

A Review of Energy Management Strategies for Ship Hybrid Power Systems

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Abstract: With the enhancement of environmental awareness and the increase in the demand for sustainable development in the shipping industry, the energy management strategy of ship hybrid power systems has become a research hotspot. This paper integrates multiple related papers and comprehensively expounds the current research status of energy management strategies for ship hybrid power systems. A variety of energy management strategies are introduced in detail, including rule-based control strategy, model predictive control, equivalent consumption minimization strategy, intelligent algorithm control strategy, etc., and the principles, applications, advantages and disadvantages of each strategy are analyzed in depth. The types, compositions of ship hybrid power systems and their application examples on different ships were discussed, as well as the problems and challenges these systems face in terms of energy management. Through the comparative analysis of different strategies, it is clarified that future research should be carried out in the direction of optimizing algorithms, considering multi-factor coupling, strengthening experimental verification, and promoting the development of standardization and intelligence, aiming to provide references for the further research and application of energy management in ship hybrid power systems and promote the green development of the shipping industry.

Keywords: Ship Hybrid Power System, Energy Management Strategy, Sustainable Development, Optimization Algorithm, Green Shipping.

1. Introduction

Green shipping has become a core issue in the development of the global shipping industry, and under the impetus of the International Maritime Organization's emission reduction targets, optimizing ship energy management technology has become a key way to achieve low-carbon and efficient operation [1]. Ships consume a large amount of fossil fuels during operation, which not only causes energy waste, but also brings pollutant emissions such as carbon dioxide and nitrogen oxides, which have a serious impact on the environment. International organizations such as the International Maritime Organization (IMO) have introduced a series of strict regulations, such as the Ship Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP), aiming to promote the ship industry to reduce energy consumption and emissions [2-3]. In such a situation, ship hybrid power system comes into being, which integrates multiple energy sources and provides an effective way to improve ship energy utilization efficiency and reduce environmental pollution. As the core of ship hybrid power system, the energy management strategy is directly related to the system performance and energy saving and emission reduction effect. A reasonable energy management strategy can intelligently allocate the output power of different energy sources according to the ship's operating conditions, load demand, and energy status, realizing the efficient operation of the system, reducing the operating cost, and reducing the pollutant emission [4]. Therefore, in-depth study of the energy management strategy of ship hybrid power system has important practical significance and engineering application value.

2. Overview of Hybrid Power Systems for Ships

2.1. System Type and Composition

Ship hybrid power system mainly includes diesel-electric hybrid, gas-electric hybrid, fuel cell-battery hybrid and other types. Diesel-electric hybrid system combines the advantages of diesel engine and electric motor, the diesel engine provides stable power at high loads, and the electric motor plays a role at low loads or start-stop phases, and can recover braking energy [5]. Gas-electric hybrid systems, on the other hand, utilize the clean-burning characteristics of natural gas, which works in tandem with electric power to reduce emissions. Fuel cell-battery hybrid systems use fuel cells as the primary energy source, assisted by batteries, to achieve efficient and low-pollution electricity supply [11]. These systems usually consist of an energy generation device (e.g., diesel engine, gas turbine, fuel cell, etc.), an energy storage device (e.g., battery, supercapacitor, etc.), a power conversion device (e.g., inverter, DC/DC converter, etc.), and a propulsion system (e.g., electric motor, propeller, etc.). The components work in tandem, with the energy generator generating power on demand, the energy storage device storing excess energy and releasing it when needed, the power conversion device converting electrical energy to mechanical energy, and the propulsion system converting the power into propulsion for the ship [6-7].

2.2. Application Status

Marine hybrid power systems are widely used in a variety of ship types. In the field of tugboats, the tugboat studied by Kalikatzarakis etc all. uses a hybrid propulsion and power system equipped with a diesel engine, an induction motor, and a battery pack, which effectively reduces fuel consumption and emissions by optimizing energy management strategies.

For ferries, some ferries utilize hybrid power systems to reduce pollution in the harbor area by using electrical energy when docking, and to improve energy efficiency by flexibly switching energy sources according to load demand when sailing. In the fields of yachts, research vessels and naval vessels, hybrid power systems are also applied due to their

advantages, which fulfill different needs of use, such as reducing noise and improving range[2,7].

3. Classification and Principles of Energy Management Strategies

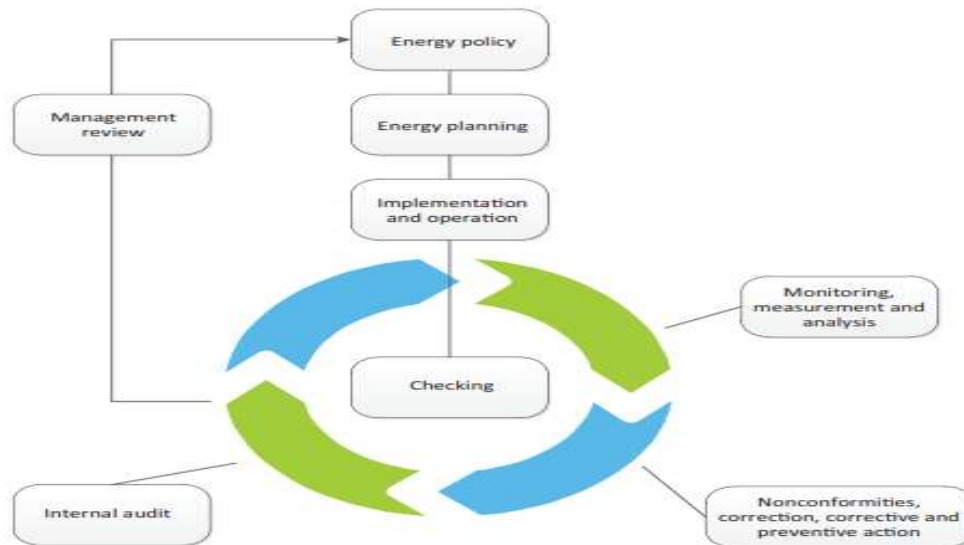


Fig.1 Energy management system methodology

3.1. Rule-based Control Strategy

Rule-based control strategy is to manage energy allocation based on pre-set rules. For example, in a marine hybrid power system, the energy allocation rules are formulated according to the operating conditions of the ship (e.g., sailing, mooring, acceleration, deceleration, etc.), the state of charge (SOC) of the battery, and the load demand. Common rules include prioritizing the use of battery power when the SOC of the battery is high and the load is low; when the load is high and

the SOC of the battery is low, start the diesel engine to generate power and charge the battery at the same time [8]. The advantages of this strategy are that it is simple and easy to understand, easy to implement, does not require complex calculations and models, and can respond quickly to changes in the system. However, its disadvantages are also more obvious, as the rules are fixed, lack of adaptability to the dynamic changes of the system, difficult to optimize in real time according to the actual situation, and may lead to inefficient energy use [9].

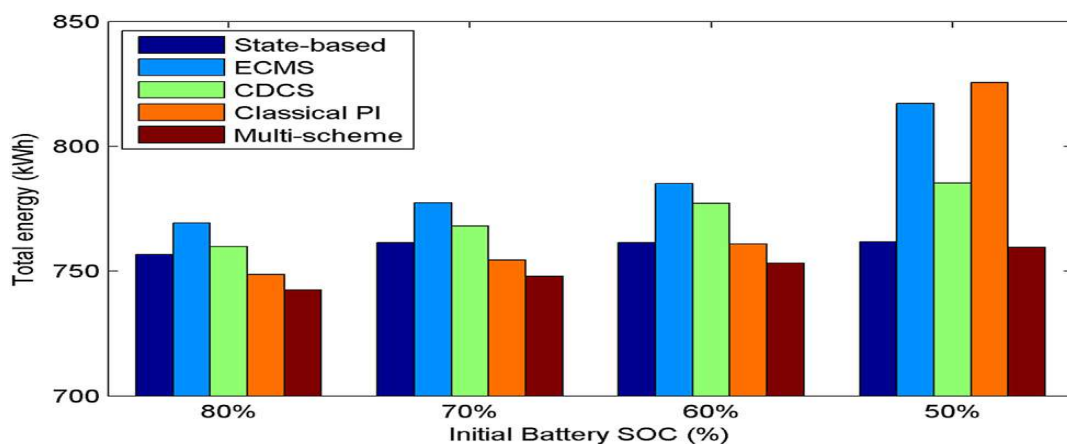


Fig. 2 Impact of different initial battery SOC on total energy saving percentage of the developed multi-scheme EMS compared to other EMS

3.2. Model Predictive Control

Model predictive control is a model-based optimization control strategy. It predicts the future state of the system by building a model of the ship's hybrid power system, and then solves the optimization problem in the prediction time domain to determine the optimal control inputs (e.g., the output power of each energy source). In Jun Hou [10-11] etc all. study, for the propulsion system of an all-electric ship, a model containing the power generation system, the propulsion motor, and the hybrid energy storage system was developed

considering the fluctuation of the propulsion load, and the model predictive control was applied to energy management. The advantage of this strategy is that it can take into account the dynamic characteristics and constraints of the system and achieve the prediction and optimization of the future state, thus improving the performance and stability of the system. However, it also has some limitations, such as high requirements on model accuracy, uncertainty of model parameters will affect the control effect; high computational complexity, real-time performance may be affected, and powerful computational hardware support is required in

practical applications [12].

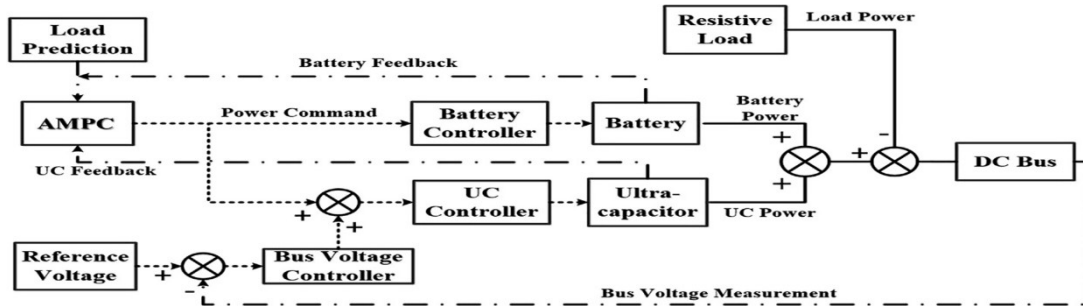


Fig. 3 Schematic of the real-time adaptive MPC

3.3. Equivalent Consumption Minimization Strategy

The equivalent consumption minimization strategy is based on the concept of considering the battery as an auxiliary reversible fuel tank, which transforms the energy management problem into a problem of minimizing the equivalent fuel consumption by introducing an equivalence factor to equate the electrical energy consumption to the fuel consumption [13]. In marine hybrid power systems, an equivalence factor is calculated to determine the optimal power allocation between the engine and the battery based on

the operating status and efficiency of the system. Kalikatzarakis [14] et al. applied ECMS to a ship with a hybrid propulsion and power system and achieved a reduction in fuel consumption by optimizing the equivalence factor. The advantage of this strategy is that it is relatively simple to calculate, and it can take into account the real-time operation status of the system to a certain extent, so that real-time optimization can be realized. However, the determination of the equivalence factor is more critical, and its accuracy has a greater impact on the control effect, and it usually assumes that the system parameters are known, which is less adaptable to changes in system parameters [15-17].

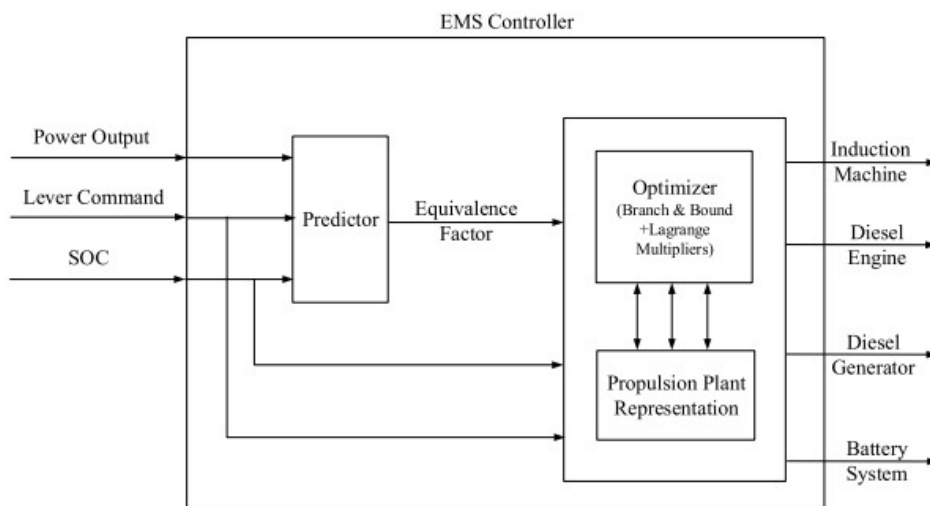


Fig.4 Schematic overview of the EMS controller

3.4. Intelligent Algorithm Control Strategies

3.4.1. Fuzzy Logic Control

Fuzzy logic control imitates the human fuzzy reasoning and decision-making process, and realizes the control of the system through three steps: fuzzification, fuzzy reasoning and defuzzification. In marine hybrid systems, input variables (e.g., battery SOC, load power, etc.) are fuzzified, reasoning is carried out according to predefined fuzzy rules, and finally the fuzzy outputs are de-fuzzified to obtain the actual control quantities (e.g., power allocation of each energy source) [18]. Its advantage is that it can deal with uncertain and imprecise information, has less dependence on the system model, and has strong robustness. However, the formulation of fuzzy rules often relies on experience and lacks a systematic design approach, which may lead to poor control results [19].

3.4.2. Neural Network Control

Neural network control learns and trains a large amount of input data by constructing a neural network model to realize the control of the system. In ship energy management, the powerful learning ability of neural network is used to learn the complex nonlinear relationship of the system, so as to realize the optimization of energy allocation [20-21]. It can automatically adapt to the changes of the system and has strong adaptive and learning ability. However, the training of neural networks requires a large amount of data, the training time is long, and the selection of the network structure and the adjustment of the parameters are more difficult, which is prone to overfitting phenomenon and leads to poor generalization ability [22].

3.4.3. Genetic Algorithm

Genetic algorithm draws on the heredity, mutation and selection mechanisms in biological evolution to find the

optimal solution through iterative optimization of individuals in the population. In the energy management of the ship hybrid power system, the parameters of the energy management strategy are encoded as individuals, and through the operation of the genetic algorithm, the individuals are continuously optimized to obtain the optimal energy

management strategy [23]. The algorithm has a strong global search ability and can find a better solution in the complex solution space. However, it has higher computational complexity, slower convergence, and is prone to premature maturity and falling into local optimal solutions.

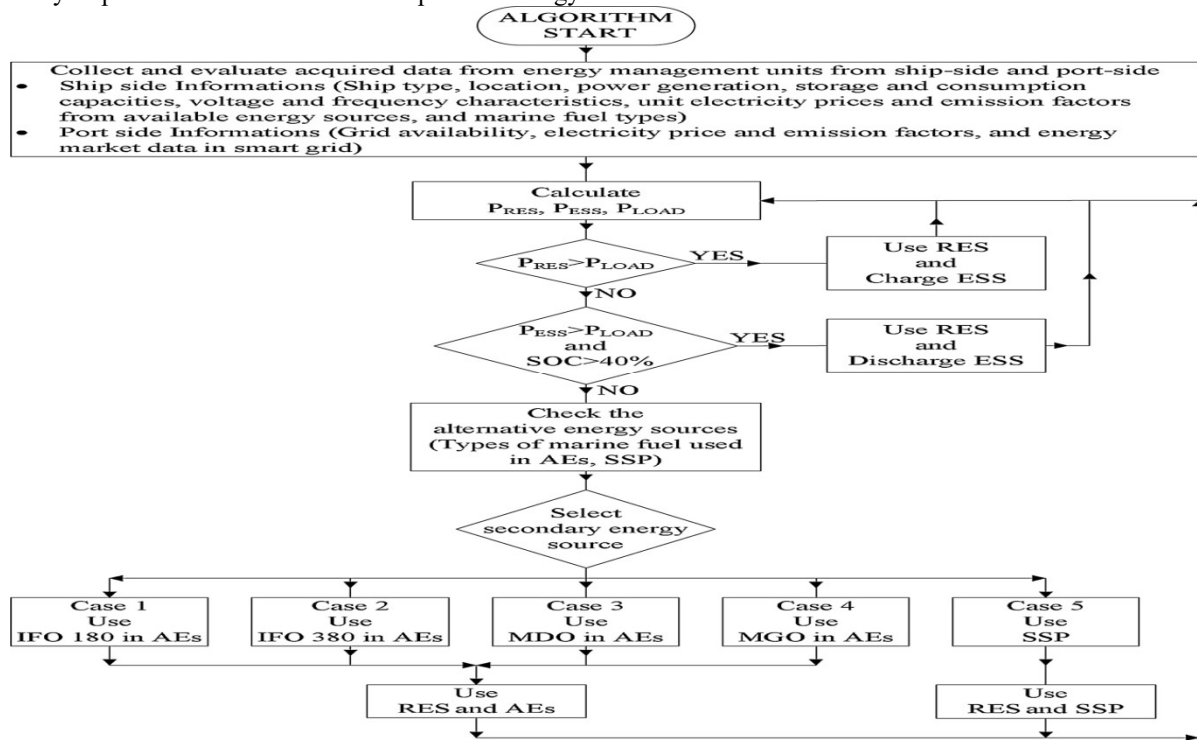


Fig. 5 Algorithm flow chart for electrical energy management of a ship

4. Application and Comparative Analysis of Different Energy Management Strategies

4.1. Application Case Analysis

In practical application, different energy management strategies show their own characteristics [24]. Taking an inland waterway ship as an example, when a rule-based control strategy is adopted, energy is allocated according to pre-set rules, which can basically satisfy the ship's operating requirements under simple working conditions, but cannot realize optimal energy utilization due to the limitations of the rules under complex working conditions. In some ships with model predictive control, such as all-electric ships, the prediction of propulsion loads and optimization of the system model can effectively reduce the system losses and improve the efficiency of energy utilization under different sea conditions. For ships using equivalent consumption minimization strategy, the reduction of fuel consumption can be achieved by reasonably adjusting the equivalence factor when the load demand is known, such as in the application of a tugboat, which saves a certain percentage of fuel compared to the traditional rule-based controller. In terms of intelligent algorithm control strategies, fuzzy logic control shows better robustness in dealing with uncertainties in ship operation; neural network control can achieve more accurate energy allocation by learning complex operating modes; and genetic algorithms provide a better solution for the formulation of energy management strategies by optimizing parameters [25].

4.2. Comparison of Strategies

Different strategies are compared in terms of control

performance, computational complexity, and robustness. In terms of control performance, model predictive control and intelligent algorithm control strategies (e.g., neural network control, genetic algorithm) are able to achieve more accurate energy allocation and optimize system performance, but rule-based control strategies and equivalent consumption minimization strategies may not be able to achieve the optimal effect in some cases. In terms of computational complexity, model predictive control and genetic algorithms have high computational complexity and require high computational equipment; rule-based control strategies and fuzzy logic control are relatively simple to compute. In terms of robustness, fuzzy logic control has better adaptability to system parameter changes and external disturbances; neural network control and genetic algorithm can also show certain robustness after sufficient training, but the adaptability of rule-based control strategy and equivalent consumption minimization strategy to system changes is relatively weak [26]. Taken together, each strategy has its advantages and disadvantages, and a suitable strategy needs to be selected according to the specific needs of the ship and the operating environment in practical applications.

5. Issues and Challenges in Energy Management of Ship Hybrid Power Systems

5.1. Complexity of System Modeling

Ship hybrid power system contains a variety of energy sources and complex equipment, the interaction between the components and dynamic characteristics make the system modeling difficult. Different types of energy sources (e.g. diesel engines, fuel cells, storage batteries, etc.) have different

working principles and performance characteristics, and their output power, efficiency and other parameters are affected by a variety of factors, such as ambient temperature, load changes, etc [27]. In addition, the ship is subject to different operating conditions, such as the temperature of the environment, the load changes, etc. In addition, under different operating conditions (e.g. sailing, mooring, acceleration, deceleration, etc.), the energy demand and operating state of the system will also change significantly, which further increases the complexity of modeling. Accurately establishing a model that can reflect the real characteristics of the system is the basis for realizing effective energy management, but the current modeling methods still have certain limitations, and the accuracy and reliability of the model need to be improved.

5.2. Trade-offs in Multi-objective Optimization

Energy management strategies usually need to consider multiple objectives at the same time, such as reducing fuel consumption, reducing emissions, improving system efficiency, extending battery life, etc. However, there are often conflicting relationships between these objectives. For example, excessive pursuit of fuel consumption reduction may lead to frequent charging and discharging of the battery, affecting the battery life; while too much focus on battery life may not fully utilize the energy-saving potential of the system. In practical applications, how to find a reasonable trade-off point between these conflicting objectives is an important challenge for the design of energy management strategies. Scientific and reasonable multi-objective optimization models and algorithms need to be established to achieve comprehensive system performance optimization.

5.3. Parameter Uncertainty and Environmental Changes

The parameters of the ship hybrid power system (e.g., the capacity and internal resistance of the battery, the efficiency of the engine, etc.) will change with the use of time, environmental conditions and other factors, and have uncertainty. At the same time, the environment in which the ship operates (e.g., meteorological conditions, sea state, etc.) is also complex and variable, and all these factors will have an impact on the effectiveness of the implementation of energy management strategies. For example, under severe sea conditions, the ship's load demand will increase dramatically, while the performance of the battery may decline, at which

time the original energy management strategy may not be able to adapt to the new situation, resulting in a decline in system performance. Therefore, the energy management strategy needs to have a certain adaptive ability, which can sense the changes of system parameters and environment in real time, and adjust the control strategy in time to ensure the stable operation and performance optimization of the system [13].

6. Future Research Directions

6.1. Improvement and Fusion of Optimization Algorithms

Aiming at the shortcomings of the existing energy management strategy algorithms, future research can be devoted to the improvement and fusion of different algorithms. For example, model predictive control algorithms are optimized to use more efficient solvers and prediction models to reduce computational complexity and improve real-time performance; intelligent algorithms are combined with model predictive control and equivalent consumption minimization strategies to give full play to their respective advantages [12,18]. For example, the genetic algorithm is used to optimize the equivalent factor in the equivalent consumption minimization strategy, or the neural network is combined with the model predictive control to improve the adaptability to system uncertainty. Through the improvement and integration of algorithms, it is expected to improve the performance and adaptability of energy management strategies and realize more efficient energy management.

6.2. Energy Management Strategy Considering Multi-factor Coupling

During ship operation, multiple factors are coupled with each other and affect the effect of energy management. Future research should pay more attention to consider these multi-factor coupling. For example, a more comprehensive and accurate energy management model is established by comprehensively considering the ship's navigation state (speed, heading, etc.), load characteristics (power demand, change frequency, etc.), energy price fluctuations, and environmental factors (meteorological conditions, sea state, etc.). Through in-depth analysis of the interrelationships and influence mechanisms between these factors, a more reasonable energy management strategy is formulated to adapt to the complex and changing ship operation environment and realize the optimal operation of the system.

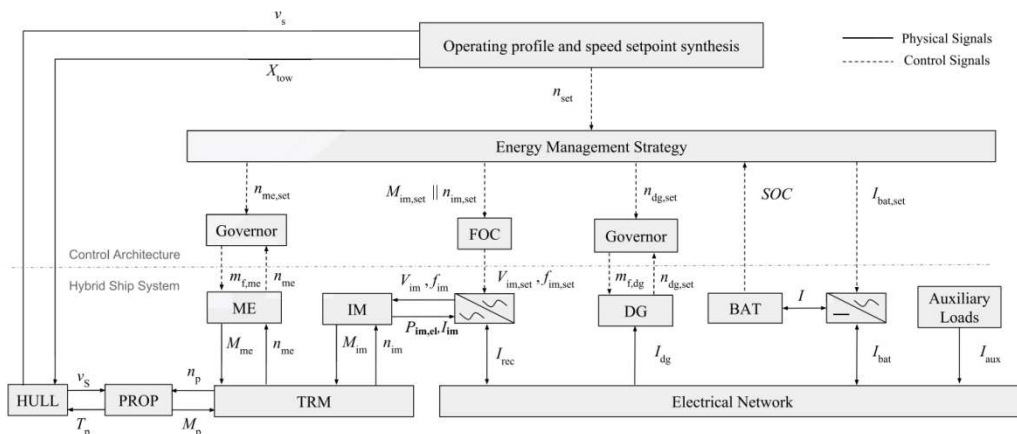


Fig. 6 Schematic presentation & causality graph of the simulation model (propulsion and control system) showing coupling between models.

6.3. Experimental Verification and Practical Application Expansion

At present, the research of many energy management strategies mainly focuses on the theoretical analysis and simulation stage, and the practical application verification is relatively less.[3,22] In the future, it is necessary to strengthen the experimental validation work, build a real ship hybrid power system experimental platform, and carry out practical testing and evaluation of different energy management strategies. Through experiments, the performance of strategies in actual operation can be more realistically understood, potential problems can be found, and targeted improvements can be made [5,19]. At the same time, the practical application scope of energy management strategies is actively expanded, and the research results are promoted to more types of ships to promote energy conservation, emission reduction and sustainable development of the shipping industry[28].

6.4. Standardization and Intelligent Development

With the continuous development of ship hybrid power system, it is of great significance to establish a unified standard of energy management strategy. Standardization can promote compatibility and interoperability between different systems and facilitate the promotion and application of technology. In the future, research on the standardization of energy management strategies should be strengthened and relevant standards and specifications should be formulated. At the same time, with the development of artificial intelligence, big data and other technologies, energy management strategies are promoted in the direction of intelligence. For example, the use of big data to analyze the ship's operating data, realize real-time monitoring and prediction of the system state, and automatically adjust the energy management strategy; the use of intelligent sensors and communication technology to realize efficient collaboration and intelligent control between the various parts of the system [24].

7. Conclusion

The study of energy management strategies for ship hybrid power systems is of vital significance in promoting the sustainable development of the shipping industry. At present, a variety of energy management strategies have been proposed and applied to actual ships, and each strategy has its unique advantages and limitations. The rule-based control strategy is simple and easy to implement but lacks flexibility; the model predictive control can take into account the dynamic characteristics of the system but is complicated to compute; the equivalent consumption minimization strategy is relatively simple to compute but relies heavily on the equivalence factor; the intelligent algorithmic control strategy has a strong adaptability but also has some problems. In practical application, it is necessary to choose the appropriate strategy or a combination of strategies according to the specific conditions of the ship.

In the future, the research on energy management strategies for ship hybrid systems should be carried out in the direction of optimizing algorithms, considering multi-factor coupling, strengthening experimental verification, and promoting

standardization and intelligent development. Through the advancement of these research directions, it is expected to further improve the performance of energy management strategies, realize the efficient and stable operation of ship hybrid power systems, reduce energy consumption and emissions, and promote the green development of the shipping industry, so that it can better adapt to the future needs of environmental protection and energy development.

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