Research on Multi-objective Optimization of Capacity Allocation for Marine Hybrid Energy Storage System

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Abstract. The hybrid energy storage system's allocation problem is a multi-target and multi-direction optimization problem. Single-objective allocation for the Marine Hybrid Energy Storage System (MHESS) cannot help the hybrid energy storage system unit give play to its optimal effect. A diesel-electric hybrid ship is used as the object. In this paper, a mathematical model of a hybrid energy storage device is established, and multi-objective optimization allocation is performed on the model based on the NSGA-II. Finally, the optimized model is applied to a ship, and eleven kinds of batteries and six supercapacitors are selected for simulation. The simulation results show the relationship between the objective functions.

1. Introduction
It is an unstoppable trend to design and study large-scale marine batteries and adopt energy storage technology to integrate energy storage devices such as batteries and supercapacitors with marine electric propulsion systems, so as to form propulsion devices that can replace diesel engines [1]. The output characteristics of the main power plant composed of electric propulsion systems depend on the degree of interference suffered by the load. Besides, the single energy storage system has a low energy supply rate, which cannot adapt to ocean voyages. In this case, a supercapacitor and a marine battery are combined to form a hybrid energy storage system, so that the energy density of both can be enhanced and amplified. When the output power of the system changes due to interference, the stored energy is released to keep the output of the propulsion device constant, thus adapting to ocean voyages [2].

At present, the optimal allocation of the hybrid energy storage system based on microgrid is a mainstream research direction. However, the microgrid can only allocate the capacity of the energy storage unit against a single objective function, did not take the practical working condition of each unit into account. In order to make the hybrid energy storage unit exert the optimal effects, multi-directional and multi-objective analysis is required [3]. In [4], based on the demand of the marine navigation load characteristics, the allocation method of the total capacity of the energy storage system is given. Besides, the hybrid allocation of supercapacitor and marine battery is analyzed based on the required cost, which reduces the number of battery discharge cycles and increases the battery capacity. In [5], chance-constrained programming is introduced to make the capacity allocation more practical. Moreover, the genetic algorithm is used to achieve a moderate compromise between power quality and economy. In [6], the energy storage system is applied to the icebreaker to analyze the operation of the electric
propulsion device under extreme conditions, and then the optimal allocation of the energy storage system is obtained. In [7], a hybrid energy storage device is added to the traditional energy consumption device of the rake suction dredger. The simulation results show that the output power fluctuation of the modified main engine is significantly reduced, which can better meet the power requirements of various working conditions and improve the practical operating power value of the main engine.

To explore the optimization strategy of the hybrid energy storage system of diesel-electric hybrid ships under different operating modes and various working conditions, a mathematical model of the MHESS is constructed and optimized based on NSGA-II in this paper. Then, the mathematical model of MHESS is described in Section 2, and the optimal allocation based on NSGA-II is introduced in Section 3. Thereafter, the strategy is applied to the marine energy storage system, and a variety of energy storage devices are selected for comparison to study the relationship between objective functions. Finally, the conclusions of the study are presented.

2. Mathematical model of MHESS optimization

The design of energy storage device for electric propulsion ships should meet the needs of actual ship operation. In this section, a mathematical model of MHESS, considering the cost, battery life cycle, power constraints, and state of charge constraints, is constructed, the objective of which is to maximize the cycle life of the battery and minimize the design cost of marine energy storage devices.

2.1. Objective functions

The optimization of energy storage devices includes two parts: cost target and battery cycle life target. The cost objective function of MHESS should consider the unit capacity price, purchase quantity, number of replacements, and waste disposal cost of supercapacitors and batteries. According to [8], the cycle life target is to maximize the cycle life of the battery, and its evaluation index is a function of the depth of discharge (DOD). The general formulas of the objective functions are as follows:

\[
 f_1 = \min(C_1 + C_2 + C_3) = \min \left\{ \left[ C_b n_b + C_u n_u \right] + \left[ (k_b -1) n_b C_b + (k_u -1) n_u C_u \right] \right\}
\]

\[
 f_2 = y \left( m_1 d_1^{(k-DOD)} + m_2 d_2^{(l-DOD)} \right)
\]

\[
 DOD = \frac{\int_0^t P_b(t) dt}{E_b}
\]

Where \( C_1, C_2, C_3 \) are the initial purchase cost, replacement cost, and waste disposal cost, respectively. \( C_b \) and \( C_u \) are the prices of batteries and supercapacitors, respectively. \( n_b \) and \( n_u \) are the number of batteries and supercapacitors purchased for the first time, respectively. \( k_b \) and \( k_u \) are the number of replacements of battery and supercapacitor throughout the life cycle, respectively. \( C_{br} \) and \( C_{ur} \) are the waste disposal prices of batteries and supercapacitors, respectively. \( P_b \) and \( E_b \) are the power and energy of the battery, respectively. \( DOD \) is the depth of discharge at time \( t \). \( y \) is a coefficient related to battery life. The values set of the parameters \( m_1, d_1, m_2, d_2, l \) in the above expressions can be found in [8].

2.2. Constraints of the energy storage device

There are many kinds of constraints in the practical application of marine energy storage devices. This paper lists some typical constraints, such as minimum rated capacity, minimum rated power, power constraints, and state of charge constraints (SOC), which are shown below, respectively:
\[ E_r = \max \left\{ \frac{E_d}{\eta_{\text{dis}} \eta_i}, \frac{E_c}{\eta_{\text{ch}} \eta_i} \right\} \]

\[ P_r = \max \left\{ \frac{P_s}{\eta_{\text{dis}} \eta_i}, \frac{P_e}{\eta_{\text{ch}} \eta_i} \right\} \]

\[ \text{SOC}_{\text{min}} \leq \text{SOC}_i \leq \text{SOC}_{\text{max}} \]

\[ P_d = \sum_{i=1}^{r} (-P'_{o,t} / P_o) \]

\[ P_{\text{rmin}} \leq P_d \leq P_{\text{rmax}} \]

Where \( \eta_i \) is the efficiency of the inverter. \( E_d \) and \( E_c \) are the minimum discharge and charge energy, respectively. \( P_s \) and \( P_e \) are the maximum power shortage and the maximum power excess, respectively. \( P_r \) and \( E_r \) are the minimum rated power and the minimum rated capacity, respectively. \( P'_{o,t} \) is the load power of the ship after the energy storage device compensates for the period \( t \). \( P_{\text{rmin}} \) and \( P_{\text{rmax}} \) are the maximum Power missing value and the maximum power overflow value, respectively. The expressions of the remaining parameters can be found in [3].

### 2.3. Decision vector

After the battery and supercapacitor monomer models are determined, the decision variables of the cost target are the number of monomers \( n \), and the number of replacements \( k \). The power output capability, energy output capability, and optimal working area of the energy storage device are described in the Ragone curve, from which the minimum number of energy storage components required for each batch can be calculated. Since the supercapacitor has a long service life of several decades, the cycle life of the battery should be mainly considered. By analyzing the relationship between the cycle life of lithium iron phosphate battery and the service life of MHESS, the number of replacements can be calculated. Therefore, the decision vector can be expressed as:

\[ X = [n_b, n_u, k_b, k_u] \]

### 3. Optimized allocation based on the NSGA-II

NSGA-II is a frequently used algorithm in current multi-objective optimization research, which can speed up the calculation, and reduce computational complexity [10]. In this paper, the process of the algorithm is introduced, and its three subroutine algorithms are analyzed. Based on NSGA-II, the capacity of the MHESS is optimized, and the input program of the objective functions and the constraint functions are proposed.

#### 3.1. NSGA-II flow

The NSGA-II flow is as follows: (1) Fast non-dominated sorting. Based on the individual's non-inferior solution level, the overall \( M \) is cyclically stratified to obtain \( F_i \). Through fast non-dominated sorting, the optimal value of the objective function is searched for many times to make the solution close to the optimal solution. (2) Individual crowding distance and distance calculation. According to the respective crowded distances, non-dominated solutions are selectively classified in the same layer \( F_k \), and the
individuals with large crowded distances are preferentially selected. Place the calculation results in the target space to maintain spatial diversity. (3) The elitist strategy generates a new population. According to certain principles, select outstanding individuals from the parents and put them into the children to prevent the loss of the optimal solution.

3.2. Optimize the allocation
The multi-objective optimization steps for the capacity allocation of MHESS based on NSGA-II are as follows: (1) Determine the optimization target, namely, cost target and battery cycle life target. (2) Clarify variables, namely the number and type of batteries and supercapacitors. (3) Set the population number pop=200, the number of iterations gen=500. Initialize the population first, and then perform the non-dominated quick sorting and crowding calculation on the initialized population. After selection, crossover, and variation, the elitist strategy is used to generate a new population until the iteration is completed. Finally, the Pareto optimal solution is obtained. (4) Four parameters are obtained through the optimal solution, namely the capacity N1 and model K1 of the battery, the capacity N2 and model K2 of the supercapacitor to obtain the subsequent parameters.

4. Simulation results and discussion
For the simulation experiment, a ship is taken as the research object, and eleven kinds of batteries and six kinds of supercapacitors are selected. In the Pareto Optimal Front diagram obtained through MATLAB simulation experiment, the investment cost of batteries and supercapacitors is taken as the abscissa, and the evaluation index of battery cycle life is taken as the ordinate. Through the continuous optimization of NSGA-II, 50 feasible solutions are generated in the feasible region, as shown in Figure 1:

![Figure 1. Pareto Optimal Front](image)

It can be seen from Figure 1 that the greater the investment cost, the greater the cycle life evaluation index of the battery. The relationship between the two is close to a smooth curve, which can establish a specific functional relationship. In this paper, six feasible solutions are selected as specific solutions for analysis, in order to further study the relationship between the two objective functions. Meanwhile, based on the models of batteries and supercapacitors used in the six scenarios, the related costs are obtained, and the percentage of the two energy storage components are calculated. The specific values can be found in Table 1 and 2, respectively.
Table 1. Six typical scenario values

| Scenario  | Cost of investment (¥) | The evaluation index of battery life | The number of batteries | The number of supercapacitors | The type of battery | The type of supercapacitor |
|-----------|------------------------|-------------------------------------|-------------------------|-------------------------------|-------------------|--------------------------|
| 1         | 82190208               | 10                                  | 6465                    | 1338                          | 2                 | 5                        |
| 2         | 172866383              | 38                                  | 1635                    | 1328                          | 8                 |                          |
| 3         | 254265795              | 54                                  | 25228                   | 1332                          |                   |                          |
| 4         | 320203795              | 64                                  | 32421                   | 1328                          |                   |                          |
| 5         | 376951089              | 69                                  | 38605                   | 1328                          |                   |                          |
| 6         | 430262019              | 74                                  | 37009                   | 1330                          |                   |                          |

Table 2. The cost ratio of the two energy storage elements

| Scenario  | Percentage of battery cost | Percentage of supercapacitor cost |
|-----------|---------------------------|-----------------------------------|
| 1         | 13%                       | 87%                               |
| 2         | 28%                       | 72%                               |
| 3         | 37%                       | 63%                               |
| 4         | 43%                       | 57%                               |
| 5         | 48%                       | 52%                               |
| 6         | 51%                       | 49%                               |

From Table 1 and Table 2, it can be seen that by increasing the investment cost of MHESS, the number of batteries has increased gradually, which makes the depth of discharge (DOD) of a single battery during the normal navigation of the ship decreased gradually and the evaluation index of the battery life improved gradually. As the number and cost ratio of batteries have increased sequentially, the number of supercapacitors has hardly changed, but the cost ratio of supercapacitors has decreased sequentially.

5. Conclusion

In order to study the multi-objective capacity optimization allocation of ship hybrid energy storage, a mathematical model of MHESS is established, and two objective functions are proposed in this paper. Then, the system allocation is optimized based on NSGA-II to acquire the Pareto optimal solutions, and the capacity allocation is optimized through a range of simulation experiments. The results show the relationship between the cost target and the battery cycle life target in MHESS, which can help select suitable hybrid energy storage devices for ships.

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References

[1] Yelet S, Fu Y. (2010) Impacts of energy storage on the future power system. North American Power Symposium. IEEE, 2010: 1-7.

[2] WU Shuli, YANG Xiangguo, SUN Pan, YU Tong, TIAN Lei. (2019) Modeling and Simulation Analysis of Energy Storage Unit in Ship Hybrid Energy Storage System. Journal of Wuhan University of Technology (Transportation Science & Engineering), 2019: 718-722.

[3] YANG Xiangguo, SUN Pan, YANG Cheng, et al. (2018) Multi-Objective Optimization of capacity of Hybrid Energy Storage Device for Ship Electric Propulsion System. Navigation of China, 41 (2): 9-14.

[4] LI Cheng, YANG Xiu, ZHANG Meixi, et al. (2013) Optimal Allocation Scheme for Hybrid Energy Storage System of Super-capacitors and Batteries Based on Cost Analysis. Automation of Electric Power Systems, 37 (18): 20-24.

[5] Lina Li, Li Yang. (2012) A chance-constrained programming based energy storage system sizing model considering uncertainty of wind power. In: International Conference on Sustainable Power Generation and Supply. IEEE. Hangzhou, China. pp. 1-6
[6] LIU Yusheng, E Fei, FENG Hao, et al. (2019) Optimal Capacity of Energy Storage System for Icebreaker Vessel. Journal of Shanghai Ship and Shipping Research Institute, 39 (03): 47-51.

[7] Kanellos F D. (2014) Optimal power management with GHG emissions limitation in all-electric ship power systems comprising energy storage systems. IEEE Transactions on Power Systems, 29 (1): 330-339.

[8] NoshinOmar, Mohamed Abdel Monem, et al. (2014) Lithium iron phosphate based battery – Assessment of the aging parameters and development of cycle life model. Applied Energy, 113 (2014): 1575-1585.

[9] Paska J, Bicz P, Klos M. (2009) Technical and economic aspects of electricity storage systems co-operating with renewable energy sources. In: 10th International Conference on Electrical Power Quality and Utilisation. IEEE. Lodz Poland. pp. 1-6.

[10] Deb K, Pratap A, Agarwal S, et al. (2002) A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE transactions on evolutionary computation, 6 (2): 182-197