Evaluation on the energy efficiency and emissions reduction of a short-route hybrid sightseeing ship

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Abstract: This paper is to develop a coordinated control strategy of a ship with hybrid power and evaluate on the energy efficiency and emissions reduction of the case ship. The hybrid power system consists of 4-stoke diesel generator, solar panels and battery packs. A micro-grid power system was structured to offer an optimal combination of the three power sources in terms high efficiency and low emissions of the overall system. The control requirements for the developed micro-grid power system were analysed according to the principles of priority to use renewable energy. A power distribution control strategy was designed by applying the logic threshold method. A system simulation model was established and the simulation was carried out with MATLAB. An experimental test rig was built to evaluate the simulation results and develop the control system. The developed marine micro-grids power system has been applied on a case ship and run stably. Compared with the conventional power system, the performance of emission and economic of the hybrid system is studied with the case ships. The results of case ship and experimental have shown that the developed hybrid micro grid system can be managed effectively by the proposed control strategy. The emission of CO_2 is dramatically decreased in any cases and the energy cost is reduced considering for the ship life-cycle.

Keywords: Marine Micro-Grids, Control Strategy, Solar Energy, Lithium-ion Batteries, Diesel Generator.

Nomenclature

G	Generator
PV	Photovoltaic
DC	Direct current
AC	Alternating current
PLC	Programmable logic controller
CAN	Controller area network
MPPT	Maximum power point tracking
SOC	State-of-charge
SFOC	Specific fuel oil consumption
P_{load}	Load power demand
P_{pv}	Output power of photovoltaic panels
P_{bat}	Output power of lithium batteries
P_{dg}	Output power of diesel generator

1. Introduction

Since ship emissions have become increasingly a serious problem, the technology of high energy efficiency and emissions reduction of shipping industry has brought a great attention from the international community. Air pollution from ships mainly comes from using heavy fuel oils for power generation. Although, these fuels are economical, they produce significant amounts of pollutant emissions (Rehmatulla et al, 2017). Designing and building new green ships with low energy consumption and low emission has become an important trend in the shipbuilding and shipping industry. On the one hand, several solutions exist for shipping to mitigate its emissions and transition towards low carbon shipping, and one of them is using renewable energy sources (Ammar et al, 2017). On the one hand, more and more are marine applications where traditional thermal engines are not the best option to cope with regulation limits and constraints, as in the case of passenger transportation in coastal cities waterways or in marine protected areas (Balsamoa et al, 2017). The electric propulsion technology is considered as the best candidate to take the place of the internal combustion engine propulsion. Therefore, in view of the higher requirements of environmental performance for traveling water area (IMO, 2016), the application of new energy technology and electric propulsion technology to develop a comfortable and environment-friendly sightseeing ship is an effective solution to solve the environmental pollution and improve the tourism quality.

With the development of electronics technology and control technology, the micro grid with new energy has been widely applied on land. The power output characteristics of new energy sources in the marine environment are not essential different from land-used type. However, the ship micro-grid system must deal with the special operating environment in marine application. In particular, the complicated and changeable working conditions during ship navigation would make the load power fluctuate and frequently change. When solar energy is concerned, it is also necessary to take into account of the influence on the power output by the limitation of the navigation area and the installation area of the solar panel. In addition, compared with onshore power system, one of the characteristics of ship power system is small capacity and large load. Therefore, the ship micro-grid, as a relatively independent system, has typical characteristics that distinguish it from the physical structures and characteristics of the power grid for land application. It is not possible to directly apply the micro-grid technology in the land grid to the marine application. Smith et al. (2016) mentioned in their research to combine different energy-efficient technologies in order to reduce shipping emissions. In this particular application, three energy sources are considered, including solar energy, lithium battery pack and diesel generators. The influence of the power quality (static and dynamic response of voltage and frequency) and the operation reliability of the micro grid system are to be studied.

At present, researchers and scholars around world have conducted research on the application of new energy sources in ships. Some research results have been obtained for using the solar energy and battery as an auxiliary power supply to ship application (Glykas et al, 2010). However, the study of solar energy and battery power as a component of ship's main power supply is still in the exploratory stage, especially in the research of ship's micro-grid technology. There has been very little literature published on relevant research. The DC Bus technology of ship power supply system, mixed with diesel generator and photovoltaic cells, is introduced by many previous researches (Bartelt et al, 2011; Jusoh et al, 2013; Zahedi and Norum, 2013). It has the advantages of simplified transmission systems, high stability of system operation and transmission of active power. Also there is no frequency fluctuation and phase difference problem. The power supply system is reliable and can be easily achieved (Zahedi and Norum, 2013). An energy management control system of the DC power system of the solar and lithium batteries has been developed by researchers already (Yu et al, 2013; Yu, 2013). Although the DC power system is easy to implement, there are also many drawbacks in ship application, such as small power capacity, low economic benefit, low reliability of equipment and so on. Reports (Wei et al, 2010; Sun, 2013; He et al, 2013) discussed the AC (alternating current) Bus technology of ship power supply for a system with a combination of diesel generator and photovoltaic cells. The report investigated the stability of power provision based on the maximum power output of solar photovoltaic and the synchronous generator speed regulation and excitation system control when the two power sources are operating in parallel.

However, the system is lack of power storage and could not use solar energy to its maximum advantage.

Therefore, according to the characteristics and operation requirements of the sightseeing ship, aiming to the shortage of the existing ship's micro grid, this paper investigates a ship micro-grid power system which consists of photovoltaic cell, diesel generator and battery with AC Bus. At first, the topology of the ship micro grid power system is introduced, and the power control strategy and the optimization of the coordinated control are presented. Secondly, the paper presents the procedure of system modelling and simulation. The results of system operation stability and reliability were studied. Further, combined with electric propulsion technology, an energy management system is developed and applied on a sightseeing ship. Finally, A case study is carried out in order to estimate the energy saving and emissions reduction due to the installation of the hybrid power system.

The rest of this paper is organized as follows: Section 2 presents a topological structure of micro grid with AC Bus. In section 3, according to the output characteristics of different energy sources, the operation control requirements of the ship's micro grid are analysed, and the energy management control strategy is put forward. Section 4 introduces the related simulation research of the diesel generator, lithium-ion battery and photovoltaic, and develops a system simulation model of the micro grid. In section 5, the system under different load conditions is simulated and analysed. Section 6 introduces the control system and corresponding experimental platform, and analyses the experimental results. Section 7 described the parameters of the case ship, evaluates the energy saving and emission reduction performance and the economic performance of the ship life-cycle. Finally, this paper is concluded in section 8.

2. The topology of ship micro-grid power system

The continuity, reliability and quality of power supply of ship will directly impact the economy performance, technical performance and safety of ship (Sun, 2013). For ship power system with multi-energy, the stable and reliable operation of the micro-grid system must be satisfied. In order to highlight the performance of energy saving and emissions reduction, according to the performance requirements of the sightseeing ship, the general design idea of the micro grid is as follows:

1) Based on most loads of the ship are supplied AC, the AC power grid is adopted.

2) Due to the excellent electrical properties of lithium-ion batteries, the lithium battery packs which are certified by the ship classification society have been promoted and used on ships, and it is also adopted by the system.

3) The inverter power supply of lithium battery pack and solar energy is applied as the main power, and the diesel generator is used as auxiliary power or emergency power supply.

4) MPPT algorithm of solar energy is adopted.

So, the architecture of a micro-grid system with a combination of a diesel generator, lithium-ion batteries and solar energy is developed and shown in Fig.1. The solar energy and the lithium-ion batteries are connected by an inverter to the AC Bus. The load includes electrical propulsion system and other electricity consumers and lighting on board.

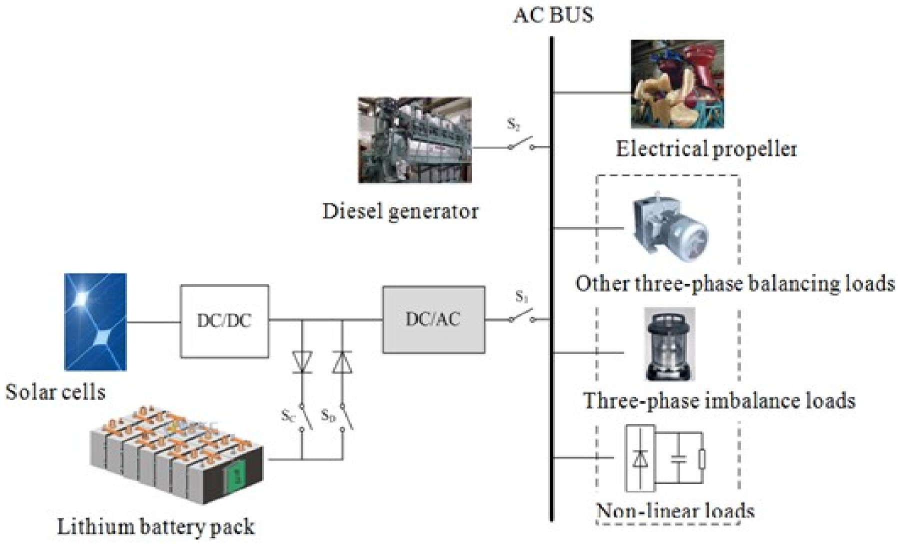

Fig.1 The proposed architecture of ship micro grid system

3. Analysis of energy control strategy

For the developed ship's micro-grid system above, the most critical part is the distribution and control of each energy source. The energy distribution and control strategy is to meet the ship power demand and distribute power reasonable and optimized between the three kinds of energy sources, in order to maintain the efficiency and stability of the whole ship power system operation. At the same time, in order to maximize the use of renewable energy, the power output from solar energy source is maintained to be the maximum with a reference of the research outcomes of power distribution strategy of multi-energy sources on ships (Gao et al, 2015; Li, 2014).

The control method of micro grid has logic threshold method and some new control methods based on classical and modern control theory, such as PID control, sliding mode variable structure control and fuzzy control. However，because of the theory is immature and the algorithm is too complex, the software and hardware of the control system with modern control method are too complex, and it is not suitable for applying the control system in micro grid now. At present, the logic threshold control method is widely used at home and abroad because of it is not necessary to establish the complex mathematical model and to detect data with high accuracy, and it is very effective for the system nonlinear control. When the control method is used in the ship's micro grid, the basic energy management can be realized only through controlling the power threshold of output power of solar power and lithium battery pack, and power of load demand. Therefore, how to design a set of reasonable control strategy is the premise of logic threshold method can be used in ship micro grid. A novel power distribution control strategy based on a logic threshold value is developed and its working principles are shown in Fig.2. There are two operating modes of this control strategy. One is the power supply mode of a combination between solar and lithium-ion batteries. The other one is a combination of all three energy sources.

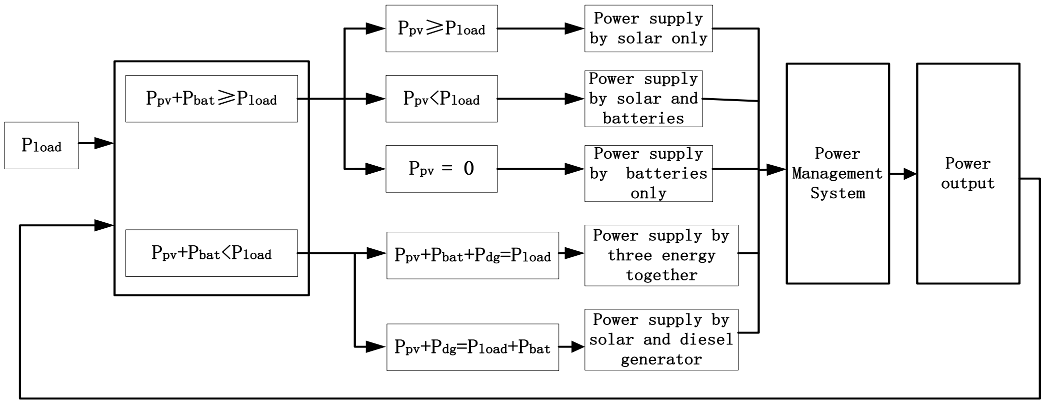

Fig.2 Power distribution control strategy based on logic threshold method

The details of the control strategy are described under the normal working conditions as follows:

1) When the total output power provided by solar energy and lithium-ion batteries is greater than the load demand. The solar power generation system will be working as the main energy source to provide electricity load and lithium-ion battery pack provides complementary power to stabilise the whole power supply system. According to the solar power output and load demand, the operation mode of the system can be divided into the following three sub-modes:

a) When the power output of the solar system is greater than that of the load demand, the power supplied will be only from the solar energy. The batteries will be charged according to the batteries SOC.

b) When the power output of the solar system is less than the load demand, the power will be supplied by the solar energy and the batteries together. In this mode, all the solar power will be used to meet the power load demand and the rest will be replenished by the batteries.

c) When the solar power output of is zero, the power will be supplied purely by the batteries.

2) When the total power output of the solar and battery systems is less than the load demand, the power output of the solar energy system is maintained at its maximum. The power output of diesel generator and the battery is depending on the change of demand load and the batteries SOC.

In addition, as an energy supply and the storage equipment of the shipping micro-grid system, a safe, stable and efficient operation of energy storage system is very important. In order to protect the energy storage system and prolong its service life, its SOC must be controlled in a certain range (Kim et al, 2015). As a suggestion of the study, the power discharge of the batteries is not allowed when the SOC of the batteries is less than 30%. Similarly, when the SOC is more than 90%, the batteries are not to be charged either.

4. System simulation model

According to the proposed system structures and the control strategy described above, the models of the three power source modules and the inverter module are developed respectively. The micro-grid system model is built by the MATLAB/Simulink as shown in Fig.3.

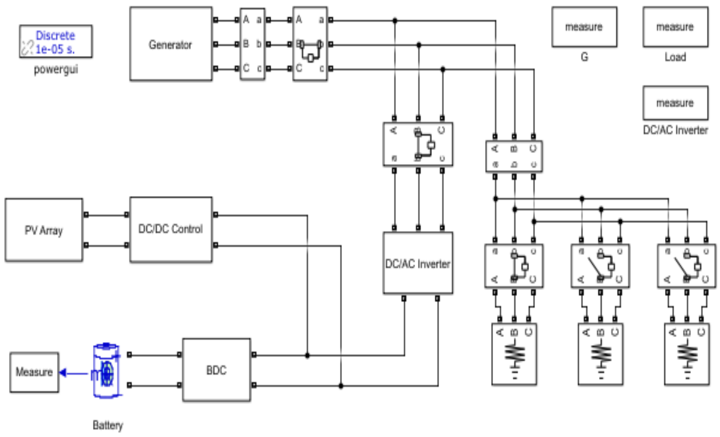

Fig.3 The simulation model of marine micro-grid

With the developed model of solar photovoltaic cell power module, the power output characteristics of the photovoltaic cells can be examined by changing the input parameters of the module, such as the light intensity and temperature. A DC/DC converter is connected with the solar photovoltaic cell module. The DC/DC converter applies the maximum power point tracking algorithm for solar energy output (Camacho et al, 2013).

The model of lithium-ion battery is developed from the SYS module library of MATLAB. This is a model based on the improved Shepherd curve fitting. The effect of SOC on the battery performance is simulated by increasing the voltage polarization in the model. In order to improve its stability, the model calculates the polarization resistance through the current after filtration (Majumder, 2013). The bidirectional DC/DC converter is then connected with the lithium-ion battery module to realize the charge and discharge control of the battery.

The diesel generator module is simulated by using the 4-stroke diesel engine model and the permanent magnet synchronous generator model in MATLAB. In the model of diesel generator, the torque and throttle control signals are adopted as the input and the engine speed and generator power are the outputs (Shafiee et al, 2014; Ahmadi and Wang, 2014).

The load module in Fig .3 is in the form of pure resistance. Thus, the load profile of the whole power system is then simulated. A multi-energy power management system is a self-contained module by adopting the proposed control strategy. The measurement and display module in Fig.3 is used to indicate the power, current and other operational data of the power system.

5. Simulation and result analysis

Of course, there are many factors that can affect solar power output and influence the emissions of diesel engine and efficiency. But in view of the energy control strategy is proposed, the system can be controlled to make the micro grid stable operation under its normal conditions as long as the output power of each source and the load are detected. So, the input parameters of the simulation are given as the following:

1. Diesel generator outputs are 100kW, 380V and 50Hz,
2. The maximum power output of photovoltaic cells is 30kW,
3. The rated capacity of the battery is 50kWh.

Based on the overall model of ship micro-grid system developed by MATLAB/SIMULINK, simulation is run to evaluate the effectiveness of the power distribution, control strategy and the operation stability of the system. The initial setting conditions of the system are that the initial load is 20kW and the PV output is 30kW. The system reaches to stable operation status after 2 seconds from of the start of the simulations. The operational profile of individual energy module is shown in Fig 4.

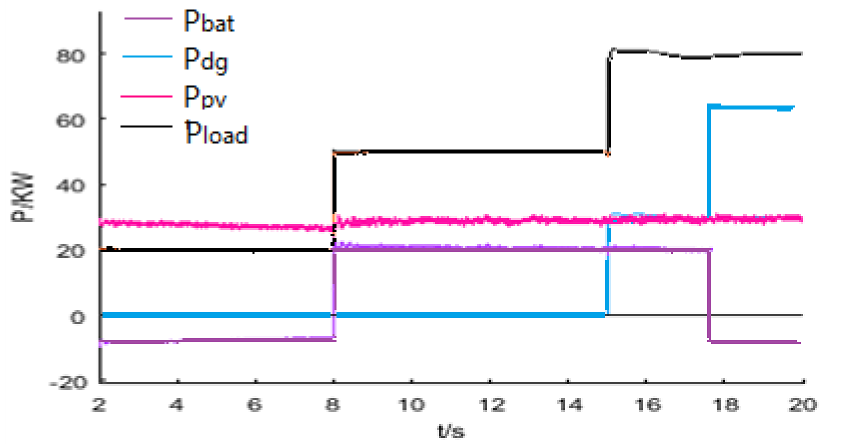

Fig.4 Output power of difference energy modules

Between 2 and 8s, the 30 kW power output of the PV module is consumed by the load at 20kW and 10 kW for battery charge through the inverter. During this time, the diesel generator is not in operation.

For the 8th to 15th second, the load is increased to 50kW which is met by the photovoltaic output of 30kW and the battery output of 20kW through the inverter, and the diesel generator is still not in operation.

At the 15th second, the load is increased to 80kW. 50kW of the load is provided by the combination of the photovoltaic output and that of the battery. Whereas the remaining power 30 kW is supplied by the diesel generator.

At the17.5th second, when the lithium battery discharge current and SOC reach the set values, the battery pack changes its operation mode from discharge to being charged conditions. The power generated from the diesel engine is increased to 60 kW to complement with the solar panel power to drive the load. Whereas the additional power of 20 kW from the diesel generator is to charge the batteries.

Fig. 5 and Fig. 6 show the voltage and frequency of micro-grid system output through the simulation. It can be seen that both the voltage and frequency of the system output are stable and meet the requirement of classification requirements. The detailed permission levels of voltage and frequency deviations can be found in Table 1 (Josep et al, 2016).

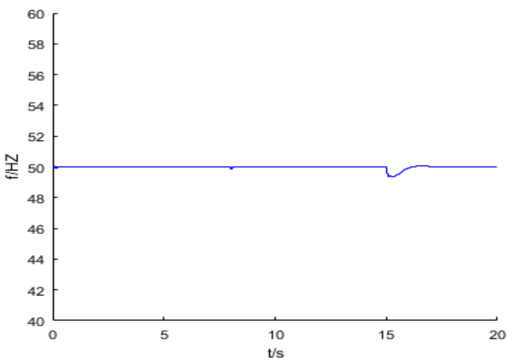

Fig.5 Frequency of AC Bus

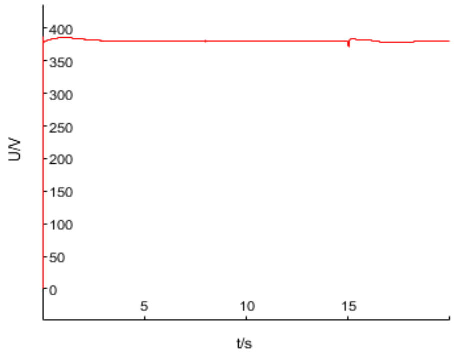

Fig.6 Voltage of AC Bus

Table 1. Permitted levels of voltage and frequency deviations for ship power supply system

Standards	Instruments and Parameter Variations		
	Range of The Standard	Voltage	Frequency
Polish Register IEC60092-101	Electrical Installations in ships. Definitions and general requirements	+ 6%, -10% ±20%(1.5s)	±5% ±10%(5s)
Lloyd's Register	Selection and Use of Standards for Naval Ship	+ 6%, -10% ±20%(1.5s)	±5% ±10%(5s)
STANAG1008	Characteristics of Shipboard Electrical Power Systems in Warships of the North Atlantic Treaty Navies, NATO, Edition9, 2004	±5% ±16%(2 s)	±3% ±4%(2s)

American Bureau of shipping 2008	Rules of International Ship Classification Societies, eg PRS/25/P/2006	+ 6%, -10% ±20%(1.5s)	±5% ±10%(5s)
IEEE Std.45-2002	IEEE Recommended Practice for Electrical Installations in ships	±5% ±16%(2 s)	±3% ±4%(2s)
China classification society	Electrical devices, Standard for classification of steel ships (2014).	+ 6%, -10% ±20%(1.5s)	±5% ±10%(5s)

The simulation test is carried out in the normal conditions of the system, and the running status and power quality are simulated under different working conditions. The simulation results verify the correctness and feasibility of the proposed system scheme and control strategy, and the power quality in line to certain standards. A solution for the ship power system of a green ship is provided. The simulation tests are of reference for the research and development of the control system which is applied to the case ship. There is another control strategy for the system in case of failure conditions or emergency conditions, and it doesn't involve in this paper

6. Experiment and result analysis

The experimental test rig is constructed according to the proposed topology of a micro grid system with multi-energy modules, which is located at Jimei University. The test rig consists of a 75kW diesel generator, a 30kW photovoltaic system and a 53.7kWh lithium-ion battery pack. The diesel generator and power distribution device are shown in Fig.7. The solar panels are of 200m^2 shown in Fig.8. The battery pack consists of 168 lithium batteries (3.2v/100Ah) which are connected in series shown in Fig.9. Fig.10 shows the DC converter, PV inverter and other power transformation device.

Fig.7 Diesel generator and main switchboard

Fig.8 Solar panels

Fig.9 Lithium battery pack

Fig.10 Inverter, control system and charger

According to the control strategy proposed above, the developed power control system is implemented by the PLC from ABB Company as shown in Fig.11. Water is used to disperse the power generated from the power modules as the load of the system. All system operation data are collected and transmitted to the PLC by the CAN bus. A monitoring and alarm system is developed and connected with the PLC. A touch screen is applied as the terminal to display parameters of system operation. The Modbus protocol is employed for two-way data communication between the PLC and the terminal. Fig.12 is the software interface showing system control and operational parameters on the terminal.

Fig.11 Power control system

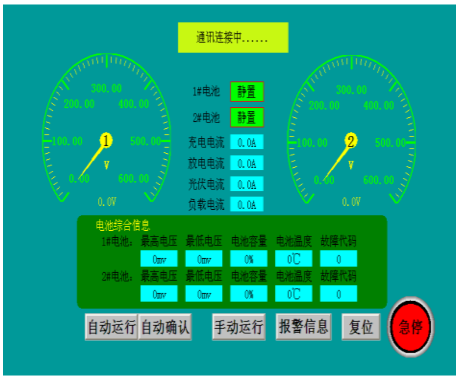

Fig.12 Monitor interface

The system is tested during the period of mid-day to make the best use of the solar energy. The tests were conducted with 3 scenarios. Table 2 presents the test data of power distribution among the three power sources obtained from the monitoring display unit and the power quality analyser CA8335.

Table 2 Power output of different power modules

No. of scenario	Power of load	Power of batteries	Power of PV	Power of DG
1	4.1 kW (6.2A)	7.1kW (-12.7A)	11.3kW (20.1A)	0
2	17.3kW (26.8A)	8.7kW (15.6A)	9.4kW (16.8A)	0
3	42.8kW (65A)	-5.7kW (-10.3A)	6.8kW (12.1A)	45.9kW (70A)

Scenario one was to set the load to be less than the solar power module output so that the extra power from the solar system is used to charge the battery. As shown in table

1, the solar power output was 11.3kW and load was 4.1kW. The difference of 7.1kW was used to charge the battery pack. Under this working condition, the system ran on the mode of the power supplied by the solar energy alone.

Scenario two was to increase the load to be more than the solar penal output power. In this case, the power supply from the battery system was required. During the test, it was observed that the battery pack charging current was reducing gradually until it was switched from the charging mode to the discharging mode. The output voltage of the battery pack was slightly reduced as the load was increased. In scenario2, the sum of the power outputs from the solar panel and the battery pack was slightly more than that of the load. Under this working condition, the system should run on the mode with the power supply from the combination of solar panel and batteries.

It was also observed that the battery discharge current will increase or decrease as the load increases or decreases in this scenario. The output current of the solar system remained almost the same. This reflects the developed control strategy of maximising the use of solar energy.

In scenario 3, the load was further increased to be more than the total power output of solar panels and the power of battery pack which was set at 0.8C discharged current so that the diesel generator started automatically and to provide the additional power required in parallel. During the operation, when the battery discharge current and residual capacity reaches the set value as shown in table 2, the power generated from the diesel engine is to complement with the solar panel power to drive the load. Meantime, the extra power from the diesel generator is to charge the batteries.

Table 3 the set value of batteries operation mode from discharge to charge

Set value	Current of batteries	SOC of batteries
1	0.6C -1C	<70%
2	0.4C-0.6C	<50%
3	<0.4C	<35%

The test results of the experiment show that the system is able to operate stably under different working conditions. With the change of load, the system is able respond automatically to vary the power distribution among power modules and supply the power from one power module to another following the control strategy designed, which verify the effectiveness of the developed control strategy.

7. Case ship study

A case study was carried out in order to demonstrate feasibility of the designed control strategy and determine the fuel saving and emissions reduction of the installation of the hybrid power system.

1) Case vessel

The technology of the developed control strategy and hybrid power system has been applied to the retrofit of a sightseeing ship serving in between two ports in Guilin, China, shown in Fig.13. The main particulars of the case ship are: L x B x D is 30.5 m x 5.3 m x 0.53 m; Displacement is 39.16 tons (steel structures); the average speed of a ship is 8 knots; the number of operation days per year is 200 days. Life span is 30 years. The power system configuration of the ship before retrofit is: 1 set of 75 kW diesel engines for propulsion and 1 set of 32.4kW diesel generator. The power system configuration of the ship after retrofit is: 1 set of 50kW motor as the propeller driver; 1 set of 75 kW diesel generator; 3 sets of 537V and 100Ah lithium-ion batteries, 1set of solar panel with 110m^2 producing 12kW of power. In this research only propulsion power requirement is under investigation and other power consumers are not considered. The hybrid power system fully meets the requirements of design function and has obtained the certificate of seaworthiness which was issued by China Classification Society.

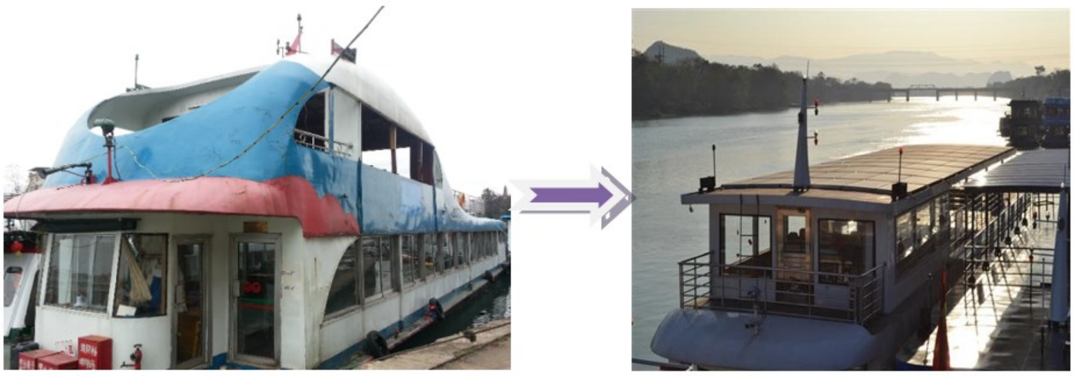

Fig.13 Sightseeing ship installed with the developed hybrid power system

2) Daily operation profile

The Sightseeing ship departs from the port of WenChangQiao at 8:30 a.m. and arrives at port of MoPanShan at 11:48; Departure from the MoPanShan port at 14:28 and return to WenChangQiao port at 17:46. A charging station was installed at the WenChangQiao port to recharge the batteries to full SOC overnight. Table4 shows the operation profile of the case vessel.

Table 4 Operation profile of the case ship

Conditions *		Mode 1	Mode 2	Mode 3	Mode 4	Mode 1	Mode 2	Mode 3	Mode 4	Total sailing hours
Time	Min	8	180	10	160	8	180	10	884	
	Hour	0.13	3	0.17	2.7	0.13	3	0.17	14.7	9.3
Propulsion power	kW	25	40	25	0	25	40	25	0	

* Mode 1: departing from port to cruise speed

* Mode 2: cruise speed

* Mode 3: approaching to port

* Mode 4: in port

3) Fuel consumption and emissions reduction

According to the operation profile of the case ship, it can be estimated that the total power needed for the entire voyage is of 255 kWh. To determine the fuel consumption and emission released, three cases are established.

Case 1: hybrid system applied with sunny all day which means the solar panel has a constant power output of 12kW. In this case, the power supplied by the solar panel is 111.6kWh, and the power supplied by the batteries is 255-111.6=143.4kWh;

Case 2: hybrid system applied with no solar energy available all day which means the solar panel has a zero power output. In this case, the power supplied by the batteries is

53.7x3x0.6=96.7kWh, and the power supplied by the diesel generator is 255-96.7=158.3 kWh;

Case 3: conventional system. In this case, all power of 255 kWh was supplied by the diesel engine.

The fuel consumptions for the three cases are determined according to the specification of the diesel engine where the SFOC at the output power of 25kW is found to be 220g/kWh and 200g/kWh at 40kW. In the first two cases, the developed control strategies have been taken into account in order to determine the distributions of power from the three power modules. The fuel oil used on board is marine diesel oil and it has a carbon emission factor of 3.223 kg CO_2/kg fuel (Greenhouse gas reporting, 2017). Then the emission released can be derived and the carbon credit is obtained with a consideration of 25$/tonne CO_2 (Luckow et al., 2016). Therefore the total daily consumption and operational cost are determined and presented in Table 5.

Table 5 Cost and consumption of fuel and electricity and emission released

Daily consumption		Quantity				Price			Cost
Case	Description	Solar power output (kW)	Battery electricity consumption (kWh/day)	Fuel oil consumption (kg/day)	CO2 emission (kg/day)	Electricity price ($/kWh)	Fuel oil price ($/tonne)	Carbon credits ($/tonne)	Total daily cost ($)
1	Sunny	12	96.66	9.47	30.53				14.0
2	No sun	0	161.1	18.9	60.8	0.07[1]	662[2]	25	30.7
3	Conventional	0	0	51.3	165.3				38.1

[1] National report of annual electricity price for commercial use 2013-2014, 2015; [2] Shanghai Bunker Price, 2017.

From the above table, it is obvious that the daily operational cost of using conventional propulsion system is the highest among all. Considering the annual sunshine in Guilin is 1160 hours (of 365 days in 2016) (Guilin Current weather report, 2017), there is approximately 1160/(365x9.3)=34% of total ship operation hours under the sunny condition. Therefore, the ship would navigate in case 1 with 34% and case 2 of 66%. As the ship will operated 200 days per year for 30 years, the total cost is saved approximately $78,719, and the amount of fuel saving is about 162.5ton, and the total CO2 emission is reduced about 523.9ton.

4) Initial investment

In order to derive the life cycle profit, the investments of battery and solar system are taken in to account. Based on the case ship study, the cost of solar panels is about 90$/kW (Alibaba, 2018), therefore, the initial cost is about 90*12 = $1,080. The cost of battery is about 312.5$/kWh (Alibaba, 2018) so the initial cost is 312.5*161.1 = $50,344. Hence the total investment is about $51,424. Considering there is one engine less than conventional ship, the cost of one engine purchase is reduced which is assume to be $1,600. Therefore, the total saving of whole life cycle is: 78,719+ 1,600 - 51,424 = $28,895.

Considering the worst case scenario which has no sun during operation in all years, the savings are listed in Table 6 to compare with the results from Year 2016.

Table 6 Savings under Year 2016 and worst case scenario.

Items ($)		Year 2016	Worst case scenario
	Fuel saving	65621	35044

Savings	CO2 credits	13097	9378
	Engine purchase	1600	1600
Total investment		51424	51424
Total saving		28895	-5401

5) Discussion

From above analysis, with application of battery and solar system, the emission of CO_2 is dramatically reduced from 165.3kg/day for case 3 to 102.8 kg/day for case 2 and to 78.0 kg/day for case 1. Similarly, the total energy (fuel and electricity) costs are lowest in scenario 1 among all cases which indicate the usage of solar power will definitely reduce the operation costs. From the aspect of investment, the costs are due to the purchase of new equipment (solar panels and battery packs) and fuel/electricity consumed. Since using hybrid power system, the energy cost is significantly reduced and it can recover the initial investments by saving fuel. The payback time for the investment is 19 years under scenario 1 condition. As the worst scenario is investigated in previous section, the result of using only battery is also a profitable strategy. It may meet the expectation of new clients whose vessel is operated in a less sunny region.

8. Conclusions

A ship micro-grid system is constructed to control the power distribution from solar energy, lithium battery pack and diesel generator. A control strategy is developed to coordinate energy allocation between different energy modules and optimize the energy management of different power sources. A monitoring system is developed and integrated with the energy management system. The effectiveness and feasibility of the proposed control strategy have been validated through the system modelling, simulation, experimental study and the application on case ship. From case ship study, compared with conventional power system, the emission of CO_2 is dramatically decreased and the energy cost is significantly reduced. The developed micro-grid and control strategy will provide an environmentally friendly solution for the waterborne tourism economy and promote the development and application of green ships. The research and development shall lay a foundation for further research on key technologies of intelligent ships.

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