Energy Conversion and Management 172 (2018) 50–66

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Power management optimization of hybrid power systems in electric ferries

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ARTICLE INFO

Keywords:
Battery
DC power system
Electric ferry
Energy storage system
Hybrid power system
Power management

ABSTRACT

The integration of more-electric technologies, such as energy storage systems (ESSs) and electric propulsion, has gained attention in recent years as a promising approach to reduce fuel consumption and emissions in the maritime industry. In this context, hybrid power systems (HPSs) with direct current (DC) distribution are currently gaining a commendable interest in research and industrial applications. This paper examines the impact of using HPS with DC distribution and a battery energy storage system (BESS) over a conventional AC power system for short haul roll-on/roll-off (RORO) ferries. An electric ferry with a HPS is modeled in this study and the power management system is simulated using the Matlab/Simulink software. The result is validated using measured load profile of a ferry. The performance of the DC HPS is compared with the conventional AC system based on fuel consumption and emission reductions. An approach to estimate the fuel consumption of the diesel engine through calculation of specific fuel oil consumption (SFOC) is also presented. This study uses two optimization techniques: a classical power management method namely Rule-Based control (RB) and a meta-heuristic power management method known as Grey Wolf Optimization (GWO) to optimally manage the power sharing of the proposed HPS. Fuel consumption and emission indicators are also used to assess the performance of the two power management methods. The simulation results show that the HPS provides a 2.91% and 7.48% fuel consumption reduction using RB method and GWO method respectively. It is apparent from the result that the HPS has more fuel savings while running the diesel generator sets (DGs) at higher operational efficiency. It is interesting that the proposed HPS using both power management methods provided a 100% emission reduction at berth. Finally, it was found that using a meta-heuristic optimization algorithm provides better fuel and emission reductions than a classical method.

1. Introduction

Emission regulations imposed by the international marine organization (IMO), along with growing concerns on the environment, are causing a major shift in the industry's approach to propulsion system design and increasing the demand for environmentally friendly marine power system solutions [1,2]. In addition, the fluctuation of oil prices required the incentive to investigate more technologically advanced and efficient solutions to reduce operational expenses in the transportation industry [3,4]. Therefore, the industry has collectively been exploring other opportunities for emissions control and energy savings which range from burning low emission fuels such as liquefied natural gas [1] and using dual fuel [5] to progressively electrify ships through increasing hybridization [6]. In the same context, the IMO suggested the concept of hybrid electric vessels as one of the energy efficient index to control and limit a vessel's emissions [7]. This has opened up the integration of energy storage systems (ESSs) and renewable energy sources (RESs) into ship power systems [8,9].

As the overwhelming majority of present electric vessels use AC distribution systems, the hybridization of ship power systems is complex as synchronization of each generation unit is required. In addition, ship AC distribution systems have drawbacks such as inrush current of transformers, three-phase imbalances, harmonic currents, and reactive power flow [10]. On the other hand, a DC distribution system provides an efficient distribution of electric energy by linking AC and DC energy sources through power-electronic devices which customize energy flow to the load [11,12]. However, power electronic converters add complexity to the system due to their non-linear characteristics and switching behavior [13,14]. Nevertheless, the recent progressive developments of power electronics devices make them more reliable and

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https://doi.org/10.1016/j.enconman.2018.07.012
Received 19 March 2018; Received in revised form 8 June 2018; Accepted 4 July 2018
0196-8904/

Nomenclature

E_B	BESS energy [kWh]
FC_{berth}	Fuel consumption at berth [L]
$FC_{cruising}$	Fuel consumption while cruising [L]
FC_m	Fuel consumption at a certain operating condition [L]
N_S	Number of stops per ferry round-trip
N_p	Number of poles
P_B	BESS power [kW]
P_{EL}	Instantaneous power at the specified engine load [kW]
P_L	Load power [kW]
P_{cha}	Charging power [kW]
P_{dcha}	Discharging power [kW]
P_n	Generated power from n-th DG [kW]
P_n^{max}	Maximum power of n-th DG [kW]
P_{rated}	Rated power of DG (maximum power) [kW]
P_{tn}	Power generated by n-th DG at t-th time [kW]
$SFOC_{EL}$	SFOC value at specified engine load [L/kWh]
$SFOC_n$	SFOC of n-th DG
SOC^{high}	Upper SOC limit [%]
$SOC^{initial}$	Initial SOC [%]
SOC^{max}	Maximum SOC [%]
SOC^{min}	Minimum state of charge [%]
e_{berth}	Emissions at terminal (berth) [g/kWh]
$e_{cruising}$	Emissions while cruising [g/kWh]
Δt	Time step
DoD	Depth of discharge [%]
E	Energy [kWh]
e	Emission [g/kWh]
EL	Engine load
FC	Fuel consumption [L]
FC_{total}	Total fuel consumption of one round trip [L]
i	Current (A)
N	Number of DGs
R	Resistance [Ω]
SFOC	Specific fuel oil consumption [L/kWh]
SOC	Battery state of charge [%]
T	The total time period
V	Voltage [V]
b	BESS operating variable [‘0’ discharge, ‘1’ charge]
g	DG operating variable [0 or 1]
η	Efficiency
θe	Electrical angle
θr	Rotor angle
λ	Ratio of load

Abbreviation

BESS	Battery energy storage system
CO_2	Carbon dioxide
DG	Diesel generator-set
ESS	Energy storage system
GWO	Grey wolf optimization
HPS	Hybrid power system
IMO	International marine organization
NO_X	Nitrogen oxide
PMS	Power management strategy
RB	Rule-based
RES	Renewable energy source
RORO	Roll-on/roll-off
SO_X	Sulfur oxides

Subscripts

t_c	The index time of charging
B	Battery
bus	Bus
cha	Charging
discha	Discharging
EL	Engine load
L	Load
loss	Power loss
m	Operating condition
max	Maximum
min	Minimum
n	n-th DG
prop	Propulsion
ref	Reference
rms	Root-mean square
serv	Service
t	t-th time interval
T	Terminal

efficient. This makes the DC distribution is more feasible in various applications [12]. Therefore, the use of a HPS with DC distribution enables easier integration of RESs and ESSs [10,15]. In addition, synchronization of generation units is not required which enables the prime movers to operate at their optimal speeds providing a reduction of fuel consumption and emissions [10,16]. This also offers further advantages, such as space and weight savings, flexible arrangement of equipment and noise reduction from a diesel gen-set (DG) in the harbor [17,18]. Moreover, retrofitting of a conventional marine power system with emerging renewable energy and energy storage technologies provides significant cost and environmental benefits [9,19,20]. As a result, the transition from a ship power system with AC distribution to a HPS with DC distribution is gaining more attention [12,17].

The aforementioned advantages of a HPS with DC distribution give an efficient power system solution for short-haul ferries as most ferries operate closer to urban areas where the reduction of noise and emissions is required [21]. As most of the ferries use fossil fuels such as diesel to produce on-board power, they produce pollutant emissions, include CO_2, NO_X, SO_X and particular matter [22,23]. When a ferry is berthed at a terminal, these emissions occur close to human habitation and result in a more direct impact on health [24]. Moreover, ferries account for a significantly high percentage of in-port emissions based on frequencies of calls compared to other types of vessels [25]. Such greenhouse gas emissions have a significant risk on human health including chronic bronchitis, heart disease, stroke and respiratory tract infection [22]. Therefore, policy makers have explored and introduced several methodologies in limiting port emissions based on port structural changes [26,27]. A cold-ironing method can be considered as a common solution to reduce in-port emissions and noise at terminals [28]. This method uses shore power to supply power to the on-board engines [29]. However, sometimes the shore power supply uses non-renewable energy sources [30]. In addition, economic factors need to be taken into account to justify investment in a shore power station as short-haul ferries usually berth for short period [28]. Therefore, there should be a more reliable solution to eliminate in-port emissions from ferries. Thus, all-electric and hybrid-electric ferries are practically achievable and the integration of RESs greatly reduces their emissions and fuel consumption. However, the slow dynamics or intermittent nature of RESs prevents them being the main source of power in ferries. Thus, a battery energy storage system (BESS) has become an integral part in such systems to ensure a reliable supply of power [31]. Therefore, the trend towards integration of the BESS into ferries has gained more attention in recent years. For example, MV Hallaig, the first hybrid electric ferry with battery storage, started operation in 2013