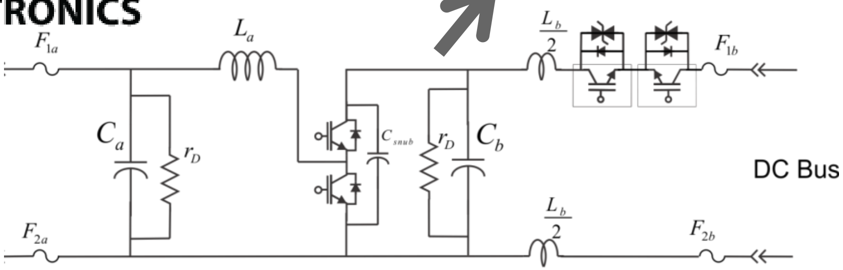
SSM Testbed Handles Stochastic and Deterministic Sources

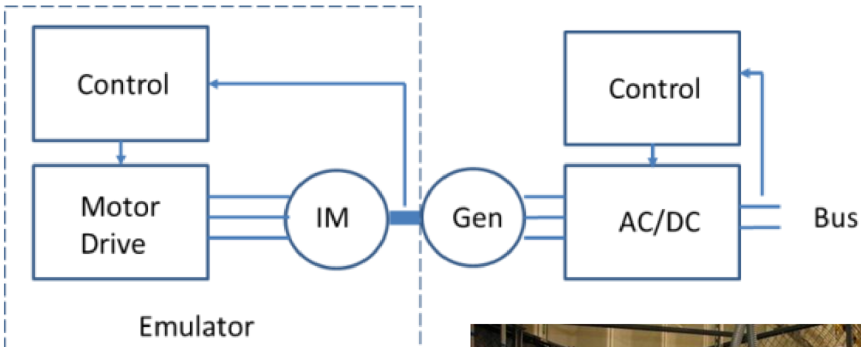


Solar (8 kW, 16 A)

DC/DC converter



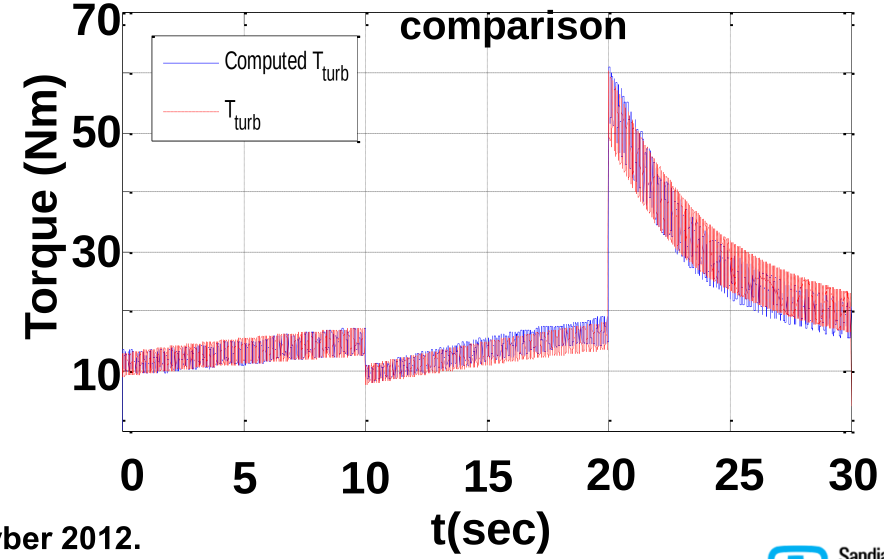




Wind turbine emulator 7.5 kVA

Diesel generator emulator 10 kVA

Simulated turbine and emulator comparison



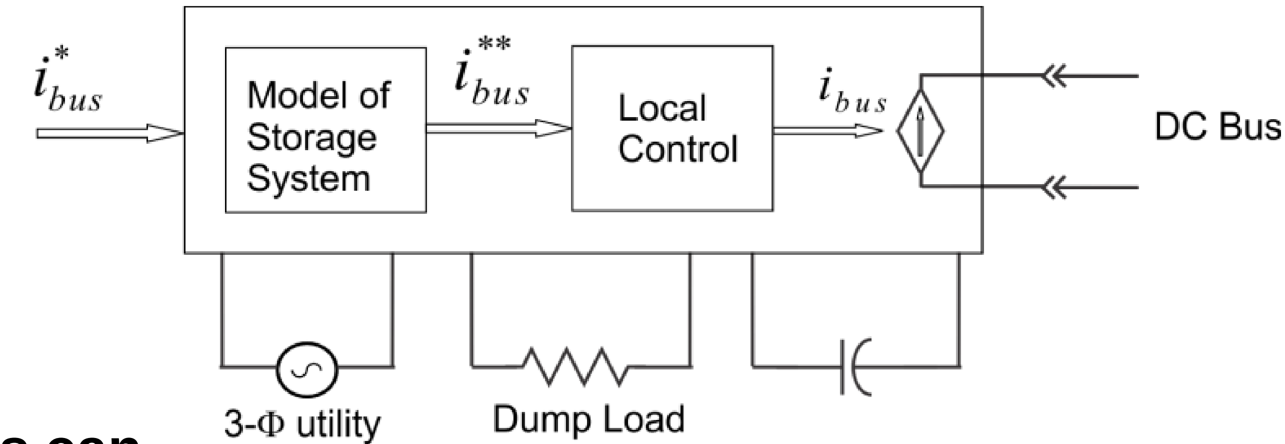
J. Neely, et al., "Wind turbine emulation for microgrid development," Cyber 2012.

J. Neely, et al., "An economical diesel engine emulator for microgrid research," SPEEDAM, June 20, 2012.

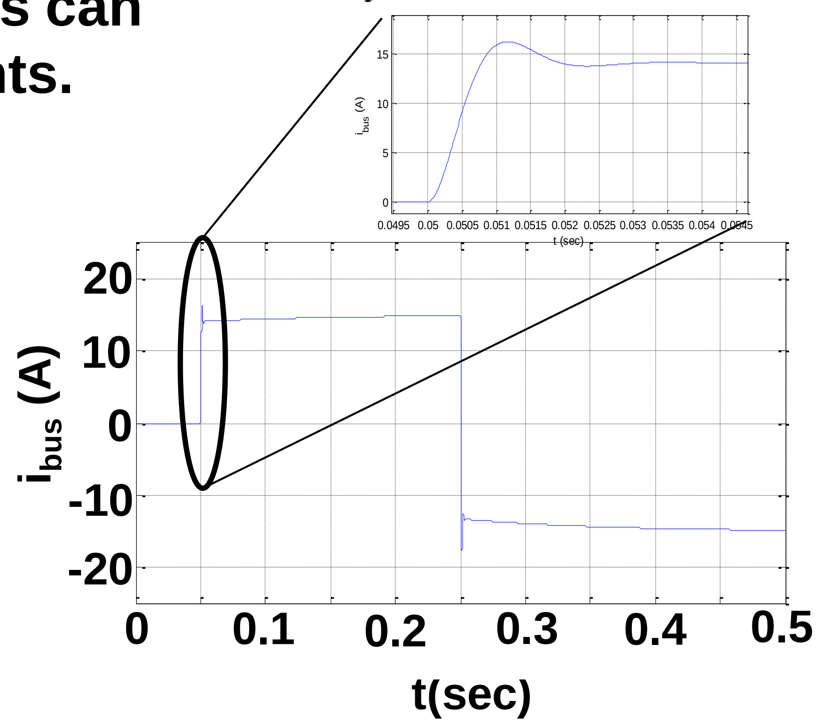
SSM Testbed Includes Energy Storage Emulation

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.



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

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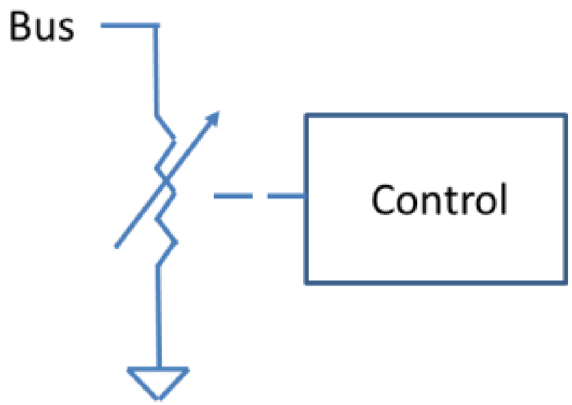
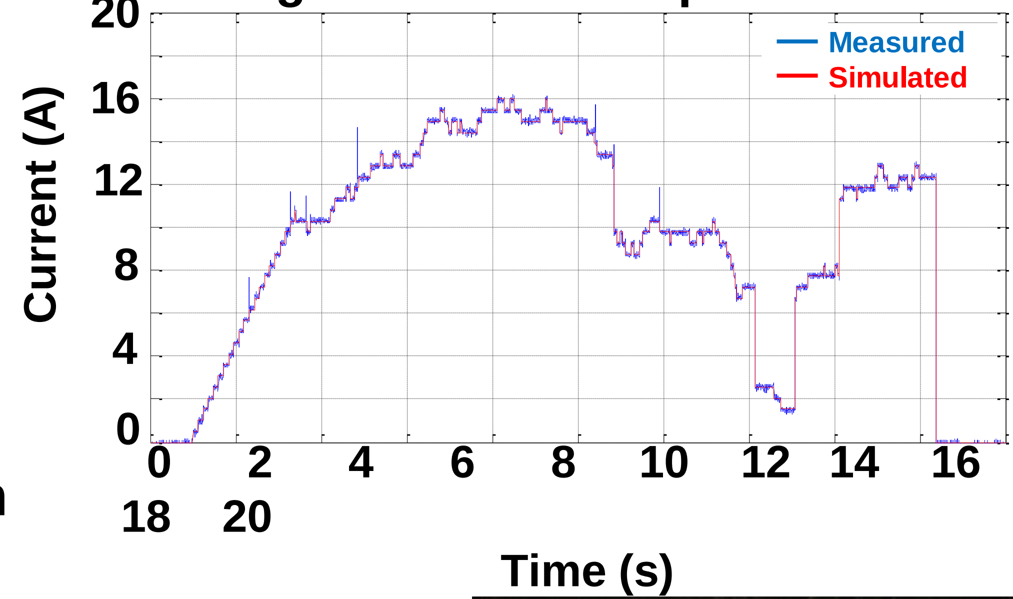
SSM Testbed Handles Active and Passive Loads and a Range of Profiles

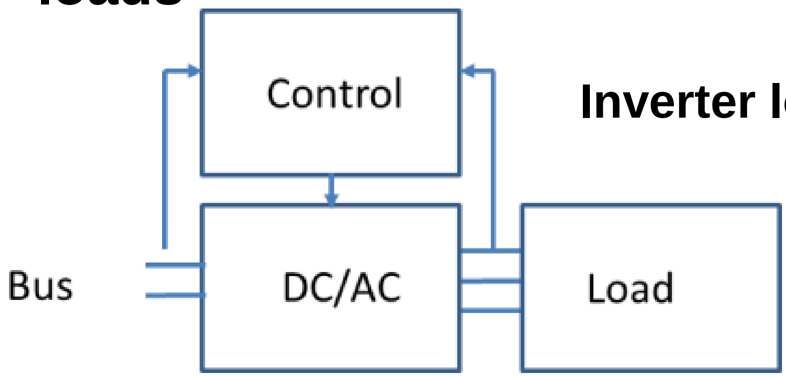
Resistive load and profile (6.7 kW max)



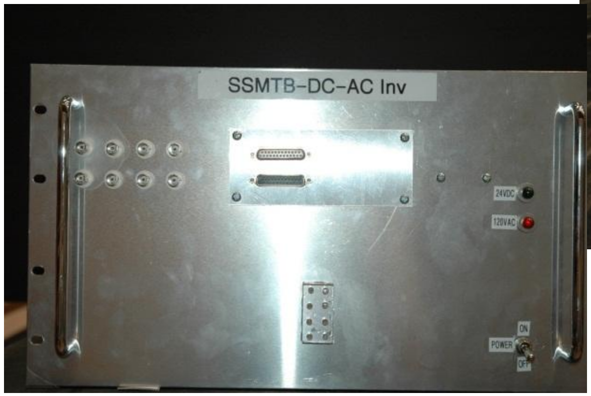
Programmable load profile

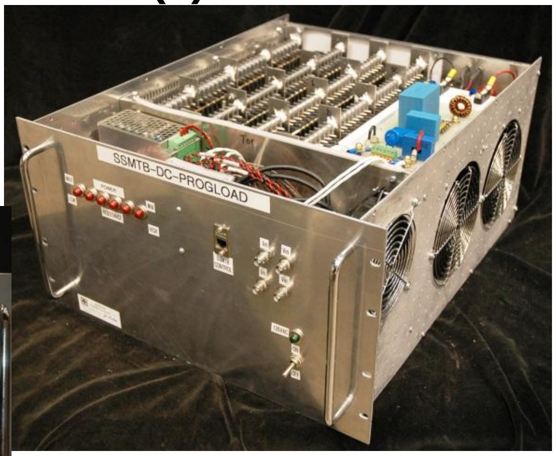


High level control can interact with loads



Inverter load (5 kW max)



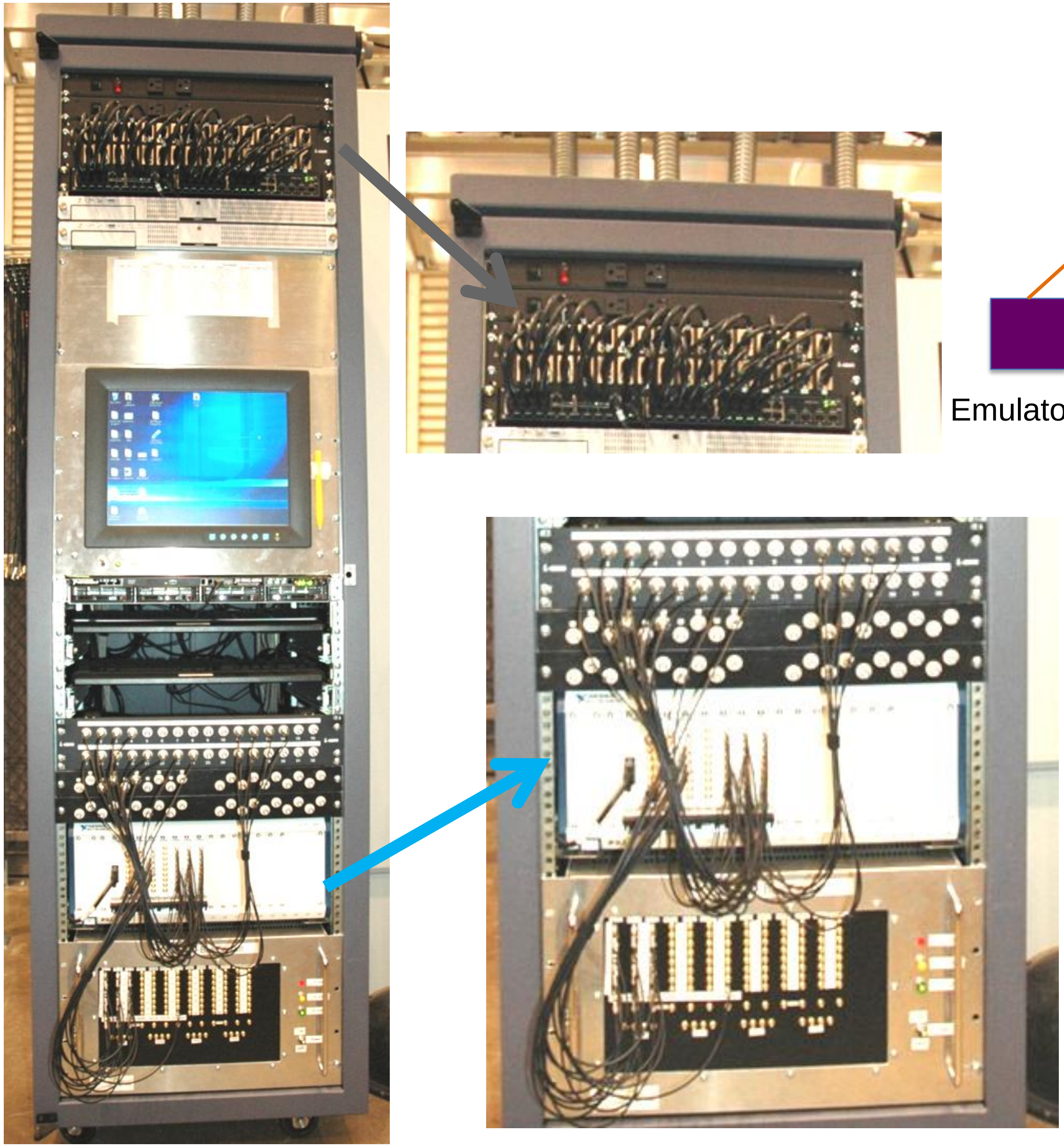


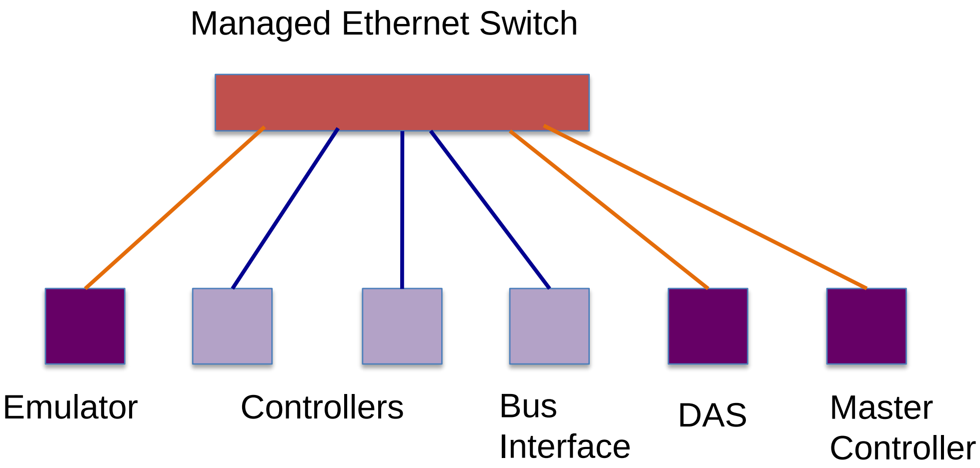
SSM Test bed Includes a Controllable Buss Enabling Adaptive Topologies

- **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**

Energy Challenge - Harvest, Transform, and Control Delivery of Available Energy

Energy & Material Resources

- Fossil (coal, oil, gas)
- Solar (including wind and hydro)
- Geothermal
- Nuclear
- Plant, animal, and human waste
- CO_2 & other energy conversion byproducts

Energy Processing

Harvest, transform, and deliver exergy* at the necessary amount and rate.

Energy Needs or Services

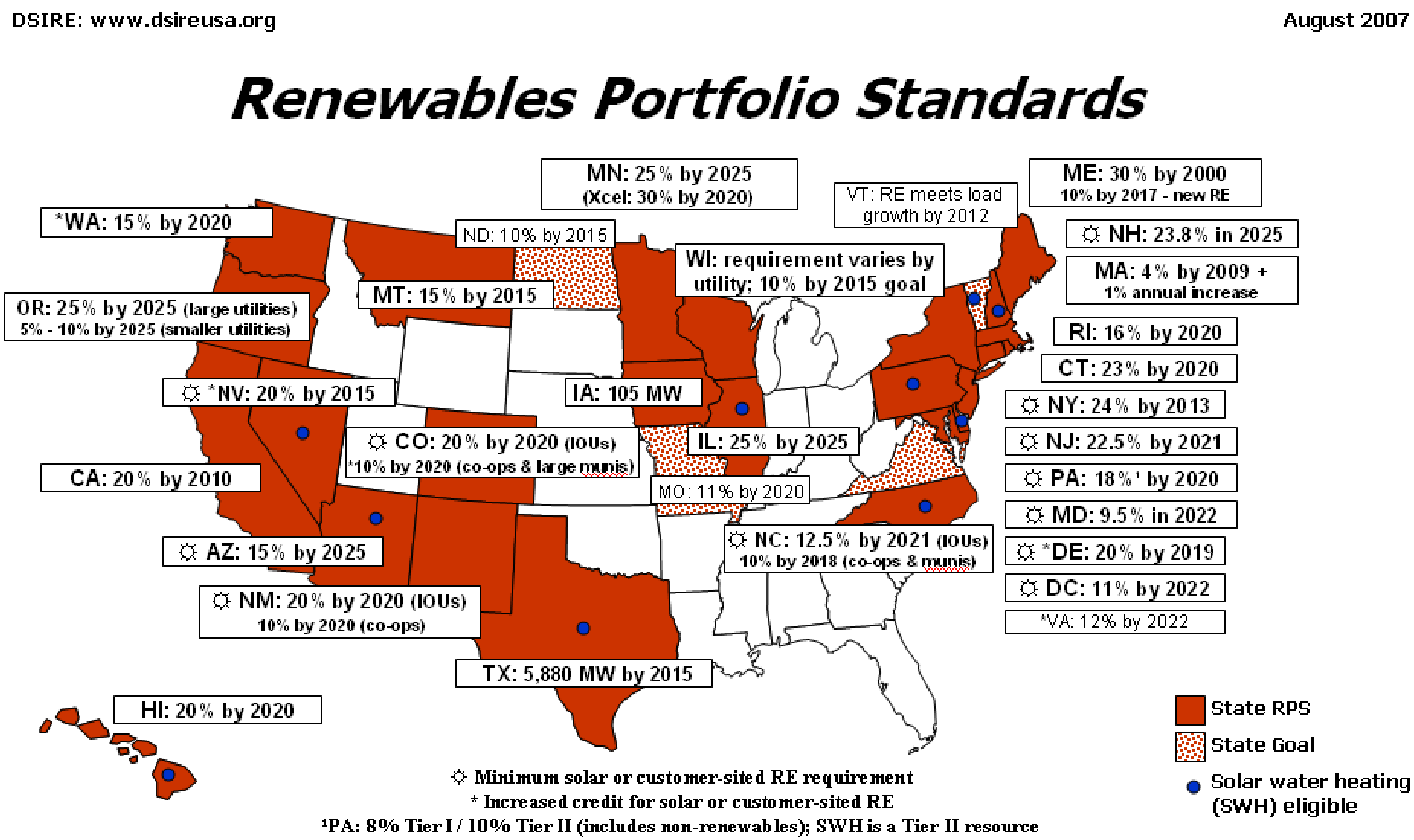
- Electricity
- Fuel
- Heat
- Cooling
- Chemicals (such as lubricants)
- Clean Water

*EXERGY = AVAILABLE ENERGY = useful portion of energy that allows one to do work and perform energy services

Future Grid Needs to Handle Large-Scale Renewable Energy

Climate change concerns, renewable portfolio standards, incentives, and accelerated cost reduction driving steep growth in U.S. renewable energy system installations.

Managing stochasticism inherent in renewable sources is challenging and / or costly (i.e., storage, fallback generation capacity).



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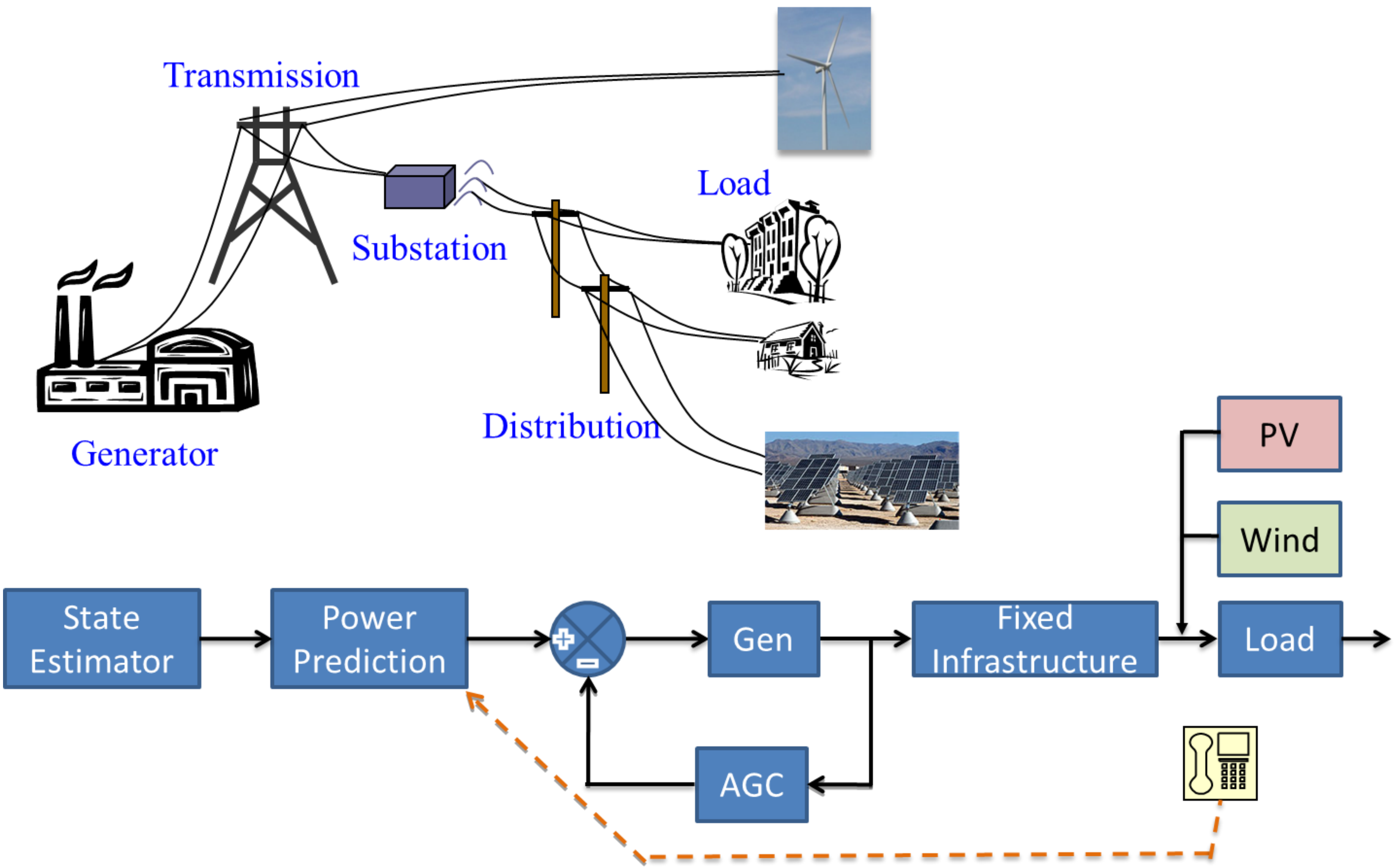
SSM Status

- The SSM test bed is operational
- Hamiltonian based control design techniques have been experimentally validated with 100% stochastic generation
- Agent design advancements have demonstrated agent based partitioning of energy management set points
- Real time simulation capabilities have been demonstrated with the SSM models
- Distributed Hamiltonian based control design method for AC systems has been determined and can be structured like a DC system
- Army Network exploitation tool has been connected to the SSMGC communication network
  - Threat analysis continues

SSM Collective Status

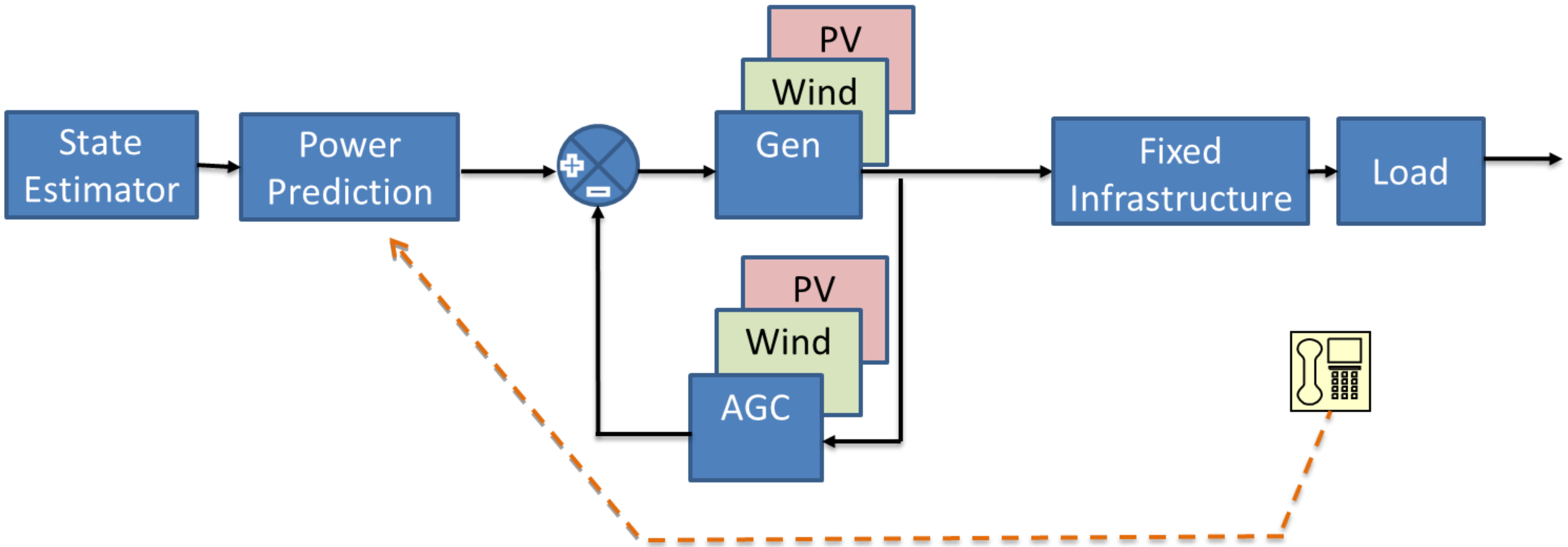
- Power sharing between microgrids has been demonstrated with limited controls
- Distributed Hamiltonian based control design method for networked DC systems is in progress
- Distributed Hamiltonian based control design method for networked AC systems is in progress
- Informatics based algorithms for collectives are under development

Today Stochastic Renewable Sources are 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.



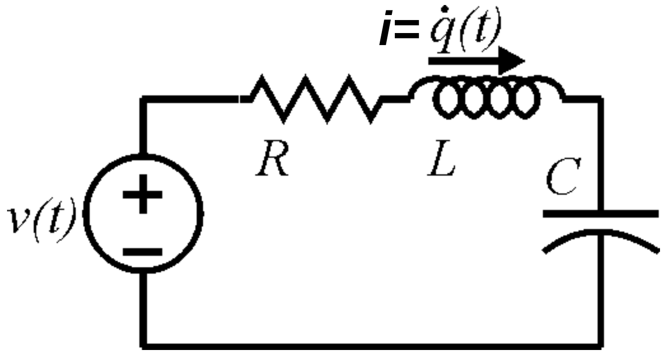
Both our generation and our loads are now random!

Accomplishments: Control Theory Expanded from Simple to Complex Systems

Example system with control input v(t).

$$\sum v = 0 \qquad L\frac{di}{dt} + \frac{1}{C}\int i dt = v(t) - Ri$$

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



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

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

Control gains

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

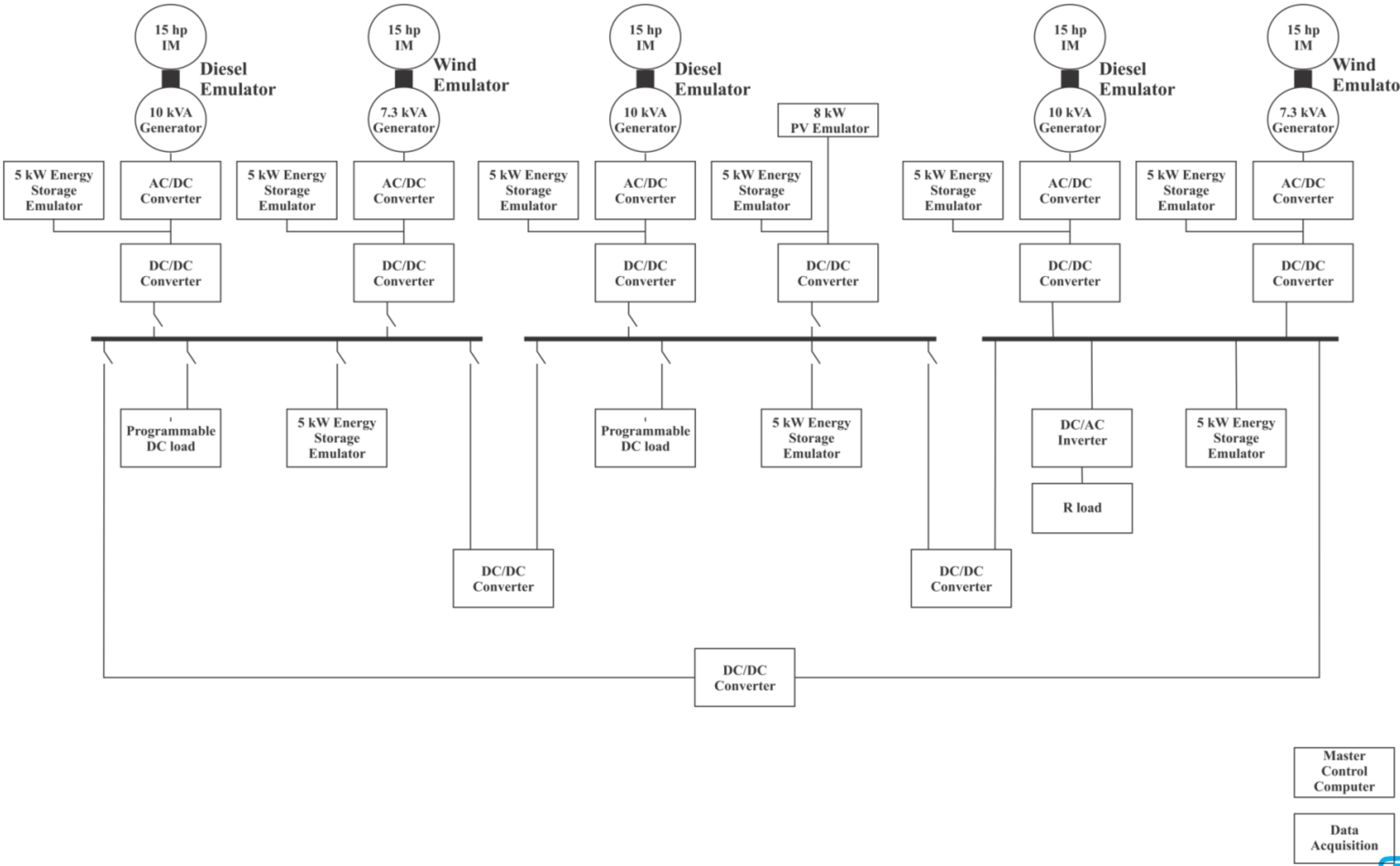
Storage **Generation, G** **Load, L**

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

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

$$\int_0^{\tau_c} \dot{H} dt = \int_0^{\tau_c} [G - L] dt < 0$$

SSM collective structure



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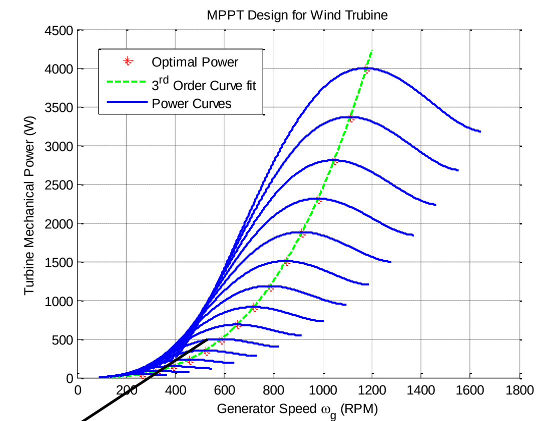
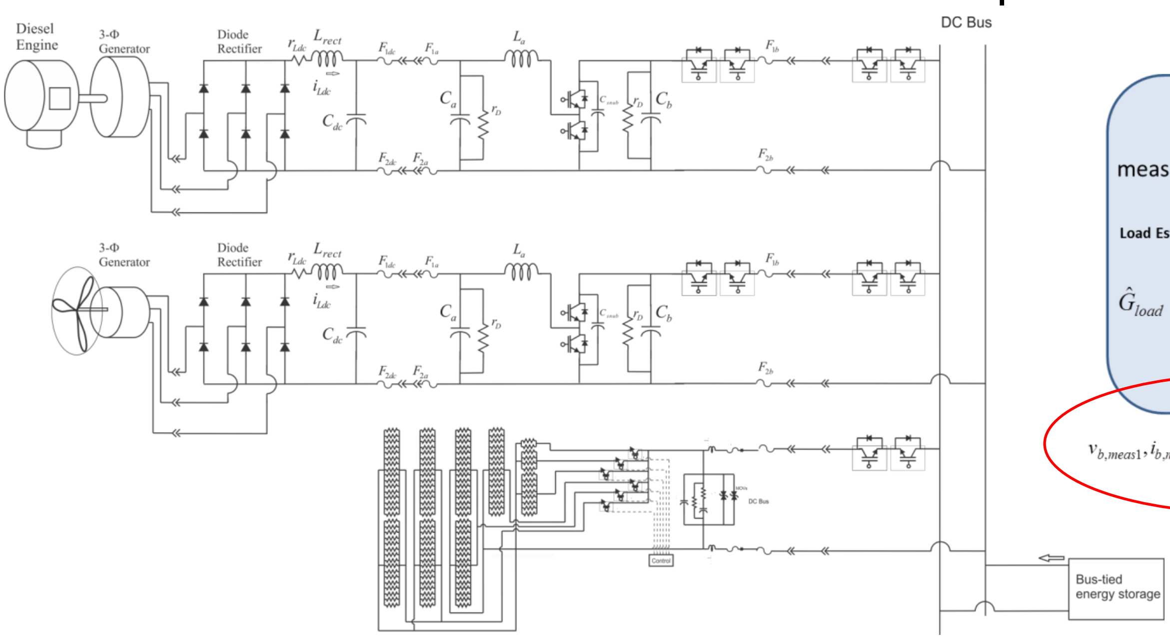
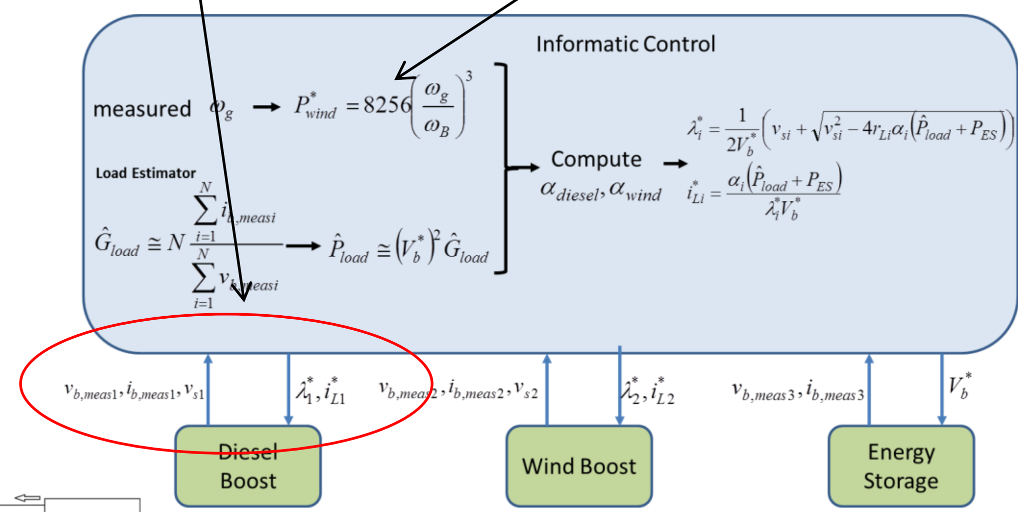
Testbed Allows Network Interface of Different Control Platforms for Advanced Control

- **Given Candidate System Configuration, load/weather profile and candidate control scheme**
- **Example Objective:**
  - **Achieve power balance, MPPT of Wind, SOC regulation of Energy Storage**



All inputs/outputs available over network for use by conventional computer





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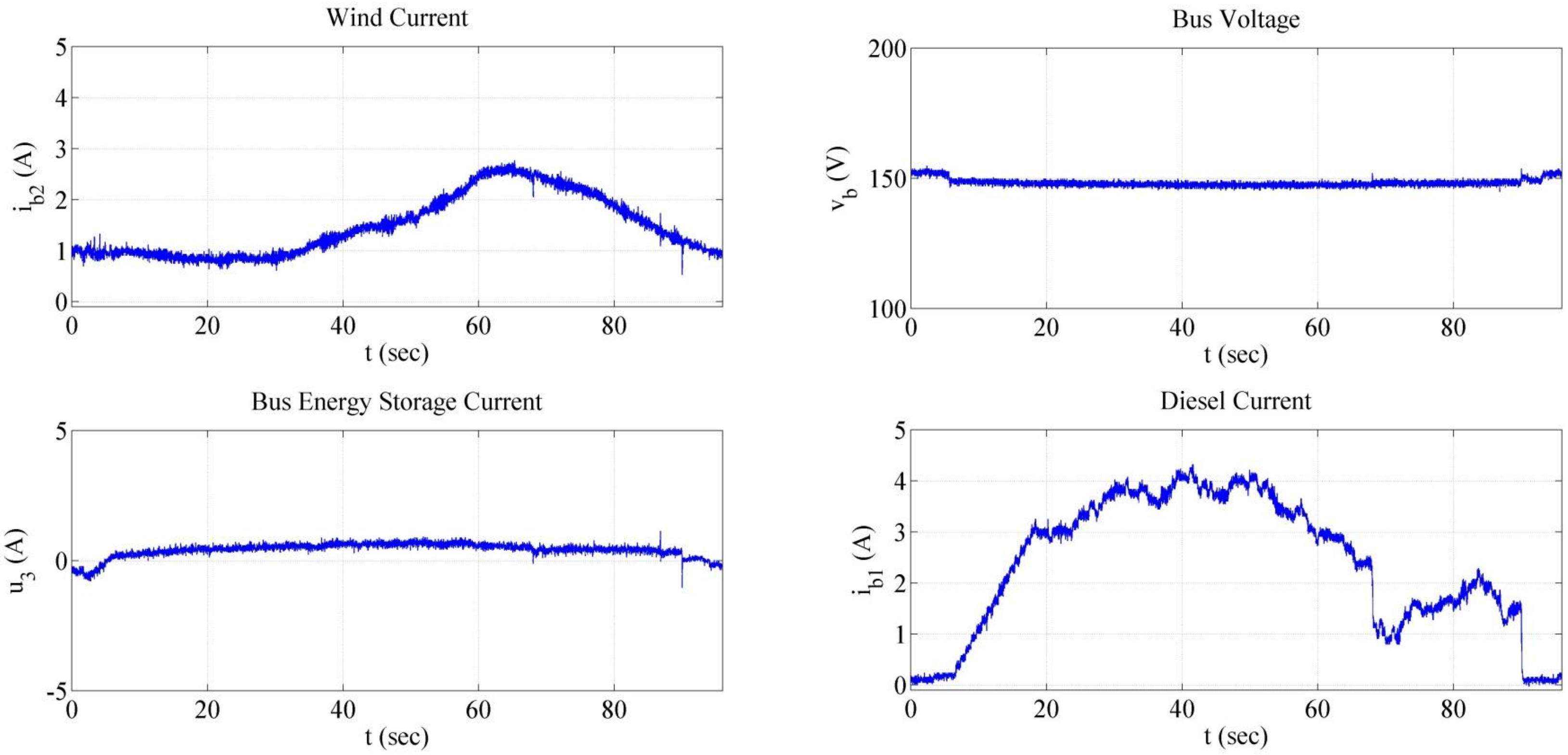
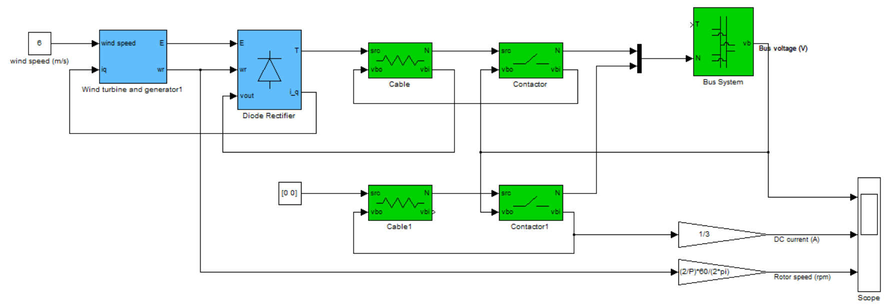
Testbed Allows Network Interface of Different Control Platforms for Advanced Control

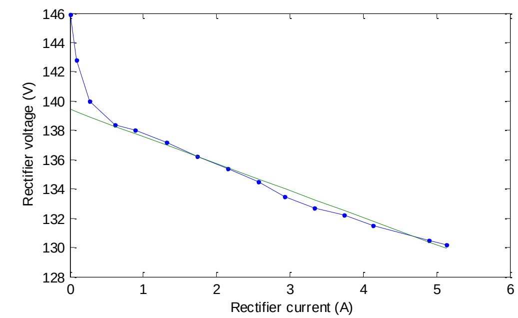
- Given Candidate System Configuration, load/weather profile and candidate control scheme
- Example Objective:
  - Achieve power balance, MPPT of Wind, SOC regulation of Energy Storage
- Automated synchronized data acquisition for post processing



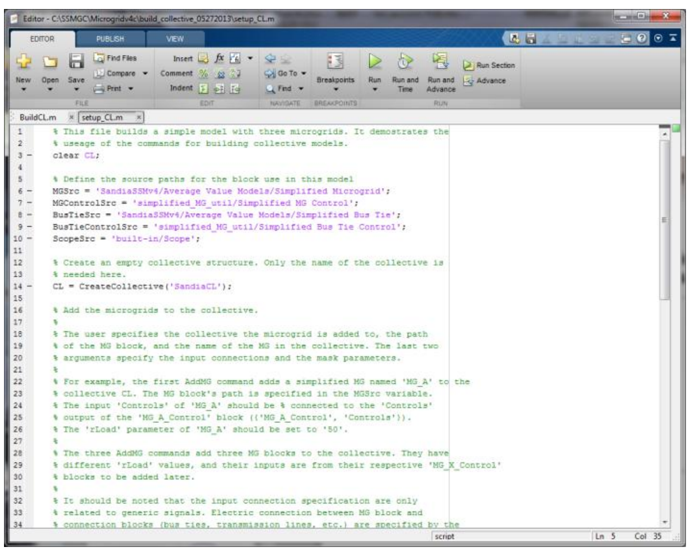
Hardware Components are Represented in a Matlab/Simulink Library

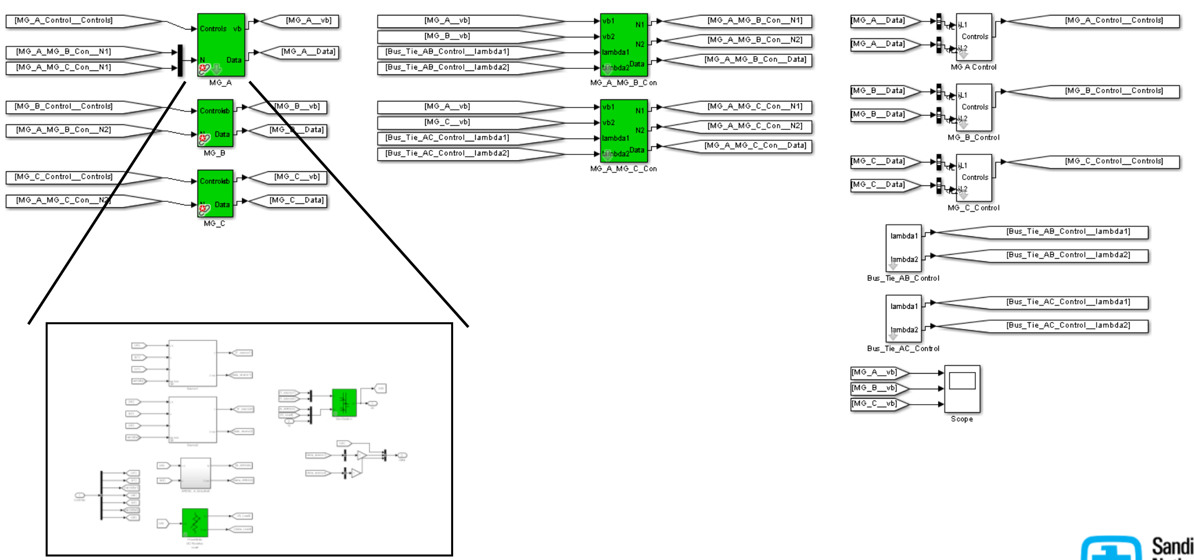
- **System components are modeled and calibrated to lab hardware**





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





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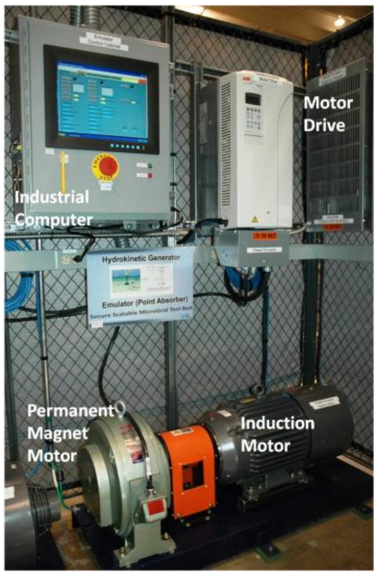
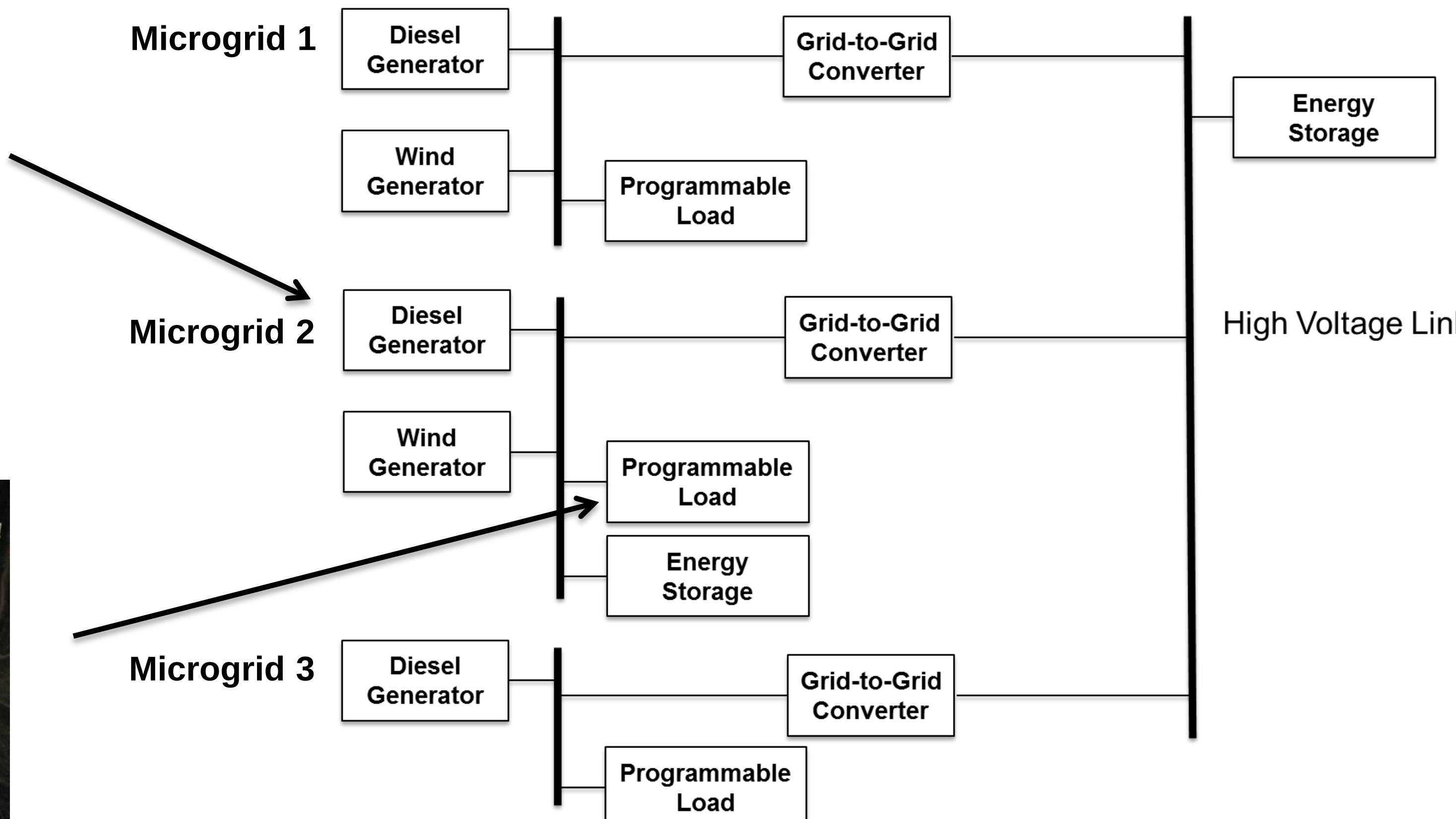
SSM Testbed Allows Study of Microgrid Collectives

- **A sophisticated heterogeneous microgrid collective may be configured from standard components in our testbed**





Our Basic Control Structure adds Capability and Supports Flexibility