Applied Energy 212 (2018) 919–930

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Control development and performance evaluation for battery/flywheel hybrid energy storage solutions to mitigate load fluctuations in all-electric ship propulsion systems

Jun Hou[a,*], Jing Sun[a,b], Heath Hofmann[a]

[a] Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109, USA
[b] Department of Naval Architecture and Marine Engineering, University of Michigan, Ann Arbor, MI 48109, USA

HIGHLIGHTS

- A new B/FW HESS is proposed to isolate load fluctuations from the shipboard network.
- A periodic DP algorithm is developed to reduce the computational cost.
- A comparative study illustrates the advantages and limitations of B/UC and B/FW HESS.
- A novel MPC-based approach is developed to facilitate real-time implementation.
- The proposed MPC is validated in a laboratory-scaled experiment.

ARTICLE INFO

Keywords:
Electric ship propulsion
Hybrid energy storage
Multi-objective optimization
Model predictive control
Energy management
Dynamic programming

ABSTRACT

Current trends in both commercial and military ship development have focused on ship electrification. A challenge for electric-ship propulsion systems, however, is large propulsion-load fluctuations. To address this issue, this paper explores a new solution, namely a combined battery and flywheel (B/FW) hybrid energy storage system (HESS) as a buffer to isolate load fluctuations from the shipboard network. Our two main objectives, power-fluctuation compensation and energy saving under various operating constraints, are formulated as a multi-objective optimization problem. Pareto fronts, which illustrate the trade-offs between the main objectives, are obtained by using dynamic programming with the weighted sum method. To quantitatively analyze the performance of B/FW HESS, a comparative study is performed under different sea conditions, where a battery/ultra-capacitor (B/UC) HESS configuration is used as a reference in performance evaluation. Simulation results show the feasibility and effectiveness of B/FW to mitigate the load fluctuations for all-electric ships, especially at high sea states. Furthermore, a model predictive control (MPC) algorithm is developed to facilitate real-time implementation of the proposed solution. A performance comparison between the proposed MPC energy management strategy and the global dynamic programming is performed, and this comparison demonstrates the effectiveness of the proposed MPC strategy.

1. Introduction

Ship electrification has become a dominant trend for both commercial and military ship development to improve efficiency, reduce emissions, support high-power mission systems, and provide a more comfortable environment for crew and passengers [1–5]. The all-electric ship propulsion system provides new opportunities to solve old problems and develop new solutions. One of the classic problems is propulsion-load fluctuations, which are caused by the propeller rotation and encounter waves and can significantly affect both mechanical and electrical systems [6–9]. While the problem exists in conventional mechanical drivetrains, the resulting consequences of power fluctuations can be more pronounced for electrical propulsion systems. In addition to mechanical wear and tear caused by high-frequency unbalanced torque and speed oscillations, reliability and efficiency of shipboard power system can be negatively impacted. To address load fluctuations, several methods have been proposed, such as using thruster biasing for vessels with dynamic positioning systems [10]. This approach is mainly used for low-frequency fluctuations, and is applied to dynamic positioning systems. Another popular solution is to

* Corresponding author.
E-mail addresses: junhou@umich.edu (J. Hou), jingsun@umich.edu (J. Sun), hofmann@umich.edu (H. Hofmann).

https://doi.org/10.1016/j.apenergy.2017.12.098
Received 21 October 2017; Received in revised form 11 December 2017; Accepted 27 December 2017
Available online 04 January 2018
0306-2619/

incorporate an energy storage system (ESS) to smooth the load power [11–14]. Different combinations of ESSs should be considered for different applications [15–18]. Only using one single type of ESS can result in increased size, weight and cost for electric ship operations [19]. With multi-frequency characteristics of the propulsion-load fluctuations, a combination of battery packs and ultra-capacitor modules (B/UC) has been investigated and analyzed [20], where the complementary characteristics of B/UC hybrid energy storage system (HESS) have been exploited with properly coordinated control.

Besides ultra-capacitors and batteries, flywheels have been widely used as uninterruptible power supplies (UPS) [21], and for wind power smoothing [22,23], heavy haul locomotives [24] and frequency response [25]. The importance of flywheels for electrified ships has been mentioned in the Naval Power System Technology Development Roadmap [26]. In [27–29], flywheels were explored to address pulse power loads on the shipboard power network. Compared to batteries and ultra-capacitors (UC), flywheels offer an intermediate choice with respect to energy and power density. Note that the batteries investigated in this paper is lithium-ion batteries, which have higher power and energy densities than other batteries [30]. Flywheels have been enhanced with the development of magnetic bearings, which facilitates high-speed flywheels with significantly reduced the friction losses [31]. In general, flywheels provide a higher power density compared to batteries and a higher energy density compared to ultra-capacitors [32,33]. Furthermore, compared to batteries, flywheels have a long lifetime without capacity degradation, and the ability to operate over a much wider temperature range without performance degradation [31]. Given the considerable benefits of flywheels, we investigate the feasibility of a battery/flywheel (B/FW) HESS to mitigate the effect of propulsion-load fluctuations on the shipboard power network. The B/UC HESS solution proposed in [20] is used as a reference to demonstrate the advantages and limitations of the B/FW HESS solution.

In this paper, the potential of the B/FW HESS in counteracting load fluctuations is formulated as a multi-objective optimization problem (MOP). Two main objectives are power-fluctuation compensation and HESS loss minimization. Since these objectives conflict with each other in the sense that effective compensation of fluctuations will lead to HESS losses, the weighted-sum method is used to convert this MOP into a single-objective problem. Global optimal solutions are obtained using dynamic programming (DP) by exploiting the periodicity of the load. These global optimal solutions form the basis of a comparative study of B/FW and B/UC HESS, where the Pareto fronts of these two technologies at different sea state (SS) conditions are derived. The analysis aims to provide insights into the advantages and limitations of the B/FW HESS solution.

Due to the high computational cost, DP typically cannot be directly used for real-time applications. In order to enable real-time applications, rule-based control approaches abstracted from the optimization results with DP algorithm, have been explored in the literature [17,34,35]. Model predictive control (MPC) is another effective approach for energy management [36]. MPC is able to obtain the optimal solution and deal with constraints. Optimization-based energy management is also recommended in the Naval Power Systems Technology Development Roadmap [26]. Therefore, a MPC-based approach is developed in this paper. For nonlinear optimization problems, a short predictive horizon is preferred for real-time applications. However, the effectiveness of MPC could be limited by a short predictive horizon [17]. To enable real-time application and achieve desired performance, a novel MPC strategy is developed. In this MPC formulation, a state of charge (SOC) reference is used to address the limitations imposed by short predictive horizons.

This paper is built on our previous work presented at the 2017 IEEE American Control Conference [37]. However, this paper provides substantial new results by: (a) taking the battery nonlinear dynamics (SOC vs open circuit voltage) into consideration; (b) developing a dynamic programming algorithm based on a periodic load characteristic to obtain global optimal solutions (Pareto-fronts); (c) analyzing the Pareto-fronts of B/FW and B/UC at different sea states; and (d) evaluating the effectiveness of the proposed MPC strategy compared with the global optimal solutions. The contributions of this paper are summarized in the following:

- A new B/FW HESS configuration is proposed to deal with propulsion-load fluctuations from the shipboard network.
- To our best knowledge, this is the first study to quantitatively analyze the performance of two HESS configurations, namely B/UC and B/FW HESS, in addressing the multi-frequency propulsion-load fluctuation problem for all-electric ships. This study provides insights into the advantages and limitations of each configuration.
- A dynamic programming algorithm based on a periodic load characteristic is developed to reduce the required hardware memory and computational time.
- A novel MPC approach is developed to facilitate real-time implementation of the proposed solution. The proposed approach is validated in a laboratory-scaled experiment.

This paper is organized as follows. The control-oriented ship propulsion model is summarized and dynamic models of battery, flywheel and ultra-capacitor are described in Section 2. In Section 3, the key components of the B/FW and B/UC HESS are sized according to the frequency components of the load fluctuations at nominal sea state. In Section 4, the MOP is formulated and solved, and a comparison study between B/UC and B/FW is performed. In Section 5, an MPC strategy is developed and evaluated to enable real-time implementation. Section 6 concludes the paper.

2. Dynamic model of an electric ship propulsion system with hybrid energy storage

The models presented in this section were developed in [20,37] and will be essential for the performance analysis. The key elements of the model are presented in this section for easy reference, while details can be found in [20].

2.1. Propeller and ship dynamic model

The propeller and ship model captures the dynamic behavior of the propeller and ship motion, including the power and torque fluctuations induced on the motor drive shaft, and determines the power demand (P_{FL}) for the HESS. The mechanical load power transmitted to the ship body from the propeller can be expressed as:

$$P_{Load} = 2\pi nQ, \tag{1}$$

where Q is the propeller torque and n is the rotational speed of the propeller in revolutions-per second. The induction motor is assumed to be directly connected to the propeller (as typically done for all-electric ships), so n is also the rotational speed of the induction motor. The torque generated by the propeller can be expressed as:

$$Q = \mathrm{sgn}(n)\beta K_{Q0}\rho n^2 D^5, \tag{2}$$

where K_{Q0} denotes the torque coefficient when no losses are present, β is the loss factor, which is used to capture the effects of in-and-out water motion of the propeller, ρ is the density of water, and D is the diameter of the propeller. The torque coefficient is determined as follows:

$$K_{Q0} = f_{K_Q}(J, PR, A_e/A_o, Z, R_n), \tag{3}$$

where $J = \frac{V_a}{nD}$ is the advance coefficient with V_a being the ship advance speed, PR is the pitch ratio, A_e/A_0 is the expanded blade-area ratio, Z is the number of blades, and R_n is the Reynolds number. Note that the wake field, defined as , should be taken into account, which includes the average and fluctuation components.

The ship dynamics encompass the response of the ship speed U to