Fuel Optimization Under Quality of Service Constraints for Shipboard Hybrid Electric Drive

Sudipta Lahiri  
Karen Miu  
Harry Kwatny

Drexel University  
Philadelphia, PA

Gaurav Bajpai  
Adam Beytin  
Jaymit Patel

Techno Sci, Inc  
Beltsville, MD

International Symposium on Resilient Control Systems, Boise, 08/08/11
1. Background

2. Problem Formulation
   a. Objectives
   b. Static Constraints
   c. Dynamic Constraints

3. Analysis Tool

4. Initial Results
   a. Benchmark Shipboard System
   b. Sample Results

5. Conclusions and Future Work
Shipboard Hybrid Electric Drive

- Integrated Power System Architecture
- Mechanical Drive: Propulsion shaft driven by dedicated prime movers
- Electric Drive: Motors supplied by electric power system drive propellers
- Hybrid Drive: Mechanical + Electric Drive
- Propulsion turbines can supply ship service loads
- Permanent Magnet Synchronous Machines capable of motor and generator operation
Shipboard Hybrid Electric Drive

- Hybrid Drive: Mechanical + Electric Drive
- Propulsion turbines can supply ship service loads
- Permanent Magnet Synchronous Machines (PMSM) capable of motor and generator operation
- PEBB based systems
Efficiency vs. Reliability

Efficiency: Primary Cost Benefits of Hybrid Propulsion Drive

- Fuel savings at low propulsion
- More efficient – less turbines at more load.
- Increased electric generation capacity and redundancy
- Increased effective range between refueling

Reliability: Primary Operating Concern

- For naval vessels, reliability takes precedence
- Will hybrid propulsion drives decrease, maintain and/or increase reliability with respect to e.g. contingency analysis?
- Architecture of shipboard systems makes them susceptible to transient stability issues
Goals

Methodology

• Develop reliability criteria for naval shipboard power systems

• Analyze efficiency for shipboard system configurations under reliability criteria

Analytical Tools

• Optimization tools

• Modeling and simulation tools to capture pertinent system behavior

Evaluation Cases

• Different mission scenarios

• Various configurations
Problem Formulation - Objectives

\[
\min_{c_{k,l} \in C, P_{v,l}} \left( \sum_{i=1}^{n} J_v \left( P_{v,l}, c_{k,l} \right) \right)
\]

$L$: set of load levels

$l$: selected load level

$C$: set of all possible commitments

$C_{k,l}$: selected commitments at load level $l$

$n$: number of power sources including storage

$J_v$: cost function in fuel per unit energy of power source $v$

$P_{v,l}$: real power output of source $v$ at loading level $l$
Static Constraints

Constraints are decoupled for electrical and mechanical loads

$$\sum_{i \in \alpha_k} P_i = P_{e,l}, \sum_{\kappa \in \beta_k} P_\kappa = P_{m,l} \quad \forall l \in L$$

$$P_{v,\text{min}} \leq P_{v,l} \leq P_{v,\text{max}}, \forall v \in \alpha_{k,l} \cup \beta_{k,l}, \forall l \in L$$

$$g_{k,l}(x, y, u) = 0$$

$P_{e,l}$: maximum real power demand for electrical loads at loading level $l$

$P_{m,l}$: maximum real power demand for mechanical loads at $l$

$P_{v,\text{min}}, P_{v,\text{max}}$: min and max real power demand of gen source $v$

$\alpha_{k,l}$: set of online power sources supplying electric load in $c_{k,l}$ at $l$

$\beta_{k,l}$: set of online power sources supplying mechanical load in $c_{k,l}$ at $l$

$g_{k,l}$: power flow equations for commitment $c_{k,l}$
Dynamic Quality of Service Constraints

\[
x(t) < x_{\text{min}} \quad t \in t_{x,\text{margin}}, \quad 0 < t_{x,\text{margin}} < T
\]

\[
x(t) > x_{\text{max}} \quad t \in t_{x,\text{margin}}, \quad 0 < t_{x,\text{margin}} < T
\]

\[
y(t) < y_{\text{min}} \quad t \in t_{y,\text{margin}}, \quad 0 < t_{y,\text{margin}} < T
\]

\[
y(t) > y_{\text{max}} \quad t \in t_{y,\text{margin}}, \quad 0 < t_{y,\text{margin}} < T
\]

- Limit violations in state and algebraic variables are permitted over a certain duration.

- Examples of dynamic reliability parameters:
  - Frequency at different nodes
  - Generator rotor angles
  - Charge of DC bus for inverter systems
  - Bus voltage magnitudes and angles
  - Current and power flows through lines

- Quality of Service (QOS) criteria can be selected according to the security requirements of the mission.

- Dynamic constraint evaluation requires simulation of shipboard power system in fidelity that captures pertinent behavior.
Solution Method

1. Formulate commitment profile
2. Formulate dynamic reliability constraints – mission security requirement
3. Select contingencies – depends on mission security requirement
4. Evaluate feasibility of commitments by simulation
5. Perform economic dispatch on feasible commitments
6. Select feasible commitment with minimum fuel cost

Points of Interest

- Application of traditional power system methods – contingency analysis, unit commitment, economic dispatch
- Dynamic contingency analysis
- Separation of mechanical and electrical power delivery systems.
Simulation and Modeling Tools

- Modeling and simulation of Switched Dynamical Systems
- Simulates discrete behavior of state and algebraic variables – expansion, contraction and reset of continuous parameter space
- Embedded logic to model dynamics of discrete states
- Supports models of varying fidelity
- Tools for user model generation
- 2 – 3 orders of magnitude faster than real time
- Easily portable to real time hardware in the loop testing
Software Description

Top Level of simulation platform in Simulink

User interface

Model Generation in Mathematica
Application – Benchmark Hybrid Drive System

Electric Supply Gas Turbine 1 (GTG1)  
Rolls-Royce 501K, 5.3 MW

Electric Supply Gas Turbine 2 (GTG2)  

Electric Supply Gas Turbine 3 (GTG3)  

Energy Storage Module (ESM)  
2.2 MW  
340 KW-HR

Non vital load  
(2MW, 1,5 Mvar)

13.8 KV  
450 V

6 MW, pulse

1

Propulsion Turbine 1 (GTM1)  
GE LM2500, 25.1 MW

Propulsion Turbine 2 (GTM2), 25.1 MW

Propulsion Turbine 3 (GTM3), 25.1 MW

Propulsion Turbine 4 (GTM4), 25.1 MW

Reduction Gear

Reduction Gear

PMSM2 2.6 MW  

PMSM2 2.6 MW

Propulsion Shaft 1 (PS1)  

Propulsion Shaft 2 (PS2)

Vital load  
2 MW

Non vital load  
(2MW, 1,5 Mvar)

375 VDC

UPS

UPS

UPS
Benchmark Description

Configurations

1. Trail Shaft - 1 GTM driving 1 PS, 1 or more GTGs supply electric load
2. Full Power – 4 GTMs driving 2 PSs, 1 or more GTGs supply electric load
3. Electric Propulsion System – 1 PMSM under motor operation drives 2 PSs, 1 or more GTGs supply electric load.
4. Cross Connected – 1 GTM drives 1 PMSM as generator, 1 PMSM under motor operation drives 2 PSs, 1 or more GTGs supply electric load
5. Hybrid Generation – 1 GTM drives 2 PSs, 1 GTM drives 1 PMSM as generator, 1 or more GTGs supply electric load.

Mission Loading Levels

<table>
<thead>
<tr>
<th>Mission</th>
<th>Propulsion Load (Max MW)</th>
<th>Ship Service Load (Max MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge to Theater</td>
<td>60</td>
<td>6</td>
</tr>
<tr>
<td>Economic Transit</td>
<td>18</td>
<td>8</td>
</tr>
<tr>
<td>Operational Presence</td>
<td>2</td>
<td>6</td>
</tr>
</tbody>
</table>
Sample Results

Comparison of Fuel Costs between three feasible commitments for mission Economic Transit

- Contingency – Outage on 1 operational GTG
- QOS criteria – System frequency always within +/- 3%

System frequency deviates +/-1% for no more than 3 s
Future Work

- Component losses in efficiency calculations
- Effect of storage devices
- Fuel capacity optimization over mission duration
- Inclusion of damage mitigation strategies in reliability criteria
Thank You!