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

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International Symposium on Resilient Control Systems, Boise, 08/08/11

Outline

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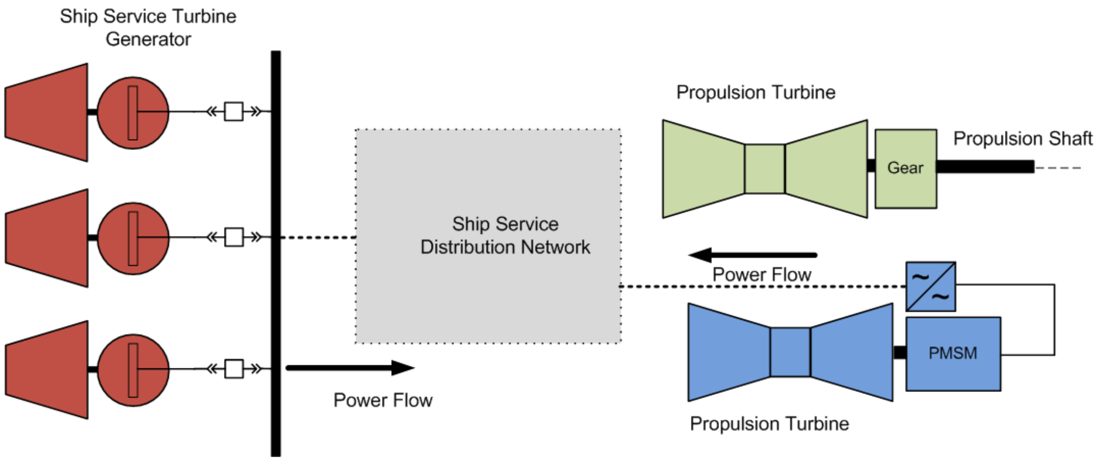
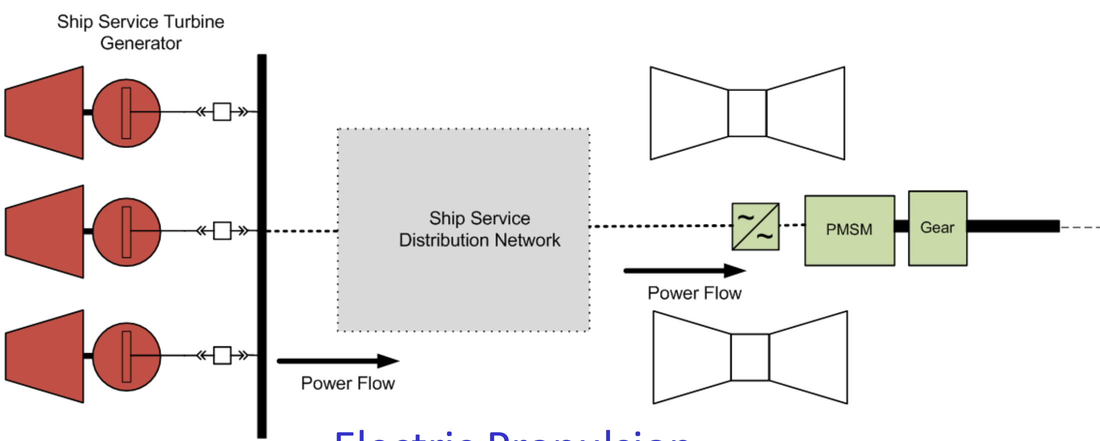
Shipboard Hybrid Electric Drive

- 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



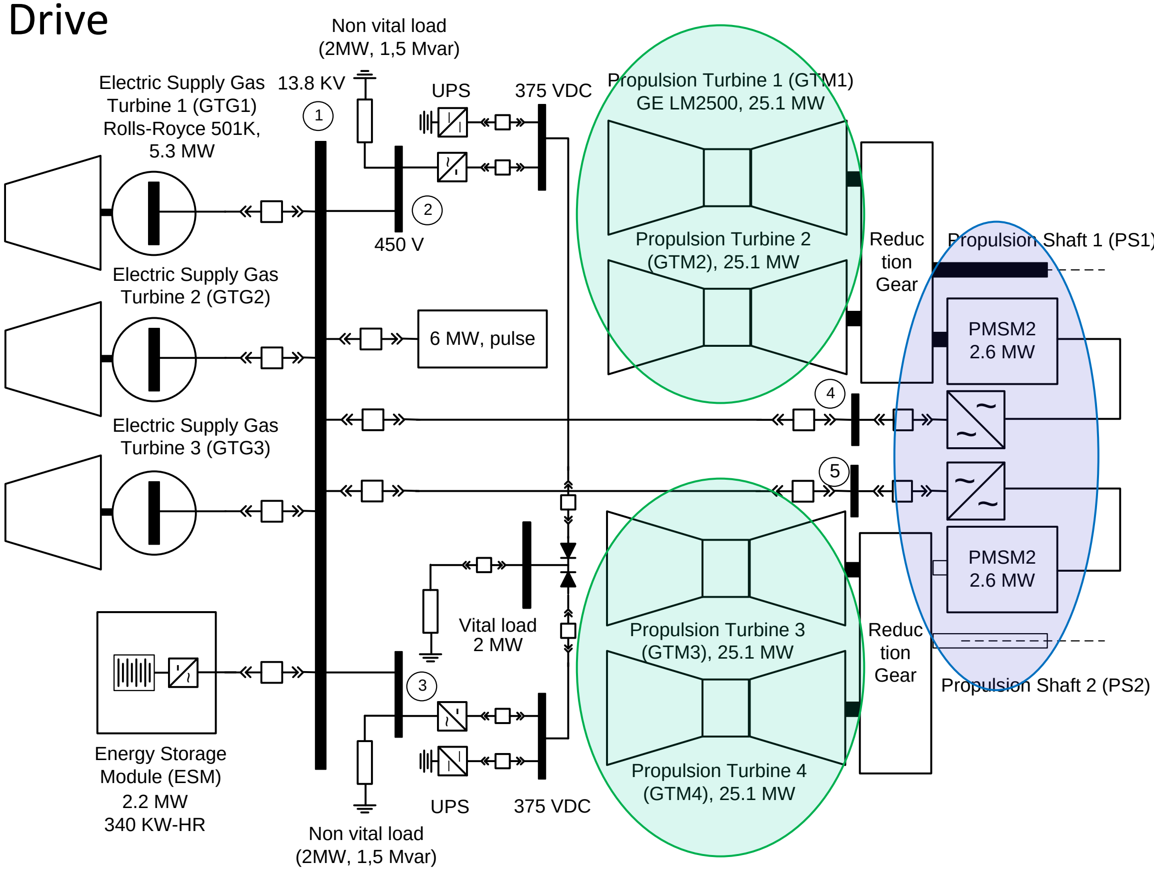
Mechanical propulsion and generation by propulsion turbine



Electric Propulsion

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



Hybrid Electric Drive Example

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

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

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

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

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

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

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

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

$P_{v,min}$, $P_{v,max}$: 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

$$x(t) < x_{\min};\ t \in t_{\text{x,margin}},\ 0 < t_{\text{x,margin}} < T$$
$$x(t) > x_{\max};\ t \in t_{\text{x,margin}},\ 0 < t_{\text{x,margin}} < T$$

$$y(t) < y_{\min};\ t \in t_{\text{y,margin}},\ 0 < t_{\text{y,margin}} < T$$
$$y(t) > y_{\max};\ t \in t_{\text{y,margin}},\ 0 < t_{\text{y,margin}} < T$$

- 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

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- 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

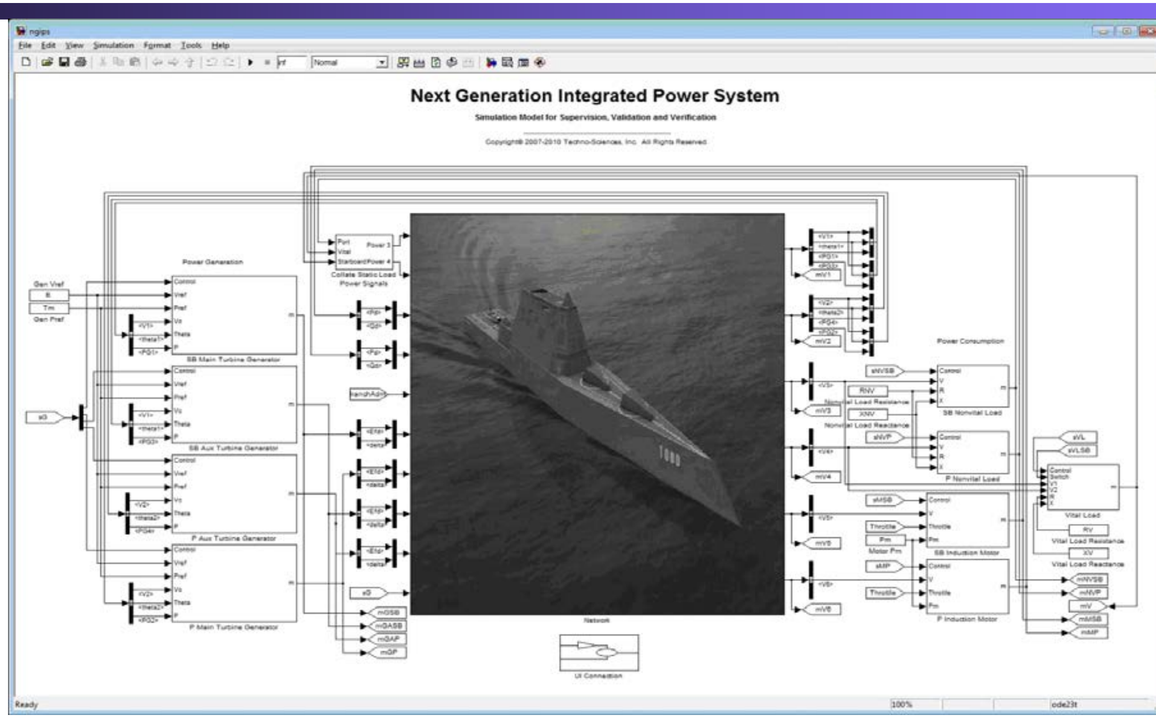
Points of Interest

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

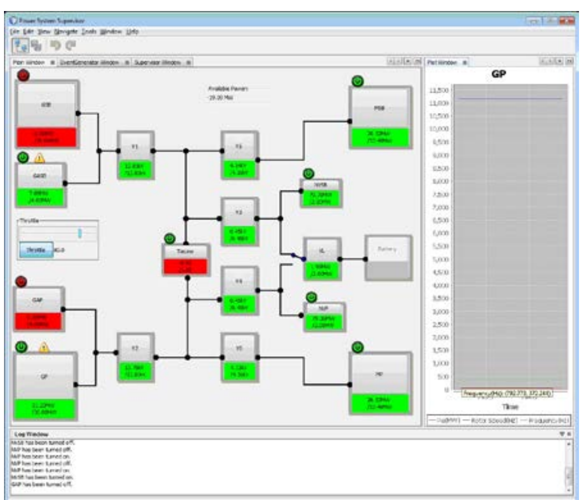
Simulation and Modeling Tools

- 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

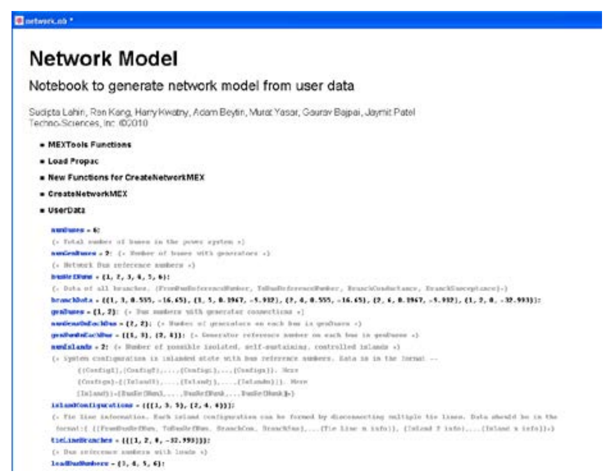
Software Description



Top Level of simulation platform in Simulink

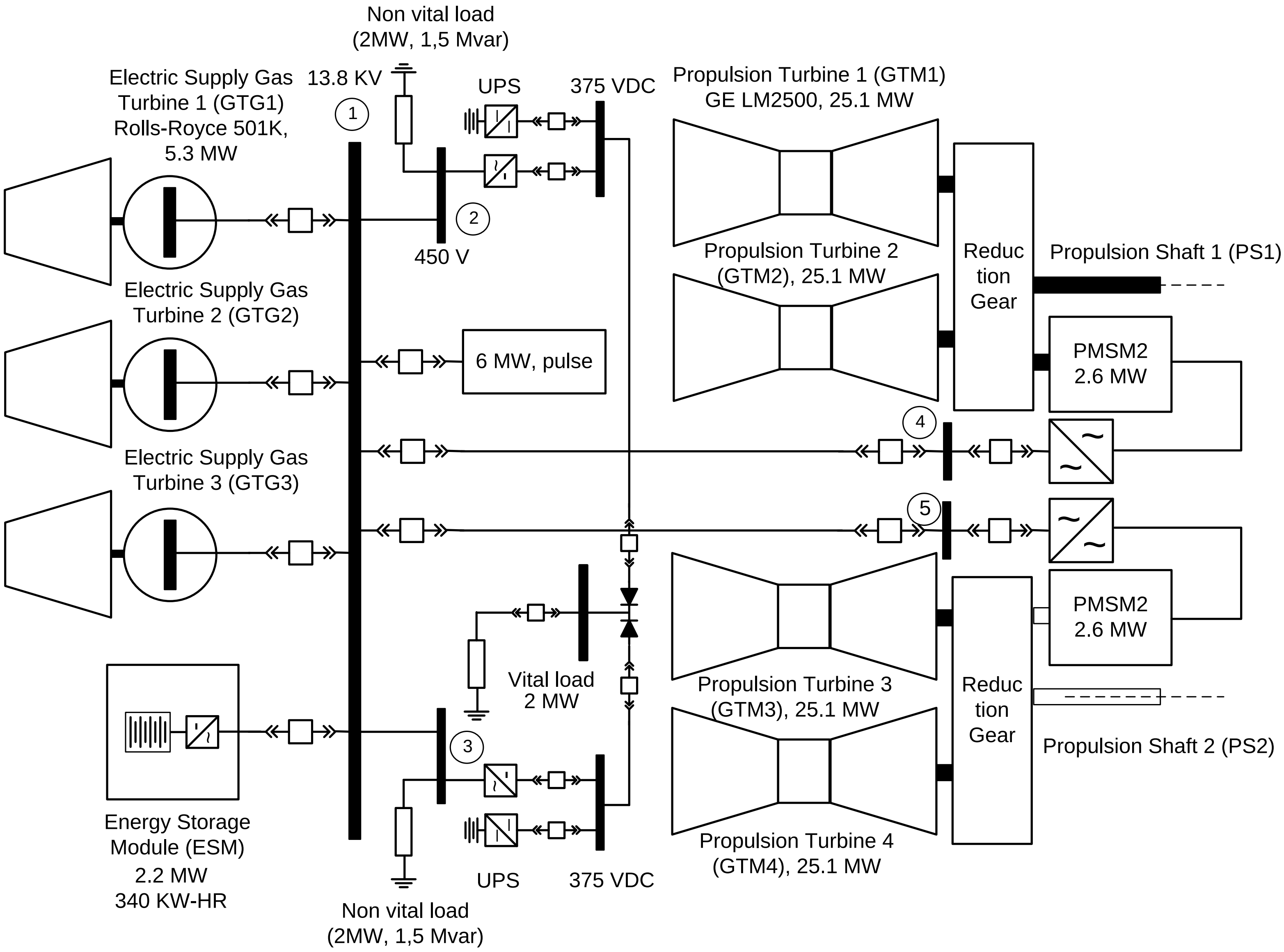


User interface



Model Generation in Mathematica

Application – Benchmark Hybrid Drive System



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

Mission	Propulsion Load (Max MW)	Ship Service Load (Max MW)
Surge to Theater	60	6
Economic Transit	18	8
Operational Presence	2	6

Sample Results

	Commitment ID		
Status of power sources	Trail Shaft 1	Full Power 1	Hybrid Generation 5
GTG 1	3 MW	3 MW	3.4 MW
GTG 2	3 MW	3 MW	Spinning
GTG 3	Spinning	Spinning	Offline
GTM1 + PS	18 MW	4.5 MW	18 MW
GTM2 + PS	Offline	4.5 MW	Offline
GTM3 + PS	Offline	4.5 MW	Spinning
GTM4 + PS	Offline	4.5 MW	Offline
GTM2 + PMSM	Offline	Offline	2.6 MW
Cost (GPH)	1992.44	2293.52	2163.21
% savings	13.12	0	5.68

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!