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INTEGRATED POWER SYSTEMS FOR ELECTRIFIED SHIPS: REAL-TIME CONTROL AND OPTIMIZATION

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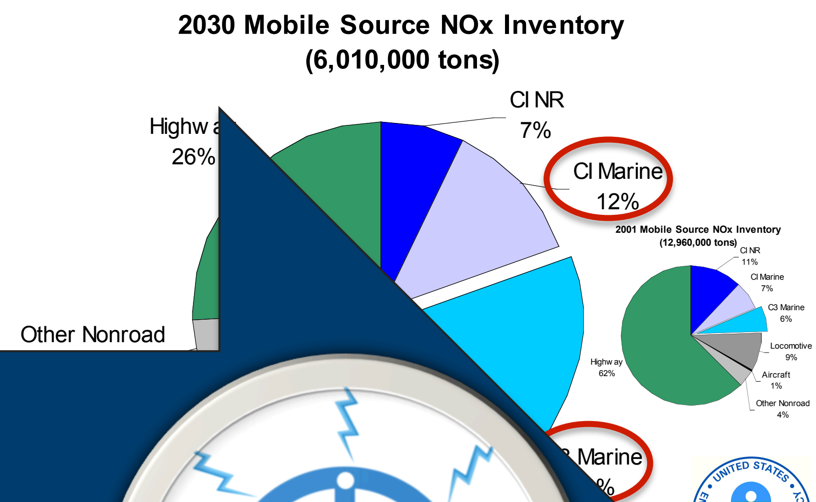
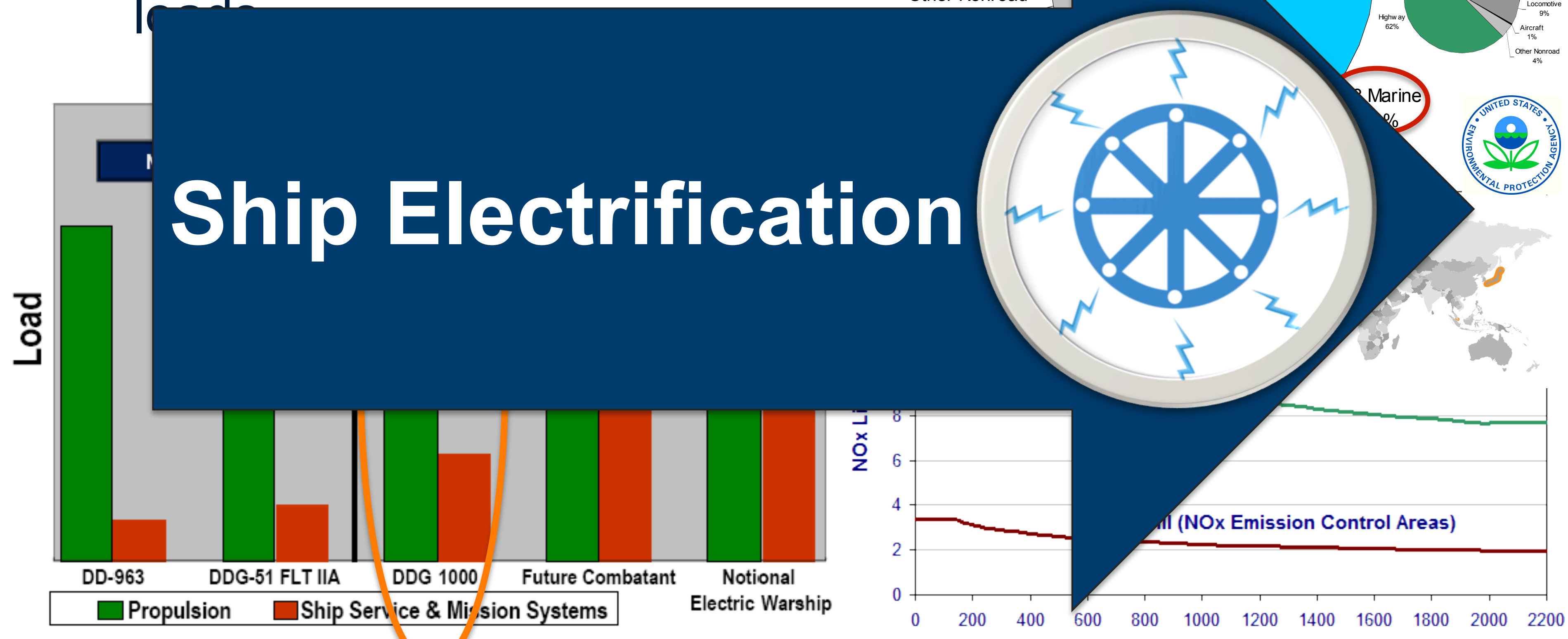
Sion, Switzerland
(from Ann Arbor, Michigan)

Pushes and Pulls

- Environmental concerns for emissions from marine engines
- New emission regulations
- Dramatically increased electrical loads





Source: Dr. Norbert Doerry

Source: IMO Nitrogen Oxides (NOx) Regulation 13

Ship Electrification

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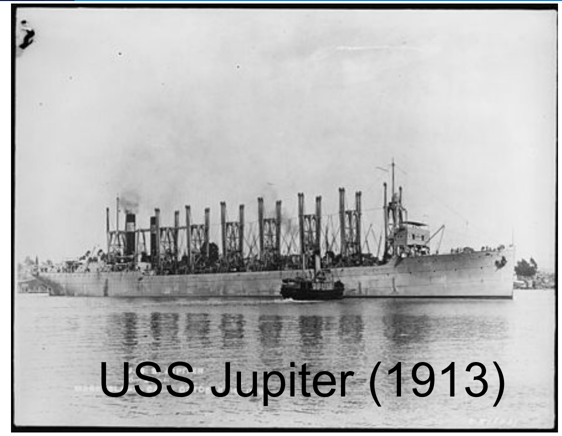
- 1st electrically propelled US Navy ship commissioned in 1913
- By 1934, all US Navy carriers were electrically propelled
- Retrofitted Queen Elisabeth 2, 1988
- Electrical propulsion fleet grew three times faster than the rest of the world fleet.
- Most cruise ships are all-electric now
- All-electric USS Zumwalt launched October, 28, 2013, US Navy accepted the delivery May 20, 2016, commissioned in 2016.


USS Jupiter (1913)

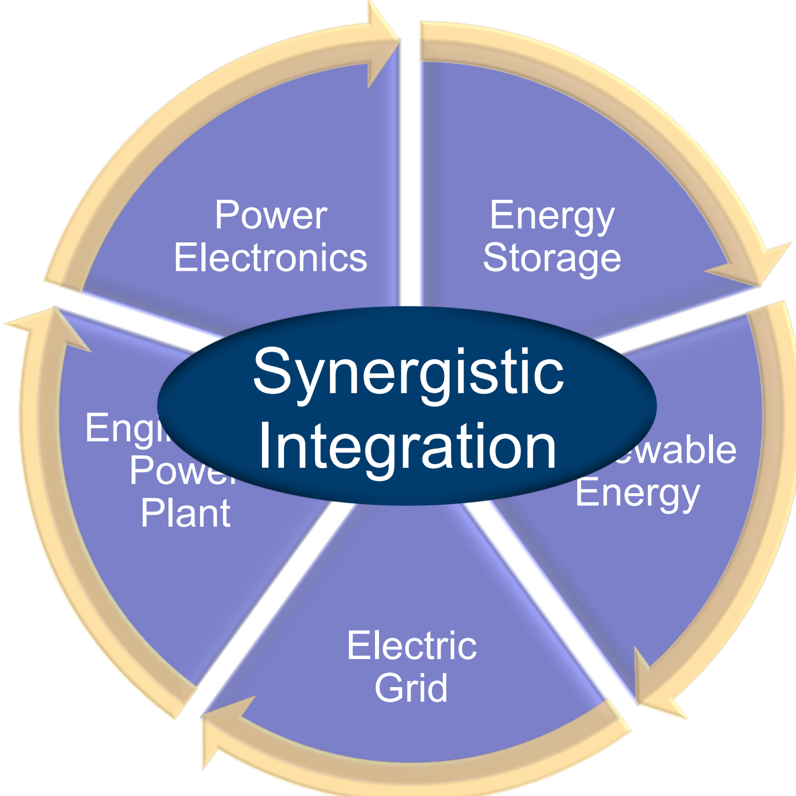

Queen Mary 2 (Image: Brian Burnell)

https://www.youtube.com/watch?v=ST_gpsdTaZI

"Integrated electric drive, with its associated cluster of technologies, will be the method of propulsion for the next class of surface batter-force combatants, and I am directing all the major Navy organizations involved in these efforts to concentrate their energies towards that objective." Adm Krolick and Graham, 1988

Vehicle Electrification

- All kinds: hybrid vehicles, all-electric ships (AES), electrified or more-electric airplanes (MEA)
- Key enabling technologies:




USS Zumwalt-DDG1000 (Wikipedia.org)


Boeing 787, the Dreamliner (wired.com)

Outline

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- Integrated power systems and electrified vehicles/ ships
- Optimization-based control and power/energy management for IPS
- Integrated perturbation analysis and sequential quadratic programming
  - Real-time optimization through prediction-correction
  - Applications to shipboard power management
  - Application to hybrid energy storage systems
- Conclusions

Integrated Power Systems

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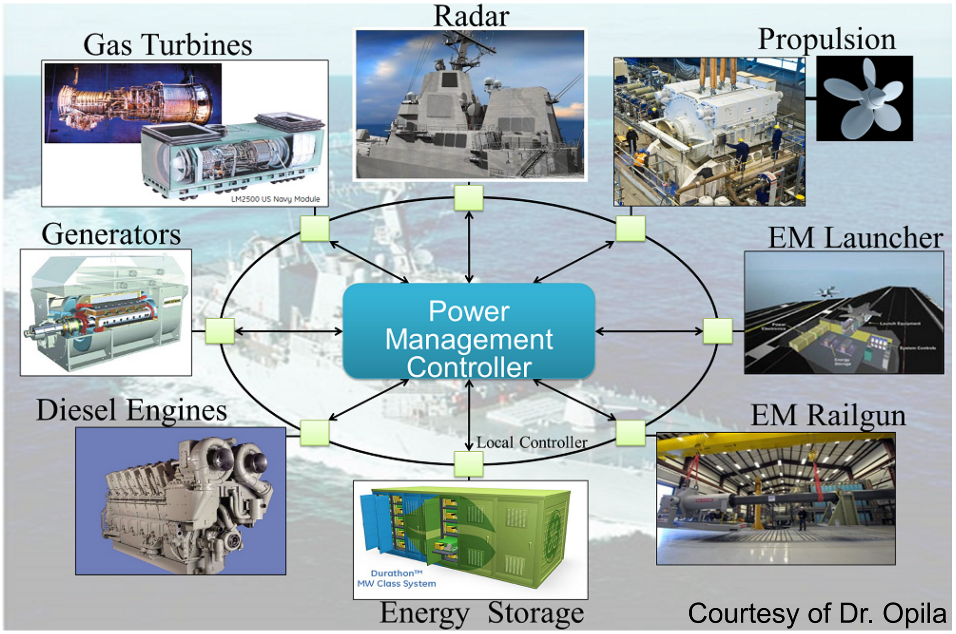
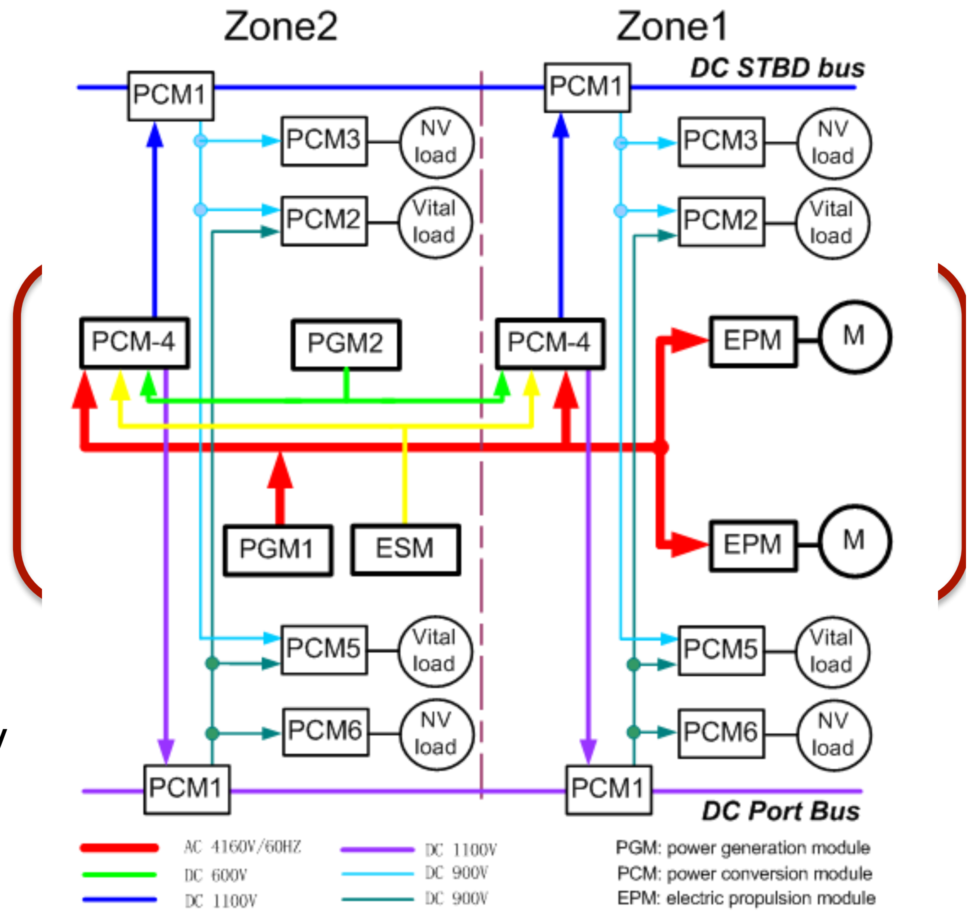




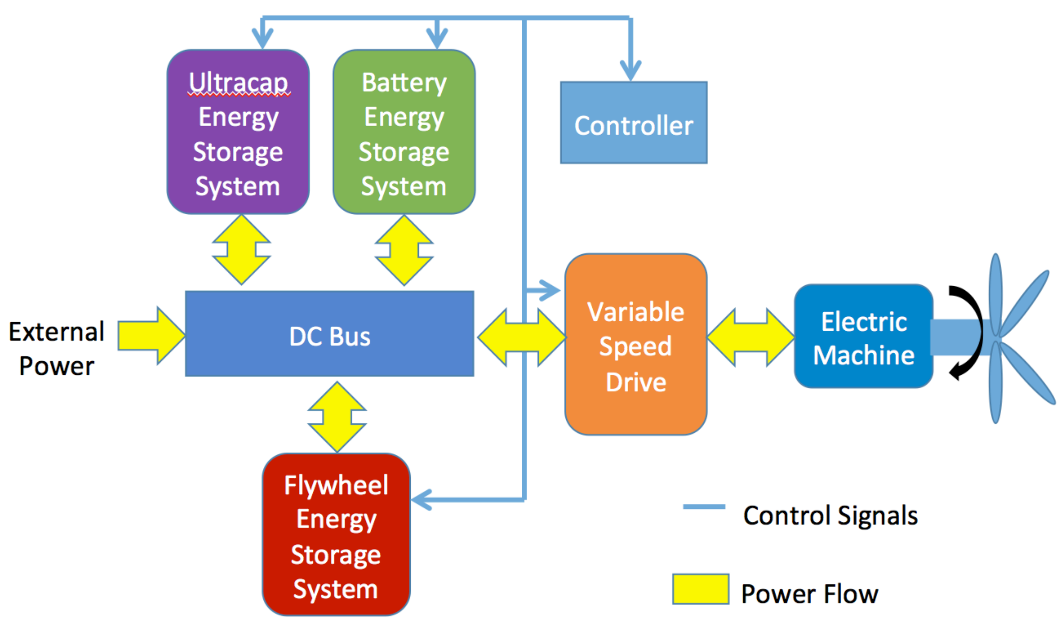
IPS Advantages:

- Provide General Arrangements Flexibility
- Support High Power Mission Systems
- Reduce Number of Prime Movers/Allow Modularization of Prime Movers
- Improve System Efficiency
- Improve Ship Producibility
- Facilitate Fuel Cell Integration
- Improve Quality of Service

- Better reliability and ship power network protection.

Hybrid Energy Storage for Electric Drives

- Energy storage for ship electrification
- Distributed and hybrid energy storage being proposed for AES
- Problem: Wave excitation and propeller rotational motions cause load fluctuation
- Solution: Hybrid energy storages systems with complementary characteristics



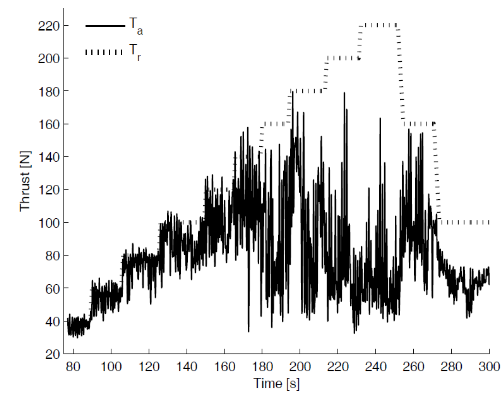


Figure 2.14: Measured thrust T_a of a ducted propeller for increasing thrust reference T_r in irregular waves. From experiments.

Smogeli (2006)

Combined SOFC/GT Cycle System

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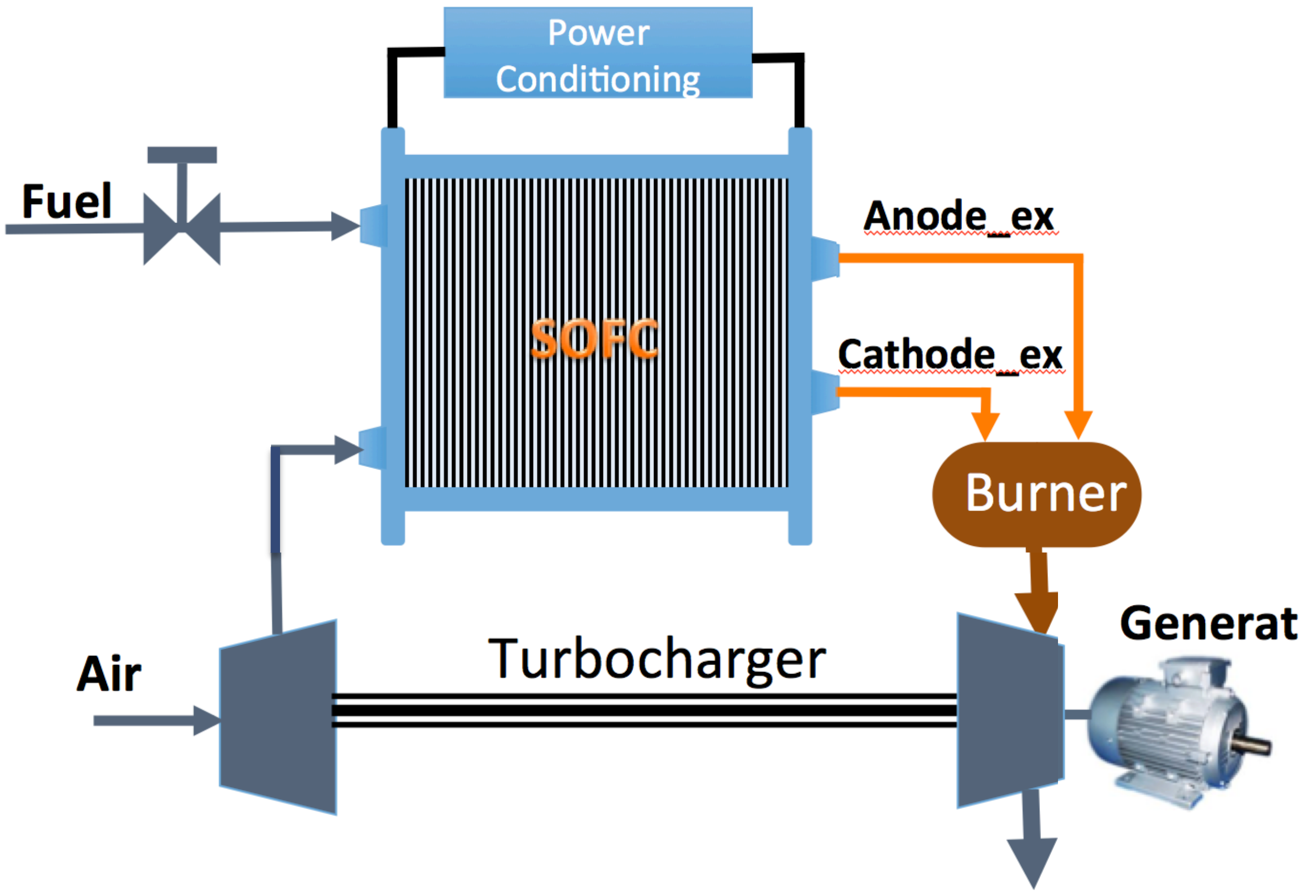
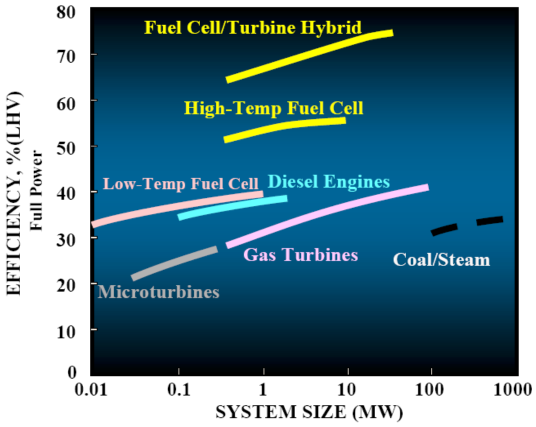
- Combined solid oxide fuel cell and gas turbine system as a new efficient power generation solution
- High efficiency achieved through tight thermal, mechanical, and electric integration





Integrated Power Systems

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- Multiple <u>heterogeneous</u> power sources and power loads combined to provide energy/power solutions
  - Multiple power/heat plants involved in energy conversion
  - Shared loads and sources
  - High efficiency and (intended for) self-sustaining
  - Close thermal, chemical, mechanical and electrical couplings
  - Pervasive use of power converters, energy storage
  - Significant dynamic and control implications

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Power Management for HPS

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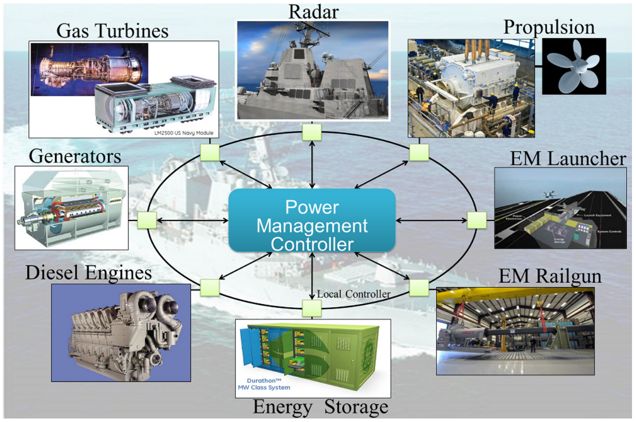
- Coordinate multiple, heterogeneous power plants (including energy storage devices) and controllable loads

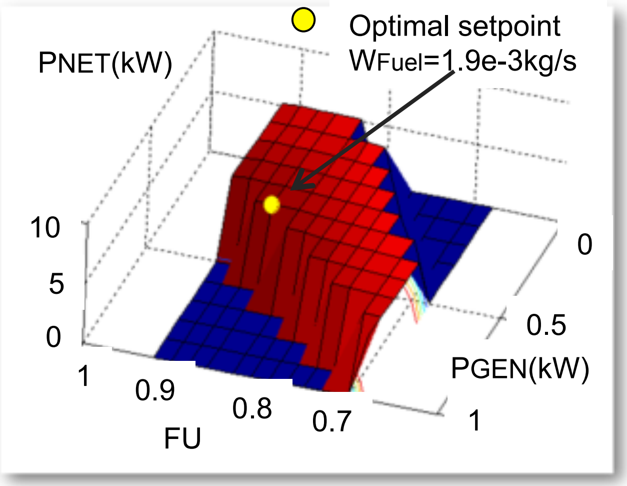


- Manage transient operations
- Assure safe operation in case of component and subsystem failure
- Facilitate effective system reconfiguration
- Achieve optimal performance in terms of power quality and system operation efficiency

→ **Optimization-based Control**

Special Challenges for IPS

- Nonlinear and MIMO plant characteristics
- Reconfigurable underlying physical components
- Operating near boundary
- Fast dynamics
  - Power electronics: 10kHz
  - Diesel or gas turbine: ~10Hz
- Limited on-board computational resources
- Real-time operation requirements



→ **Efficient real-time optimization solvers are the key**

Where are we now?

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- Power management for electrified vehicles/ships
  - Hybrid vehicles power management:
    - Horizon-based optimization: dynamic Programming (Mosbach, Brahma et al, Lin at al, Sciarretta et al, Scordia et al, Liu et al, Johannesson et al, Rousseau et al, Murgovski et al,…)
    - Instantaneous optimization: equivalent consumption minimization strategy (Kim et al, Paganelli et al, Won et al, Pisu et al, Musard et al, Onori et al, …)
  - Shipboard power management:
    - Device/hardware oriented: ABB, Electric-ships Research and Development Consortium (ESRDC), Dwanty et al, Feng et al, Huang et al, Kanellos, Largose et al, Mitra et al, Srivastava et al, …
    - System/control oriented: ABB, Seenumani et al, Bø et al, Veksler et al, Park et al, Opila,…
- Optimization-based control
  - Model predictive control (…too many to list...), reference governor (Gilbert, Kolmanovsky)
  - Applications: power converters (>10kHz), engine controls (100Hz), shipboard power management, large chemical processes…

Our Approach

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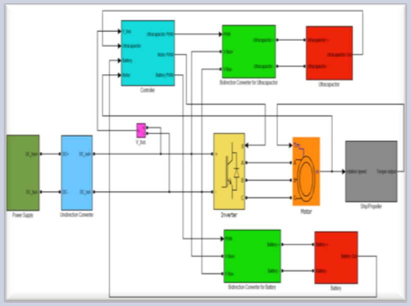
Methodology and Tool Development

- Model development
- Model order reduction
- Algorithm development
- Real-time optimization

Simulation → Real-time simulation → Experiment



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Real-time Optimization Solvers

Dominant approaches: SQP and interior point (IP) methods

- Early termination methods By Li & Biegler, Diehl et al., Ohtsuka…
  - Only one or few iterations at each sampling time
  - Deteriorated results for systems with significant nonlinearities
- Advance step controller by Zavala & Biegler
  - Complete IP type procedure
  - Predicting future state and solving optimal control problem for this future state
- Feasibility-perturbed SQP by Tenny et al.
  - All feasible intermediate iterations

IPA-SQP

Perturbation Analysis (PA)

- Derives a solution from a nominal one when some parameters are changed
- Maintains necessary conditions satisfied to first order
- Suitable in MPC context: states do not change much from step to step

Sequential Quadratic Programming (SQP)

- Popular approach to solve constrained optimization problem
- Improves the solution to satisfy necessary conditions

IPA-SQP [Ghaemi et al. 2007;2008;2009; Park et al., 2014]

- Integrated Perturbation Analysis - Sequential Quadratic Programming
- Combines the solutions derived using PA and SQP
- Predictor-corrector type scheme
  - Predictor: obtains the solution to MPC problem using neighboring optimal control theory
  - Corrector: corrects the result using SQP updates
  - Two updates merged into one: provides an efficient algorithm for nonlinear MPC implementation

Problem formulation

$$\min_{u(\cdot)} \; J(x(\cdot),u(\cdot)),$$

where $J(x(\cdot),u(\cdot)) = \Phi(x(t+N)) + \sum_{k=t}^{t+N-1} L(x(k),u(k)),$

subject to

$$x(k+1) = f(x(k),u(k)), \quad f : \mathrm{R}^{n+m} \to \mathrm{R}^{n},$$

$$x(t) = x_t, \quad x_t \in \mathrm{R}^{n},$$

$$C(x(k),u(k)) \le 0, \quad C : \mathrm{R}^{n+m} \to \mathrm{R}^{l},\; k = t,\cdots,t+N-1,$$

$$\bar{C}(x(k)) \le 0, \quad \bar{C} : \mathrm{R}^{n} \to \mathrm{R}^{q},\; k = t,\cdots,t+N.$$

Neighboring Extremal Problem

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Minimize:

$$\delta^2 J = \frac{1}{2}\delta x(N)^T\left(\Phi_{xx}(N) + \frac{\partial}{\partial x}\overline{C}_x^T(N)\overline{\mu}(N)\right)\delta x(N)$$

$$+\frac{1}{2}\sum_{k=0}^{N-1}\begin{bmatrix}\delta x\\ \delta u\end{bmatrix}^T\begin{bmatrix}H_{xx} & H_{xu}\\ H_{ux} & H_{uu}\end{bmatrix}\begin{bmatrix}\delta x\\ \delta u\end{bmatrix}$$

Subject to

$$\delta x(k+1) = f_x(k)\delta x(k) + f_u(k)\delta u(k); \delta x(0) = \delta x_0$$

$$C_x^a(x(k), u(k))\delta x(k) + C_u^a(x(k), u(k))\delta u(k) = 0;$$

$$\overline{C}_x^a(x(k))\delta x(k) = 0$$

C^a, C^a: active constraint sets

H: Hamiltonian function of the original optimization problem

Neighboring Extremal Solution

With proper assumptions, the NE problem has a closed-form solution:

$$\delta x(k+1) = f_x\big(x^0(k), u^0(k)\big)\delta x(k) + f_u\big(x^0(k), u^0(k)\big)\delta u(k)$$

$$\delta u(k) = -K^*(k)\delta x(k)\,, \qquad K^*(k) = [I\ 0]K_0 \begin{bmatrix} Z_{12}(k) \\ C_x^a(k) \end{bmatrix}$$

$$K_0(k) = \begin{bmatrix} Z_{11}(k) & C_u^{aT}(k) \\ C_u^a(k) & 0 \end{bmatrix}^{-1} \quad \begin{aligned} Z_{11}(k) &:= H_{uu}(k) + f_u^T(k)S(k+1)f_u(k) \\ Z_{12}(k) &:= H_{ux}(k) + f_u^T(k)S(k+1)f_x(k) \\ Z_{22}(k) &:= H_{xx}(k) + f_x^T(k)S(k+1)f_x(k) \end{aligned}$$

$S(k)$ is defined through a backward-in-time iterative algorithm

Notes On NE Solution

- Constraint activity set unchanged
  - Small perturbations
- Matrix $K_0(k)$ is invertible

$$K_0(k) = \begin{bmatrix} Z_{11}(k) & C_u^{aT}(k) \\ C_u^a(k) & 0 \end{bmatrix}^{-1}$$

  - $Z_{11}(k)$ non-singular
  - C_u^a must be of full row rank.
  - Can not handle the constraints of the type:

$$\bar{c}\big(x(k)\big) \leq 0$$

Dealing with Large Perturbations

- Divide the large perturbation into smaller incremental perturbations
- However, optimality conditions may not be satisfied at each intermediate point
- Sequential quadratic programming can be used to achieve optimality at the intermediate points

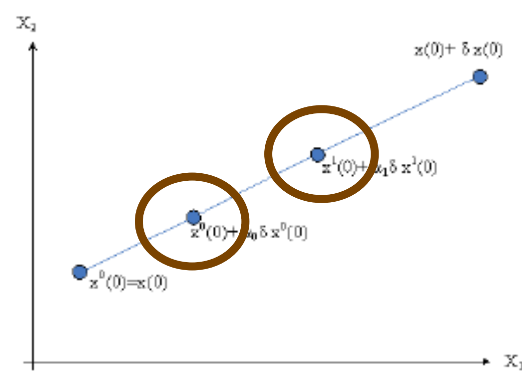
$$\delta^2 \bar{J} = \frac{1}{2}\delta x(N)^T \Phi_{xx}(N)\delta x(N) + \boxed{\sum_{k=0}^{N-1} H_u^T(k)\delta u(k)}$$

$$+\frac{1}{2}\sum_{k=0}^{N-1}\begin{bmatrix}\delta x\\ \delta u\end{bmatrix}^T\begin{bmatrix}H_{xx} & H_{xu}\\ H_{ux} & H_{uu}\end{bmatrix}\begin{bmatrix}\delta x\\ \delta u\end{bmatrix}$$

$$\delta x(k+1) = f_x(k)\delta x(k) + f_u(k)\delta u(k); \boxed{\delta x(0) = 0;}$$

$$C_x^a(x(k),u(k))\delta x(k) + C_u^a(x(k),u(k))\delta u(k) = 0;$$

$$\bar{C}_x^a(x(k))\delta x(k) = 0.$$



Avoiding Singularity

Matrix K_0 will be non-invertible if

$$\begin{bmatrix} Z_{11}(k) & C_u^{aT}(k) \\ C_u^a(k) & 0 \end{bmatrix}$$

- C does not explicitly depend on u or
- The active constraints outnumber the controls

Use back-propagation to avoid matrix singularity

$$\bar{C}_x^a(k)\delta x(k) = 0$$

$$^a_x(k)(f_x(k-1)\delta x(k-1) + f_u(k-1)\delta u(k-1)) = 0$$

IPA-SQP Algorithm

Step 1
- Nominal solution $(x^0(\cdot), u^0(\cdot))$ from previous time step

Step 2
- Closed-form neighboring extremal solution $\delta u(k) = K_1(k)\delta x(k)$

Step 3
- Handling changes in the activity status of constraints

Step 4
- Update solution $x^1(\cdot) = x^0(\cdot) + \delta x(\cdot), \quad u^1(\cdot) = u^0(\cdot) + \delta u(\cdot)$

Step 5
- Optimality condition $H_u(x^1(\cdot), u^1(\cdot)) = 0$ Yes: Stop, No: Step 6

Step 6
- Use SQP to improve the solution $\left(x^1(\cdot), u^1(\cdot)\right) \rightarrow \left(x^1_{correct}(\cdot), u^1_{correct}(\cdot)\right)$

A Bench-mark Test (Non-realtime)

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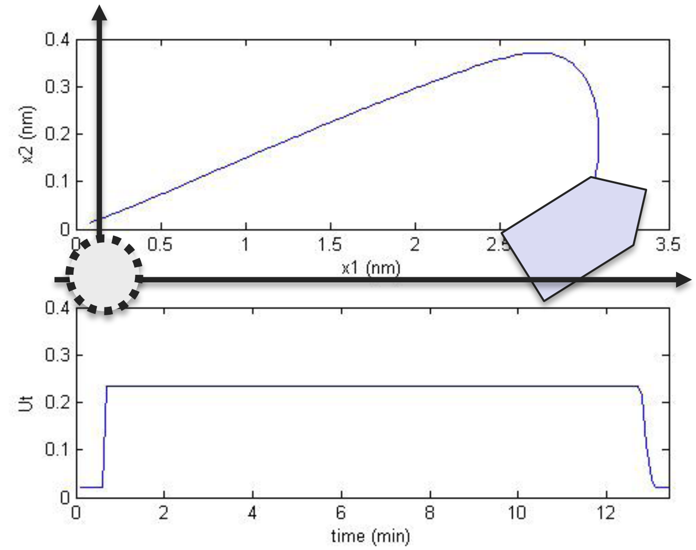
A ship steering problem

- Nonlinear model: 5 states
- Nonlinear cost and constraints:
  - state dependent constraints (obstacle avoidance)
  - Input constraints (rudder saturation)
- Long prediction horizon:
  - N=140

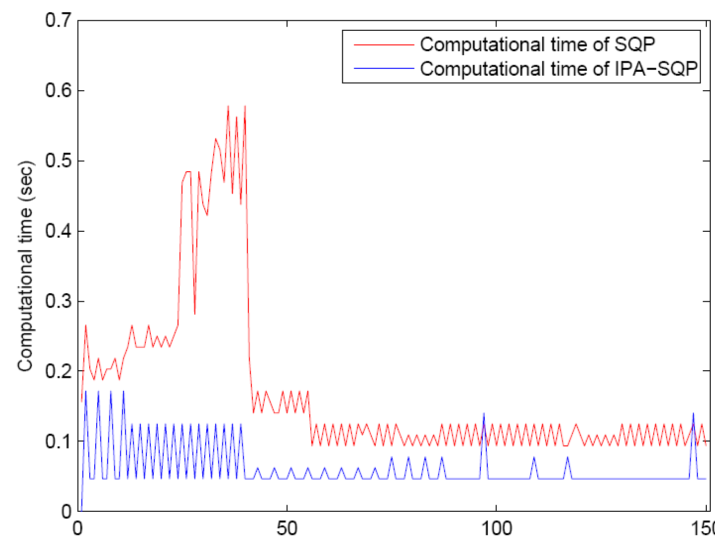


Simulation platform

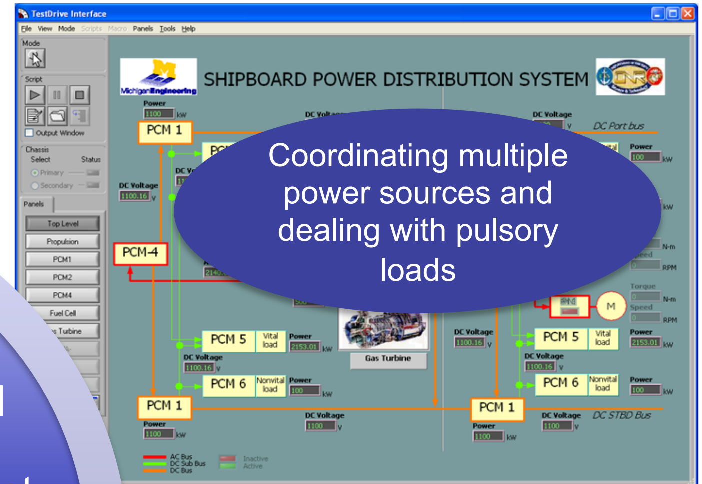
- PC with Intel® CPU
- 1.83GHz

Simulation results (compare SQP vs. IPA-SQP)

- Identical trajectory
- Average computational time(measured by CPU time) reduction for IPA-SQP: 280%



Application Examples

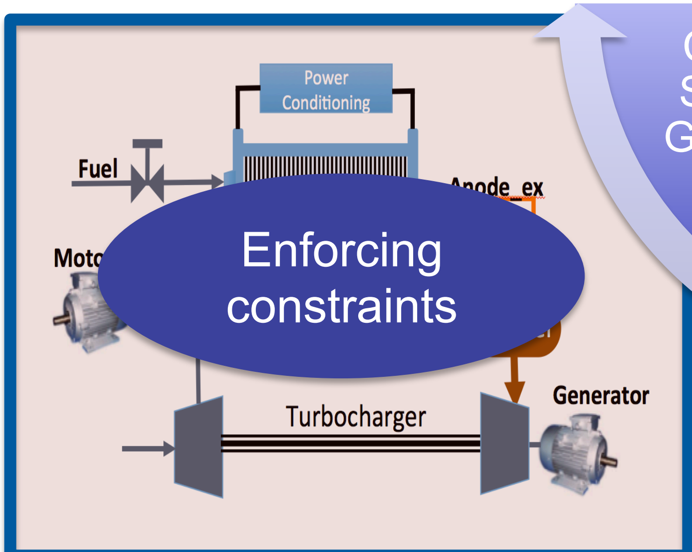


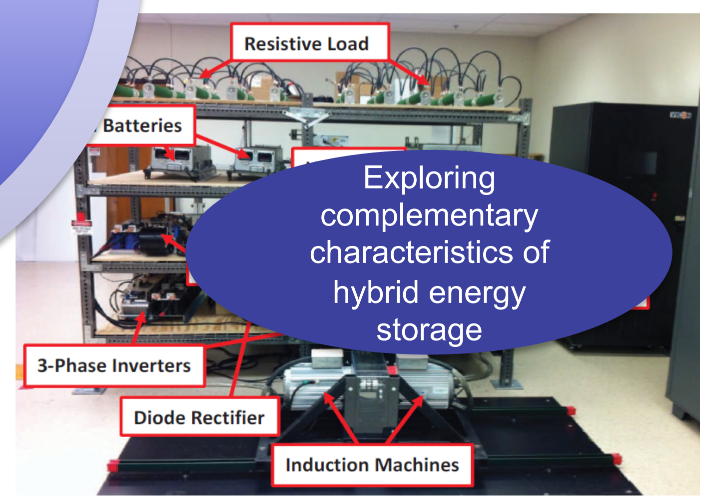
Electronic Power Converters

Shipboard Power Management

Combined SOFC and Gas Turbine System

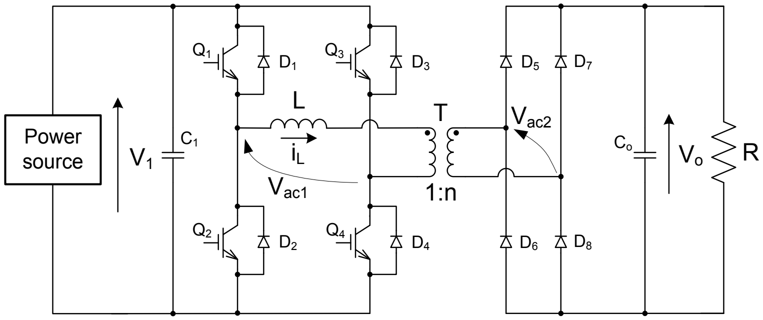
Hybrid Energy Storage





MPC of Full Bridge DC/DC Converter

- Power converter:
  - Rated at 1kW
  - Hard constraint on peak operating current
  - Fast sampling
- Algorithm specifics
  - Sampling time: T=150μs
  - Prediction horizon: N=8
  - Control horizon=8



Y. Xie, et. al., “Model Predictive Control for a Full Bridge DC/DC Converter,” *IEEE TCST*, 2012.
Y. Xie, et. al., “Implicit Model Predictive Control of a Full Bridge DC/DC Converter,” *IEEE TPE*, 2009.

Real-time Ship Power Management

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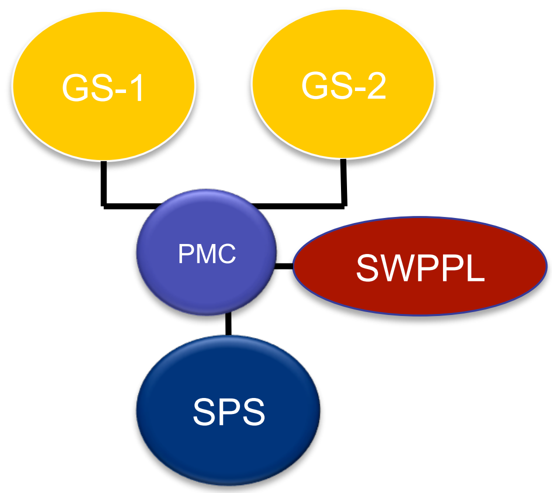
- ❑ Shipboard integrated power systems include multiple power sources and loads
- ❑ Large pulse load presents a special challenge for power management
- ❑ Power management controller (PMC) coordinates power sources and loads to achieve efficient and robust operation
- ❑ Real-time implementation of MPC-based PMC is a key challenge

Collaborative work with Purdue and GE



H. Park, J. Sun, et. al., "Real-time Model Predictive Control for Shipboard Power Management Using the IPA-SQP Approach," IEEE TCST, November, 2015.
G. Seenumani, et.al., "Real-time Power Management of Integrated Power Systems in All Electric Ships Using Time-Scale Separation," *IEEE TCST,* 2012.

Hybrid Energy Storage System

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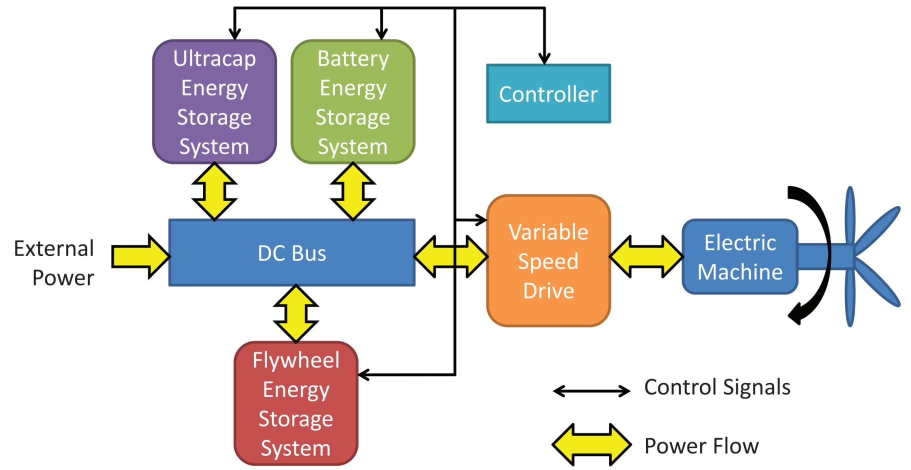
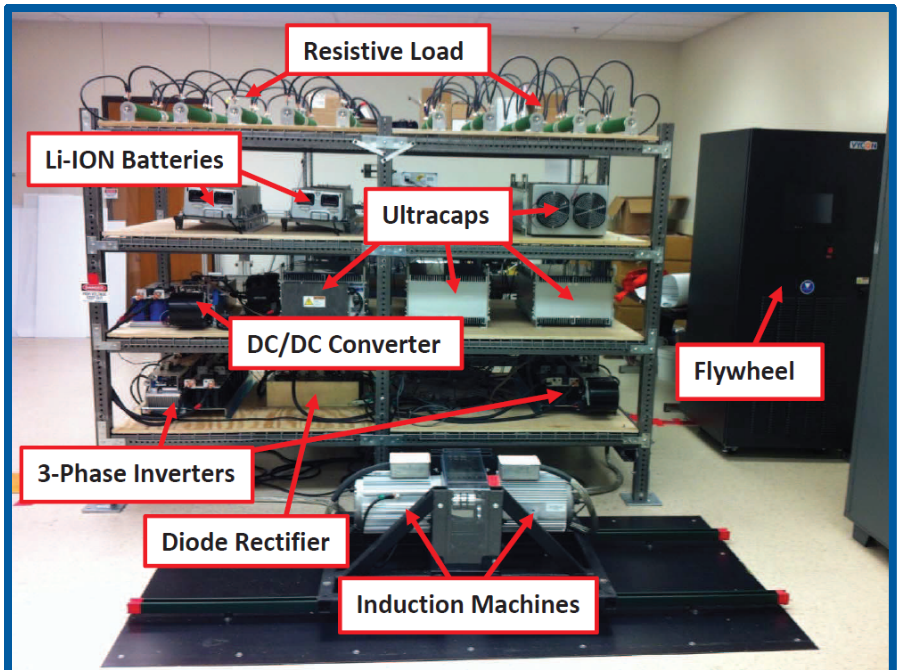
Control Objectives:

- System reliability:
  - Maintain the DC bus voltage at 200V
- System efficiency:
  - Minimize hybrid energy storage system (HESS) losses;
- Long self-sustained time
  - Take advantage of the battery high energy density to maintain UC working at high-efficiency range (around 145V).
- Extend battery life cycle:
  - Reduce battery peak current
  - Reduce battery RMS current





Experiment Setup

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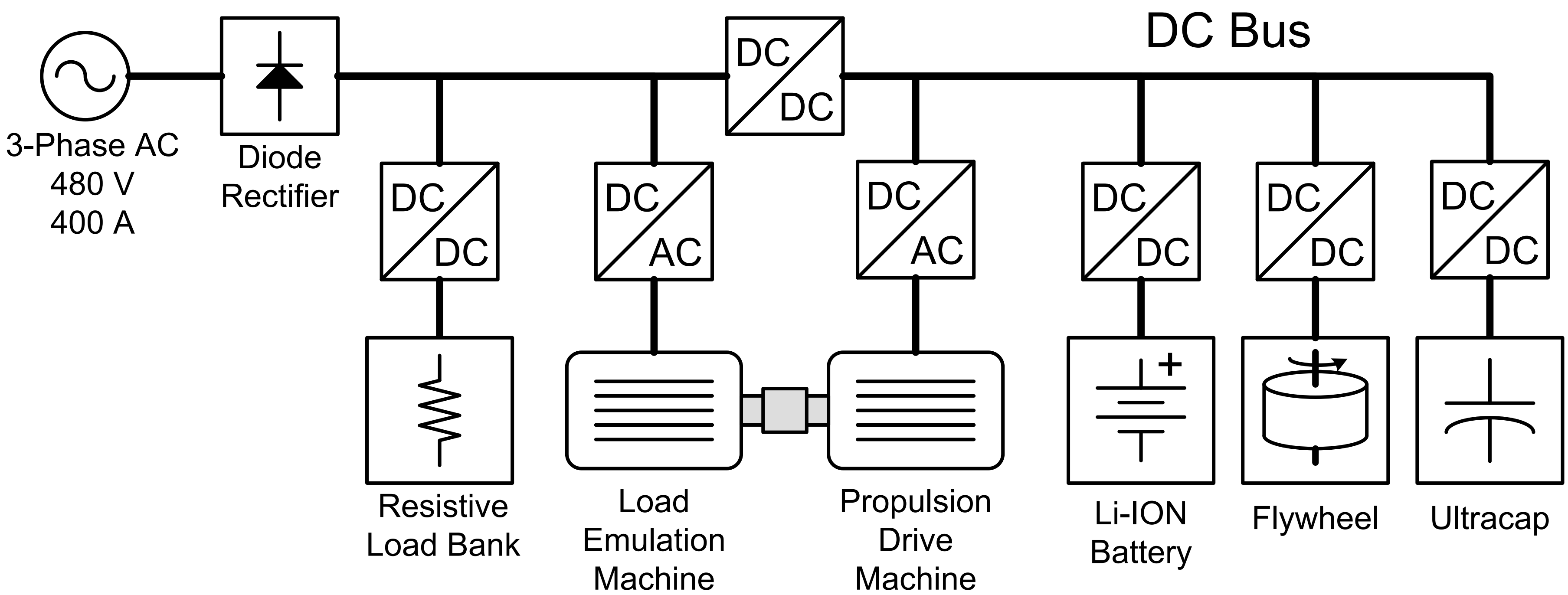
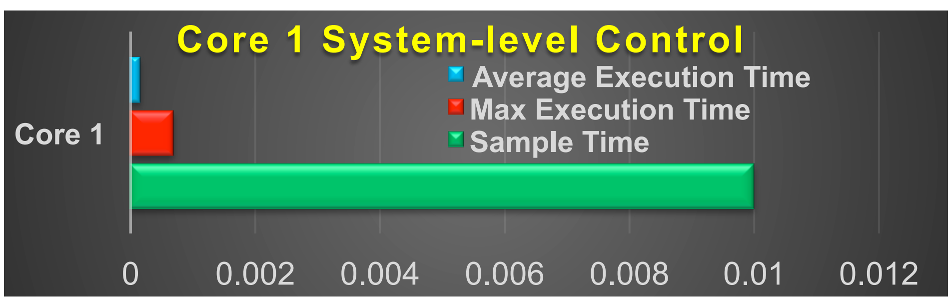
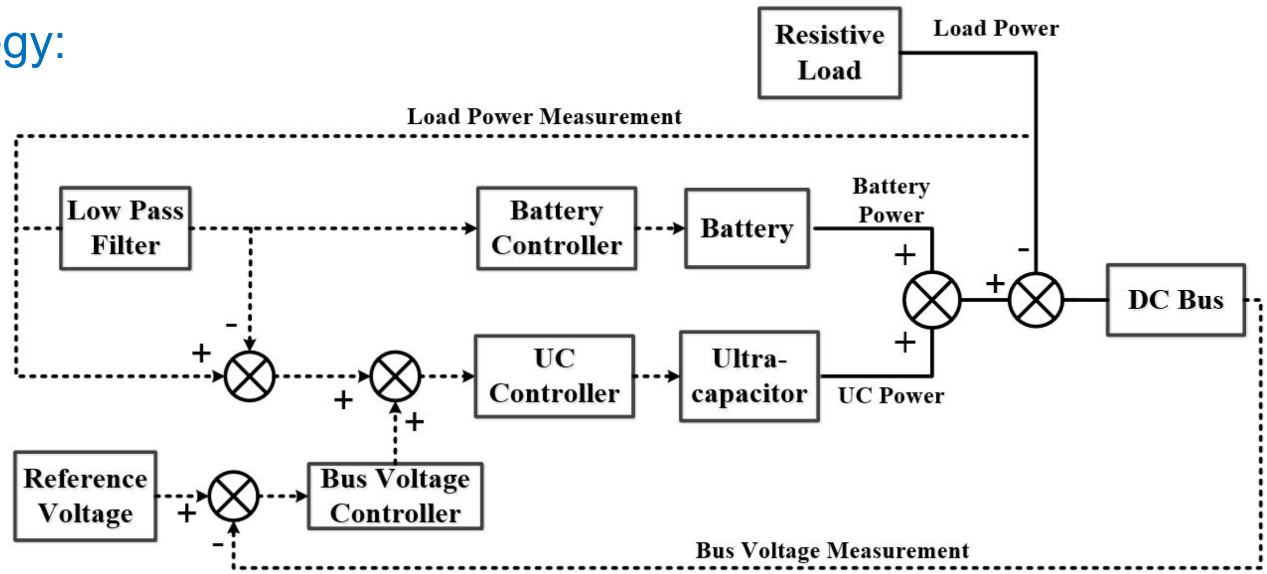


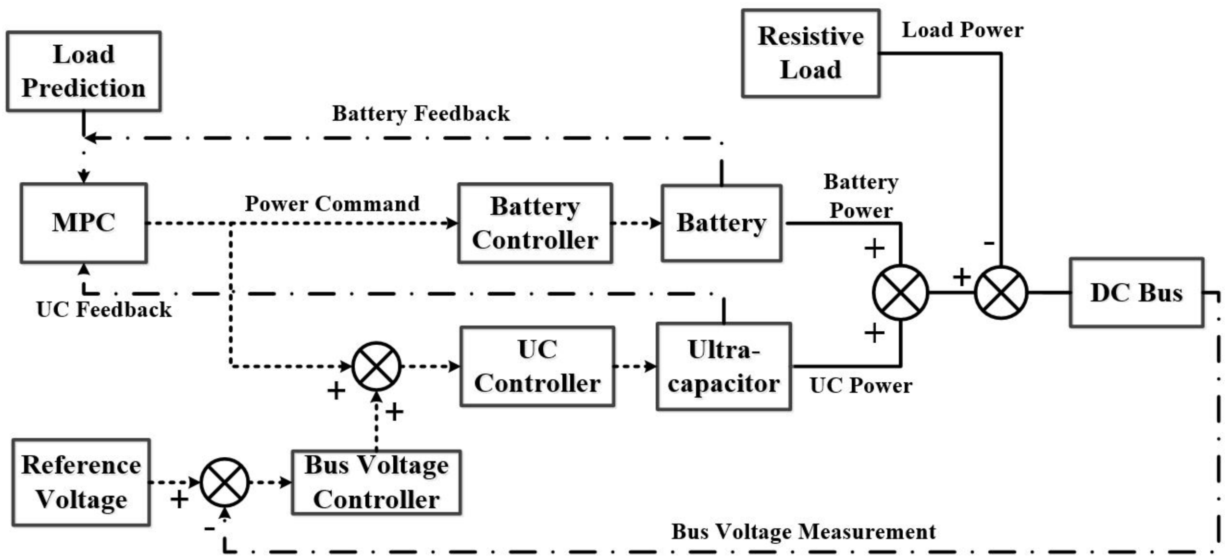


Schematic

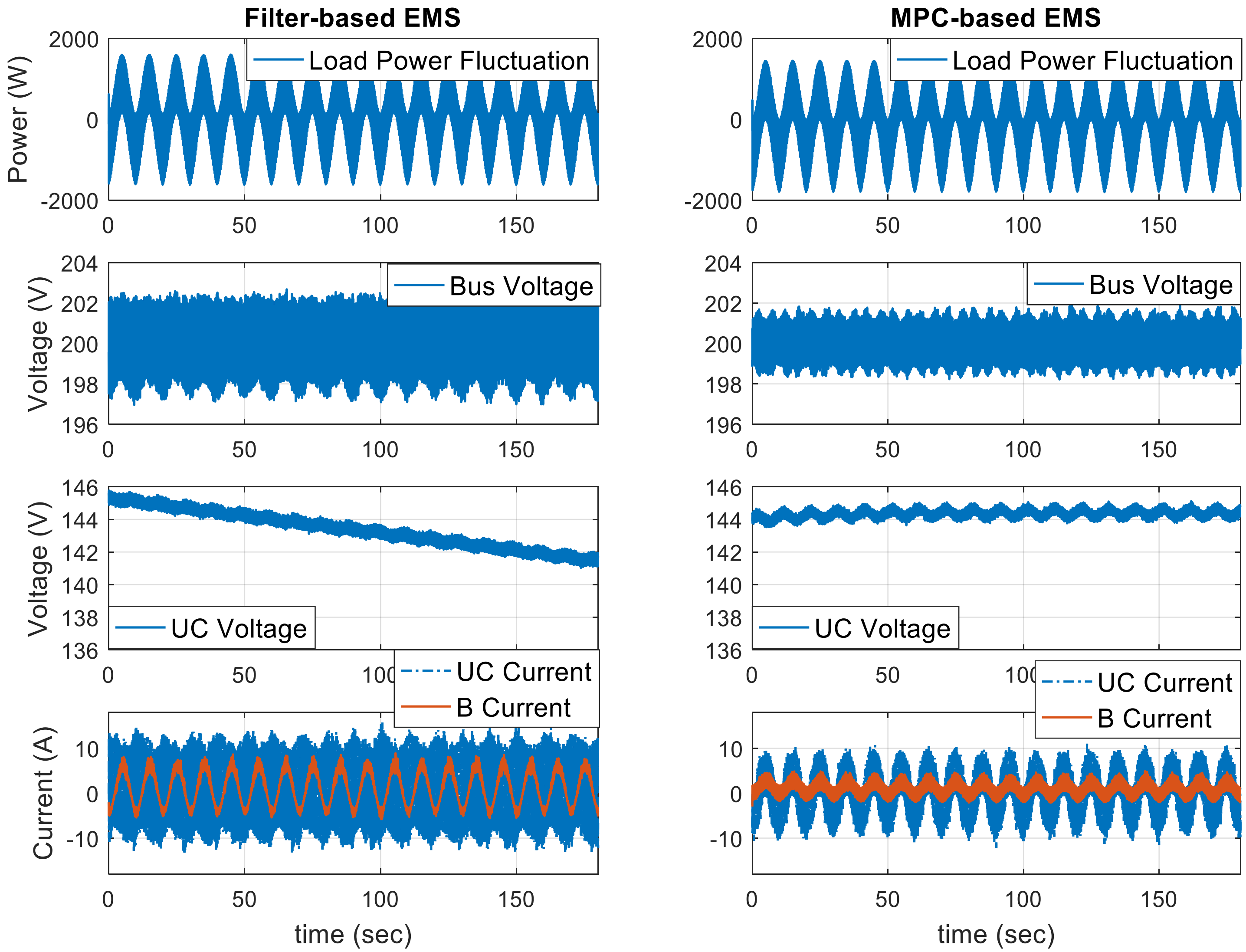
Filter-based strategy:



Real-time MPC:



Experimental Result



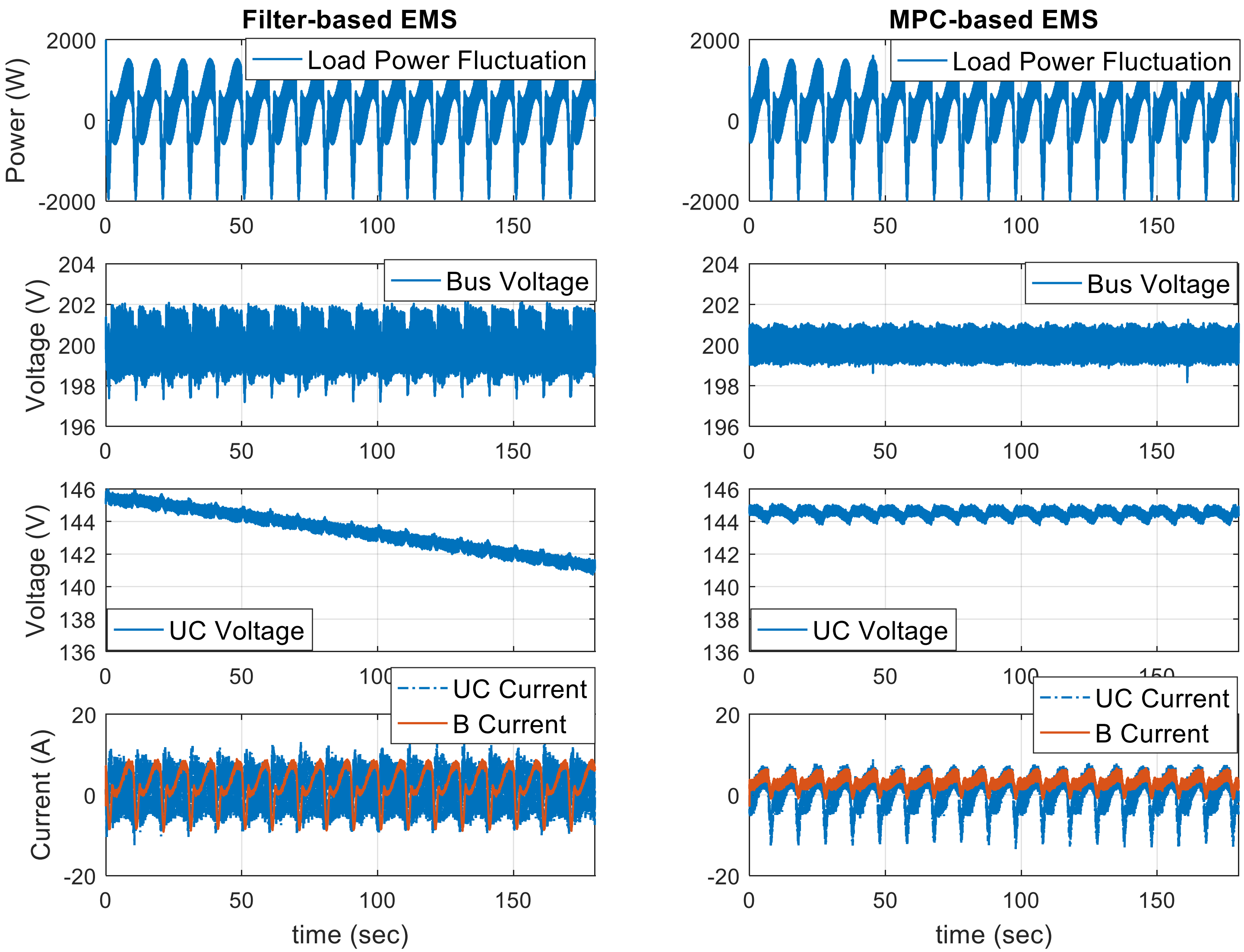
Load power fluctuations

Reduced bus voltage variations: 61.96%

High-efficiency operation around 145V

Reduced battery peak (51.11%) and rms current (40.99%); Reduced losses: 34.05%

Experimental Result



Load power fluctuations

Reduced bus voltage variations: 63.95%

High-efficiency operation around 145V

Reduced battery peak (67.35%) and rms current (64.19%); Reduced losses: 49.77%

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Conclusions

- HPS/IPS is a critical enabling technology for vehicle/ship electrification
- The integrated systems are control intensive and requires reliable and efficient power/energy management
- Controlling the flows of electrons is delicate
- The special characteristics of IPS lend itself for predictive and optimization-based control
- The unique challenges (real-time, fast update) offer opportunity for research and development
- Understanding and exploiting the dynamic characteristics is the key

Acknowledgements

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Contributions from collaborators

- Current and former students
  - Reza Ghaemi, Jun Hou, Soryeok Oh, Hyoengjun Park, David Reed, Gayathri Seenumani, Vasilis Tsarapas, Yanhui Xie, …
- Colleagues
  - Heath Hofmann, Ilya Kolmanovsky, Huei Peng, Anna Stefanopoulou

Supports from ONR, DoE, US Army, NSF, ABS, Ford, and Toyota (over the past 10+ years)

Thank you!

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