SSM
SECURE SCALABLE MICROGRIDS
It's the end of the grid as we know it

SAND2014-15152PE

Hamiltonian Control Design for DC Microgrids with Stochastic Sources and Loads with Applications

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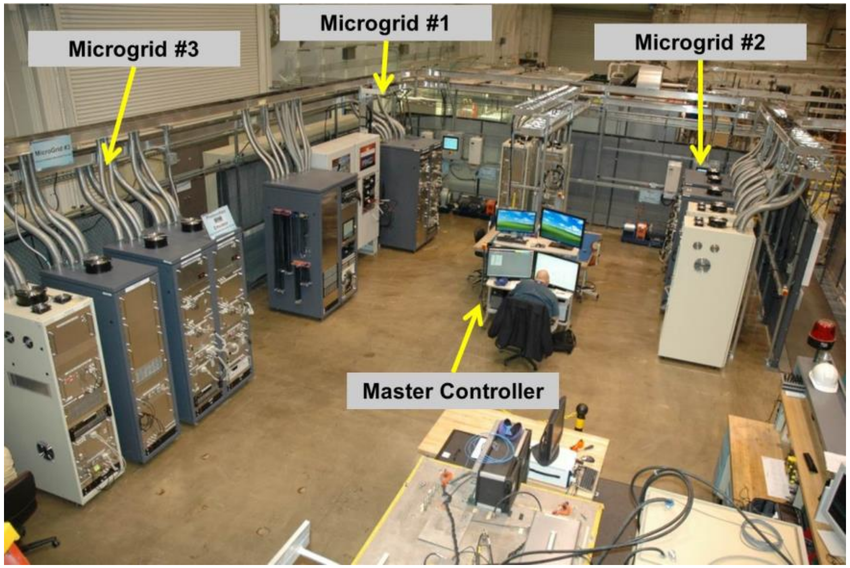
Outline

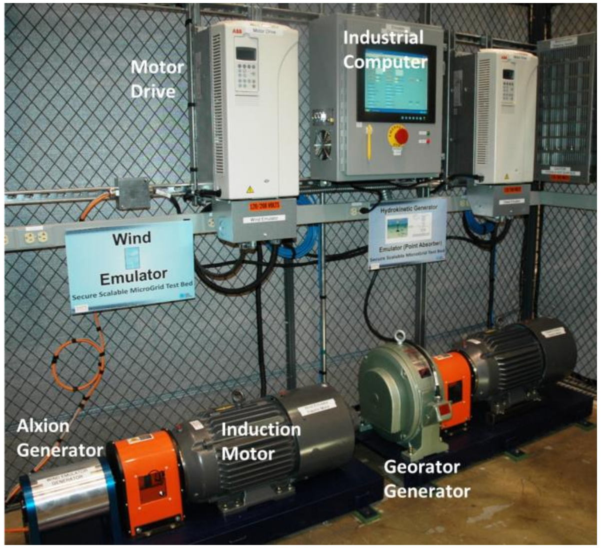
- **Secure Scalable Microgrid Testbed**
- **Microgrid Configuration and Modeling**
- **Dynamic Optimization/Planner**
- **Nonlinear Distributed Controller Design (HSSPFC)**
- **Single DC Microgrid Experimental Results**
- **Multiple Microgrid System Navy Electric Ship**
- **Conclusions**

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

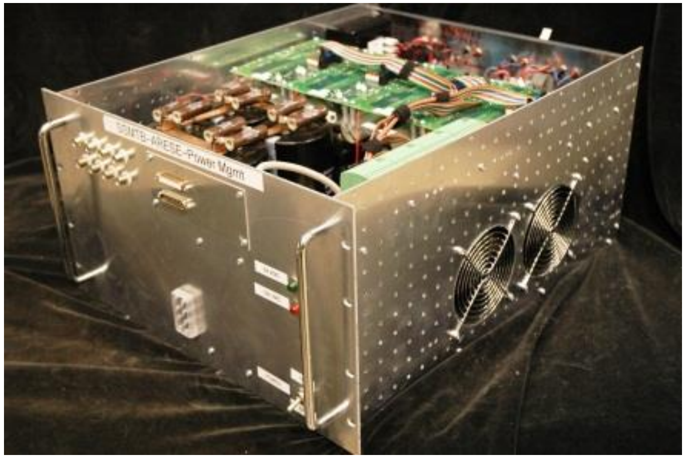
Multiple Microgrid Testbed



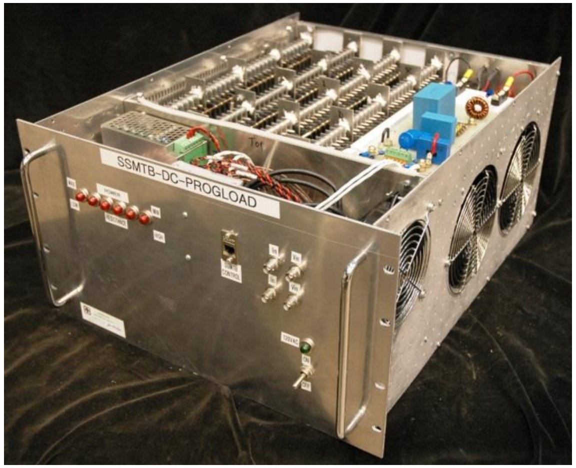
Mechanical Source Emulators



Energy Storage Emulators

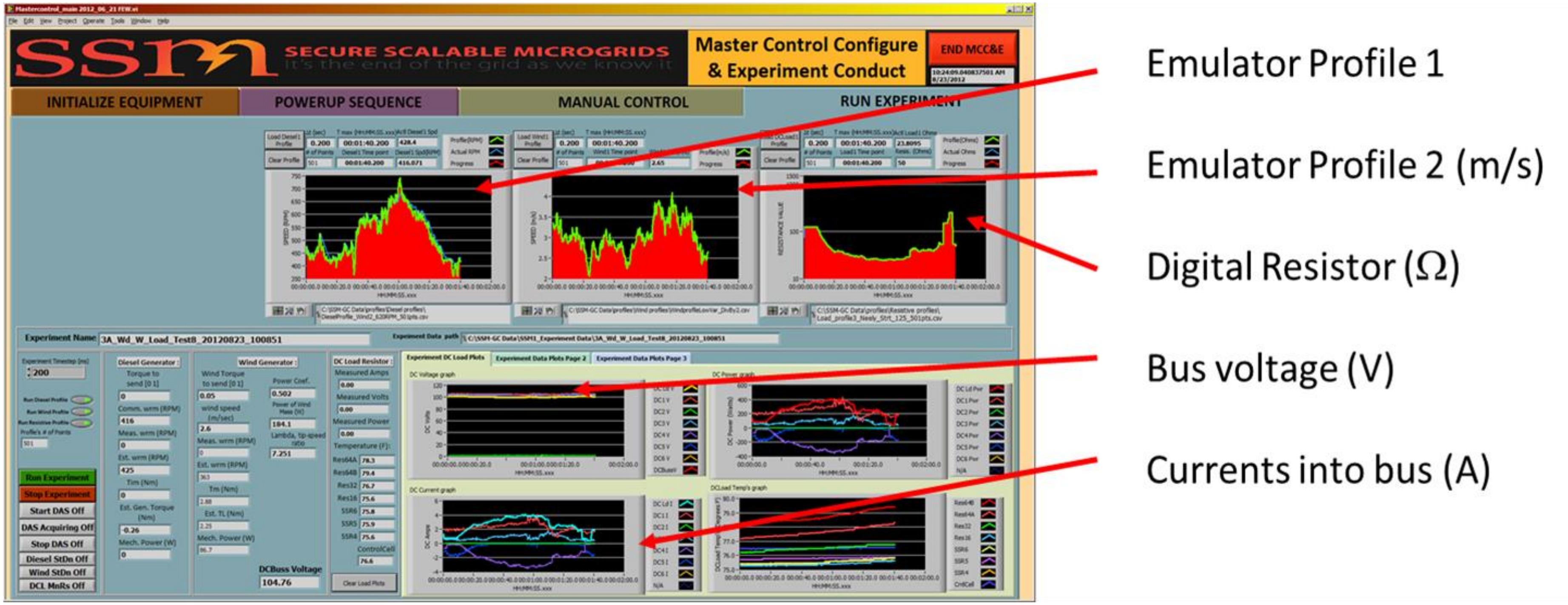


High Power Digital Resistor – Load Bank

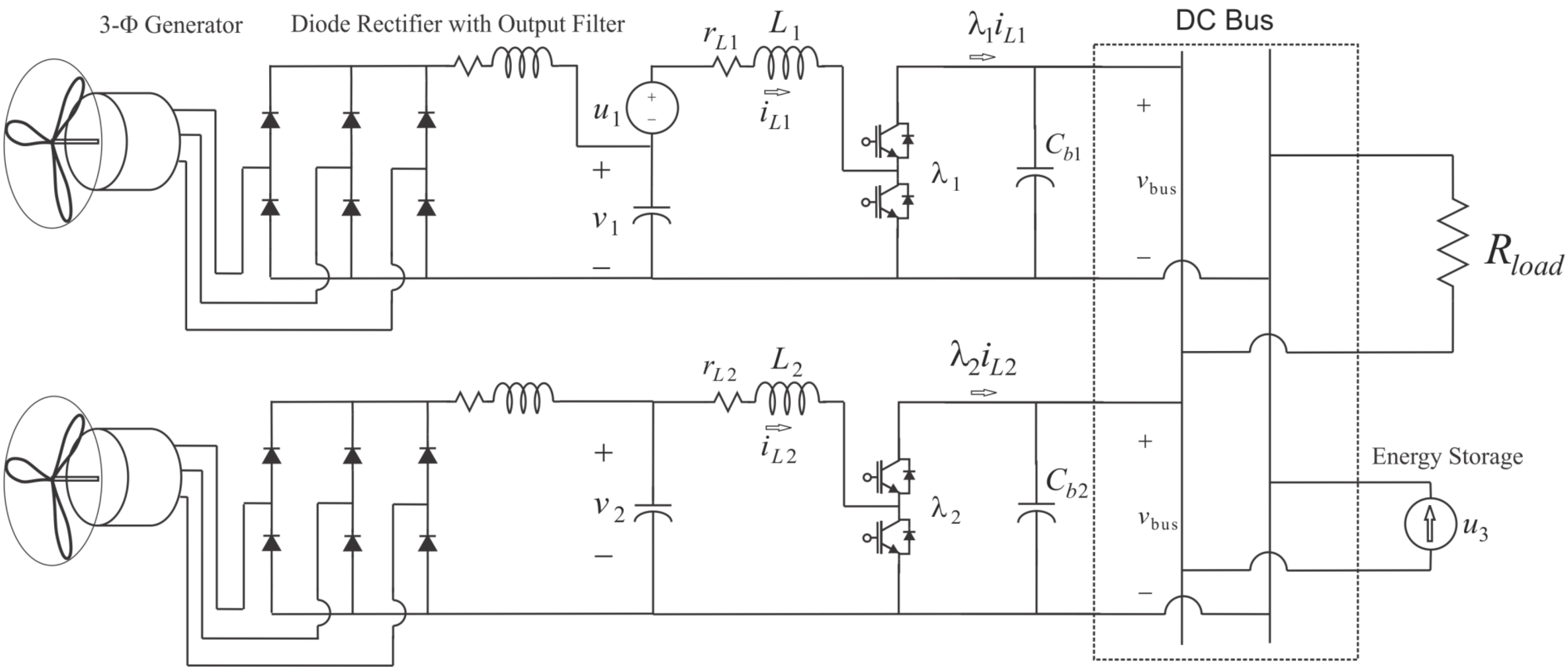


SSM Master Controller Coordinates HSSPFC Control Experiments

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

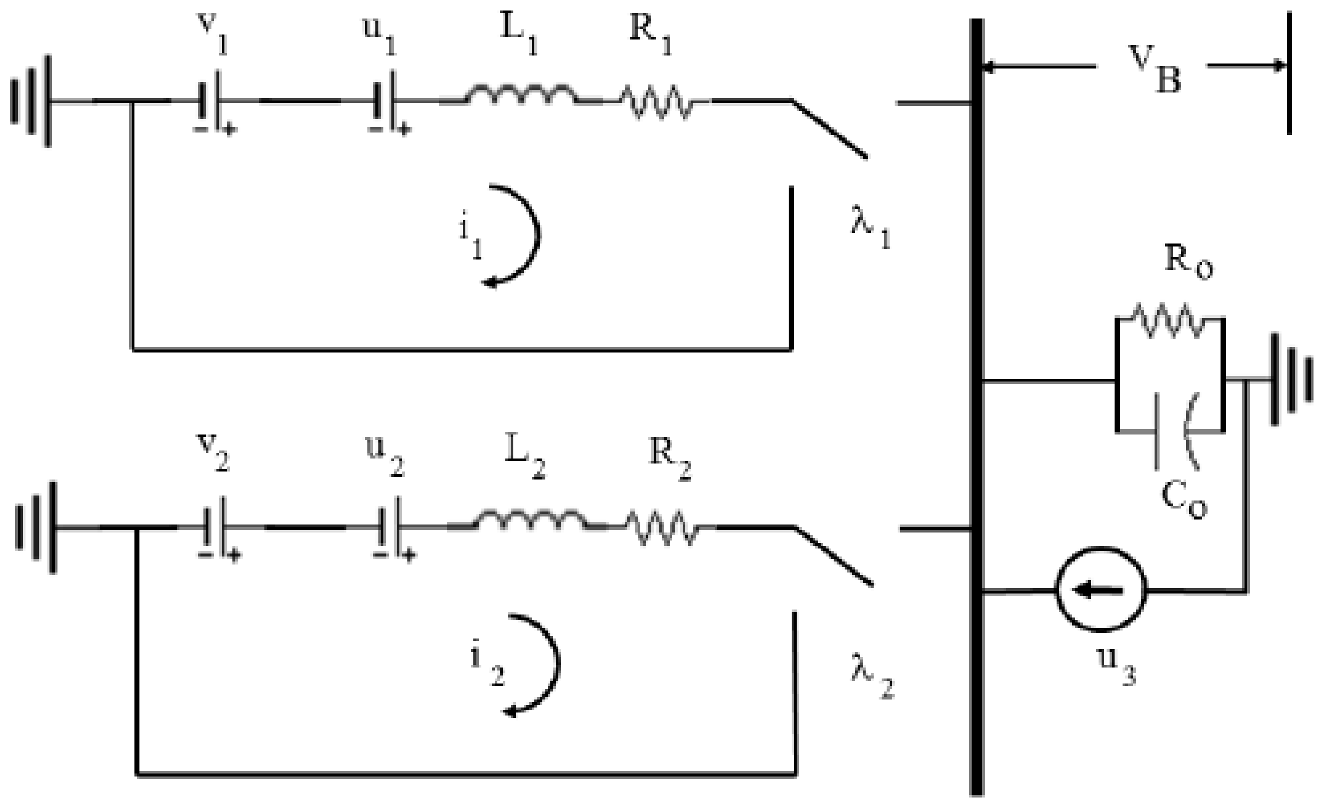


A Single DC Microgrid Configuration with Two Stochastic Sources was Studied



A Simplified Circuit Model is Used for HSSPFC Control Development

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



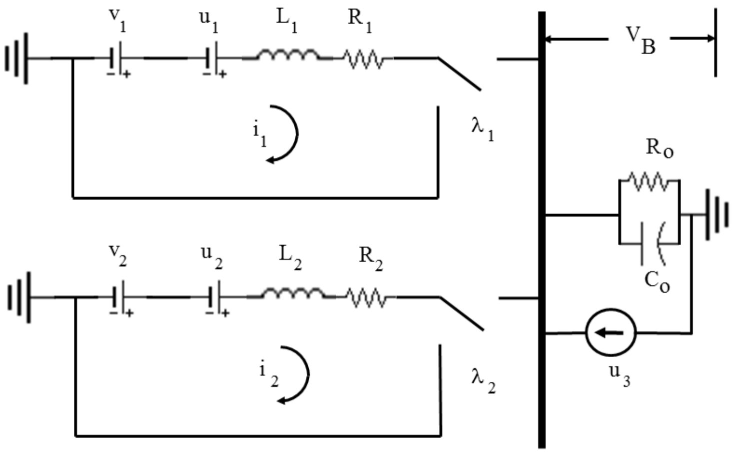
DC Microgrid Model:
2 Boost Converters with Voltage Sources

- Circuit equations for 2 boost converters and DC bus:

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

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

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



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

- Represented in matrix form as:

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

- or compactly as:

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

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

A Dynamic Optimizer/Planner Computes Optimal Operating Points

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

Optizelle

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

Ethernet
TCP IP
Network

Informatic Control Layer

AGENT 153772
AGENT 253752
AGENT 153773
AGENT 253753

SSM Testbed

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Optizelle uses a Model-Based Formulation

- **Guidance (duty cycle, set-points) algorithm utilizes single DC microgrid model**

  1) steady-state solution

  2) dynamic optimization formulation

- **General formulations identified for the following microgrid configurations:**
  - **Single DC microgrid: Multiple boost converters on single DC bus**
  - **Multiple DC microgrid: Multiple boost converters on multiple DC buses connected by multiple DC transmission lines**
  - **Multiple AC microgrid: Multiple three phase inverters on multiple AC buses connected by multiple DC transmission lines**
- **Concrete optimization codes developed using Optizelle for above formulations**

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Single DC Microgrid Optimization Problem is Defined

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

where

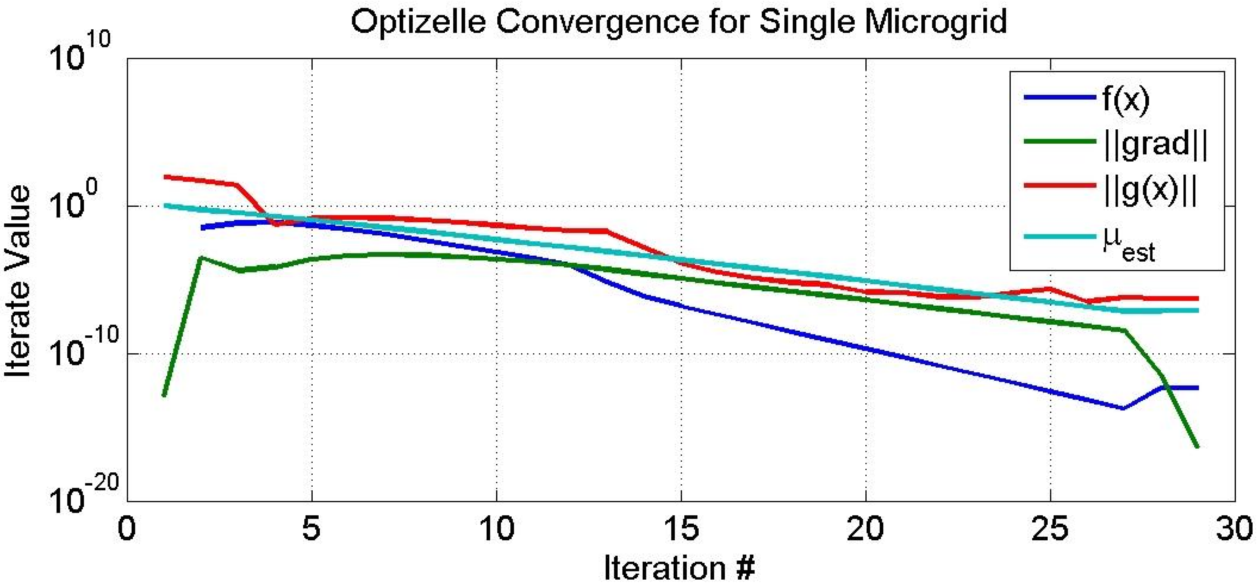
$$
\bar{R} = \begin{bmatrix} -R_1 & & & \\ & \ddots & & \\ & & -R_d & \\ & & & -1/R_o \end{bmatrix}, \quad \tilde{R}(\lambda) = \begin{bmatrix} & & & -\lambda_1 \\ & & & \vdots \\ & & & -\lambda_d \\ \lambda_1 & \cdots & \lambda_d & \end{bmatrix}
$$

Optizelle Numerical Convergence Single Microgrid Results

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

*Convergence time is affected by optimization input parameters

Optizelle NL MPC Optimizer Single DC Microgrid Convergence



HSSPFC Controller is Designed for Energy Storage

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

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

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

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

$$u_{ref} = -\left[\overline{R} + \tilde{R}\right]x_{ref} - v \qquad (1)$$

- **Next step define the Hamiltonian as:**

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

Static stability condition

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

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HSSPFC Controller is Designed for Energy Storage

- **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** $\tilde{x}^T \tilde{R} \tilde{x} = 0$

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

HSSPFC Controller is Designed for Energy Storage

- **Next step, select a PI controller as:**

$$\Delta u = -K_P \tilde{x} - K_I \int \tilde{x} dt$$

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

- **Substitute and simplify leads to:**

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

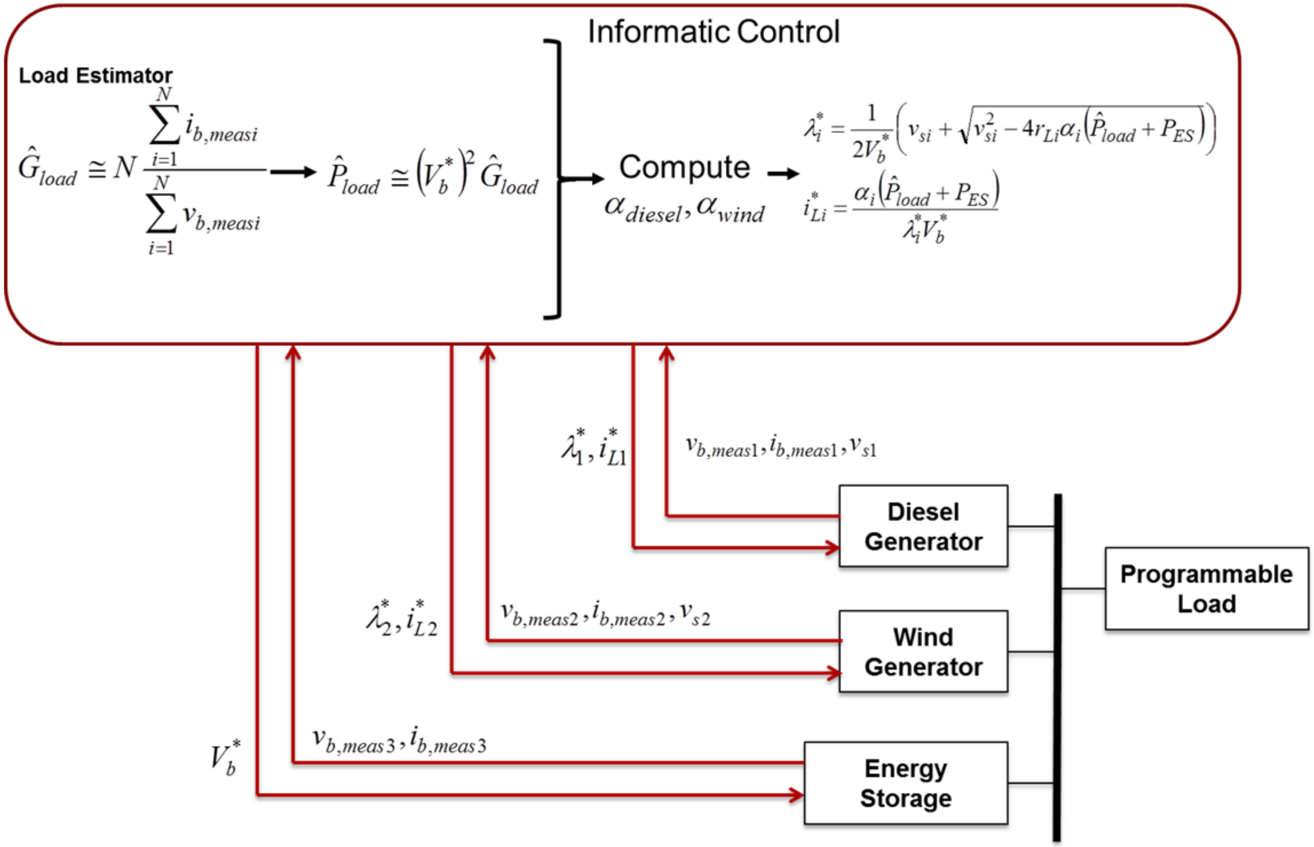
$$-\tilde{x}^T \left[K_P - \overline{R} \right] \tilde{x} < 0$$

Dynamic stability condition

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

Trade-off between Information Flow and Energy Storage was Investigated

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



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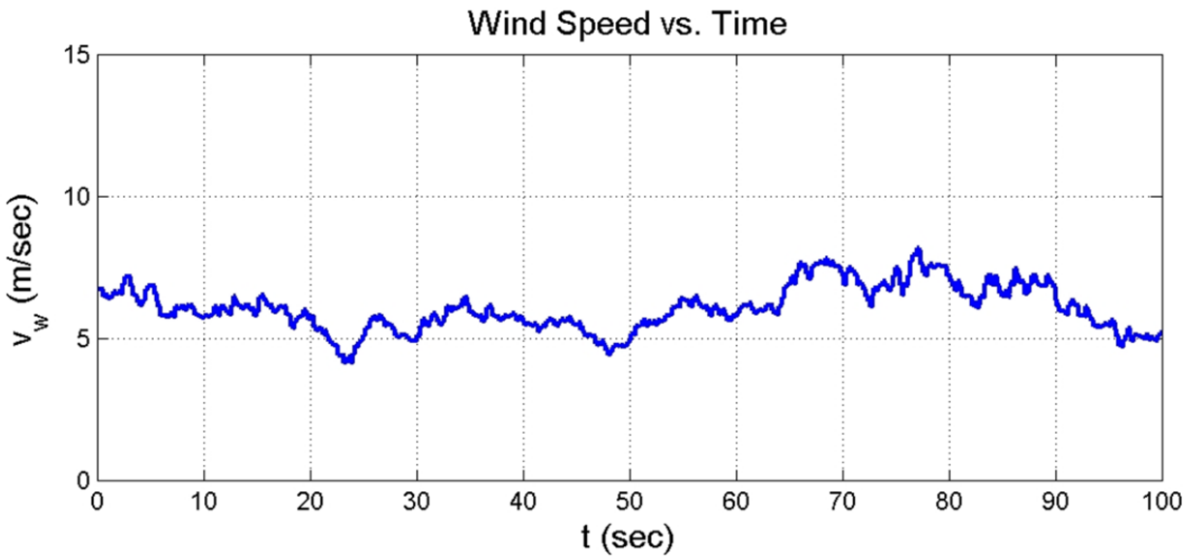
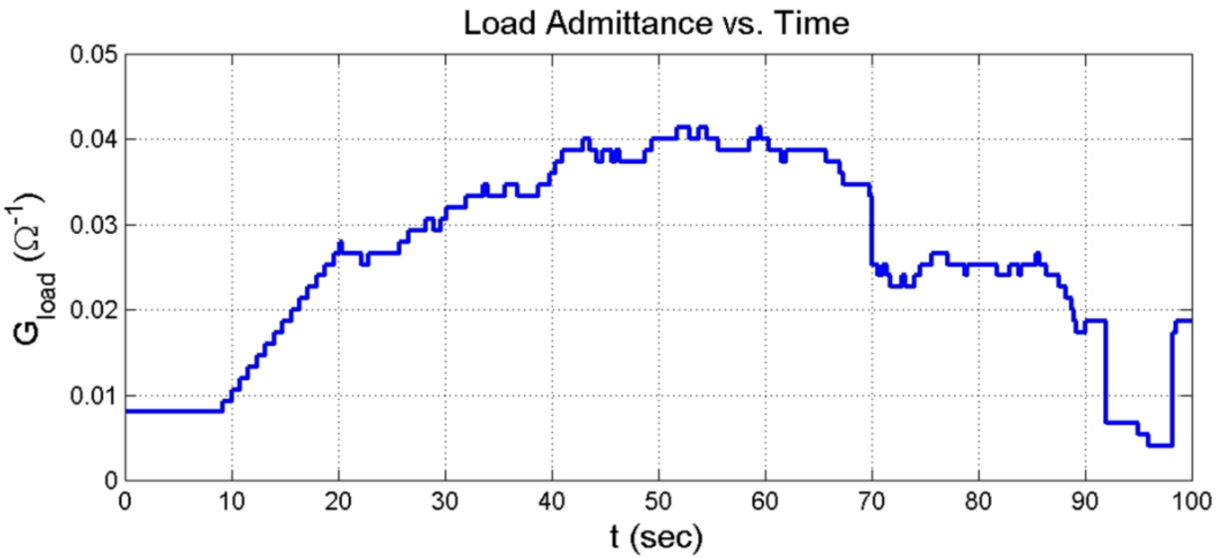
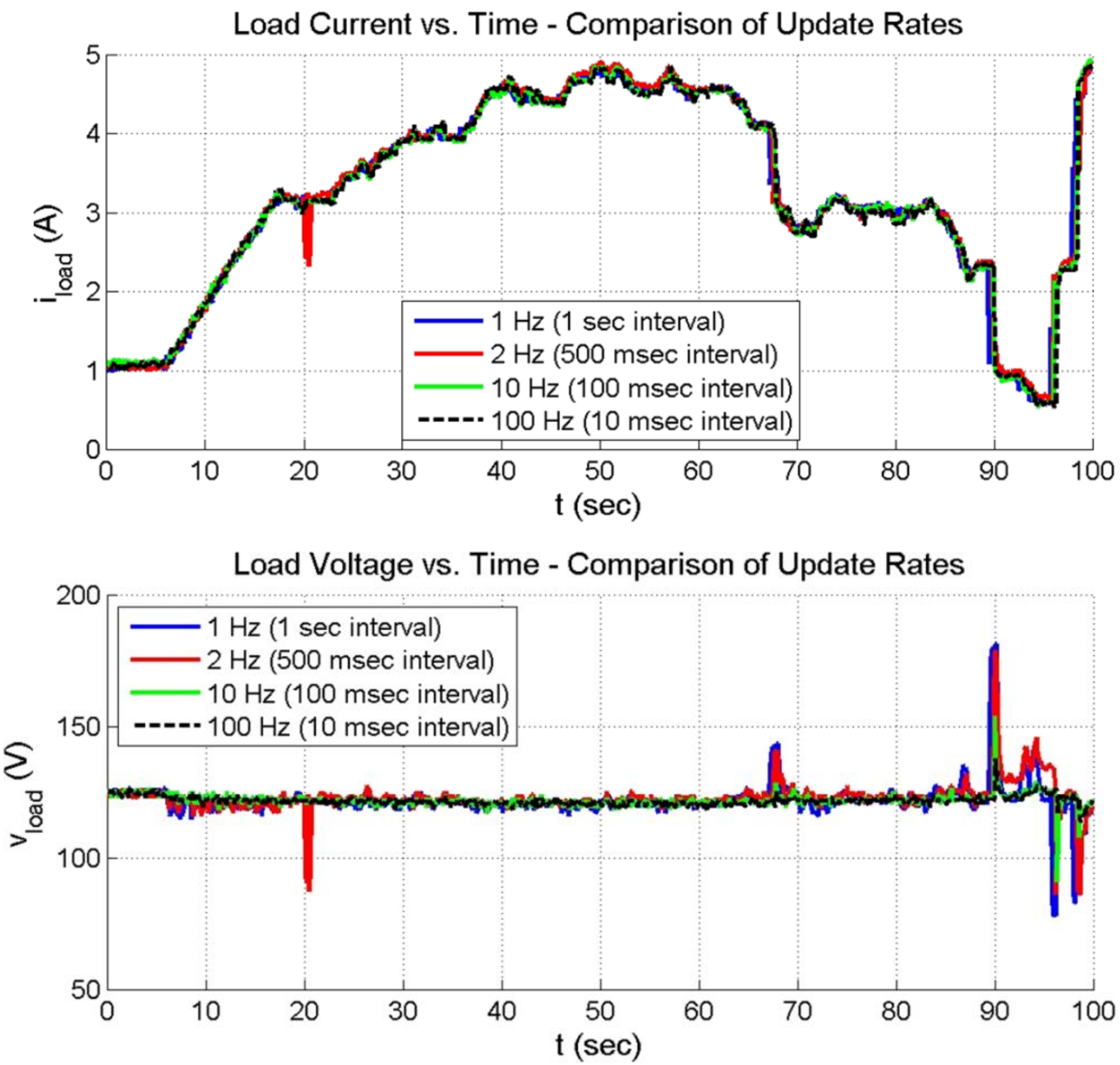
Communication Rate Without Energy Storage Experiment: Input Profiles

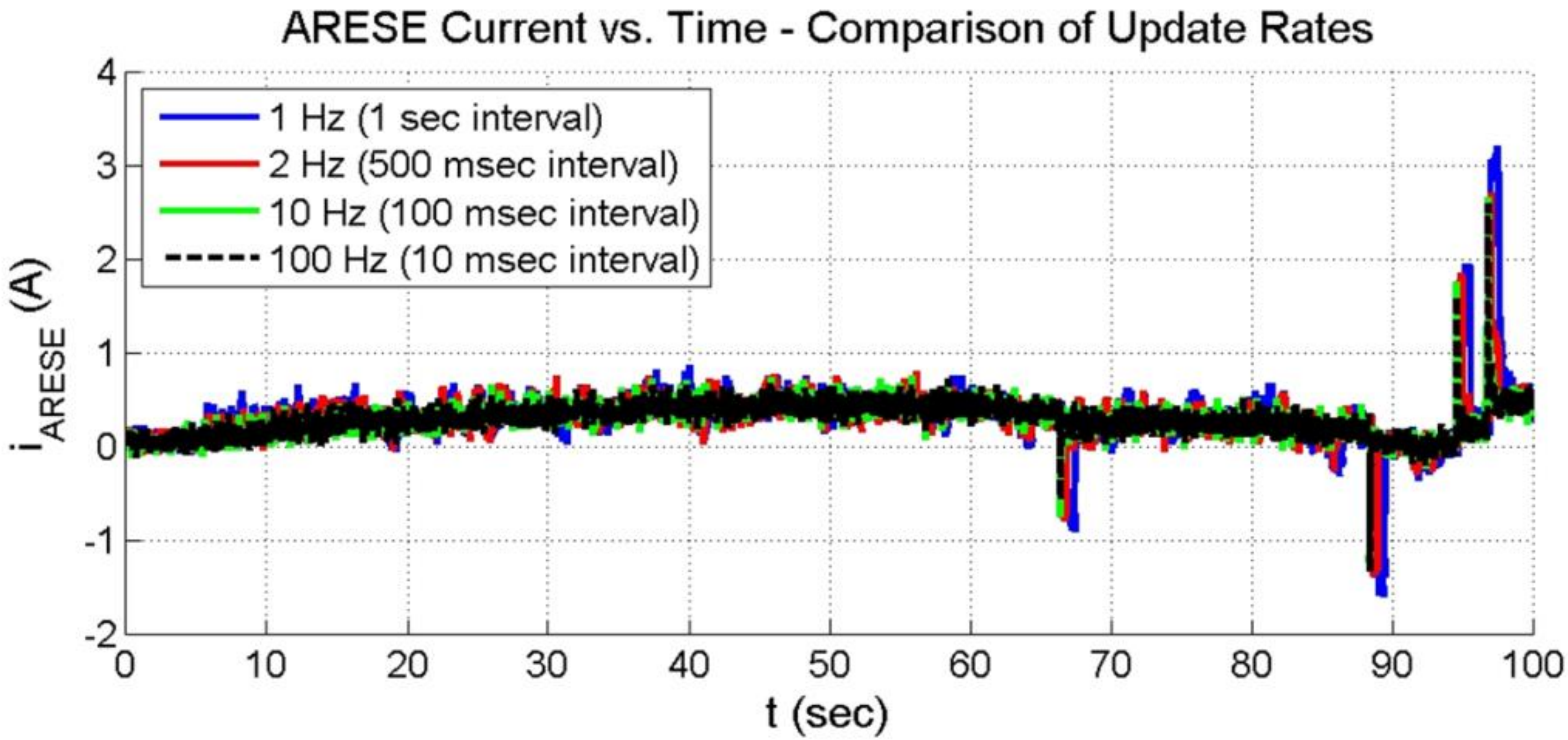




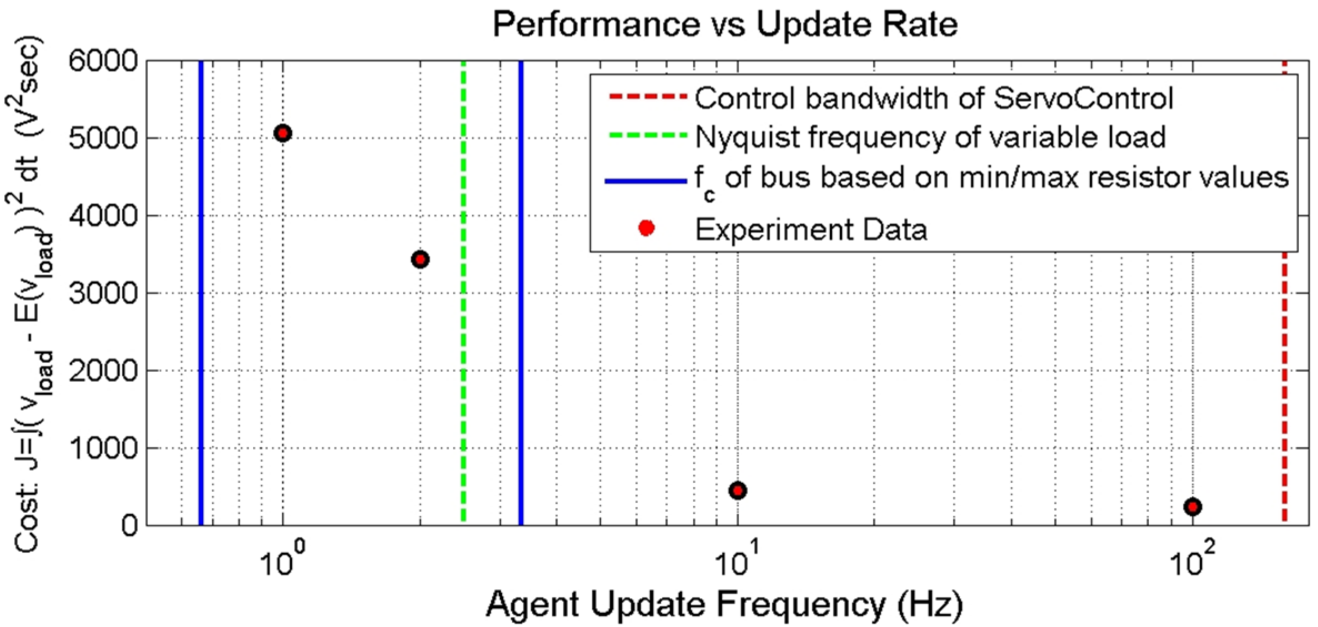
Communication Rate Affects System Performance



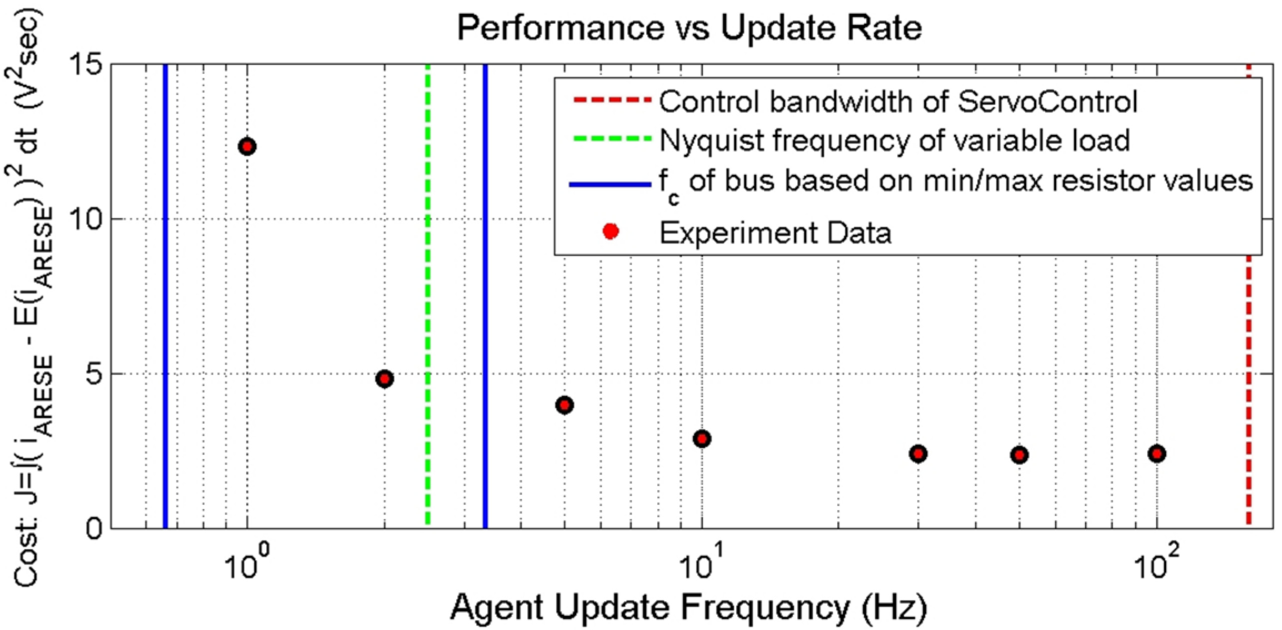
Communication Rate Affects Energy Storage Control Effort



Cost Function Values are Evaluated

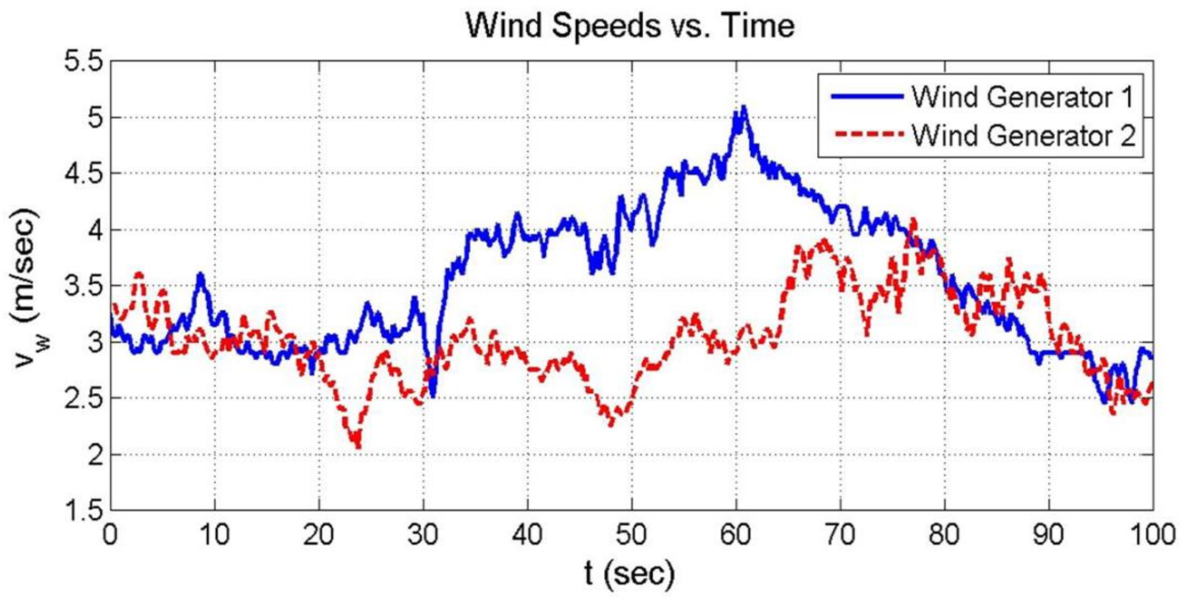


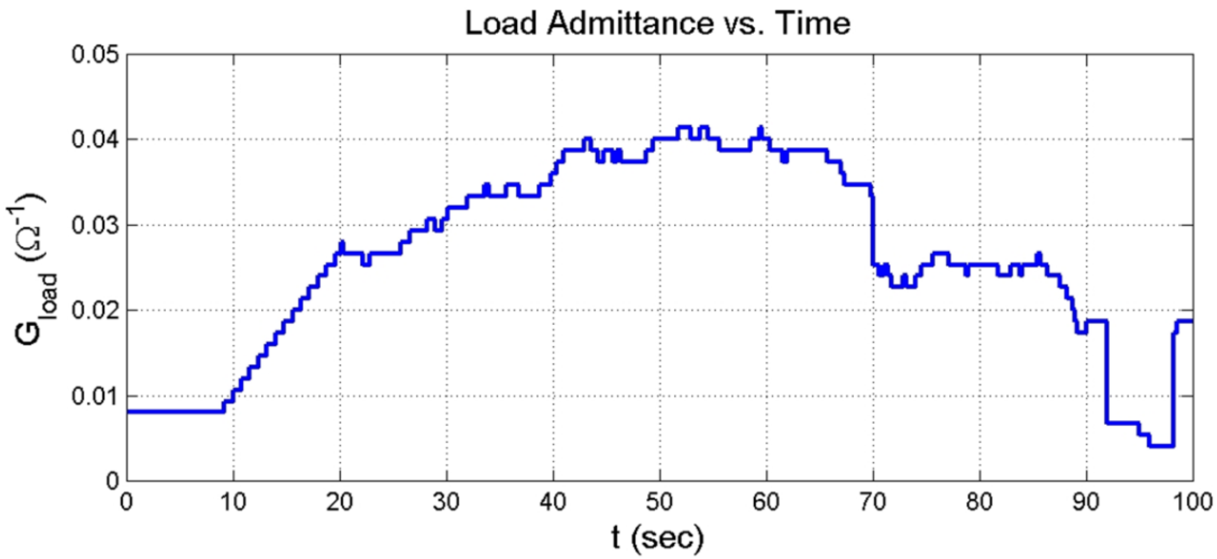
Without energy storage



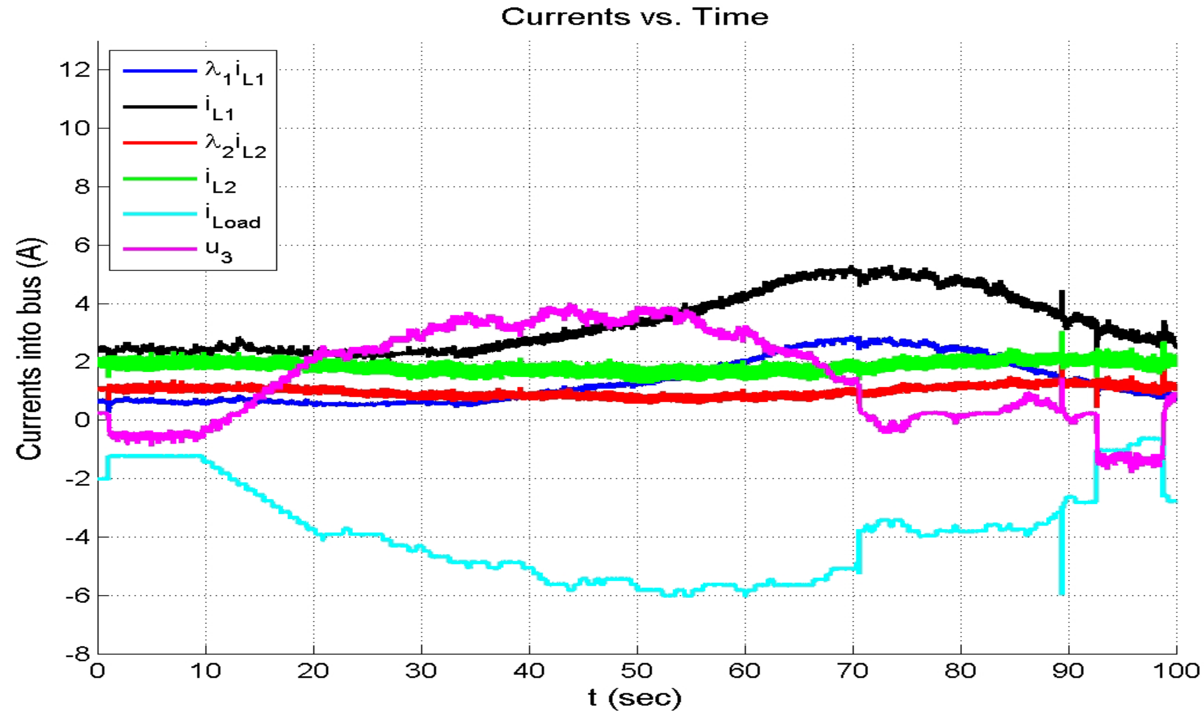
With energy storage

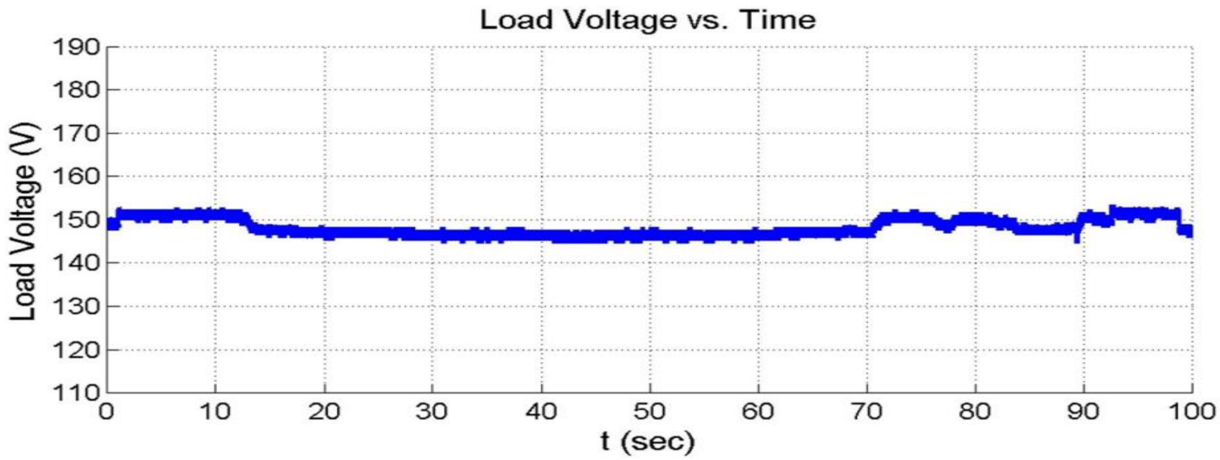
Experiment Input Profiles: Two Variable Wind Turbines and Variable Load



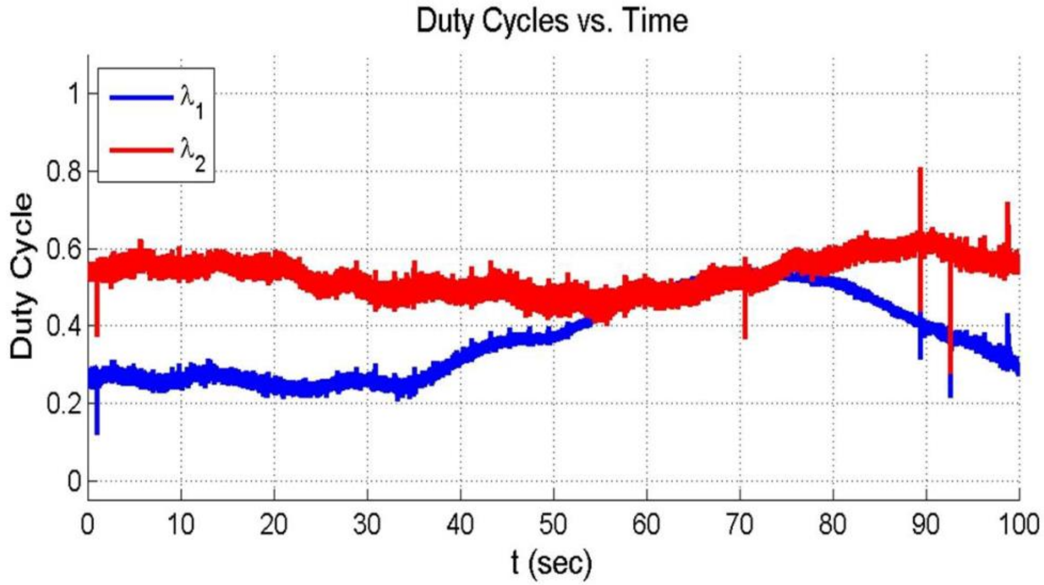


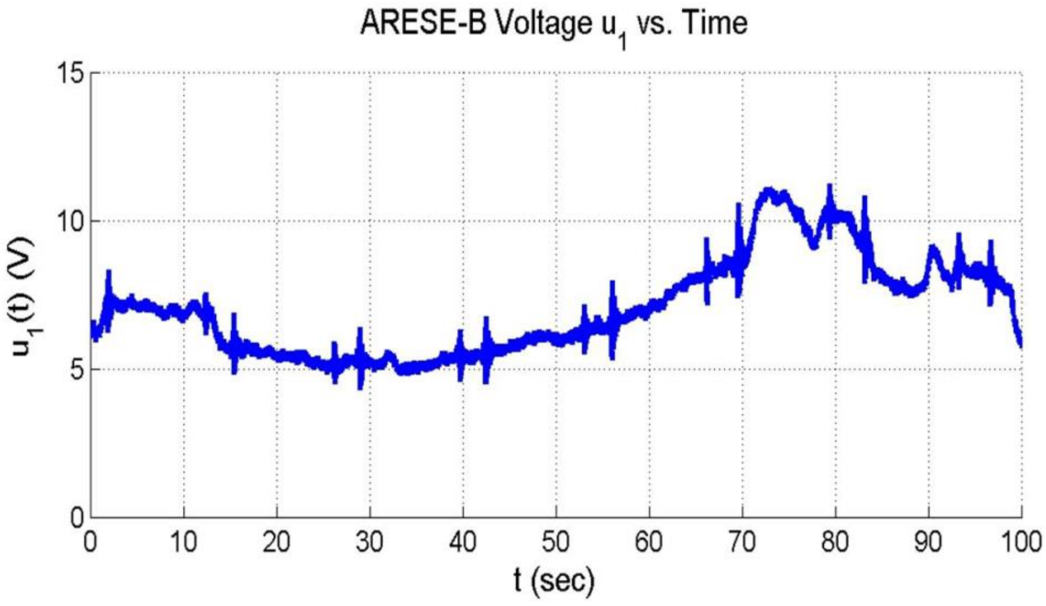
Two Variable Wind Turbine Variable Load Experimental Results (1)



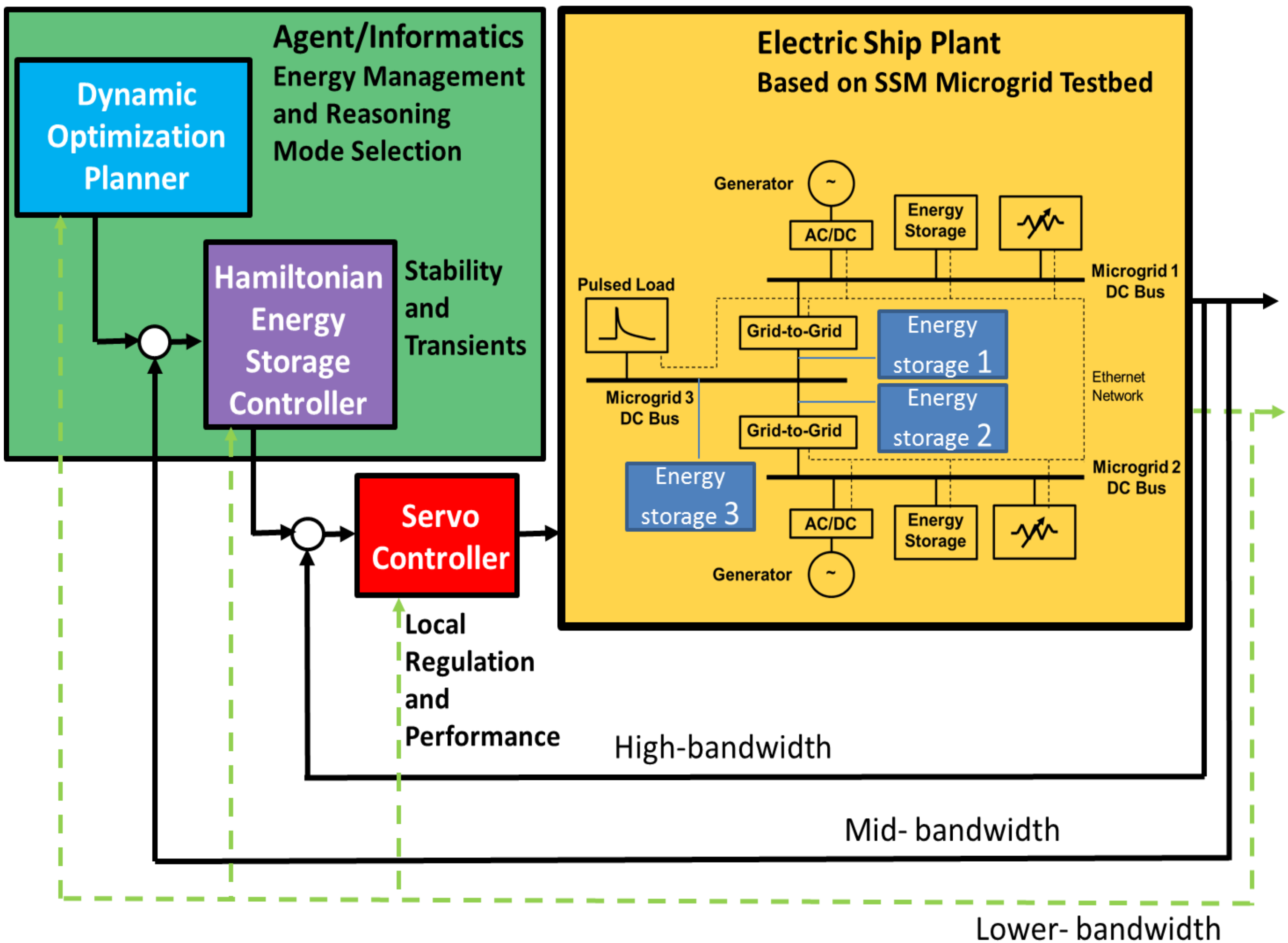


Two Variable Wind Turbine Variable Load Experimental Results (2)



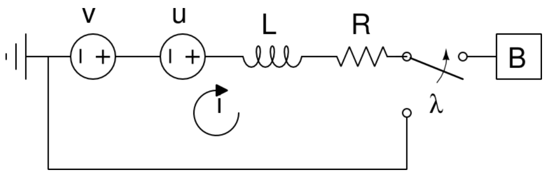


Multiple Microgrid System Represents a Navy Electric Ship Configuration

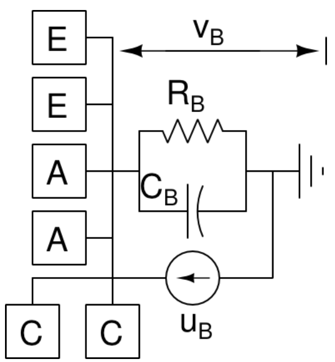


Multiple DC Microgrid Model

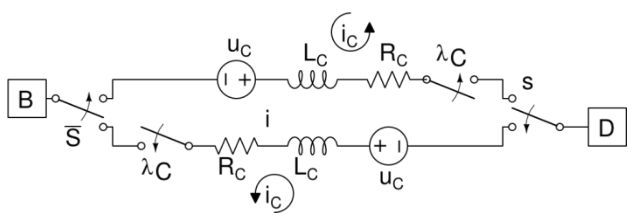
- **Focused on multiple boost converters connected to multiple DC buses connected to multiple DC transmission lines**
- **Various topologies possible**
- **Multiple microgrids utilize modular approach:**
  - Component A describes the boost converter:



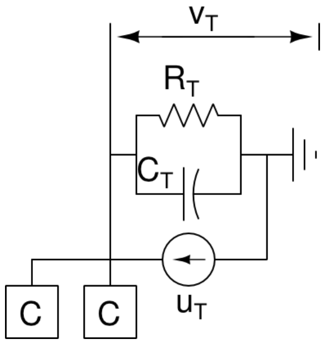
  - Component B describes DC bus:



  - Component C describes connection between DC bus and DC transmission line:



  - Component D describes DC transmission line:



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Multiple DC Microgrid Optimization Formulation

Performance Index:

$$PI_{multiple} = \frac{w_1}{2}\left(\|\lambda - \lambda_0\|^2 + \|\lambda_C - \lambda_{C0}\|^2\right)$$

$$+\frac{w_2}{2}\left(\|u\|^2 + \|u_B\|^2 + \|u_C\|^2 + \|u_T\|^2\right)$$

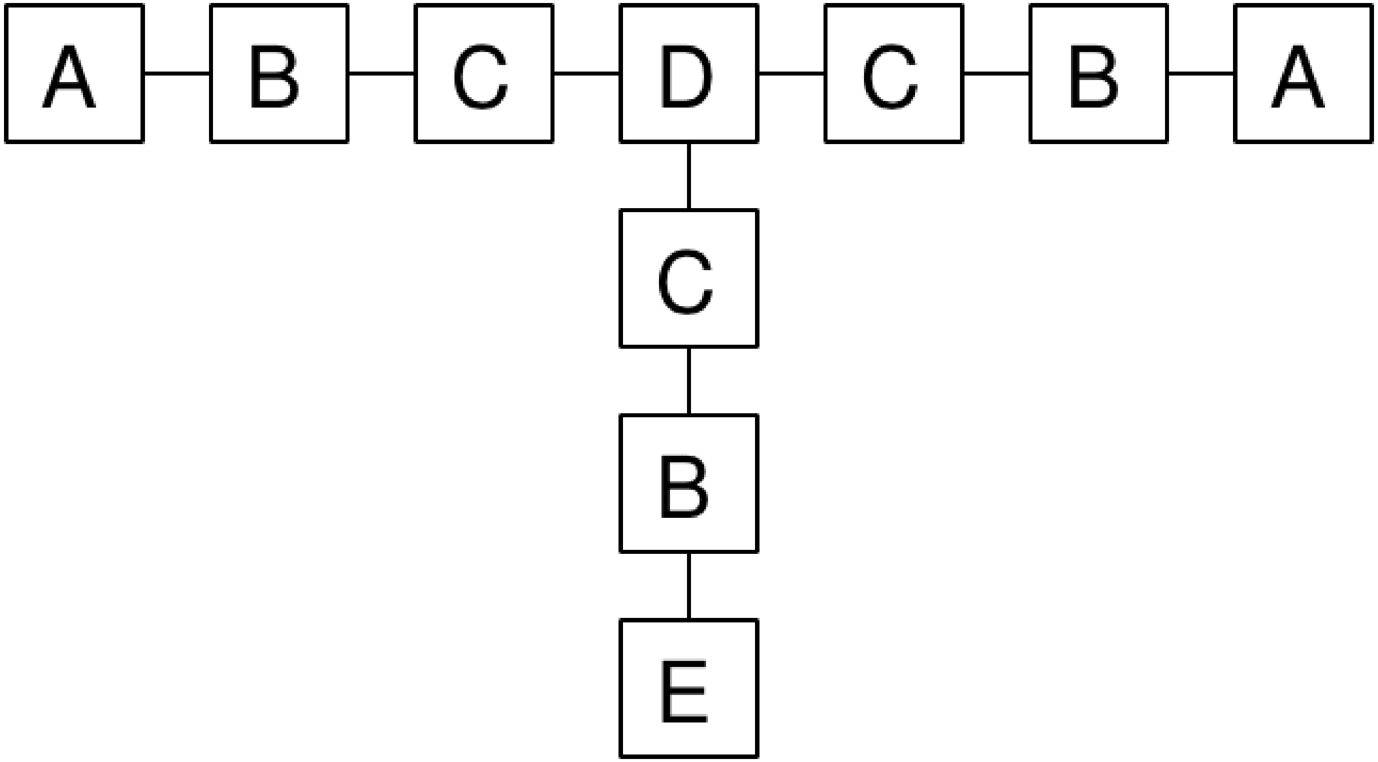
$$+\frac{w_3}{2}\left(i^T \mathrm{Diag}(R) i + {i_C}^T \mathrm{Diag}(R_C) i_C\right)$$

$$+\frac{w_4}{2}\left((i^T u)^2 + (v_B^T u_B)^2 + ({i_C}^T u_C)^2 + (v_T^T u_T)^2\right)$$

Subject to:

- Circuit equations
- Discretization equations
- Parameter bounds

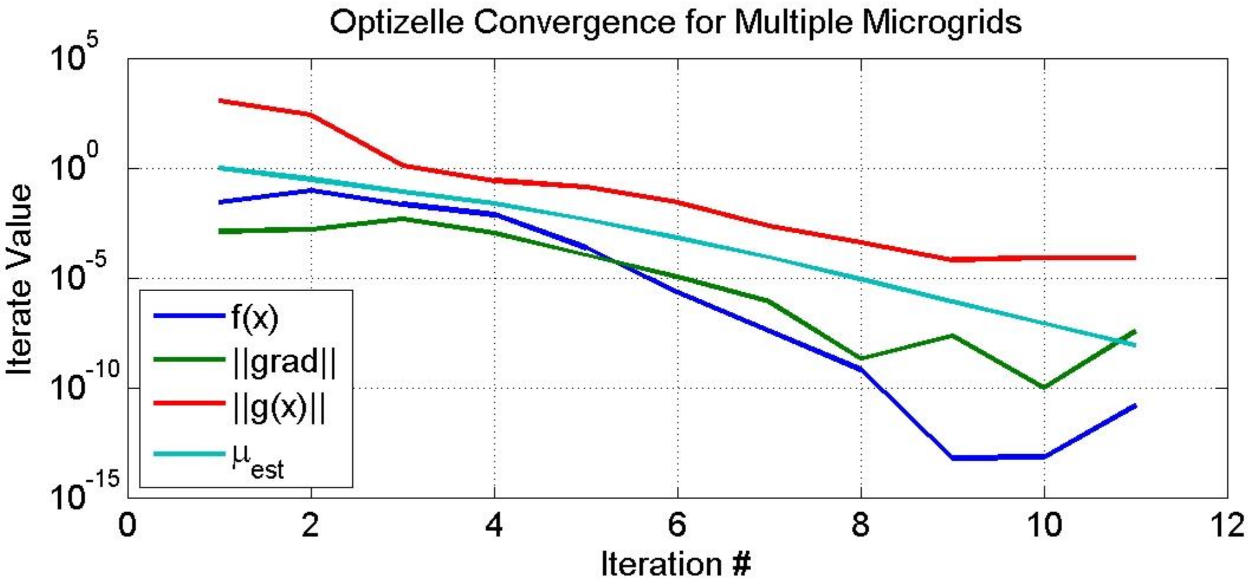
Simple Multiple Microgrid Example



Optizelle Numerical Convergence Multiple Microgrid Results

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

Optizelle NL MPC Optimizer Multiple DC Microgrid Convergence



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Summary and Conclusions

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

Acknowledgments

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

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Backup Slides

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

Today's Grid | Fossil ▷ | Fixed Infrastructure ▷ | Load ▷

- Large spinning machines → Large inertia (matrix); dispatchable supply with storage
- Constant operating conditions → well-ordered state
- Well-known load profiles → excellent forecasting

$$[I]\dot{\underline{x}}=\underline{f}(\underline{x},\underline{u},t)\ ;\ [I]^{-1}\simeq[0]\ \rightarrow\ \dot{\underline{x}}=[I]^{-1}\,\underline{f}(\underline{x},\underline{u},t)\simeq\underline{0}\ ;\ \underline{x}(t)=\underline{x}_0$$

$$G-L\geq 0\ \forall t$$

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

RE ▷ Energy Storage Load ▷ Fixed Infrastructure ▷ Load

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

Future Grid:

1. **High penetration of renewables: loss of storage**
   - ➞ Loss of large spinning machines
   - ➞ Loss of dispatchable supplies
2. **Variable operating conditions → variable state x(t)=?**
3. **Stochastic load profiles → renewables as negative loads**

   $[I_F]\,\dot{\underline{x}} = \underline{f}_F(\underline{x},\underline{u},t) \rightarrow \dot{\underline{x}}_F(t) = [I_F]^{-1}\,\underline{f}_F(\underline{x},\underline{u},t)$

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

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

Our Solution Approach:

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

2. **Develop a set of tools**

The Details:

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

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

3. **Need to stabilize the grid and define stability boundaries (nonlinear)**
   - *Hamiltonian Surface Shaping and Power Flow Control (HSSPFC)*
   - *Measure of order*

4. **Need to span the space of solutions for optimization process**

RE ▸ **Fixed Infrastructure** ▸ **Load** ▸

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

Fossil ▸ **Fixed Infrastructure** ▸ **Load** ▸

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

SNL Innovative Nonlinear Control Design: Based on Latest R&D Results Custom Designed for This Problem

- 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

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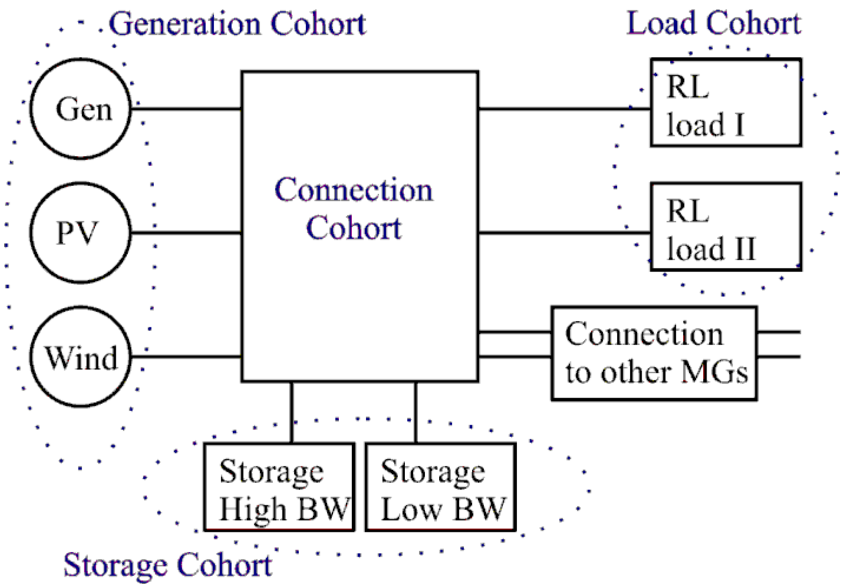
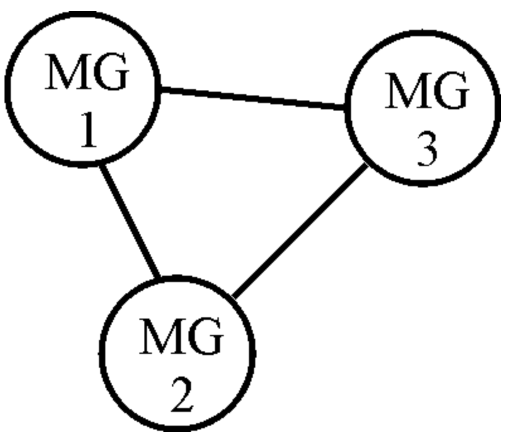
Summary
Nonlinear Power Flow Control Design Steps





Microgrid and Collectives of Microgrid Configurations

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

Nonlinear Control Design
HSSPFC Energy Storage

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

Duty Cycle Commands

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

$$0 = -R_1 x_1 - \lambda_1 x_3 + v_1$$
$$0 = -R_2 x_2 - \lambda_2 x_3 + v_2$$
$$0 = \lambda_1 x_1 + \lambda_2 x_2 - \frac{1}{R_0} x_3$$

- **Or in matrix form as:**

- **Leads to quadratic equation in duty cycles:**

$$\left[\overline{R} + \widetilde{R}\right] x + v = 0$$

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

HSSPFC for Energy Storage Design Observations

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

$$u_{ref} = -\left[\overline{R} + \widetilde{R}\right] x_{ref} - v \qquad (1)$$

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

a) *Equation (1) is an equivalent guidance command that is fully coupled in the states and dependent upon the duty cycle commands. The duty cycle commands will be determined from an optimization routine (SQP, DP, etc.) when desired cost functions and constraints are included.*

b) *For renewable energy sources, v will be time varying and possibly stochastic which leads to an under-actuated system, for 0% energy storage, u=0.*

c) *For fossil energy sources, v will be dispatchable with excess capacity which leads to an over-actuated systems with 100% energy storage even with u=0.*

d) *For u not equal to zero, microgrid with 100% transient renewable energy sources(PV and wind) will lead to requirements for energy storage systems (power, energy, frequency specs., etc.)*

e) *Controller, u, is decoupled which simplifies design procedure*

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Energy Storage

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

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

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

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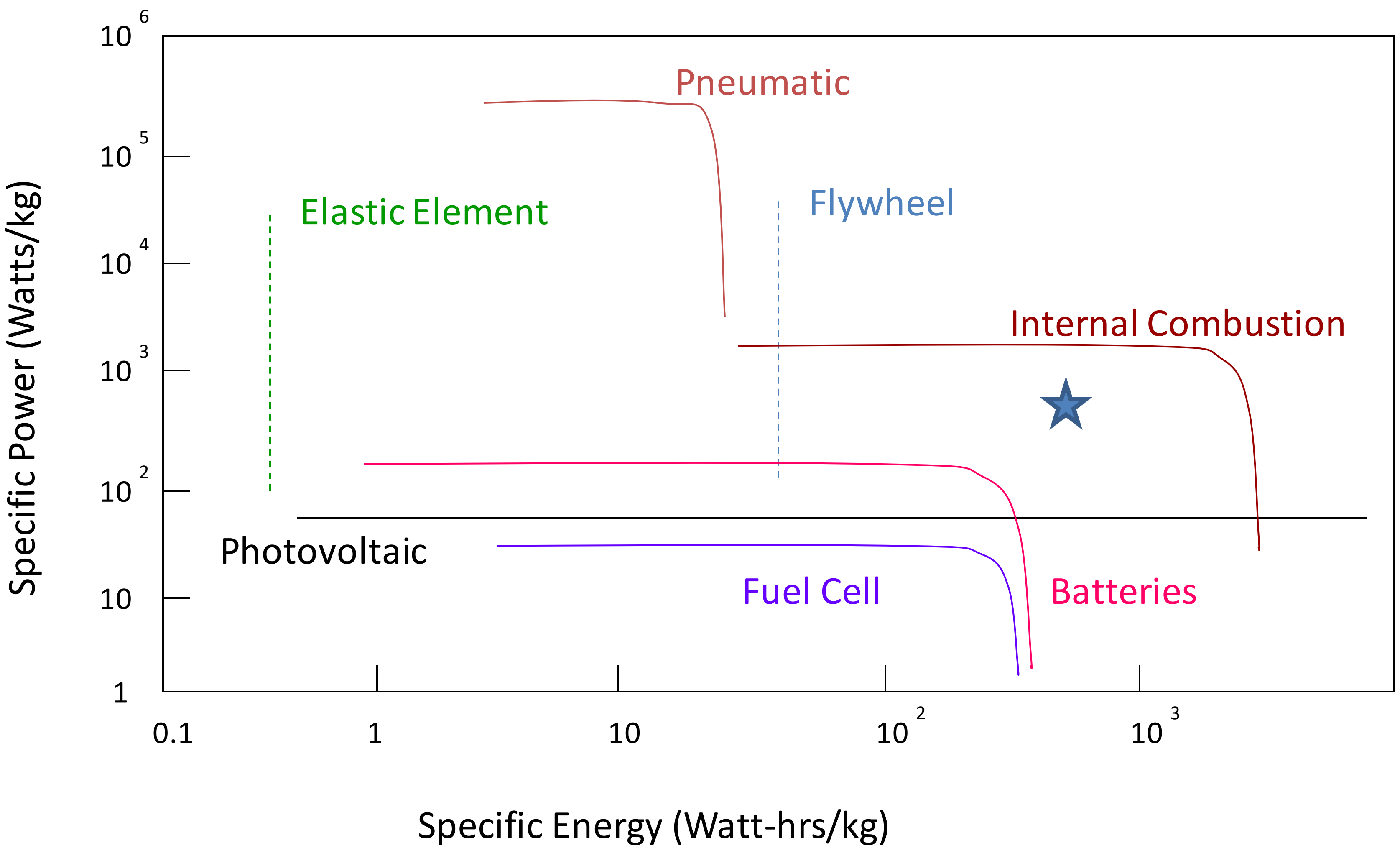
Impedance/Capacity Mismatch (Duty Cycle)



Summary and Future Work

- Present design of feedback controllers for integration of renewable energy into DC bus microgrid system
- HSSPFC used to determine both static stability and dynamic stability conditions
- Model used to produce energy storage requirements
  - Power/energy transients
  - Peak values
  - Frequency response specifications

Future work:

- Include detailed component/subcomponent models
- Further refinement of specific scenarios that demonstrate larger penetration of variable generation (stability/performance)
- AC microgrid systems
- Demonstrate that HSSPFC control technique is self-similar and scales to a collective of microgrids (both DC and AC)

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