Ship Energy Management Based On Differential Evolution Algorithm

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Abstract

modern maritime shipping industry provides a very convenient way for China's trade with other countries, but maritime shipping industry also brings some negative effects on the Marine environment and atmospheric environment.All kinds of anti-pollution conventions require the transformation of shipping industry.This paper proposes an energy management strategy based on ship power system operation constraints and greenhouse gas emission constraints.This strategy aims at the minimum energy consumption, and within the limitation of ship operation efficiency, intelligent scheduling is carried out for power distribution, power generation, switch start and stop, so as to reduce environmental pollution and fuel consumption at the same time.Taking the navigation data of a certain ship as the object, the energy management strategy is compared with the unused strategy. The results show that the strategy can ensure the fuel economy and reduce the greenhouse gas emission while keeping the ship stable under various constraints.

Keywords

Marine power system, energy management strategy, differential evolution algorithm, economic environment scheduling.

1. Introduction

Ship energy management system is very important for ships. A good energy management system can reduce ship operation cost, save energy and reduce greenhouse gas emissions [1-2].

Therefore, when designing the ship energy management system, it is necessary to consider the operation cost and environmental protection issues [3-4].

Liu le, Gao haibo et al. designed a ship energy management system based on the fuzzy controller of particle swarm optimization algorithm for the hybrid power system of diesel engine and battery to reduce fuel consumption and greenhouse gas emissions [5].Under the same condition, the simulation results show that the proposed method has better performance than the conventional fuzzy controller.Shang, Srinivasan et al. proposed an energy management system combining power generation scheduling, load management (propulsive load-cruise speed) and energy storage system to optimize the operation of diesel generator set with non-dominant sequencing genetic algorithm[6].Chen chen et al. proposed an energy management strategy based on load power transmission model, proposed to use the performance index with the least fluctuation of the power station, and adopted particle swarm optimization algorithm to conduct energy allocation between the power station and the energy storage system of the system[7].Seenumani, Sun et al. proposed the energy relationship strategy based on renewable energy and energy storage system, and analyzed the marginal cost of the ship's power system from the perspective of economy[8].

For classical optimization problems of ship energy management system, this article uses the differential evolution algorithm, based on the ship speed, generators, generating set start-stop state power allocation optimization scheduling, in meet the generator and diesel engine related constraints, navigation related constraints, as well as greenhouse gas emissions constraints, reduce operating costs and greenhouse gas emissions.

2. Objective Function and Constraint Conditions

2.1 Objective Function

The purpose of putting forward the energy management strategy is to optimize and adjust the ship speed, power of generator set and start and stop, so as to reduce the cost and environmental pollution as much as possible under the condition that it meets the constraint conditions.

The objective is formulated as follows:

$$\min Co = Co_e + Co_{pr} \tag{1}$$

Where, Co is the total operating cost(m.u.);Co_e is the total cost of the electrical service system(m.u.);Co_{pr} is the cost of propulsion power(m.u.).The total cost of the power service system can be determined by the following formula:

$$Co_e = \sum_{j=1}^{T}\sum_{i=1}^{N_D}\left\{P_{ij}\cdot \Delta T_j \cdot \left[t_{ij}\cdot\left(F_{c_i}\cdot S_{FC_i}\left(P_{ij}\right)+W_{Cij}\right)\right]+Q_{Cij}\right\} \tag{2}$$

Where，T is running time, N_D is the number of generators, P_{ij} is the i th generator in interval ΔT_j generated within the power; F_{ci} is the fuel unit price of the generator; S_{FCi} is generator specific fuel consumption; W_{Cij} is the maintenance cost of the operating unit; Q_{Cij} is the start-up cost; t_{ij} is 1 or 0, 1 means on, 0 means off.

The power generated by the i th generator is:

$$P_{ij} = \frac{P_{el-L,j}\cdot P_{n,i}}{\sum_{i'\in N} P_{n,i'}} \tag{3}$$

Where, N is the number of running generators; $P_{el-L,j}$ is Power load for the generator; $P_{n,i}$ is the rated power of the i th generator.

The fuel consumption per hour of a generator can be approximately expressed by a polynomial (4) :

$$F_{C_i}(P_i) = a_{0i} + a_{1i}\cdot P_i + a_{2i}\cdot P_i^2 + a_{3i}\cdot P_i^3 \tag{4}$$

In order to determine the optimal operating point of the system, the specific fuel consumption is defined as the fuel consumption required to produce one thousand watts of power per hour (5) :

$$S_{FC_i}(P_i) = F_{C_i}(P_i)/P_i \tag{5}$$

For the propulsion system, its operating cost is calculated according to equation (6) :

$$Co_{pr} = \sum_{j=1}^{T}\sum_{q=1}^{N}\left\{t_{qi}\cdot P_{qj}\cdot \Delta T_j \cdot \left[t_{qj}\cdot\left(F_{c_q}\cdot S_{FC_q}\left(P_{qj}\right)+W_{Cqj}\right)\right]+Q_{Cqj}\right\} \tag{6}$$

Where, N_{pr} is the number of diesel engines; P_{qj} is the power generated by the diesel engine of the q th engine. F_{cq} is the fuel cost of the q th engine; S_{FCq} is diesel engine specific fuel consumption; W_{Cqj} and Q_{Cqj} are respectively the maintenance cost and start-up cost of the operating unit;t_{qj} is 1 or 0, 1 means on, 0 means off.

Suppose the power generated by the q th diesel engine is as follows:

$$P_{qj} = P_{pr-L,j}\cdot P_{n,q} / \sum_{q'\in N} P_{n,q'} \tag{7}$$

Where: N is the number of all running diesel engines; $P_{pr-L,j}$ is the propulsion loads provided by all running diesel engines; $P_{N,q}$ is the rated power of the q th diesel engine.

2.2 Constraint Conditions

2.2.1 Constraint Conditions of Generators

(1) Power constraint of generator

$$P_{\min,i} \le P_i \le P_{\max,i} \tag{8}$$

Where, $P_{max,i}$ and $P_{min,i}$ are the maximum and minimum values of the generator power respectively.

(2) Constraint between the total power generated by the generator set and the power load.

$$\sum_{i=1}^{N_E} t_{ij} \cdot P_{ij} = P_{el-L,\mathrm{j}} \tag{9}$$

(3) Constraint of climbing speed of generator set.

$$\frac{\left|P_{ij} - P_{i,j-1}\right|}{\Delta T_j} \le R_{ei} \tag{10}$$

Where, R_{ei} is the maximum climbing slope of the i th generator.

(4) Minimum continuous running time constraint of generator set.

$$T_{on\to off,i} - T_{off\to on,i} \ge T_{on\_\min,i} \tag{11}$$

(5) Constraint of minimum downtime of generator set.

$$T_{off\to on,i} - T_{on\to off,i} \ge T_{off\_\min,i} \tag{12}$$

(6) Prevent abnormal flameout limit (even if the largest generator is offline, the generator should be able to provide sufficient load)

$$\sum_{i=1}^{N_E} t_{ij} \cdot P_{\max,i} - \max_i \left\{ t_{ij} \cdot P_{\max,i} \right\} \ge P_{el-L,j} \tag{13}$$

2.2.2 Constraint Conditions of Diesel Engine

(1) Power constraint of diesel engine

$$P_{\min,q} \le P_q \le P_{\max,q} \tag{14}$$

(2) Constraint between the power generated by the diesel unit and the propulsion load

$$\sum_{q=1}^{N_E} t_{qj} \cdot P_{qj} = P_{pr-L,\mathrm{j}} \tag{15}$$

Diesel unit climbing speed constraints

$$\frac{\left|P_{qj} - P_{q,j-1}\right|}{\Delta T_j} \le R_{eq} \tag{16}$$

Where, R_{eq} is the maximum climbing slope of the q th diesel engine

Minimum continuous running time constraint of diesel unit

$$T_{on\to off,q} - T_{off\to on,q} \ge T_{on\_\min,q} \tag{17}$$

Constraint of minimum shutdown time of diesel unit

$$T_{off\to on,q} - T_{on\to off,q} \ge T_{off\_\min,q} \tag{18}$$

2.2.3 Constraints of Sailing Distance and Speed

In the energy management optimization case, fuel consumption can be reduced by optimizing ship speed adjustment. The relationship between the effective propulsion of a ship and its resistance (which is related to the ship's cargo weight, environmental temperature and other factors) and the ship's speed *1* is shown in equation (19) .

$$P_{e-pr} = k \cdot V^3 \tag{19}$$

Where, V is ship speed; k depends on the objective conditions of the ship, such as hull shape, loading conditions, etc.

The speed constraint is as follows:

$$V_{\min,j} \le V_j \le V_{\max,j} \quad (20)$$

Where, $V_{max,j}$ and $V_{min,j}$ are respectively the maximum and minimum values of sailing speed.

The constraint of the initial voyage distance of the ship and the voyage distance when reaching the destination.

Suppose the ship starts at time 0 and reaches the terminal at time T, then

$$t = 0: \qquad D_0 = 0 \quad (21)$$

$$t = T = \sum_{j}^{N_T} \Delta T_j: \qquad D_{N_T} = d_{total} \quad (22)$$

Where, N_T is the number of discrete time points from the beginning time to the last time T;D_{Nt} is the sailing distance, and d_{total} is the total distance of the route.

Restrictions on the sailing distance of a ship when it arrives at an intermediate port:

$$D_j = d_j \quad (23)$$

Where, D_j is the sailing distance to the middle port, and d_j is the actual distance to the middle port.

The ship's speed, sailing distance and constraint curve of a certain voyage are shown in fig.1.

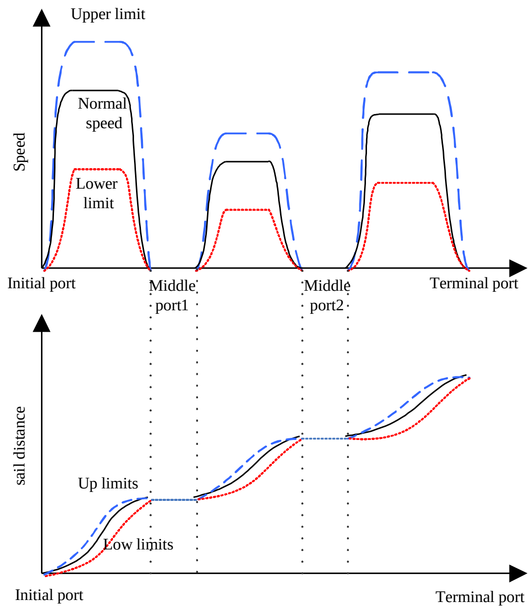

Fig.1 ship speed constraints and voyage distance constraints

2.2.5 greenhouse gas emission constraint

Energy Efficiency operation-convolutional Indicator(EEOI) is a method of evaluating the operating Efficiency of ships. It refers to the greenhouse gas emissions per unit of cargo turnover (ship's cargo volume times transport volume) , and ships must follow the constraints of EEOI on gas emissions during navigation [9].η_{EEOI} is defined as the ratio of the mass of carbon dioxide produced per unit of transport effort per unit of time interval D_{Tj}.

$$\eta_{EEOI_{1,j}} = \frac{m_{CO_2,j}}{\alpha_{LF} \cdot V_j \cdot \Delta T_j} \quad (24)$$

Where, m_{CO2} is the mass of CO_2 emitted;α_{LF} is the ship load factor.

As greenhouse gas emissions are directly proportional to fuel consumption,they can be calculated by the fuel consumed by generators and diesel engines multiplying the conversion coefficient c_i and c_q respectively.

Therefore, the total carbon dioxide emissions of the ship in each time period D_{Tj} are as (25):

$$m_{CO_{2},j}=\sum_{i=1}^{N_E} ti_j\cdot c_i\cdot S_{FC_i}(P_{ij})\cdot P_{ij}+\sum_{q=1}^{N_{pr}} t_{qj}\cdot c_q\cdot S_{FC_q}(P_{qj})\cdot P_{qj} \tag{25}$$

Where,α_{LF} depends on the type of ship.If the ship's rated number of passengers and number of vehicles are respectively n_p and n_v, and the actual number of passengers and number of vehicles are respectively $n_p^{'}$ and $n_v^{'}$, then α_{LF} is (26):

$$\alpha_{LF}=\frac{0.1n_p^{'}+n_v^{'}}{0.1n_p+n_v}\cdot G_T \tag{26}$$

Where G_T is the gross tonnage of the ship.

When the ship is in berth, its speed is 0, η_{EEOI} is calculated by the following formula(27):

$$\eta_{EEOI_{2,j}}=\frac{m_{CO_{2},j}}{\alpha_{LF}\cdot\Delta T_j} \tag{27}$$

The EEOI limit should be less than its maximum value:

$$\eta_{EEOI_{1,j}}\le\eta_{EEOI_{max,1}} \tag{28}$$

$$\eta_{EEOI_{2,j}}\le\eta_{EEOI_{max,2}} \tag{29}$$

It takes a variety of methods to reduce the carbon dioxide emissions of ships , and adopts the strategy of reducing the speed for the ship's navigation, which achieves the goal of reducing the greenhouse gas emissions and has practical reference significance.

2.3 Description of Power Generation Scheduling

In order to determine the number of generators and diesel engines used to achieve the optimal load power distribution, it is necessary to accurately predict the ship load. This is achieved by systematically recording cargo loads and passenger Numbers during the voyage.

When given the time sequence curve of the power load, the running generator and the power generated can be selected. In conventional ship power system configuration, load is managed by adjusting ship speed to reduce CO2 emissions to meet environmental constraints.

In any case, for the small fluctuation of actual load beyond the expectation, the real-time optimal control system can be used by the ship power system to manage through appropriate power generation adjustment[9] and load priority start and stop .

3. Differential evolution algorithm

Differential evolution algorithm is a kind of intelligent optimization algorithm based on population. It does not rely on the characteristic information of the problem. It searches the entire individual space by means of the perturbation formed by the difference information between individuals in the population, and using the greedy competition mechanism to optimize, so as to seek the optimal solution of the problem.it adopts the real number coding method and mainly solves the optimization problem in the continuous field[10].The variation of the algorithm can effectively utilize the distribution characteristics of the population to improve the search ability of the algorithm.For optimization problems:

$$\min f(x_1,x_2,x_3,\cdots,x_D) \tag{29}$$

Where j= 1,2..., D, D is the dimension of the solution space, respectively representing the lower bound and the upper bound of the value range of the j th component.

3.1 Differential Evolution Algorithm

The differential evolution algorithm is based on real number coding. Firstly, the random initializing species group should be generated in the interspace of the feasible solution of the problem. The initial population is generated randomly in the parameter space and should cover the whole parameter space.

In each generation of evolution, each target individual is mutated and intersected to generate the test individual, and then the target individual and the test individual are selected to select the individuals with better adaptive value into the next generation.

After scaling the difference vector of the individuals in the population, the variation vector is obtained by adding the difference vector with other dissimilar individuals in the population.

$$v_{i,g} = x_{r_1,g} + F \cdot \left(x_{r_2,g} - x_{r_3,g} \right) \tag{30}$$

Where, g is algebra;r_1, r_2, r_3 are taken randomly from the population set, which also makes the population size N_P impossible less than 4;F is the scaling factor, which controls the scaling of the difference vector to avoid the stagnation of search, and its selection range is 0.5~1[10].In the crossover process after mutation, at least one component of the generated test vector is generated by the mutation vector through random selection.

$$u_{i,j,g} = \begin{cases} v_{i,j,g} & rand(0,1) \le CR \ or \ j = j_{rand} \\ x_{i,j,g} & others \end{cases} \tag{31}$$

Where, J_{rand} is a randomly selected integer in [1, D];$CR \in (0,1)$ was the crossover rate.

The test vector $u_{i,g}$ and the target vector $x_{i,g}$ generated after mutation and crossover operation are competitive. When the fitness value of $u_{i,g}$ is better, it is selected as the offspring. Otherwise, $x_{i,g}$ are the children.

$$x_{i,g+1} = \begin{cases} u_{i,g} & f(u_{i,g}) < f(x_{i,g}) \\ x_{i,g} & others \end{cases} \tag{32}$$

Where, $x_{i,g+1}$ are the target vectors of the next generation. The flow chart of the application of differential evolution algorithm in this paper is as follows:

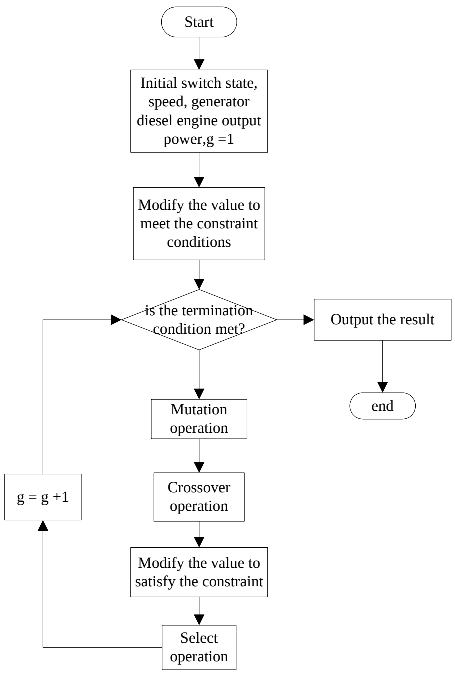

Fig.2 implementation flow chart of differential evolution algorithm

4. Simulation and Analysis

4.1 Simulation

In order to verify the effectiveness of the differential evolution algorithm for this problem, the data in literature [11] were used for comparative verification. With a gross tonnage of 48,750*t*, a maximum speed of 23.5*kn*, a maximum transport capacity of 1,800 passengers and 500 vehicles, a maximum allowable CO_2 emission value of 21*g /(t·kn)* for $EEOI_1$, and a maximum allowable CO_2 emission value of 120*g /(t·h)* for $EEOI_2$.The simulated ship is equipped with 3 generators and 2 diesel engines. All parameters of the generator and diesel engine are shown in table 1.

Table1 Ship Power System Model Data

Pamameters	IDG1	IDG2	IDG3	PM1	PM2
Rated power/MW	4	4	4	17.5	17.5
Minimum on/off time/h	1/1	1/1	1/1	1/1	1/1
on/off cost /m.u.	200/0	200/0	200/0	200/0	200/0
SFC /(kg·MW-1·h-1)	345.4-80.4P+12.6P2	345.6-73.8P+11.11P2	345.4-69.6P+10.45P2	211.6-5.21P+0.2316P2	211.6-4.47P+0.1987P2
CO2 emission per unit/g	2.5	2.5	2.5	3.2	3.2
Fuel cost(m.u.·t-1)	500	500	500	450	450
Pmin/MW	1	1	1	4.35	4.35
Pmax/MW	4	4	4	17.5	17.5

There are two intermediate ports in the route. Passengers, vehicles and corresponding ship load factors of each part of the transit route are shown in table 2.Figure 3 shows the ship's electric load, including the total electric load, propulsion load and service load. Generators are numbered according to their operation priority, and the minimum allowable time between continuous start and stop is 1 *h*. Each working diesel engine drives the propeller with the same propulsion load, and the diesel engine is numbered according to its running priority.

Table2 Data for Ship Fullness

route	passagers	cargo	load
harbor 0-harbor 1	1315	400	38103
harbor 1-harbor 2	1255	375	35880
harbor 2-destination harbor	1319	402	38276

In this paper, two different operation cases are adopted for comparative test. The cases are as follows:

case 1: with three generators and two independent propulsion diesel engines, no power scheduling, propulsion adjustment and no EEOI limitation, the generator and diesel engine adopt the proportional distribution method.

case 2:three generators and two independent propulsion diesel engines, with power scheduling, propulsion adjustment and EEOI limitation.

4.2 Simulation results and analysis

The operation cost of case 1 is 2721.1 m.u. and that of case 2 is 2640.1 m.u. The energy management strategy proposed in case 2 is used to adjust the power distribution and propulsion to improve the operational efficiency of the ship's power system and to limit the EEOI during navigation. The results are shown in Fig. 4-9.

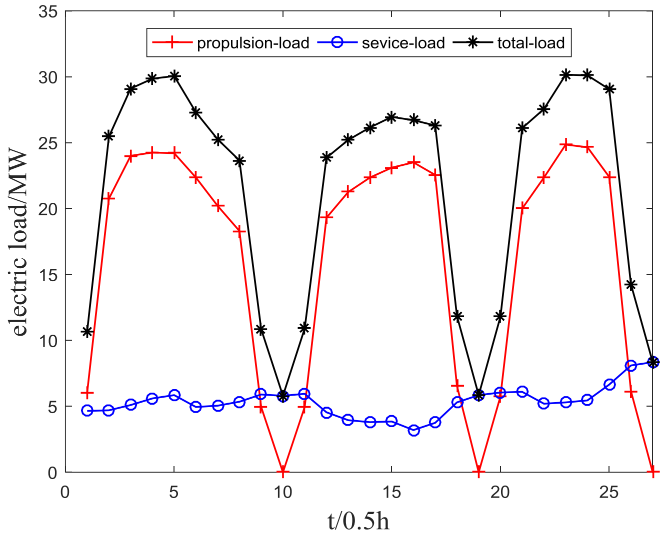

Fig.3 Propulsion load, service load and total ship electric load

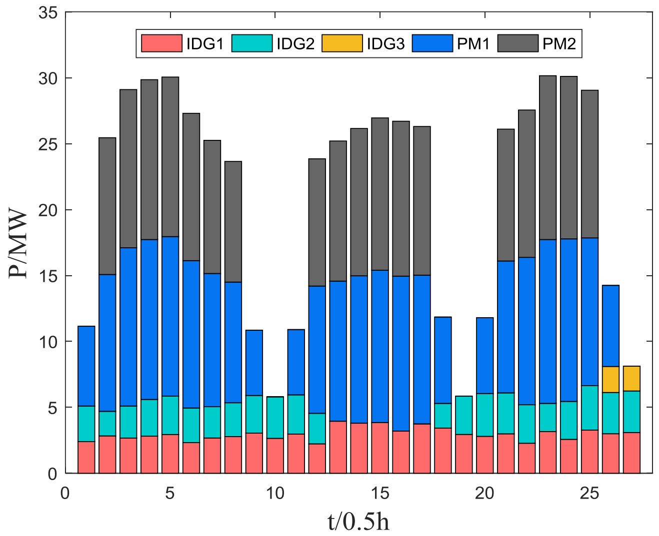

Fig.4 Power provided by generators and diesel engines in case1

It is assumed that under all operating conditions, PM1, IDG1 and IDG2 have been running for 0.5h at t=1.The power generated by the main generator and the propulsion system diesel engine is shown in figure 4-5. IDG is the generator and PM is the diesel engine.

In case 1 and 2, the propulsion load is equally distributed to the running diesel engine; In case 1, the power load is also equally distributed to the running generator. In case 2, the distribution mode is changed.IDG1 is in continuous operation, and IDG2 is almost in continuous operation (except T13~T17), while IDG3 is only in high power load period (T26~T27).

In case 1, the ship speed and propulsion are not adjusted, and only the electric power distribution is adjusted, so the results are only different in the electric power distribution. The total load of the ship will deviate greatly in adjacent time periods and cannot keep relatively stable, so the reduction of operation cost can be ignored.

In case 2, power and propulsion are adjusted. the diesel engine's output power changes greatly, the total load of the ship fluctuates less in adjacent time periods, and the operation cost is greatly reduced.

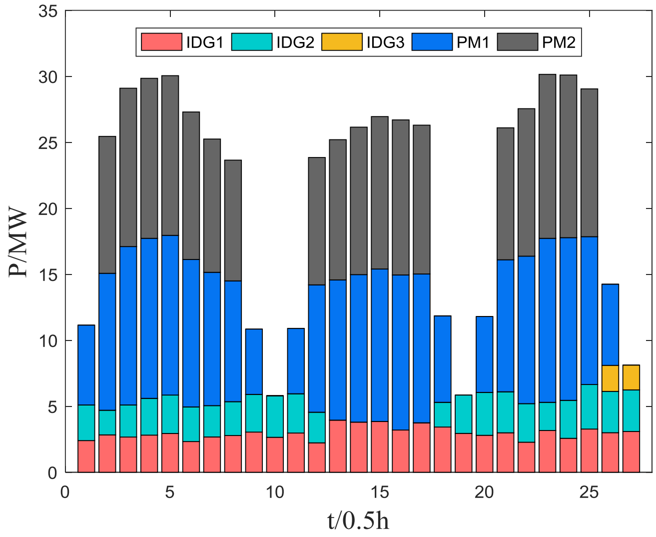

Fig.5 Power provided by generators and diesel engines in case2

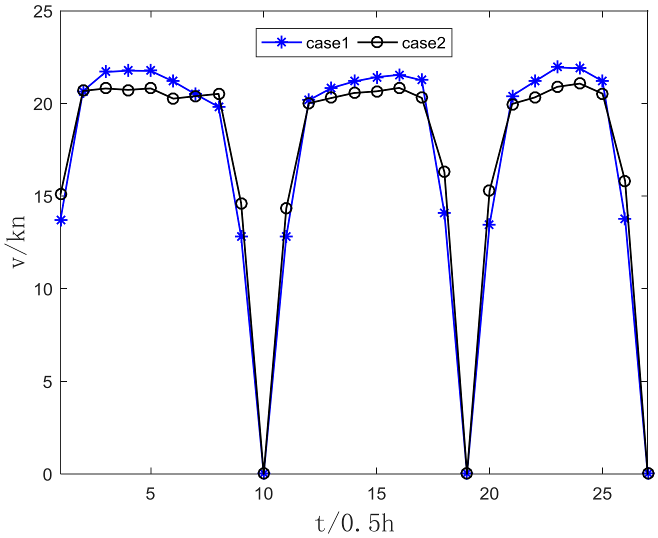

Fig.6 ship speed

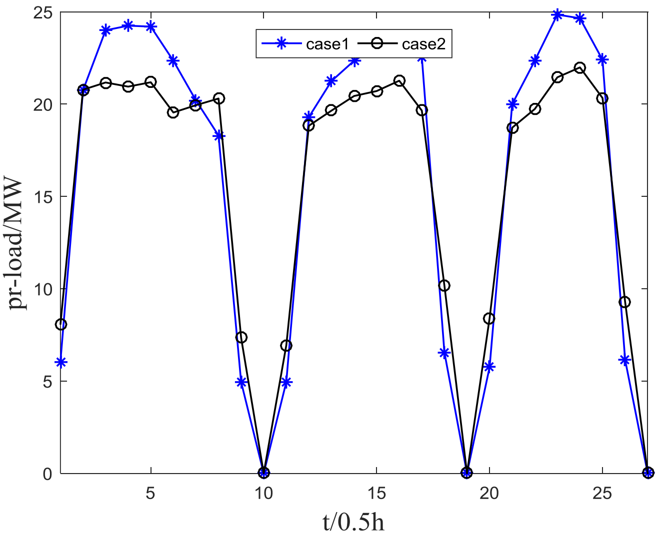

Fig.7 Propulsion load

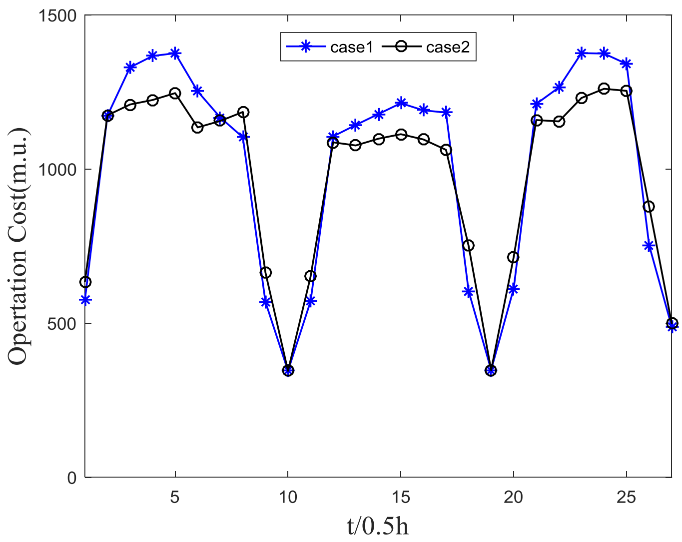

Fig.8 operation cost

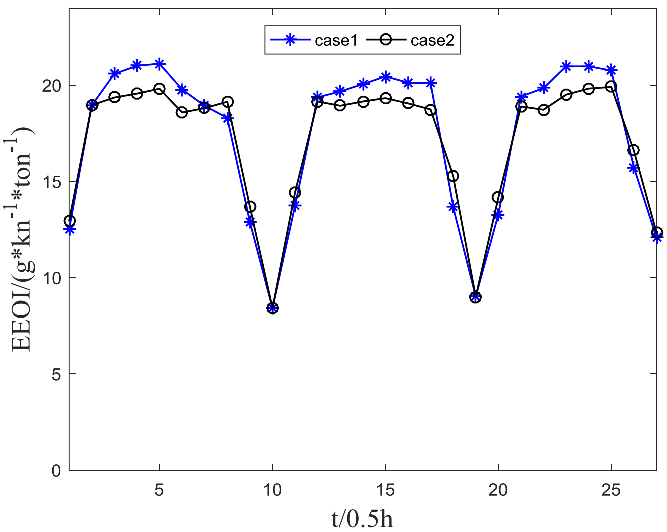

Fig.9 EEOI

In case 1 and case 2, the sailing speed of the ship at each time interval is shown in figure 6.Compared with case 1, with the optimal adjustment of propulsive force, the ship's speed remains relatively stable during sea navigation. When approaching the port, the ship's speed decreases, and when arriving at the port, the speed drops to 0.The ship's speed increases as it leaves the port. In this way, the ship speed and propulsion load curves become relatively stable and not too discrete in figure 7.This makes the curve of ship operation cost closer to the trapezoid and the operation more economical, as shown in figure 8.In addition, although the ship speed deviates from the initial (non-optimized) predetermined value, it will not exceed its upper limit (23.5*kn*).In the intermediate port and the destination port, the navigation distance limit is also satisfied.

The values of the EEOI at all time intervals are shown in figure 9.case 2 uses propulsion adjustment and EEOI limits, which are guaranteed under its upper limit (21 *g/(t· kn*) at sea and 120 *g/(t·h)* at berth.

In Fig.6-9, it can be seen that the ship speed changes as expected. The ship speed in plan 1 remains unchanged, while the change in speed is observed in case 2, because the diesel engine power providing propulsion is adjusted to meet the EEOI limit. Therefore, simulation results show that the optimization method proposed in this paper effectively reduces the operating cost and greenhouse gas emissions.

5. Conclusion

In this paper, a ship energy management strategy based on differential evolution algorithm is proposed to minimize the operation cost of ship power system. This strategy considers economy and environmental protection at the same time, so that the ship can meet the technical and operational limits (including production and consumption balance, total voyage distance, greenhouse gas emission and other limits) of the ship's power system during the voyage, and at the same time minimize the operation cost. The proposed algorithm can be used to evaluate any type of ship. It is fully parameterized and does not depend on any specific characteristics of the ship diesel engine or generator because its main input is the fuel consumption curve of the engine and generator.

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