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Optimal sizing of hybrid PV/diesel/battery in ship power system ☆

Hai Lan [a], Shuli Wen [a,*], Ying-Yi Hong [b], David C. Yu [c], Lijun Zhang [a]

[a] College of Automation, Harbin Engineering University, Harbin 150001, China
[b] Department of Electrical Engineering, Chung Yuan Christian University, Chung Li District 320, Taoyuan City, Taiwan
[c] Department of Electrical Engineering and Computer Science, University of Wisconsin-Milwaukee, Milwaukee 53211, USA

HIGHLIGHTS

- An optimal sizing method is developed for a hybrid PV/diesel/ESS ship power system.
- The output of PV along a navigation route is explored for the ship power system.
- Five operating conditions of the load in the ship power system are modeled.
- The impact of various prices of PV on cost is studied.

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ABSTRACT

Owing to the strict restrictions imposed by the Marine Pollution Protocol and the rapid development of renewable energy, the use of solar generation and energy storage systems in ship power systems has been increasingly attracting attention. However, the improper sizing of a hybrid power generation system in a ship power system will result in a high investment cost and increased greenhouse gas emission. This paper proposes a method for determining the optimal size of the photovoltaic (PV) generation system, the diesel generator and the energy storage system in a stand-alone ship power system that minimizes the investment cost, fuel cost and the CO_2 emissions. The power generation from PV modules on a ship relies on the date, local time, time zone, longitude and latitude along a navigation route and is different from the conditions of power systems on land. Thus, a method, which takes the seasonal and geographical variation of solar irradiations and temperatures along the route from Dalian in China to Aden in Yemen into account, for correcting the output of PV modules is developed in this paper. The proposed method considers five conditions along the navigation route to model the total ship load. Four cases are studied in details to demonstrate the applicability of the proposed algorithm.

1. Introduction

As the amount of greenhouse gas that is produced by the ship systems increases, the International Convention for the Prevention of Pollution from Ships (MARPOL) [1] recently has made the claim that the ships must find a new way to reduce their collective emissions of greenhouse gas. Serious environmental pollution and the low energy efficiency of traditional ship systems whose power is supplied only by diesel generators can be mitigated by properly integrating renewable energy. Recently, photovoltaic (PV) energy has been introduced into ship power systems to reduce their greenhouse gas emissions, improve energy efficiency and reinforce the ship power system stability. However, the use of too much solar energy may increase investment cost and make the power system unstable owing to the uncertainty associated with solar power [2,3]. Additionally, a wide range of investigations [4–9] have found that the use of an energy storage system (ESS) is one of the most effective solutions for ensuring the reliability and power quality of power systems and favors the increased penetration of distributed generation resources. Some studies [10,11] have demonstrated that an optimal management of ESS with distributed generators in power systems can shave the peak load, decrease the cost of updating the power system and reduce negative impact on the environment.

A ship power system with PV and ESS can be regarded as a special mobile and islanded microgrid. Previous studies have

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* Corresponding author.
E-mail address: wenshuli2010@126.com (S. Wen).

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investigated hybrid power arrangements on ships [12–14]. A lithium-ion battery in conjunction with diesel generations has been explored for ship crane operations in [14]. To maximize fuel savings, battery storage systems have been utilized in converting the bulk carriers to all-electric ships in [15]. Other works have elucidated various control strategies to prolong the battery life and reduce fuel consumption [13,16,17].

Many works related to hybrid PV/diesel systems in electrical power systems with ESS on land have been published in [18–24]. In particular, the economic and environmental merits of a hybrid PV/diesel system with flywheel energy storage have been analyzed in [22]. An optimal design for a standalone wind/PV/diesel hybrid system under uncertainties of renewable energy has been proposed to minimize the levelized cost of energy and maximize reliability [23]. An optimal unit sizing method for a stand-alone microgrid has also been proposed [24].

To the best of the authors' knowledge, the hybrid PV/diesel/battery ship power system has not been extensively discussed [25–27]. In [25], the PV system applied to merchant marine vessels has been discussed to reduce the fuel cost. A stability assessment and economic analysis of a hybrid PV/diesel ship system has been studied in [26]. The authors in [27] have proposed a preliminary analysis to reduce the emission of electrical ship at berth. In addition, the integration of a significant amount of PV power into a ship power system to reduce CO_2 emission is challenging. The PV power generation in a ship power system depends on its position in the ocean. Previous studies [28–34] on the use of PV systems have considered the date, local time, time zone, longitude and latitude to formulate the power generated by PV on a moving shipboard. In [28], the optimal sizing of hybrid PV/battery/diesel power system was proposed, taking into account various tilt angles of PV panels. Owing to the strong dependency of the performance and rating of a solar-based system on climatic conditions [29], parameters such as date, local time, longitude and latitude were considered and corrections for the output of PV modules were made for different locations. The authors in [30] have proposed the optimal design for hybrid PV/wind system which considered various environmental conditions. Particle swarm optimization was used in [31] to optimize a hybrid system that included PV panels, wind turbine, diesel generator, batteries, fuel cell, electrolyzer, and hydrogen tank. A detailed PV system model has been established and optimized in [32,33], which took actual environmental conditions and uncertain operating situations into consideration. A method has been developed in [34] to estimate the global tilted irradiance which considered temperature and solar spectrum distribution.

This paper presents a novel method for optimally sizing a hybrid PV/diesel/ESS in a standalone ship power system for a typical navigation route from Dalian in China to Aden in Yemen. Specifically, this work proposes an approach to generating power from PV arrays on the shipboard along that route. Variations of the load under five conditions are modeled; these are regular cruising, full-speed sailing, docking, loading/unloading and anchoring. For economic analysis, Multi-Objective Particle Swarm Optimization (MOPSO) is used to determine the optimal sizes of various sources of power and to minimize CO_2 emissions.

The rest of this paper is organized as follows: Section 2 models the hybrid ship power system. Section 3 formulates the problem. Section 4 proposes solution method. Section 5 describes four case studies to verify the proposed algorithm and Section 6 draws conclusions.

2. Mathematical model of hybrid ship power system

2.1. Difference between standalone power systems on land and hybrid ship power systems

The studied problem related to the generation expansion planning in ship power systems differs considerably from that in standalone power systems on land. The details are described as follows.

(1) The standalone power system on land is still; however, a ship power system usually operates in a mobile mode.
(2) The PV array receives fixed irradiations in the standalone power system on land. The irradiation on a sailing ship changes continuously even though the magnitude of solar radiation is fixed. That's, the irradiation in the ship power system also relies on the longitude and latitude, in addition to the date and time.
(3) The load changes continuously in the standalone power system on land. However, the total load varies with some operating conditions (regular cruising, full-speed sailing, docking, load/unloading and anchoring) in a ship. Please note that the steam engine of an oil tanker ship is used to drive ship propellers, which are independent from the oil tanker ship power system.
(4) The angle of incidence on the PV array in the standalone power system on land is fixed at a moment; however, fluctuations of the ship result in changes of angle of incidence.
(5) The crashing of sea water onto the deck in a ship power system has impacts on the efficiency of PV modules. This phenomenon does not occur in the PV module on land.
(6) It is not necessary to ensure that loss of load probability (LOLP) is zero in the standalone power system on land; however, the LOLP in a ship power system must be zero.

To simplify the studies, the above descriptions (4) and (5) will not be addressed in this work.

2.2. Problem description

The focus of this work is to optimize the size of a hybrid PV/diesel/ESS system in a ship power system which is based on the project named "Study on the Application of Photovoltaic Technology in the Oil Tanker Ship" in China [35]. The detailed parameters of this oil tanker are that the length, width, and height are 332.95 m, 60 m and 30.5 m, respectively. The total area for PV array installation is 2000 m^2. The deadweight of this oil tanker is 100,000 tons.

This study analyzes the cost and emissions of a hybrid PV/diesel/ESS power system in an oil tanker ship which is presented in Fig. 1. The system consists of a generating PV array, a diesel generator to supply the main power and an ESS to store excess energy and improve the reliability of the system. The diesel generator must be able to supply the whole load all the time since the ship's power system always operates in stand-alone mode.

Navigating the ship route in Fig. 2 from Dalian in China to Aden in Yemen takes 20 days. The oil tanker sails four times annually. Specifically, the ship sets sail at 8:00 am on January 1st, April 1st, July 1st and October 1st separately from Dalian and returns on January 25th, April 25th, July 25th and October 25th respectively from Aden. Consequently, the optimization involves 3840 h in a year and the irradiation, temperature and the load profile are sampled every hour. The impacts of fluctuations of the ship and the crashing of sea water onto the deck on PV arrays are not taken into account.