Journal of Computers Vol. 35 No. 1, February 2024, pp. 217-225
doi: 10.53106/199115992024023501017

Optimization of Ship Power Supply Network and Intelligent Energy Management Strategy Under Multiple Energy Modes

Bo-Wei Zhou, Yong Huang, Bin Jiang, Fei Geng*

Tangshan Polytechnic College,
Tangshan City 063299, Hebei Province, China
{bowei98673, yong77976, binbin8987, gengfei3286}@163.com

Received 15 December 2023; Revised 15 January 2024; Accepted 31 January 2024

Abstract. Purpose: This article aims to address the issues of incomplete management models and slow convergence speed of optimization models in energy management in ship multi energy systems, and to construct a comprehensive dynamic optimization objective model. Method: Firstly, establish an optimization design model with the objective functions of energy storage system cost, grid power fluctuation smoothing, and energy supply and demand balance; Then, in the optimization process of the objective function, a bus voltage coordination control strategy is adopted, and for the parameter optimization problem in the strategy, a cuckoo search algorithm based on population feature feedback is used for optimization. Result: Through simulation experiments, the method proposed in this article provides effective guidance for capacity configuration and energy management of multi energy ship microgrids, improving quality and efficiency.

Keywords: energy management, microgrids, e-commerce, cuckoo search algorithm

1 Introduction

Multi energy ships, characterized by integrated propulsion systems, have the advantages of fast maneuverability, low noise, low fuel consumption, low maintenance costs, and high reliability due to their ability to achieve comprehensive utilization of all ship energy. They have become the development direction of future ships. The representative countries in this field are the United Kingdom and the United States, and China is also accelerating its pursuit of international advanced levels in this field.

The ship energy management system is a new type of system that generates unified scheduling, management, and control of ship electrical energy based on the actual needs of integrated energy propulsion systems after the emergence of multi energy ships. Through the interaction of energy management and other control functions, combined with intelligent decision-making technology, the environmental adaptability and response level of ships can be improved.

There are currently the following issues in the optimization of power supply networks and intelligent energy management strategies in the shipbuilding industry:

1) The lack or incompleteness of ship multi energy power system models results in unclear optimization objectives of existing optimization algorithms used in research. Therefore, this article explores a comprehensive power optimization objective model for typical power sources.

2) At present, some researchers use various optimization algorithms to optimize their respective models, but the algorithms generally suffer from large model size, slow optimization speed, and the existence of local optimal solutions.

Therefore, the work done in this article is as follows:

Firstly, a mathematical model based on a combination of fuel system, fuel cell, energy storage battery system, and shore power system was established for a reasonable ship energy structure as the optimization objective of the optimization algorithm.

Secondly, in response to the current problems of large models and slow speeds in optimization algorithms, an improved algorithm based on the cuckoo search algorithm is proposed, which improves the convergence speed and accuracy of the algorithm.

Finally, by conducting simulation experiments to analyze the power load of ships under different operating

* Corresponding Author

conditions, the scientific and effective nature of the algorithm proposed in this paper is verified.

The chapter composition of this article is as follows: Chapter 2 mainly discusses the relevant research results and development status, Chapter 3 is the process of establishing an energy management model, Chapter 4 is the objective function optimization stage, Chapter 5 is the experimental and result analysis section, Chapter 6 is the conclusion section of the article, and further research directions are discussed.

2 Related Work

There is relatively more research on ship microgrids and multi energy systems both domestically and internationally. Ancona proposed an optimization framework based on genetic algorithms, which optimizes the load distribution of ship energy systems to maximize energy efficiency while minimizing fuel consumption and heat dissipation. Through this method, ship energy supply is optimized [1]. In order to improve the efficiency of ship energy management, Yinbo first established a mathematical model for energy management, using arrival time and carbon dioxide emissions as constraints. Finally, an improved particle swarm optimization algorithm was used to optimize and iterate the established model. Finally, simulation experiments proved that this method can significantly reduce operating costs and ensure relatively stable ship speed and load distribution curves [2]. Zexin Yang mainly aims to establish an objective function with minimum consumption as the objective, and then chooses differential evolution algorithm for optimization algorithm. Finally, after optimization, the ship speed and propulsion curve become stable, significantly improving the efficiency of ship power system and fuel economy while reducing greenhouse gas emissions [3]. Nengqi Xiao set the research object as the ship's four engine dual propeller hybrid propulsion system, and studied the operating characteristics and corresponding energy flow of the system's four single machine modes, six PTI modes, and two parallel modes. Real time identification of ship operating conditions during ship operation was carried out to minimize fuel consumption and emissions [4]. Lanxi aimed at a hybrid power ship power supply system composed of two different power sources, a generator set and a power battery. By reasonably allocating the power output of the two sources, the total fuel consumption of the hybrid power ship throughout the entire navigation cycle was minimized. Simulation results showed that compared with the switch control strategy, this method can effectively reduce the fuel consumption of the hybrid power system [5]. Liyun Fan, taking parallel vessels as the research object, matched the parameters of the main components such as the hull, propellers, natural gas engines, reversible motors, and power batteries in the system, and studied an energy management strategy based on logical threshold values. Simulation experiments showed that the proposed parallel vessel hybrid power system can achieve a natural gas consumption savings of 4.66% to 7.00% [6].

3 Establishment of an Optimization Model for Ship Energy Management

Compared to ordinary electric propulsion ships, multi energy electric propulsion ships have a more complex composition of their ship power system. When optimizing the energy management strategy of multi energy electric propulsion ships, the problem solved is essentially a complex multivariate, multi constraint, multi-objective non-linear optimization problem. The ship studied in this article consists of a diesel generator set, a fuel power generation system, and a composite energy storage device, which includes a battery section and a supercapacitor section. Ship shore power technology refers to the technology of providing the required electrical energy to the ship through the land power supply at the port during the berthing period. When the shore power system is connected to the land power supply, it can charge the onboard energy storage device as an additional supplement to the ship's electrical energy source, thereby further reducing the ship's fuel consumption and pollution emissions.

3.1 Model Structure

The optimization model for ship energy management strategy of multi energy propulsion ships established in this article is a nonlinear mathematical model with multiple variables, constraints, and objectives. The optimization objective is to improve the economic and environmental efficiency of multi energy electric propulsion ships, and the optimization object is the output schemes of various distributed power sources of multi energy propulsion ships [7]. The optimization model consists of four parts, namely optimization variables, evaluation indicators, limiting conditions, and solution methods. The construction method of the optimization model is:

(1) Select optimization variables from the mathematical model of the research object based on optimization problems;

(2) Design objective functions based on optimization objectives and use them as evaluation indicators for optimization variables;

(3) Set constraints based on the constraints experienced by the research object during actual operation and use them as constraints for optimization variables;

(4) An optimization algorithm that uses evolutionary algorithms as candidate solutions, that is, a method for solving approximate optimal solutions as optimization variables.

3.2 Objective Function

The optimization objective is to improve the economic and environmental efficiency of multi energy electric propulsion ships [8], and the objective function is expressed as follows:

$$\begin{cases} \min y = F\left(x\right) = \left(f_1(x), \cdots, f_n(x)\right) \\ f = \left(f_1, \cdots, f_n\right) \in Y \subset R^n \\ x = \left(x_1, \cdots, x_d\right) \in X \subset R^d \end{cases} . \tag{1}$$

Therefore, economic and environmental goals are expressed as:

$$\begin{cases} \min F = \min(f_1(x), f_2(x)) \\ f_1 = C_Y + C_X + C_R + C_A \\ f_2 = Q_{gas} \end{cases} . \tag{2}$$

In the formula, F represents the total operating cost of the ship, while $f_1(x)$ and $f_2(x)$ represent the economic and environmental costs of the ship, namely the operating cost of the multi energy propulsion ship's power system and the total amount of pollution emissions from the ship; C_Y. C_X, C_R, and C_A represent the usage costs of marine diesel generator sets, battery packs, supercapacitors, and shore power systems, respectively; Q_{gas} represents the total amount of pollutant gas emissions from marine diesel generator sets, and the specific representation of each parameter is as follows:

(1) The operating cost of marine diesel generator set C_Y:

$$C_Y = price \cdot Q_F + \alpha \cdot P_{CY} . \tag{3}$$

$$Q_F = \eta_F \cdot P_{CY} . \tag{4}$$

$$\eta_F = \begin{matrix} a_1 \cdot L_{load} + a_2 & 0 < L_{load} \le 60 \\ a_3 \cdot L_{load} + a_4 & 60 < L_{load} \le 80 \\ a_5 \cdot L_{load} + a_6 & 80 < L_{load} \le 100 \\ a_7 \cdot L_{load} + a_8 & 100 < L_{load} \le 120 \\ a_9 \cdot L_{load} + a_{10} & 120 < L_{load} \le 130 \end{matrix} . \tag{5}$$

price is the fuel price, Q_F is the real-time fuel consumption of the marine diesel generator, α is the coefficient of operation and maintenance costs of the diesel generator, P_{CY} is the real-time output power of the marine diesel generator, η_F is the fuel consumption rate of the diesel generator at the corresponding output power, and the fuel consumption rate will change with the load rate of the diesel generator.

(2) The usage cost C_X of a battery pack is expressed as:

$$C_X = D_T = \beta_X \cdot \left(B_T + B_F\right) . \tag{6}$$

In the formula, D_T represents the performance degradation cost of the battery pack; β_X is the performance degradation coefficient of the battery pack; B_T is the number of alternating charging and discharging cycles of the battery pack; B_F is the degree of excessive use of the battery pack. During the use of batteries, there will be indirect usage costs caused by battery aging and degradation. Each charge and discharge of a battery will damage its remaining life, and the rate of decline in its remaining life is influenced by multiple factors such as charge and discharge rate, depth of charge and discharge, state of charge, battery usage frequency, and battery usage environment. Moreover, there is currently no unified and accurate calculation model for calculating the remaining life of batteries, most of them are prediction models for the remaining life of batteries.

(3) The usage cost C_R of supercapacitors is expressed as:

$$C_R = Deg_R = \beta_R \cdot C_c . \quad \mathbf{(7)}$$

In the formula, Deg_R represents the performance degradation cost of the supercapacitor; β_R is the performance degradation coefficient of the supercapacitor; C_c is the number of alternating cycles of charging and discharging for the battery pack. Among them, similar to the degradation phenomenon of battery packs, supercapacitors also exhibit performance degradation. However, in the practical application of supercapacitors, the reasonable range of current capacity that can be achieved is 0-100% of rated capacity, so the impact of current capacity of supercapacitors on their performance degradation can be ignored.

(4) The usage cost C_R of fuel cells is represented as follows [9]:

$$C_R = \lambda_r H_Z(t) . \quad \mathbf{(8)}$$

Among them, λ_r is the penalty coefficient for fuel cells, and $H_Z(t)$ is the direct hydrogen energy consumption of vehicle fuel cells.

(5) The usage cost C_A of the ship's shore power system is expressed as:

$$C_A = \tau C_{A-F} . \quad \mathbf{(9)}$$

In the formula, C_{A-F} is the cost required for a marine diesel generator set assuming that the electricity produced by the marine diesel generator set is the same as that produced by the shore power system. τ is a constant, and the electricity production cost of the land power grid is usually only about 30% of the electricity production cost of the ship.

(6) The total amount of pollutant gas emissions Q_{gas} is expressed as follows:

$$Q_{gas} = \sum_{i=1} \rho_i \cdot \xi_i \cdot Q_F . \quad \mathbf{(10)}$$

In the formula, Q_F is the real-time fuel consumption of the marine diesel generator; ρ_i is the low load rate regulation coefficient of marine diesel generator sets; ξ_i is the conversion coefficient of different pollutant gases emitted by marine diesel generators when consuming fuel. Assign weight coefficients to each objective to transform multi-objective problems into single objective problems, using currency as a unified settlement method. Therefore, the improved pollution emissions are represented as:

$$f_2 = \theta_i \cdot \xi_i \cdot Q_F . \quad \mathbf{(11)}$$

Among them, θ_i represents the treatment cost of different types of pollution gas emissions from marine diesel generators. Therefore, the final optimization model objective function is expressed as:

$$\begin{aligned} \min y &= prince \cdot \eta_F \cdot P_{CY} + \alpha \cdot P_{CY} + \beta_X \cdot (B_T + B_F) \\ &+ \beta_R \cdot C_c + \lambda_r H_Z(t) + \tau C_{A-F} + \sum_{i=1} \rho_i \cdot \xi_i \cdot Q_F \end{aligned} . \quad \mathbf{(12)}$$

3.3 Constraint Condition

The constraint conditions consider the output power constraints of distributed power sources, capacity constraints of energy storage devices, and range constraints. The various constraint conditions are represented as follows:

(1) Distributed power output power constraints:

$$P_i^{\min} \le |P_i| \le P_i^{\max} . \tag{13}$$

In the formula, P_i represents the output power of each distributed power source, and $P_i^{\max}$ and $P_i^{\min}$ represent the upper and lower power limits of each distributed power source.

(2) Capacity constraints of energy storage devices.

$$E_i^{\min} \le E_i \le E_i^{\max} . \tag{14}$$

In the formula, E_i represents the current capacity of each energy storage device; $E_i^{\max}$, $E_i^{\min}$ represents the upper and lower capacity limits of the energy storage device, respectively.

(3) Range constraints

$$\sum_{t=i}^{T} V_S(t) \cdot \Delta t - DIS_i < \Delta DIS_i . \tag{15}$$

In the formula, $V_S(t)$ is the real-time speed of the ship; Δt is the time interval; ΔDIS_i is the expected planned voyage for the i-segment navigation mission.

4 Establishment of an Optimization Model for Ship Energy Management

When ships work under complex working conditions, in order to ensure the power performance of the ship, fully utilize the advantages of fuel cells and lithium batteries, reasonably allocate power between multiple power sources, improve energy utilization efficiency, and extend the service life of energy storage units, this paper adopts a bus voltage coordination control strategy, and optimizes the parameters in the strategy using a cuckoo search algorithm based on population feature feedback [10]. The coordinated control strategy for bus voltage is shown in Fig. 1.

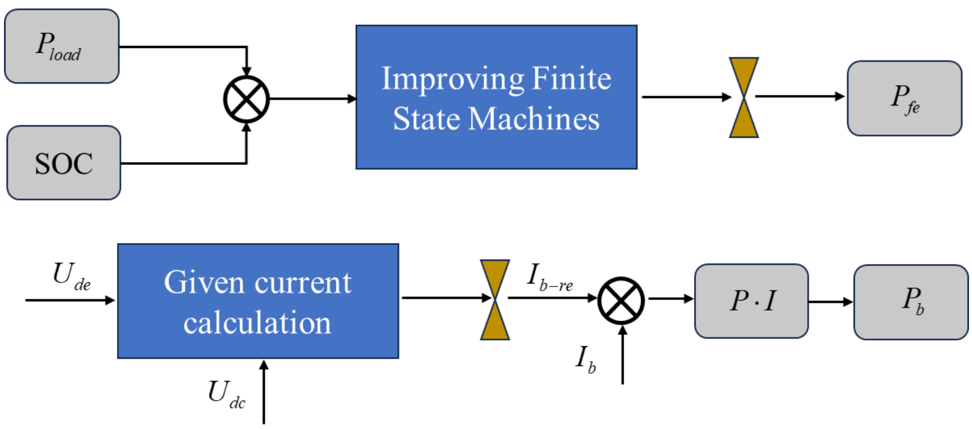


Fig. 1. Schematic diagram of coordinated control strategy

The power balance equation of the ship's DC power grid busbar is expressed as follows:

$$\begin{cases} P_b = P_{load} - P_{fe} \\ I_b = \dfrac{P_b}{U_{dc}} = \dfrac{P_{load} - P_{fe}}{U_{de}} \end{cases} . \quad \textbf{(16)}$$

Assuming that the output power P_{fe} and load power P_{load} of the fuel cell are not affected by the bus voltage, and regardless of how P_{fc} and P_{load} change, given a bus voltage U_{dc}, there is always a bus current I_b that holds. There is a deviation relationship between the bus voltage of the ship's DC power grid, the ship's load, and the various power sources of the ship, as follows:

$$\varepsilon = \frac{V_{cl} - V_{ck}}{V_{cl}} \times 100\% . \quad \textbf{(17)}$$

In the formula, V_{cl} is the measured value of the DC bus voltage, and V_{ck} is the reference value of the DC bus voltage.

The optimization of control strategy parameters is based on the basic cuckoo algorithm. In the early stage of evolution, the population diversity is low, the search space is narrow, and the convergence ability is insufficient in the later stage of search. Therefore, the overall search speed is slow. Therefore, this article uses an improved cuckoo search algorithm to optimize control strategy parameters. The parameter optimization principle of the intelligent search algorithm is shown in Fig. 2.

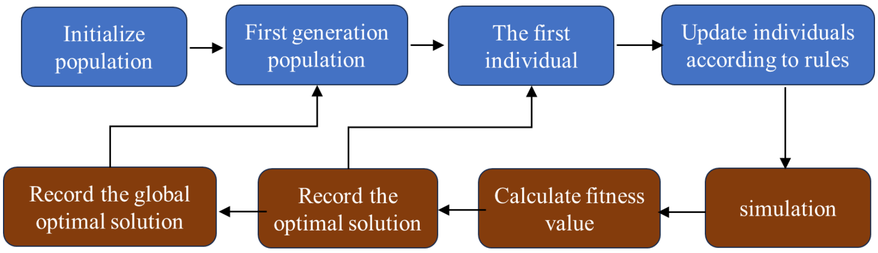


Fig. 2. Schematic diagram of coordinated control strategy

The improved cuckoo search algorithm steps are as follows:

Step 1: Initialize the population and set the termination conditions for the algorithm;

Step 2: For each individual, i.e. a candidate solution in the search space, each candidate solution corresponds to a fitness value, and the cuckoo algorithm searches for the next candidate solution in a random walk manner. If the new solution is retained, the number of cuckoo bird juveniles increases by 1 and the number of elderly individuals decreases by 1, thus obtaining the ratio of the number of juveniles to the number of elderly individuals in the population;

Step 3: Generate random numbers between [0,1], compare them with the probability of discovering the optimal solution, and determine the number of individuals exploring new fields based on probability. Record the mutation status of each individual as 0, indicating failure;

Step 4: Generate a random number between [0,1], compare it with the probability of selecting an evolutionary strategy, walk randomly according to preferences, and improve two evolutionary strategies to control changes one by one dimension. Then, gradually generate fresh solutions. If the new solution is retained, the number of successful individuals increases by 1. Otherwise, the number of unsuccessful individuals increases by 1. Regardless of which evolutionary strategy an individual follows, as long as a new solution is retained, it is considered to have successfully mutated, Record the mutation status as 1.

Step 5: Repeat the above process to determine the search step size, discovery probability, and evolutionary strategy selection probability for the next generation population.

Step 6: Record the global optimal solution. If the termination condition is not met, repeat steps 2 to 5.

5 Simulation Experiments and Result Analysis

To verify the effectiveness of the proposed method, a simulation was conducted using a certain ferry as an example. The relevant parameters of the ferry, as well as the technical parameters of the generator set and diesel engine it is equipped with, are shown in Table 1. The relevant parameters of lithium batteries are shown in Table 2. The parameters related to fuel cells are shown in Table 3.

Table 1. Technical parameters of ship diesel engines and generators

	Ship power system		Ship fuel system
	Generator 1	Generator 2	Diesel engine
Minimum start stop time (on/ off)	1/1	1/1	1/1
Start stop consumption (*m.u.*)	200/0	200/0	200/0
Minimum power/ *MW*	1	1	4.6
Maximum power/ *MW*	4	4	24.5
Fuel consumption (*m.u.*/ *tn*)	500	500	450
Fuel consumption rate (*kg*/ *MWh*)	343.5-80.3P	343.5-80.3P	210.5-80.3P
Mass of CO2 released per g of fuel (g)	2.5	2.5	3.2

Table 2. Energy storage lithium battery parameters

Parameter	Numerical value
Power cost coefficient/ yuan	2500
Capacity cost coefficient/ yuan	670
Operation and maintenance cost coefficient/ yuan	0.06
charge-discharge efficiency/ %	97
rated power/ *kw*	229
rated capacity/ *kw·h*	1.7
Upper limit of state of charge/ %	80
Lower limit of state of charge/ %	15

Table 3. Model parameters of hydrogen supply system

Parameter	Numerical value
Hydrogen adiabatic index	1.41
Nozzle emission coefficient	0.87
Effective area of nozzle/ m^2	3.5×10^{-6}
Molar mass of hydrogen gas/ *kg*/ *mol*	0.002
Gas constant of hydrogen/ *J*/ (*kg* · *K*)	4124.3
Volume of intake duct/ m^3	0.002
The nozzle coefficient of the intake duct/ *kg*/ (*s* · *Pa*)	3.7×10^{-5}
Faraday constant	96485
Number of stack batteries	423
Anode flow field volume/ m^3	0.006
Exhaust pipe volume/ m^3	0.006
Exhaust valve flow coefficient/ *kg*/ (*s* · *Pa*)	5×10^{-9}

Assuming the total distance of the route from the port of departure to the destination port is 302.6nm, which requires passing through three intermediate ports. The distances between each intermediate port and the port of departure are 86.13nm, 162.04nm, and 227.69nm, respectively. The optimization results are shown in Fig. 3.

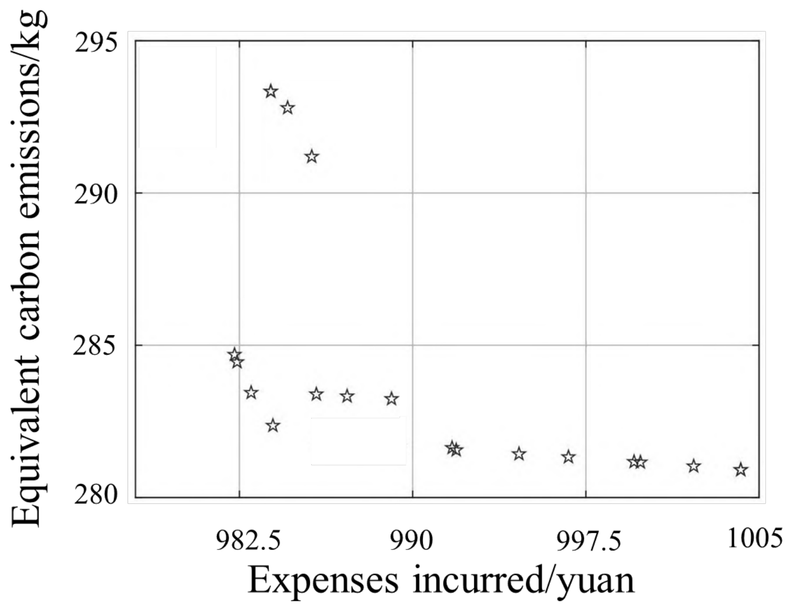
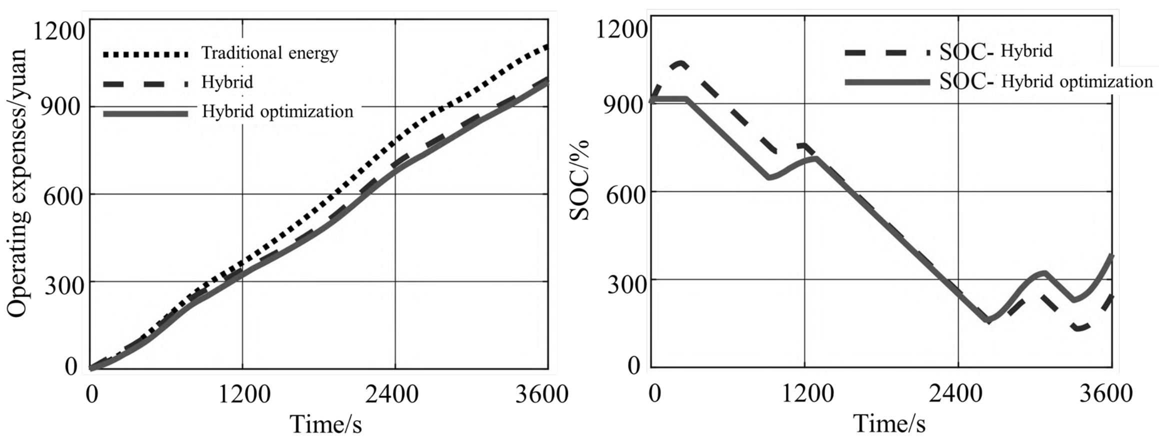


Fig. 3. Optimal Results

Comparing the traditional driving mode and energy management mode with initial and optimized parameters, the results are shown in Fig. 4. Fig. 4(a) shows a comparison of fuel consumption. The traditional power system has a fuel consumption of 73.78 kg, while the energy managed power system has a fuel consumption of 66.38 kg, which is 10.03% less than the transmission power. The optimized hybrid system has a fuel consumption of 65.60 kg, which is 11.09% less than the traditional power system and 1.18% less than the unoptimized hybrid system. Fig. 4(b) shows a comparison of battery SOC. The final SOC value of the hybrid system is 49.12%, while the optimized hybrid system has a final SOC value of 50.93, which is 1.81% higher than the unoptimized value.



(a) Economic consumption

(b) Battery SOC

Fig. 4. Optimize simulation results

Under the same ship operating conditions, when the initial SOC of the lithium battery is 45%, 70%, and 90% respectively, the output power of the fuel cell and the change in SOC of the lithium battery under the power tracking strategy and the energy management strategy proposed in the article are compared. When the initial values of the lithium battery are 45%, 70%, and 90% respectively, after completing the same operating condition, the range of SOC change of the lithium battery is about 0.9%, And when the lithium battery is in low SOC mode and medium SOC mode, the output power of the fuel cell exceeds the maximum output power in 370-430s.

6 Conclusion

The development direction of future ships is fully electric ships with integrated electric propulsion system as the core technology. Energy management system is one of the control cores of multi energy ships. Good cooperation with other control systems of ships can maximize their performance, which is of great significance for reducing crew and increasing efficiency, and improving survival ability of ships. This article mainly studies the intelligent decision-making system for multi energy ship energy management, including the design scheme of the intelligent decision-making system for ship energy management, modeling research on ship propulsion system, and research on the coordinated control strategy of “power generation energy storage” energy. After the above work, the expected results have been achieved.

References

[1] M.A. Ancona, F. Baldi, M. Bianchi, L. Branchini, F. Melino, A. Peretto, J. Rosati, Efficiency improvement on a cruise ship: Load allocation optimization, Energy Conversion and Management 164(2018) 42-58.

[2] B. Yin, X.-H. Wang, J.-M. Xiao, Ship energy management scheme based on improved particle swarm optimization algorithm, Chinese Journal of Ship Research 15(6)(2020) 37-45.

[3] Z.-X. Yang, J.-M. Xiao, X.-H. Wang, J. Deng, Optimization strategy of ship energy management system based on differential evolution algorithm, Chinese Journal of Ship Research 13(4)(2018) 134-141.

[4] N.-Q. Xiao, X. Xu, R.-P. Zhou, Energy management and control strategy of ship diesel-electric hybrid power system, Journal of Harbin Engineering University 41(1)(2020) 153-160.

[5] L.-Y. Fan, H.-X. Zhang, C. Xu, S.-H. Xu, Z.-J. Jiang, Parameter Matching and Energy Management of Parallel Marine Hybrid Power System, Ship Engineering 43(4)(2021) 60-65.

[6] X. Lan, A.-D. Shen, D.-J. Gao, Y.-Y. Sun, Optimal control of hybrid ship energy management system, Chinese Journal of Power Sources 40(9)(2016) 1859-1862.

[7] D.-X. Miao, L. Chen, X.-R. Wang, Energy management strategy of marine series hybrid system based on NSGA-II optimization, 44(14)(2022) 113-118.

[8] Y.-P. Si, R.-J. Wang, S.-Q. Zhang, W.-T. Zhou, A.-H. Lin, G.-M. Zeng, Multienergy complementary optimal management for a new type of energy system for ships, Journal of Harbin Engineering University 43(7)(2022) 1051-1058.

[9] Z.-Y. Li, L.-P. Duan, S.-H. Li, J. Feng, Modeling and Simulation Analysis of MW-Level Fuel Cell Distributed Generation System Based on AspenPlus, Southern Energy Construction 9(4)(2022) 78-86.

[10] Y.-Y. Gao, X.-H. Miao, Fuzzy Clustering Algorithm Based on Adaptive Cuckoo Search, Control and Instruments in Chemical Industry 49(6)(22) 725-731.