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Energy Management Strategy of Multi-Energy Ship Based on New Generator Set Structure

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ABSTRACT

The multi-energy ship, which is composed of renewable energy and hybrid ship, has the advantages of energy saving and emission reduction under the background of increasing global oil resources' tense. At the same time, structure improvement is an effective way to improve the effectiveness of energy management strategy. To the above end, based on the wind and solar power data generated by HOMER, we establish and apply the extreme scenarios of wind and solar output power. Secondly, we propose a main and auxiliary generator set structure in which the main generator bears the baseload and the auxiliary generator bears the fluctuating load. Based on the structure and dynamic programming algorithm, we establish an energy management model of multi-energy ship with the battery and generator power as the control variables and the minimum operating cost as the optimization goal. The simulation results show that the application of dynamic programming algorithm, wind-solar energy, and main and auxiliary generator set structure combined with dynamic programming algorithm can respectively reduce the ship energy consumption by 0.54%, 5.07%, and 0.80%. The results show that supposed method can effectively reduce the energy consumption of the ship.

Keywords: multi-energy ship; generator set structure; energy management; dynamic programming; scenario analysis

1. INTRODUCTION

With the world's increasing attention to ship energy conservation and emission reduction, and since the 62th environmental protection meeting, the International Maritime Organization has taken the energy efficiency design index of new ship as an important index for ship acceptance [1]. Multi-energy ship composed of renewable energy and diesel-electric hybrid ship system is gradually becoming a research hotspot. At present, renewable energy that has been successfully used on the ship includes wind and solar energy, fuel cells, biomass energy, etc. [2]. However, wind and solar energy and other renewable energy are low-density energy, so the mixed use of various renewable energy is one of the effective ways to reduce ship energy consumption.

Among the existing studies on reducing energy consumption of multi-energy ship, some of them are optimized in terms of energy management strategies, while others are optimized in terms of the structure of the ship power system. Energy management strategy optimizes the energy flow distribution, which can effectively reduce the energy consumption of ship. For example, Zhu et al. [3] used fuzzy rules to realize the optimal allocation of energy flow, which improved the efficiency of ship operation. Given the poor performance of rule-based strategy, Zahedi et al. [4] extended the equivalent minimum energy consumption strategy proposed in reference [5] to ship, and obtained a real-time and better energy management strategy. However, it is not enough to optimize the strategy only. Because the basis of strategy optimization is the structure of ship power system, the improvement of ship power system structure can improve the effect of strategy optimization. For example, Sun et al. [6] demonstrated that the hybrid energy storage structure of battery and super-capacitor plays an important role in realizing effective acceptance of intermittent energy in ship

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power system and stabilizing power fluctuation in ship power grid. At the same time, compared with the direct drive of diesel engine, DC network electric propulsion technology has the advantages of higher fuel efficiency and higher dynamic characteristics [7]. It can be seen from the above analysis that the structural improvement can effectively reduce the energy consumption of ship.

In this paper, we establish the extreme scenarios of wind-solar power and propose a generator set structure where the main generator bears the baseload and the auxiliary generator bears the fluctuating load so that the main generator with high power is always in the high-efficiency working zone. Secondly, we establish an energy management model of multi-energy ship with the power of main and auxiliary generator set and battery as the control variables and the minimum operating cost of the ship as the optimization goal. Finally, the effects of wind-solar energy, main and auxiliary generator set structure, and dynamic programming (DP) on the energy consumption of the ship are analyzed.

2. MULTI-ENERGY SHIP SYSTEM MODEL

The multi-energy ship is based on hybrid propulsion technology, which is a typical multi-energy system with electrical energy as the core. And the structural diagram of multi-energy ship system is shown in Fig 1.

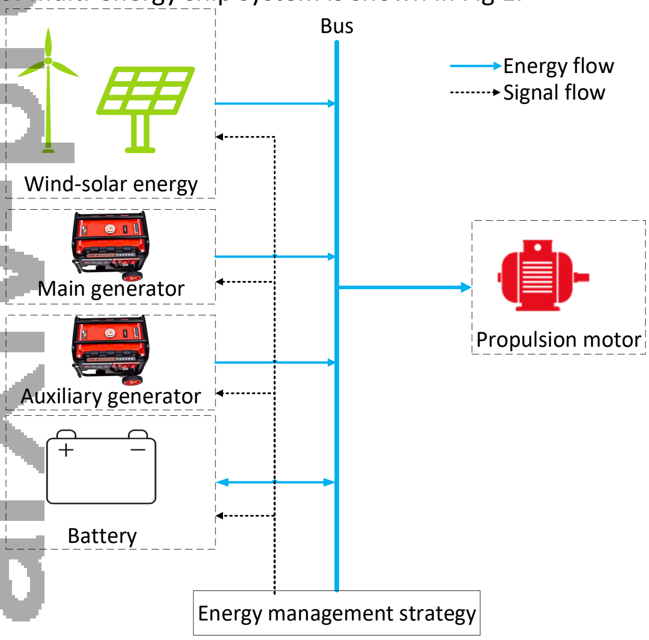

Fig 1 Structural diagram of multi-energy ship system

2.1 Diesel Generator Model

In the commonly used hybrid energy simulation software such as HOMER[8], the fuel consumption of a diesel generator is usually simplified as:

$$F = a + bP \tag{1}$$

Where F is the fuel consumption rate, a is the no-load fuel consumption rate, b is the generation of a kilowatt electric power fuel consumption rate, P is the diesel generator output power.

2.2 Battery Model

For battery management, the most important is its state of charge (SOC) monitoring and management, its SOC change can be formulated as:

$$\triangle S_{\mathrm{SOC}} = \frac{1}{Q_{\mathrm{C}}}\int_0^t \eta I \mathrm{d}\tau \tag{2}$$

Where ΔS_{SOC} is the change of battery SOC, Q_{C} is the rated capacity of battery, η is the charging and discharging efficiency of battery, I is the charging and discharging current, t is the charging and discharging time.

2.3 Renewable Energy Model

The relationship between wind speed and wind turbine output power can be approximated as:

$$P_{\mathrm{W}} = \begin{cases} 0 & v \le v_{\mathrm{in}} \\ av^3 - bP_{\mathrm{r}} & v_{\mathrm{in}} < v \le v_{\mathrm{r}} \\ P_{\mathrm{r}} & v_{\mathrm{r}} < v \le v_{\mathrm{out}} \\ 0 & v > v_{\mathrm{out}} \end{cases} \tag{3}$$

$$a = \frac{P_{\mathrm{r}}}{v_{\mathrm{r}}^3 - v_{\mathrm{in}}^3} \tag{4}$$

$$b = \frac{v_{\mathrm{in}}^3}{v_{\mathrm{r}}^3 - v_{\mathrm{in}}^3} \tag{5}$$

Where P_{W} is the power generated by the wind turbine, P_{r} is the rated power of the wind turbine, v_{in} is the cut-in wind speed, v_{out} is the cut-out wind speed, v_{r} is the rated wind speed, v is the actual wind speed.

The electrical power output of a photovoltaic panel can be expressed as:

$$P_{\mathrm{PV}} = rS\eta \tag{6}$$

Where P_{PV} is the total output electric power of photovoltaic panel, r is the light intensity, S is the total area of photovoltaic panel, η is the efficiency of photovoltaic panel.

3. EXTREME SCENARIOS

To analyze the influence of the randomness of the wind-solar energy on the energy management strategy, we generate wind speed and light intensity data within a year by HOMER. Then we select the data of a certain day with the largest daily peak of wind speed and light intensity as scenario 1, and the smallest daily peak of wind speed and light intensity as scenario 2. Scenario 1 and scenario 2 are shown in Fig 2 and Fig 3, respectively.

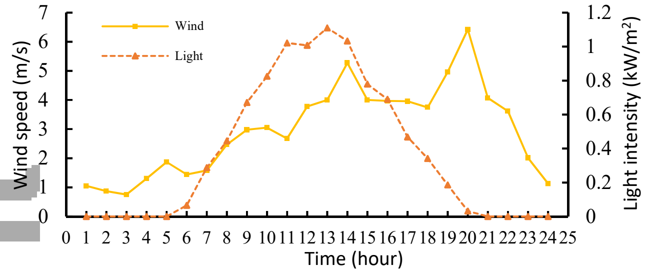

Fig 2 Scenario 1: maximum daily data of daily peak value of wind speed and light intensity

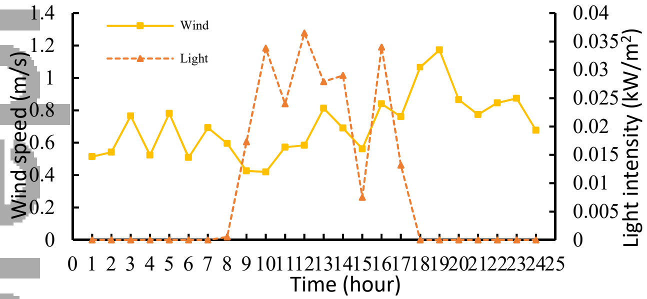

Fig 3 Scenario 2: minimum daily data of daily peak value of wind speed and light intensity

4. MULTI-ENERGY SHIP ENERGY MANAGEMENT

We comprehensively consider the above-mentioned application of wind-solar energy and reasonable power distribution between diesel generator and battery, and incorporate them into the unified energy management problem. At the same time, according to the characteristic that the closer the diesel generator is to its rated power, the smaller the fuel consumption per unit of power generation, we propose a new diesel generator set structure, i.e. main and auxiliary generator set structure. The main generator bears the baseload and the auxiliary generator bears the fluctuating load so that the main generator with large power is always in the high-efficiency working area.

4.1 Multi-energy ship energy management modeling

The control sequence that makes the ship consume the least fuel is obtained by minimizing the function (7).

$$J[x(0),u]=\sum_{k=0}^{N-1}F(x(k),u(k))+\gamma\left|S_{\mathrm{SOC}}(k)-S_{\mathrm{SOCref}}\right|^2 \quad (7)$$

$$\begin{aligned}F\left(x(k),u(k)\right)=F_1(P_{\mathrm{G1}}(k))P_{\mathrm{G1}}(k)\Delta t+\\F_2(P_{\mathrm{G2}}(k))P_{\mathrm{G2}}(k)\Delta t\end{aligned} \quad (8)$$

where $k\in\{0,1,2,\ldots,N-1\}$, γ is the SOC penalty factor, S_{SOCref} is the desired maintenance value of *SOC*, $F(x(k), u(k))$ is the fuel consumption of state $x(k)$ in the kth stage that is transferred to the next state under the control of $u(k)$, $F_1(P_{G1}(k))$ is the fuel consumption function of the main generator, $F_2(P_{G2}(k))$ is the fuel consumption function of the auxiliary generator.

The state transfer equation in the energy management problem can be developed as:

$$\begin{aligned}S_{\mathrm{SOC}}(k+1)=S_{\mathrm{SOC}}(k)\text{-}\Delta S_{\mathrm{SOC}}(k)=\\S_{\mathrm{SOC}}(k)-\frac{1}{Q_{\mathrm{C}}}\int_0^t\eta I\mathrm{d}\tau\end{aligned} \quad (9)$$

Where $S_{SOC}(k)$ is the battery SOC.

4.2 Constraints related to state and control variables

The energy management problem should have the following inequality constraints.

(1) battery restraint.

$$S_{\mathrm{SOC\,min}}\le S_{\mathrm{SOC}}(k)\le S_{\mathrm{SOC\,max}} \quad (10)$$

$$P_{\mathrm{cmin}}\le P_{\mathrm{b}}(k)\le P_{\mathrm{dmax}} \quad (11)$$

(2) diesel generator output power constraints.

$$P_{\mathrm{G1min}}\le P_{\mathrm{G1}}(k)\le P_{\mathrm{G1max}} \quad (12)$$

$$P_{\mathrm{G2min}}\le P_{\mathrm{G2}}(k)\le P_{\mathrm{G2max}} \quad (13)$$

where S_{SOCmin} is the minimum value of SOC, S_{SOCmax} is the maximum value of SOC.

The energy management issue should have the following equation constraints.

$$P_{\mathrm{d}}(k)=P_{\mathrm{G1}}(k)+P_{\mathrm{G2}}(k)+P_{\mathrm{r}}(k)+P_{\mathrm{b}}(k) \quad (14)$$

Where $P_d(k)$ is the power demanded by the propulsion motor of the multi-energy ship, $P_{G1}(k)$ is the main generator output power, $P_{G2}(k)$ is the auxiliary generator output power, $P_r(k)$ is the renewable energy output power, $P_b(k)$ is the battery output power.

The energy management problem can be solved in MATLAB using a quadratic search based on DP algorithm.

5. CASE STUDY

We set up three experimental groups for DP of 100kW single generator with or without wind-solar energy, and 70kW and 30kW main and auxiliary generator set without wind-solar energy. The power requirements of the motor are shown in Fig 4.

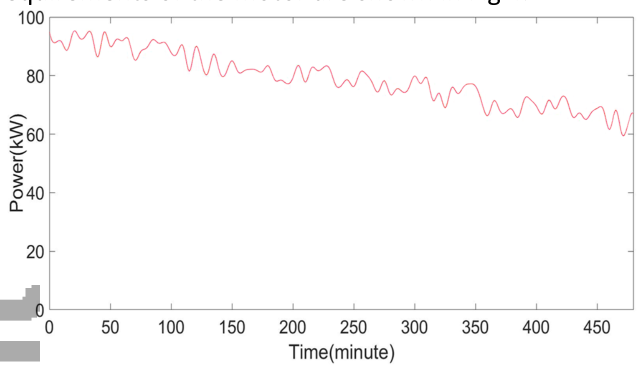

Fig 4 8-hour intercepted segment of typical working condition

5.1 DP results for 100kW single generator

5.1.1 *Without wind-solar energy*

Fig 5 and Fig 6 show the generator output power and battery SOC variation of the 100kW single generator with DP without photovoltaic panel, respectively.

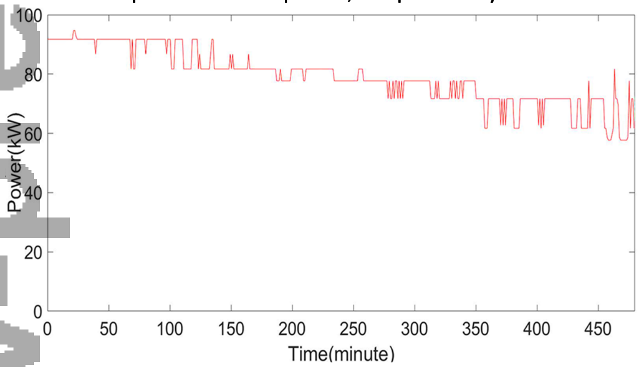

Fig 5 Generator power programming result without wind-solar energy

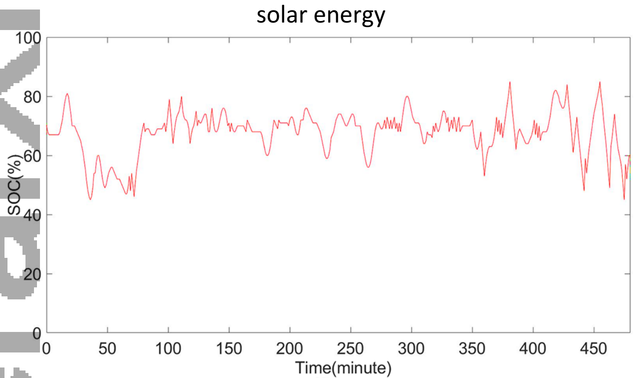

Fig 6 SOC change of battery without wind-solar energy

Comparing Figure 5 with Figure 4, it can be seen that the DP algorithm smooths the output power waveform of the diesel generator by flattening the power waveform. As shown in Figure 6, the battery SOC changes smoothly without wind-solar energy. Compared with the power-following control algorithm, the DP algorithm can reduce the energy consumption of the ship by 0.54%, which shows that better fuel economy can be obtained by using the DP algorithm.

5.1.2 *With wind-solar energy*

Fig 7 and Fig 8 show the generator output power results and battery SOC changes after DP of the 100kW single generator in Scenario 1, with Pd as the demand power and Pg as the generator power, respectively.

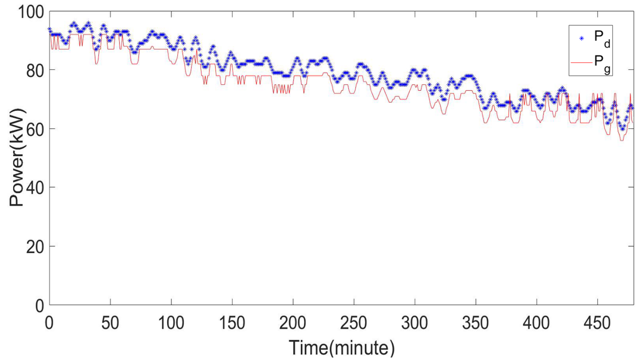

Fig 7 Generator power programming result in scenario 1

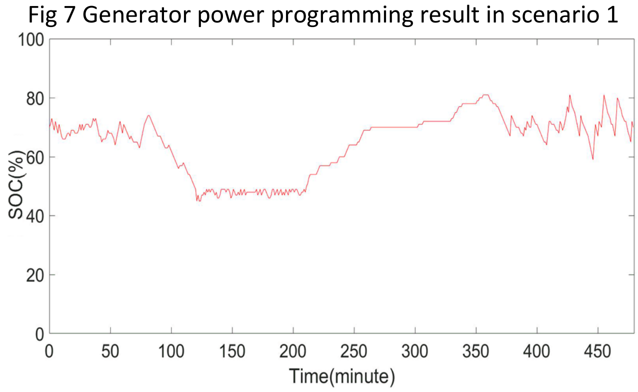

Fig 8 Battery SOC change in scenario 1

Comparing Fig 8 with Fig 6, it can be seen that in scenario 1, although the SOC maintenance coefficient is increased by 5 times, the wind-solar energy has great randomness, resulting in a more drastic change in generator output power and battery SOC than without the wind-solar energy. At the same time, it can be seen from Fig 7 that the wind-solar energy can effectively reduce the generator output power by a level that reduces the total energy consumption of the ship by about 5.07%, which reduces the energy consumption by a larger amount, which indicates that the application of wind-solar energy on the ship is feasible and can effectively reduce the energy consumption of the ship. In scenario 2, the total energy consumption is reduced by about 0.12%, the small value indicates that if the ship adopts wind-solar energy to reduce energy consumption, the meteorological conditions of the location should be assessed in advance to decide whether to adopt wind-solar energy.

5.2 DP results of 70kW and 30kW main and auxiliary generators

Fig 9 and Fig 10 show the DP results of 70kW main generator output power and 30kW auxiliary generator output power, respectively, without wind-solar energy.

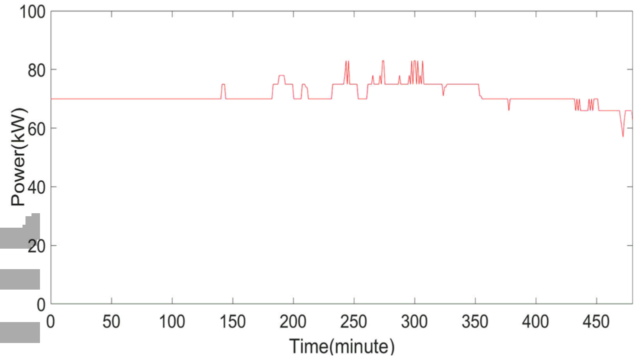

Fig 9 DP results of 70kW main generator power

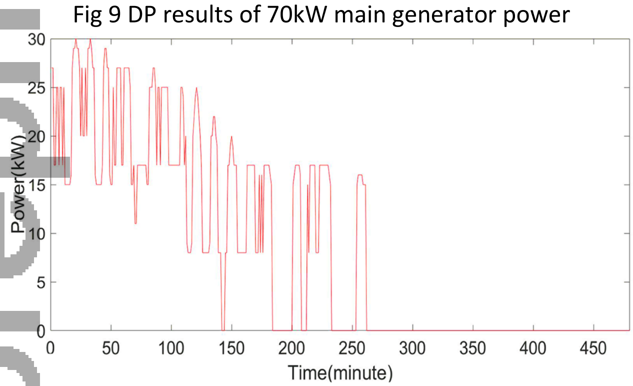

Fig 10 DP results of 30kW auxiliary generator power

It can be seen that the output power waveform of the main generator can be very well smoothed if the base load is carried by the main generator with higher power and the fluctuating load is carried by the auxiliary generator. The energy consumption can be reduced by about 0.80% compared to that of a single generator with a power-following control algorithm.

6. CONCLUSION

In this paper, the energy consumption of the ship can be effectively reduced by applying wind-solar energy, adopting energy management strategy with DP and main and auxiliary generator set structure. And the simulation results show that:

(1) Under the scenario of extreme daily with wind-solar energy and without wind-solar energy, the wind-solar energy can effectively reduce the energy consumption of the ship, but at the same time, it will bring relatively large random interference to the ship power system, indicating that the application of the wind-solar energy needs to evaluate the local wind-solar energy resources and distribution characteristics.

(2) Compared with the power-following algorithm, the DP algorithm can effectively reduce the energy consumption of the ship. And the case study verifies the effectiveness of the method, in which the proposed main and auxiliary generator structure provides a feasible idea for reducing ship energy consumption.

There are still some deficiencies. Firstly, the DP algorithm has poor real-time applicability. In the future, the rules that can be applied in real-time can be extracted from the energy management strategies. Secondly, the impact of wind turbines on the ship's travel resistance and the increase of ship power caused by the weight of wind-solar power generation devices are not taken into account. In the future, the operation mode of wind turbine can be controlled by comprehensively considering ship resistance and wind power revenue. Finally, the capacity of the main and auxiliary generator that we have not optimized is worthy of further study.

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