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Optimal design of a hybrid electric propulsive system for an anchor handling tug supply vessel

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HIGHLIGHTS

- Multi-objective optimization is proposed by considering fuel economy, emission and cost.
- Optimal sizing of a hybrid diesel/battery/shore power system is obtained by NSGA-II.
- Performance tests are conducted on a real-time hardware-in-the-loop platform.

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ABSTRACT

Hybrid electric propulsive systems (HEPSs) attract increasing research interest due to their environmental and economic merits. However, the design optimization of HEPSs with the single objective of fuel saving may result in increased greenhouse gas (GHG) emission and high cost. The present study proposes a multi-objective optimization method to obtain an optimal trade-off with respect to fuel consumption, GHG emission, and lifecycle cost. Due to high convergence in solving constrained multi-objective optimization problems, the non-dominated sorting genetic algorithm II (NSGA-II) is developed to explore an optimal design space. Performance tests are conducted on a real-time hardware-in-the-loop (HIL) platform. The hybrid diesel/battery/shore power system on an anchor handling tug supply vessel is considered as a study case. The results of the proposed NSGA-II are compared with those from a single-objective optimization pursuing minimum fuel consumption. The proposed method outputs designs that can significantly reduce GHG emission and lifecycle cost by sacrificing low fuel consumption when compared with that of single objective optimization. Furthermore, the HEPS designed by the proposed method exhibits advantages over the conventional propulsive system in terms of all the three aspects.

1. Introduction

With respect to the challenges of petroleum exhaustion and global warming, international regulations, such as the energy efficiency design index (EEDI) and ship energy efficiency management plan (SEEMP), were enacted to a decrease the growth rate of fuel consumption and greenhouse gas (GHG) emission in the shipping industry [1]. Thus, the requirement of developing energy-efficient and environment-friendly ships resulted in the development of several types of hybrid propulsion and power supply architectures [2–4]. Among them, hybrid electric propulsive systems (HEPSs) attract significant academic interest due to their potential for fuel saving and GHG emission reduction in part load and dynamic load operation, which are commonly required by off-shore vessels such as anchor handling tug supply vessels (AHTSs) [5–8].

Since HEPSs are characterized by two or more power sources that bring an additional degree of freedom that allows for more efficient operation, design optimization is required to clarify the economic and environmental merits of HEPSs [9–11]. However, in previous studies, the optimization was performed only with the goal of fuel saving while GHG emission and lifecycle cost were not considered in the objective function [12,13]. In [12], an optimization approach was proposed to maximize the overall propulsive efficiency of a submarine system. A solution involving the tradeoff between high-speed performance and low-speed performance was determined. In [13], a HEPS was optimized for a medium-size boat by considering the objective of minimum fuel consumption. The simulation results indicated that a HEPS leads to 40% reduction in fuel consumption when compared to that of a conventional propulsive system. However, fuel saving does not necessarily mean low GHG emission and generally requires additional equipment investment that increases cost. Specifically, GHG emission reduction is a major

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reason for the implementation of HEPSs, and the lifecycle cost determines the economic feasibility of the widespread application of HEPSs. Thereafter, it is important to examine a multi-objective optimization design that achieves a compromise with respect to the fuel consumption, GHG emission, and lifecycle cost.

Multi-objective optimization can obtain better designs in terms of comprehensive performance when compared with the single-objective optimization [9,14]. Specifically Lan et al. demonstrated the cost and emission for four cases designed by the three-objective optimal method for a hybrid photovoltaic (PV)/diesel/battery system in a ship [9]. It is observed that the optimization only accounts for the power provided for the non-propulsive load without considering the power for the propulsive load. Optimization with respect to two of the three objectives (i.e., minimization of fuel consumption, GHG emission, and cost) of hybrid urban buses was performed by Ribau et al. by using a vehicle simulation software ADVISOR [14]. The results indicated that the two-objective optimizations exhibit clear advantages over the single-objective optimizations. Nevertheless, a more comprehensive optimization that simultaneously considers fuel consumption, GHG emission, and lifecycle cost was not explored. On the other hand, significant differences are observed between the hybrid vehicles and HEPS vessels. First, long range and durable endurance is essential for HEPS vessels while hybrid vehicles can be refilled, recharged, or conveniently repaired. Furthermore, relatively large non-propulsive power is commonly required in HEPS vessels to drive working devices, such as cranes, radars, and laser weapons, while the auxiliary power requirement of hybrid vehicles is relatively low. Additionally, HEPS vessels typically use multiple gensets or even multiple types of prime movers that are connected to a common power bus and independently controlled while the hybrid vehicles typically use a set of power devices. Finally, in contrast to hybrid vehicles that are likely to stop-and-go frequently, HEPS vessels typically keep sailing in a mode for a long time with a relatively stable power requirement, and it is inefficient to apply regenerative braking technology due to the lack of direct adhesion between the propeller and water [15].

Several algorithms that address the multi-objective optimization problem were examined and recently developed in various applications. The adaptive simulated annealing genetic algorithm (ASAGA) was developed by Hui et al. to develop a bi-objective optimal design for minimal fuel consumption and maximal dynamic performance of a hydraulic hybrid vehicle [16]. The ASAGA aggregates all objectives into a single objective formulation by introducing weighting factors. The disadvantage is that inappropriate weighting factors can deteriorate the performance of the optimization, and thus the selection of the weighting factors is a challenging issue. A Pareto optimal solution set provides an effective method to deal with multi-objective optimal problems as opposed to using the weighting factors. Thus, a family of multi-objective ant colony optimization (MOACO) algorithms was designed by Mora et al. to solve a pathfinding problem for a military unit by considering the objectives of maximum speed and safety [17]. However, the MOACO always involves a long period to reach convergence and tends to be confined to the local optimum solution. Several advanced multi-objective optimizations were examined with the aim of overcoming the disadvantages of the MOACO. For example, a multi-objective particle swarm optimization algorithm (MOPSO) was developed by Borhanazad et al. to optimally design a hybrid micro-grid system involving diesel generators, wind turbines, PV panels, and batteries [18]. A non-dominated sorting genetic algorithm II (NSGA-II) was developed by Ahmadi et al. to design a solar-based multi-generation energy system that is targeted at improving the cost rate and exergy efficiency [19]. A comparison between the MOPSO and NSGA-II was examined by Ghodratnama et al. to solve a multi-objective multi-route flexible flow line problem [20]. Results indicated that the NSGA-II provides better results in terms of space and quality criteria although it provides fewer Pareto solutions. Furthermore, the NSGA-II is insensitive to initial values [21] and is proven as efficient for the sizing of power systems [22]. In order to explore effective design space, both the NSGA-II and MOPSO are developed for optimal design in the present study. Their Pareto solution sets are compared for the convenience of locating the optimal solution.

The present study proposes a multi-objective optimization methodology for the optimal design of HEPSs by considering the comprehensive goal of simultaneously minimizing fuel consumption, GHG emission, and lifecycle cost. Five sizing parameters and two energy management parameters are considered as the optimization variables. The Pareto solution sets calculated from the NSGA-II and MOPSO are compared. The optimal design is selected from the Pareto sets. A 120-ton bollard pull AHTS is considered as a study case. The performance tests are performed on a hardware-in-the-loop (HIL) platform. In order to highlight the advantage and significance of the multi-objective optimization, the results of the multi-objective optimization are compared with those from a single-objective optimization by only focusing on minimum fuel consumption as well as those from the conventional propulsive system.

The contributions of the present study can be summarized as follows.

(1). When compared with the conventional single-objective optimization that only focuses on minimum fuel consumption, multi-objective optimization is proposed for the design of HEPSs by introducing two additional objectives, namely GHG emission and lifecycle cost. Minimum fuel consumption does not necessarily mean low GHG emission and low lifecycle cost, and thus multi-objective optimization can be more significant for industrial applications.
(2). The NSGA-II is developed to explore an effective design space. The Pareto solution set is compared with that from the MOPSO in terms of the space criteria and quality criteria.
(3). A real-time HIL platform is developed to test the performance of HEPSs. The platform is flexible because its program can be modified to fit different configurations and working conditions.

The present study is organized as follows: Section 2 constructs mathematical models for the HEPS. Section 3 describes the energy management strategy. Section 4 presents the optimal algorithm. Section 5 provides the results and discussion. Finally, Section 6 presents the conclusions.

2. Mathematical modeling

In the conventional propulsive system with twin propellers as shown in Fig. 1(a), two diesel engines (propulsive engine) drive two propellers through two gearboxes. Additionally, two gensets are connected to a power bus to provide non-propulsive load including the hotel load and operational load. Comparatively, in the HEPS as shown in Fig. 1(b), two motors drive the two propellers through two gearboxes. The propulsive load (required by the motors) and non-propulsive load are fed by electric power from an integrated power bus. The power bus coordinates the storage and utilization of the electricity from the two gensets, battery pack, and shore power plant based on appropriate energy management strategies. Therefore, the examined HEPS is termed as the hybrid diesel/battery/shore power system. The differences between the HEPS and its conventional benchmark are summarized in Table 1. In order to facilitate design optimization, the modeling of the HEPS is given as follows.

2.1. Diesel engines

The two diesel engines in the examined HEPs are identical. The energy management strategy determines whether or not each of the two engines works. A scalable model is constructed for each engine by using the Willans line method [23,24]. The method defines the break mean