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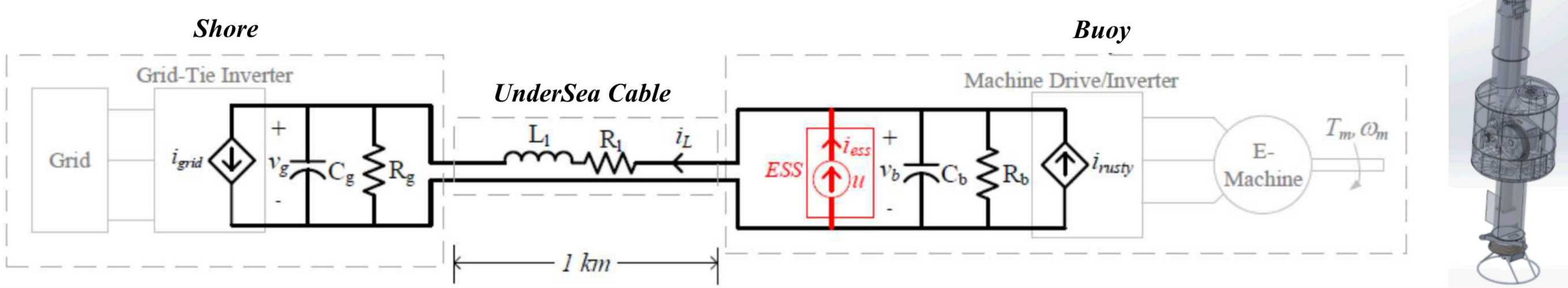

WEC Array Networked Microgrid Control Design and Energy Storage System Requirements

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

AQUA HARMONICS

Michigan Tech
Michigan Technological University

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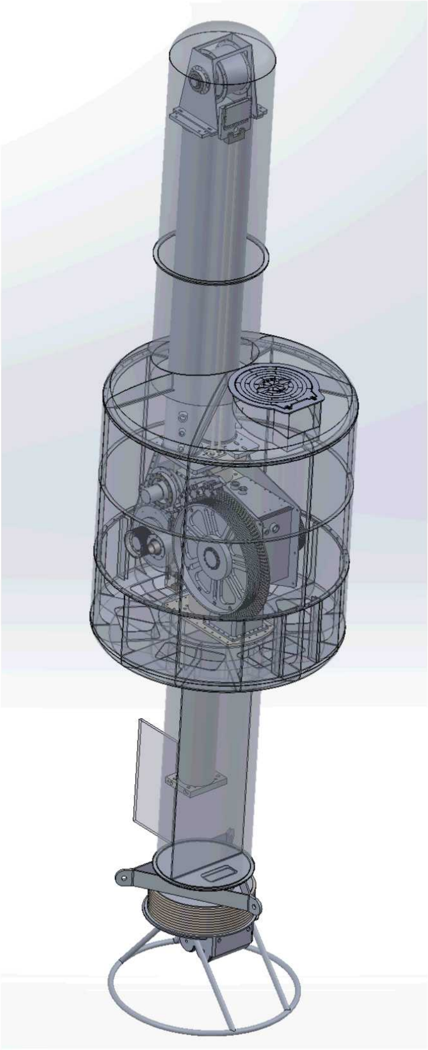
Outline

- Introduction
- Circuit Model
- HSSPFC Controller Design
- Wave Tank Data and PTO Simulations
- Conclusions
- Acknowledgments

Introduction

- WEC technology transforms power from water to grid
- WEC components investigated support the performance, stability, and efficiency as part of a WEC array
- AquaHarmonics, Inc. winner $1.5M grand prize in 2016 by US DOE Wave Energy prize 18 month design-build-test competition
- Goal was to increase the energy capture potential of WECs
- AquaHarmonics intends to develop, build, and perform open ocean testing on a 1:7 scale device
- Preliminary wave tank testing at 1:20 scale yielded data-set for operational conditions and performance
- HSSPFC employing data-set explored for electrical transmission of energy to sore-side power grid
- Primary interest: ESS linking WEC to shore
- Initial analysis results provide trade-off in ESS performance/design selection

Second Generation WEC Point Absorber by AquaHarmonics



Electrical power determined from Mechanical motor/drive power:

- Efficiency estimated from power rating of inverter

$$\eta_m = 100\% \left(\frac{P_{m,out}}{P_{m,in}}\right) \eta_{drive} = 89.97\ \%$$

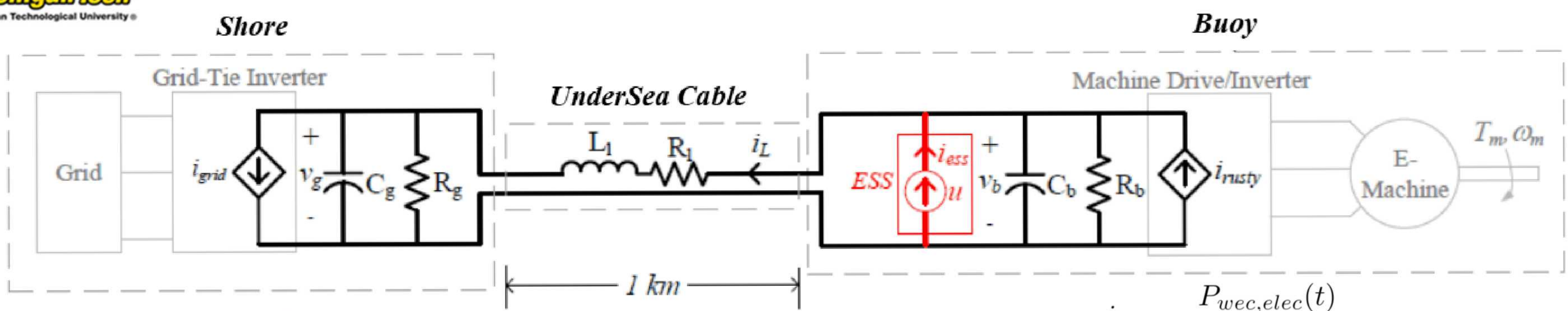
- Inverter/machine power limited and bi-directional defined as

$$P_{wec,elec}(t) = \begin{cases} P_{wec,mech}(t)\eta_m & P_{wec,mech}(t) \leq 0 \quad and \quad P_{wec,mech}(t) > -P_{limit} \\ \frac{P_{wec,mech}(t)}{\eta_m} & P_{wec,mech}(t) > 0 \quad and \quad P_{wec,mech}(t) < P_{limit} \\ P_{limit}(sgn(P_{wec,mech}(t))) & Otherwise. \end{cases}$$

- The current from the inverter to the bus is

$$i_{wec} = \frac{P_{wec,elec}(t)}{v_b}$$

Circuit Model of the WEC System



$$i_{wec} = \frac{P_{wec,elec}(t)}{v_b}$$

MODEL VARIABLES

Variable	Description
v_b	Bus voltage (V)
i_L	Undersea Cable Current (A)
v_g	Grid Invereter dc voltage (V)
i_{wec}	Current from motor/inverter drive (A)
i_{grid}	Current draw into grid-tie inverter(A)
$i_{ess} = u$	Current from ESS (A)

MODEL CIRCUIT PARAMETERS

Parameter	Description	Value
C_b	Bus Capacitance	$2\ \mu F$
R_b	Bus Parasitic Resistance	$1000\ \Omega$
L_l	Undersea Cable Inductance	$95.6\ \mu H$
R_l	Undersea Cable Resistance	$2.5\ \Omega$
C_g	Grid Inverter Capacitance	$2\ \mu F$
R_g	Grid Inverter Resistance	$1000\ \Omega$

- Model of the system

$$C_b \frac{dv_b}{dt} = i_{wec} - \frac{v_b}{R_b} - u - i_L$$
$$L_l \frac{di_L}{dt} = v_b - i_L R_L - v_g$$
$$C_g \frac{dv_g}{dt} = i_L - i_{grid} - \frac{v_g}{R_g}$$

- Matrix form for HSSPFC design

$$\begin{aligned} \mathbf{M}\dot{\mathbf{x}} &= \mathbf{R}\mathbf{x} + \mathbf{D}^T\mathbf{v} + \mathbf{B}^T\mathbf{u} \\ &= [\bar{\mathbf{R}} + \tilde{\mathbf{R}}]\mathbf{x} + \mathbf{D}^T\mathbf{v} + \mathbf{B}^T\mathbf{u} \end{aligned}$$

HSSPFC Controller Design
Feedback Control

- **Microgrid ROM** (see [8] for details) in matrix form as

$$\begin{aligned}\mathbf{M}\dot{\mathbf{x}} &= \mathbf{R}\mathbf{x} + \mathbf{D}^T\mathbf{v} + \mathbf{B}^T\mathbf{u} \\ &= [\bar{\mathbf{R}} + \tilde{\mathbf{R}}]\mathbf{x} + \mathbf{D}^T\mathbf{v} + \mathbf{B}^T\mathbf{u}\end{aligned}$$

- **HSSPFC** uses PI control

$$\mathbf{u} = \mathbf{u_{ref}} - \boldsymbol{\Delta}\mathbf{u} \qquad \Delta\mathbf{u} = -\mathbf{K_P}\mathbf{B}\tilde{\mathbf{x}} - \mathbf{K_I}\mathbf{B}\int_0^t \tilde{\mathbf{x}}d\tau$$

- Provides **static stability** and

$$\mathcal{H} = \frac{1}{2}\tilde{\mathbf{x}}^T\mathbf{M}\tilde{\mathbf{x}} + \frac{1}{2}\left[\int_0^t \tilde{\mathbf{x}}d\tau\right]^T \mathbf{B}^T\mathbf{K_I}\mathbf{B}\left[\int_0^t \tilde{\mathbf{x}}d\tau\right] \;\forall\tilde{\mathbf{x}} \neq \mathbf{0}$$

- **Dynamic stability** with transient performance determined from power flow

$$-\tilde{\mathbf{x}}^T\left[\mathbf{B}^T\mathbf{K_P}\mathbf{B} - \bar{\mathbf{R}}\right]\tilde{\mathbf{x}} < 0 \quad \forall\tilde{\mathbf{x}} \neq \mathbf{0}.$$

- Supports WEC array integration

Feedback Control of ESS Current

- Feedback control law regulates bus voltage to reference value

$$\tilde{v_b} = v_{b,ref} - v_b$$

$$u = i_{ess} = k_p \tilde{v_b} + k_i \int \tilde{v_b} dt$$

- Control gains are selected in accordance with HSSPFC
- Control parameters are given as

Parameter	Description	Value
$v_{b,ref}$	Bus voltage reference	$400\ V_{dc}$
$i_{L,ref}$	Cable Current Reference	
$v_{g,ref}$	Grid Voltage Reference	
k_p	Feed-back proportional gain	1
k_i	Feed-back integral gain	10
$P_{m,out}$	Machine Rated Output Power	$55.53\ kW$
$P_{m,in}$	Machine Rated Input Power	$56.52\ kW$
P_{limit}	Inverter Power Limit	$60\ kW$
η_{drive}	Estimated Inverter Drive Efficiency	0.95

Feedforward Control - Current to Grid

- Power export command significantly impacts bus/line voltage/current
- Continuous update power command ideal, impractical (inverter and communication limitations)
- Therefore update rate on power (current) to grid should be explored
- Reference current into grid-tied inverter found from feedforward process:

$$
\begin{aligned}
i_{L,ref} &= i_{wec} - \frac{v_{b,ref}}{R_b} \\
v_{g,ref} &= v_{b,ref} - i_{L,ref} R_l \\
i_{g,ref} &= i_{L,ref} - \frac{v_{g,ref}}{R_g} \\
&= i_{wec}\left(1 + \frac{R_l}{R_g}\right) - v_{b,ref}\left(\frac{R_b + R_g + R_l}{R_b R_g}\right)
\end{aligned}
$$

- Grid reference current is updated at the rate of τ_{ff}
- τ_{ff} greatly impacts the ESS design

Wave Tank Data and PTO Simulations

- Mechanical torque and speed of PTO scaled from wave tank data with Froude scaling factor

$$\lambda = (1/7)/(1/20)$$

- Then speed and torque at e-machine for simulation is

$$\omega_{scaled} = \omega_{data}\lambda^{-0.5}$$

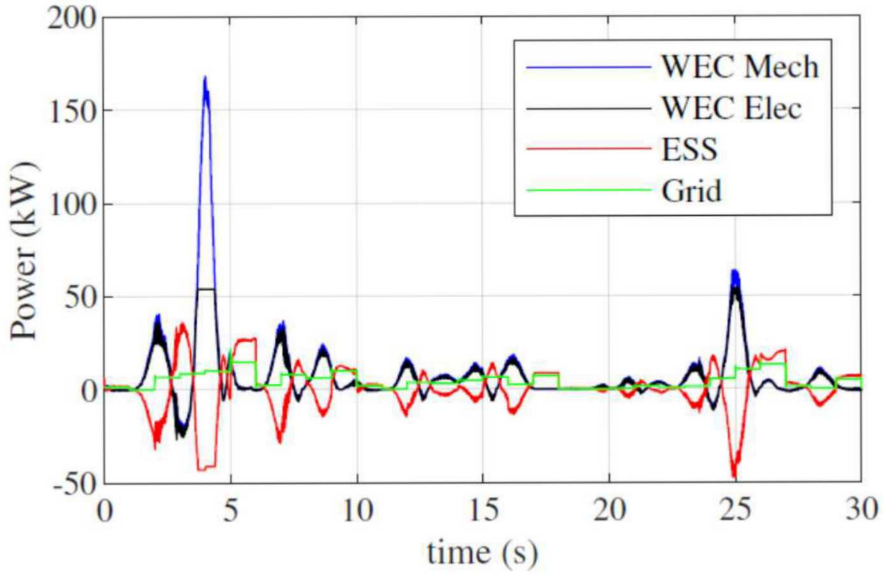
$$torque_{scaled} = torque_{data}\lambda^{4}$$

- Scaled mechanical power used for model and electrical PTO simulation

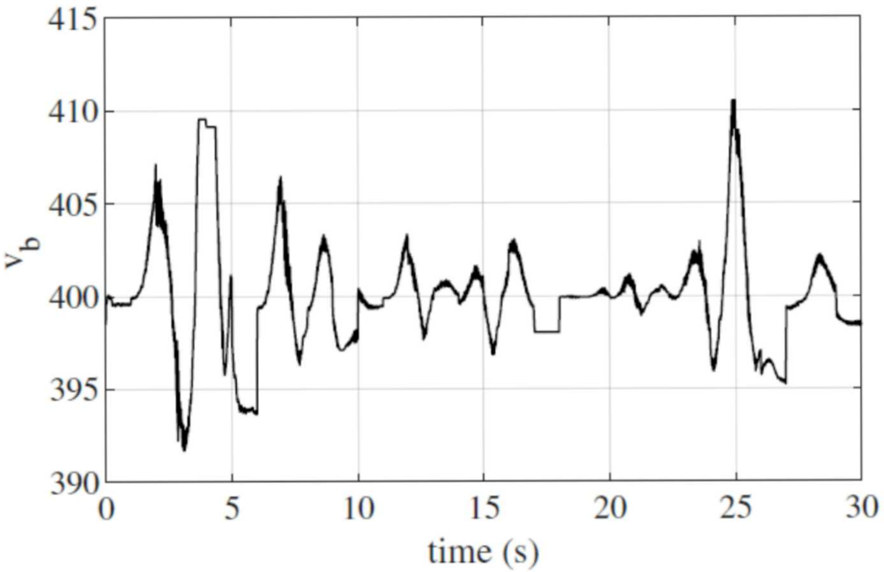
$$P_{wec,mech} = \omega_{scaled}(torque_{scaled})$$

- Simulation Based Parameter Sweep Study for τ_{ff} from 5s to 30s in 1s steps
  - ESS Capacity
  - Bus voltage ripple and ESS power
  - Power to the grid
  - ESS frequency content

Wave Tank Data and PTO Simulations

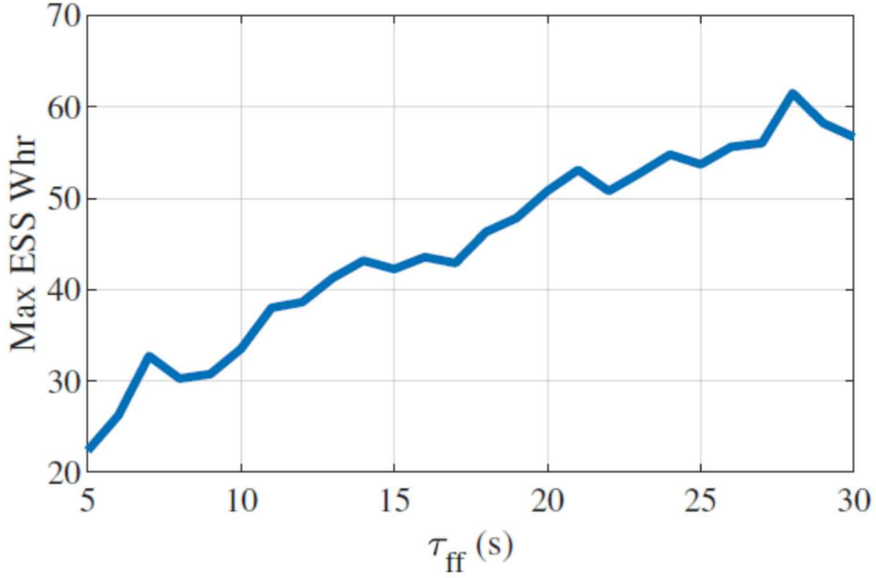


- Example time series simulation powers with τ_{ff} = 1 sec

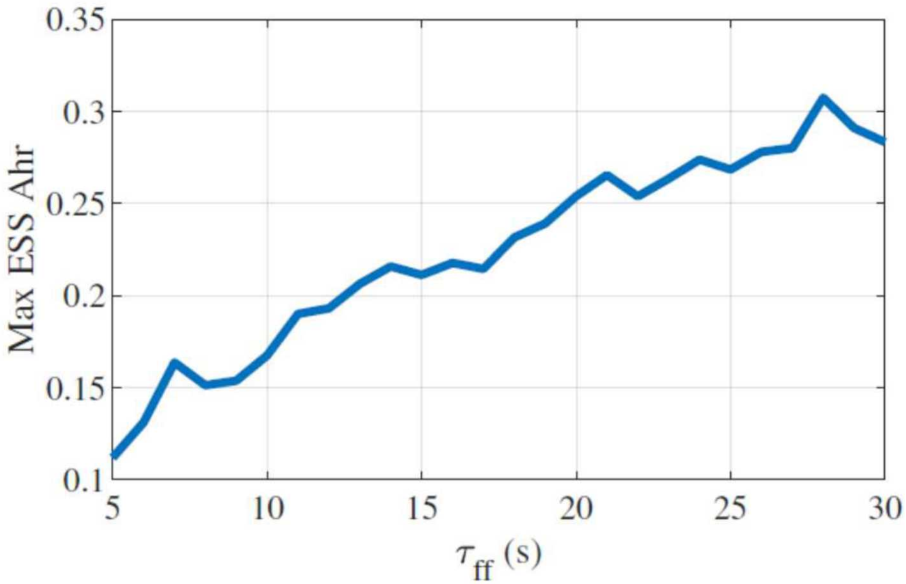


- Example time series simulation bus voltage with τ_{ff} = 1 sec

Wave Tank Data and PTO Simulations

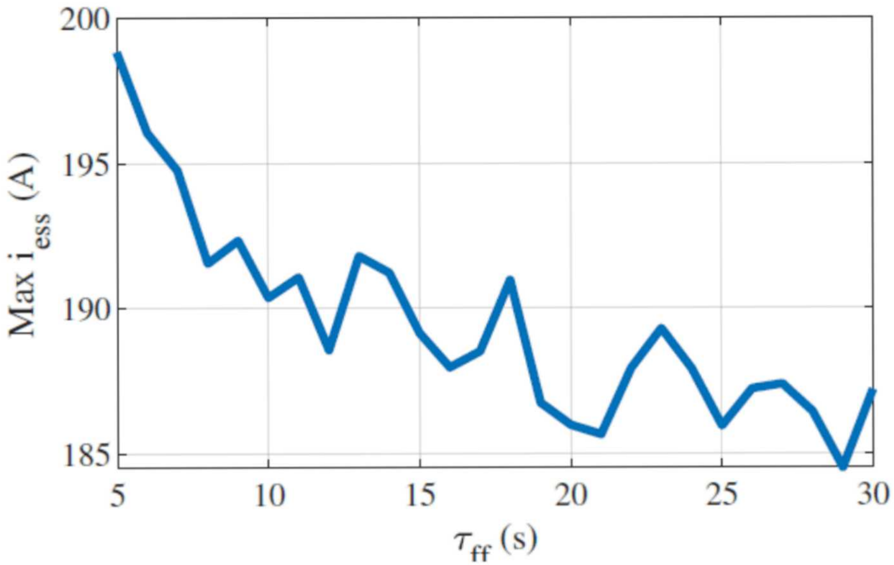


- ESS required energy capacity (kW-Hr) vs grid power export rate update τ_{ff}

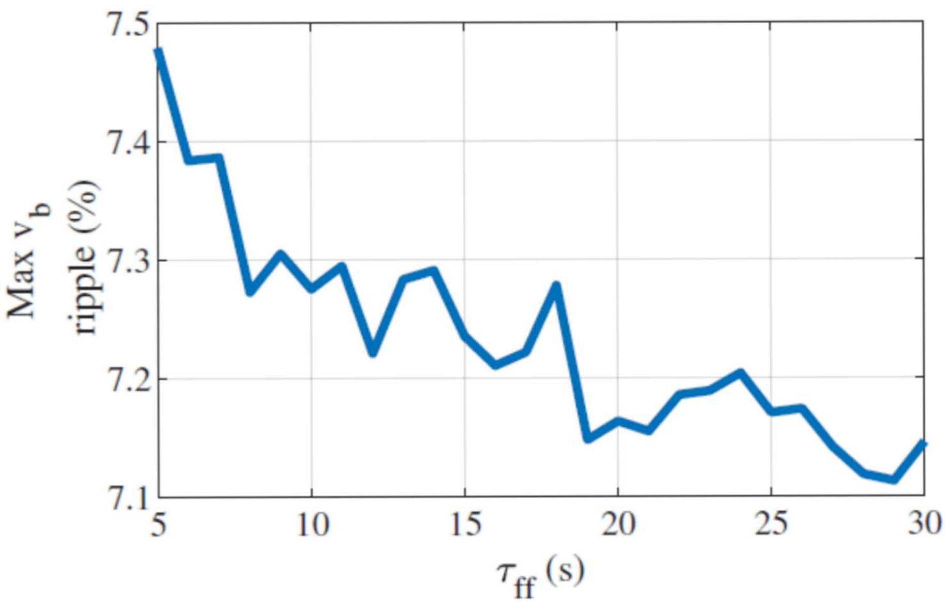


- ESS required energy capacity (A-Hr) (assuming 200 V battery) vs grid power export rate update τ_{ff}

Wave Tank Data and PTO Simulations

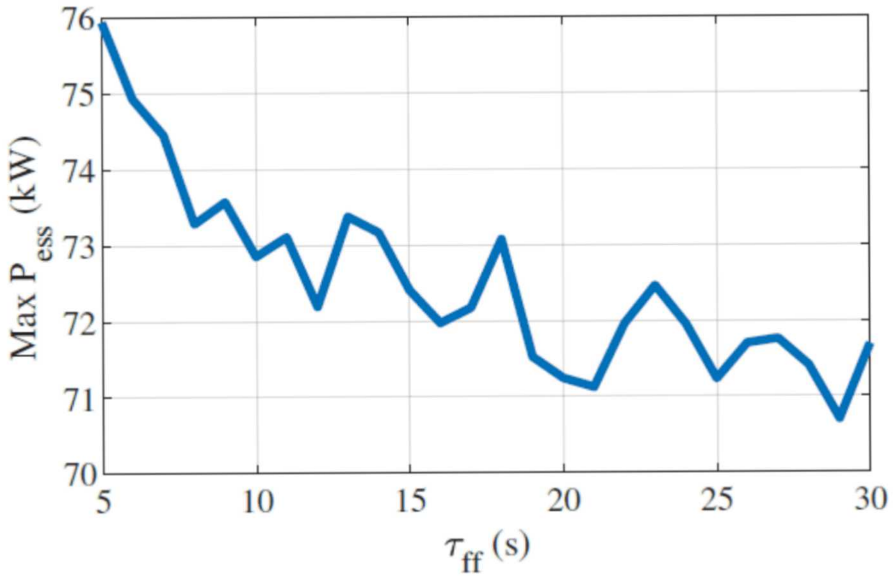


- Max ESS current vs grid power export rate update τ_{ff}

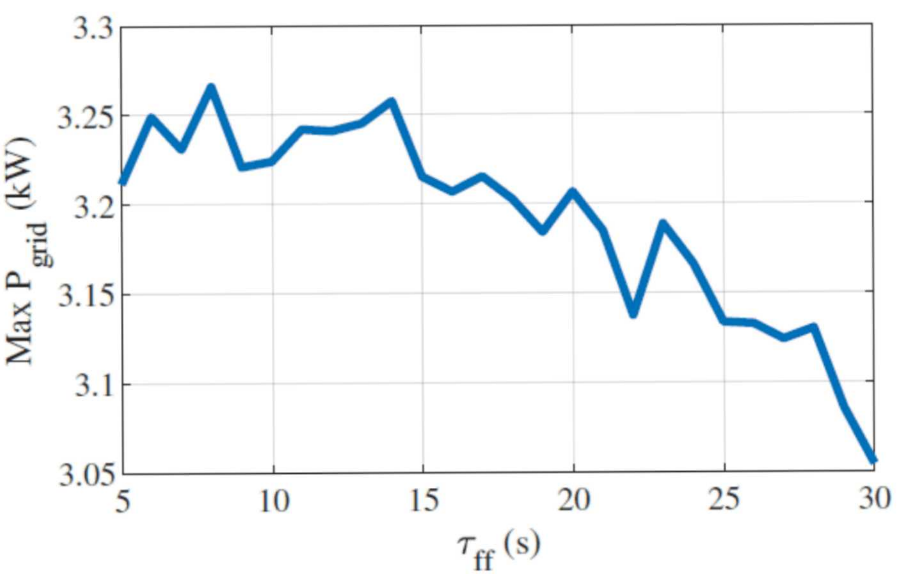


- Bus voltage ripple vs grid power export rate update τ_{ff}

Wave Tank Data and PTO Simulations

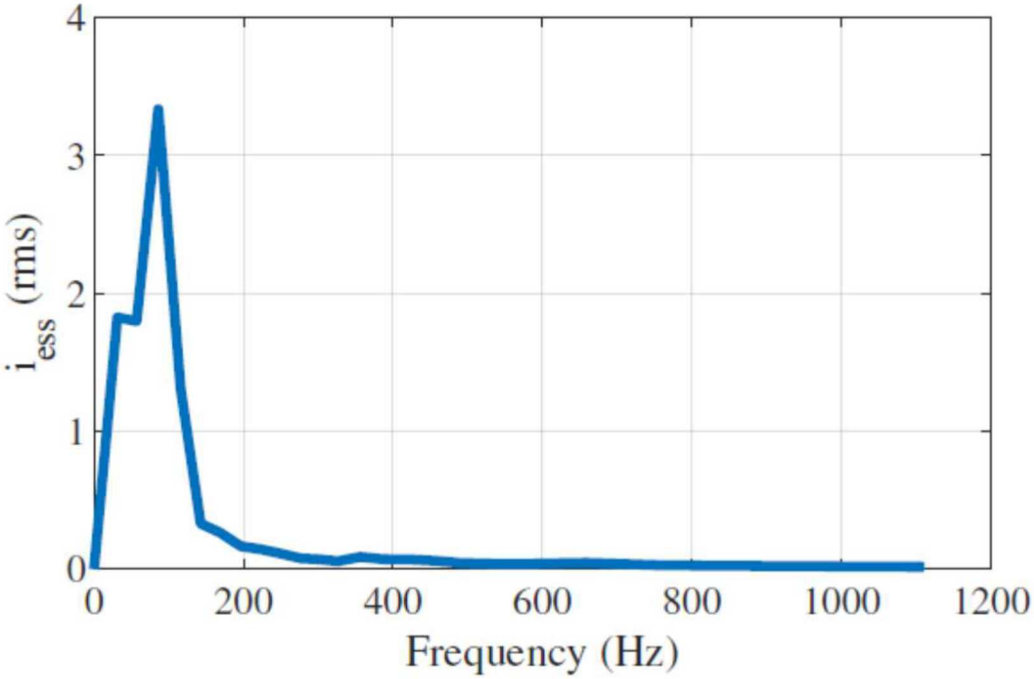


- Max ESS power vs grid power export rate update τ_{ff}



- Max power export vs grid power export rate update τ_{ff}

Wave Tank Data and PTO Simulations



- Average frequency content of ESS current for all simulation tests

ESS Analysis and Discussion

- Observations from analyses and simulation results
  1. Total required ESS capacity is small < 50 W-Hr
  2. Average required frequency response ESS current low < 200 Hz
  3. Peak ESS current is high approximately 200 A
- 1 and 2 suggest single small battery for ESS would suffice
- However, peak current in 3 is problematic
- Example: 200 V batty 2 A-Hr Li-Ion battery would work
  - However, violates manufactures limit discharge rate 100 C > 10 C
  - Therefore, a 20 A-Hr battery works, but life of battery may be shortened with high discharge rate

Conclusions

- Presented HSSPFC method to explore design space for electrical transmission of energy to shore-side power grid from WEC device
- Presented approach and preliminary analysis that highlighted some of the design trade-offs in ESS configurations
- Single ESS is just one of many possible configurations
- Other potential configurations to meet all the specs:
  - Use battery for energy capacity and super capacitor to meet maximum current
  - However super capacitor bank volume is large and require 2nd DC/DC converter
  - Could place super capacitor/converter at buoy to supply high peak currents and battery/converter on shore to regulate cable and bus voltages
  - May prevent excessive losses under-sea cable due to large current variations
- Future investigations would need to be performed to realize optimal design; multiple rows of devices, bus integration, ESS, shoreline interface, etc.
- HSSPFC optimization determines trade-off between centralized, local, and decentralized ESS locations, most efficient use/requirements for ESS, etc.
- Tool for developers to evaluate WEC systems; optimal power and efficiency

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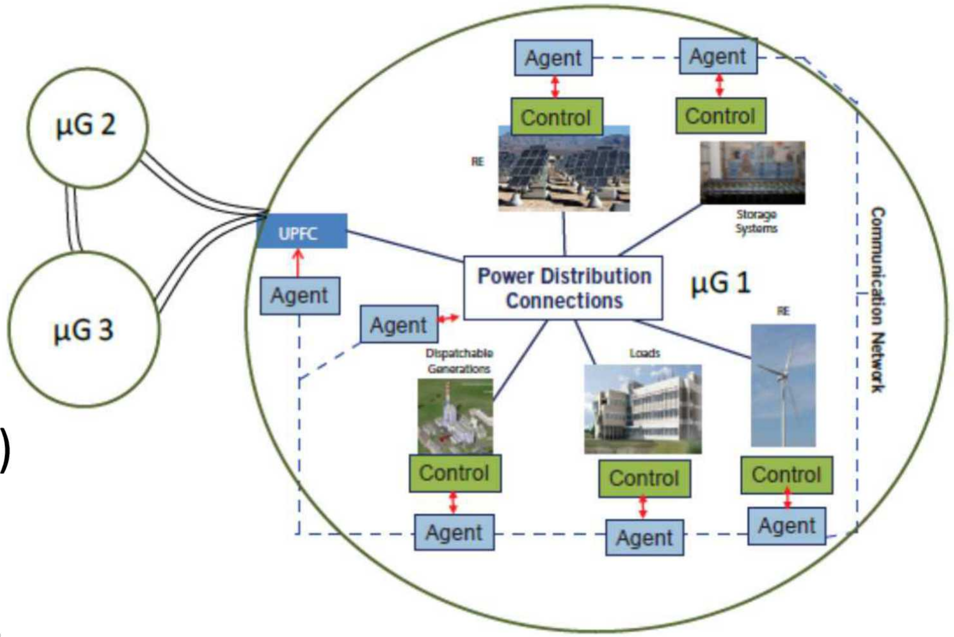
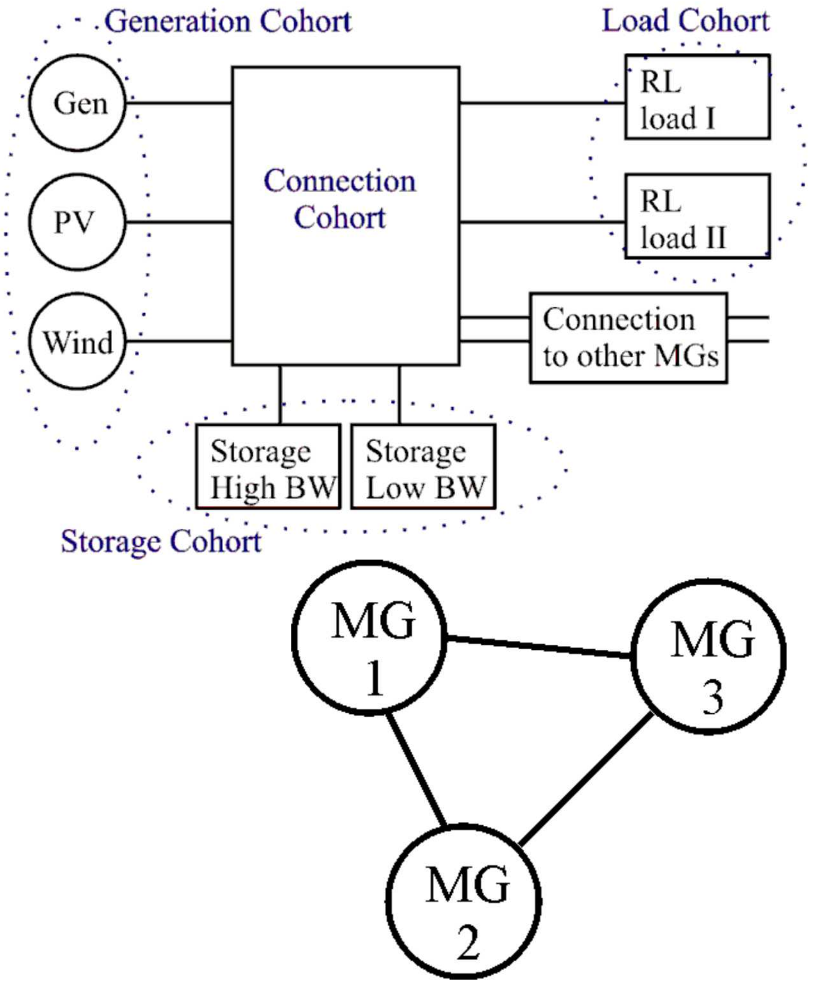
Backup Charts

DOE and DoD Focus Energy Surety

- **Energy Surety**— provides cost effective supplies of energy that are reliable, safe, secure, and sustainable.
- **Requires** - forward-looking energy surety; development of novel intelligent grid architecture in order to be robust, effective, and efficient.
- **Desirable metrics SSM:**
  - Unlimited use of renewable energy power sources
  - Reduced fossil fuel-based power generation
  - Reduced energy storage system (ESS) requirements
  - Balanced control of generation, storage, and loads in an efficient and secure paradigm



Summary
Nonlinear Power Flow Control Design Steps

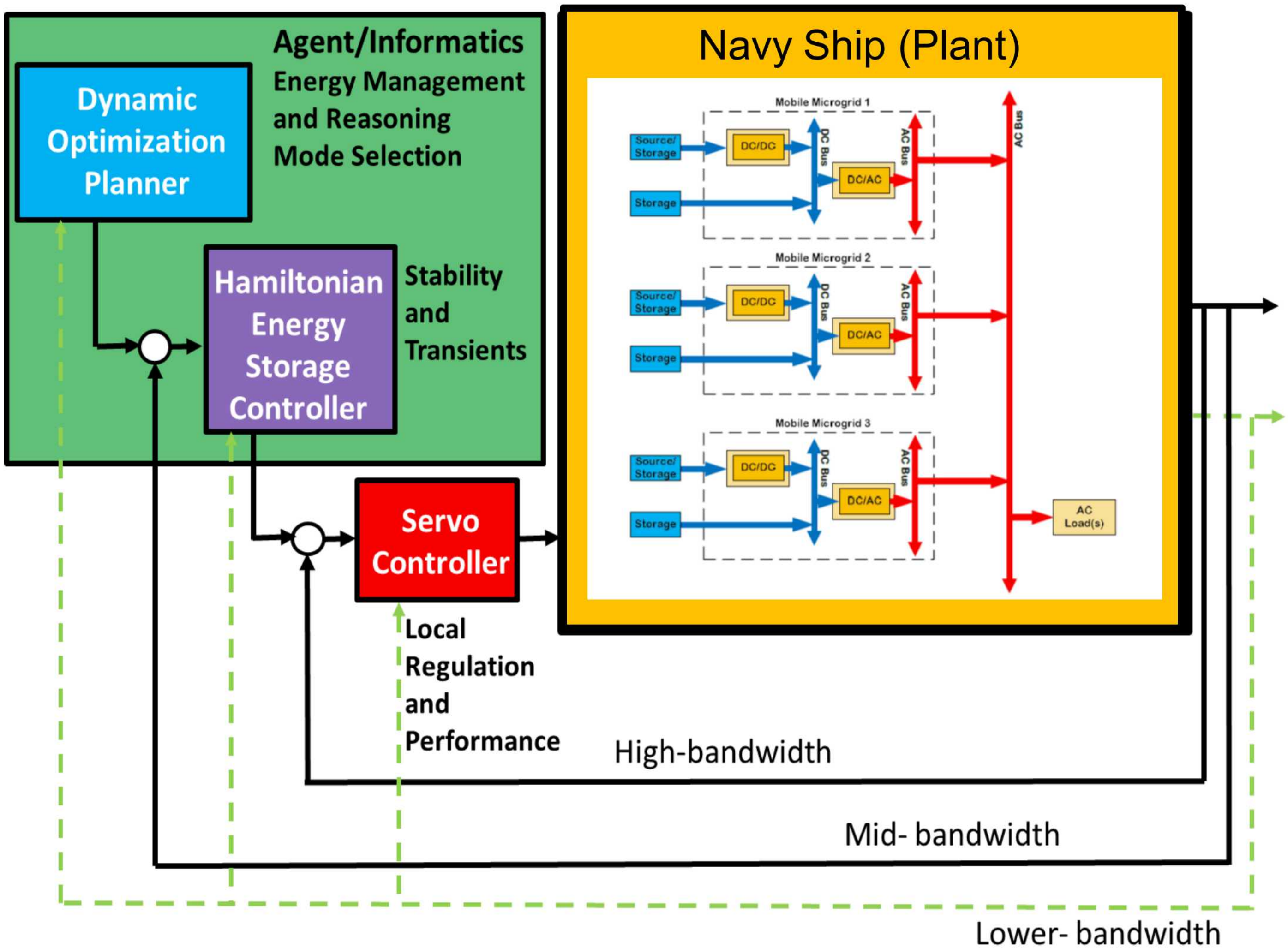


Microgrid and Collectives of Microgrid Configurations

1. Define Reduced Order Model (ROM)
2. Formulate K.E. and P.E.
3. Formulate Hamiltonian (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*

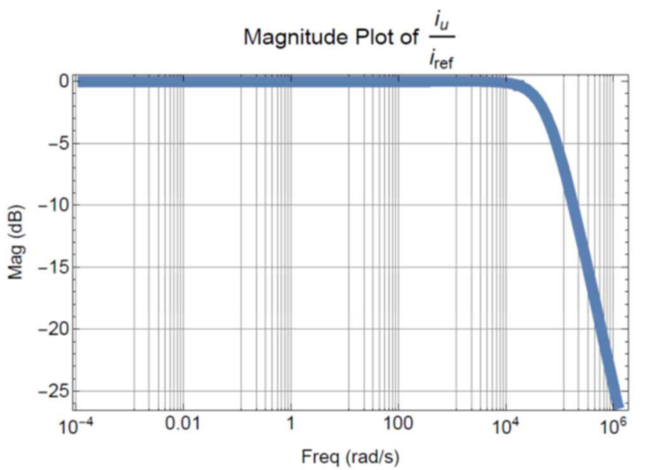
Distributed HSSPFC Configuration Architecture

- **Agent based** implementation / **Optizelle** I/F through host computer (slowest update rate)
- **Hamiltonian ESS control** realized in the RT-control level
- **Servo Controller** realized in RT-controller level with faster computation capable at the FPGA level



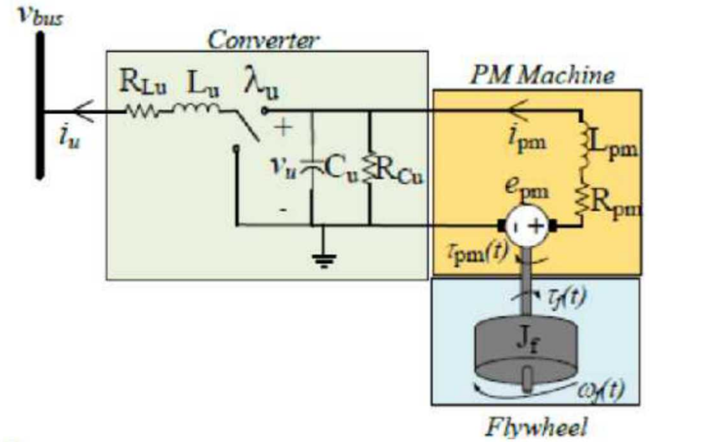
Utilized to Design and Specify ESS

- Requirements matched to specific ESS (Device Examples)
  - Power
  - Energy
  - Frequency
  - Flywheel ESS Example:

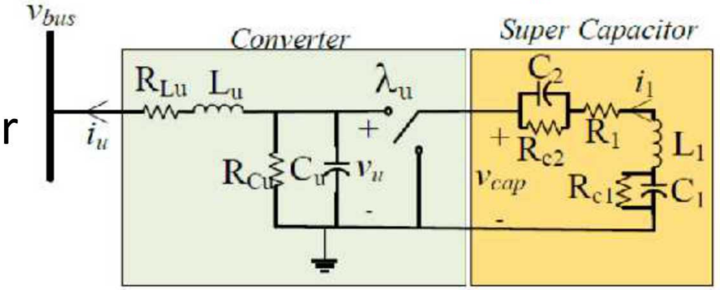


Derive:
Closed loop Bode plot – determines frequency characteristics contrast with specifications and requirements

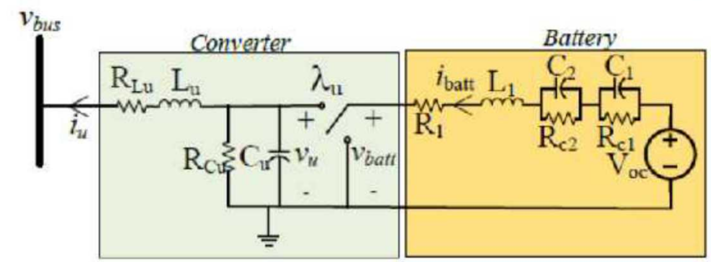
- Flywheel



- Super Capacitor

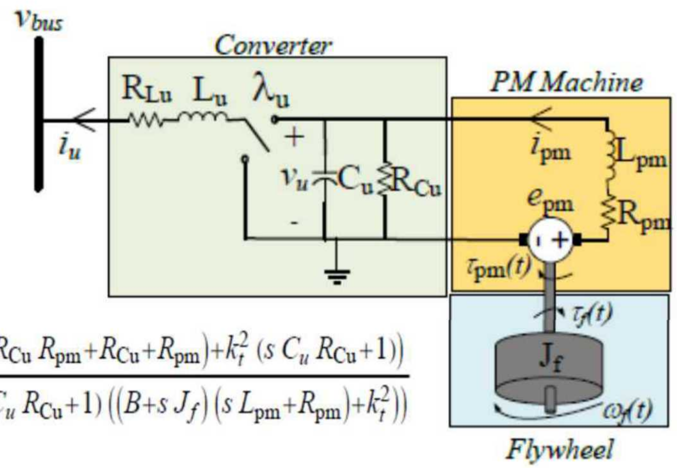


- Battery



EXAMPLE: ESS Flywheel Energy Storage Transfer Function First-Order Band-Limited ESS Design

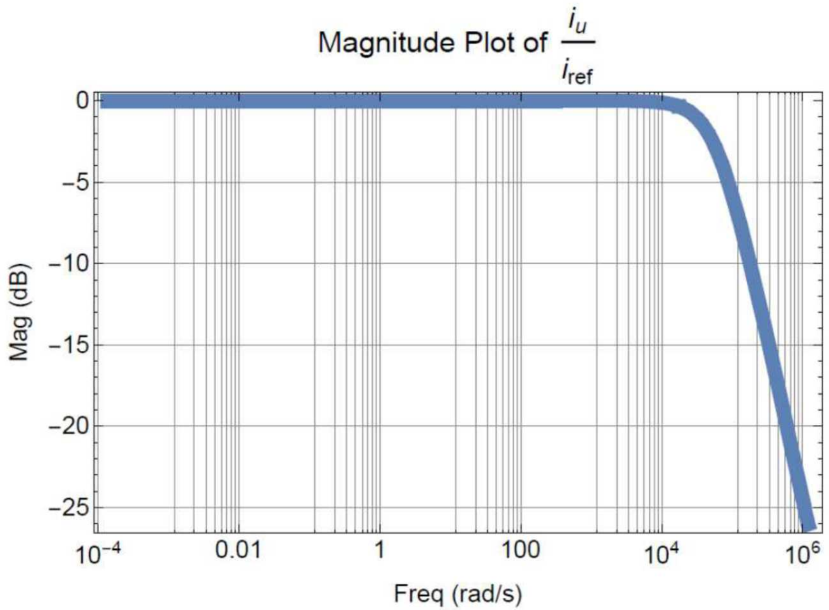
- Monolithic Flywheel ESS



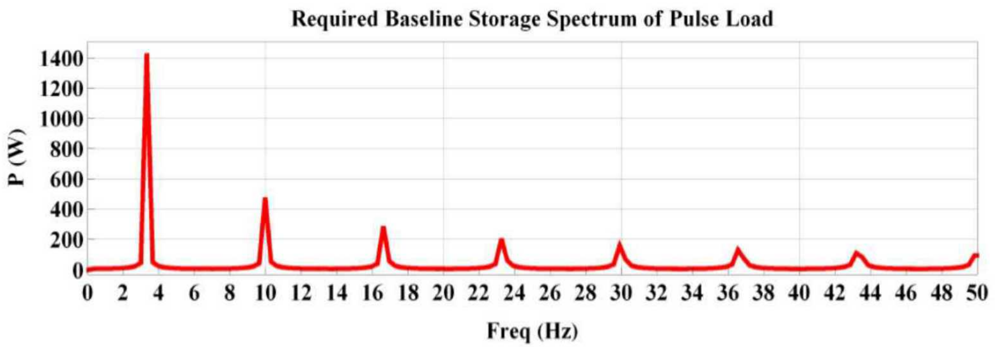
- Transfer function

$$G(s) = \frac{i_u}{i_{ref}} = -\frac{v_{uo}\left(s\,k_p+k_i\right)\left(\left(B+s\,J_f\right)\left(s\,L_{pm}\left(s\,C_u\,R_{Cu}+1\right)+s\,C_u\,R_{Cu}\,R_{pm}+R_{Cu}+R_{pm}\right)+k_t^2\left(s\,C_u\,R_{Cu}+1\right)\right)}{\left(v_{uo}\left(s\,k_p+k_i\right)+s\left(s\,L_u+R_{Lu}\right)\right)\left(R_{Cu}\left(-\left(B+s\,J_f\right)\right)-\left(s\,C_u\,R_{Cu}+1\right)\left(\left(B+s\,J_f\right)\left(s\,L_{pm}+R_{pm}\right)+k_t^2\right)\right)}$$

Derive:
Closed loop Bode plot – determines frequency characteristics contrast with specifications and requirements



- **Frequency Design Requirement**



Flywheel Frequency Response Meets Design Requirement

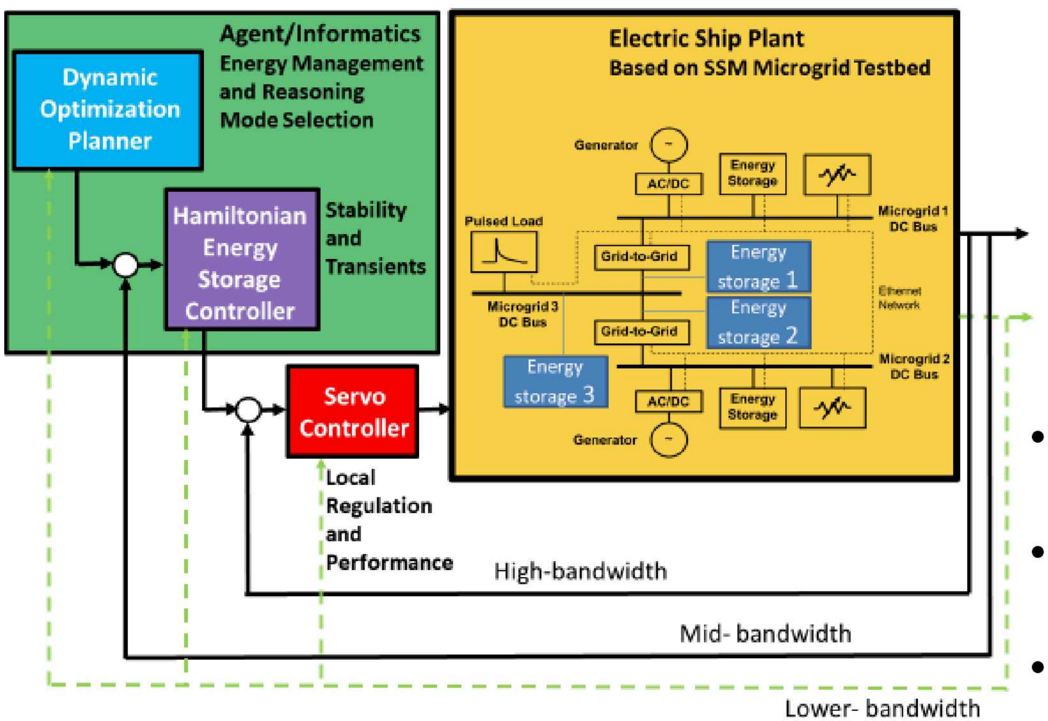
Ongoing/Future Work

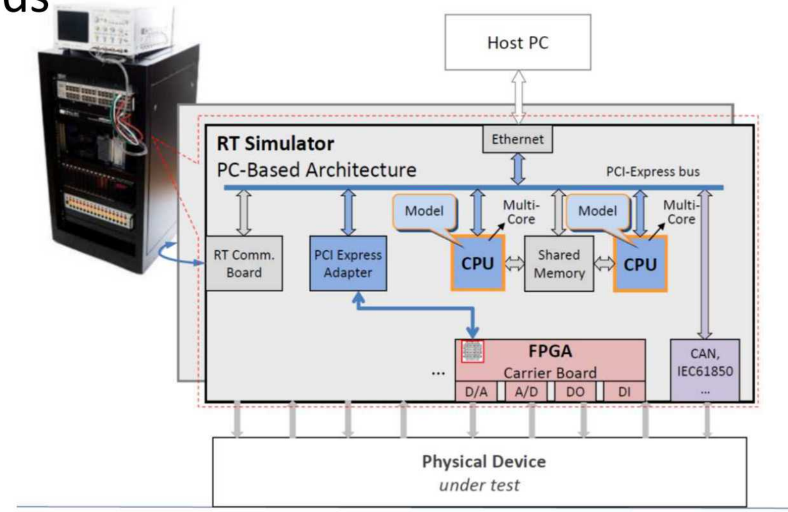
- Tri-level HSSPFC architecture for Navy All-electric Ship and EPG **networked Secure-Scalable Microgrid** (SSM) Applications
  - Trade off and selection ESS
  - RT, HIL, PHIL integration/validation
  - Coupled generator/bus networked microgrids

Rapid Prototyping Controller:

i) Coupled models (EMT)

ii) Controller validation





- **OPAL-RT** System Architecture (standard configuration)
- **SNL Architecture** custom configuration (OPAL-RT)
- **Prototype control** Matlab/Simulink/ RT-Lab environment

AC/DC Microgrid ROM Details

$$
\begin{aligned}
\mathbf{M}\dot{\mathbf{x}} &= \mathbf{R}\mathbf{x} + \mathbf{D}^T\mathbf{v} + \mathbf{B}^T\mathbf{u} \\
&= [\bar{\mathbf{R}} + \tilde{\mathbf{R}}]\mathbf{x} + \mathbf{D}^T\mathbf{v} + \mathbf{B}^T\mathbf{u}
\end{aligned}
$$

where $\mathbf{R} = \bar{\mathbf{R}} + \tilde{\mathbf{R}}$ is composed of a symmetric and skew-symmetric matrices, respectively.

$$
\mathbf{M} = diag[L_{s1}\; C_{dc1}\; L_{ac1}\; L_{ac1}\; L_{s2}\; C_{dc2}\; L_{ac2}\; L_{ac2}\; L_{s3}\; C_{dc3}\; L_{ac3}\; L_{ac3}\; C_B\; C_B]
$$

$$
\mathbf{R} = \begin{bmatrix}
-R_{s1} & -\lambda_{s1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\lambda_{s1} & -\frac{1}{R_{dc1}} & -\gamma_{cdc1} & -\gamma_{sdc1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \gamma_{cdc1} & -R_{ac1} & \omega L_{ac1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\
0 & \gamma_{sdc1} & -\omega L_{ac1} & -R_{ac1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\
0 & 0 & 0 & 0 & -R_{s2} & -\lambda_{s2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \lambda_{s2} & -\frac{1}{R_{dc2}} & -\gamma_{cdc2} & -\gamma_{sdc2} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \gamma_{cdc2} & -R_{ac2} & \omega L_{ac2} & 0 & 0 & 0 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 & 0 & \gamma_{sdc2} & -\omega L_{ac2} & -R_{ac2} & 0 & 0 & 0 & 0 & 0 & -1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -R_{s3} & -\lambda_{s3} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda_{s3} & -\frac{1}{R_{dc3}} & -\gamma_{cdc3} & -\gamma_{sdc3} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \gamma_{cdc3} & -R_{ac3} & \omega L_{ac3} & -1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \gamma_{sdc3} & -\omega L_{ac3} & -R_{ac3} & 0 & -1 \\
0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & \tilde{G} & \tilde{C} \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & -\tilde{C} & \tilde{G}
\end{bmatrix}
$$

where $\gamma_{c,dc,k} = \beta(\lambda c)_{dc,k}, \gamma_{s,dc,k} = \beta(\lambda s)_{dc,k}$ for $\ldots k = 1, \ldots 3, \tilde{G} = -\frac{1}{R_B}, \tilde{C} = C_B$, the matrix

AC/DC Microgrid ROM Details (2)

$$\mathbf{D}^T = \begin{Bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{Bmatrix} \quad \text{and the matrix } \mathbf{B}^T = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$