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

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October 24, 2017
Sion, Switzerland
(from Ann Arbor, Michigan)
Pushes and Pulls

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

Ship Electrification

Source: Dr. Norbert Doerry

Source: IMO Nitrogen Oxides (NOx) Regulation 13
Ship Electrification

- 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

"Integrated electric drive, with its associated cluster of technologies, will be the method of propulsion for the next class of surface battle-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:
Outline

- 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**

**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.
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 $T_s$ of a ducted propeller for increasing thrust reference $T_r$ in irregular waves. From experiments. Smogeli (2006)
Combined SOFC/GT Cycle System

- 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
Multiple heterogeneous 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

- 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?

- Power management for electrified vehicles/ships
  - Hybrid vehicles power management:
    - 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

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
\[
\min_{u(\cdot)} J(x(\cdot),u(\cdot)),
\]

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

subject to
\[
\begin{align*}
x(k + 1) &= f(x(k),u(k)), \quad f : \mathbb{R}^{n+m} \to \mathbb{R}^n, \\
x(t) &= x_t, \quad x_t \in \mathbb{R}^n, \\
C(x(k),u(k)) &\leq 0, \quad C : \mathbb{R}^{n+m} \to \mathbb{R}^l, \quad k = t, \ldots, t + N - 1, \\
\bar{C}(x(k)) &\leq 0, \quad \bar{C} : \mathbb{R}^n \to \mathbb{R}^q, \quad k = t, \ldots, t + N.
\end{align*}
\]
Neighboring Extremal Problem

Minimize:

\[
\delta^2 J = \frac{1}{2} \delta x(N)^T (\Phi_{xx}(N)) + \frac{\partial}{\partial x} \bar{C}_x(N) \bar{\mu}(N)) \delta x(N)
\]

\[
+ \frac{1}{2} \sum_{k=0}^{N-1} \left[ \begin{array}{c} \delta x \\ \delta u \end{array} \right]^T \left[ \begin{array}{cc} H_{xx} & H_{xu} \\ H_{ux} & H_{uu} \end{array} \right] \left[ \begin{array}{c} \delta x \\ \delta u \end{array} \right]
\]

Subject to

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

\[
C^a_x(x(k), u(k)) \delta x(k) + C^a_u(x(k), u(k)) \delta u(k) = 0;
\]

\[
\bar{C}^a_x(x(k)) \delta x(k) = 0
\]

\( C^a, C^a \): active constraint sets

H: Hamiltonian function of the original optimization problem
With proper assumptions, the NE problem has a closed-form solution:

\[
\delta x(k + 1) = f_x(x^0(k), u^0(k))\delta x(k) + f_u(x^0(k), u^0(k))\delta u(k)
\]

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

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

\[
Z_{11}(k) := H_{uu}(k) + f_u^T(k)S(k + 1)f_u(k)
\]

\[
Z_{12}(k) := H_{ux}(k) + f_u^T(k)S(k + 1)f_x(k)
\]

\[
Z_{22}(k) := H_{xx}(k) + f_x^T(k)S(k + 1)f_x(k)
\]

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

  - $Z_{11}(k)$ non-singular
  - $C_u^a$ must be of full row rank.
  - Can not handle the constraints of the type:
    $$\tilde{C}(x(k)) \leq 0$$
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

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

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

\[ \delta x(k+1) = f_x(k) \delta x(k) + f_u(k) \delta u(k); \delta x(0) = 0; \]

\[ C_x(x(k), u(k)) \delta x(k) + C_u(x(k), u(k)) \delta u(k) = 0; \]

\[ C_x^a(x(k)) \delta x(k) = 0. \]
Matrix $K_0$ will be non-invertible if
- C does not explicitly depend on $u$ or
- The active constraints outnumber the controls

Use back-propagation to avoid matrix singularity

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

$$z_c(k)(f_x(k-1)\delta x(k-1) + f_u(k-1)\delta u(k-1)) = 0$$
**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 \((x^1(\cdot), u^1(\cdot)) \rightarrow (x^1_{correct}(\cdot), u^1_{correct}(\cdot))\)
A Bench-mark Test (Non-realtime)

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

Fast updating at 8kHz

Coordinating multiple power sources and dealing with pulsory loads

Enforcing constraints

Exploring complementary characteristics of hybrid energy storage

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: $T=150\mu s$
  - Prediction horizon: $N=8$
  - Control horizon=8

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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.


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

3-Phase AC
480 V
400 A

Diode Rectifier

DC Bus

 Resistive Load Bank

Load Emulation Machine

Propulsion Drive Machine

Li-ION Battery

Flywheel

Ultracap

Core 1 System-level Control

- Average Execution Time
- Max Execution Time
- Sample Time

Core 1
Filter-based strategy:

Real-time MPC:
Experimental Result

Filter-based EMS
- Load Power Fluctuations
- Bus Voltage
- UC Voltage
- UC Current
- B Current

MPC-based EMS
- Load Power Fluctuations
- Bus Voltage
- UC Voltage
- UC Current
- B Current

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

Filter-based EMS

- Load power fluctuations
- Bus voltage variations: 63.95%
- UC Voltage

MPC-based EMS

- Load power fluctuations
- Bus voltage
- UC Voltage
- UC Current, B Current
- 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
Contributions from collaborators

- Current and former students
  - Reza Ghaemi, Jun Hou, Soryeok Oh, Hyoengjun Park, David Reed, Gayathri Seenumani, Vasilis Tsaraparas, 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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