2023 62nd IEEE Conference on Decision and Control (CDC)
December 13-15, 2023. Marina Bay Sands, Singapore

Multi-Objective Optimal Dispatching for Heterogeneous Multienergy Ship Microgrid

Ke Shang, Xiaolei Li, Xiaoyuan Luo, Jiange Wang, Qianwen Xu

Abstract— **With the growth of energy and transportation demand, the integrated energy dispatching of ship power grid has become the focus of researchers. The optimization technique is used to reduce the total energy consumption and pollutant emissions of ships, optimizing the ship power generation planning. The purpose is to achieve environmental protection and energy saving while ensuring the continuous and reliable power supply of ships. However, heterogeneous ship microgrid poses new challenges to integrated energy dispatch. This paper proposes an integrated energy scheduling scheme that integrates photovoltaic, wind power, diesel engine, gas turbine, and battery for a heterogeneous multienergy ship microgrid. Under the system constraints, a multi-objective optimal scheduling model including operating costs and pollutant emissions is established, then the gravity search algorithm is applied to solve such an issue. The simulation results show that the scheme can effectively reduce the cost of energy consumption and pollutant emissions of ships, improving the economy, reliability and energy conservation, which verify the advantages of the proposed scheme.**

I. Introduction

Existing ships' energy consumption and pollutant discharge account for a larger proportion of the total energy consumption of shipping. As the number of ships increases, it is foreseeable that the total energy consumption and emissions of ships will continue to increase. Therefore, the effective reduction of fuel costs and the introduction of low-carbon environmental protection elements become an important part of ship control technology [1-2]. Thus reducing pollutant emissions in the marine field and carrying out a more environmentally friendly industrial technology have gradually become the core goal for developing new energy ships. As a distributed power system with the potential to achieve this goal, the ship microgrid combines various kinds of renewable energy resources, energy storage equipments, and load organically by using intelligent algorithms [3-6].

Note that there are many kinds of energy in the ship microgrid and the change of power supply is random and intermittent. Therefore, the ship comprehensive energy dispatch is a multi-variable, multi-constrained, nonlinear combination optimization problem [7]. At present, adding sustainable clean energy to the comprehensive energy system of ships has gradually become the mainstream of research and development of ship power grid [8]. A typical hybrid power ship system is shown in Fig. 1. A power scheme that combines wind energy with light energy was proposed in [9]. Its advantages are that it can provide continuous and reliable power for ships, which is thus widely used for long distance navigation. However, the power requirement of the ship is too high to promote its usage. A hybrid energy system structure including diesel as the main power source and clean energy such as wind and light energy as the supplementary power source was designed in [10]. The weight summation scheme was used to convert the multi-objective problem into a single-objective problem, then an optimal energy dispatching scheme was proposed to keep the charging curve of the accumulator within a reasonable range to satisfy the energy supply. However, the lowest energy consumption point cannot be guaranteed by the proposed approach and the weight selection is difficult and complex. As a result, the intelligent bionic optimization algorithms that simulates the biological evolution laws are began to be used to optimize the ship energy system. In [11], a control optimization model based on fuzzy comprehensive evaluation was presented based on the decision output of working mode of hybrid energy system which takes the battery balance, operating temperature, and ship propelling power as indicators. This model can realize the intelligent automatic switching of the hybrid power system of electrical propelling vessel such that the optimal power management, the optimized battery performance, and prolonging service life can be achieved. Then, a hybrid energy dispatch scheme for firewood electric vessels based on artificial bee colony algorithm with dual goals of reducing maintenance cost and prolonging battery life was proposed in [12]. By adjusting

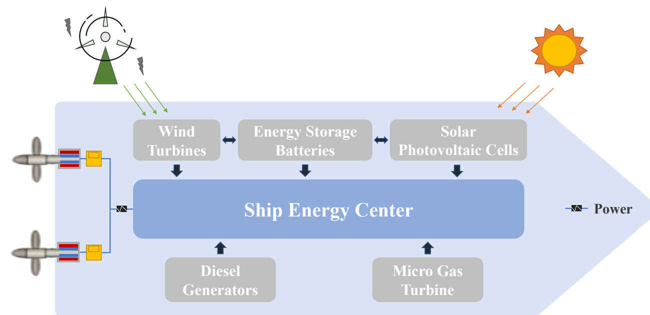


Fig. 1: Electric diagram of hybrid power ship system.

This work is supported in part by the National Natural Science Foundation of China under Grant 62103352 and Grant 62033011 and is also partly supported by Swedish Foundation for International Cooperation in Research and Higher Education (STINT) under Grant MG2021-8973.

Ke Shang, Xiaolei Li, Xiaoyuan Luo, and Jiange Wang are with the School of Electrical Engineering, Yanshan University, Qinhuangdao, China, 066004. (E-mail: shangke@stumail.ysu.edu.cn, xiaolei@ysu.edu.cn, xyluo@ysu.edu.cn, Jiange@ysu.edu.cn.)

Qianwen Xu is with the School of Electrical Engineering and Computer Science, KTH Royal Institute of Technology, 10044 Stockholm, Sweden. (E-mail: qianwenx@kth.se)

the parameters of the energy system, a more configurable optimization scheme was established. However, the safety factor of the sustainability of ship electricity utilization are ignored in these mentioned results, which also have not taken into account the impact of objective disturbances such as abrupt changes in ship load at sea.

Motivated by the above discussions, this paper presents a ship multienergy optimization scheme based on gravitational search algorithm. The purpose is to reduce the operation and maintenance costs of ship integrated energy system under greenhouse gas emission limits. This paper establishes a multi-module integrated energy management model for ships including photovoltaic, wind power, energy storage batteries, diesel engine, and gas turbine. The optimization problem is solved by a gravity search algorithm with strong global search ability, fast convergence, and particle perception without environmental factors. The simulation results show that the proposed scheme has good optimization performance and ensures the economy and environmental protection of the ship.

II. Mathematical Model of Ship Integrated Energy System

Compared to the traditional fossil powered ships, the integrated energy ships mentioned in this paper are more complex and heterogeneous. Due to the usage of hybrid power systems for load balancing, the consumption of fossil fuels is reduced and thereby reducing emissions of pollutants and carbon dioxide. This strategy reasonably considers the environmental protection operation of ships and able to reduce the overall operating cost of ships. In this section, the components of distributed energy are firstly introduced, then the optimization scheme are given.

A. Distributed energy

1) Solar Photovoltaic Cells: The output power of solar photovoltaic cells is related to the intensity of solar radiation [13]. In this paper, the output power of photovoltaic batteries is predicted first, which can be expressed as

$$P_{PV}=R_{PV}\varsigma_{\mathrm{PV}}\frac{I_T}{I_{STC}}\left[1+\alpha_{\mathrm{p}}\left(\mathrm{T}_c-\mathrm{T}_{stc}\right)\right], \tag{1}$$

where P_{PV} is the output power of photovoltaic cells; R_{PV} is the rated power of the photovoltaic cell; ς_{PV} is the derating coefficient and generally is chosen as 0.8; I_T is the actual sunlight intensity; I_{STC} is the sunlight intensity under standard test; α_{p} is the power temperature coefficient; T_c is the current PV cell temperature; T_{stc} is the standard PV cell temperature.

2) Wind Turbines: The output power of the wind turbine is related to the wind speed [14], which can be written as

$$P_{WT}=\begin{cases}0 & \mathrm{v}<\mathrm{v}_{\mathrm{ci}}, v>\mathrm{v}_{co}\\ av^3+bv^2+cv+d & \mathrm{v}_{\mathrm{ci}}<\mathrm{v}_r\\ P_e & \mathrm{v}_r<\mathrm{v}_{co},\end{cases} \tag{2}$$

where P_{WT} and P_e are the actual and rated power of wind turbines, respectively; v_{ci}, v_{co}, and v_r are the cut-in wind speed, cut-out wind speed, and rated wind speed of the fan, respectively; a,b,c,d are the wind speed power calculation coefficients.

3) Micro Gas Turbine: In this paper, a freely adjustable micro-gas turbine is added to the ship microgrid. The fuel cost of the gas turbine is related to its operating efficiency, which can be expressed as

$$\begin{aligned}\eta_{MT}(t)=&0.0753\left[\frac{P_{MT}(t)}{65}\right]^3-0.3095\left[\frac{P_{MT}(t)}{65}\right]^2\\&+0.4174\frac{P_{MT}(t)}{65}+0.1068,\end{aligned} \tag{3}$$

where $\eta_{MT}(t)$ is the efficiency of a gas turbine; $P_{MT}(t)$ is the actual output power of the gas turbine. Micro gas turbines generate electricity by consuming fuel. In the process of operation, there will be costs such as operation maintenance, fuel, pollutant discharge treatment and so on [15]. The cost of a gas turbine can be expressed as

$$\begin{cases}C_{MT.om}(t)=K_{MT.om}P_{MT}(t)\\ C_{MT.f}(t)=C\frac{1}{LHV}\frac{P_{MT}(t)}{\eta_{MT}(t)}\\ C_{MT.en}(t)=\sum_{k=1}^{n}\left(C_k\gamma_{MT,k}\right)P_{MT}(t),\end{cases} \tag{4}$$

where $C_{MT.om}(t)$, $C_{MT.f}(t)$, and $C_{MT.en}(t)$ are the operating and maintenance costs, fuel costs, and pollutant discharge treatment costs of gas turbines at the current time; $K_{MT.om}$ is the operating and maintenance cost factor of gas turbine; $P_{MT}(t)$ is the output power of the micro gas turbine at the current moment; C is the price of natural gas, which is chosen as 2 yuan/m^3; LHV is the minimum heat value of natural gas, which is chosen as 9.7 kWh/m^3; C_k is the cost factor for the treatment of class k pollutants; $\gamma_{MT,k}$ is the amount of k pollutants discharged from the micro gas turbine.

4) Diesel Generators: Diesel generator is a very important part of the ship energy system. Its power output will directly affect the stability and reliability of the whole power supply system. Diesel generators generate fuel costs, maintenance costs, pollutant discharge and treatment costs during operation [16]. The cost of a diesel generator can be expressed as

$$\begin{cases}C_{DE.om}(t)=K_{DE.om}P_{DE}(t)\\ C_{DE.f}(t)=\alpha P_{DE}^2(t)+\beta P_{DE}(t)+\gamma\\ C_{DE.en}(t)=\sum_{k=1}^{n}\left(C_k\gamma_{DE,k}\right)P_{DE}(t),\end{cases} \tag{5}$$

where $C_{DE.om}(t)$, $C_{DE.f}(t)$, and $C_{DE.en}(t)$ are the operating and maintenance costs, fuel costs and pollutant discharge treatment costs of the current time of the diesel generator; $K_{DE.om}$ is the operating and maintenance cost factor of the diesel generator; $P_{DE}(t)$ is the output power of the diesel generator at the current moment; α, β, and γ are the fuel cost coefficients of the diesel generators, this factor depends on the type of generator, which is respectively chosen as 0.00011, 0.1801, and 6; $\gamma_{DE,k}$ is the amount of K pollutants discharged from the diesel generator, K represents the type of pollutant emission, which includes CO_2, SO_2, and NO_{x}.

5) Energy Storage Batteries: The solar photovoltaic module and wind power module in the ship energy system have great randomness and the power output fluctuates greatly in practical application [17]. Therefore, this paper uses energy storage batteries, which can reduce voltage fluctuations and harmonic distortion to adjust them. Storage batteries can be charged and discharged according to the changes in the power of solar photovoltaic batteries and wind turbines and act as buffers in the marine energy system. The charging state of a storage battery can be expressed as

$$SOC(t) = \begin{cases} SOC(t-1) + \frac{1}{\lambda_-}P_{BESS}(t), P_{BESS}(t) \leq 0 \\ SOC(t-1) + \lambda_+ P_{BESS}(t), P_{BESS}(t) \geq 0, \end{cases} \tag{6}$$

where $SOC(t)$ represents the capacity of the storage battery at time t; $P_{BESS}(t)$ represents the current charging and discharging power of the storage battery, where the positive value represents charging and the negative one represents discharging; λ_+ and λ_- represent charge and discharge efficiencies, respectively.

B. Multi-objective optimization of ship microgrid

1) Objective Function: The multi-objective mathematical model of ship microgrid optimization is established based on the premise of meeting multiple system constraints and the goal of minimizing the total cost. The objective function includes ship operation and maintenance costs and pollutant emissions, which can be expressed as

$$C_{MIN} = C_1 + C_2, \tag{7}$$

where C_{MIN} is the total cost of a ship's operation, which consists of the cost of operation and maintenance C_1 and pollutant discharge level C_2.

2) Operation and Maintenance Cost of Ship Microgrid: For a ship microgrid, its total operating and maintenance costs can be expressed as

$$C_1 = C_{MT}(t) + C_{DE}(t), \tag{8}$$

$$\begin{cases} C_{MT}(t) = C_{MT.om}(t) + C_{MT.f}(t) \\ C_{DE}(t) = C_{DE.om}(t) + C_{DE.f}(t), \end{cases} \tag{9}$$

where $C_{MT}(t)$ is the total cost of the micro gas turbine at the current moment; $C_{DE}(t)$ is the total cost of the current moment of the diesel generator.

3) Pollutant emission: In this paper, the pollutants generated in the process of micro gas turbine is considered, whose expression is

$$C_2 = C_{MT.en}(t) + C_{DE.en}(t), \tag{10}$$

where $C_{MT.en}(t)$ is the pollutant emission of micro gas turbine at the current moment; $C_{DE.en}(t)$ is the pollutant emission of diesel generator at the current moment.

C. Constraint Condition

To increase the safety and reliability and extend the service life of the integrated heterogeneous ship microgrid, this paper presents several constraints on the load output of each energy module and the power balancing of the entire ship microgrid. In addition, this paper also presents constraints on the power ramp rate due to the devastating impact of extreme power mutations on the use of generators. The constraints are given as follows.

1) Output Constraints of Micro Gas Turbine:

$$\begin{cases} P_{MT.\min}(t) \leq P_{MT}(t) \leq P_{MT.\max}(t) \\ |P_{MT}(t) - P_{MT}(t-1)| \leq \gamma_{MT}, \end{cases} \tag{11}$$

2) Diesel Generator Output Constraints:

$$\begin{cases} P_{DE.\min}(t) \leq P_{DE}(t) \leq P_{DE.\max}(t) \\ |P_{DE}(t) - P_{DE}(t-1)| \leq \gamma_{DE}, \end{cases} \tag{12}$$

3) Charging and Discharging Constraints of Energy Storage Battery:

$$\begin{cases} P_{BESS.\min}(t) \leq P_{BESS}(t) \leq P_{BESS.\max}(t) \\ SOC_{\min}(t) \leq SOC(t) \leq SOC_{\max}(t), \end{cases} \tag{13}$$

4) Power Balance Constraints:

$$\begin{aligned} P_{LOAD}(t) =& P_{PV}(t) + P_{WT}(t) + P_{MT}(t) \\ &+ P_{DE}(t) + P_{Bess}(t), \end{aligned} \tag{14}$$

where $P_{MT.\max}(t)$, $P_{MT.\min}(t)$, $P_{DE.\max}(t)$, $P_{DE.\min}(t)$, $P_{BESS.\max}(t)$, and $P_{BESS.\min}(t)$ are the upper and lower limits of the treatment of micro gas turbine, diesel generator, and energy storage battery, respectively; $P_{LOAD(t)}(t)$ is the total load of the ship system at the current time t; γ_{MT} and γ_{DE} are the maximum climbing power of micro gas turbine and diesel generator, respectively; $SOC_{\max}(t)$ and $SOC_{\min}(t)$ represent the upper and lower limits of the energy storage capacity of the energy storage battery.

III. Gravitational Search Algorithm

The essence of current common swarm intelligence algorithms, such as particle swarm optimization, simulated annealing algorithm, ant colony algorithm, etc., is to imitate the behavior and interaction rules between species in nature to infer the rules of population habits. The universal gravitation search algorithm (GSA) is derived from the universal gravitation law in physics. It simulates the driving force between particles due to the action of universal gravitation to search for optimization. As stated in [18], GSA has stronger search ability and efficiency over particle swarm optimization algorithm. In this paper, the GSA will be used to solve the multi-objective, multi-constraint, and nonlinear optimal dispatching problem for an integrated ship microgrid.

According to the universal gravitation law, any two particles have a force of mutual attraction in the direction of their connecting center line. The gravitational force is proportional to the product of their masses and inversely proportional to the square of their distance, which is independent of the type of medium between the two particles. The formula is given as

$$F = G\frac{M_1 \times M_2}{R^2}, \tag{15}$$

where F is the gravitational force between particles; G is the gravitational constant; M_1 and M_2 are inertia masses of particles; R is the Euclidean distance between particles.

Suppose there are N particles in an independent search space, the position of each particle can be expressed as

$$x_i = (x_i^1, x_i^2, \ldots, x_i^k, \ldots, x_i^d), i = 1, 2, \ldots, N \quad (16)$$

where x_i^k represents the position of the ith particle on the k-th dimension.

A. Inertia Mass Calculation

The inertia mass of each particle is indirectly calculated according to the fitness function. The larger the inertia mass of the particle, the closer the fitness value is to the optimal solution [19]. At the same time, particles with large inertia mass have greater attraction to other particles and move more slowly. The inertia mass of particles can be expressed by the following equations:

$$\begin{cases} m_i(t) = \frac{fitness_i(t) - worst(t)}{best(t) - worst(t)} \\ M_i(t) = \frac{m_i(t)}{\sum_{j=1}^{N} m_j(t)}, \end{cases} \quad (17)$$

where $fitness_i(t)$ represents the fitness function value of particle x_{i} at time t; $best(t)$ and $worst(t)$ are given as follows

$$\begin{cases} best(t) = \min_{i \in \{1,2,\ldots,N\}} fitness_i(t) \\ worst(t) = \max_{i \in \{1,2,\ldots,N\}} fitness_i(t), \end{cases} \quad (18)$$

B. Gravity Calculation

In the k-th dimensional space, the total gravity received by particle i is shown as follows [20]

$$\begin{cases} G(t) = G_0 \times e^{-\alpha t/T} \\ F_{ij}^k(t) = G(t) \frac{M_{pi}(t) \times M_{aj}(t)}{R_{ij}(t) + \varepsilon} (x_j^k(t) - x_i^k(t)) \\ R_{ij}(t) = \|x_i(t), x_j(t)\|_2, \end{cases} \quad (19)$$

where $G(t)$ represents the gravitational constant; in this paper, G_0 is taken as 100, α is taken as 20, and T represents the maximum number of iterations of the cycle; the gravitational constant will decrease with time; $M_{pi}(t)$ is the inertial mass of particle i; $M_{aj}(t)$ is the inertial mass of particle j; ε is a minimal constant; $R_{ij}(t)$ represents the Euclidean distance between particle i and j. Then the sum of gravity received by particle x_i at time t can be expressed as

$$F_i^k(t) = \sum_{j=1, i \neq j}^{N} rand_j F_{ij}^k(t). \quad (20)$$

C. Particle Position Update

According to Newton's second law, the acceleration of particle i in the k-th dimension is the ratio of the sum of its gravitation to the inertial mass, which can be expressed as:

$$a_i^k(t) = \frac{F_i^k(t)}{M_{ii}(t)}. \quad (21)$$

During the iteration process, particles can update the speed and position information according to the calculated acceleration, which is given as follows:

$$\begin{cases} v_i^k(t+1) = rand_i \times v_i^k(t) + a_i^k(t) \\ x_i^k(t+1) = x_i^k(t) + v_i^k(t+1). \end{cases} \quad (22)$$

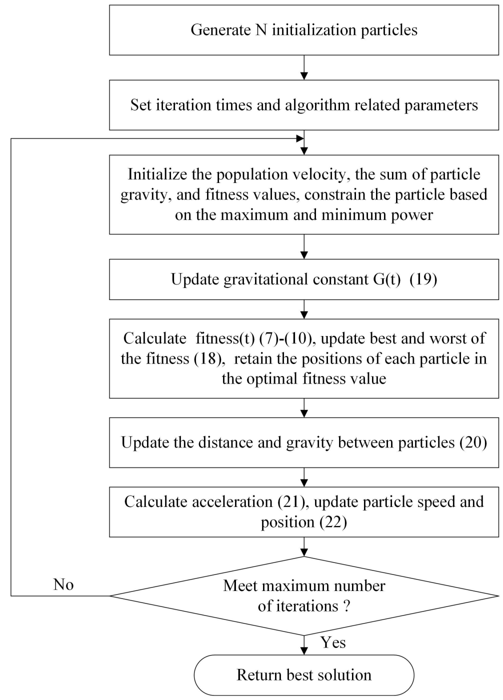


Fig. 2: GSA algorithm flowchart.

D. Application of Gravity Search Algorithm in Ship Integrated Energy System

In this part, we will consider the optimal scheduling problem for the multienergy ship microgrid. The distributed energy models are given in (1)-(6), while the objective functions are shown in (7)-(10), the multiple constraints are given in (11)-(14). Next, we will use GSA approach to solve this problem. The multi-step solution is given as follows.

Step 1: Randomly generate N particles in the gravity search algorithm. In this paper, N is set as 120 and are averagely divided into 5 groups, representing the power of solar photovoltaic cells, wind turbines, micro gas turbines, diesel generators, and energy storage batteries for 24 hours. Then initialize the position and acceleration of all particles, after that set the parameters such as the number of iterations, the gravitational constant in the algorithm, the distance constant in the gravitational formula, the fitness optimal ratio solution, and the time of each iteration.

Step 2: Initialize the population speed, the sum of gravitation, and fitness value of the particle. Constrain the maximum/minimum power of the particle at the same time, then start the cycle and update the gravitation constant with equation (19).

Step 3: Calculate the fitness value using equations (7)-(10) and apply equation (18) to obtain the best and worst fitness values. Compare the updated optimal fitness value with the historical optimal fitness value. If the current fitness value is less than the historical optimal fitness value, replace it. Otherwise, keep the historical optimal fitness value as the optimal one. At the same time, the position of each particle in the optimal fitness value is retained, and then the inter-particle distance and inter-particle gravity are updated using equation (20).

Step 4: Using equations (21)-(22) to calculate the speed of particles, update the position of particles, judge whether the current position of particles meets the constraints (11)-(13), and if not, converge to the boundary position of the constraint conditions.

Step 5: Return to the loop to determine whether the output condition reach the maximum number of iterations. If it is met, the loop output result will be terminated. Otherwise, return to Step 3 to continue the loop. The flowchart of the algorithm is shown in Fig. 2.

IV. Simulation and Analysis

A. Example Parameters

In this section, a simulation example is given to verify the effectiveness of the proposed optimal scheduling scheme. The integrated energy system of the ship in this paper includes solar photovoltaic battery, wind generator, micro gas turbine, diesel generator, and storage battery. The specific parameters of the ship power system are shown in Table I-III, which also can be seen in [21] and [22].

TABLE I: Dynamic parameters of main energy sources of ships

Parameter Name	MT	DE
Maximum Power/KW	30	30
Minimum Power/KW	0	0
Maximum Climbing Power/(kW/min)	1.5	1.5
Maintenance Price/(yuan/Kw · h)	14.0523	14.151
Emission Factor/(g/kW·h)	724	680
Emission Factor/(g/kW·h)	0.0036	0.306
Emission Factor/(g/kW·h)	0.2	10.09

TABLE II: Load power constraint parameters of clean energy

Parameter Name	PV	WT	BESS
Maximum Power/KW	50	50	30
Minimum Power/KW	0	0	0

TABLE III: Specific parameters of energy storage battery

Parameter Type	Numerical Value
initial energy storage capacity/(kW·h)	50
maximum energy storage capacity/(kW·h)	100
minimum energy storage capacity/(kW·h)	0
charge and discharge efficiency	0.9

B. Result Analysis

This article runs two simulation cases of benchmark strategies under the gravity search algorithm and compares them. In Case 1, solar photovoltaic cell and wind turbine are not used as two clean energy sources, and only three energy modules, namely micro gas turbine, diesel generator and energy storage battery, are used. In Case 2, all five distributed energy modules participate in system scheduling.It can be seen from Fig. 3 that the gravity search algorithm converges iteratively in about 40 generations and achieves global optimization, which means that the algorithm has good global search ability, and has excellent convergence and stability.

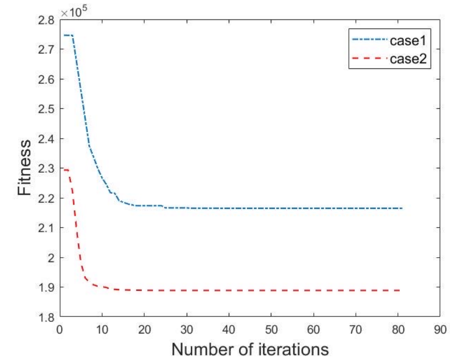
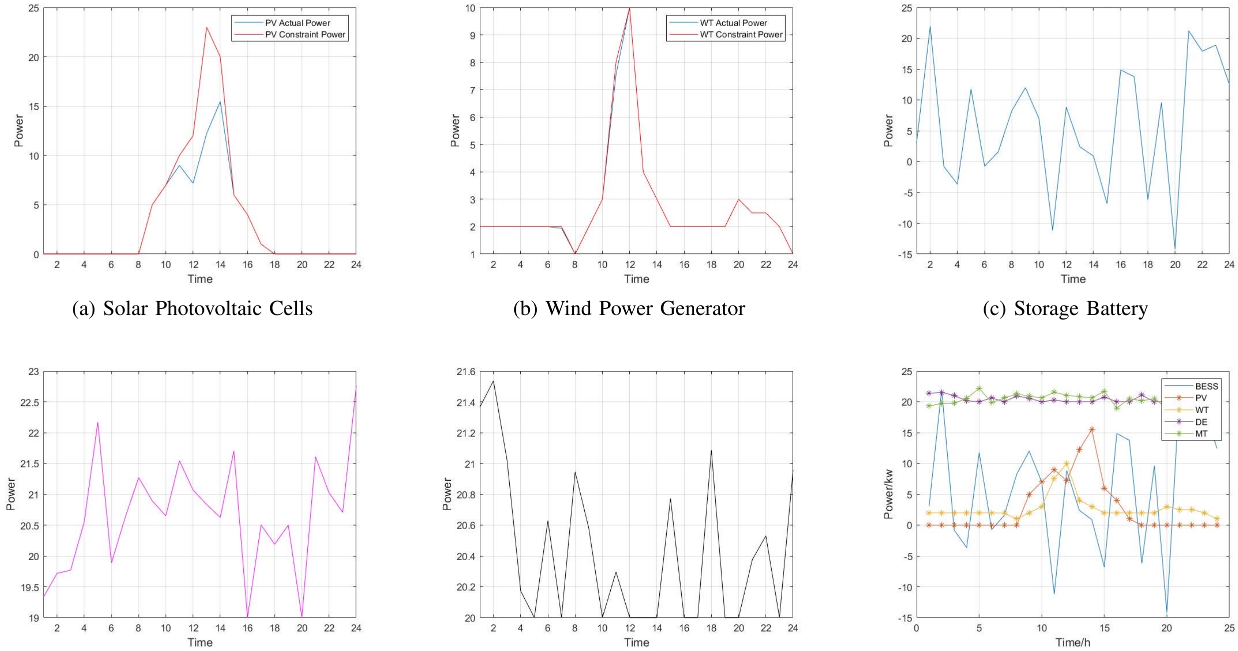


Fig. 3: Convergence curve of gravity search algorithm.

The optimization model proposed in this paper aims to reduce the total cost of ship navigation, which includes the operation and maintenance costs (8)-(9) and environmental protection costs (10) of the ship integrated energy system. Fig. 4 shows the scheduling results of each energy module under the objective function. Fig. 4(a)-(b) show that the solar photovoltaic cell is greatly affected by the solar panel area and sunshine factors of the ship, and the power generation of the wind turbine will change due to the real-time sea conditions. Therefore, they are probably better used as auxiliary propulsion power or to charge the energy storage battery. It can be seen from Fig. 4(c) that the energy storage battery plays an auxiliary role in regulation, and can charge and discharge according to the real-time load. In addition, it can be seen from Fig. 4(d)-(e) that the diesel generator and micro gas turbine are still the main propulsion power of the ship, but due to the regulation of the clean energy module and the energy storage battery, they can be in a relatively low and stable power generation state, which greatly reduces the energy consumption cost and the carbon dioxide emissions generated during the voyage of the ship. In addition, this paper sets the real-time changing load value and restricts the ship load balance. From Fig. 4(f), it can be seen that the ship energy system will give priority to the use of energy storage batteries rather than solar photovoltaic cells or wind turbines to provide power load when using micro gas turbines and diesel generators to meet the basic power generation, the advantage of this scheduling scheme is that it will reduce the impact of environmental factors on the stability of ship power supply, so as to ensure the continuous and reliable power supply of ship energy system.

V. Conclusions

On the premise of meeting the basic constraints and environmental requirements of ships, this paper proposes a more economical and environmentally friendly ship energy management scheme. By optimizing the real-time load power of each module of the ship and adopting the gravity search algorithm for iterative optimization, not only the operation cost is reduced, but also the carbon dioxide emissions during the ship's navigation are reduced. This scheme can find a effective solution in a shorter optimization time, and has good response speed and optimization stability. This



(a) Solar Photovoltaic Cells (b) Wind Power Generator (c) Storage Battery

(d) Micro Gas Turbine (e) Diesel Generator (f) Total

Fig. 4: Power curve of each energy module.

paper has optimized the ship's power system and propulsion system. In the future, we will continue to improve the gravity search algorithm taking into account the impact of the ship's sailing distance and complex sea conditions on the ship's integrated energy system. Also how to improve the optimization accuracy and coupling stability of the algorithm model is an interesting direction.

REFERENCES

[1] M. Tichavska, B. Tovar, "Environmental cost and eco-efficiency from vessel emissions in Las Palmas Port," *Transportation Research Part E: Logistics and Transportation Review*, vol. 83, pp. 126-140, 2015.

[2] W. Fitzgerald, O. Howitt, I. Smith, "Greenhouse gas emissions from the international maritime transport of New Zealand's imports and exports," *Energy Policy*, vol. 39, pp. 1521-1531, 2011.

[3] Z. Li, Y. Xu, S. Fang et al, "Multiobjective Coordinated Energy Dispatch and Voyage Scheduling for a Multienergy Ship Microgrid," *IEEE Transactions on Industry Application*, vol. 56, no. 2, pp. 989-999, 2020.

[4] Z. Li, Y. Xu, S. Fang et al, "Robust Coordination of a Hybrid AC/DC Multi-Energy Ship Microgrid With Flexible Voyage and Thermal Loads," *IEEE Transactions on Smart Grid*, vol. 11, no. 4, pp. 2782-2793, 2020.

[5] S. Fang, Y. Wang, B. Guo et al, "Toward Future Green Maritime Transportation: An Overview of Seaport Microgrids and All-Electric Ships," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 1, pp. 207-219, 2020.

[6] S. Fang, Y. Xu, Z. Li et al, "Two-Step Multi-Objective Management of Hybrid Energy Storage System in All-Electric Ship Microgrids," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 4, pp. 3361-3373, 2019.

[7] M. Mohammadian, A. Lorestani, M.M. Ardehali, "Optimization of single and multi-areas economic dispatch problems based on evolutionary particle swarm optimization algorithm," *Energy*, vol. 161, pp. 710-724, 2018.

[8] Lee, Kyoung-Jun et al, "Hybrid photovoltaic/diesel green ship operating in standalone and grid-connected mode-Experimental investigation," *Energy*, vol. 49, pp. 475-483, 2013.

[9] X.Huang, S. Sun, "Application of Wind Power Generation Technology in Ships," in *2022 IEEE Asia-Pacific Conference on Image Processing, Electronics and Computers (IPEC)*, pp. 1591-1593, 2022.

[10] R. Yang, L. Jiang, K. Du et al, "Research and Experimentation on Energy Management System for Inland Diesel-Electric Hybrid Power Ships," in *2020 IEEE 8th International Conference on Computer Science and Network Technology (ICCSNT)*, pp. 102-106, 2020.

[11] W. Wei, J. ChU, F. Wang, "Operation Mode Switching Strategy of Series Hybrid Electric Ship Power System," *Ship Engineering*, vol. 38, no.4, pp. 26-30, 2016.

[12] G. Zeng, R. Wang, R. Han, "Optimization of Hybrid Energy System Configuration for Marine Diesel," *Ship Engineering*, vol. 41, no.12, pp. 1-7, 2019.

[13] Z. Wang, "Optimal Configuration of Integrated Multi-energy Microgrid System with Compressed Air Energy Storage," doi:10.27140 /d.cnki.ghbbu.2019.000893.

[14] Lacal-Arantegui R, "Materials use in electricity generators in wind turbines state-of-the-art and future specifications," *Journal of Cleaner Production*, no.87, pp. 275-283, 2015.

[15] Z. Bai, "Research on Multi-objective Optimal Scheduling of Microgrid Based on Load Forecasting," doi:10.27441/d.cnki.gyzdu.2022.000879.

[16] T. Liu, "Muiti-objective Optimization of Microgrid Basedon Pareto Archive Particie Swarm Optimization", 2018.

[17] Nazaripouya, Hamidreza, Y. Chung et al, "Energy Storage in Microgrids: Challenges, Applications and Reach Need," *International Journal of Energy and Smart Grid*, 2019.

[18] Zibanezhad B, Zamanifar K, Sadjady R.S et al, "Applying gravitational searchalgorithm in the QoS-based Web service selection problem," *Journal of Zhejiang University Science C*, vol. 12, no.9, pp. 730-742, 2011.

[19] Y. Zhao, J. Hu,B. Yang, "Prediction of Tailings Dam Infiltration Line Based on Gravitational Search Algorithm Optimized BP," *Water Resources and Power*, vol. 40, no.6, pp.97-100, 2022.

[20] Y. Yang, "Improvement of Gravitational Search Algorithm," *System Simulation Technology*, vol. 14, no. 1, pp. 78-82, 2018.

[21] J. Wang, L. Huang, Y. Yang, "Optimal Dispatch of Microgrid Based on Mult-Objective Particle Swarm Optimization," *Power System and Clean Energy*, vol. 30, no.1, pp. 49-54, 2014.

[22] X. Li, J. Zhang, Y. He et al, "Multi-objective Optimization Dispatching of Microgrid Based on Improved Particle Swarm Algorithm," *Electric Power Science and Engineering*, vol. 37, no.3, pp. 1-7, 2021.