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

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Abstract—**This paper presents an approach to optimize fuel costs of a hybrid electric ship propulsion system under different mission considerations. The static optimization problem is to commit and dispatch the generation sources such that fuel cost is minimized, while meeting load demands and complying with dynamic Quality of Service (QOS) constraints. A simulation platform capable of representing a continuous time differential algebraic model of the power system and discrete switching events has been developed. A generation commitment list is prepared for each mission requirement and commitments satisfying QOS constraints are determined by simulation. The feasible commitments are economically dispatched based on quadratic fuel cost curves, and the commitment with the lowest cost per unit time is selected as optimal for that mission. Comparative cost benefits of an optimal commitment over a non-optimal commitment are enumerated.**

I. INTRODUCTION

The Integrated Power System (IPS) architecture in the all-electric warship enables ship service and propulsion loads to be driven by common prime movers and offers considerable advantages in efficiency and flexibility of design [1]. An extension of this design principle is the hybrid drive propulsion system. This allows the propulsion shaft to be driven through mechanical coupling with dedicated prime movers (mechanical drive) or through electric motors being supplied by the electric power system (electric drive). A key feature, enabling greater efficiency at low speeds, is the capability of additional support to the electric system through generators driven by propulsion prime movers. The rationale for the hybrid drive and its significance for improving ship fuel economy and operational reliability are described in [2] and [3].

In addition to varied distributed generation sources, the next generation of warships will have directed energy weapons, advanced sensors, critical and non-critical loads. A majority of the sources and loads will be interfaced through power electronics modules which rely on very fast switching signals for effective operation, while de-coupling sources of inertia from the traditionally low-inertia ship power system. Furthermore, the loads interfaced by power electronics are sensitive to transient disturbances, leading to a greater stress on system security.

Reduction in fuel costs is one of the main drivers in reducing operational costs for existing naval fleets. Most naval ships have very low propulsion power requirement for a substantial portion of their operating time [2]. Advanced configurability of the hybrid propulsion drive presents significant opportunity for optimization of fuel by operating the generation sources efficiently. However, for naval ships, the most important element in the decision process is survivability. It is improbable that a commanding officer might put the ship at hazard by operating close to stability margins in order to reduce operational expense.

The fuel optimization problem for the hybrid shipboard drive has to be considered in the context of reliability. While the methods of unit commitment, economic dispatch and contingency analysis, [4] - [7], have been in extensive use for decades in terrestrial power systems, their applicability has been limited due to the restricted nature of traditional shipboard systems. A novel feature in this approach is the extension of these methods to dynamic constraints in varied time-scales in order to accommodate the vulnerability of the next generation shipboard system to transient disturbances.

Another novel feature is the application of tools developed for modeling and analysis of Switched Dynamical Systems (SDS). Power systems are traditionally represented by a set of continuous time differential algebraic equations. The inherent discrete behavior in power systems, such as disturbances, reconfiguration, or discrete controller action, can be modeled by a set of logical conditions. The discrete and continuous sub-systems can be combined to create a framework of switched differential algebraic systems where the switching is governed by logic. Extensive work has been done in the design of power management systems through optimal control [8] or supervisory control [9] using this framework. The modeling and simulation tools for SDS have been utilized for the current application.

The paper is organized as follows: Section II presents the formulation of the constrained optimization problem. Section III describes the benchmark shipboard power system relevant

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to the problem. Section IV outlines the solution approach. Section V presents an example of the cost benefits. Future avenues of work are outlined in Section VI.

II. PROBLEM FORMULATION

The fuel minimization problem is formulated as a constrained, multi-objective, mixed integer, non-linear optimization problem. The problem is related to unit commitment and economic dispatch within terrestrial power systems [7]. Yet, several characteristics arise within a shipboard power system environment which impacts the resulting problem formulation.

Turbines connected to the propulsion shaft, driving propulsion loads are decoupled from the electric power system and form a part of the mechanical drive. As such, propulsion loads can be supplied entirely by the mechanical drive, electrical power system or can be shared among the two. Ship service loads are supplied solely by the electrical power system. The loads supplied by the electrical power system are referred to as electrical loads, whereas the loads supplied by the mechanical drive are mechanical loads.

A. *Objectives*

The objectives are to 1) select a commitment of generation sources that minimize the fuel cost for each loading level, 2) economically dispatch the generation sources within each commitment. Here, a power source includes 1) generators coupled with prime movers and, 2) battery banks. A commitment of power sources indicates the service status of all power sources in the system; e.g. a power source might be on-line, spinning or off-line. Thus, a commitment can be denoted by a vector of integer valued elements. Neglecting power losses in the system, for each load level *l*, objectives are given by:

$$\min_{\substack{c_{k,l}\in C,\, P_{\nu,l}\\ l\in L}} \left(\sum_{\nu=1}^{\mu} \chi_\nu \left(P_{\nu,l}, c_{k,l} \right) \right) \tag{1}$$

where,

L : set of load levels; l : selected load level;

C : set of all possible commitments;

$c_{k,l}$: selected commitment at *l*, $c_{k,l} \in C \subseteq Z^{\mu}$;

μ : number of power sources in the system;

χ_ν : cost function in fuel per unit energy of power source ν ;

$P_{\nu,l}$: real power output of source ν at *l*;

B. *Constraints*

Both static and dynamic constraints are considered for each load level. The static constraints of the problem include:

$$\sum_{\iota\in\alpha_k} P_\iota = P_{e,l},\ \sum_{\kappa\in\beta_k} P_\kappa = P_{m,l}\quad \forall l \in L \tag{2}$$

$$P_{\nu,\min} \le P_{\nu,l} \le P_{\nu,\max}, \forall\, \nu \in \alpha_{k,l} \cup \beta_{k,l}, \forall l \in L \tag{3}$$

$$g_{k,l}\left(x, y, u\right) = 0 \tag{4}$$

where,

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

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

$P_{\nu,\min}, P_{\nu,\max}$: minimum and maximum real power output of generation source ν ;

$\alpha_{k,l}$: 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 the commitment $c_{k,l}$;

$x \in X \subseteq R^n$: system dynamic variables;

$y \in Y \subseteq R^p$: system algebraic variables;

$u \in U \subseteq R^l$: continuous system inputs;

It is noted that the ship electrical loads and mechanical loads are treated here as electrically isolated. Thus, the algebraic constraints (3) are decoupled.

Dynamic constraints are now discussed. They include quality of service constraints under normal operating conditions and under select contingencies. The evolution of power system dynamics can be described by a set of Ordinary Differential Equations (ODEs) constrained by (4).

$$\dot{x} = f\left(x, y, u\right) \tag{5}$$

Dynamic Quality of Service (QOS) constraints can now be formulated as

$$\begin{aligned} x(t) < x_{\min};\ t \in t_{\text{x,margin}},\ 0 < t_{\text{x,margin}} < T \\ x(t) > x_{\max};\ t \in t_{\text{x,margin}},\ 0 < t_{\text{x,margin}} < T \end{aligned} \tag{6}$$

$$\begin{aligned} y(t) < y_{\min};\ t \in t_{\text{y,margin}},\ 0 < t_{\text{y,margin}} < T \\ y(t) > y_{\max};\ t \in t_{\text{y,margin}},\ 0 < t_{\text{y,margin}} < T \end{aligned} \tag{7}$$

Equations (6) and (7) denote that state and algebraic variables are checked for limit violations, permitted over a certain duration. $x_{\min}, x_{\max}$ and $y_{\min}, y_{\max}$ are the minimum and maximum limits of state and algebraic variables, $t_{x,\text{margin}}, t_{y,\text{margin}}$ are the durations over which the violations are tolerated and *T* is the time over which the system is observed.

A contingency in the shipboard system can be an uncontrolled event such as component failure, or a controlled event such as battery charging. Let $R = \{r_1, ..., r_s\}$ denote the set of *s* predefined contingencies.

For load level *l*, a commitment $c_{k,l}$ satisfies a contingency $r \in R$, if the solution of (5) over $t \in [0,T]$ does not violate constraints (2) - (4), (6) - (7) when r occurs at t_r, $0 < t_r < T$. Time t_r and T are such that the dynamic system is in equilibrium, if it exists, before and after the contingency. If a commitment $c_{k,l}$ satisfies r_i, $\forall i = 1,...,s$, then the commitment is feasible for the load level *l*.

The QOS constraints as well as the contingency set can be formulated according to security requirements of different missions. In general, the dynamic variables over which the constraints are checked can be frequency measurements at different nodes in the system, rotor angle of the generators or charge of a DC-bus of a power-electronic interfaced device. The algebraic variables over which violations are checked can be bus voltages at specified nodes, angle difference between certain buses and current or power flows through a line.

Although the solution methods to economic dispatch and unit commitment problems are well documented, their application to shipboard power systems presents a unique set of challenges. As a result the benchmark shipboard system is presented in Section III followed by the solution approach in Section IV.

III. BENCHMARK EXAMPLE

A. Benchmark Configuration

The shipboard power system shown in Figure 1 is an abstraction of the DDG-51 Burke class destroyer.

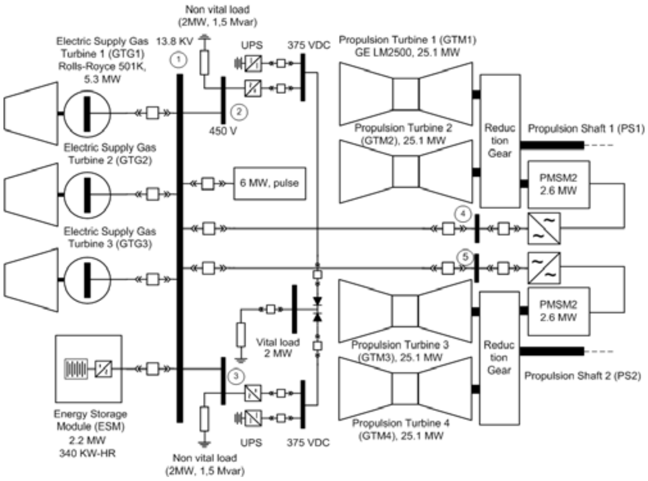

Figure 1. Benchmark hybrid drive configuration

The benchmark configuration includes the following components:

1) 3 Gas Turbine Generators (GTG, 5.3 MW)
2) 4 Gas Turbine Propulsion Engines (GTM, 25.1 MW)
3) 2 Permanent Magnet Synchronous Machines (PMSM, 2.6 MW)
4) Energy Storage Module (ESM, 2.2 MW, 340 KWhr). The ESM is attached to the vital load bus to provide backup, as well as the generator bus to smooth the effect of the pulse load.
5) 2 Propulsion Shafts (PS) connected to the prime mover through reduction gear.
6) Static Non Vital Loads (NVL) connected to the port and starboard sides (4 MW, 3 MVar total).
7) 2 MW power factor corrected static load considered as Vital Load (VL). This load can be switched between the port and starboard sides.
8) Pulse load of 6 MW with pulse duration of 0.1s.

Three loading levels have been considered for the fuel optimization problem as shown in Table I. These are based on mission requirements as stated in [10]. The ship service load consists of non-vital and vital static loads. In addition, it can also include charging of ESM (max 4 MW) and a pulse load of 6 MW. Note that the electrical load consists of the ship service load and the portion of propulsion load supplied by the electrical power system.

TABLE I. LOADING LEVELS

Mission	Propulsion Load (max MW)	Ship Service Load (max MW)
Surge to Theater (ST)	60	6
Economical Transit (ET)	18	6
Operational Presence (OP)	2	6

The operational states of GTMs and GTGs are 1) online, 2) offline and, 3) spinning. The PMSMs can be online as motor or generator, can spin as generator or may be offline. Spinning operation implies that the machine has been brought up to required speed and can be connected to the system with negligible delay. As a generator, the PMSM has to be connected to a GTM which acts as a prime-mover. While spinning, the PMSM has to be connected to a spinning GTM. As an electric motor, the PMSM is supplied from the electric power system.

The Propulsion Operational Mode (POM) is determined from the ship mission by considering a combination of fuel economy, reliability and survivability [2]. The 5 propulsion and power supply configurations considered for this problem are:

1) Trail Shaft (TS) – 1 GTM driving 1 PS supply mechanical load, 1 or more GTGs supply electric load.
2) Full Power (FP) – 4 GTMs driving 2 PSs supply mechanical load, 1 or more GTGs supply the electric load.
3) Electric Propulsion System (EPS) – 1 PMSM operating as motor drives 2 PSs, 1 or more GTGs supply the electric load.
4) Cross Connected (CC) – 1 GTM drives 1 PMSM as generator, 1 PMSM operating as electric motor drives 2 PSs, 1 or more GTGs supply electric loads.

5) Hybrid Generation (HG) – 1 GTM driving 2 PSs supply mechanical load, 1 GTM drives 1 PMSM as generator, 1 or more GTGs supply electric loads.

Table II lists the minimum number of generation components that have to be online for each configuration, assuming that the minimum electric ship service load is 6 MW. The units that are not online may be offline or spinning. The term '1m' in Table 2 implies 1 PMSM operates as motor, while '1g' implies 1 PMSM operates as generator.

TABLE II. COMPONENT STATUS FOR SYSTEM CONFIGURATIONS

	On-line				**Off-line or Spinning**			
Operation/ Component	GTM	PS	GTG	PMSM	GTM	PS	GTG	PMSM
Trail Shaft	1	1	2	0	3	1	1	2
Full Power	4	2	2	0	0	0	1	2
EPS	0	2	2	1m	4	0	1	1
Cross Connected	1	2	2	1m, 1g	3	0	1	0
Hybrid Generation	2	2	1	1g	2	0	2	1

B. *Simulation Platform*

Modeling and simulation tools have been developed based on *Mathematica* and *MATLAB/Simulink* platforms. The GTG's are modeled as wound rotor synchronous generators [11] with aero-derivative gas turbines [12]. Local controllers for the generators are excitation control through the IEEE Type I exciter and speed control by droop and/or Automatic Generation Control (AGC) regulated speed control [13]. The GTM's are modeled as aero-derivative gas turbines. The permanent magnet synchronous machine model is provided in [14]. The PMSMs are connected to the electric system through back-to-back PWM converters, which are classified as machine and grid side converters. An intermediate DC link decouples the operation of the converters, enabling them to be controlled independently. The controller models are taken from [15]-[16]. The energy storage modules are modeled as Li-Ion battery banks [17]. For now, component losses are not considered.

The models for the dynamic components as well as the algebraic transmission/distribution network are defined symbolically in *Mathematica* and converted to *Simulink* compatible C-code, which compiles as a *Simulink* S-function. The power flow equations of the network is converted to a discrete time block and solved by multiple iterations of Newton's method. The Ordinary Differential Equations (ODEs) of dynamic components are approximated by trapezoidal difference time integration formulas. Power system components interface with the network through PQ, PV or IV ports. Switching is implemented by connecting/disconnecting components or enabling/disabling elements within the network.

IV. SOLUTION METHODOLOGY

The fuel optimization problem is solved separately for the three loading levels in Table 1. First, feasible commitments are identified for each load level. Then, the minimum cost commitment and dispatch is selected for each load level. The solution steps are outlined below:

1) A commitment list of possible generation commitments is prepared for each system configuration shown in Table II. The number of possible commitments for each configuration are: trail shaft – 2, full power – 2, electric propulsion system – 18, cross connected – 8, hybrid generation – 15.

2) The commitments are economically dispatched by solving (1). For a particular power source, the cost function is assumed to be a second order quadratic polynomial given by

$$\chi_v\left(P_v\right) = a_v P_v^2 + b_v P_v + c_v \tag{8}$$

where χ_v is the cost function of the vth generation source i.e. prime mover and generator in Gallons Per MW hour (GPMWh). The unit of cost is Gallons Per Hour (GPH). Table III shows sample a-, b-, and c-parameters used in the problem. They are derived from [18].

3) The contingency events for the problem are:

   i. Full ESM charging (4 MW).

   ii. Failure of 1 GTG

   iii. Failure of 1 machine driving a propulsion shaft.

   The system is simulated by solving (5) under constraints (2) - (4) over time *T*. Contingency analysis is performed as follows:

   i. Select a commitment and loading level. Generate initial conditions by solving steady state power flow. If static constraints are violated, reject commitment.

   ii. Start dynamic simulation. At time t_1 generate contingency event. t_1 is large enough for the dynamics to reach steady state.

   iii. Run simulation till time t_2. t_2 is large enough for the post-contingency system to reach a steady state if it exists.

   iv. If any of the QOC constraints are violated between 0 to t_2, stop simulation and reject commitment as infeasible.

4) Compile list for feasible commitments for each loading level.

5) An optimal configuration for a loading level is the feasible configuration that has the minimum cost for the loading level.

TABLE III. COST FUNCTION AND LOADING LIMITS FOR POWER SOURCES

	a-coef	b-coef	c-coef	Spinning cost (GPH)	Min load (MW)	Max load (MW)
GTG	2.08	51.98	24.85	20	0.1	5.3
GTM + PMSM	0.859	58.83	185.4	120	0.1	2.6
GTM + PS	0.603	57.89	195.9	140	0.5	25.1

V. FUEL COST COMPARISON

An example of comparative fuel costs between optimal and non-optimal commitments for the loading level Economic Transit is enumerated in Table IV.

TABLE IV. COMPARISON BETWEEN 3 SAMPLE COMMITMENTS

	TS1	FP1	HG5
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**

The commitments are denoted by their commitment code – Trail Shaft 1 (TS1), Full Power 1 (FP1) and Hybrid Generation 5 (HG5). All three commitments are feasible under the specified contingencies. It is assumed that identical machine and prime mover combinations have the same cost function. The status of each generator combined with a prime-mover source is shown. Commitment TS1 has a saving of 13.12% over FP1, while HG5 has a saving of 5.68%.

VI. SUMMARY AND CONCLUSIONS

An approach for load and generation management for efficient and fault tolerant operation of integrated power systems has been described. The work presented is a demonstration of tools and techniques in development towards the operation of self-contained power systems with distributed resources, integrating multiple generator alternatives, accommodating all operational modes, load demands and even component failures. At the core of the approach are modeling and analysis methods developed for handling complex, non-linear switched dynamical systems.

The formulation presented in this work, can be extended to solve related problems such as fuel capacity optimization over mission duration, or fuel cost optimization over selective QOS criteria that depends on the mission requirement.

The approach can also be extended to create power system solutions that maintain efficiency of operation while responding to discrete events such as operational mode change, failure of components or availability of generation resource, while respecting the dynamic constraints of the system. Since the exact load profile or the nature of disturbances cannot be known in advance, control tools that deal with uncertainty using discrete mechanisms is the key to efficient and secure power management.

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