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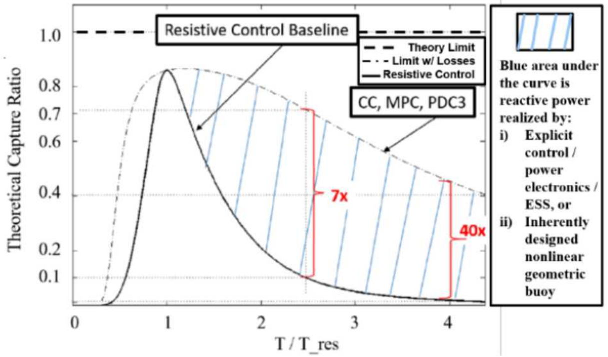

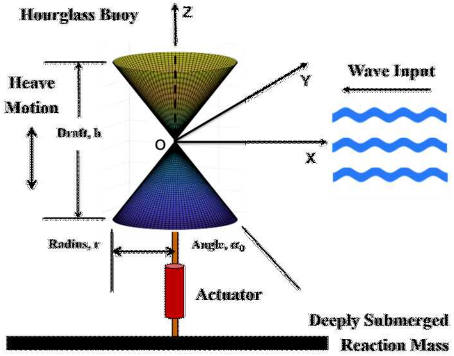

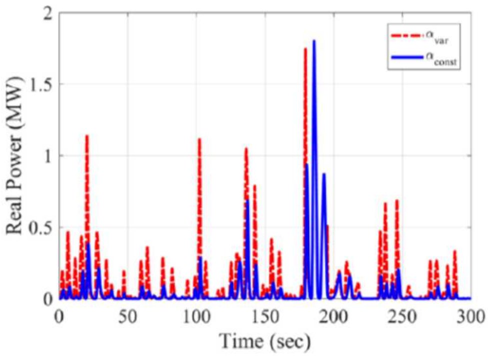

Nonlinear WEC Optimized Geometric Buoy Design for Efficient Reactive Power Requirements

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SAND2019-11980 C

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Outline

- Introduction
- WEC Geometry and Model Description
- WEC Control Buoy Design
  - PDC3 Design Methodology for RCC WEC
  - NL Control Design for RCC WEC
  - NL Control Design for NL HG Buoy Geometry WEC
- Numerical Simulations
  - Single Frequency Case
  - Bretschneider Spectrum Case
- Summary and Conclusions
- Acknowledgments

Introduction

- Abundant resource of untapped energy exists in ocean
- Energy from ocean waves may provide regular source of power with intensity that can be accurately predicted several days before arriving at capture point
- Energy from waves considered more predictable (less stochastic) in nature then wind or solar energy
- Wave energy capacity in entire ocean estimated between 8K-80K TWh/yr or 1-10 TW future energy and power generation
- On average each wave crest can transmit 1—50 kW/m
- Many WEC devices are being considered by private industry to harvest energy
- Specific class for this study will focus on omni-directional point absorber/buoy

- Biggest challenges for all renewable energy generation is for variable power - reactive power or ESS will be required to deliver quality power at the grid

WEC Geometry and Model Description

- Approximate hydrodynamic model known as Cummins' equation of motion

$$(\tilde{m}+\tilde{a}(\infty))\ddot{z}+\int_0^\infty h_r(\tau)(t-\tau)d\tau+kz=F_e+F_u$$

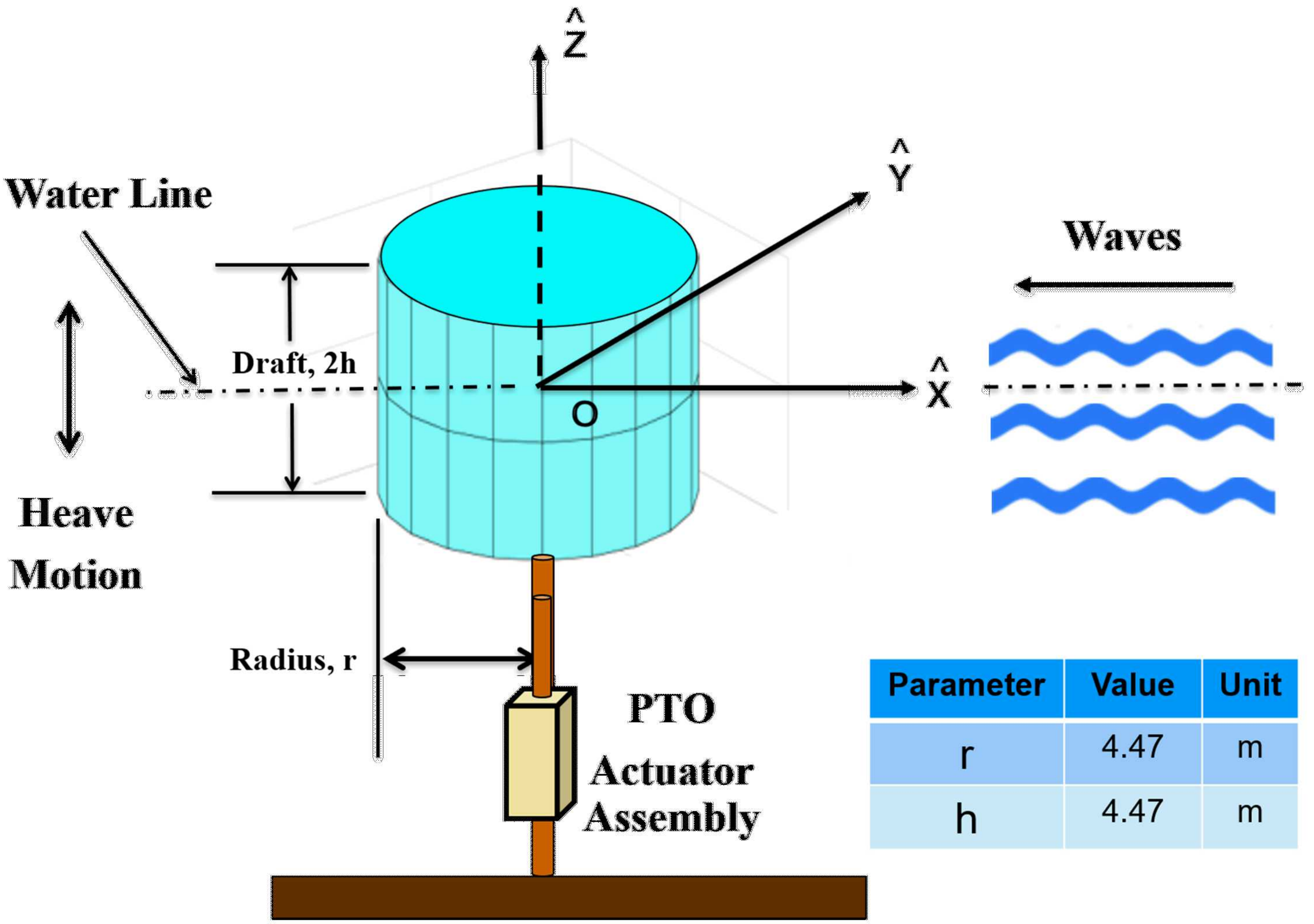
- Simple case defined for regular wave with single frequency excitation force

$$(\tilde{m}+\tilde{a}_1)\ddot{z}_1+c_1\dot{z}_1+kz_1=f_{e_1}+f_{u_1}$$

- Excitation force for a single frequency is

$$f_{e_1}=A_{e_1}\sin(\omega_1 t+\phi_1)$$

WEC Geometry and Model Description

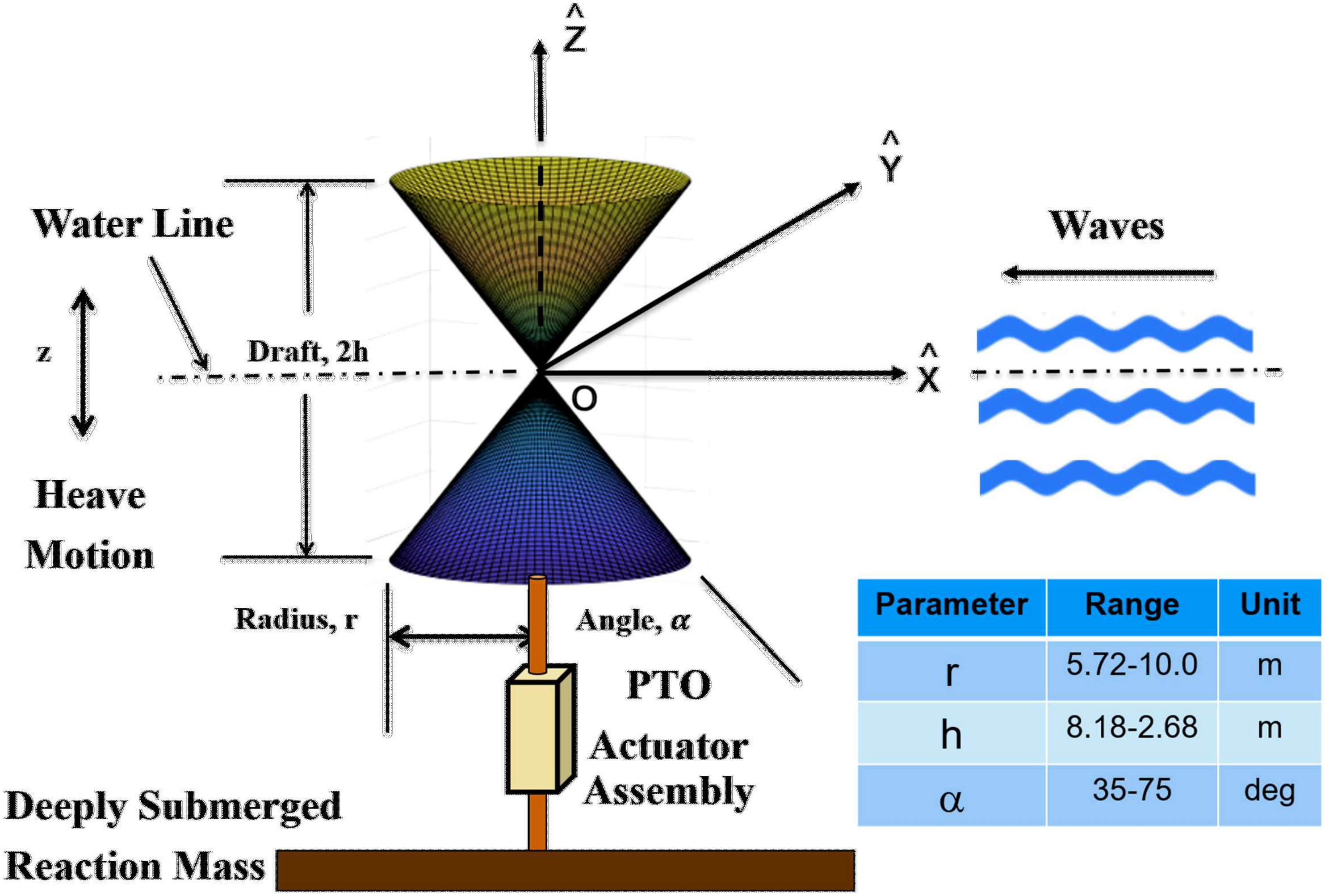


Parameter	Value	Unit
r	4.47	m
h	4.47	m

- WEC modeled as linear actuator
- Part of PTO system
- Reactive mass submerged deep enough oscillations are negligible
- Baseline linear geometry defined as RCC

- RCC geometry WEC buoy design and corresponding parameters

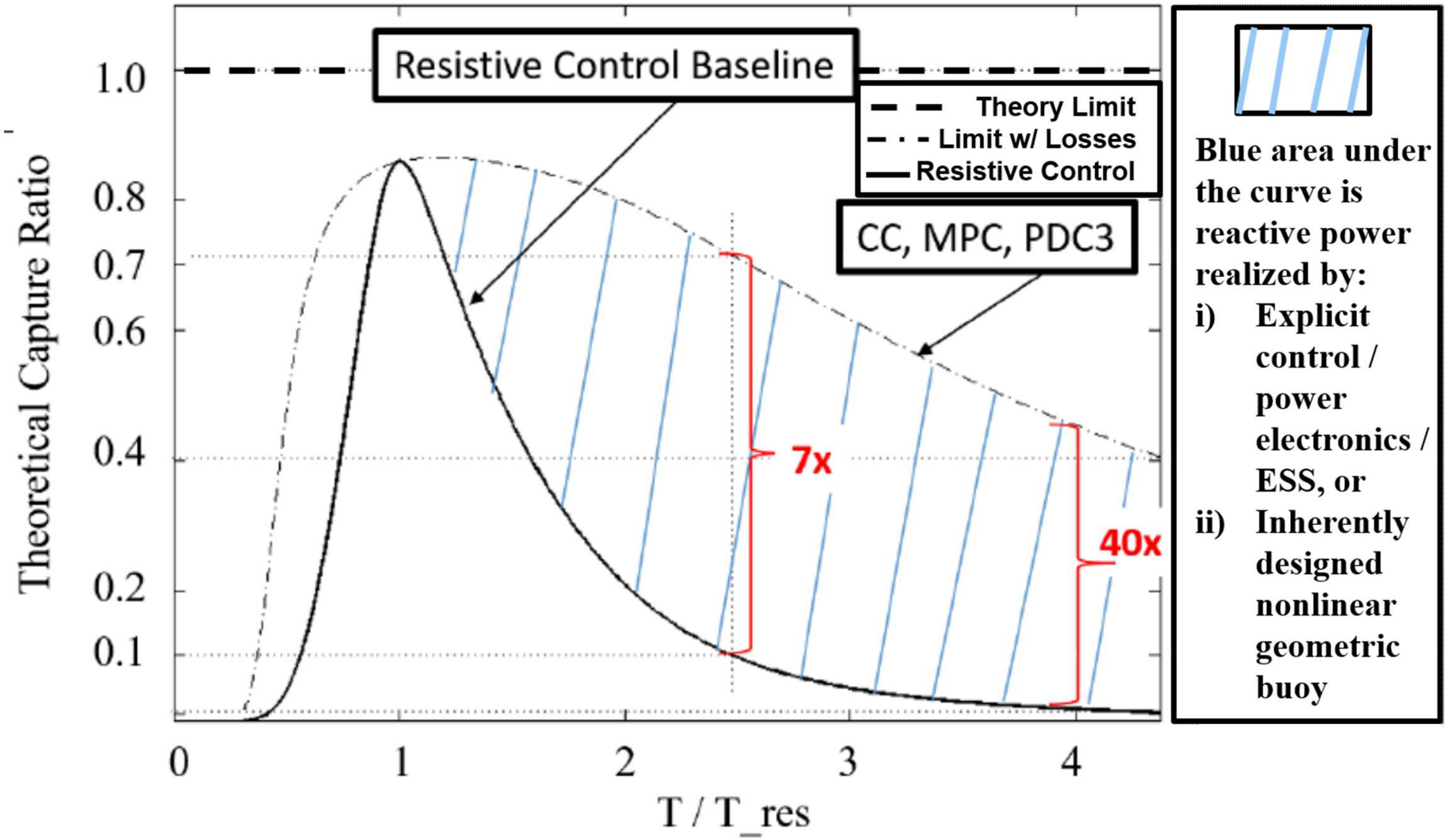
WEC Geometry and Model Description



Parameter	Range	Unit
r	5.72-10.0	m
h	8.18-2.68	m
α	35-75	deg

- HG geometry WEC buoy design and corresponding parameters

WEC Control Buoy Design



▨ **Blue area under the curve is reactive power realized by:**

- **i) Explicit control / power electronics / ESS, or**
- **ii) Inherently designed nonlinear geometric buoy**

Heave
1-DOF
System

- Example capture ratios for several difference control strategies:
  - CC – complex conjugate
  - MPC – model predictive control
  - PDC3 – proportional derivative CC control

WEC Control Buoy Design

PDC3 design methodology for RCC WEC

- WEC modeled as simple MSD plant

$$m\ddot{z} + c\dot{z} + kz = F_u + \sum_{j=1}^{N} F_{e_j} \sin \Omega_j t \quad \text{(Fourier series)}$$

- PD controller per channel j

$$F_u = \sum_{j=1}^{N} F_{u_j} = \sum_{j=1}^{N} \left[-K_{P_j} z_j - K_{D_j} \dot{z}_j\right]$$

- Results in

$$m\ddot{z}_j + (c + K_{D_j})\dot{z}_j + (k + K_{P_j})z_j = F_{e_j} \sin \Omega_j t$$

- For single frequency forcing function

$$m\ddot{z} + (c + K_D)\dot{z} + (k + K_P)z = F_0 \sin \Omega t$$

WEC Control Buoy Design

NL Control Design for RCC WEC

$$m\ddot{z} + (c + K_D)\dot{z} + K_{NL}z^3 = F_e$$

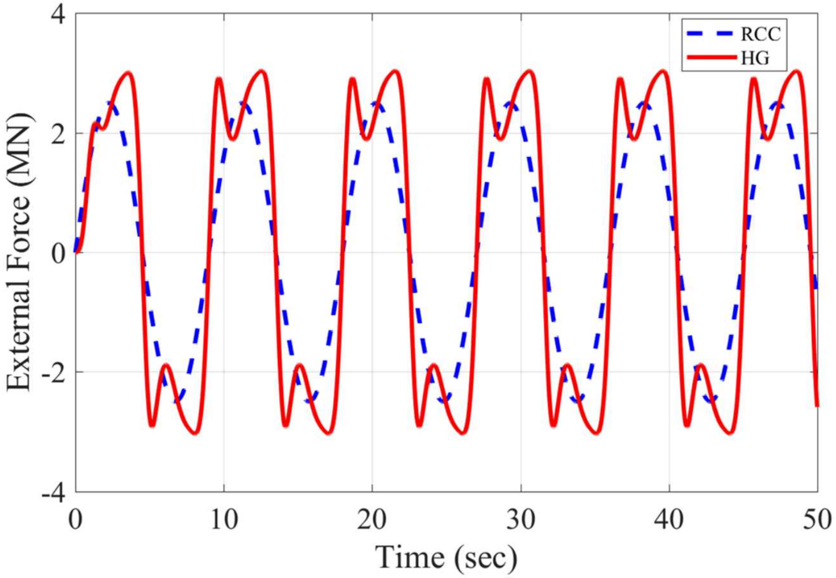
NL Control Design for NL HG Buoy Geometry WEC

- Equation of motion

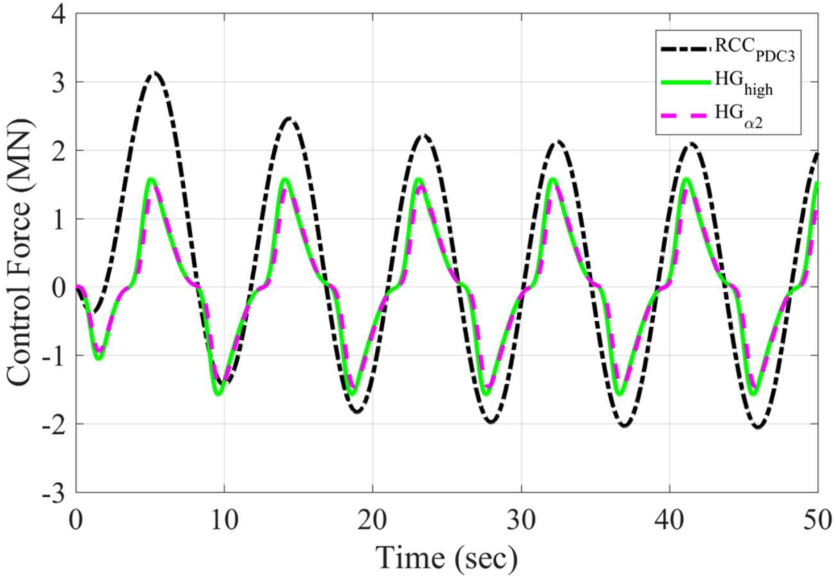
$$m\ddot{z} + c\dot{z} + K_{HG}(\alpha)[\frac{1}{3}z^3 - \eta z^2 + \eta^2 z] = \frac{1}{3}K_{HG}(\alpha)\eta^3 + F_u$$

- Wave elevation given as η
- Function of steepness angle parameter is $K_{HG}(\alpha)$
- Rate feedback term is $F_u = -K_D\dot{z}$
- Contains cubic spring "like" term $\frac{1}{3}K_{HG}(\alpha)z^3$

Numerical Simulations

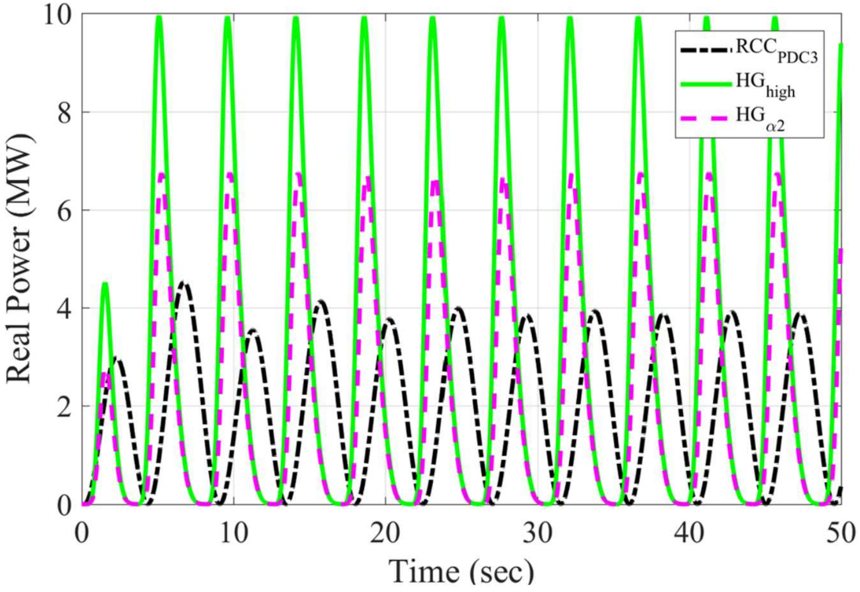


- Single frequency excitation force response

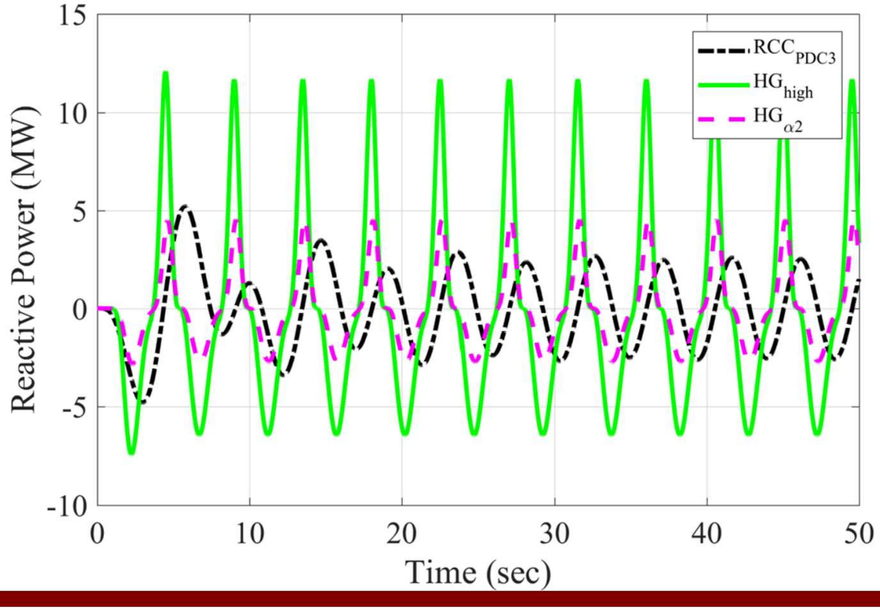


- Single frequency control force response

Numerical Simulations

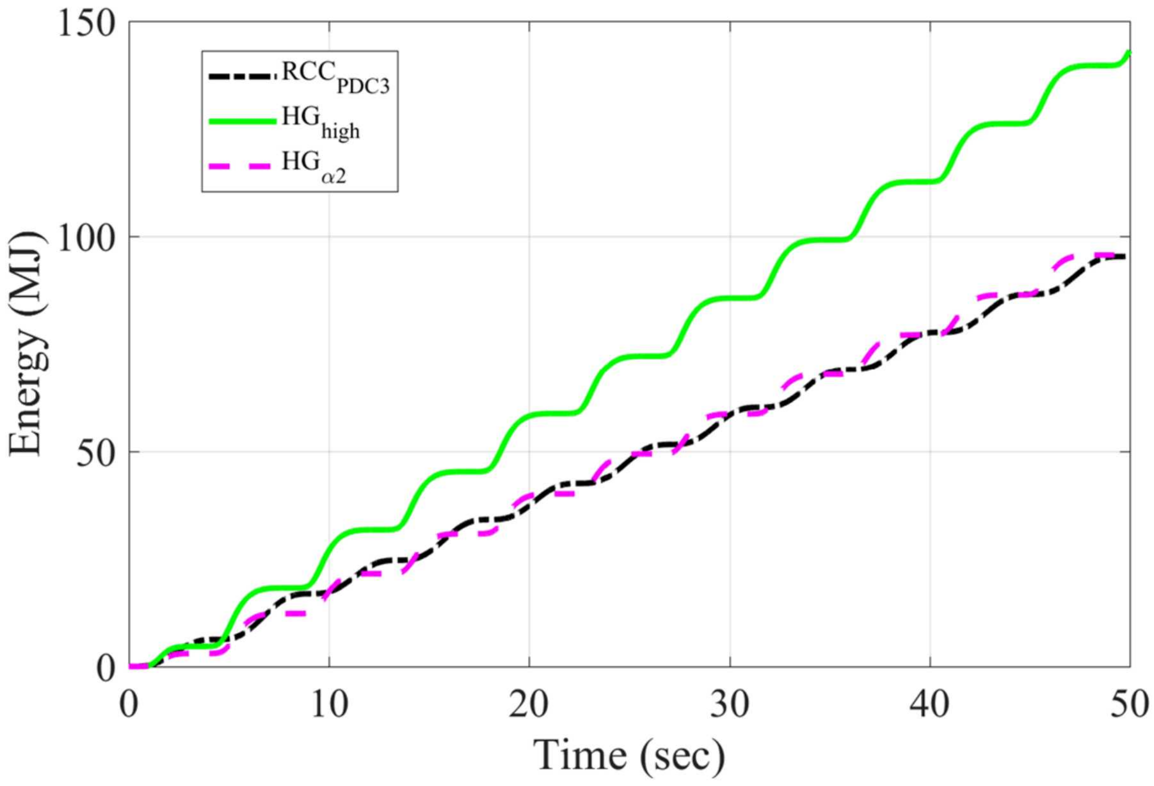


- Single frequency real power response



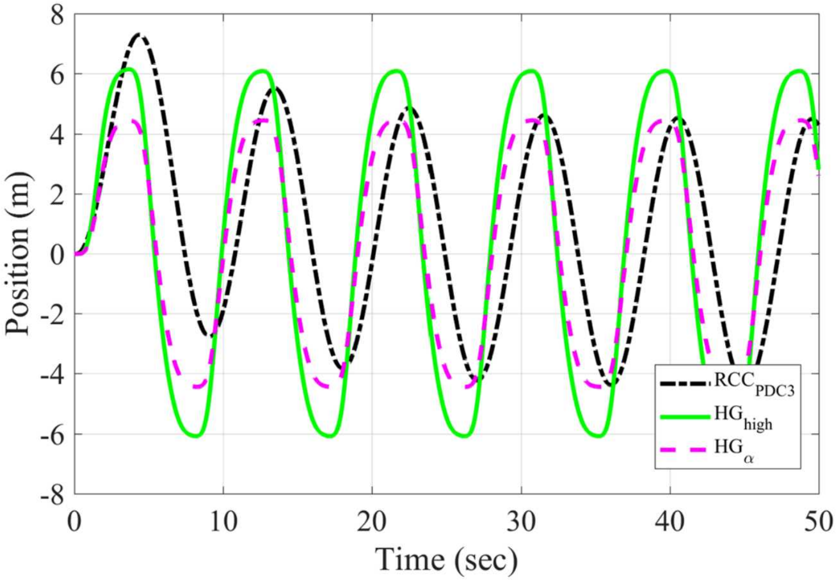
- Single frequency reactive power response

Numerical Simulations

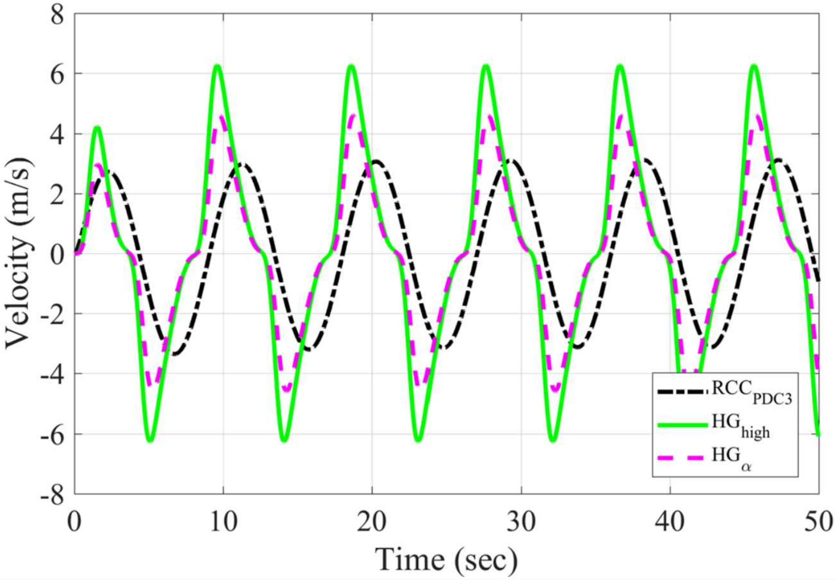


- Single frequency energy capture response

Numerical Simulations



- Single frequency position response



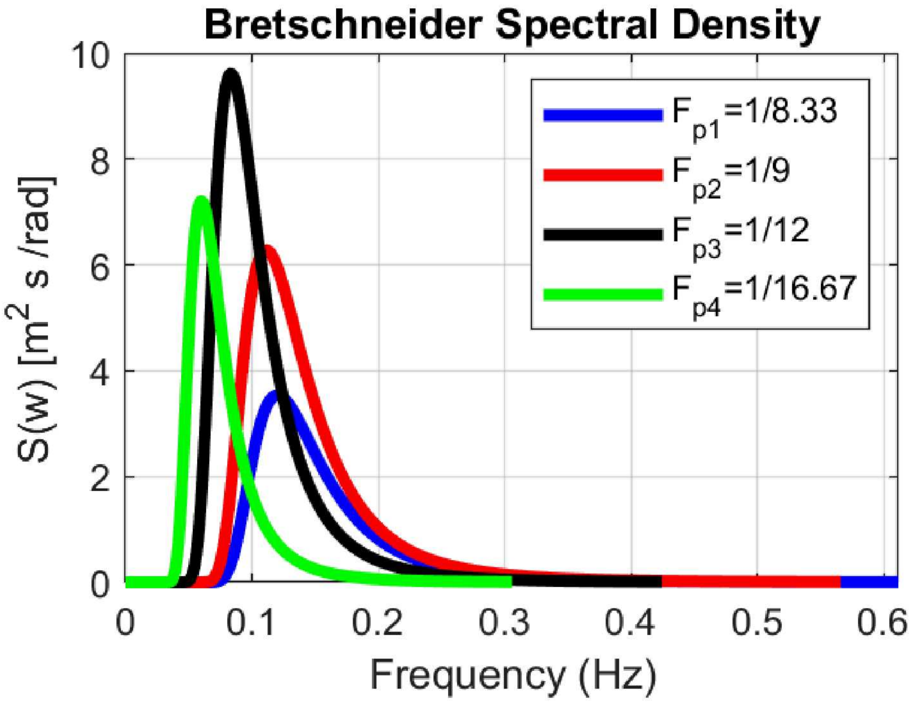
- Single frequency velocity response

4 Sea States Analyzed

These 4 Sea States with 5 min Durations will be applied to the HG buoy design to fully evaluate power/energy extraction

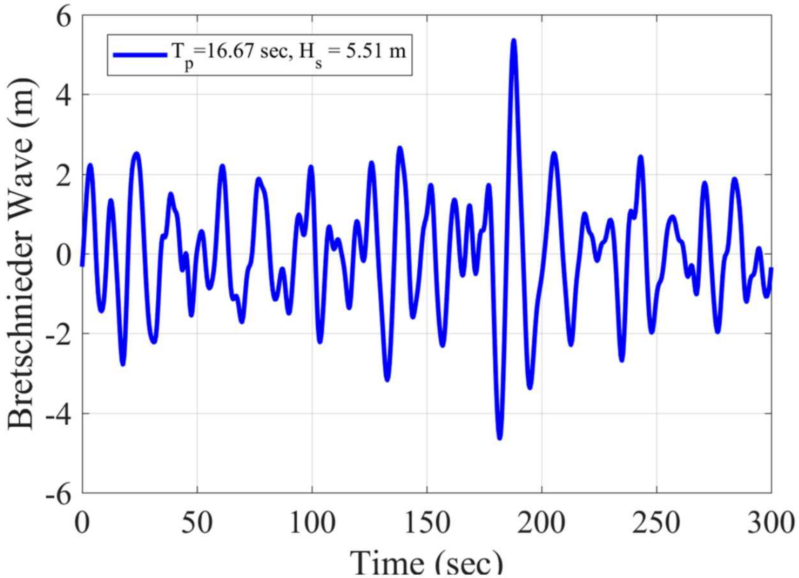
2 Sea States* related to Nags Head in NC

Sea State	Hs (m)	Tp (sec)	Duration (sec)
1*	5.46	8.33	300
2	7.0	9	300
3	7.5	12	300
4**	5.51	16.67	300

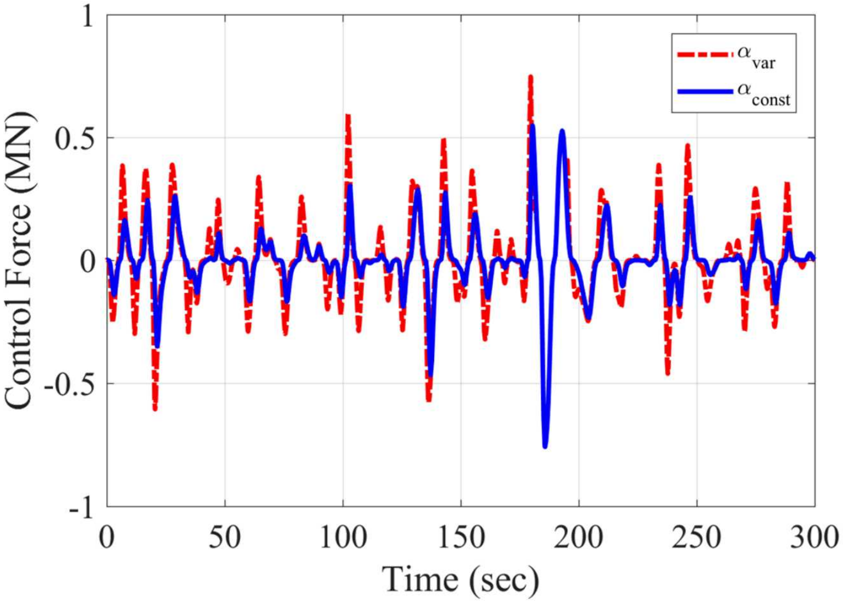


Note: Spectrum generated by *Bretschneider* and corresponding time domain data by *spec2sdat* Matlab functions from:
Perez, T.; Fossen, T. A Matlab *Toolbox for Parametric Identification of Radiation-Force Models of Ships and Offshore Structures*, Modeling, Identification, and Control 2009, 30, 1–15.

Numerical Simulations

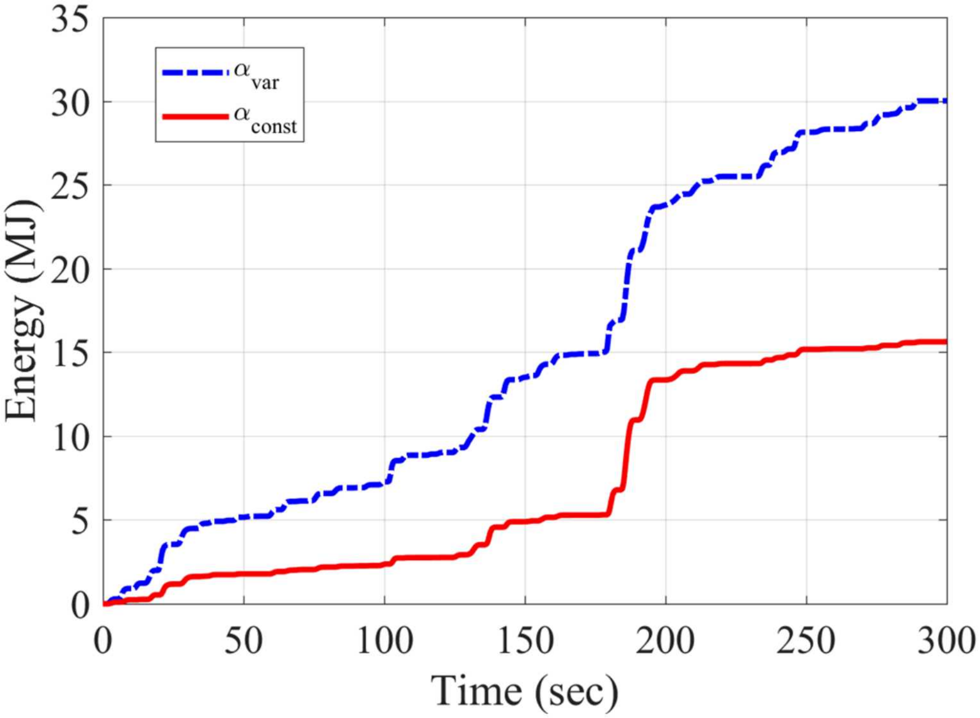


- Bretschneider spectrum wave input Sea State 4



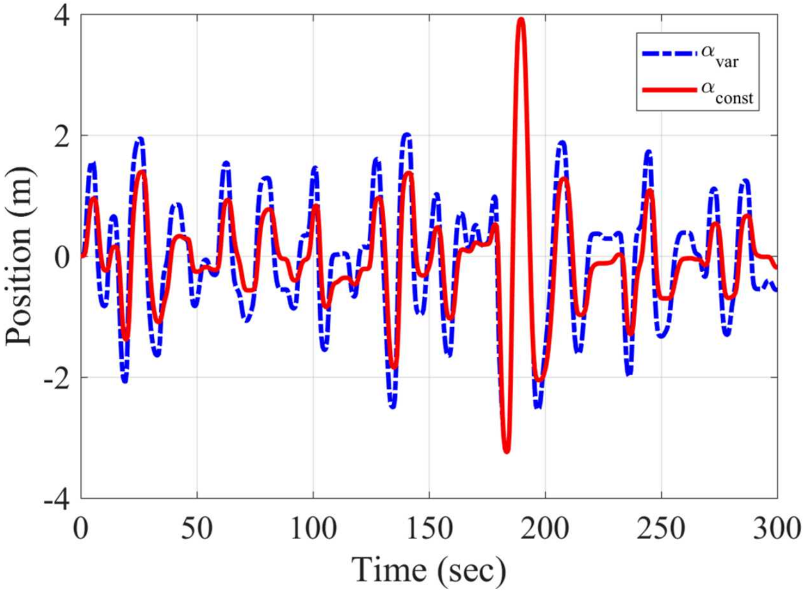
- Bretschneider spectrum control force response

Numerical Simulations

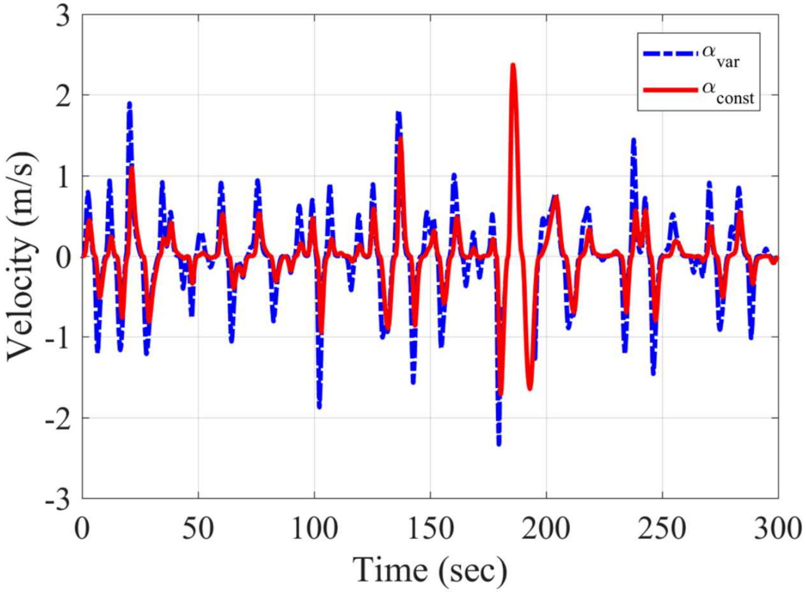


- Bretschneider spectrum energy capture response

Numerical Simulations

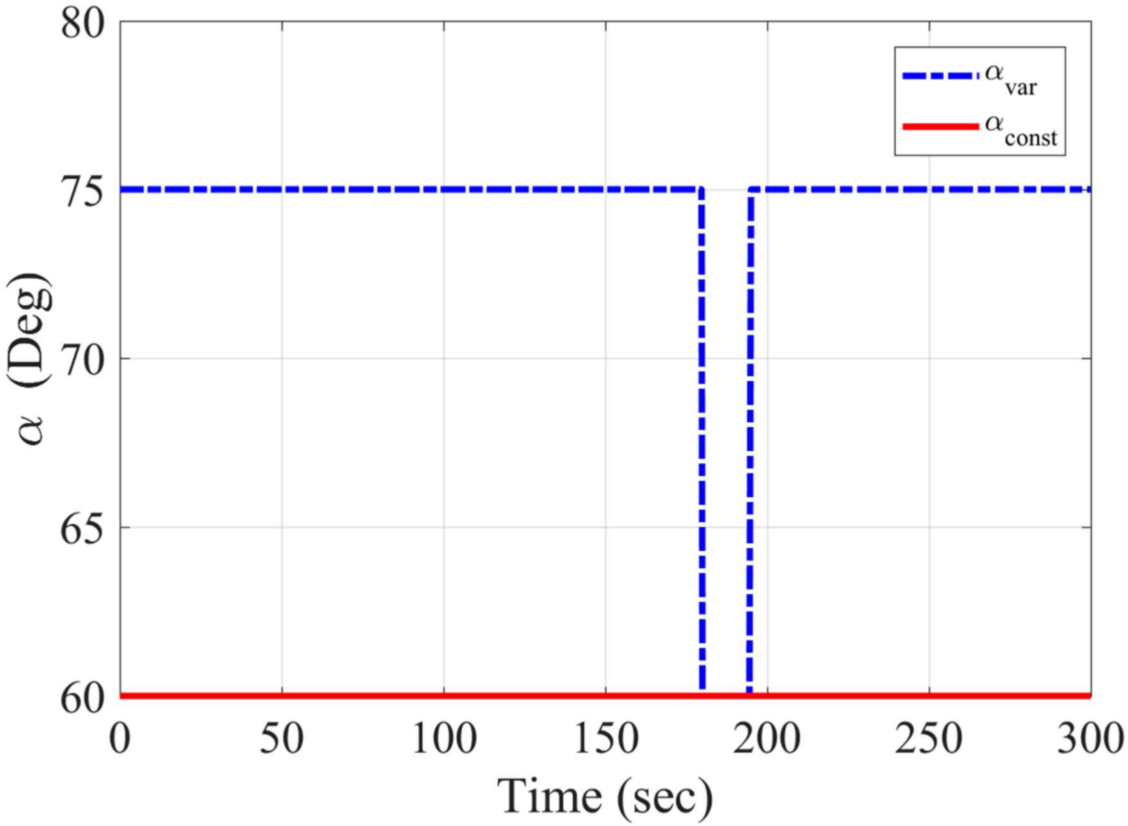


- Bretschneider spectrum position response



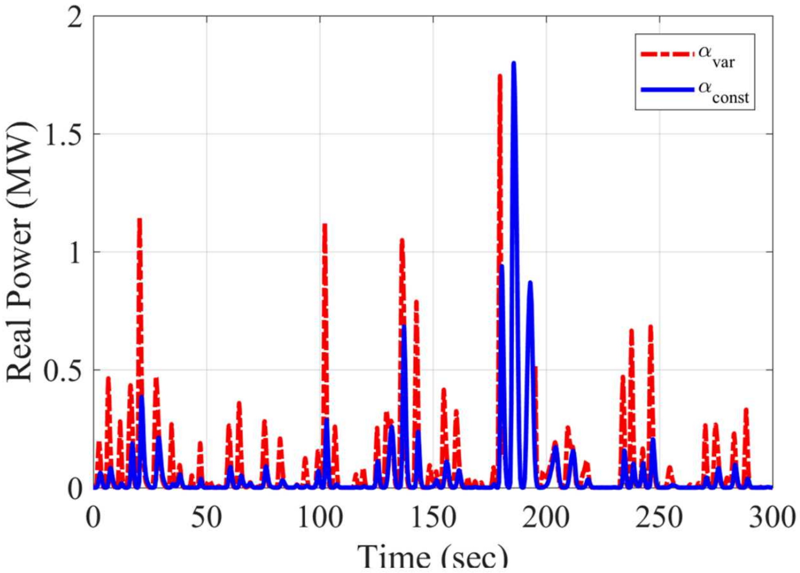
- Bretschneider spectrum velocity response

Numerical Simulations

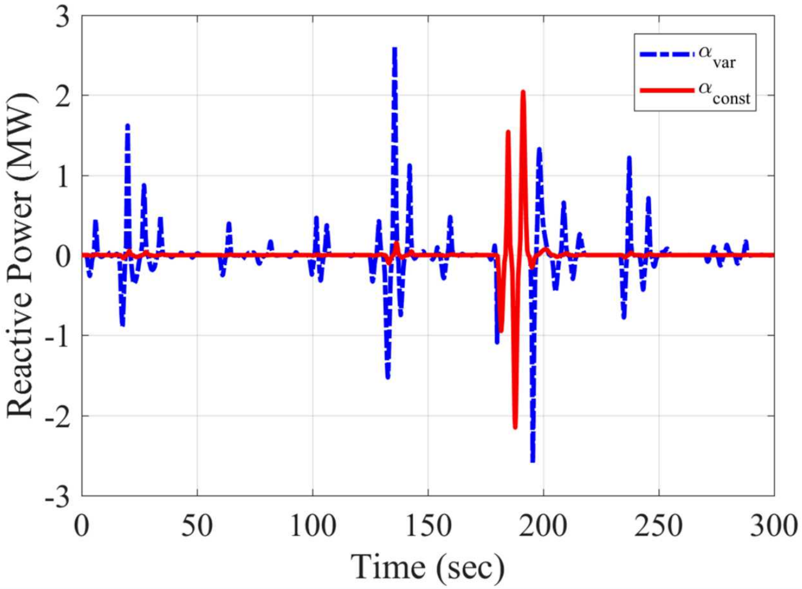


- Bretschneider spectrum wave input Sea State 4
- Vary alpha to increase energy capture

Numerical Simulations



- Bretschneider spectrum real power response



- Bretschneider spectrum reactive power response

Conclusions

- Presented nonlinear geometric buoy design for WECs
- HG geometry produced nonlinear dynamic model with inherent reactive power
- Reactive power produced from interaction with the waves and buoy
- For single frequency PDC3 RCC compared with HG buoy design
- Simulations demonstrated increase power and energy capture for the HG design
- A Bretschneider spectrum of wave excitation input conditions evaluated HG design
- Exploiting NL physics in HG design simplified operational performance compared to optimized linear RCC WEC
- HG steepness angle was varied wrt wave and an initial optimization produced double the energy capture
- Future work will include multiple sea states and more refined optimization for the steepness angle

Acknowledgments

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- The views expressed in the article do not necessarily represent the views of the U.S. Department of Energy or the United States Government

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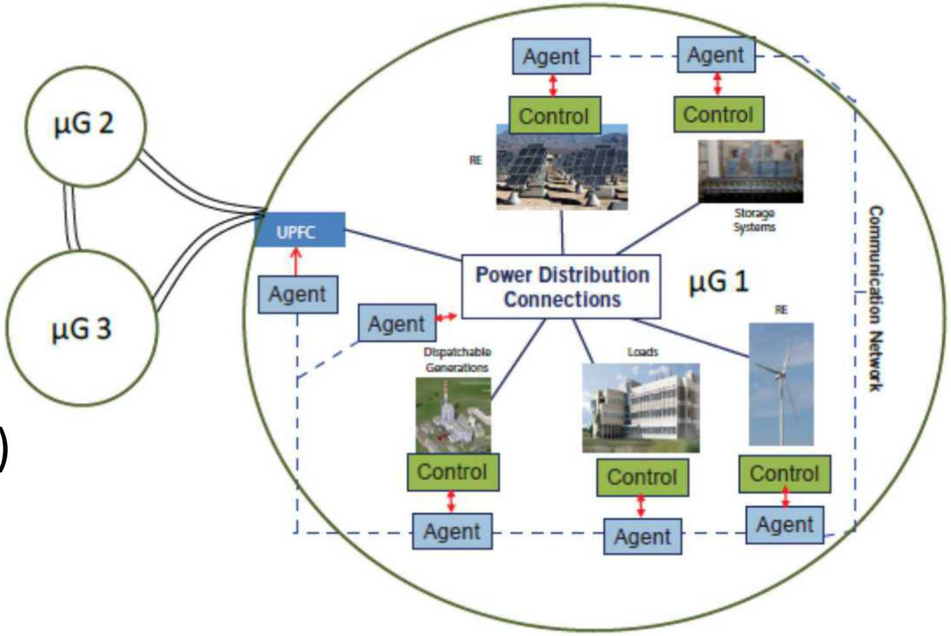
Backup Charts

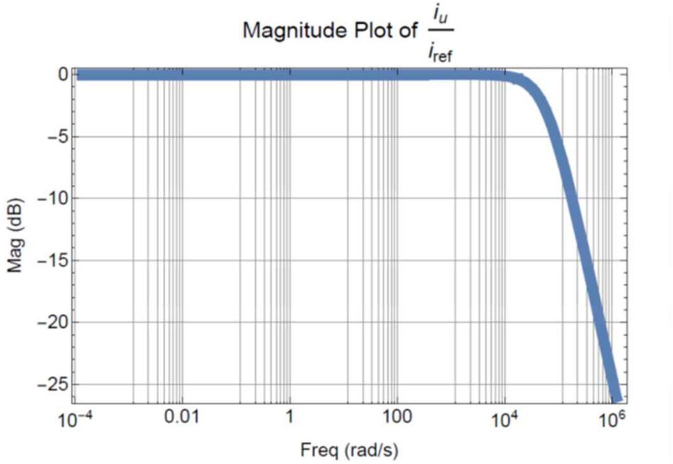
DOE and DoD Focus Energy Surety

- **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



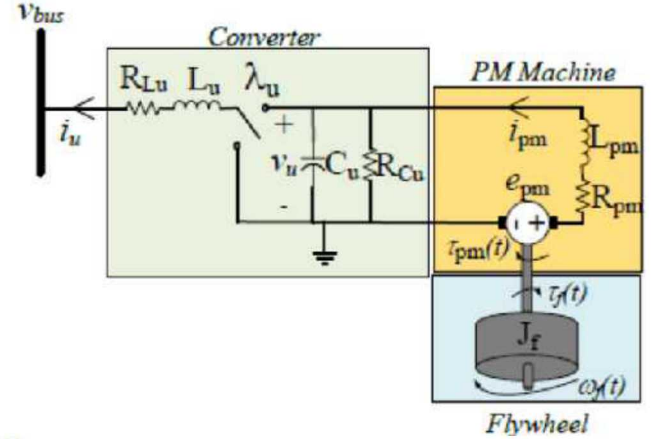
Utilized to Design and Specify ESS

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

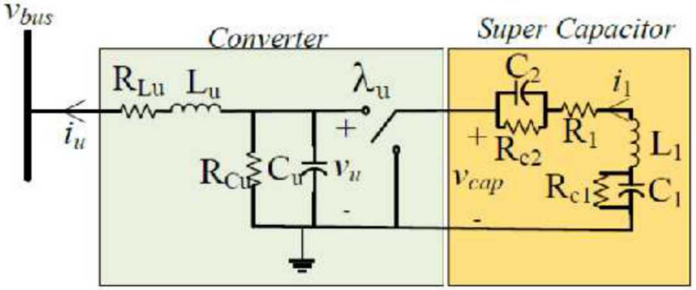


Derive:
Closed loop Bode plot – determines frequency characteristics contrast with specifications and requirements

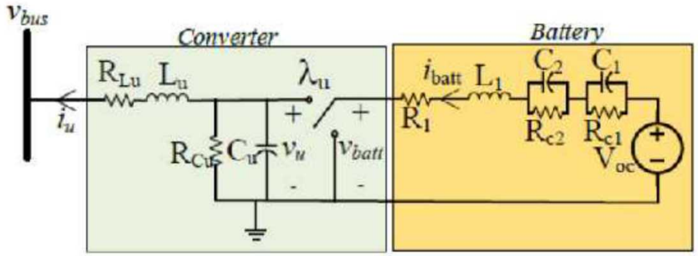
- Flywheel



- Super Capacitor

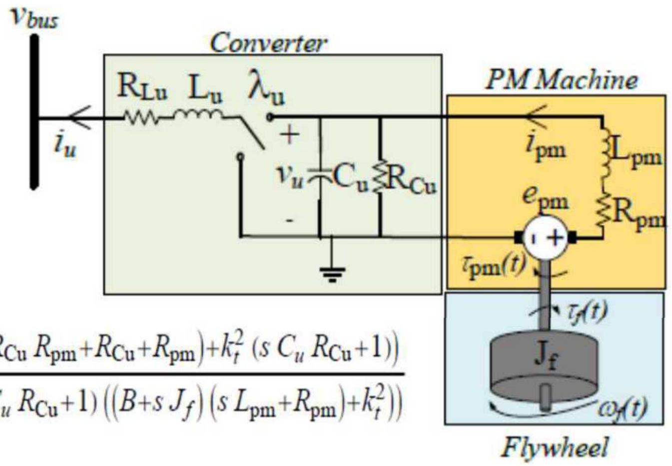


- Battery



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

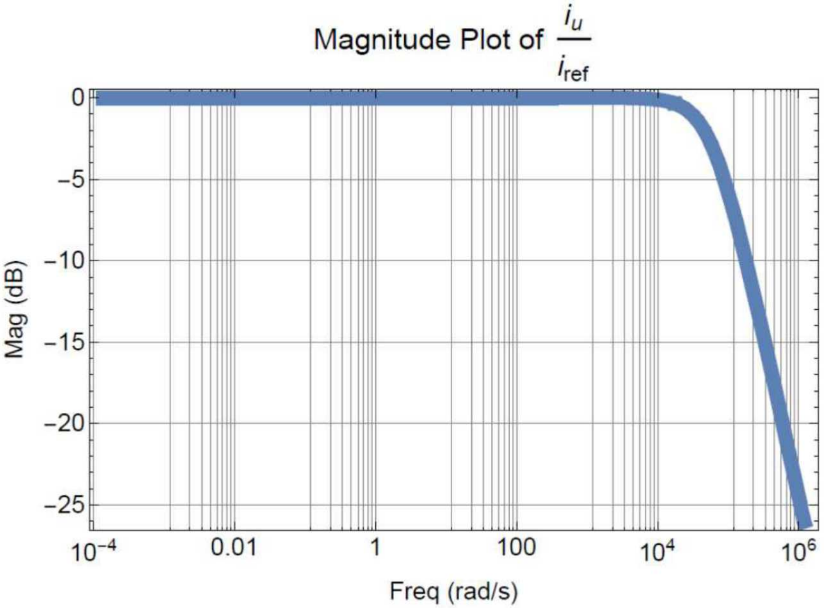
- Monolithic Flywheel ESS



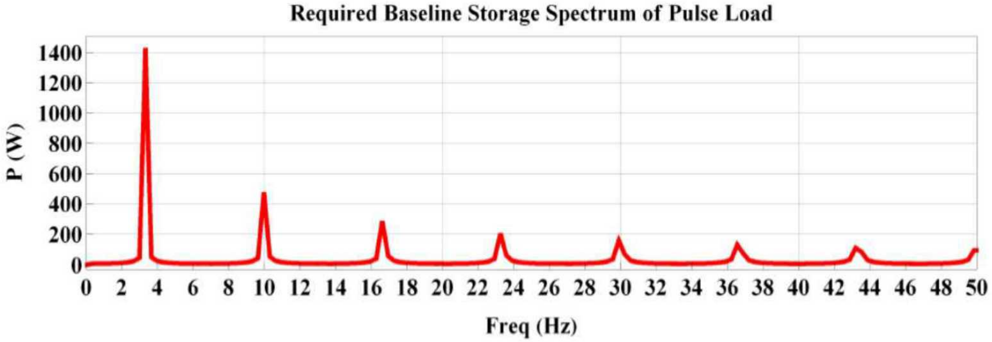
- Transfer function

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

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



- **Frequency Design Requirement**



Flywheel Frequency Response Meets Design Requirement

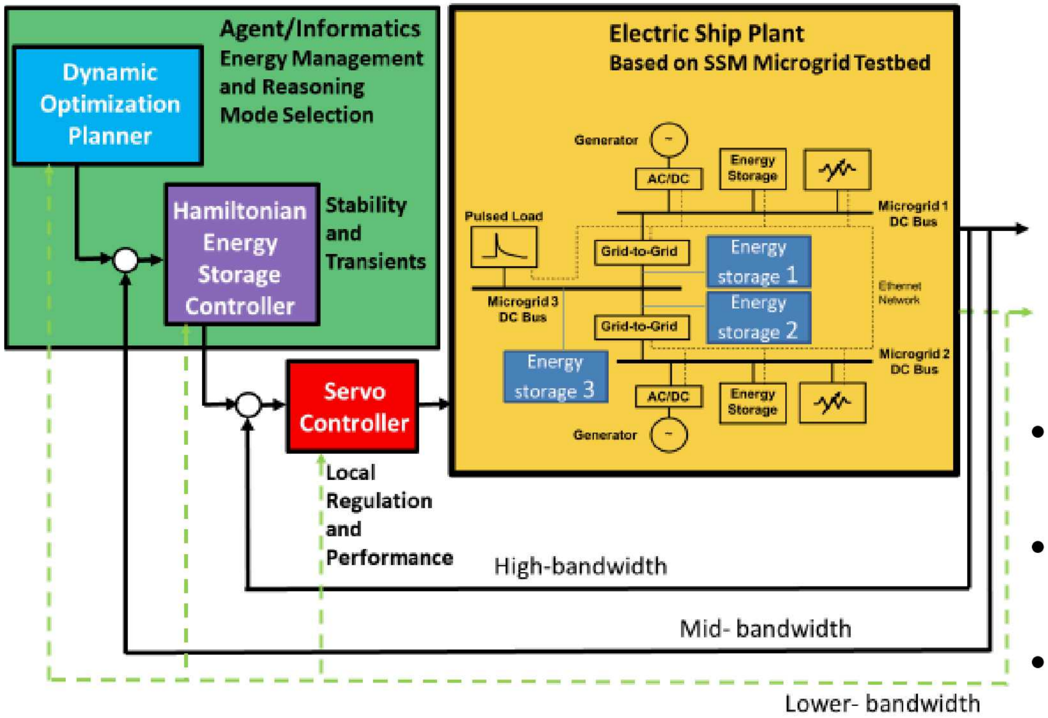
Ongoing/Future Work

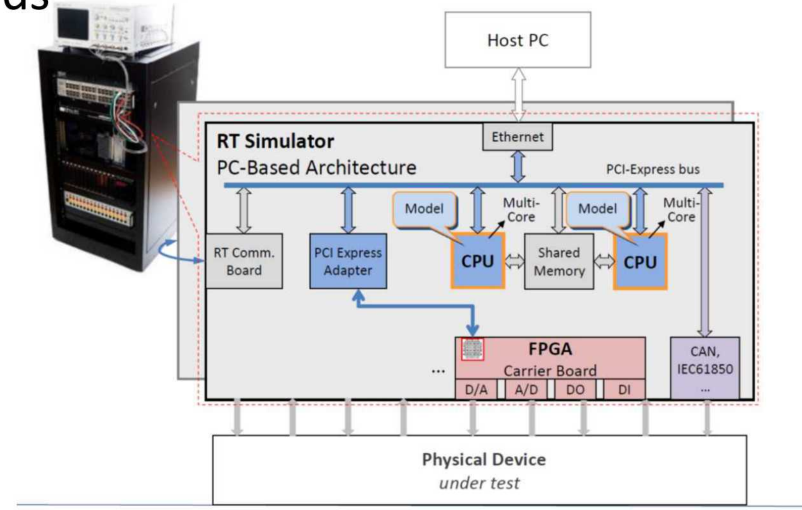
- Tri-level HSSPFC architecture for Navy All-electric Ship and EPG **networked Secure-Scalable Microgrid** (SSM) Applications
  - Trade off and selection ESS
  - RT, HIL, PHIL integration/validation
  - Coupled generator/bus networked microgrids

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