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Optimal Energy Flow Allocation for Hybrid Electric Propulsion System Based on the Dynamic Programming Method

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To evaluate the performance of real-time energy management strategies, we utilize the dynamic programming method to find the optimal energy flow allocation among two engines and batteries for a dual-engine hybrid power system (DHPS). First, the mathematical models of the DHPS are established. Then, the optimization problem, aimed at minimizing fuel consumption, is formulated. Next, the flowchart of the energy management strategy based on dynamic programming is introduced. Finally, the superiority of the proposed method is validated by comparing it with two real-time energy management strategies. The results show that up to 12.79% of fuel consumption is saved.

INTRODUCTION

In the context of high operating costs and global warming, energy conservation and emission reduction have become a focus of concern for shipping companies and the international community (Huang and Duan, 2023). To address this issue, the International Maritime Organization has promulgated increasingly stringent international regulations. The latest strategy for reduction of greenhouse gas (GHG) emissions strives to reach net-zero GHG emissions in 2050, which is 50 years ahead of schedule compared to the initial strategy proposed in 2018 (IMO, 2023). Therefore, it is urgent to improve the energy efficiency level of ships. One effective method recognized by both academia and the industry is the utilization of hybrid power systems (HPSs), especially for ships with complex working conditions, such as the polar mini cruise ship (Inal et al., 2022).

The HPSs contain at least two types of energy. Compared with conventional single-screw propulsion (one engine, one propeller), the operating model of the HPS has higher flexibility under complex navigation conditions. By selecting appropriate operating modes, the efficiency of the HPS can be improved. How to choose the best operating mode is the issue. To address this, energy management strategies (EMSs) have been widely studied by researchers. An EMS can control the allocation of energy flow in the HPS and can be categorized as rule-based or optimization-based. Furthermore, the rule-based EMS can operate with deterministic rules as well as fuzzy rules. An optimization-based EMS can be categorized as local-based optimization or global-based optimization (Yuan et al., 2020). The rule-based EMS depends mainly on expert experience. The most representative one is the charge-depleting and charge-sustaining strategy (CDCS) (Zhu et al., 2018). However, the CDCS strategy relies heavily on expert experience and has poor adaptability under dynamic working conditions. To this end, the current research focus is based on fuzzy rules and optimization-based EMSs, and the CDCS is often used for comparison. For example, an improved fuzzy logic control was studied based on a parallel hybrid ship. The results show that as much as 3.35% of fuel consumption and 14.2% of GHG emissions were reduced compared with the traditional rules (Fan et al., 2024). An adaptive equivalent consumption minimization strategy was employed to enhance the system efficiency and stability based on a hybrid battery and fuel cell power system. The results showed that the proposed method could maintain the fuel cell efficiency at around 60% and obtain a stable output power (Ge et al., 2023). A hierarchical distributed model predictive control method was studied based on a hybrid engine/shaft generator/LNG generator sets/battery propulsion system, and the performance of energy saving, emission reduction, robustness, and real-time was verified by model-in-the-loop and hardware-in-the-loop simulations (Liu et al., 2024). An adaptive moth flame optimization based on multi-populations was proposed to schedule the electric and thermal energy simultaneously, and the economic and environmental benefits were verified by comparison (Xu et al., 2024). The above-mentioned methods illustrate their potential to improve ship energy efficiency compared to the conventional methods. However, the solutions obtained by these methods are not globally optimal in theory.

To better evaluate the control effect of the EMSs, it is necessary to obtain the global optimum of the problem. The global optimum can intuitively reflect the maximum potential for energy efficiency improvement. If the results of the EMS can approach the global optimal solution, the superiority can be further verified. Currently, one of the most commonly used methods to solve the global optimum in the EMS field is the dynamic programming (DP) method. Although the DP method is computationally intensive and can only be applied offline, in theory, it can obtain the optimal solution. For example, the equivalent consumption minimization strategy (ECMS) based on the model predictive control (Zhang et al., 2021), reinforcement learning method (Lee et al., 2020), and adaptive real-time optimal control method (Yao et al., 2021) were all verified by DP. However, these methods are primarily applied in the automotive sector, and there are few reports in the shipping sector. This is because the research on ship EMS is relatively late compared to that of automobiles, and there are no standard working conditions, such as the World Light Vehicle

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