SAND2018-9697C

Energy Storage Design Considerations for an MVDC Power System

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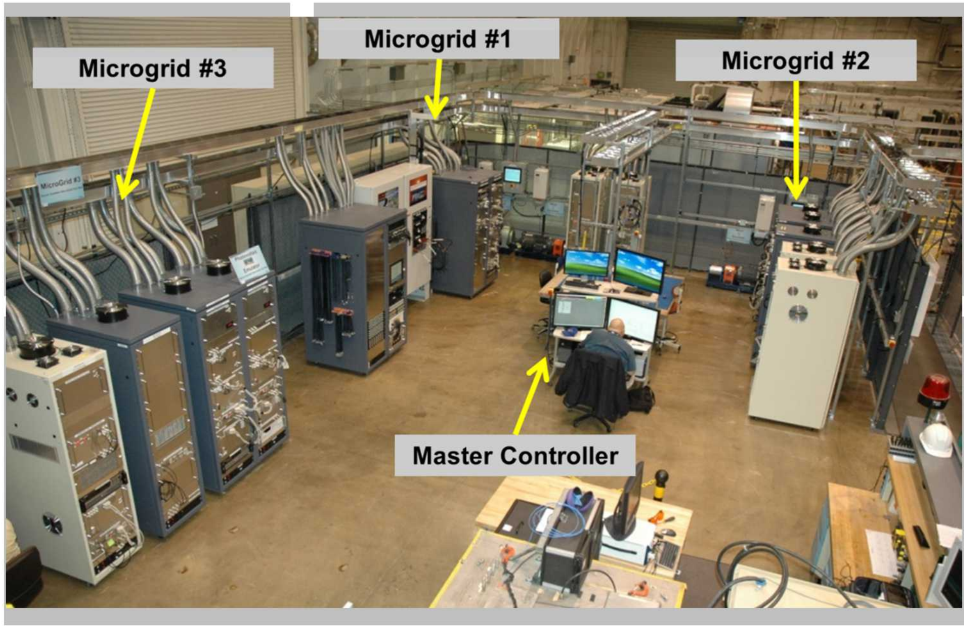

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Outline

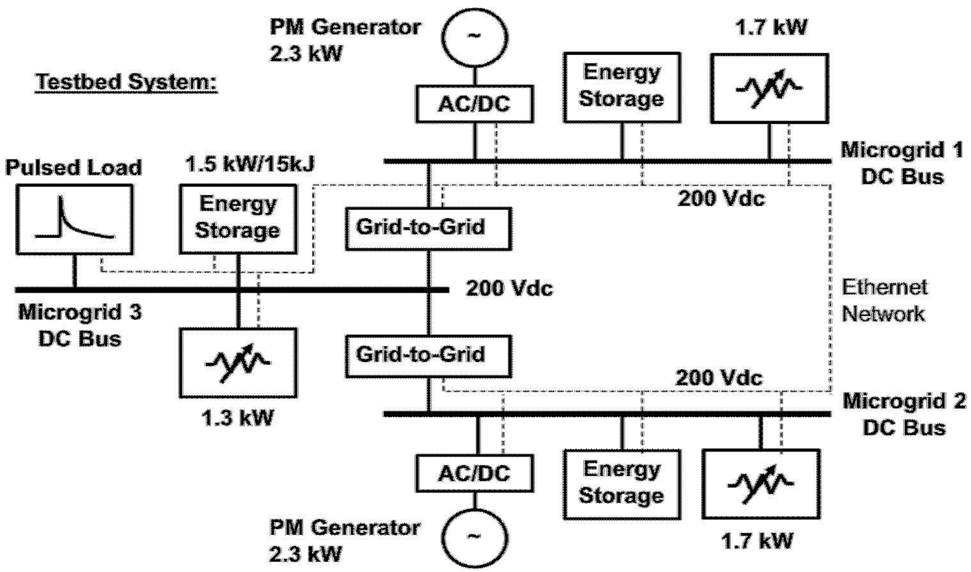
- Introduction
- Model Development
  - System Layout
  - Control Algorithm
  - Load Profiles
  - Simulation Results
- Energy Storage Requirements
  - Power and Energy Requirements
  - Frequency Analysis
- Conclusions

Introduction

- Controls are recognized as a primary challenge to fielding a medium voltage DC (MVDC) power system for future Navy ships
- The service power demands of these future naval warships may include advanced mission systems which need large amounts of power in short pulses
- Energy storage is a key component of shipboard MVDC architecture
  - Minimum sizing
  - Trade offs between performance and size

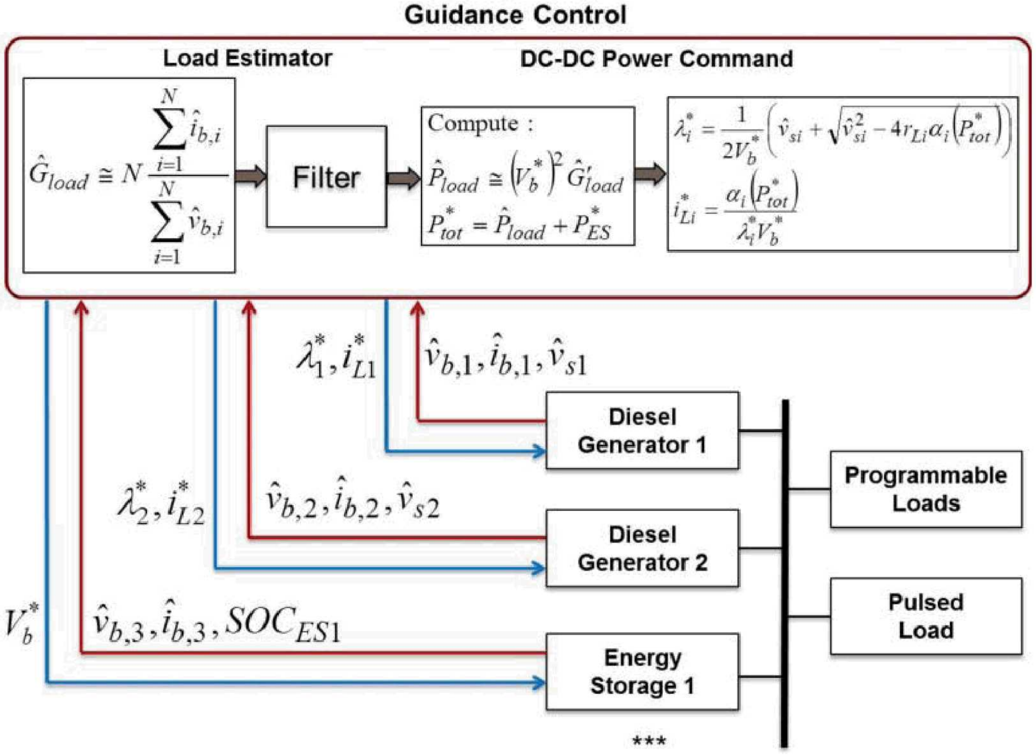
Scaled notional model of ship power system was developed

- An electric ship is emulated using the Secure Scalable Microgrid Testbed (SSMTB) hardware at Sandia National Laboratories (SNL)
- 3 networked microgrids
- Power electronics interfaces
- Agent based control
- Repeatable experiment profiles
- Simulink model library

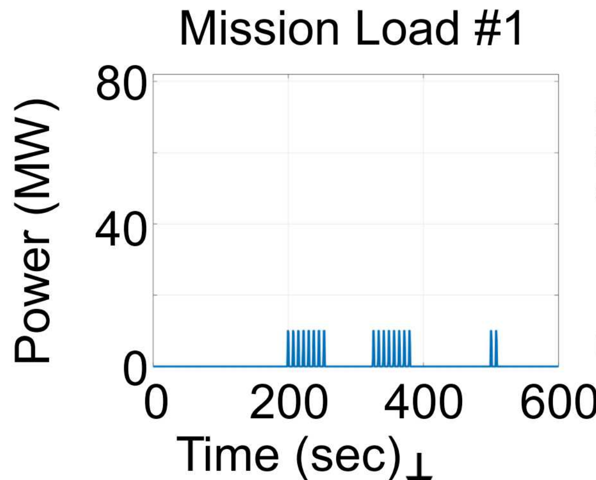


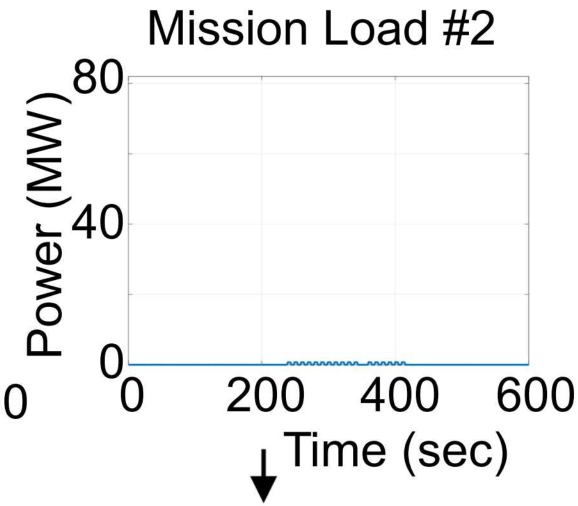
Optimization control determines set-points based on system status

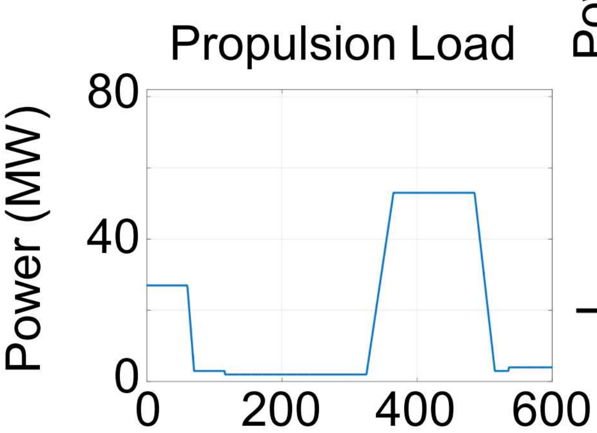
- Based on guidance control algorithm
- Reads terminal voltages, output currents, and state of charge (SOC) for all sources
- Estimates load
- Determines power demands
- Sets operational set points for sources
- Filter used to determine power balance between energy storage and generator resources

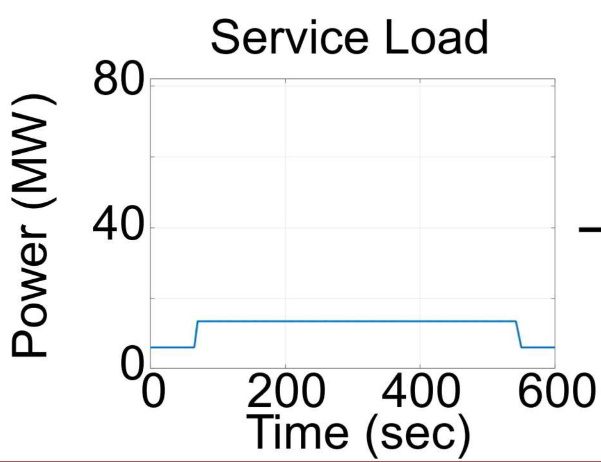


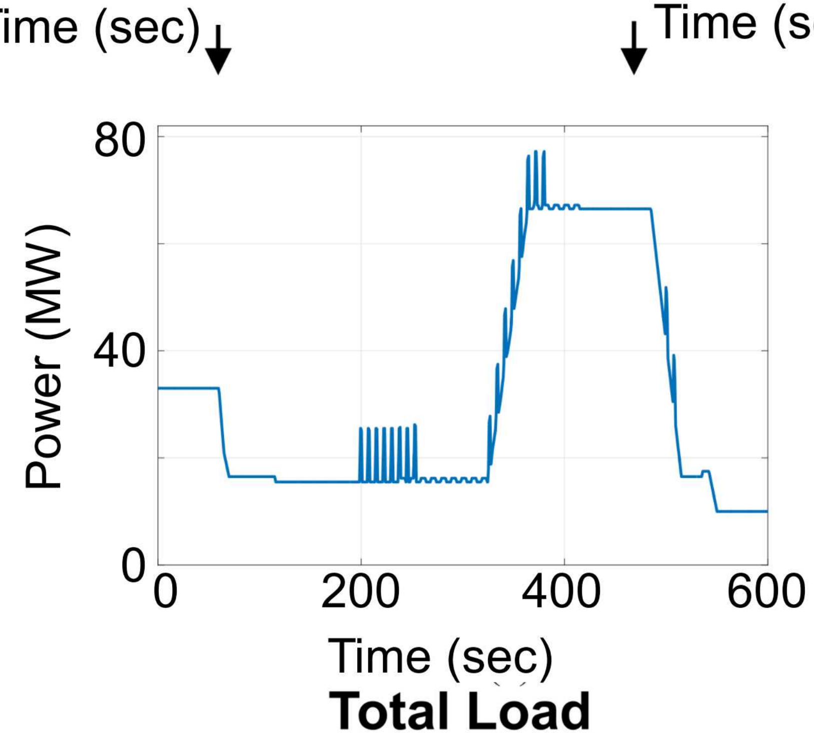
Load vignettes were obtained for different types of loads









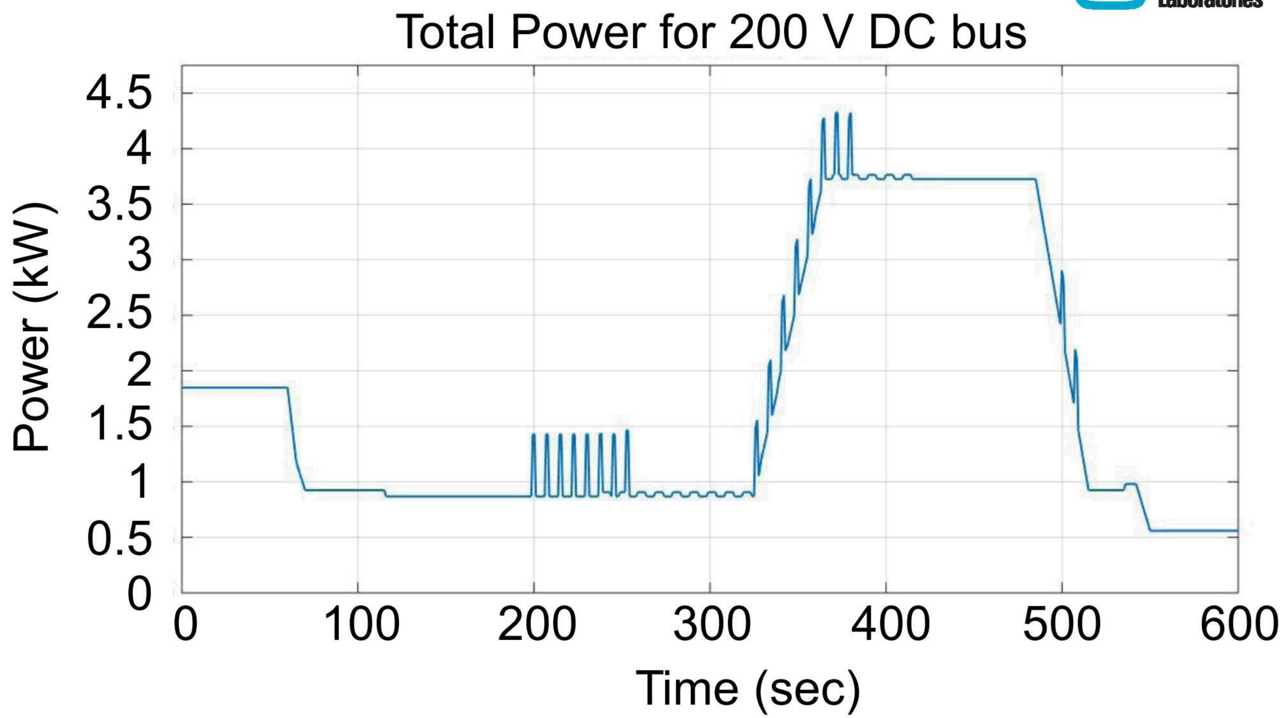


A.M. Cramer, X. Liu, Y. Zhang, J. D. Stevens and E. L. Zivi, "Early-stage shipboard power system simulation of operational vignettes for dependability assessment," *2015 IEEE Electric Ship Technologies Symposium (ESTS)*, Alexandria, VA, 2015, pp. 382-387.

Potential shipboard load profiles are identified and positioned on power system

- Propulsion load – 60 MW variable load
  - Split between Microgrid 1 and 2
- Service load – 20 MW variable load
  - Microgrid 3
- Mission Load 1 – 10 MW pulsed load
  - Microgrid 3
- Mission Load 2 – 700 kW pulsed load
  - Microgrid 3

Vignettes were scaled to hardware capabilities

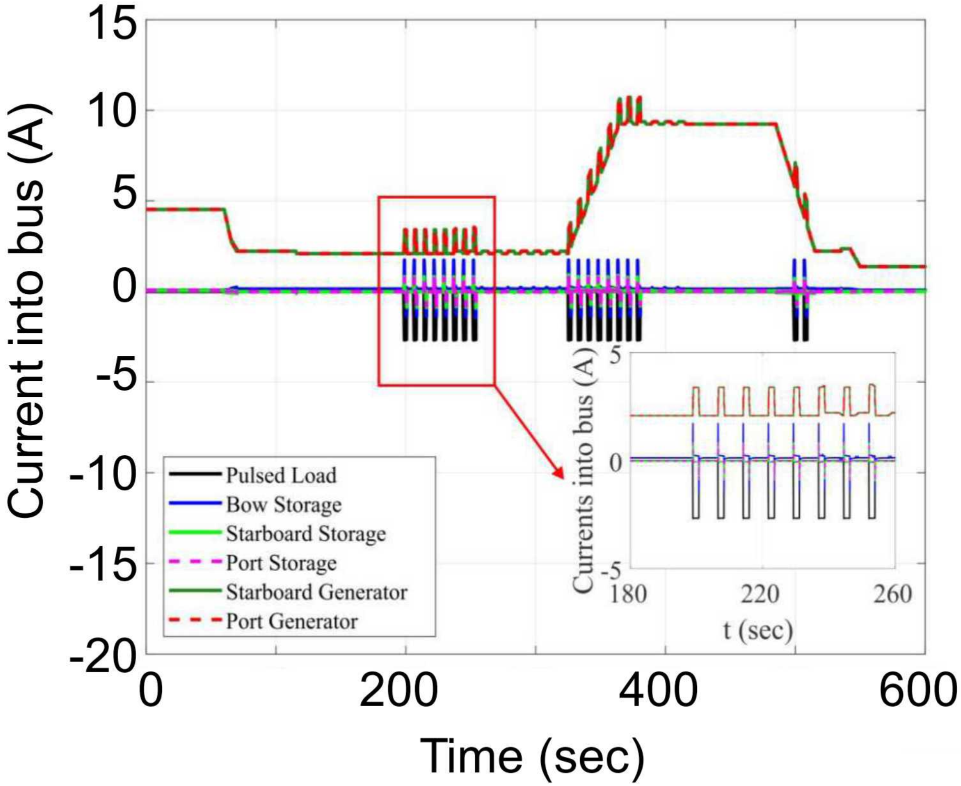


- Original system
  - 82 MW
  - 20 kV
- SSMTB system
  - 5 kW
  - 200 V
- Four load cases considered
  - No pulsed loads
  - Mission load 1 only
  - Mission load 2 only
  - All Mission loads
- Five filter constants considered
  - 0.1356 sec
  - 0.5299 sec
  - 2.0049 sec
  - 7.5117 sec
  - 28.5643 sec

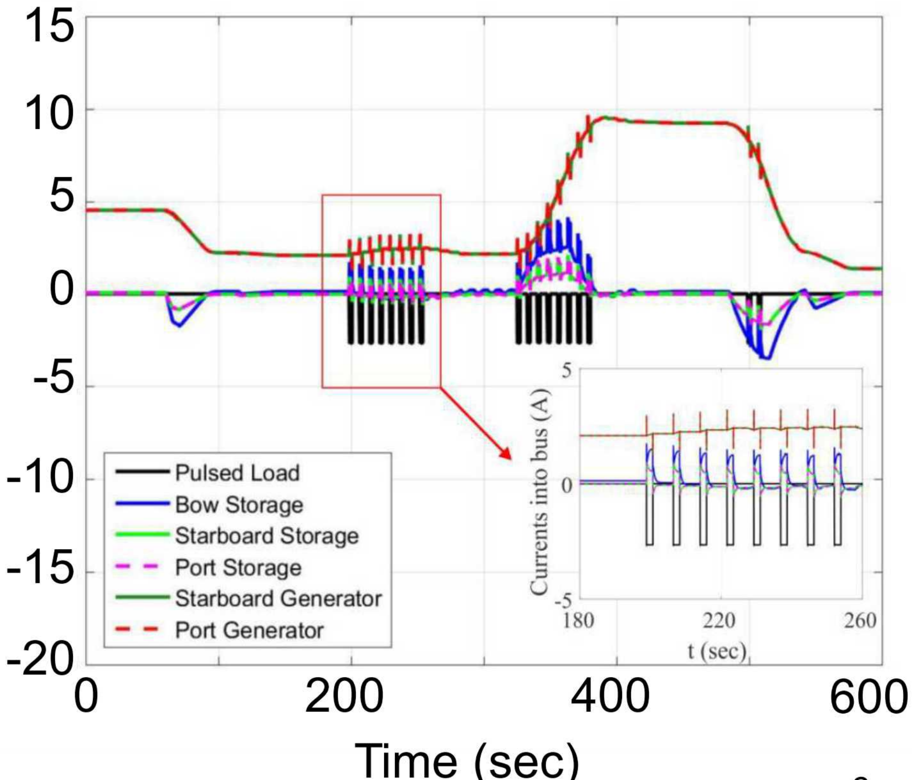
Load Responses were simulated for each controller time constant

- Faster time constants result in more pulse delivery from generators
- Slower time constants result in more pulse delivery from storage

Controller time constant of 0.1356 sec

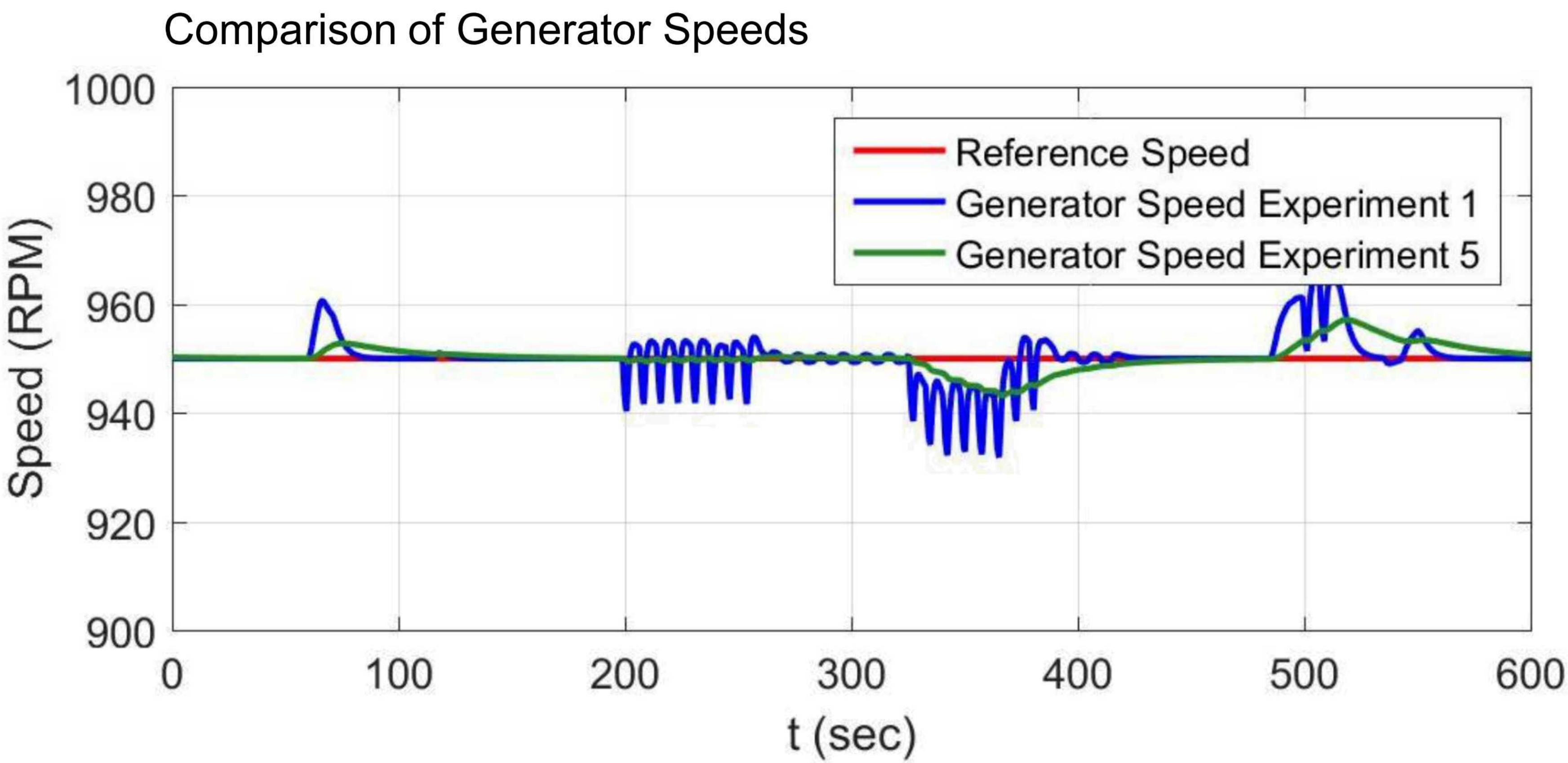


Controller time constant of 28.56 sec



Load Responses were simulated for each controller time constant

- Inertia and rate of power extraction govern speed variation
- Faster time constant results in more spikes in speed



Control effort is considered by a set of cost functions

Cost is determined by the functions:

$$J_1 = \int_{t_0}^{t_f} \left(\sum_{i}^{N_{Gens}} \left(i_{bi}(\tau) - \hat{i}_{bi} \right)^2 \right) d\tau$$

$$J_2 = \int_{t_0}^{t_f} \left(\sum_{i}^{N_{ES}} \left(i_{ESi}(\tau) - \hat{i}_{ESi} \right)^2 \right) d\tau$$

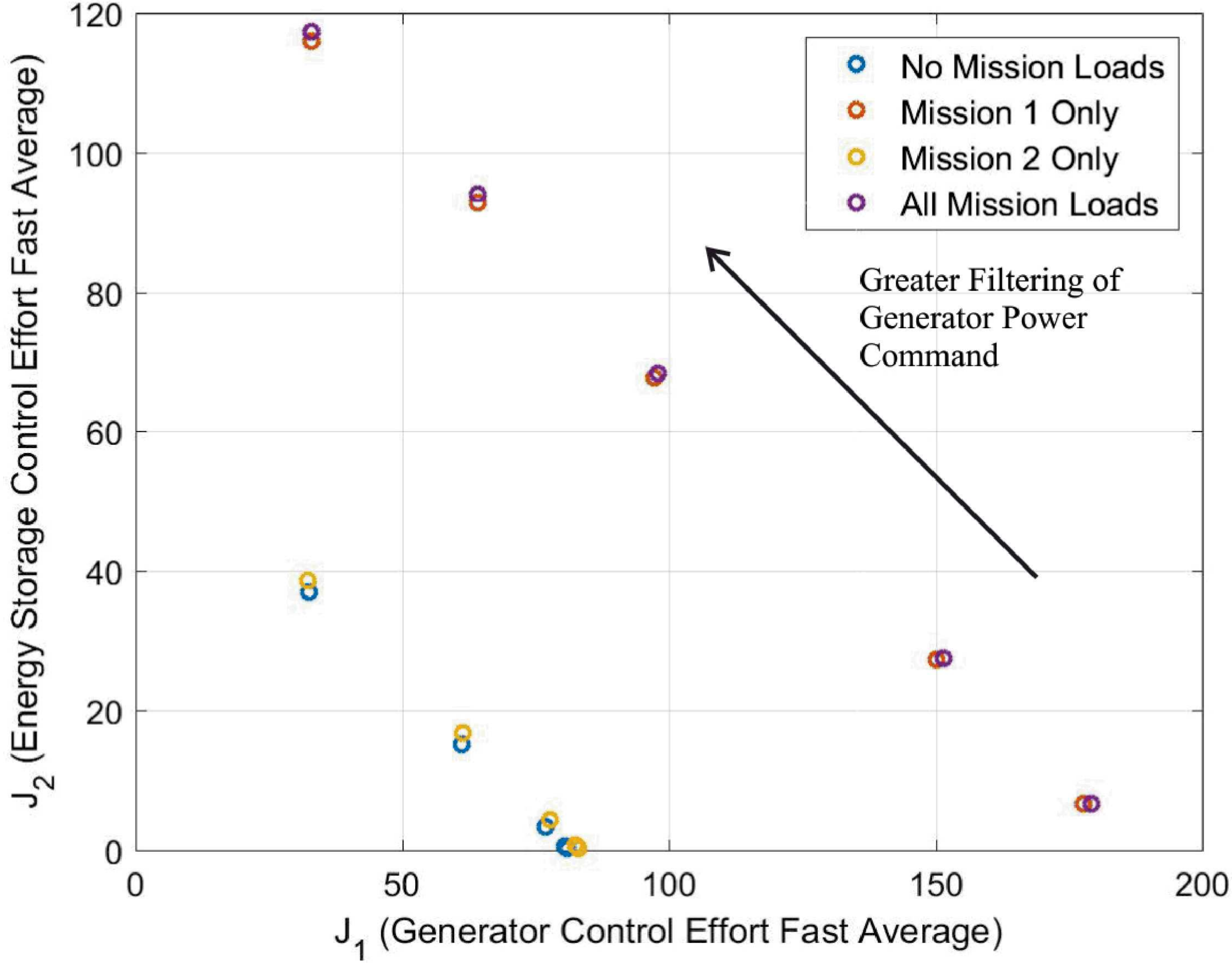
where $i_{bi}(t)$ are the currents delivered to the respective busses by the starboard and port generator converters as a function of time, N_{Gens} is the number of generators, and $i_{ESi}(t)$ are the bus currents from the N_{ES} energy storage systems.

$$\hat{i}_{bi} = \frac{1}{T_{fa}} \int_{t-T_{fa}}^{t} i_{bi}(\tau) \mathrm{d}\tau$$

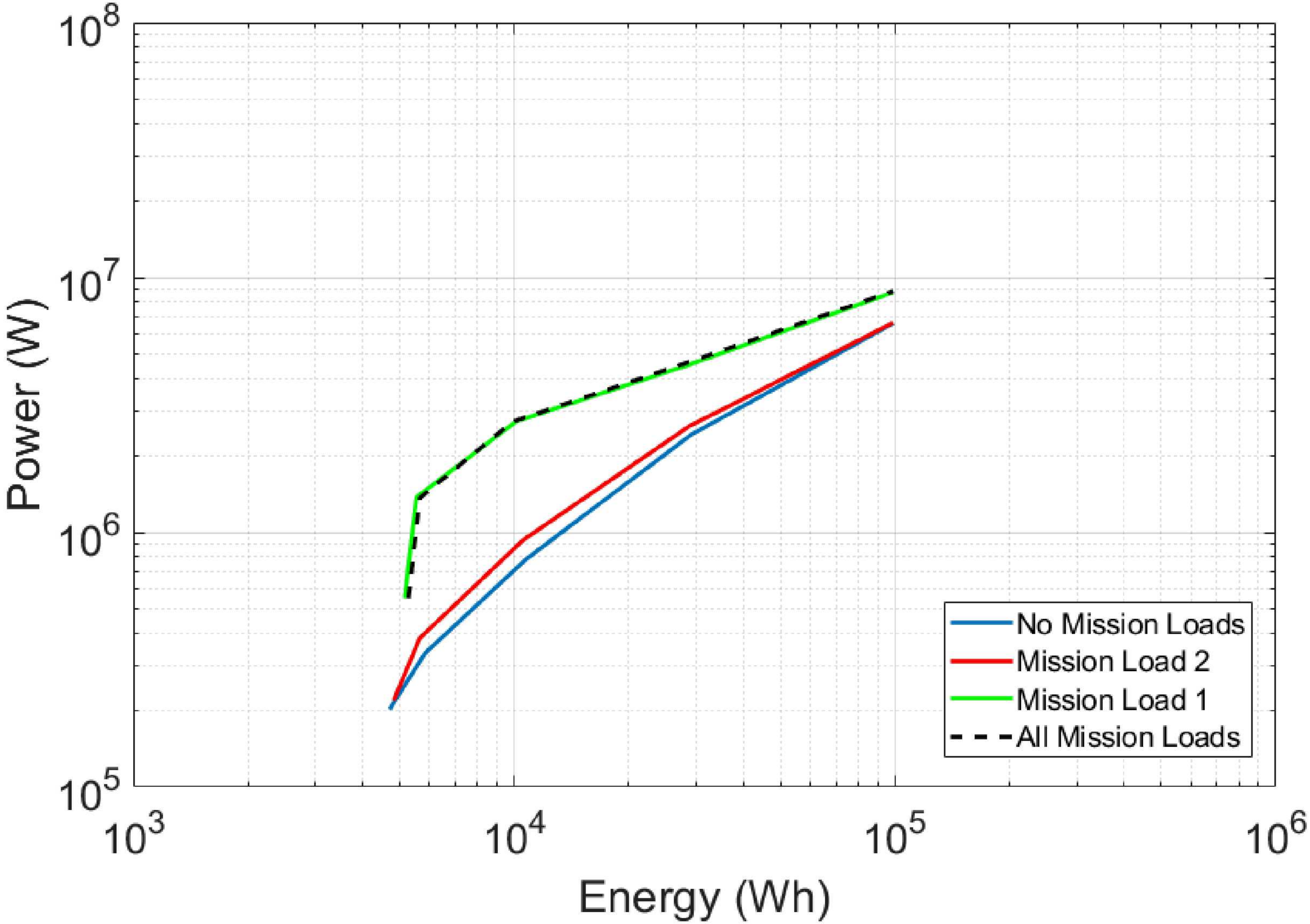
$$\hat{i}_{ESi} = \frac{1}{T_{fa}} \int_{t-T_{fa}}^{t} i_{ESi}(\tau) \mathrm{d}\tau$$

where T_{fa} is the period of the fast average.

System behavior is dependent on load and control filter



Energy storage power and energy requirements are determined from simulations



Energy Storage technologies vary in specific power / specific energy and frequency response

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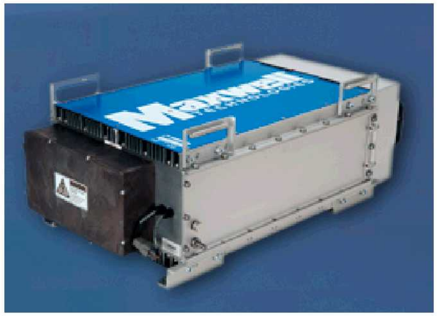
Energy storage strategies vary in the technology used; each technology has different size/weight and performance capabilities, examples include:

- Flywheel energy storage
- Electrochemical Cells/Batteries (i.e. Lithium Ion)
- Super Capacitor

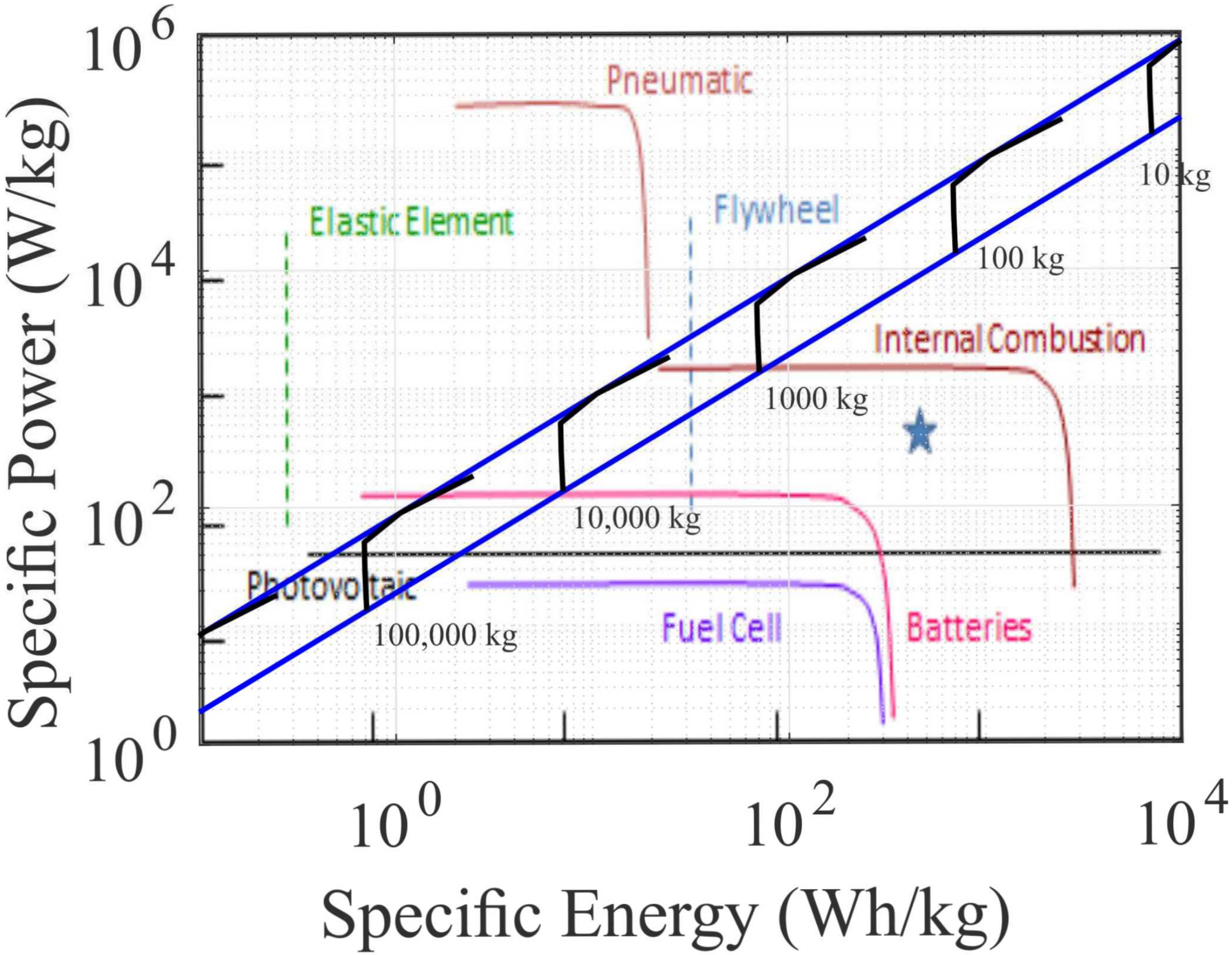
Capabilities are usually identified over a range of values based on demonstrated systems [1]



Technology	Energy Density (Wh/L)	Power Density (W/L)	Specific Energy (Wh/kg)	Specific Power (W/kg)	Approx. Bandwidth (Hz)
Flywheel	20-90	1000-5000	5-100	400-1500	20
Lithium-Ion	150-500	1500-10000	75-200	150-2000	80
Super Cap	10-30	>100000	2.5-15	500-10000	80

[1] Xing Luo, Jihong Wang, Mark Dooner, Jonathan Clarke, Overview of current development in electrical energy storage technologies and the application potential in power system operation, Applied Energy, Vol 137, 2015, pgs 511-536,

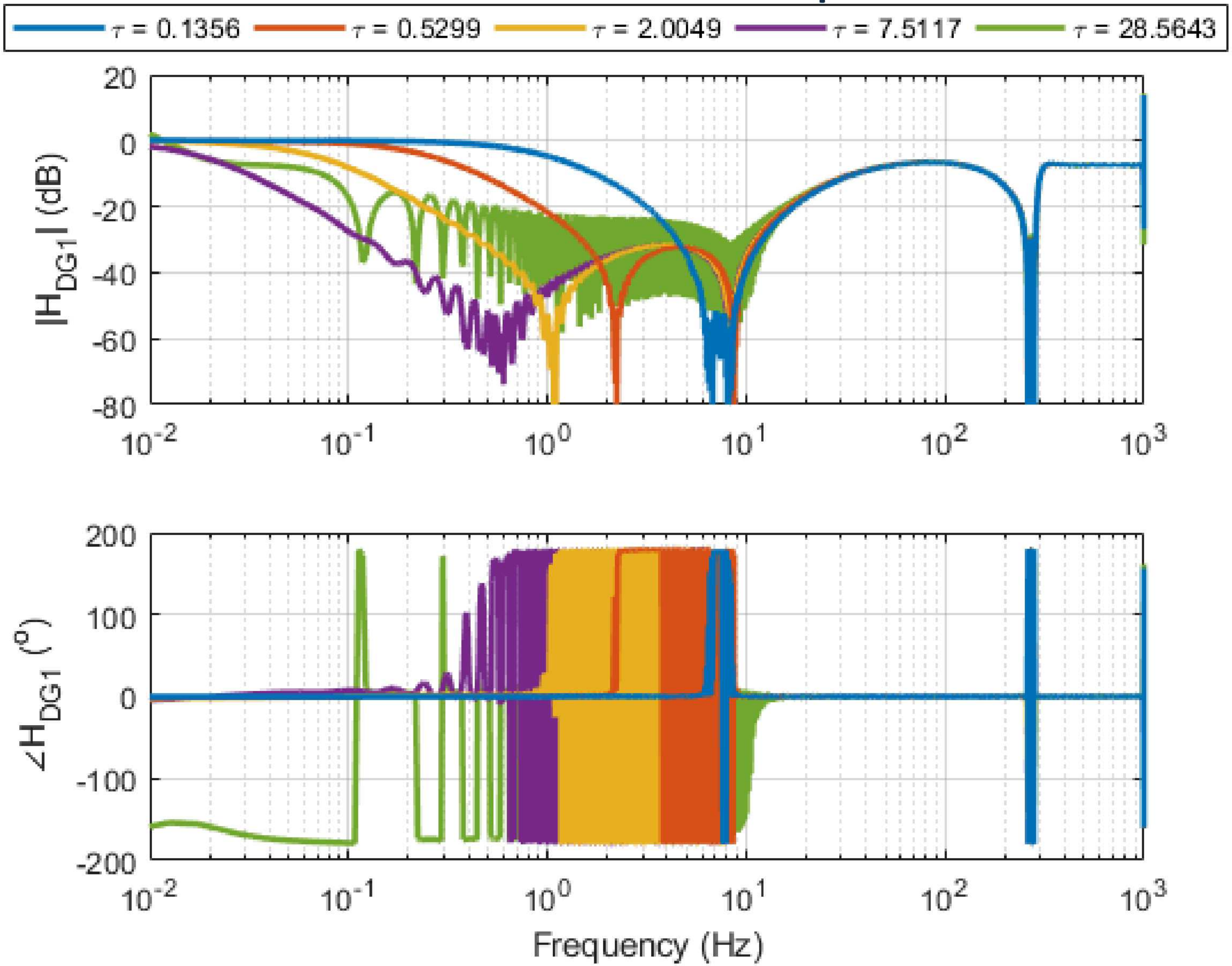
Storage technology and system size are determined from a Ragone plot



Energy storage frequency requirements determined from chirp response of the system

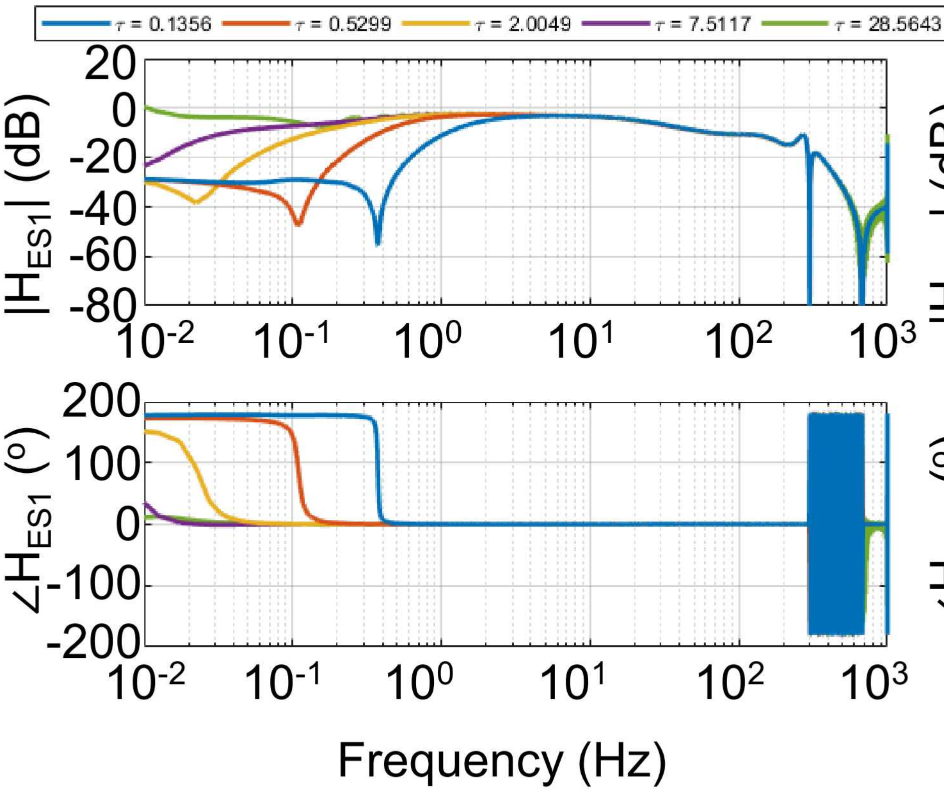
- Applied a log-sine chirp to the load on microgrid 3
  - $A \sin\left(2\pi f_o \left(\frac{f_1}{f_0}\right)^{t/t_1} t\right)$
  - Where f_0 is the initial frequency in Hz and f_1 is the frequency at time t_1 in Hz
- System input is load power on microgrid 3
- System output is the output power of the generators and energy storage systems
- Frequency domain behavior of inputs and outputs are found using a fast Fourier transform (MATLAB fft function)

Frequency Response of diesel generators show they are most effective at low frequencies

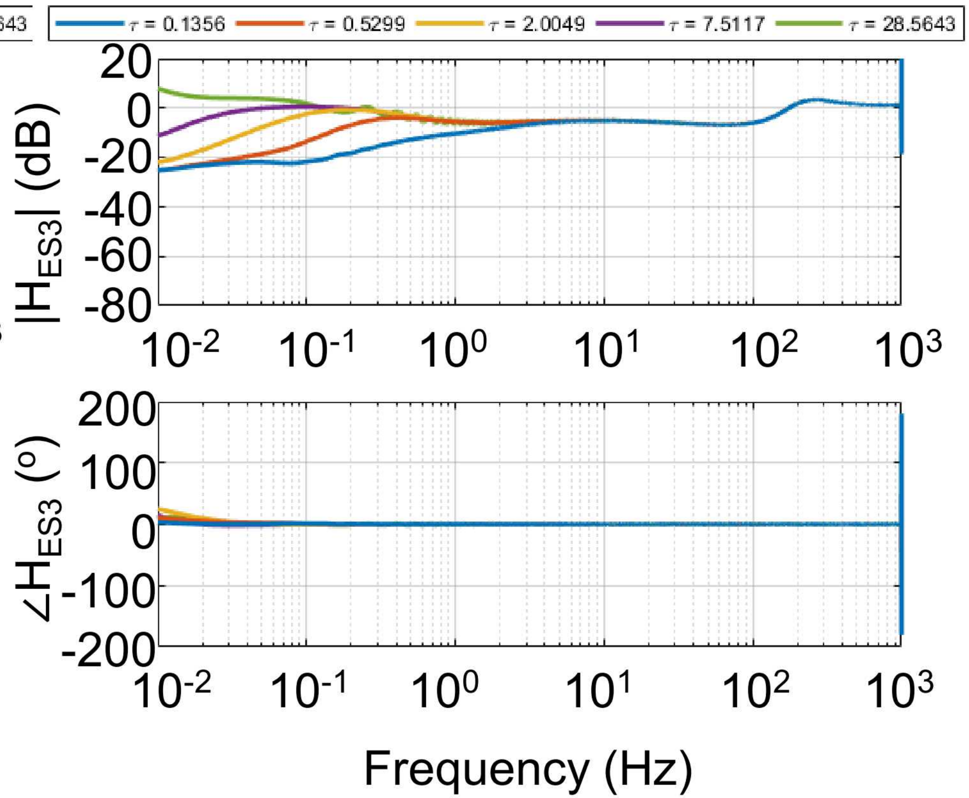


Results show that the energy storage is most needed at frequencies above 10 Hz

Microgrid 1&2



Microgrid 3



Summary and Conclusions

- Analysis of notional ship microgrid was performed
- Requirements for the energy storage system in terms of the specific energy and power densities of the system were found
- Requirements were applied to a Ragone plot
  - Flywheel storage technology would meet the energy and power requirements
- Frequency behaviour of the system shows that this technological solution may not be able to supply the necessary frequency content
- This result calls for a hybrid energy storage solution that could combine the advantages of multiple different technologies
- Future work
  - Optimisation of a hybrid energy storage design to meet the power demands of such a system.

For more information

- “Deriving specifications for coupling through dual-wound generators”
- “Nonlinear power flow control design methodology for navy electric ship microgrid energy storage requirements”