Energy 165 (2018) 965–978

Contents lists available at ScienceDirect

Energy

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

A design and experimental investigation of a large-scale solar energy/diesel generator powered hybrid ship

Yupeng Yuan [a, b, d, *], Jixiang Wang [a, d], Xinping Yan [a, d], Qing Li [a, c], Teng Long [b]

[a] Reliability Engineering Institute, School of Energy and Power Engineering, Wuhan University of Technology, Wuhan Hubei, 430063, China
[b] Department of Engineering, University of Cambridge, Cambridge, CB3 0FA, UK
[c] China Waterborne Transport Research Institute, Beijing, 100088, China
[d] National Engineering Research Center for Water Transport Safety, Wuhan University of Technology, Wuhan Hubei, 430063, China

ARTICLE INFO

Article history:
Received 7 June 2018
Received in revised form
3 August 2018
Accepted 12 September 2018

Keywords:
Solar energy
Hybrid powered ship
Grid-tied/stand-alone
Energy conservation and emission reduction

ABSTRACT

Due to the increasing demand for energy conservation and the reduction of emissions, renewable energy applications for ships have attracted a great deal of attention. In this paper, a 5000-vehicle space pure car and truck carrier (PCTC) is selected as the research object. Then, on the basis of the existing power system, a unified grid-tied/stand-alone solar system is designed with a built-in battery energy storage system. The system includes a solar energy generation unit, a battery storage system, a diesel generating set, grid-tied/stand-alone controlled inverters, a battery management system (BMS) and an energy management system. According to an analysis of the experimental data, it can be concluded that the use of solar energy hybrid power, in theory, can reduce fuel consumption by 4.02% and carbon dioxide (CO_2) emissions by 8.55% a year.

1. Introduction

Energy shortages, environmental pollution, and global warming are common challenges faced by the global energy community today. The fossil fuel energy systems established in the 20th century are unsuitable for the efficiency, economic, and safety demands of today's society. According to a forecast of the International Energy Agency, the annual global energy demand will increase from 12 billion tons of oil equivalent in 2009, to 17–18 billion tons of oil equivalent in 2035. Moreover, if the current emissions policy is maintained, emissions will increase from 29 billion tons in 2009 to 43 billion tons in 2035; furthermore, even taking into account the new regulations, emissions will rise to 36 billion tons [1].

Whilst it is an important part of intercontinental communication and economic activity, the shipping industry causes a much higher emission of pollutants than the aviation industry. Additionally, the energy consumption of ships is quite significant and problems such as the exhausting of resources and oil leakages are also severely threatening the environment. Accordingly, the emission requirements for coastal ships, or those sailing on inland lakes, are more stringent [2]. The results of the Greenhouse Gas (GHG) study completed by the International Maritime Organization (IMO) in 2009 showed that in 2007, the global shipping industry's CO_2 emissions were approximately 1.046 billion tons, accounting for 3.3% of the total global carbon dioxide emissions. Moreover, if no restrictions were imposed, by 2050, the CO_2 emissions from the shipping industry would increase by 150%–250%, accounting for between 12% and 18% of the global allowable carbon dioxide emissions [3]. The latest report of the International Energy Agency in October 2017 stated that the current total global carbon dioxide emissions are 800 million tons and, according to the IMO, this number will double by 2060. In order to deal with the stringent demands of the regulations relating to ships' emissions, all major shipping nations in the world have adopted “green ships”, as these are seen as the future of the shipping industry [4].

Against this background, all countries in the world, including China, are faced with the problem of the structural reform of energy. The development and utilization of clean energy, such as solar energy, wind energy, hydropower, hydrogen energy and liquefied natural gas (LNG), is an effective way of conserving energy and reducing the emissions of ships [5–7]. These clean energy sources,

* Corresponding author. Reliability Engineering Institute, School of Energy and Power Engineering, Wuhan University of Technology, Wuhan Hubei, 430063, China.
E-mail addresses: yy440@cam.ac.uk, ypyuan@whut.edu.cn (Y. Yuan).

https://doi.org/10.1016/j.energy.2018.09.085
0360-5442/

which do not pollute the environment, are increasingly becoming more widely appreciated. Inexhaustible solar energy is a good example of a renewable energy source and in the post-fossil fuel era, it will become one of the most important natural energy sources [8]. To date, solar energy has been widely used on land [9–12]; however, research and development regarding its use as a power source for transport, particularly in water transportation, has been slower to progress. If solar power can be used to provide electricity for ships, or as a propulsion system to replace traditional diesel power, it can greatly reduce both a ship's energy consumption and emissions [13].

However, due to the limitations of solar energy conversion efficiency for ships that have relatively large power requirements and a limited installation area for solar panels, solar energy often needs to be combined with a diesel engine or other energy sources to act as a hybrid power system [14,15]. In recent years, researchers around the world have conducted a large number of studies on the design of solar photovoltaic (PV) systems. For example, literature [16] proposed a method of using solar energy and ocean thermal energy as a means of propulsion for ships, and provided a detailed design proposal. Moreover, Zhu Y et al. [17] studied the factors affecting the power generation of solar PV systems for newly constructed ships, and concluded that ships using solar energy as an auxiliary power, at a latitude of 31.9° north, can achieve a reduction in fuel consumption and emissions that meets the requirements of the energy efficiency design index (EEDI). Atodiresei D et al. [18] analyzed the economics of using solar PV systems in commercial ships on the northwest route of the Black Sea Basin. Their results show that at different latitudes and climatic conditions, more energy can be generated by adjusting the optimal angle of the solar panel. Liu H [19] proposed a marine hybrid power system consisting of a diesel generator, solar energy, a battery, and a super capacitor, and established a mathematical model of solar power generation under ocean conditions. Accordingly, the fluctuation characteristics of the solar output power and the optimal capacity of the supercapacitor were analyzed. Although the ship used as the research object was large with a displacement of 5878.8t, the capacity for installing a solar energy system was very small, with only a PV panel area of 1.25 m^2. Salem A A et al. [20] proposed a scheme for the installation of marine grid-connected solar power systems, and analyzed their economical and emission characteristics. The authors then used a case study, where the object boat was 43.1 m in length and the power of the solar energy system was 260 W, to prove that the proposed power system solution could achieve the dual goal of energy conservation and the reduction of emissions. Atkinson G M [21] used a high-speed passenger ship with a deadweight of 2775 t as the research object and designed a solar energy PV system with a peak power of 2.32 kWp and a battery energy storage system with a capacity of 5.4 kWh. Their test results showed that there was a 28% loss in the performance ratio of the system and further testing and evaluation were required. Wen S and Lan H et al. [22,23] proposed a PV/diesel/energy storage system (ESS) ship's power system, which used an interval optimization algorithm and particle swarm optimization algorithm to ascertain the optimal size of a hybrid power system. Japan's Kokusho T [24] proposed a Sailing Solar-Cell Raft Project, which was supposed to develop a large wind-sailing solar cell raft that could produce 8 $kwh/m^2/day$ of solar energy when the weather was good. Finally, Kyoung-Jun Lee et al. [25] designed a solar PV system using the stand-alone mode and used a cruise ship, whose displacement was 1.154 t, as the research object. The maximum peak power of the solar energy was calculated to be 3.2 kW.

Most of the above-mentioned hybrid systems were based on boats, while designs and applications that are based on large scale vessels are rare. Even in a small number of cases when there were designs for large ships, the related solar and battery capacities were relatively small. In addition, the results relating to energy conservation and the reduction of emissions were only based on theoretical analysis and simulation, and any experimental verification was usually lacking.

Against this background, in 2013, the Wuhan University of Technology undertook a high-tech marine scientific research project on behalf of the Ministry of Industry and Information Technology. A unified grid-tied/stand-alone integrated solar PV system, with a peak power of 143 kW, was designed, which had a built-in 652.8 kWh lithium ion battery storage system. In March 2014, it was installed in an actual 5000-vehicle space PCTC, the "COSCO Tengfei", and put into operation. This ship was the world's first large-scale cargo ship to use solar energy, and it also has the world's largest solar installation area. Although the "COSCO Tengfei" has been in operation since March 2014, the PV system and energy storage system on board are still in a good condition and to date, no failures have occurred.

The main contribution of this paper is the design of a hybrid power system consisting of solar energy, diesel generators, batteries, inverters, a battery management system (BMS), and energy management system (EMS), based on the existing power system of the "COSCO Tengfei". The energy saving and emission reduction effect of the solar PV system is verified through an experimental test on the actual ship. The proposed hybrid system will hopefully provide guidance for the future design of solar ships. It also will lead to the conservation of energy and environmental protection. In addition, the solar hybrid power system design scheme in this paper has broad application prospects for various types of energy storage power plants, small and medium-sized PV grid-connected power stations and microgrids.

The paper is organized as follows. Section 2 introduces the parameters of the research object, and discusses the configuration and operation modes of the solar hybrid system. Section 3 discusses the experimental results of tests conducted on the solar ship. Section 4 analyzes the energy-saving and emission reduction effects of the solar energy system. Conclusions are drawn in Section 5.

2. A design for the solar/diesel hybrid power system

The "COSCO Tengfei" is a ship belonging to COSCO Shipping Co., Ltd. It is an ocean-going ship built in 2011, which has parking spaces for 5000 vehicles. The ship is classified in the China Ships Classification Society and flies the flag of Panama, as shown in Fig. 1.

The ship has a total length of 182.80 m, a profile width of 32.20 m, a depth of 14.95 m, a design draught of 8.40 m, a structural draught of 9.40 m, a design speed of 20.20 kn, and a cruising range of 20,000 nautical miles. The technical parameters of the ship are listed in Table 1.

Based on the parameters of the "COSCO Tengfei" and the original power configuration, a hybrid solar energy system was designed, as shown in Fig. 2. The system consists of solar panels, PV controllers, on/off-grid inverters, lithium-ion battery packs, a BMS, diesel generator sets, transformers, and power distribution cabinets. The parameters of the system's main components are shown in Table 2. The system's operation mode can be set by the user to four different modes using a manual selection switch. These modes are now outlined.

1. The off-grid operation mode. PV modules charge the battery through the PV controller. The off-grid mode directly converts the PV and battery's direct current (DC) voltage to a 450 V alternating current (AC) voltage. Then the AC voltage is stepped down using a three-phase transformer, and directly supplied to the lights.