Solar Energy 170 (2018) 991–1000

Contents lists available at ScienceDirect

Solar Energy

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

Tariff-driven demand side management of green ship

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ARTICLE INFO

Keywords:
Green ship
Demand side management
Economic load dispatching
Receding horizon control

ABSTRACT

Green ships with hybrid renewable energy systems become important resources of demand side management, when ships in port have the grid connection. Variance of electricity tariff has influenced the optimal solutions to power management. Current power management methods for stand-alone green ships cannot be applied to this new situation. To enable tariff-driven power management, a unified model is proposed for a green ship under different time-of-use (TOU) tariffs. In the proposed model, diesel generation, solar energy, and battery storage could support auxiliary power demand, and the surplus of solar energy could be sold to grid when the ship is connected to grid. A power flow dispatching problem is then formulated as the optimization of operational cost. To cope with variance of tariff, solar energy, and on-board load demand, a receding horizon control approach is employed to ensure a closed-loop control mechanism. Experimental results indicate the tariff-driven model can effectively reduce the overall cost of green ships, and the receding horizon control can improve the performance in terms of fuel consumption and greenhouse gas emission.

1. Introduction

Over 90% of cargoes are transported by ships over the world, while greenhouse gas (GHG) emission and fossil fuel consumption are two critical problems in the shipping industry. In 2007, international shipping is responsible for approximately 3% global GHG emission, and 277 million tons of diesel/gasoline, in which the dry bulk shipping is the first contributor with about 52 million tons (Buhaug et al., 2009). To suppress the continuous increase of GHG emission and fossil fuel demand in the international shipping, international maritime organization (IMO) has issued strict regulations for shipping energy efficiency and GHG emission. Therefore, green ship technologies become urgent to improve shipping energy efficiency and reduce GHG emission. One of the most popular technology is to find clean energy to take the place of fossil fuel (Diab et al., 2016). Renewable energy (RE) resources have played increasingly significant roles to reduce fuel consumption and GHG emission in the green ship. Among available RE resources, solar energy is the most promising option of green ship, as solar is clean, safe, omnipresent, and freely available.

In general, photovoltaic (PV) panels have to be equipped together with storage components (battery, ultra-capacitor, and so on) for providing stable and sustainable power. Multiple renewable sources and storage components are usually combined in a hybrid renewable energy system (HRES). In the stand-alone application, e.g., remote communities, the HRES is able to supply electricity for off-grid customers (Tazvinga et al., 2013, 2015; Nema et al., 2009; Shaahid and El-Amin, 2009). In the grid-connected application, e.g., the berthing green ship, the HRES can also serve as distributed generation to sell the surplus of renewable energy on grid, which can bring financial profits on the electricity market (Palma-Behnke et al., 2013; Wu et al., 2015; Wu and Xia, 2015). Researchers have studied many theoretical and practical issues arisen in HRES applications, including optimal design (Arun et al., 2009), scheduling and control (Gabash and Li, 2013; Kanchev et al., 2011), maximum power point tracking (MPPT) (Soto et al., 2006), and economic analysis (Wies et al., 2005; Esen et al., 2007).

In recent years, the HRES has been applied to hybrid-electric ships and all-electric ships (Zahedi and Norum, 2013). On the one hand, new green ships are built with electric power systems, including PV, diesel generators (DGs), and battery (Lan et al., 2015; Wen et al., 2016; Banaei and Alizadeh, 2016). On the other hand, existing fossil fuel ships are undergoing energy efficient retrofit, and the HRES is installed to meet the axillary demand, such as loading, unloading, lighting, heating, cooling, and other on-board hotel services (Lee et al., 2013; Ovrum and Bergh, 2015). Compared with the fossil-fuel ships, the hybrid-electric ships are less dependent on fossil fuel, and have more integration of solar or wind energy. The use of renewable energy can improve energy efficiency of ship, enhance reliability and quality of power supply, and reduce shipping cost and GHG emission. The hybrid power system on

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https://doi.org/10.1016/j.solener.2018.06.033
Received 16 February 2018; Received in revised form 31 May 2018; Accepted 7 June 2018
0038-092X/

Nomenclature

$P_1(t)$	power flow from diesel generator to internal bus (kW)
$P_2(t)$	power flow from internal bus to battery (kW)
$P_3(t)$	power flow from battery to internal bus (kW)
$P_4(t)$	bidirectional power flow between grid and internal bus (kW)
$P_{pv}(t)$	power output of PV panels (kW)
$P_{pl}(t)$	propulsion load of green ship (kW)
$P_{al}(t)$	auxiliary load of green ship (kW)
$P_D(t)$	power output of diesel generator (kW)
P_D^{max}	maximal power output of diesel generator (kW)
P_D^{max}	minimal power output of diesel generator (kW)
P_i^m	allowable maximal power on the *i*th line (kW)
v	status of switch on the grid connection
$\bar{v}$	inverse status of switch on the grid connection
$S(t)$	state of charge (SOC) of battery (%)
S^{max}	allowable maximum SOC (%)
S^{min}	allowable minimum SOC (%)
Q	capacity of battery (kWh)
η_C	charging efficiency of battery (%)
η_D	discharging efficiency of battery (%)
$\rho(t)$	price of electricity (\$/kWh)

the green ship is usually regarded as a special case of mobile microgrid, which appears more complicated characteristics than the microgrid on land. System configurations are different when the ship is on voyage and berth, respectively. Environmental conditions are also extremely varying for the mobile microgrid. For the green ship, the mobile power system works on two modes, i.e., off-grid mode (stand-alone mode), and on-grid mode (grid-connected mode).

For the off-grid mode, many results have been reported in terms of optimal sizing (Lan et al., 2015; Wen et al., 2016; Yao et al., 2017), and power management (Banaei and Alizadeh, 2016; Ovrum and Bergh, 2015; Tsekouras and Kanellos, 2013). In Lan et al. (2015), an optimal sizing problem of stand-alone green ship has been formulated to minimize investment cost, fuel cost, and GHG emission, in which seasonal and geographical variation is considered for different routes. Interval optimization and clustering-based optimization methods have been proposed to determine the optimal size of energy storage system with uncertain PV power and load (Wen et al., 2016; Yao et al., 2017). To improve operational efficiency, power management has been studied for an electric ship with fuel cell, battery, PV panels, and diesel generators (Banaei and Alizadeh, 2016; Tsekouras and Kanellos, 2013). For crane ships, lithium-ion batteries have been employed to take part into power management, in which a hybrid control strategy is developed to reduce fuel cost and GHG emission (Ovrum and Bergh, 2015).

Other than the off-grid mode, green ships sometimes work on the grid-connected mode, when the shore-side grid power is available (Lee et al., 2013; Kanellos et al., 2017). As reported in Kökkülünk et al. (2016), average harboring time of bulk carrier ship is about 2 months per year. As the shore-side power is usually cleaner than the power generated on board, the use of shore-side power, called cold ironing, can effectively reduce annual fuel cost and GHG emission, when the green ship is on berth. With the help of HRES, solar energy can be used to supply the on-board demand instead of the shore-side electricity, and electricity cost can be significantly reduced. In Lee et al. (2013), a green cruise ship has been studied for delivering PV power to grid, and a rule-based strategy has been developed to satisfy auxiliary demand with batteries. In Kanellos et al. (2017) and Kanellos et al. (2014), a unit commitment problem has been studied to optimally allocate power output of each diesel generator, in which cold ironing is considered.

Considering bidirectional power flow between green ship and shore-side grid, electricity tariffs must influence electricity cost of cold ironing, and possible reward from selling renewable energy to grid. Thus, the change of electricity tariff will drive a different optimal solution to power management. To our best knowledge, very limited studies have evaluated tariff effects on power management of hybrid-electric ship. As a kind of demand side resources, on-grid green ships could take part into demand response programs, such as, time-of-use (TOU), and real time pricing tarrifs (Aalami et al., 2010). In this paper, the TOU tariff is studied as an instance of tariff-driven demand side management (DSM) of green ship. In the DSM, the HRES on a green ship can help owners to reduce electricity cost, and also can help utilities to enhance grid security and efficiency. Tariff-driven DSM of on-grid ship is more complicated than usual power management of off-grid ship, as demand-side management is required to consider the variance of electricity price and incentive reward, as well as the variance of renewable generation and load demand. One challenge of tariff-driven power management is to find an optimal control strategy for consuming grid power at the low-price period, and for selling renewable energy at the high-price period, while physical constraints have to be satisfied. Another challenge is to integrate the new capability of tariff-driven DSM into existing power management systems, which mainly focused on the off-grid management. The green ships often switch between on-grid and off-grid modes, especially for short-route ships, such as ferry and cruise. For this purpose, these challenging problems will be responded in the tariff-driven power management of green ship.

The contributions of this paper include three aspects. Firstly, tariff effects are studied for the power management of green ship with HRES, which is formulated as an optimal power dispatching problem to minimize the operational cost. Secondly, a unified tariff-driven power management system for off-grid and on-grid modes is proposed to optimally schedule the ship all the time. Thirdly, receding horizon control is proposed in the green ship application, so that system disturbances on solar energy and load demand can be detected and corrected. The resulted performance is promising with respect to energy efficiency and robustness. This paper is organized as follows. A HRES is introduced for the green ship in Section 2. Optimal power management problem of off-grid green ship is formulated in Section 3. A tariff-driven power management model is proposed in Section 4. Receding horizon control is proposed to control power flows for the minimization of operational cost in Section 5. Results and discussions are presented in Section 6, while the last section is the conclusion.

2. Hybrid renewable energy system of green ship

PV-DG-battery (PDB) hybrid systems are successfully applied to green ships (Banaei and Alizadeh, 2016; Tsekouras and Kanellos, 2013). The PDB system is made up of three main subsystems, i.e., PV panels, battery storage, and DG. The ship load includes propulsion load and auxiliary load. Auxiliary load consists of lights, water heating, air conditioners, plug-in devices, and other on-board hotel facilities. For the PDB hybrid system of green ship, the basic requirement is to keep the power balance, and to reduce operational cost and GHG emission.

Regarding to different volume and rated power, the hybrid electric ship can be categorized into two types. The first kind of ships, such as, bulk cargo vessels, which has large volume and rated power, only depends on DGs for the propulsion power. The solar energy is used to meet the hotel and auxiliary load, as shown in Fig. 1(a). The second kinds of ships, such as, cruises and ferries, usually have small volume and rated power. Both DG and solar energy are integrated to supply power for the propulsion load and auxiliary load, as shown in Fig. 1(b).

In this paper, we study the power management of a retrofitted green ship, which belongs to the first type, as shown in Fig. 1(a). The propulsion load is directly supplied by the DG. For the auxiliary load, the