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A cost-effective and emission-aware power management system for ships with integrated full electric propulsion

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ABSTRACT

The extensive exploitation of electric power in ships enables the development of more efficient and environmentally friendlier ships, as it allows for a more flexible ship power system operation and configuration. In this paper, an optimal power management method for ship electric power systems comprising integrated full electric propulsion, energy storage and shore power supply facility is proposed. The proposed optimization method is exploiting an interactive approach based on particle swarm optimization (PSO) method and a fuzzy mechanism to improve the computational efficiency of the algorithm. The proposed fuzzy-based particle swarm optimization (FPSO) algorithm aims at minimizing the operation cost, limiting the greenhouse gas (GHG) emissions and satisfying the technical and operational constraints of the ship.

1. Introduction

The extensive electrification of large ship power systems by exploiting integrated full electric propulsion system (IFEP) is a very promising solution for ship efficiency improvement and GHG emission limitation [1–8]. In such type of ships, the major part of the electric power produced by ship generator sets is consumed by large propulsion electric motors. IFEP is deemed to be a very promising solution for ship designers as it results in increased sustainability and enables conformity with ship energy efficiency directives [9,10]. Moreover, IFEP provides operation flexibility as a large variety of power plant components can be exploited. The capability of integrating several types of electric power generators also enables conformity with ship energy efficiency directives, not attainable by each single type [11]. On the other hand, the optimized operation of a ship electric power system can lead by its own to fuel consumption reduction and energy efficiency improvement [10–12]. Hence, the deployment of innovative and well-designed power management systems for ships with IFEP that will address all the above issues is becoming a pressing necessity. The major targets of the future ship power management systems will be operation cost minimization and GHG emissions limitation. Especially, the limitation of GHG emissions is expected to be a critical issue in near future. These targets combined with the satisfaction of ship operation constraints render the optimal power management in ships a very complex problem. At the same time, demand side management will also play a key role in the optimal operation of shipboard systems. In ships with IFEP, the major part of the produced electric power is supplied to the propulsion system. Hence, demand side management depends highly on the adjustment of the propulsion power and subsequently ship speed. Furthermore, another factor that has not been exploited adequately in ships and can contribute greatly to operation cost minimization is the optimal scheduling of the operation of the electric power generation system. Optimal power generation scheduling combined with demand side management will result in several positive effects in ship design and operation; like the reduction of the number of the prime movers, further fuel cost reduction, efficient limitation of GHG emissions etc. Some other measures that are examined in the related literature to improve ship power system efficiency are listed in the following: energy management and vessel performance [12–29], route optimization and voyage efficiency [22,23], slow-steaming (reduction of ship cruising speed) [28], effective demand side/load management [11,18,19,23], means of smart electric energy generation [16,25], cold ironing [17,22], and electric energy saving devices and energy storage systems (ESS) [19,20,23].

This paper deals with all issues listed above. A method for optimal power management and GHG emissions limitation suitable for ships employing IFEP, ESS and cold ironing facility is proposed.

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The target is to optimize the power generation/storage and the ship speed within ship travel time period. This is achieved by optimally adjusting ship speed and producing power with the lowest possible cost by using optimal generator commitment scheduling. The achievement of these goals is subject to several technical and operational constraints; like power balance, generators' loading, generators' ramp rates and minimum up/down times, ship speed limits, total route length, constraints stemming from calls at intermediate ports, etc. It should be noted at this point, that demand side management and power generation scheduling problems are mutually coupled. Moreover, the optimization objectives are antagonistic. Thus, the problem under examination requires sophisticated solution methods that would be able to tackle with the above challenges. In this regard, an interactive approach based on particle swarm optimization (PSO) method enhanced by a fuzzy mechanism that improves the computational efficiency of the algorithm, is proposed. The algorithm is capable of solving the examined problem in one step while the number of the decision variables is independent of the complexity of the power generation system. The efficiency of the examined method is demonstrated through detailed case studies and compared with that of the dynamic programming method. As a whole, the main contributions of this paper can be summarized as follows:

- Coordinated system-level power generation and demand side management for operation cost minimization and GHG emission limitation,
- Optimal exploitation of energy storage systems and shore-side power supply facilities,
- Design and application of an interactive optimization algorithm based on PSO and fuzzy rule-based approach to improve the computational efficiency.

It is noted that the available relative research in the topic is very limited. Moreover, the existing power management methods for shipboard power systems with IFEP are based mainly on the exploitation of classical optimization techniques that are not able to handle the increased complexity of the system and the multiple antagonistic goals described above. For instance, optimization methods based on dynamic programming [23] are able to provide solution with realistic computation facilities only if the examined problem is divided in two optimization sub-problems.

The rest of this paper is organized as follows: Section 2 deals with the ship energy efficiency assessment. Section 3 introduces the configuration of a ship power system with IFEP and ship power management concept. The mathematical model and formulation of the optimization problem for the examined system is presented in Section 4. The implementation of the proposed optimization method with a Fuzzy-PSO approach is discussed in Section 5. The evaluation of the method for several typical operation scenarios is performed in Section 6 while Section 7 concludes the paper and discusses future works.

2. Ship energy efficiency assessment

According to the International Maritime Organization (IMO) policy, ship operation efficiency indicator (*SOEI*) is defined as the ratio of the produced CO_2 mass (m_{CO_2}) per unit of transport work (TW) [9,10].

$$SOEI = m_{CO_2}/TW \tag{1}$$

So far, ship energy efficiency management plans are focused only on CO_2 emissions and this has been also adopted in this paper. However, the formulation of the problem can be easily generalized by including any other pollutant gas. In this paper, *SOEI* can be slightly modified to facilitate the optimization procedure if it is referred to an arbitrary observation time interval ΔT_j. When ship is in the open sea, *SOEI* can be defined as follows:

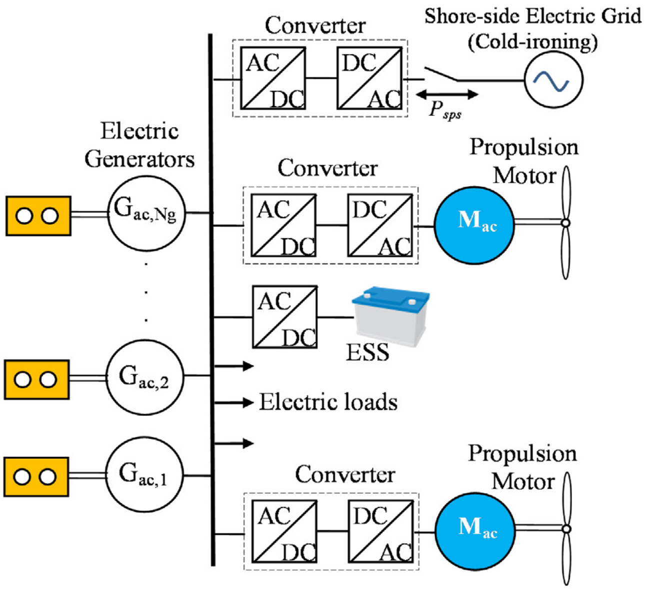

Fig. 1. Generic single-line electric diagram of ship power system with IFEP.

$$SOEI_{1,j} = \left(\varphi \cdot V_j \cdot \Delta T_j\right)^{-1} m_{CO_2} = \left(\varphi \cdot V_j\right)^{-1} \sum_i \sigma_i \cdot P_{ij} \cdot H_i(P_{ij}) \tag{2}$$

where φ is ship loading factor (tns), V_j is ship speed (kn) in the j-th time interval, H_i is the specific fuel consumption (gFuel/kW h) of the i-th power unit, P_{ij} is the power produced by i-th power unit in the j-th time interval ΔT_j and σ_i is a factor used to convert the fuel consumed by the i-th generator to CO_2 mass (gCO_2/gFuel).

When the ship is in port, its speed is zero and previous definition of *SOEI* should be modified as follows:

$$SOEI_{2,j} = \left(\varphi \cdot \Delta T_j\right)^{-1} m_{CO_2} = \frac{1}{\varphi} \sum_i \sigma_i \cdot P_{ij} \cdot H_i(P_{ij}) \tag{3}$$

Ship loading factor φ depends on the type of the examined ship, e.g. passenger ship, RO-PAX ferry, etc. In this study, φ is applied to a RO-PAX ferry and it is calculated as:

$$\varphi = \left(\frac{APL}{NPL}\right) FLD = \left(\frac{0.1 \times NP + NV}{0.1 \times NP_{\max} + NV_{\max}}\right) FLD \tag{4}$$

where *APL* and *NPL* are the actual and the nominal payloads respectively, *NP* is the number of the passengers, NP_{max} is the maximum number of passengers, *NV* is the number of the carried vehicles, NV_{max} is the maximum number of the carried vehicles and *FLD* is the full load displacement of the ship (tns).

In the near future, the limitation of *SOEI* will be one of the major targets of ship power management systems. The optimal adjustment of ship speed according to ship electric load variation could lead to efficiency improvement and *SOEI* limitation. This is a further measure proposed in this paper. However, ship speed adjustment is subject to several limitations like, ship speed limits, total route length constraint, traveled distance at intermediate port calls etc.

3. Ship power system configuration and ship power management concept

The generic single-line electrical diagram of ship power systems with IFEP is shown in Fig. 1. In this concept, it is assumed that there exists a main bus/switchboard (SWBD) where all electric generators are connected to. Each generating unit has its own fuel cost