Optimization of Hybrid Energy System Configuration for Marine Diesel Engine

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SUMMARY Because solar energy is intermittent and a ship’s power system load fluctuates and changes abruptly, in this work, the solar radiation parameters were adjusted according to the latitude and longitude of the ship and the change of the sea environment. An objective function was constructed that accounted for the cost and service life simultaneously to optimize the configuration of the marine diesel engine hybrid energy system. Finally, the improved artificial bee colony algorithm was used to optimize and obtain the optimal system configuration. The feasibility of the method was verified by ship navigation tests. This method exhibited better configuration performance optimization than the traditional methods.

key words: artificial bee colony algorithm, hybrid energy system, diesel engine, optimal configuration, photovoltaic power generation

1. Introduction

A diesel engine generates power using petroleum fuel, which is a heavy polluter. In recent years, green clean energy, such as solar and wind energy, has been used together with diesel engines to supply power to loads, thereby achieving the goal of conserving energy and reducing emissions [1]. To realize the optimal configuration of hybrid energy systems, researchers have proposed methods based on genetic algorithms [2]–[4], the particle swarm optimization algorithm [5], [6], differential evolution [7], and harmonious search [8], [9]. These methods are mainly used for stationary hybrid energy systems. In previous reports, [8], [10], the researchers calculated the solar-panel size, tilt angle, and power output in photovoltaic-power-generation systems based on the geographical location of the city in which the study was conducted to determine the optimal configuration of such hybrid energy systems. The existing methods are used more for onshore hybrid energy systems and less for optimization of shipboard hybrid energy system configurations. Ships are in motion, and long-haul ships, in particular, have long operating hours and travel long distances. Therefore, a ship hybrid energy system used for maritime navigation must consider the geographical location of the ship and its associated solar radiation. There have been multifaceted studies on energy storage systems on land [11]–[15]. The coordinated operation of battery packs and solar systems was analyzed to optimize the hourly battery power allocation strategy [16], [17]. The energy storage equipment in the microgrid was analyzed, and the performance of the system was optimized by changing the layout [18], [19]. Three different battery technologies were proposed to optimize unit cost of electricity [20]. Compared with onshore hybrid energy systems, a ship energy system’s operation mode is island-type. In addition to the equipment cost, the service life of the equipment is an important factor in the optimal configuration. Therefore, using a combination of three different battery technologies, the configuration of a marine diesel hybrid energy system was optimized from a cost and service life perspective in this study.

The paper is organized as follows. Optimization of the hybrid energy system configuration is formulated in Sect. 2. In Sect. 3, we first introduce an improved artificial bee colony (IABC) algorithm. We subsequently proposed the optimized configuration of a hybrid diesel energy system using an improved artificial bee colony algorithm. Finally, the performance of the proposed method is numerically evaluated in Sect. 4, and concluding remarks are presented in Sect. 5.

2. Problem Formulation

The studied marine diesel hybrid energy system is shown in Fig. 1. In a ship hybrid energy system, the power to the load is supplied mainly by solar and wind energy. If the solar and wind energy cannot meet the load requirement at a certain time, auxiliary power is sequentially supplied by battery packs and the diesel engine. When solar and wind energy are abundant, excess energy is stored in the battery packs.

2.1 Photovoltaic-Power-Generation Module

Different from the land, the application of photovoltaic power generation modules on ships has limitations. Due to the variety of ships, unlike oil tankers, some ships are not suitable for laying large-scale solar panels on decks, such as bulk carriers and container ships. Therefore, individual analysis is needed in practical applications.

During ship navigation, the amount of solar radiation received by the photovoltaic-power-generation module varies constantly. Therefore, the method illustrated in Fig. 2 was used to adjust the quantity of the solar radiation of the
ship’s photovoltaic-power-generation module. $I_t$ in the figure is the actual radiation intensity of the unit photovoltaic-power-generation module at time $t$. In [21], a method for calculating the correspondence between the solar radiation intensity and the solar position is provided.

$$e = 9.87 \sin 2B - 7.53 \cos B - 1.5 \sin B,$$

(1)

where $B = \frac{360(n-81)}{365}$, $n = 1, 2, \ldots, 365$, $e$ represents the time difference (in min), and $n$ represents the number of days (on January 1, $n = 1$).

The true solar time $H$ can be obtained by

$$H = H_s \pm \frac{L - L_s}{15} + \frac{e}{60},$$

(2)

$$L_s = 15^\circ \cdot t_s,$$

(3)

where $H_s$ is the standard time of the region in $h$, $L$ is the local longitude in degrees, $L_s$ is the longitude of the local area standard in degrees, $\pm$ is positive for the Eastern Hemisphere and negative for the Western Hemisphere, and $t_s$ is the local time zone.

The solar zenith angle $h$ can be obtained from

$$\sin h = \sin \varphi \sin \delta + \cos \varphi \cos \omega, \quad \omega = 15^\circ \cdot (H - 12), \quad \delta = 23.45 \cdot \sin \left(360 \times \frac{284 + n}{365}\right),$$

(4)

where $\varphi$ is the local latitude, $\delta$ is the declination angle, and $\omega$ is the solar time angle, which are all in units of degrees.

The solar incidence angle $i$ can be obtained from

$$\cos i = \cos \theta \sin h + \sin \theta \cos h \cos(\alpha - \gamma),$$

(7)

where $\theta$ is the slope inclination angle, $\alpha$ is the solar azimuth angle, and $\gamma$ is the slope azimuth angle, which are all in units of degrees.

The total solar radiation intensity $I_\theta$ on the inclined surface can be obtained by

$$I_\theta = I_{D0} + I_{d0} + I_{R0},$$

(8)

$$I_\theta = I_{DN} \cdot \left(\cos i + \cos^2 \frac{\theta}{2} \cdot \cos h + \rho \sin h + C \cdot \sin^2 \frac{\theta}{2}\right),$$

(9)

where $I_{D0}$ is the direct solar radiation intensity on the inclined surface, $I_{d0}$ is the Sun’s scattered radiation intensity on the inclined surface, and $I_{R0}$ is the ground-reflected radiation intensity obtained on the inclined surface.

The solar radiation intensity actually applied to the unit photovoltaic-power-generation module during the navigation, $I_t$, is calculated by

$$I_t(t) = \sum_{i=1}^{t} I_\theta(i).$$

(10)

Therefore, the power $P_{pv}(t)$ generated by a solar panel per unit time can be obtained from

$$P_{pv}(t) = I_t(t) \times A \times j_{pv},$$

(11)

where $A$ represents the area of the solar panel (in m²) and $j_{pv}$ represents the electric energy conversion rate of the solar panel.

The total power $P_{pv}(t)$ generated by the photovoltaic-power-generation module of the system at time $t$ can be obtained by

$$P_{pv}(t) = N_{pv} \times P_{pv}(t),$$

(12)

where $N_{pv}$ is the total number of solar panels in the system, given by

$$0 \leq N_{pv} \leq N_{max,pv},$$

(13)

where $N_{max,pv}$ represents the maximum value of $N_{pv}$.

2.2 Wind-Power-Generation Module

For the wind-power-generation module [9], the power $P_{wt}(t)$ generated by the turbines per unit time can be obtained by
\[
\begin{align*}
    P_{\text{wt}}(t) &= \begin{cases} 
    0, & v_i \leq v_{\text{min}} \quad \text{or} \quad v_i \geq v_{\text{max}} \\
    P_{r,\text{wt}} \frac{v_i - v_{\text{min}}}{v_r - v_{\text{min}}}, & v_{\text{min}} < v_i < v_r \\
    P_{r,\text{wt}}, & v_r \leq v_i < v_{\text{max}}
    \end{cases},
\end{align*}
\]

where \(v_i\) is the wind speed at time \(t\), \(v_r\) is the rated wind speed of the wind turbines, and \(P_{r,\text{wt}}\) is the corresponding rated power of the wind turbines. When the actual wind speed is greater than the starting wind speed \(v_{\text{min}}\), the turbines start to operate. When the wind speed is greater than the warning wind speed \(v_{\text{max}}\), the turbines stop, to protect the turbines.

The total power \(P_{\text{wt}}(t)\) generated by the wind-power-generation module of the system at time \(t\) can then be obtained by

\[
P_{\text{wt}}(t) = N_{\text{wt}} \times P_{\text{wt}}(t),
\]

where \(N_{\text{wt}}\) is the total number of wind turbines in the system and its value range is given by

\[
0 \leq N_{\text{wt}} \leq N_{\text{max,wt}},
\]

where \(N_{\text{max,wt}}\) is the maximum value of \(N_{\text{wt}}\).

2.3 Battery Energy-Storage Module

Owing to the intermittent nature of new energy sources, such as solar and wind energy, and because electric loads fluctuate and change abruptly, hybrid energy systems should have sufficient stored energy in addition to meeting the load energy requirements at any time. In [20], the impact of different battery types on hybrid systems was proposed. The calculation method of battery energy storage is as follows.

In a battery energy-storage module, the maximum electric quantity \(E_{\text{max,batt}}\) and the minimum electric quantity \(E_{\text{min,batt}}\) that can be stored in a battery can be obtained from

\[
e_{\text{min,batt}} = (1 - \text{DoD}) \times e_{\text{max,batt}},
\]

where DoD is the maximum depth of discharge of the battery.

Usually, a battery is shipped with its rated maximum capacity. In this case, the maximum electric quantity \(E_{\text{max,batt}}\) and the minimum electric quantity \(E_{\text{min,batt}}\) stored in all the batteries can be obtained from

\[
E_{\text{max,batt}} = N_{\text{batt}} \times e_{\text{max,batt}},
\]

\[
E_{\text{min,batt}} = N_{\text{batt}} \times e_{\text{min,batt}},
\]

where \(N_{\text{batt}}\) is the total number of battery packs in the system, with its range of values given by

\[
0 \leq N_{\text{batt}} \leq N_{\text{max,batt}},
\]

where \(N_{\text{max,batt}}\) is the maximum value of \(N_{\text{batt}}\).

At time \(t\), if the sum of the electric energy generated by the photovoltaic-power-generation module and the wind-power-generation module is higher than the load demand, the batteries are charged, and the battery power \(E_{\text{batt}}(t)\) can be obtained by

\[
E_{\text{batt}}(t) = E_{\text{batt}}(t-1) + \left( P_{\text{pv}}(t) \times \Delta t + P_{\text{wt}}(t) \times \Delta t - \frac{E_{\text{f}}(t)}{j_{\text{inv}}} \right) \times j_{\text{batt}}.
\]

If the sum of the electric energy generated by the photovoltaic-power-generation module and wind-power-generation module is less than the load demand, the batteries are discharged, and the total power of the batteries can be obtained by

\[
E_{\text{batt}}(t) = E_{\text{batt}}(t-1) - \left( \frac{E_{\text{f}}(t)}{j_{\text{inv}}} - P_{\text{pv}}(t) \times \Delta t - P_{\text{wt}}(t) \times \Delta t \right) \times j_{\text{batt}}.
\]

In Eqs. (21) and (22), \(E_{\text{batt}}(t)\) is the sum of the stored energy of the batteries at time \(t\), \(E_{\text{f}}(t)\) is the demand for the electric energy of the load, \(j_{\text{inv}}\) and \(j_{\text{batt}}\) are the inverter conversion rate and battery charging efficiency, respectively, and \(\Delta t\) is the change in time. The total battery capacity should always be between \(E_{\text{max,batt}}\) and \(E_{\text{min,batt}}\). If a battery is fully charged, it cannot be recharged. Conversely, if the battery is not charged, its charge will not drop to 0 but will drop to \(E_{\text{min,batt}}\) at a minimum. The power \(P_{\text{batt}}(t)\) that the battery can provide at time \(t\) can be obtained by

\[
P_{\text{batt}}(t) = \frac{E_{\text{batt}}(t) - E_{\text{min,batt}}}{\Delta t}.
\]

2.4 Diesel Power-Supply Module

In the diesel power-supply module [9], if at time \(t\) the total energies provided by the above three modules are less than the load demand, the output power \(P_{d}(t)\) of the diesel engine can be obtained by Eq. (24); otherwise, there is no need for the load to be powered by the diesel engine, or \(P_{d}(t)\) is equal to zero:

\[
P_{d}(t) = \frac{E_{\text{f}}(t)}{\Delta t} - P_{\text{pv}}(t) - P_{\text{wt}}(t) - P_{\text{batt}}(t).
\]

The fuel consumption amount \(F_{d}(t)\) (in units of l/h) of the diesel engine can be obtained from

\[
F_{d}(t) = B_{D} \times \frac{P_{N} + A_{D} \times P_{d}(t)}{P_{N}},
\]

where \(P_{N}\) is the rated output power of the diesel engine, \(A_{D} = 0.246\) (l/kW·h), and \(B_{D} = 0.0845\) (l/kW·h). According to the fuel unit price \(P_{F}\), the fuel consumption cost \(C_{f,d}(t)\) of the diesel engine at time \(t\) can be obtained from

\[
C_{f,d}(t) = P_{F} \times F_{d}(t).
\]

2.5 Objective Function

First, there are three parameters to be considered for the cost
savings: annual input cost $C_c$, annual maintenance cost $C_m$, and annual fuel consumption cost $C_f$.

The annual input cost $C_c$ can be obtained from

$$C_c = \frac{i(1 + i)^{n_w}}{(1 + i)^{n_w} - 1} C_{pv} N_{pv} + \frac{i(1 + i)^{n_w}}{(1 + i)^{n_w} - 1} C_{wt} N_{wt}$$

$$+ \frac{i(1 + i)^{n_w}}{(1 + i)^{n_w} - 1} C_{batt} N_{batt} + \frac{i(1 + i)^{n_w}}{(1 + i)^{n_w} - 1} C_d,$$

(27)

where $i$ is the equipment depreciation rate; $n_{pv}$, $n_{wt}$, $n_{batt}$, and $n_d$ are the service lives and $C_{pv}$, $C_{wt}$, $C_{batt}$, and $C_d$ are the initial input costs of the solar panels, wind turbines, batteries, and diesel engine, respectively.

The annual maintenance cost $C_m$ can be obtained from

$$C_m = N_{pv} \times C_{min,pv} + N_{wt} \times C_{min,wt} + C_{min,d},$$

(28)

where $C_{min,pv}$, $C_{min,wt}$ are the annual maintenance cost per unit of the solar panels and wind turbines, respectively. These costs are determined by the type of solar panels and wind turbines and the environment in which they operate.

The diesel engine annual maintenance cost $C_{min,d}$ can be obtained from

$$C_{min,d} = \sum_{t=1}^{N_{data}} P_{min,d} \times P_d(t).$$

(29)

where $N_{data}$ is the number of samples, $N_{data} = 8760$, and $P_{min,d}$ is the maintenance cost of the diesel engine.

The annual fuel consumption cost $C_f$ of the diesel engine can be obtained from

$$C_f = \sum_{t=1}^{N_{data}} C_{f,d}(t).$$

(30)

Based on the above analysis, the total cost $C_T$ of the ship’s hybrid energy system can be obtained from

$$C_T = C_c + C_m + C_f.$$  

(31)

Second, to extend the operational hours of the system, the concept of availability is introduced, which is the key objective to determine whether the system is able to continue to operate stably [3]. The availability $T$ can be obtained from

$$T = 1 - \frac{DNM}{\sum_{t=1}^{N_{data}} E(t)}.$$  

(32)

where $DNM$ represents an unmet demand, which can be expressed by

$$DNM = \sum_{t=1}^{N_{data}} \left( E_{min,batt} - E_{batt}(t) \right) \left( P_{pv}(t) \times \Delta t + P_{wt}(t) \times \Delta t - E(t) \times u(t) \right).$$  

(33)

where $u(t)$ is a step function. When the total power generated by the photovoltaic-power-generation module and wind-power-generation module is greater than or equal to the load demand, $u(t) = 1$; otherwise, $u(t) = 0$.

If the objective is only to maximize the cost savings, the service life of the equipment may not be long. Conversely, if the objective is only to maximize the service life, the cost can be high. Neither system is likely to be useful in actual applications. Therefore, it is crucial to choose a system that has a low cost and long service life. Therefore, the values of the variables $N_{pv}$, $N_{wt}$, and $N_{batt}$ are determined when the objective function $C_T$ reaches the minimum value and $T$ reaches the maximum value. The operating process of the hybrid energy system is shown in Fig. 3.

### 3. Overview of IABC Algorithm and Optimization Based on It

The optimization of the hybrid energy system configuration of marine diesel engines with the objectives of Eqs. (30) and (31) is a multi-dimensional hyperplane optimization problem. Many studies have shown that the swarm intelligence optimization algorithm exhibited good optimization performance in similar problems [11]–[13]. The artificial bee colony (ABC) algorithm is a new type of intelligent optimization algorithm proposed recently. It imitates the mechanism of bees eating nectar to obtain the global optimal solution of an optimization problem. It has the advantage of not falling into local optima [14], [15]. The particle swarm optimization (PSO) algorithm converges rapidly for the first half of the iteration [4], [5]. Using the PSO algorithm to improve the ABC algorithm allows the improved algorithm to converge more quickly in the early stages of the iteration. Thus, the IABC algorithm was used to optimize the configuration objective function of the marine diesel hybrid energy system.

#### 3.1 IABC Algorithm

According to the principle of bee foraging, the process of the IABC algorithm applied to optimizing the solution is divided into four stages: the initialization phase, employee bee (EB) optimization phase, onlooker bee (OB) optimiz-
of food sources is the number of solutions to be optimized, \( x(l, d) \). The value of \( x(l, d) \) can be obtained from

\[
x(l, d) = x_{\text{min}}(d) + \text{rand} \times (x_{\text{max}}(d) - x_{\text{min}}(d)),
\]

where \( x_{\text{max}}(d) \) and \( x_{\text{min}}(d) \) are their maximum and minimum values, respectively, and \( \text{rand} \) represents a random number between 0 and 1.

In the EB and OB optimization phases, the update solution \( z(l, d) \) can be obtained from

\[
z(l, d) = x(l, d) + y_{td} \times (x(l, d) - x(r, d)),
\]

where \( y_{td} \) is a random number between \(-1\) and \(1\), and \( r \) is a random integer between \(1\) and \(N_p\) and is not equal to \(l\). Because \( x(l, d) \) has maximum and minimum values, the calculated \( z(l, d) \) may be outside the range of \( x(l, d) \). In this case, this new solution must be discarded and another new solution as a substitute is obtained from Eq. (34).

The OB optimization phase comprises the evaluation of the optimal solution obtained from the EB optimization phase. The food source is selected by a probability corresponding to the amount of nectar using the greedy principle. This method does not always select the best data, but better data are more likely to be selected. This can prevent the value of the objective function from falling into a local optimum, allowing a global optimal solution to be obtained.

The probability \( p_l \) used in the OB optimization phase is calculated as follows:

\[
p_l = \frac{F(l)}{\sum_{l=1}^{N_p} F(l)},
\]

where \( F(l) \) is the value of the objective function corresponding to the optimal solution.

Since the original ABC algorithm is slow in the early stages of the iteration, the self-defined variable \( e \) is introduced to determine if optimization acceleration is required. If \( e \) is less than the optimal solution at this time, the algorithm is in the middle and early stages of the iteration, and acceleration optimization is required. The update solution \( z'(l, d) \) can be obtained from

\[
z'(l, d, t + 1) = \omega \cdot v'(l, d, t) + \eta_1 \cdot \text{rand} \times (p_l(l, d) - z(l, d, t)) + \eta_2 \cdot \text{rand} \times (p_{\text{ob}}(d) - z(l, d, t)),
\]

where \( \omega \) represents an inertia weight, \( \eta_1 \) and \( \eta_2 \) are acceleration constants, \( v' \) is the particle velocity, \( p_l \) is the optimal solution found by the particle itself, and \( p_{\text{ob}} \) is the optimal solution. In this case, a single bee in the swarm is used as a particle, and the update method uses the optimization iteration formula of the particle swarm.

If \( e \) is greater than the optimal solution at this time, the algorithm is in the middle and late stages of the iteration,
and there is no need to speed up the optimization.

The optimization method of the IABC algorithm is shown in Fig. 5. The solid line indicates the completion of one iteration, the dashed line indicates the completion of multiple iterations, and the arrows indicate the iterated solutions. The solid circles indicate the optimized solutions found by the ABC algorithm, the solid squares indicate the optimized solutions found by the PSO algorithm, and the hollow circle indicate the optimal solution. The black part of the figure shows the update path of the ABC algorithm and the blue part shows the accelerated update path of the IABC algorithm. The number of iterations for the to-be-optimized solution $x_1$ to reach point A changes from 3 to 2 after acceleration through the iterative formula of the PSO algorithm. The optimizing solution $x_2$ arrives at point B after 2 iterations, and its distance from the optimal solution is less than point C. The red part is the solution that is discarded after the optimization search.

In the SB optimization phase, if the previously obtained optimal solution has not been updated for a long time, when the number of un-updated times $k_{\text{count}}$ is greater than the threshold $k_{\text{limit}}$, the bees have not found a better solution for a long time. Eq. (34) is then used to randomly obtain a new solution to compare with the previous optimal value. If the new solution is better, it replaces the current optimal solution.

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3.2 Optimization of Hybrid Diesel Energy System Configuration Based on IABC Algorithm

Because there are two objectives to be optimized and they also affect each other, the function $u(C_T, T)$ describing the performance of the system can be obtained from the following equation, which takes both objective variables into account:

$$u(C_T, T) = \lambda_1 \frac{C_T - \min(C_T)}{\max(C_T) - \min(C_T)} \frac{T - \max(T)}{\max(T) - \min(T)},$$

(38)

where $\lambda_1$ and $\lambda_2$ are self-defined parameters that can indicate the importance of $C_T$ and $T$ in the system. In this paper $\lambda_1 = \lambda_2$, which means that the cost and availability are equally important. MatLab (MathWorks, USA) was used to obtain the final optimal result and the minimum value of $u(C_T, T)$. At this point, $C_T$ in Eq. (31) is closer to its minimum and $T$ in Eq. (32) is closer to its maximum. The optimization process is shown in Fig. 6.

4. Performance of the Proposed Method

To verify the effectiveness and validity of the hybrid energy optimal configuration, the ship navigation test was carried out with a route from Dalian, China to Aden, Yemen. Due to the limitations of the experimental conditions, we were unable to retrofit the ship and conduct a case test. So, this experiment is based on simulation. The ship’s single round trip time was approximately 38 d, a total of 912 h. The ship had a total length of 332.95 m, a profile width of 60.00 m, a depth of 30.50 m. The areas of the solar panels were 10,000 m², the number of fans was 300, and the battery pack is 4000 sets. Owing to the geographical location of the ship during the journey, the amount of solar radiation also changed. Through Eqs. (1)–(10), the amount of solar radiation ($I_t$) the ship received in a single round-trip simulation is shown in Fig. 7.

In the wind-power-generation module, the data of the wind speed $v_t$ per hour is shown in Fig. 8. Owing to the randomness of the wind, the data were obtained by simulating the average climates of the areas on the navigation route.

Five different operating modes of the ship-navigation experiments are described in this section, and the corresponding load power is given in Table 1. When the ship was navigating in ordinary seas, it was in full-speed mode. When the ship was navigating in the Straits of Malacca, it was in cruising mode. The ship was docked in Dalian, Shanghai, Hong Kong, Singapore, Sri Lanka, and Aden for transactions and maintenance. The time spent docked is given in Table 2. Therefore, in a single round-trip simulation, the
data for the hourly electric loads are shown in Fig. 9.

The simulation calculation was performed on different modules of the hybrid energy system, and the specific parameters required for the calculation are given in Table 3. To study the influence of different kinds of batteries on the system, lead-acid (LA) batteries, lithium-ion (Li-ion) batteries, and nickel-cadmium (Ni-Cd) batteries were tested as the battery energy-storage modules of the system. The specific parameters have been described previously [20] and are given in Table 4.

To verify the optimization performance of the proposed method, we also optimized the configuration and simulation of the hybrid energy system using the IABC algorithm introduced in Sect. 2.1, the original ABC algorithm [9], the PSO algorithm [5], and the DE algorithm [7]. The optimization curves are shown in Fig. 10.

![Fig. 7 Solar radiation during navigation.](image)

![Fig. 8 Wind speed during navigation.](image)

![Fig. 9 Load during navigation.](image)

**Table 3** Numerical value of different modules parameters.

<table>
<thead>
<tr>
<th>PV module</th>
<th>Wind power module</th>
<th>Diesel power supply module</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{PV}$</td>
<td>$P_{wind}$</td>
<td>$P_{diesel}$</td>
</tr>
<tr>
<td>210W</td>
<td>1500W</td>
<td>1900W</td>
</tr>
<tr>
<td>$A$</td>
<td>$V_{ref}$</td>
<td>$C_d$</td>
</tr>
<tr>
<td>1.02m²</td>
<td>2.5m/s</td>
<td>1713.15$</td>
</tr>
<tr>
<td>$C_{pv}$</td>
<td>$V_{max}$</td>
<td>$P_{max}$</td>
</tr>
<tr>
<td>487S</td>
<td>13m/s</td>
<td>0.012588$kJ/h</td>
</tr>
<tr>
<td>$f_{pv}$</td>
<td>$V_r$</td>
<td>$P_f$</td>
</tr>
<tr>
<td>16.5%</td>
<td>13m/s</td>
<td>1.24$/$</td>
</tr>
<tr>
<td>$n_{pv}$</td>
<td>$C_{max}$</td>
<td>$n_d$</td>
</tr>
<tr>
<td>25 years</td>
<td>4500$</td>
<td>5 years</td>
</tr>
<tr>
<td>$C_{max, pv}$</td>
<td>4.81$</td>
<td>$n_{max}$</td>
</tr>
<tr>
<td>135$</td>
<td></td>
<td>20 years</td>
</tr>
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</table>

**Table 4** Numerical value of battery energy-storage modules parameters.

<table>
<thead>
<tr>
<th>Battery energy-storage modules</th>
<th>LA</th>
<th>Li-ion</th>
<th>Ni-Cd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>$\epsilon_{max, hot}$</td>
<td>$\epsilon_{max, hot}$</td>
<td>$\epsilon_{max, hot}$</td>
</tr>
<tr>
<td>$j_{bat}$</td>
<td>85%</td>
<td>95%</td>
<td>85%</td>
</tr>
<tr>
<td>$C_{bat}$</td>
<td>255$</td>
<td>152$</td>
<td>173$</td>
</tr>
<tr>
<td>$D_{bat}$</td>
<td>0.5</td>
<td>0.5</td>
<td>0.15</td>
</tr>
<tr>
<td>$i_{bat}$</td>
<td>90%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>$n_{bat}$</td>
<td>4 years</td>
<td>15 years</td>
<td>20 years</td>
</tr>
<tr>
<td>$t$</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
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</tbody>
</table>
The worst optimization value (Worst), the best optimization value (Best), the median value (Median), the mean value (Mean), and the standard deviation (Std.) of the 30 repeated tests are shown in Table 5. These parameters can be used to quantitatively analyze the optimization effects of the different algorithms. The median reflects the quality of the optimal solution, the average reflects the convergence speed of the optimization algorithm, and the standard deviation reflects the quality of the optimal solution.

The self-defined variable $e = 3 \times 10^{-3}$ is the average of the intersection of the iterative curves of the PSO algorithm and the ABC algorithm over 30 repeated trials.

The comparison of the results in Fig. 10 and Table 5 show that the IABC algorithm exhibited better optimization effects in terms of the quality of the solution, the convergence speed, the stability, and the robustness of the algorithm compared with the other three algorithms.

Table 6 shows the time complexity comparison of the four optimization algorithms. The time consumed by a single iteration of the 50 iterations in 30 repeated experiments was calculated. It can be seen that the PSO algorithm is the fastest and the IABC algorithm is the slowest. Although IABC increases the time complexity, compared with the PSO algorithm, it can largely avoid the situation of falling into a local optimal.

Compared with ABC algorithm, IABC algorithm increases the calculation time by 28%, which not only greatly improves the optimization speed of the algorithm in the early stage, but also increases the probability of finding the global optimal solution. This indicates that the optimization idea proposed in this paper was feasible, which not only accelerated the convergence speed of the original ABC algorithm but also retained its characteristic of avoiding local optima. Thus, it exhibited better performance for this problem.

The dual-objective optimized configuration of the hybrid system detailed in Sect. 2.2 was compared with two previously reported objective function optimization systems

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**Fig. 10** Optimization process of different algorithms in each system: (a) LA batteries, (b) Li-ion batteries, (c) Ni-Cd batteries.

**Table 5** Comparison of test results by four different optimization algorithms.

<table>
<thead>
<tr>
<th>Battery technology</th>
<th>Numerical categories</th>
<th>Different algorithms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Worst</td>
<td>ABC</td>
</tr>
<tr>
<td></td>
<td>$3.9224 \times 10^3$</td>
<td>$4.0808 \times 10^1$</td>
</tr>
<tr>
<td>LA</td>
<td>Best</td>
<td>$3.9224 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>$3.9224 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>$3.9224 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>Std.</td>
<td>$5.6190 \times 10^4$</td>
</tr>
<tr>
<td>Li-ion</td>
<td>Worst</td>
<td>$4.3802 \times 10^1$</td>
</tr>
<tr>
<td></td>
<td>Best</td>
<td>$4.3802 \times 10^1$</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>$4.3802 \times 10^1$</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>$4.3802 \times 10^1$</td>
</tr>
<tr>
<td></td>
<td>Std.</td>
<td>$3.4040 \times 10^4$</td>
</tr>
<tr>
<td>Ni-Cd</td>
<td>Worst</td>
<td>$3.7807 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>Best</td>
<td>$3.7807 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>$3.7807 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>$3.7807 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>Std.</td>
<td>$5.6460 \times 10^7$</td>
</tr>
</tbody>
</table>
Table 6  Time complexity of different algorithms.

<table>
<thead>
<tr>
<th>Different algorithms</th>
<th>IABC</th>
<th>ABC</th>
<th>DEA</th>
<th>PSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of a single iteration (s)</td>
<td>2.2084×10⁻²</td>
<td>1.7203×10⁻²</td>
<td>5.8380×10⁻⁴</td>
<td>5.5834×10⁻⁶</td>
</tr>
</tbody>
</table>

Table 7  Optimal configuration of different optimization targets in different systems.

<table>
<thead>
<tr>
<th></th>
<th>N_{ps}</th>
<th>N_{se}</th>
<th>N_{nat}</th>
<th>C_T</th>
<th>T</th>
<th>s(C_T,T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The proposed method</td>
<td>8991</td>
<td>2</td>
<td>4000</td>
<td>8.9266×10⁶</td>
<td>4.6110</td>
<td>0.3922</td>
</tr>
<tr>
<td>LA</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4.8590×10⁴</td>
<td>3.1515×10⁴</td>
<td>0.5000</td>
</tr>
<tr>
<td>The method in [1]</td>
<td>1000</td>
<td>30</td>
<td>4000</td>
<td>1.0503×10⁵</td>
<td>4.2822</td>
<td>0.5000</td>
</tr>
<tr>
<td>The method in [3]</td>
<td>9383</td>
<td>2</td>
<td>4000</td>
<td>1.2083×10⁶</td>
<td>4.1040</td>
<td>0.4380</td>
</tr>
<tr>
<td>Li-ion</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4.8597×10⁴</td>
<td>3.1515×10⁴</td>
<td>0.5000</td>
</tr>
<tr>
<td>The method in [1]</td>
<td>1000</td>
<td>30</td>
<td>4000</td>
<td>1.3548×10⁵</td>
<td>4.2951</td>
<td>0.5000</td>
</tr>
<tr>
<td>The method in [3]</td>
<td>5480</td>
<td>2</td>
<td>4000</td>
<td>1.0863×10⁶</td>
<td>5.5875</td>
<td>0.3781</td>
</tr>
<tr>
<td>Ni-Cd</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4.8596×10⁴</td>
<td>3.1515×10⁴</td>
<td>0.5000</td>
</tr>
<tr>
<td>The method in [1]</td>
<td>1000</td>
<td>30</td>
<td>4000</td>
<td>1.3560×10⁵</td>
<td>5.9809</td>
<td>0.5000</td>
</tr>
</tbody>
</table>

[1], [3]. The results are shown in Table 7. The hybrid system optimized in this paper exhibited a significant advantage. When the lowest cost was reached, the availability of the system became very low; conversely, when the highest availability was reached, the cost became very high. However, the optimization results of the dual-objective system configuration showed that the system availability could be greatly improved by adding a certain amount of cost to the lowest cost.

In addition, three different types of batteries were used as energy storage systems to optimally configure the ship. The actual energy storage of the battery throughout the voyage is shown in Fig. 11, the power output from the diesel engine is shown in Fig. 12, and the configuration parameters for systems loaded with different batteries are given in Table 8.

According to the data in Table 4, it is known that the energy storage capacity of a single Ni-Cd battery is stronger than that of the other two batteries. So, in Fig. 11(c), the battery capacity is at its lowest for some time. However, if the total number of batteries needs to be reduced for some reason, and the number of solar panels and fans is not changed, it may happen that the system is still generating electricity power when the battery is full. At this time, the excess energy can be used in non-propulsion systems such as cabin lighting and monitoring. For propulsion systems, this part of the power is “wasted.”

As shown in Fig. 11, Fig. 12, and Table 8, the cost of the Li-ion battery was much higher than that of the LA battery. In the optimal configuration, although the availability of the Li-ion battery system was slightly lower, the total cost was 35% greater than that of the system with the LA battery. If the costs of Li-ion batteries decline in the future, systems with Li-ion batteries will be competitive. For the Ni-Cd battery system, the ship’s diesel engine consumed more power than the other two systems, consuming more
fuel and releasing more harmful gases, which is not conducive to the protection of marine environments.

Since the Ni-Cd battery has a memory effect, it is not suitable for a system that requires frequent charging and discharging of the battery compared to the other two types of batteries. It will be very competitive on ships that work only during the day, such as ships with short working routes and passenger ships that transport tourists. Therefore, in this experiment, the system equipped with the LA battery exhibited better performance.

This paper is based on the analysis of simulation experiments. In the actual situation, due to the uncertainty of weather conditions, such as calm wind in sunny days and high wind in cloudy days, the electricity provided by photovoltaic-power-generation module and wind-power-generation module fluctuates greatly. For ships with fixed routes, it is necessary to optimize the configuration based on the weather data of ship routes in recent years. For ships with non-fixed routes, the weather data of different sea areas should be statistically calculated in proportion according to the voyage frequency of different ship routes, and then optimized for configuration. Therefore, the final optimization result is more applicable to individuals.

In addition, solar energy and wind energy are used in this paper. Nevertheless, future research needs to combine more new energy sources to be promoted, such as nuclear energy and hydrogen energy, so as to further reduce the harmful gas emissions of the ship hybrid energy system. Moreover, the ship’s power system itself will have some impact. Therefore, in the following research, the focus is on the impact of distributed power on other parameters related to grid quality, such as low frequency oscillations and transients.

5. Conclusion

A dual-objective optimization method was proposed for the configuration problem of marine hybrid energy systems. First, the solar-radiation parameters were adjusted according to the latitude and longitude of the ship and the changes of the environment. The objective function of the optimal configuration was constructed considering the cost and service life. Second, the IABC algorithm was used to perform optimization. A ship-navigation experiment was carried out in five operation modes: full speed, constant-speed cruising, port entry and exit, loading and unloading, and anchoring and mooring. Finally, three different systems consisting of LA batteries, Li-ion batteries, and Ni-Cd batteries were compared. The experimental results show that the proposed method exhibited good performance characteristics for the configuration optimization.
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