Applied Energy 228 (2018) 254–264

Contents lists available at ScienceDirect

Applied Energy

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

A novel optimal energy-management strategy for a maritime hybrid energy system based on large-scale global optimization

Ruoli Tang[a,*], Xin Li[a], Jingang Lai[b,c]

[a] School of Energy and Power Engineering, Wuhan University of Technology, Wuhan, China
[b] School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan, China
[c] School of Engineering, RMIT University, Melbourne, Australia

HIGHLIGHTS

- Large-scale global optimization based energy management model for maritime hybrid energy system.
- Penalty functions for satisfying the constraints in optimal energy management.
- Swarm-intelligence-based optimal power flow dispatching strategy.

ARTICLE INFO

Keywords:
Solar energy
Hybrid energy system
Green ship
Intelligent ship
Energy management

ABSTRACT

In the hybrid energy system of large green ships, different types of energy sources are employed to feed the electricity demand. An optimal energy-management model and control methodology must be developed to obtain operational safety and efficiency. In this study, optimal power-flow dispatching of maritime photovoltaic/battery/diesel/cold-ironing hybrid energy systems is proposed to sufficiently explore solar energy and minimize the ship's electricity cost. By modelling the constraints (such as power balance, solar output, diesel output, battery capacity, and regulations from the port) as penalty functions, the optimal energy-management is described as an unconstrained, large-scale, global optimization problem, which can be effectively solved by the proposed adaptive multi-context cooperatively coevolving particle swarm optimization algorithm. The proposed approach is verified by simulation for different cases. Results of the simulation show that the optimal energy-management of the evaluated system can be obtained with great electricity cost savings and robust control performance.

1. Introduction

Due to the worldwide energy crisis and environmental pollution, many green-energy techniques for maritime applications must be developed for exploring clean energy instead of fossil fuel. Cold-ironing is the use of electric power from the shore to feed the ship's load when at-anchor in port or anchorage. As the emission from ships is a significant contributor to poor the port's local air quality, the regulations for restricting the use of on-board diesel are becoming more and more strict to protect the local environment. For example, starting in 2014, the California Air Resources Board required that at least 50% of a fleet's visits to major California ports use either cold-ironing for most of their time in port or reduce the use of on-board diesels by at least 50% compared to an historical baseline [1].

In addition to cold-ironing, the solar energy system is also widely installed in large ocean-going ships to reduce the burning of fuel oil. As a result, the ship's electric loads are always fed by the maritime hybrid energy system (MHES) [2–9], which contains the photovoltaic arrays (PV), battery banks, cold-ironing, and on-board diesel generators [1,10–12]. To achieve the optimal energy-management of MHES, an efficient power-flow dispatching methodology of each distributed energy source is required for minimizing the ship's electricity cost. In the existing studies, power-flow dispatching is always described as a linear or quadratic programming problem. However, the accurate non-linear models of energy sources like the battery bank and diesel generator cannot be directly used.

This study presents a novel, large-scale global optimization (LSGO)-based approach for obtaining the optimal energy-management of MHES. The swarm-intelligence-based models of each energy source in MHES are studied. The optimal power-flow dispatching of MHES is then

* Corresponding author.
E-mail address: ruolitang@hotmail.com (R. Tang).

https://doi.org/10.1016/j.apenergy.2018.06.092
Received 22 March 2018; Received in revised form 16 June 2018; Accepted 19 June 2018

modelled as an LSGO problem, in which all the constraints are described as penalty functions, including the power balance, solar output, diesel output, battery capacity, and regulations from the port. Finally, the adaptive multi-context cooperatively coevolving particle swarm optimization algorithm (AM-CCPSO) from our previous work is employed to solve the LSGO problem, and state-of-the-art swarm-intelligent algorithms are also employed for comparison [13].

The remainder of this study is organized as follows. In Section 2, the literature review is conducted on hybrid energy ships and power-flow dispatching strategies of the hybrid energy system (HES). Then, the sub-models of distributed power sources, including PV arrays, battery banks, on-board diesel, and the cold-ironing are studied in Section 3. In Section 4, the LSGO-based dispatching model with penalty functions is studied. Section 5 describes the power-flow dispatching methodologies based on the AM-CCPSO algorithm. The simulations and detailed analysis are conducted in Section 6. Finally, this study is concluded in Section 7.

2. Related works

In recent years, the MHES with different distributed energy sources like the PV array, battery bank, flywheel, on-board diesel generator, and cold-ironing are widely installed on ships to supply electric power [14–16]. Due to the special working environment on a ship, the design and control of MHES significantly differs from the land-based system. As a result, there are many open research issues with respect to the operational safety and efficiency of MHES.

For the use of the on-board PV system, existing studies mainly focused on the design, control, and optimal operation of the power-generation and energy-storage systems. Hou et al. proposed a combined battery and flywheel hybrid-energy storage system as a buffer to mitigate the load fluctuations of an all-electric ship. The power-fluctuation compensation and energy savings under various operating constraints were then formulated and effectively solved as a multi-objective optimization problem [2]. Liu et al. proposed an approach to model and estimate the output of a ship's PV system, considering the environmental influence when moving and rocking with the ship [3]. Wen et al. investigated the characteristics of a PV system on a moving ship by experiments, and proposed an interval optimization method for determining the optimal sizing of an on-board energy-storage system to reduce the fuel cost, capital cost, and emission of greenhouse gases [5]. Lan et al. proposed an approach for determining the optimal sizing of the on-board PV system, diesel generator and energy-storage system in a stand-alone ship power system that minimized the investment cost, fuel cost, and CO_2 emissions [7]. Tang et al. studied a novel configuration of the large-scale PV array of a ship, and the swarm-intelligence-based maximum power point tracking approach was also proposed [6,8]. Lee et al. proposed a hybrid photovoltaic/diesel ship, in which the distributed power system can be connected to the smart grid and micro-grid [9]. Visa et al. designed a solar energy conversion system on ships by considering the variation of latitude when traveling [17]. Gorter et al. evaluated 15 types of polymers to find more suitable material for use as a replacement of glass in PV modules of PV-powered boats [18].

For the use of cold-ironing from the shore, Zis et al. presented a methodology to evaluate the cold-ironing and speed-reduction policies to reduce ship emissions near and at ports [10]. Cannon et al. presented the measures adopted by the Port of Los Angeles and the Shanghai Municipal Transportation Commission for reducing the air emissions at both ports: to institute and expand the use of cold-ironing on ocean-going ships while at berth [11]. Vaishnav et al. analyzed the benefits and costs of using cold-ironing based on the historical ship call data in US ports [1]. According to their study, an air quality benefit of $70–150 million per year could be achieved by retrofitting 1/4–2/3 of all vessels that call at U.S. ports. Hou presented a droop control strategy to improve the frequency stability of shore power systems [12].

The configurations, criteria selection, sizing methodologies, and control and energy-management for the design and implementation of HES were comprehensively reviewed in [19]. For the optimal energy-management of grid-connected and stand-alone HESs, different approaches are organized into the following three categories: centralized [20,21], distributed [22], and hybrid control paradigms [23]. For the grid-connected application, Wu et al. proposed an MPC-based, closed-loop control approach for PV-battery HES management on the demand side [24]. Majidi et al. established a multi-objective model for the optimal operation of the battery/PV/fuel cell/grid HES, and the optimization problem was then solved by the fuzzy control approach [25]. Chen et al. established a simplified single-objective optimization problem considering the storage management, economic load dispatch, and operation optimization of distributed generations [26]. Kim et al. proposed a dynamic supervisory control to regulate a grid-connected PV/wind HES [27]. Wang et al. developed an energy-management strategy of HES from both the demand and utility sides to meet the electricity demand while minimizing the overall operating and environmental costs [28]. For the stand-alone application, Wang et al. proposed an AC-linked hybrid wind/PV/fuel cell alternative energy system, in which the wind and PV are the primary power sources and the FC-electrolyzer combination is used as the backup [29]. Morais et al. proposed a renewable micro-grid, including a wind turbine, PV panel, fuel cell, and storage battery. The optimal scheduling of the evaluated system was also studied by implementing mixed-integer linear programming in general algebraic modelling systems [30]. In addition, the control of the islanded micro-grid is also a popular research topic [31–33].

3. Swarm-intelligence-based sub-models of maritime hybrid energy systems

When a PV system is installed on a ship, the battery banks with a certain capacity are also required to store the redundant PV output. Therefore, when a PV/battery ship is under-sail, the MHES consists of the PV array, battery bank, and on-board diesel. The PV output is often maximized in real time and directly feeds the ship's electric load demand, and the surplus PV power is used to charge the batteries. If the ship's load cannot be satisfied by the PV output, then the deficient power will be compensated for by the battery bank or on-board diesel. The battery bank can be charged by the surplus PV power or on-board diesel, and then discharged to feed the ship's load. The schematic of the above MHES is shown in Fig. 1(a), in which arrows denote the directional power flows. P_1 and P_2 represent the PV output for charging the battery bank and feeding the ship's load. P_3 represents the battery discharging power for feeding the ship's load. P_4 and P_5 represent the output of the on-board diesel to charge the battery bank and feed the ship's load. However, when the PV/battery ship is at-anchor in port or anchorage and the cold-ironing service is enforced, the cold-ironing must be considered in the aforementioned power-flow dispatching. In this case, the MHES consists of the PV array, battery bank, on-board diesel, and the cold-ironing. The schematic is shown in Fig. 1(b), in which P_6 and P_7 represent the power-flows from cold-ironing for charging the battery bank and feeding the ship's load, respectively.

3.1. On-board PV array

As an unstable power supplier, the output of a PV panel is easily affected by the environmental conditions [34,35]. A widely used analytical model of silicon solar cells in engineering applications is shown in Eqs. (1) and (2) [36].