A review of multi-energy hybrid power system for ships

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ABSTRACT

In the face of increasingly severe energy shortage and environmental pollution, the use of new forms of energy will become an important direction for the future development of ships. A hybrid power system comprised of various types of energy, such as conventional fossil fuels, renewables, hydrogens, fuel cells and batteries, can ensure a continuous and reliable power source for ships by using different types of energy for various operating conditions. This has become an emerging solution for greener ships and attracted attention from both industry and academia. A state-of-the-art multi-energy hybrid power system for ships is introduced in this paper. The configuration and characteristics of series, parallel and series-parallel hybrid power systems are analyzed and compared. Challenges of multi-energy power system for large-scale ships such as reliability, control and efficiency are discussed, and possible solutions are proposed.

1. Introduction

With the development of global trade and shipping industry, fuel consumption in global shipping is increasing year-by-year [1]. Since fuel consumption is closely correlated with the emission of greenhouse gases and pollutants, it is estimated that the carbon dioxide (CO_2) emission of the shipping industry will account for 12-18% of global anthropogenic CO_2 emission by 2050 [2]. In addition, the shipping industry has accounted for 15% of global NOx emission, and it is estimated that this will increase in the absence of an efficient regulation strategy [3]. Pollutants emitted by ships may deteriorate the air quality in coastal areas. Particles, such as black carbon, nitrogen oxides and sulfides are diffused in the air, which may adversely affect human health, as shown in Fig. 1. With regard to future environmental challenges, the main goal of the Paris agreement is to limit the global average temperature rise in this century to less than 2 °C, and to limit the global temperature rise to less than 1.5 °C above pre-industrial levels [4].

The International Maritime Organization (IMO) has developed corresponding international regulations, including the promulgation of the International Convention for the Prevention of Pollution from Ships (MARPOL), the Ship Energy Efficiency Management Plan (SEEMP), and the Energy Efficiency Design Index (EEDI) [5]. The introduction of these regulations is intended to largely impose stringent restrictions on ship emissions, and direct the shipping industry towards a significant reduction in fossil fuel consumption and pollutant emissions in the future [6]. More than 95% of civil ships use diesel engines for propulsion [7]. Although several scholars have focused on reducing the emissions of CO_2, NOx, and SOx from marine diesel engines by using exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) [8–10], those solutions are still based on using fossil fuels, thus making it difficult to meet increasingly stringent regulations. Therefore, the exploration of alternative energy, alternative fuels, energy conservation, and environmental protection technologies have become a popular research area [11–13]. Accordingly, a number of scholars have concentrated on the applications of renewable energy systems (RESs) and energy storage systems (ESSs) for ships [14].

Clean energy can effectively achieve the goals of saving energy and reducing emission. However, due to ships' structure and operating mode, powering ships by using a single energy form is limited, and therefore using a single energy source is not a satisfactory solution. For example, the use of solar energy is influenced by the hull structure, operating conditions, and meteorological conditions, and thus is not suitable for all types ship [16,17]. In order to compensate for the shortcomings of a single energy supply, various renewable energy

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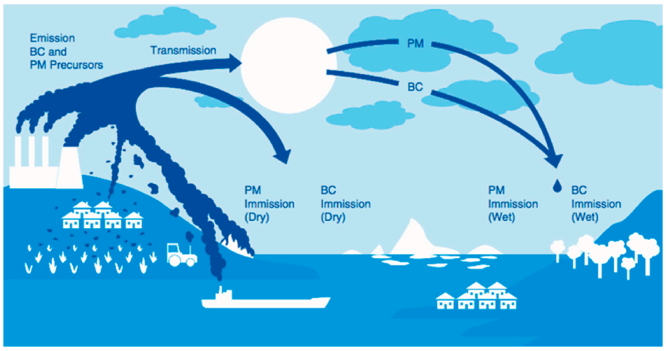


Fig. 1. Air pollution from shipping leads to poor local air quality. BC: black carbon; PM: particulate matter. (Image courtesy of DNV GL.) [15].

sources (e.g., hydrogen fuel cells, solar energy, batteries, supercapacitors, etc.) and non-renewable energy sources (e.g., fossil energies) can be helpful when combined together using multi-physics control systems to form a multi-energy hybrid power system for ships. A multi-energy hybrid power system can not only meet the requirements of economy and environmental protection, but can also overcome the inherent limitations of using any source of energy alone. Thus, compared with the traditional propulsion system and electrical propulsion system, a multi-energy hybrid power system for ships has become very attractive to engineers and scientists, as illustrated in Fig. 2. The mixing of multi-energy units increases the complexity of the system, and the problem of how to realize a stable, reliable, and efficient operation of a hybrid power system, composed of multi-energy units, is a key problem to be solved urgently. The extant research has focused on the comprehensive application of solar energy, fuel cells, diesel generators, batteries, and supercapacitors in ships. This article systematically reviews the research on multi-energy hybrid system for ships; furthermore, the structure of a multi-energy hybrid system is discussed, the key technologies and existing problems that affect the development of hybrid systems are summarized, and relevant suggestions are presented.

2. The background of a multi-energy hybrid power system

According to the characteristics of energy mixing, a multi-energy hybrid power system can be divided into the hybrid mechanical propulsion and hybrid electrical propulsion. The hybrid mechanical propulsion uses a coupling device to merge mechanical and electrical propulsion. At present, the hybrid mechanical propulsion is commonly used in naval ships, towing ships, offshore ships, research vessels, and yachts [18–20]. For instance, in January 2010, the “Greenline 33 Hybrid Yacht” was jointly developed by Italy and Slovenia (see Fig. 3(a)). The yacht is composed of a battery pack, solar energy, and diesel power, which can operate in both electric mode and diesel mode [21]. In 2015, Feadship, a Dutch ship manufacturer, launched a 274-foot (83.5-m) yacht named “Savannah” [22], as shown in Fig. 3(b). The power system of this yacht consists of a four-stroke engine, three generators, and a set of lithium-ion batteries with power of 1 Mw. The power system of the yacht has three operating modes: the diesel engine mode, hybrid diesel-electric mode, and power-only mode. A hybrid power system has the advantageous features of a long-term reliable operation in high-speed and high-power conditions, and a long-term stable operation in low-speed and low-power conditions. Mechanical propulsion devices mainly operate at high-speed, while electrical propulsion devices operate at low-speed [6].

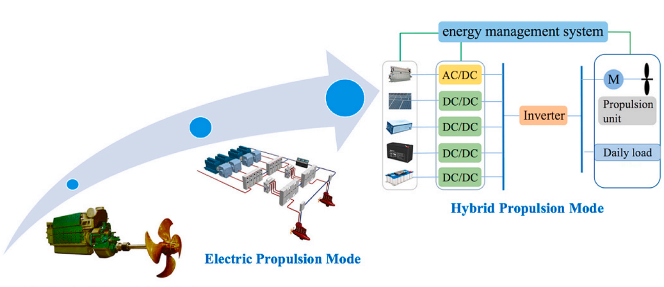


Fig. 2. Development of the propulsion system for ships.

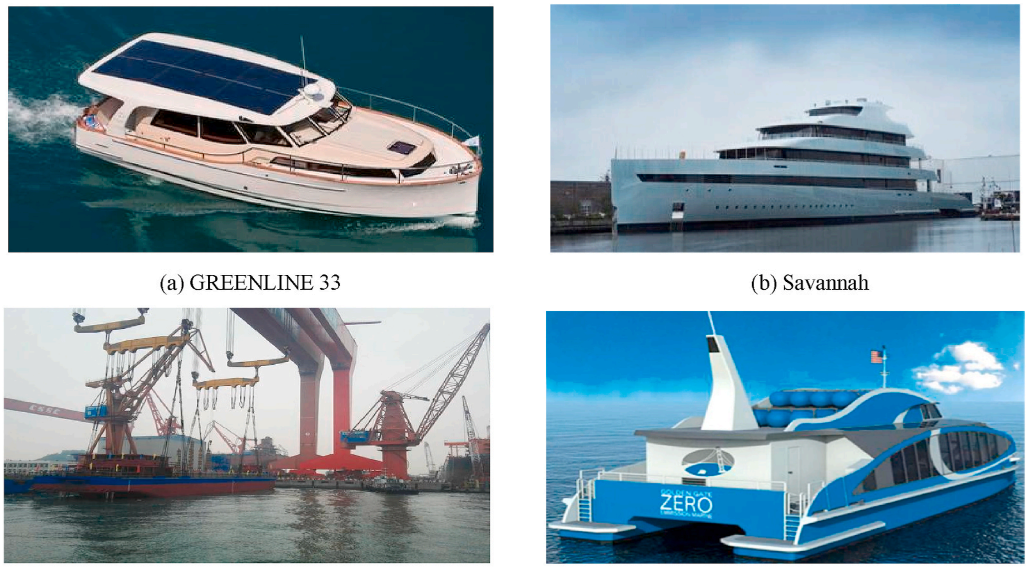
Due to the development of power electronics technology, hybrid diesel-electric propulsion technology has developed rapidly. By using this technology, all power generation and energy storage units are combined to supply electric power for propulsion, which has been applied to towing ships, yachts, ferries, research vessels, naval ships, and offshore ships [23–25]. For example, in November 2017, the first 2000-ton new energy electric ship in the world was launched, as displayed in Fig. 3(c). Powered by a composite energy storage system (a supercapacitor plus a lithium-based battery), the ship mainly uses two electrical motors to drive the straight wing omnidirectional thrusters as its control and propulsion system [26]. In June 2018, the California Air Resources Board (CARB) announced a 70-foot aluminum catamaran ferry called “Water-Go-Round” had been manufactured in the Gulf region, as shown in Fig. 3(d). This ship was powered by the combination of hydrogen fuel cells and lithium-ion batteries, and was the first ship in the world using a hybrid fuel cell system [27].

It can be seen that hybrid ships have been developed with the aim of being green, integrated, and large-scale [28]. Energy saving, high efficiency, low emission, and low noise are the main characteristics required for the next generation of power systems for ships. On the whole, from the aspect of system design, hybrid power system ships are undergoing a transition from an alternating current (AC) network to a medium and high voltage direct current (DC) network [29,30]. In the development of key equipments for the power system, a green power system associated with high efficiency and energy saving has been developed, including composite material transmission parts, podded thrusters, and shaftless propellers [31–33]. Meanwhile, for the structural form of a ship’s power system, research on the distributed electric propulsion of storage batteries, cogeneration technology of fuel cells, and efficient power generation technology using a ship’s waste heat is being carried out [34–36]. There have been several previous studies regarding the application of single energy in ships, which can be used as reliable references, and can be helpful for the development of multi-energy hybrid ships. However, the research of a multi-energy hybrid power system for ships is not a simple superposition of several single energy sources, and needs to be studied systematically. Additionally, most previous researches have focused on a certain problem of a multi-energy hybrid power system, and they still remained at a theoretical level. For instance, an energy management strategy only focuses on the existing ships’ power forms, and develops the optimization of algorithms without applying the influence of external factors, such as the performance matching of key equipment and the navigation environment [37]. Modeling software is often used to simulate the topological structure in order to verify the experimental results, but if experiments do not take place, the requisite systematic studies cannot be accomplished [38–41].

3. The structure of a hybrid power system

According to the power transmission route, the hybrid power system of a ship can be divided into three types of structure: series, parallel, and series-parallel [42–44].

A series hybrid power system belongs to the hybrid electrical propulsion power system, and its application in ships is relatively mature [6]. This form of power system integrates all energy sources into a ship power station and supplies power to a ship in the form of a comprehensive all-electric propulsion, as shown in Fig. 4. The diesel unit drives the synchronous generator to operate, and the output power is



(a) GREENLINE 33 (b) Savannah

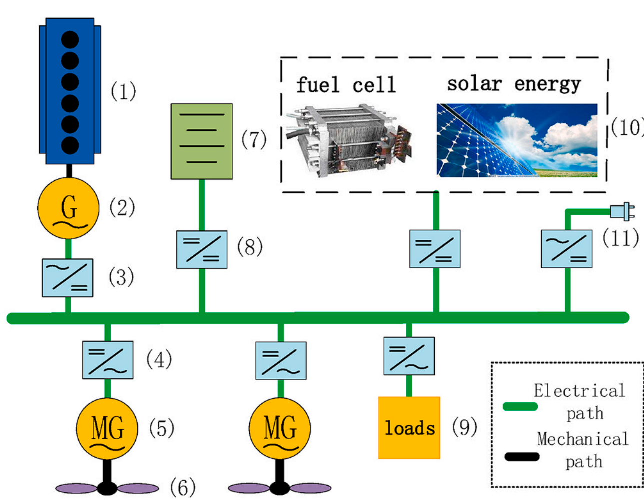
(c) Electric cargo ship (d) Water-Go-Round

Fig. 3. Hybrid ships.

transferred to the DC bus after an AC/DC. To play the role of peak shaving and valley filling, the storage battery unit and supercapacitor are connected to the DC bus through a two-way DC/DC. Fuel cells and solar energy are respectively imported into the DC bus after boosting through a one-way DC/DC. The DC bus unifies the collected electrical energy of the same voltage into AC by a DC/AC inverter to drive the propulsion motor and supply electricity.

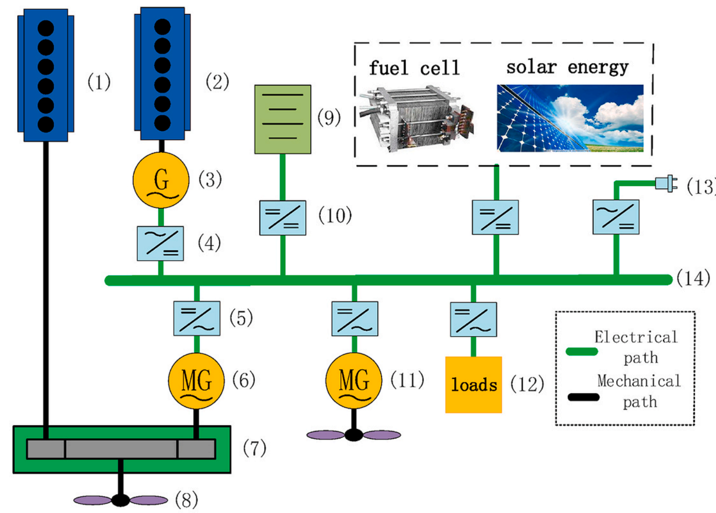
As a serial hybrid power system utilizes a bus bar to collect all the electrical energy, it has various working modes, such as a generator-set working mode, power battery working mode, fuel cell working mode, and combined power supply working mode. The series hybrid system has a secondary energy conversion process, and the loss is relatively high. Thus, the dynamic control and management of a serial hybrid power system should be carried out carefully, and one of the main tasks is to switch the operation mode of a power system. Therefore, an ideal control strategy should be used for dynamic loads among various energy sources to minimize fuel, emission, and maintenance costs for all power suppliers [6].

Different from electrical propulsion system, a parallel hybrid power system is a combination of mechanical propulsion and electrical propulsion [40,45]. Mechanical and electrical propulsions are connected in parallel through a power coupling device, so that they can operate independently or in a coupling mode [46], as illustrated in Fig. 5. Due to the existence of a coupler, on the mechanical propulsion side the main engine transfers energy to the coupling device through a shaft. When the power of the main engine is abundant, a motor/generator can operate in the generation mode to absorb any excessive energy and supply power to the grid. On the electric propulsion side, a variety of energy sources are integrated into the DC bus through a converter, and the DC grid supplies energy to the power load and motor, which forms a multi-energy hybrid



(1) Prime mover (2) Generators (3) AC/DC (4) DC/AC (5) Electric motor (6) Propulsor (7) Energy storage device (8) DC/DC (9) Loads (10) Shore power (11) DC bus

Fig. 4. The structure of a series power system.



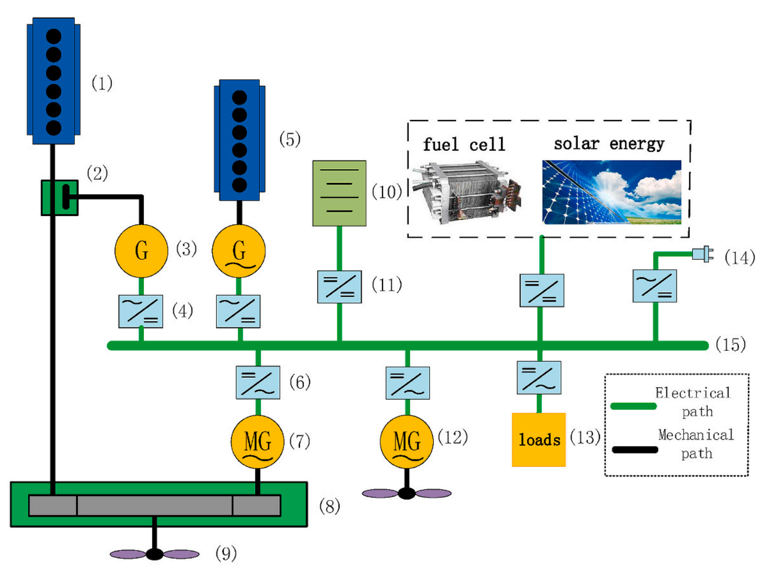
(1)Main engine (2)Prime mover (3)Generators (4)AC/DC (5)DC/AC (6)Electric motor/Alternator (7)Gearbox (8)Propulsor (9)Energy storage device (10)DC/DC (11)Electric motor (12) Loads (13)Shore power (14)DC Bus

Fig. 5. The structure of a parallel power system.

power system.

Parallel hybrid power systems can benefit from the combination of electrical and mechanical propulsions. However, in order to realize these advantages, it is essential to design an efficient parallel power system. With regard to the operating environment of a ship and working characteristics of each energy source, in order to maximize the utilization of clean energy, a robust control strategy for a hybrid power system is essential to balance various energy demands [6,47]. The current difficulties of a parallel hybrid power system mainly originate from the torque distribution of a hybrid power system, the decoupling between the main engine and load, and the the dynamic switching between various operating modes.

A hybrid series-parallel power system is a combination of series and parallel systems, comprising their main characteristics [48], as shown in Fig. 6. Due to the existence of two kinds of coupling devices, on the mechanical propulsion side, mechanical and electrical propulsion can operate in a parallel mode to drive the propeller. The main engine can directly drive the generator to supply the DC bus through a coupling



(1)Main engine (2)Gearbox (3)Generators (4)AC/DC (5)Prime mover (6)DC/AC (7)Electric motor/Alternator (8)Gearbox (9)Propulsor (10)Energy storage device (11)DC/DC (12)Electric motor (13)Loads (14)Shore power (15)DC bus

Fig. 6. The structure of a hybrid series-parallel power system.

device [43]. On the electrical propulsion side, a variety of energy sources are integrated into the DC bus through a converter, and the DC grid supplies energy to the power load and motor, forming a multi-energy hybrid power system.

A hybrid series-parallel power system combines the advantages of both series and parallel structures, making the control of the energy flow and optimization of energy consumption more flexible, with more operating modes and relatively lower fuel consumption. However, the structure of the system is relatively complex, and the cost is high, therefore, an appropriate control strategy is required. The basic idea of the control strategy for ships is as follows: when the power demand is low, it operates in a series mode; when the power demand is high, it operates in a parallel mode [49,50].

4. Key technologies for a multi-energy power system

Driven by the goals of energy saving and emission reduction, a power system may enter into a new stage of energy saving, associated with low noise and high integration. In order to achieve better energy saving and emission reduction and promote the development of a multi-energy power system, and also to achieve the balance of the energy supply and load demand of a multi-energy hybrid system, as well as the safe, reliable, and efficient operation of the system, it is essential to develop several key technologies, such as system integration and capacity optimization, medium and high voltage DC networking, energy management strategies, and security protection.

4.1. System integration and capacity optimization

Robust system integration and capacity optimization methods are essential to improve the performance of a multi-energy hybrid power system, reduce costs, save energy, and decrease emissions. A multi-energy hybrid system typically integrates different equipments, energy resources, and information into an interconnected, unified, and synchronized system through an integrated wiring system and computer network technology. This is to achieve the overall complementary energy cooperation, optimal performance, flexible control of energy, and the concentrated, efficient and convenient management of energy. The capacity optimization mainly aims to develop a mathematical model of ship components, establish an objective function under given constraints by using a mathematical method, and finally develop an algorithm to solve the objective function, in order to obtain a set of Pareto optimal solutions, and find the optimal combination method of each power source [51].

At present, there is no in-depth research on the integration of multi-energy systems for ships. More importantly, the key to system integration is to solve the interconnection and intercommunication between systems. For this purpose, a number of technical difficulties, such as hardware system integration, software system integration, and communication interfaces, and communication protocols between various devices and subsystems need to be solved [52]. To achieve the purpose of optimal capacity allocation, it is essential to carry out a further investigation into multi-energy hybrid power systems. Several scholars have studied the configuration of multi-energy hybrid power systems for ships [53,54], and the existing optimization methods mainly use a probability model or a deterministic model to simulate the ship components. Additionally, a research on the optimization of multi-energy hybrid power systems for ships mainly focuses on the optimization of constraints, objective functions, and under developing algorithms.

The optimization goal has been developed from a single objective optimization that only considers cost, to the multi-objective optimization, which fully considers factors such as economic indicators, emission indicators, energy efficiency indicators and other indicators [55–57]. After modeling all the components of a hybrid power system, the key to optimize the capacity of a multi-energy hybrid power system is to formulate an objective function and determine the conditions of constraints according to specific optimization objectives. Generally, the conditions of constraint include the capacity constraint of each power source, the constraint related to the charge and discharge of a battery, the constraint related to the reliability of the supply, and the balance constraint. For example, Chauuki et al. [58] fully considered the capacity constraints of the energy supply system in the design of a solar/fuel cell/diesel generator hybrid ship. When Balsamo et al. [59] carried out the capacity optimization for a hybrid energy storage system for all electrical ships composed of batteries and supercapacitors, in order to ensure a large capacity, high efficiency, long battery life, and strong stability of the energy storage system, capacity optimization matching was undertaken with constraints related to charging and discharging the batteries. Safeguarding the reliable power supply of multi-energy hybrid systems for ships to prevent system power loss is a primary task, thus constraints related to the reliability of a power supply system is an important ones for capacity optimization. Nasirudin et al. [60] and Divyajot et al. [61] proposed constraints related to the reliability of the energy supply when optimizing the solar power system of a ship. The balance constraint mainly refers to the power balance constraint. In order to satisfy the power balance constraint, a hybrid power system typically adds an energy storage unit to achieve peak shaving and valley filling. Duan et al. [62] and Kanellos et al. [63] added an energy storage unit to the power generation system of a ship to meet balance constraints in order to ensure the balance of the power supply and demand of the whole ship.

An optimization algorithm of capacity allocation involves a traditional optimization algorithm and an intelligent optimization algorithm. Traditional optimization algorithms (e.g., the Newton iteration method and analytic method) are generally used to solve fundamental problems with a relatively clear problem and condition description. The algorithm itself is simple and easy to operate. For a single-objective optimization problem, a traditional optimization algorithm has an appropriate performance in terms of both accuracy and speed. However, the optimal capacity allocation of a multi-energy hybrid power system is a nonlinear integer programming problem with multiple constraints. Therefore, for multi-objective optimization or multi-extremum optimization problems, intelligent optimization algorithms are generally used. Intelligent optimization algorithms mainly include a genetic algorithm, ant colony algorithm, particle swarm optimization algorithm, evolutionary algorithm, etc. [64–67]. Table 1 lists the intelligent optimization algorithms used for the capacity optimization of the multi-energy hybrid power system for ships. Since there are certain amounts of deficiencies in the common intelligent optimization algorithms, a number of scholars have conducted the research on hybrid intelligent optimization algorithms. Hybrid intelligent optimization algorithms have the advantages of combining various algorithms and learning from each other, which are both significantly important in practical applications. For example, Kong et al. [79] and Wang et al. [80] used a hybrid intelligent optimization algorithm to optimize the capacity of a multiple-energy hybrid power system for ships and achieved promising results.

Lan et al. [81] studied the capacity optimization of a hybrid cruise ship composed of photovoltaic/diesel generator/energy storage device on the route from Dalian to the Gulf of Aden in Yemen. The cruise ship and structural diagram of the hybrid power system are shown in Fig. 7. Based on the analysis of the cost and emission requirements of the power generation system, this paper uses five working conditions to model the unit time load: conventional cruise, full speed navigation, docking, loading and unloading, and anchoring. Taking the minimum investment cost, fuel cost and greenhouse gas emission as the optimization objective, the multi-objective particle swarm optimization (MOPSO), combined with NSGA-II, is used to optimize the size of each power supply in the marine power system. The optimization algorithm flow chart is shown in Fig. 8. Due to the significant influence of solar radiation on the optimal size problem, this paper analyzes the influence of the five parameters of date, local time, time zone, longitude and latitude on the

Table 1
Intelligent optimization algorithms used for the capacity optimization of the multi-energy hybrid power system for ships.

Algorithm	Advantage	Disadvantage	Reference
Genetic algorithm	Strong versatility, good parallelism, and a wide range of feasibility solutions.	The convergence speed is slower and it is easy to fall into the local optimum.	Derollepot, R. et al. [68] Jianyun, Z. et al. [69] Nikoletta L. et al. [70] Ancona, M.A. et al. [71]
Particle swarm algorithm	The optimization speed is fast and the optimization effect is obvious.	The convergence accuracy is low and it is easy to fall into the local optimum.	Wen, S. et al. [72] Zhang, J. et al. [73] Ceschia, Adriano. et al. [74]
Ant colony algorithm	Strong robustness and good parallelism.	The convergence speed is slow and it is easy to fall into the local optimum.	Jin, Y. et al. [75] Wang, Z. et al. [76]
Differential evolution algorithm	Strong robustness, fast convergence, easy to implement.	In the late optimization stage it is likely to fall into the local optimum, and cannot reach the overall optimum.	Ma, L. et al. [77] Sixin, L. et al. [78]

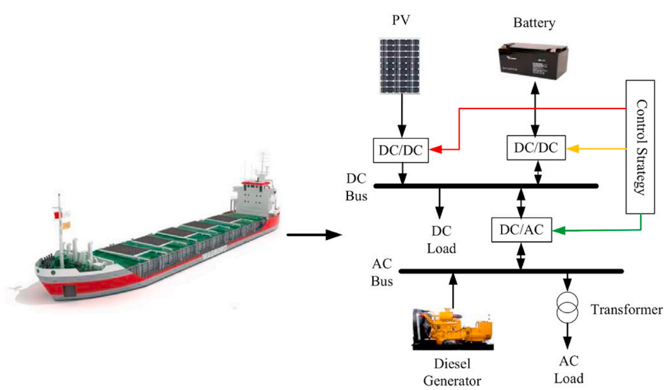


Fig. 7. Marine hybrid system.

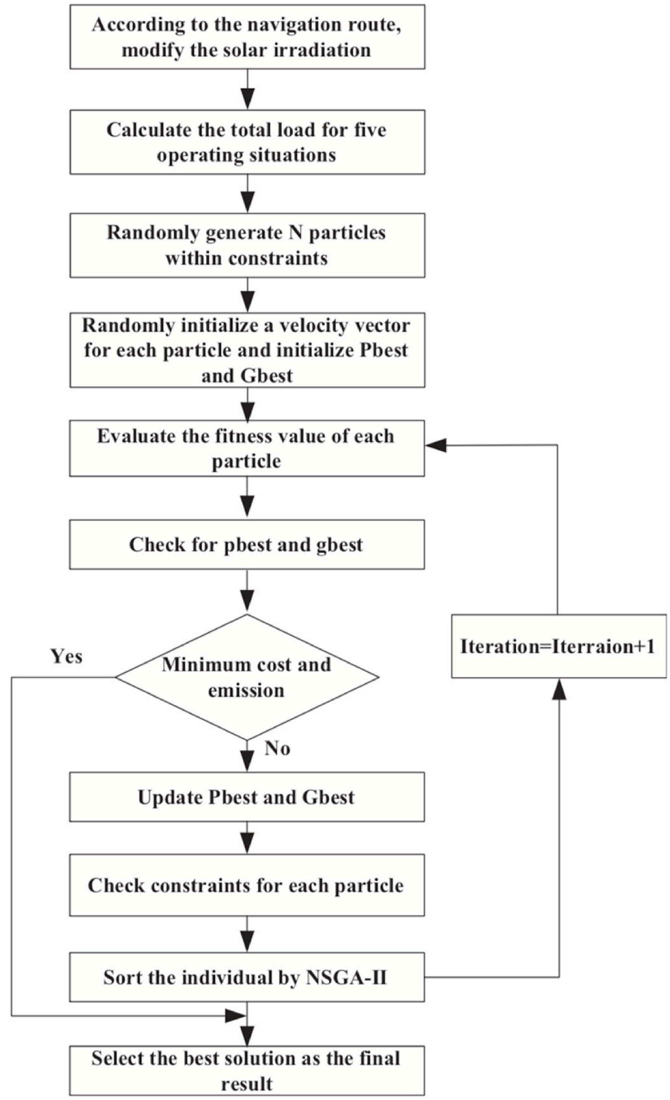


Fig. 8. Optimization algorithm flow chart: using MOPSO combined with NSGA-II.

radiation of photovoltaic modules, taking the maximum correction coefficient as an example for sensitivity analysis, with the results shown in Table 2. It can be seen that the local time and time zone have the greatest impact on the photovoltaic power generation correction coefficient of the ship's power system, and then the impact of the four different seasons on the integration of solar energy into the ship's power system, different loading conditions and the energy storage system can be considered. The simulation results show that the net present value (NPV) ofthe photovoltaic/diesel generator/energy storage hybrid generation is lower than that of the photovoltaic/diesel generator generation, which proves the applicability of the optimization method, and shows that the method can be used in the research of mobile microgrid such as container ships and high-speed trains.

In addition, a software package is often used to optimize the configuration of critical equipment capacity. In a multi-energy hybrid system, according to the optimization algorithm and scheduling strategy, combined with management and prediction methods, another software package is adopted to optimize the simulated system. RETScreen, HOMER and other software packages have all been developed for this purpose [82–84]. These software packages have a user-friendly interface and can be applied to the design and optimization of hybrid energy systems worldwide. However, these software packages

Table 2
Sensitivity of maximum correction coefficient to different parameters.

Variation	Julian days	Local time	Time zone	Altitude	Longitude
+1	5.1E-05	0.019138	0.038419	3.67E-04	5.21E-04
−1	4.8E-05	0.038419	0.019138	6.29E-05	7.79E-04

are highly professional and do not elaborate on the mathematical model, optimization algorithm, and scheduling strategy. Therefore, it is a challenge to achieve ideal optimization results, and the optimization results are not definitive.

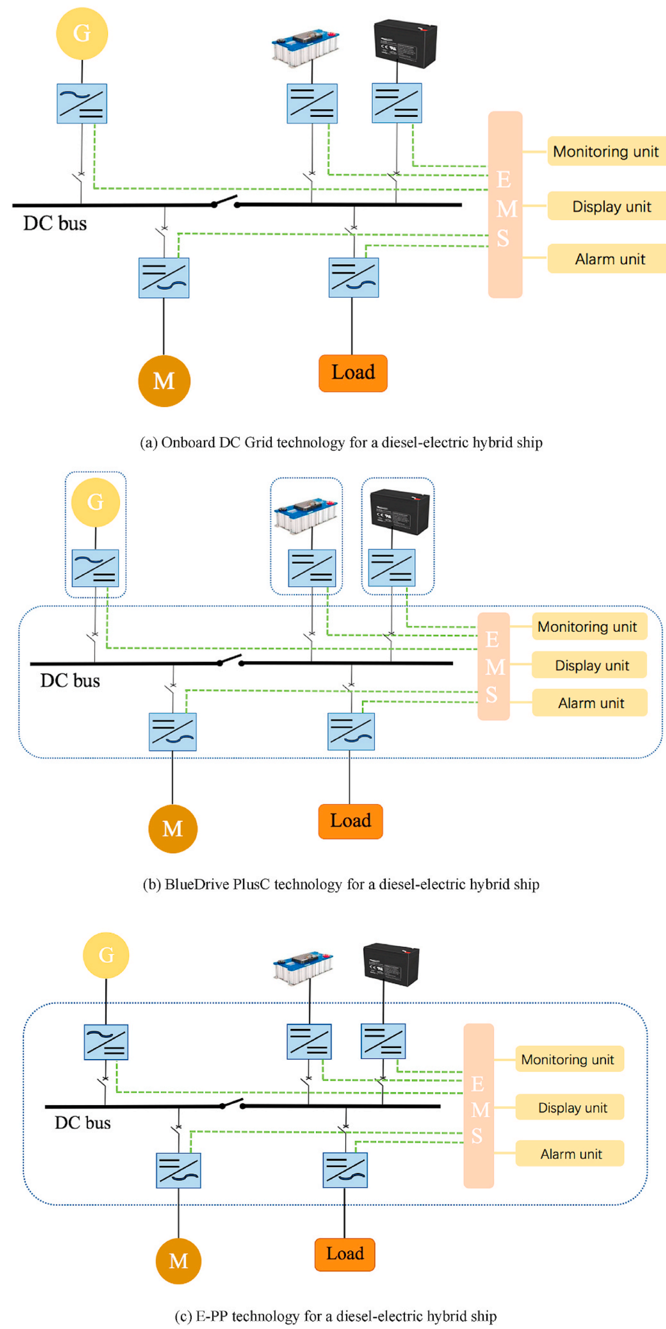
4.2. Medium and high voltage DC networks

At present, the integrated power system (IPS) of commercial ships still adopts the medium voltage alternating current (MVAC) networking mode [85,86], while the AC networking mode has several deficiencies, such as complicated control and excessive cable requirements. With the continuous development of renewable energy technologies and the improvement of power electronics conversion technology, e.g. the controllable rectifier and chopper inverter, the medium- and high-voltage DC networks using a flexible direct current transmission help to improve the performance of the IPS [87,88]. According to guidelines published by the Institute of Electrical and Electronics Engineers (IEEE), the ship system with a DC bus voltage between 1 and 35 kV is defined as a medium-voltage DC system [89]. The DC networking on ship has a great significance for the renewable distributed energy access, which can improve the stability of a power supply system [90–92]. Compared with the MVAC, medium- and high-voltage DC networks have the following advantages [6,93–96]:(i) efficient system integration, eliminating the need for the distribution of power in boards and transformers, as well as reducing the size and weight of a power system; (ii) getting rid of the speed to adjust the connection between the generator and the load motor, so that a diesel generator can operate on the optimal energy consumption curve; (iii) no skin effect of current, no transmission of reactive power, and a decrease of cable weight; (iv) a DC network has a superior technical compatibility, facilitating access to various energy sources, and significantly improving system selectivity, power supply continuity, and economy; and (v) compared with electromagnetic relays, a DC network uses power electronic devices for security protection, which can provide better fault isolation and facilitate a system reconstruction.

However, the medium- and high-voltage DC networks notably increase the complexity of, and difficulty of controlling, the system. Thus, they need to be analyzed and designed effectively by an engineering software package to realize their advantages. There are currently a good number of simulation-based studies on AC networks; however, there are limited studies on DC networks. General simulation software packages include MATLAB and PSCAD/EMTDC [97,98]; however, the models, operating conditions, and control modes used by these software packages still need to be further developed and improved. According to the bus bar configuration and the structure of the rectifier, the topology of a DC network can be divided into the Onboard DC Grid technology, BlueDrive PlusC technology, and E-PP technology [99–101]. Among them, the Onboard DC Grid technology adopts a DC bus-distributed configuration scheme, the rectifier adopts the thyristor structure, and the system integration is not sufficiently robust. The BlueDrive PlusC technology adopts a DC bus-centralized configuration scheme, the rectifier adopts the thyristor structure, and the system integration is very efficient. The E-PP technology adopts a DC bus-centralized configuration scheme, and the rectifier selects a fully-controlled rectification scheme based on an insulated gate bipolar transistor (IGBT), and the system integration is efficient. Fig. 9 is a block diagram of three DC networks for a diesel-electric hybrid ship, where the dotted frame indicates that these devices are integrated into a single unit. By comparison, as the E-PP technology adopts a fully controlled rectification scheme, the cold starting time of a generator is markedly shortened and the capacity of the generator is relatively strong. Therefore, there are a large number of ships currently using the E-PP technology structure, and it can be considered as the industry leader.

A typical application case is the "Shen Kuo", China's first DC propulsion system as shown in Fig. 10. The "Shen Kuo" scientific survey ship adopts the topology form of the e-pp DC network [102], and the single line diagram of the power system is shown in Fig. 11. Through a data analysis, it can be found that the weight of the electrical equipment and the floor area of "Shen Kuo" can be reduced by about 53% (11.8 tons) and 40% (9.5 square meters) after the DC networking technology is adopted, and the average fuel consumption of the " Shen Kuo" can be reduced by about 5.6%, when compared to the constant speed electric propulsion by testing the actual ship's variable speed unit.

In order to realize the large-scale application of medium- and high-voltage DC networks for ships, it is necessary to overcome the technical bottlenecks, including the design and development of key equipment, grid optimization and safety protection, as well as the development of corresponding specifications and standards systems [103–105]. In the selection of key DC equipments (e.g., DC circuit breaker, DC cable, high-voltage high-power converter, and DC current limiter), the current development level of equipment still cannot meet



(a) Onboard DC Grid technology for a diesel-electric hybrid ship

(b) BlueDrive PlusC technology for a diesel-electric hybrid ship

(c) E-PP technology for a diesel-electric hybrid ship

Fig. 9. DC network for a diesel-electric hybrid ship.

the application-based requirements of medium- and high-voltage DC networks [106–109]. For example, the current DC network for ships often adopts the E-PP technology. When the DC side fails, due to the operational characteristics of the anti-parallel diode in IGBT devices, the short-circuit current cannot be restricted by the blocking rectifiers. In order to ensure the safe operation of a DC network for ships and prevent the whole ship losing power, a DC circuit breaker is the most suitable device for quickly cutting off the fault current [110,111]. However, the HVDC circuit breaker is not ideal, and the breaking time and breaking capacity need to be further improved.

Due to the low damping of a DC power grid system, the fault development of a DC system is faster, and therefore keeping the system safe is more difficult. In order to ensure the safe and reliable operation of a system and supply the electrical energy appropriately, it is essential to effectively control the DC bus voltage and maintain it within a specified

Fig. 10. "Shen Kuo" scientific survey ship.

range to achieve the stability of the bus voltage. Existing DC bus voltage control methods include hybrid control, voltage droop control, energy storage unit control, and master-slave control [112–115]. A hybrid control approach uses the constant control of DC voltage, DC voltage slope control, and control of the deviation of DC voltage to achieve a constant DC bus voltage. However, this method is only applicable to a single energy system, and can have a low reliability, which is not appropriate for a multi-energy hybrid system for ships. Voltage drop control requires all units in the system to participate in the control of the grid voltage, but this may hinder some of the power generating units from operating at the maximum power output state, leading to a reduction of the overall efficiency of the system. An energy storage unit uses the input and output power of an energy storage system to adjust the DC bus voltage; however, the problem is that when an energy storage unit cannot charge and discharge effectively, an effective control of the flexible DC grid voltage cannot be accomplished. A master-slave control system uses a master controller to centrally control the common DC voltage, which can reasonably distribute the output power of each unit of the system. However, when the master controller fails, the control system may not effectively maintain a stable DC voltage. Furthermore, in terms of safety protection, it is currently limited due to the high price of a DC circuit breaker. Therefore, in order to reduce the number of DC circuit breakers in a DC network for ships, it is possible to adopt the coordinated protection mode of a DC/AC converter and a DC circuit breaker.

The establishment of a standard system and specifications is another factor that has a restraining effect on the further development of a DC network for ships. For instance, there are currently no specific DC voltage grades worldwide, imposing notable problems on the selection and compatibility of various equipments, which also becomes a major problem that needs to be solved urgently.

4.3. Energy management

Multi-energy hybrid systems have different operating modes, and they mainly use an electromechanically coupled configuration, which on the one hand endows the propulsion system with a greater redundancy, flexibility, safety, operability and economy, and on the other hand, a hybrid power system contains different kinds of power sources, accompanied by different dynamic characteristics. Therefore, in order to manage the multi-power source coupling system in a reasonable manner, it is necessary to formulate an appropriate energy management strategy to distribute the output power or torque of each power source, coordinate the mechanical and electrical propulsions, and ensure a safe supply of power for ships. This is to improve the system's efficiency and energy saving and reduce its emissions. Based on whether an actual control quantity of energy distribution is provided by the result of an optimized model, an energy management strategy can be divided into two categories: one is a rule-based control strategy that favors engineering applications, and the other is an optimal control strategy, concentrating on the optimization of simulated models [116,117]. Among them, the rule-based control strategy processes a control signal based on a pre-set threshold of control-based variables. The threshold is mainly obtained by an optimal control analysis of the rule maker according to the dynamic performance requirements of ship, operational characteristics of each power source, and operating conditions of a ship. According to the clarity of the rules in the control process, a rule-based control strategy can be refined into two types: deterministic rule control and fuzzy control. Based on the principle that an optimal control strategy follows the balance of energy supply and demand of the whole ship, a great number of optimization algorithms can be applied to the energy management of hybrid power system, such as dynamic programming, simulated annealing, and neural networks. Influenced by the algorithm itself, and the accuracy of modeling, sampling time, and defining parameters, the optimization control can be divided into global optimization control and real-time optimization control. The classification of energy management strategies is shown in Fig. 12.

Deterministic control strategies are mainly obtained through the

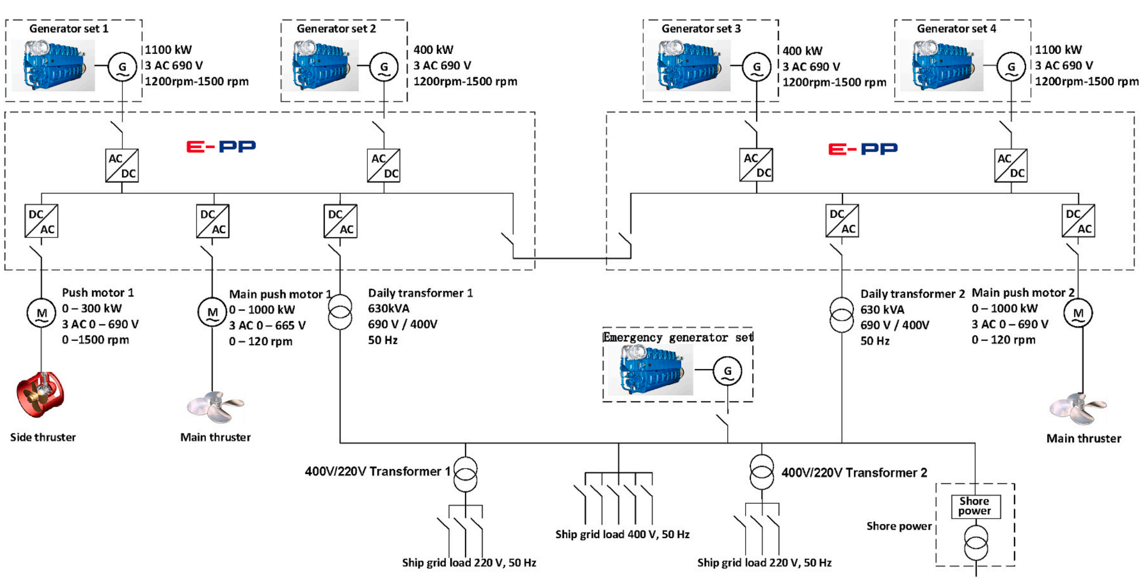


Fig. 11. Single line diagram of the power system for "Shen Kuo" scientific survey ship.

practical engineering experience, optimal engine operating point trajectory, and offline optimization strategy [118]. A commonly used deterministic rule-based control strategy is a static logic threshold-based control strategy [119]. Such strategies have a strong real-time performance, while their optimization effects are limited. For example, Nelson et al. [120], Torreglosa et al. [121], Thounthong et al. [122], and Tang et al. [123] proposed logic threshold-based control strategies for hybrid systems with the aim of energy management for multiple energy sources.

The logic threshold control strategy designed by Zhang et al. [124, 125] for a power battery/diesel generator set/solar hybrid ship, and the structure diagram of the hybrid system, is shown in Fig. 13. The system uses the power battery as the main power source of the hybrid ship, and the diesel generator set and solar energy as the auxiliary power source to charge the power battery or supply power to the load. In a hybrid electric ship, the hybrid power source is optimized and combined into different working modes according to the requirements of the driving conditions, so as to provide a reasonable power distribution. According to the working state of hybrid electric ship energy, it can be divided into six working modes, namely battery power supply mode, hybrid power supply mode, diesel generator power supply mode, regenerative braking mode, shore power mode and solar power charging mode. In the six modes, the solar power generation device is always in the working state, and according to the state of charge (SOC) value of the power battery, it can charge the battery and supply power to the load. The setting parameter in the system is the SOC value of the battery pack, which can be specifically divided into the lower limit value L_{SOC}, the upper limit value H_{SOC} and the charging state limit value C_{SOC} in the SOC work area. In this paper, by conducting repeatable experiments to determine the size of the parameter value, the working modes are shown in Table 3.

Among them: P_{req} —power required by the system; P_{sun} —solar power generation power; P_{bch} —battery charging power; P_b —battery discharge power; P_{sh} —shore power supply; V_{sh} —shore voltage; P_e —generator power generation; P_{e_ch} —generator power used to charge the battery; and P_{e_su} —generator power used to supply power to the system.

Due to the need for a multi-parameter, non-linear time-varying system in the practical application process, and considering that the logic threshold control strategy depends on the experience of the rule-maker to divide the logical range, and the division of different logical ranges will have a significant impact on the optimization results, the control effect is difficult to guarantee and is often unsatisfactory. Fuzzy control is a kind of nonlinear control strategy based on fuzzy set theory, fuzzy language, and fuzzy logic. In view of the fact that fuzzy logic control does not require accurate mathematical models and has a certain fault tolerance, Khan et al. [126], Yuan et al. [127], and Zhu et al. [128] used it to study multi-energy hybrid systems for ships and accomplished superior control effects. Although the fuzzy logic control strategy is

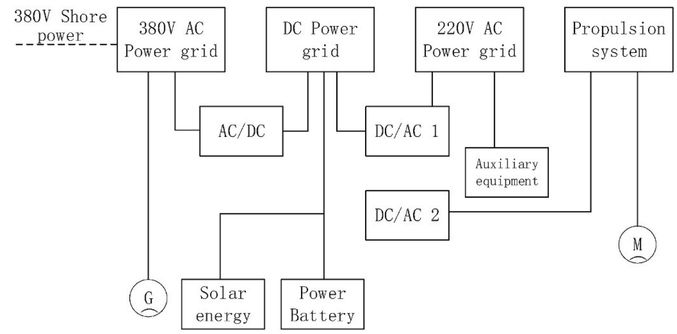


Fig. 13. Power system of a hybrid ship.

superior to the logic threshold-based control strategy in fuel economy and emission performance, the design of fuzzy control is not systematic, making it difficult to operate for complex systems. The establishment of fuzzy rules depends on the operator's experience and has certain subjective factors, which are not necessarily optimal. Moreover, a simple fuzzy process of information may lead to a reduction of control accuracy and deterioration of the dynamic quality of a system. Simultaneously, the optimization of defuzzification and the mathematical operation also impose a number of problems on the fuzzy logic control.

The main advantage of a regular control strategy is that it can be applied online based on the embedded system. However, for the energy control of multi-energy ships with complex configurations, the formulation of rules is complicated and the control effect is not ideal, and therefore the rule-based control strategies are more suitable for power systems with a low electrification. By contrast, the optimization-based control strategy is superior to the rule-based control strategy, thus an optimized energy management strategy has become a research topic of great interest. At present, a large number of optimization algorithms have been applied for conducting research on energy management. Because of the complexity, stability of an algorithm and sensitivity of the operating conditions of a ship, research in progress is mainly in the primary stage. A global optimization control algorithm is an algorithm with a global optimization performance, strong versatility, and appropriate for parallel processing. This algorithm relies on a rigorous theoretical basis, rather than merely on an empirical method, and can find the optimal solution in a certain period of time [129]. Common global optimization algorithms include dynamic programming and intelligent optimization algorithms. Intelligent optimization algorithms include the neural networks, genetic algorithm, particle swarm optimization, ant colony algorithm, simulated annealing algorithm, Tabu search algorithm, longhorn whisker search algorithm, differential evolution algorithm, etc. [130–137].

The dynamic programming algorithm decomposes the problem into several sub-problems (stages), which can be sequentially solved, and the

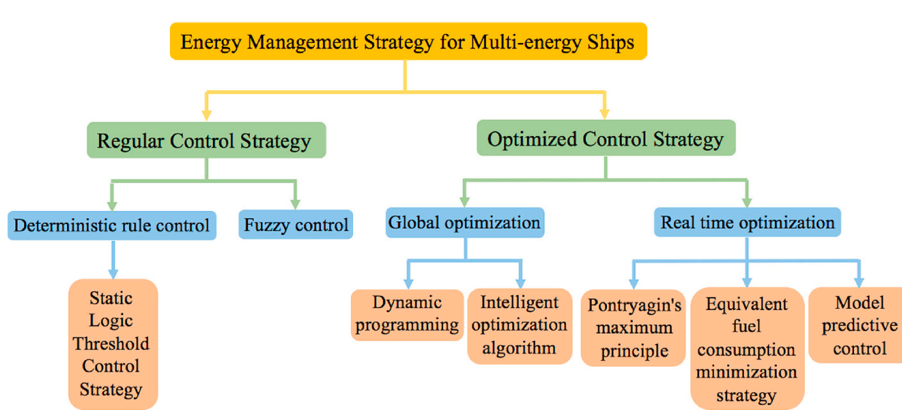


Fig. 12. Classification of energy management strategies for ships.

Table 3
Working modes of hybrid electric ship.

No.	Working mode	Description	Mode switching conditions	Power distribution
1	Battery pack power mode	The battery pack and solar power plant jointly supply power to the system	$P_{req} > 0$ $SOC > C_{SOC}$	$P_e = 0$ $P_{req} = P_b + P_{sun}$
2	Hybrid power supply mode	The diesel generator and the battery pack are mixed, and the solar power generation device charges the battery	$P_{req} > 0$ $L_{SOC} < SOC < C_{SOC}$	$P_{req} = P_e + P_b$ $P_{bch} = P_{sun}$
3	Diesel generator power supply mode	The diesel generator set supplies power to the system separately, the remaining energy is used to charge the battery, and the solar power generation device is used to charge the battery set	$P_{req} > 0$ $SOC < L_{SOC}$	$P_e = P_{e\_su} + P_{e\_ch}$ $P_{req} = P_{e\_su}$ $P_{bch} = P_{e\_ch} + P_{sun}$
4	Solar charging mode	When the ship stays in the sea area, the solar power generation device is used to charge the battery pack; when the ship comes ashore, the SOC state value of the battery pack is selected	$P_{req} = 0$ $V_{sh} = 0$	$P_e = 0$ $P_{bch} = P_{sun}$
5	Shore power mode	Solar charging or combined solar and shore power charging	$P_{req} = 0$ $V_{sh} > 0$	$P_e = 0$ $P_{bch} = P_{sun} + P_{sh}$
6	Regenerative braking mode	When the ship brakes, the braking device charges the battery pack through the driving motor combined with the solar power generation device	$p_{req} < 0$ $SOC < H_{SOC}$	$P_e = 0$ $P_{bch} = P_{sun} + P_{req}$

solutions for the former sub-problems provide significant information to solve the latter sub-problems. The algorithm guarantees the optimization of sub-problems by the optimum principle and studies possible solutions by an optimum combination, which reduces the search space and computation time. Kanellos et al. [138] developed a dynamic programming algorithm to optimize the control of the power system for the whole ship and proposed an energy management strategy to optimize the power generation dispatch, and their findings showed that their method could ensure the stable operation of the ship power system and improved energy efficiency. If using dynamic programming algorithms to solve problems, the most important thing is to determine the three elements of dynamic programming, namely, the stage of the problem, the state of each stage, and the recursive relationship between the previous stage and the next stage. A dynamic programming algorithm needs to obtain complete information about the target problem in advance; however, due to the complex operating conditions of a ship and weak anti-interference ability of a signal, a dynamic programming algorithm is used extensively in off-line analysis and optimization. An intelligent optimization algorithm is based on the bionics principle, possessing a number of advantages for solving global optimization problems. For example, Chen et al. [139], Tashakori et al. [140], and Wang et al. [141] applied a genetic algorithm to manage a multi-energy power system for ships and carried out a simulation analysis. Their results revealed that a genetic algorithm can optimize the control performance of a system. However, a genetic algorithm is associated with several control variables and they slow the convergence speed. Since the particle swarm optimization algorithm has a stronger randomness and lower computational complexity, in most cases, the particle swarm optimization algorithm can arrive at an optimal solution faster than the genetic algorithm. Divyajot et al. [142], Tang et al. [143], and Zhang et al. [144] fabricated an energy management controller for hybrid electric ships, which were composed of a solar energy system, an energy storage system, and a diesel generator. A particle swarm optimization algorithm is additionally used to solve the problem of minimum fuel consumption, taking the demand power of a hybrid power system as the input and the output power of the DC bus as the output into account. Through simulation, it was revealed that the energy management strategy optimized by a particle swarm optimization algorithm could reduce the fuel consumption effectively. Meanwhile, the advantages of intelligent optimization algorithms in global optimization have been further expanded. For example, Yang et al. [145] proposed to optimize the start-stop state and power distribution of the generator set by using the differential evolution algorithm and real number coding to reduce its fuel consumption and ensure a ship's operating efficiency. The experimental results showed that the optimized energy management strategy can significantly improve the working efficiency and fuel economy of the ship's power system.

The reason why dynamic programming and intelligent optimization algorithms belong to a global optimization is that both are essentially global search algorithms, enabling the achievement of an optimal solution of a problem by searching the entire space. In order to accelerate the search speed and reduce the calculation time, it is essential to make full use of the analytical properties of an objective function to gradually narrow the search space and then find an optimal solution. However, as the complexity of the problem deepens and the scale becomes larger, it is difficult for a global optimization algorithm to find an optimal solution within an acceptable period of time, making it difficult to be applied practically. The real-time optimization only optimizes the energy flow control of the instantaneous operating conditions of a ship, accompanied by strong real-time performance. The key to such optimization is to establish a reasonable demand power prediction model or energy consumption model. The common real-time optimization controls include the Pontryagin minimum principle, equivalent fuel consumption minimization strategy and model predictive control algorithm.

The Pontryagin minimum principle is to transform a global optimization problem into a local optimization problem, and thus reduce the calculation time. From a theoretical level, the control strategy can achieve real-time control, and can calculate the extreme value of the constrained control variables and objective functions [146]. However, the Hamilton function, as a complex function of control variable u(t), needs to search for the optimal control variable all over the control variable domain, so the control strategy based on the minimum principle needs a large amount of computation time and it is difficult to achieve real-time control. At present, this simulation method is mostly used for some hybrid vehicle, but it is rarely used for the research of hybrid ship [147,148].

The equivalent fuel consumption minimization strategy converts the energy consumption into the equivalent fuel consumption, with the aim of improving the fuel economy of the whole ship and the goal of optimizing the equivalent fuel consumption minimization strategy. This algorithm is characterized by the inclusion of fuel and power consumption in an objective function and transforms a global optimization problem into a staged instantaneous optimization problem, which decreases the dependency on the future demand power and achieves a simplified processing. A controller, that approximates the global optimal solution, can be generated by adjusting the equivalence factor appropriately. For instance, Geertsma et al. [149], Zahedi et al. [150], and Bassam et al. [151] studied a multi-energy hybrid system for ships (e.g. fuel cell), and established the minimum instantaneous equivalent fuel consumption model for a hybrid system, and they took the actual ship operation parameters as an example and used software to calculate the fuel economy of a hybrid power system through this strategy. Their results showed that the minimum instantaneous equivalent fuel consumption strategy has advantages in improving the energy saving of hybrid ships.

The strategy has a strong real-time performance, but a poor robustness and limited optimization effect; however, its robustness and optimization effect can be improved appropriately [152,153]. A model predictive control is a model-based closed-loop optimization control algorithm. A predictive model is used to predict the unknown information of the system, and an optimization model is solved to achieve the control quantity of the system, in order to achieve the real-time control of the system. Its performance depends on the module quality, sampling step size and prediction range length. There are several kinds of model predictive control algorithms, including the dynamic matrix control (DMC), model algorithmic control (MAC), and generalized predictive control (GPC) [154–156]. Haseltalab et al. [157], Ahmed et al. [158], and Raziei et al. [159] designed a model predictive controller to coordinate the output of each energy source for the stability of medium-voltage DC (MVDC) ship power grids. The simulation results show that the controller can maintain the voltage stability of MVDC under different operating conditions. The computational load of a real-time optimization algorithm is relatively small, and the real-time control of a system can be realized. However, the robustness of the algorithm is unsatisfactory, and further research on the control algorithm is required to improve the robustness.

Therefore, in order to improve the overall efficiency of the control strategy, a new idea is to combine the advantages of different algorithms to form a comprehensive algorithm. At present, this kind of control strategy is mostly used in the simulation research of hybrid electric vehicles, for example, Hu et al. [160]. In order to promote the real-time application of an advanced energy management system in a hybrid electric vehicle (HEV), the deep learning (DL) and genetic algorithm (GA) are combined to promote the power distribution control method of the battery and internal combustion engine, and the comprehensive energy management strategy is verified by a simulation. At the same time, considering the control strategy of a multi-objective optimization will also help the development of hybrid ships; although at present this optimization is mostly seen in the simulation of hybrid vehicles, for example Liu et al. [161]. In order to improve the economic performance of a fuel cell/battery hybrid vehicle, the costs of the hydrogen and the costs caused by the degradation of the fuel cell and battery are considered as multi-objective. These new ideas provide solutions for the commercial operation of hybrid ships.

4.4. Security protection

As the core of entire ship, the reliable operation of the power system directly influences the navigation safety . With the development of science and technology, the automation of ship power systems has been improved significantly. However, the complexity and strong time-variation of operating conditions may increase the probability of equipment failure, posing a serious threat to the safe operation of the system, and also causing hidden dangers to the safety of ships and personnel. Therefore, in order to ensure the safe and reliable operation of the multi-energy hybrid systems for ships, it is particularly important to carry out researches into protecting the safety of hybrid power systems. In security protection, the core issue is to perform a risk assessment at the integrated design stage of a hybrid power system [162,163], and monitor the operating conditions and parameters of a hybrid power system for a ship.

Risk assessments refer to a comprehensive analysis of the probability, cause, and loss on the basis of risk identification and estimation. There are several methods for conducting a risk assessment, including a fault tree analysis, safety assessment, and decision matrix risk assessment [164–166]. The key to risk assessments is to conduct a risk management, that is, to take various measures to reduce the probability of the occurrence of risk events and to control the losses caused by risks within a certain range. Risk control often uses four basic methods: risk avoidance, risk transfer, risk retention, and loss control. For instance, Hang et al. [167] carried out a fault analysis on a ship's power system based on an improved fuzzy analytic hierarchy process. This method shows an obvious improvement in calculation speed and accuracy, providing a reliable scientific basis for the safety management of a power system. Zhang et al. [168] proposed a fire risk assessment model based on entropy and cloud model by analyzing the fire risk of battery-powered ships. Experimental results showed that the assessment method can provide effective decision support for the safety management system of a ship.

In order to monitor and control the operating conditions and parameters of a hybrid power system, it is essential to determine the key parameters to protect a hybrid power system according to the relevant standards and results, as well as the operational characteristics of a hybrid power system. These parameters are mainly the voltage, current, temperature, pressure, and power. For example, in order to reduce the impact of load fluctuations on the system efficiency of a full-power ship, Alafnan et al. [169] used a hybrid energy storage system consisting of batteries and superconducting magnetic energy storage devices to maintain the bus voltage stability. In order to ensure the safe and long-term operation of an energy storage system, the key parameters of a battery, such as the voltage, current, temperature, and SOC, should be monitored in real-time. Shih et al. [170] monitored the maximum output power of hydrogen fuel cells using pure oxygen to ensure a reliable power supply.

Whilst monitoring the key parameters of a hybrid power system, it is necessary to diagnose the faults of the system and develop a security protection strategy. The strategy can be divided into system level and equipment level. The main purpose is to automatically detect the fault signals and disconnect the faulty facilities from the system when a ship hybrid system fails, and simultaneously issue an alarm. System-level security protection refers to the monitoring and protection of the entire power system, involving safe interconnection and disconnection of each power source. Hou et al. [154] used a hybrid energy storage system consisting of batteries and flywheels as a buffer to separate the load fluctuations from a ship power grid, to ensure the stability of the ship grid's voltage. Equipment-level safety protection refers to the protection of the equipments itself, and monitoring possible faults during operations, such as the short-circuit protection of a DC distribution unit, torque limitation of a diesel engine, overheating protection of a storage battery, and unbalanced protection of a SOC state. In order to ensure the safety of a DC power distribution unit in the case of a DC short circuit, Alho J et al. [171] proposed a time domain simulation as the analysis method of short circuit protection, and they also suggested some component-size verification tools. The simulation results verified the method's effectiveness and provided a basis for the accurate estimation of short-circuit events.

Another key issue related to safety protection is to formulate the safety grade and operation control measures of the system and equipments. At present, no research in this area has formed a specification, which is able to demonstrate the necessity of developing the corresponding hardware and software protection units, as well as the formulation of corresponding standards.

5. Problem statement

According to the findings mentioned above, it can be concluded that a multi-energy hybrid system can provide the flexible control capability for a ship, improve the fuel economy of a ship, and reduce pollutant emissions and energy consumption. However, there are still several major problems of a multi-energy hybrid system that need to besolved. The existing multi-energy hybrid systems have been faced with numerous fundamental issues before entering the market.

1) The selecting and matching of new energy sources are difficult. Due to the complex operating conditions, different kinds of ships have high requirements in terms of the type, cost, construction, installation, maintenance, and redundancy design of new energy sources. Meanwhile, matching parameters related to multi-energy hybrid systems involves a multi-objective and multi-variable optimization problem, in which the objectives include power, economy, and emission, and the variables are the specific power and specific energy of each energy source. Therefore, the achievement of the expected results can only occur after conducting repeatable optimizations based on accurate and perfect models. However, the establishment of mathematical and control models for multi-energy hybrid systems is a major challenge, and an energy control system is also complex. An energy control system consists of three modules: dynamic detection, state control, and coordinated control. The accuracy and practicability of detected data are challenging, because the monitoring data are markedly affected by environmental factors. Moreover, because the control system is not controlled by a single signal, and there are various combinations of object changes, the control system of the original fixed model cannot adapt to various combinations, resulting in a poor control performance.
2) The relay protection technology of a DC distribution network is still not mature. The system configuration, operating mode, and fault characteristics of a flexible DC distribution network are different from those of the AC distribution network, and the protection technology of an AC system cannot be extended to a DC distribution network. In addition, the power distribution equipment embedded into a DC distribution network has a very limited ability to deal with overcurrents, and therefore it is essential to ensure that a protection system can realize fault identification and isolation at a high-speed when a DC failure occurs. Since an economic and practical medium-voltage DC circuit breaker has not been extensively commercialized, the development of DC distribution network protection technology has been restricted. The protection standards for DC grid systems and the theories of corresponding protection need to be improved.
3) There are still a number of concerns about the safety and stability of multi-energy hybrid systems for ships in the industry. On the one hand, the operating conditions of a ship are complex, and changes in temperature, humidity, and vibration may weaken the insulation of the DC grid. Fuel cell ships transport a large amount of hydrogen as a fuel, whose leaking and explosive characteristics also pose a threat to the safety of ships. In order to reduce such threats, it is necessary to comprehensively employ certain measures, such as the failure mode and effect analysis (FMEA), hazard and operability study (HAZOP), and fault tree analysis (FTA). However, the shortcomings of these measures are the lack of relevant experience and data to verify. The conversion efficiency of solar cells is also an important factor that restricts their promotion. On the other hand, compared to traditional ships, the design and fabrication of multi-energy hybrid ships are more complex on the premise of ensuring safety and stability, which leads to higher requirements for the installation and pipeline layout of new energy resources on ships. Therefore, all types of ships are not fully appropriate for multi-energy hybrid power systems.
4) The control strategy for a multi-energy hybrid power system needs to be studied. Because of the complex structure of a hybrid power system, the formulation of a control strategy should not only ensure the expected response of the hybrid power system, but also consider various requirements, including the operating conditions of the ship, requirements of engine emissions, life of energy storage system, driving performance, and reliability and cost of components. In view of the characteristics of the power system components, a comprehensive optimization control should be carried out, and the standby energy scheme should be determined to restore the energy supply quickly when the energy system fails. To summarize, it is still a challenge to formulate control strategies which can achieve the requirements above.

6. Conclusions

In this paper, the important role of the multi-energy hybrid power system for ships for the purposes of energy saving and emission reduction was analyzed. The historical development of the multi-energy hybrid power system was summarized. Moreover, the structure of a multi-energy hybrid power system was discussed, and the key technologies and the background of a multi-energy hybrid power system were discussed in-depth. In addition, by analyzing the results of related fields, the problems of multi-energy hybrids were resolved. The main conclusions are as follows:

1) Multi-energy hybrid systems can effectively reduce the energy consumption and emissions of ships. However, it is crucial to perform hybrid system modeling, parameter matching and energy management.
2) The DC networking on ships plays an important role in promoting the development of new energy on ships, but breakthroughs need to be made in key technologies, such as the design and development of key equipments, power grid optimization control, safety protection technology, as well as the establishment of standard systems.
3) The research on the multi-energy hybrid system of ships is a systematic project. It is not enough to study a specific technology from a theoretical point of view and numerical methods. Therefore, it is necessary to execute a corresponding design, research, and development system.
4) In order to popularize the multi-energy hybrid power system, it is necessary to establish and popularize a platform from the perspective of safety, economy and reliability, and carry out a systematic design, reliability analysis and experimental verification of the hybrid power system for ships.

Declaration of competing interest

We declare that **no conflict of interest exists** in our submission entitled “A Review of Multi-energy Hybrid Power System for Ships”; no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of this manuscript

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References

[1] Winnes H, Styhre L, Fridell E. Reducing ghg emissions from ships in port areas. Res Transport Bus Manag 2015;17:73–82.
[2] Buhaug Ø, Corbett JJ, Endresen Ø, et al. Second IMO GHG study. London (UK): International Maritime Organization; 2009.
[3] Flower JO, Hodge CG. Stability and transient-behavioural assessment of power-electronics based dc-distribution systems. part 3: application of kharitonov polynomials. J Mar Eng Technol 2008;7(2):23–32.
[4] Andreas B, Klaus M. Standing up for the Paris Agreement: do global climate targets influence individuals' greenhouse gas emissions? Environ Sci Pol 2019;99: 72–9.
[5] IMO. Third IMO greenhouse gas study 2014, executive summary and final report. Tech rep. London (UK): International Maritime Organisation (IMO); 2015.
[6] Geertsma RD, Negenborn RR, Visser K, Hopman JJ. Design and control of hybrid power and propulsion systems for smart ships: a review of developments. Appl Energy 2017;194:30–54.
[7] Geng P, Mao H, Zhang Y, Wei L, You K, Ju J, et al. Combustion characteristics and nox emissions of a waste cooking oil biodiesel blend in a marine auxiliary diesel engine. Appl Therm Eng 2017;115:947–54.
[8] Raptotasios SI, Sakellaridis NF, Papagiannakis RG, Hountalas DT. Application of a multi-zone combustion model to investigate the nox reduction potential of two-stroke marine diesel engines using egr. Appl Energy 2015;157:814–23.
[9] Asad U, Zheng M. Exhaust gas recirculation for advanced diesel combustion cycles. Appl Energy 2014;123:242–52.
[10] Verschaeren R, Schaepdryver W, Serruys T, Bastiaen M, Vervaeke L, Verhelst S. Experimental study of NOx reduction on a medium speed heavy duty diesel engine by the application of EGR (exhaust gas recirculation) and miller timing. Energy 2014;76:614–21.
[11] Yuwei S, Xinping Y, Chengqing Y, Xujing T, Reza M, Chang G, et al. The application of hybrid photovoltaic system on the ocean-going ship: engineering practice and experimental research. J Mar Eng Technol 2018:1–11.
[12] Yuan Y, Wang J, Yan X, Li Q, Long T. A design and experimental investigation of a large-scale solar energy/diesel generator powered hybrid ship. Energy 2018;165: 965–78.
[13] Feng L, Yupeng Y, Xinping Y, Malekian Reza, Zhixiong Li. A study on a numerical simulation of the leakage and diffusion of hydrogen in a fuel cell ship. Renew Sustain Energy Rev 2018;97:177–85.
[14] Yigit K, Acarkan B. A new electrical energy management approach for ships using mixed energy sources to ensure sustainable port cities. Sustain Cities Soc 2018;40: 126–35.
[15] Alnes Φystein, Eriksen Sverre. BjΦrn-johan vartdal. Baterry-Powerd ships. IEEE Electrification 2017;5(3):10–21.
[16] Diab F, Lan H, Ali S. Novel comparison study between the hybrid renewable energy systems on land and on ship. Renew Sustain Energy Rev 2016;63:452–63.
[17] Nasirudin A, Chao RM, Utama IKAP. Solar powered boat design optimization. Procedia Eng 2017;194:260–7.
[18] Castles G, Reed G, Bendre A, Pitsch R. Economic benefits of hybrid drive propulsion for naval ships. Electric Ship Technologies Symposium. IEEE 2009: 515–20.
[19] Geertsma RD, Negenborn RR, Visser K, Loonstijn MA, Hopman JJ. Pitch control for ships with diesel mechanical and hybrid propulsion: modelling, validation and performance quantification. Appl Energy 2017;206:1609–31.
[20] Barcellos R. The hybrid propulsion system as an alternative for offshore vessels servicing and supporting remote oil field operations. In: Proceedings of the annual offshore technology conference, vol. 3; 2013. p. 1622–31.
[21] Hybrid ship Greenline 33. https://www.inautia.com/used-boat-539661001807 52695768556550664548.html.
[22] Anonymous. The world's first hybrid luxury yacht. Guangdong shipbuilding 2015;1. 74-74.
[23] Breijs A, Amam EE. Energy management – adapt your engine to every mission. Proceedings of the 13th international naval engineering conference. 2016. p. 1–8.
[24] Ovrum E, Bergh TF. Modelling lithium-ion battery hybrid ship crane operation. Appl Energy 2015;2152:162–72.
[25] Capasso C, Veneri O, Notti E, Sala A, Figari M, Martelli M. Preliminary design of the hybrid propulsion architecture for the research vessel "G. Dallaporta". International conference on electrical systems for aircraft. IEEE; 2016.
[26] Ma Q. Looking at the launching of the world's first 2000-ton electric ship, "Green Pearl River. Pearl River Water Trans 2018;10. 11-11.
[27] International Ship Network. 100% Zero Emission ~The United States will build the world's first commercial fuel cell ship. 2018. http://www.eworldship.com /html/2018/NewShipUnderConstrunction_0630/140648.html.
[28] Bennabi N, Charpentier JF, Menana H, Billard JY, Genet P. Hybrid propulsion systems for small ships: context and challenges. In: XXII international conference on electrical machines; 2016. p. 2948–54.
[29] Zhu W, Shi J, Abdelwahed S. End-to-end system level modeling and simulation for medium-voltage dc electric ship power systems. Int J Naval Arch Ocean Eng 2017;10:37–47.
[30] Kanellos FD, Anvarimoghaddam A, Guerrero JM. Smart shipboard power system operation and management. Inventions 2016;1(4):22.
[31] Ghassemi, Hassan, Ghadimi, Parviz. Computational hydrodynamic analysis of the propeller-rudder and the azipod systems. Ocean Eng 2008;35(1):117–30.
[32] Liang X, Yan X, Wu O, Liu Z, Jian W. Design and performance analysis of a hydrodynamic lubricated conical sliding bearing. Int Conf Transport Inform Saf 2017;4:1015–21.
[33] Bergthorson JM, Yavor Y, Palecka J, Georges W, Soo M, Vickery J, et al. Metal-water combustion for clean propulsion and power generation. Appl Energy 2017; 186:13–27.
[34] Geertsma R, Kalikatzarakis M, Boonen EJ, Visser K, Negenborn RR. Ship energy management for hybrid propulsion and power supply with shore charging. Contr Eng Pract 2018;76:133–54.
[35] Chiang Hsiao-Wei D, Hsu Chih-Neng. Design and performance analysis of a solid oxide fuel cell/gas turbine (SOFC/GT) hybrid system used in combined cooling heating and power system. ASME 2011 Turbo Expo: Turbine Techn Conf Exposit 2011;4:201–9.
[36] Nielsen RF, Haglind F, Larsen U. Design and modeling of an advanced marine machinery system including waste heat recovery and removal of sulphur oxides. Energy Convers Manag 2014;85:687–93.
[37] Yan XP, Ma F, Liu JL, et al. Applying the navigation brain system to inland ferries [C]//18th conference on computer and IT applications in the maritime industries. Tullamore. 2019. p. 156–62.
[38] Yuan LCW, Tjahjowidodo T, Lee GSG, Chan R, Adnanes AK. Equivalent Consumption Minimization Strategy for hybrid all-electric tugboats to optimize fuel savings. In: American control conference. IEEE; 2016. p. 6803–8.
[39] Bassam AM, Phillips AB, Turnock SR, Wilson PA. Development of a multi-scheme energy management strategy for a hybrid fuel cell driven passenger ship. Int J Hydrogen Energy 2016;42(1):623–35.
[40] Zhan K, Gao H, Chen H, Lin Z. Optimal retrofitting of a hybrid propulsion system using NSGA-II algorithm for trailing suction hopper dredger. In: 2015 IEEE electric ship technologies symposium (ESTS). IEEE; 2015. p. 201–6.
[41] Vu TL, Ayu AA, Dhupia JS, Kennedy L, Adnanes AK. Power management for electric tugboats through operating load estimation. IEEE Trans Contr Syst Technol 2015;23(6):2375–82.
[42] Dupriezrobin F, Loron L, Claveau F, Chevrel P. Design and optimization of an hybrid sailboat by a power modeling approach. IEEE Electric Ship Technol Symp IEEE 2009:270–7.
[43] Soma A, Bruzzese F, Mocera F, Viglietti E. (2016). Hybridization factor and performance of hybrid electric telehandler vehicle. In: IEEE transactions on industry applications, vol. 52; 2016. p. 5130–8.
[44] Ailong F, Yapeng H, Xinping Y, et al. The concept and key technology of intelligent new energy ship. Mar Eng 2020;3(42):9–14 [In Chinese].
[45] Nüesch T, Wang M, Isenegger P P. Optimal energy management for a diesel hybrid electric vehicle considering transient PM and quasi-static NOx emissions. Contr Eng Pract 2014;29:266–76.
[46] Kamishima H, Arai T, Yuasa K, Mae Y. Hybrid drive parallel arm and its motion control. In: IEEE/RSJ international conference on intelligent robots & systems, vol. 1. IEEE; 2000. p. 516–21.
[47] De Waard DS. Parameterization of ship propulsion drives and their fuel efficiency under different operational modes and configurations. Proceedings of the engine as a weapon VI conference. 2015. p. 44–57.
[48] Zahedi B, Norum LE. Modeling and simulation of all-electric ships with low-voltage dc hybrid power systems. IEEE Trans Power Electron 2013;28(10): 4525–37.
[49] Bayindir KC, Ali Gözüküçük Mehmet, Teke A. A comprehensive overview of hybrid electric vehicle: powertrain configurations, powertrain control techniques and electronic control units. Energy Convers Manag 2011;52(2):1305–13.
[50] Yang L, Li SZ, Zhao F, Ni QJ. An integrated optimization design of a fishing ship hullform at different speeds. J Hydrodyn 2018;30:1174–81.
[51] Papanikolaou A. Holistic ship design optimization. Comput Aided Des 2010;42 (11):1028–44.
[52] Cai H, You S, Bindner HW, Klyapovskiy S. Load situation awareness design for integration in multi-energy system. IEEE international conference on energy internet. IEEE 2017;11:42–7.
[53] Huang Z, Yu H, Chu X, Peng Z. A novel optimization model based on game tree for multi-energy conversion systems. Energy 2018;150:109–21.
[54] Murray Portia, Orehounig Kristina, Carmeliet Jan. Optimal design of multi-energy systems at different degrees of decentralization. Energy Procedia 2019; 158:4204–9.
[55] Kexing L, Illindala MS. A distributed energy management strategy for resilient shipboard power system. Appl Energy 2018;228:821–32.
[56] Sakalis GN, Frangopoulos CA. Intertemporal optimization of synthesis, design and operation of integrated energy systems of ships: general method and application on a system with diesel main engines. Appl Energy 2018;226:991–1008.
[57] Keane RG. Reducing total ownership cost: designing inside-out of the hull. Nav Eng J 2012;124(4):67–80. 14.
[58] Ghenai C, Bettayeb M, Brdjanin B, et al. Hybrid solar PV/PEM fuel Cell/Diesel Generator power system for cruise ship: a case study in Stockholm, Sweden. Case Stud Thermal Eng 2019;14:100497.
[59] Balsamo F, Capasso C, Miccione G, Veneri O. Hybrid storage system control strategy for all-electric powered ships. Energy Procedia 2017;126:1083–90.
[60] Nasirudin A, Chao RM, Utama IKAP. Solar powered boat design optimization. Procedia Eng 2017;194:260–7.
[61] Divyajot, Kumar R, Fozdar M. Optimal sizing of hybrid ship power system using variants of particle swarm optimization. In: 2017 recent developments in control, automation & power engineering (RDCAPE). IEEE; 2018. p. 527–32.
[62] Duan J, Fan S, Wu F, Sun L, Wang G. Power balance control of micro gas turbine generation system based on supercapacitor energy storage. Energy 2017;119: 442–52.
[63] Kanellos FD. Optimal power management with ghg emissions limitation in all-electric ship power systems comprising energy storage systems. IEEE Trans Power Syst 2013;29(1):330–9.

[64] Guan G, Yang Q, Gu W, Jiang W, Lin Y. A new method for parametric design and optimization of ship inner shell based on the improved particle swarm optimization algorithm. Ocean Eng 2018;169:551–66.
[65] Sakalis GN, Frangopoulos CA. Intertemporal optimization of synthesis, design and operation of integrated energy systems of ships: general method and application on a system with diesel main engines. Appl Energy 2018;226:991–1008.
[66] Alinezhad P, Bakhoda OZ, Menhaj MB. Optimal DG placement and capacity allocation using intelligent algorithms. 2015 4th Iranian Joint Congress on Fuzzy and Intelligent Systems (CFIS) 2016. https://doi.org/10.1109/CFIS.2015.7391657.
[67] Mahmoud PHA, Huy PD, Ramachandaramurthy VK. A review of the optimal allocation of distributed generation: objectives, constraints, methods, and algorithms. Renew Sustain Energy Rev 2017;75:293–312.
[68] Derollepot R, Vinot E. Sizing of a combined series-parallel hybrid architecture for river ship application using genetic algorithm and optimal energy management. Math Comput Simulat 2018;158(4):248–63.
[69] Jianyun Z, Li C, Bin W, Lijuan X. Optimal design of a hybrid electric propulsive system for an anchor handling tug supply vessel. Appl Energy 2018;226:423–36.
[70] Trivyza Nikoletta L, Rentizelas Athanasios, Theotokatos Gerasimos. A novel multi-objective decision support method for ship energy systems synthesis to enhance sustainability. Energy Convers Manag 2018;168:128–49.
[71] Ancona MA, Baldi F, Bianchi M. Efficiency improvement on a cruise ship: load allocation optimization. Energy Convers Manag 2018;164:42–58.
[72] Wen S, Lan H. Optimal sizing of hybrid energy storage sub-systems in PV/diesel ship power system using frequency analysis. Energy 2017;140:198–208.
[73] Zhang J, Li Q, Cong W, Zhang L. Restraining integrated electric propulsion system power fluctuation using hybrid energy storage system. In: IEEE international conference on mechatronics & automation; 2015. p. 336–40.
[74] Ceschia Adriano, Azib Toufik. Optimal design of fuel cell hybrid power source under energy constraints. In: 2018 IEEE international conference on electrical systems for aircraft, railway, ship propulsion and road vehicles and international transportation electrification conference; 2018.
[75] Jin Y, Zhao Y. Chaotic ant colony algorithm for preliminary ship design. In: International conference on natural computation, vol. 4. IEEE Computer Society; 2017. p. 776–81.
[76] Wang Z, Wang YJ, Li Z. Reconfiguration of shipboard power system using improved ant colony optimization. Key Eng Mater 2011;480–481:1185–90.
[77] Ma L, Zhang J, Ren G. An improved selection strategy differential evolution algorithm for reconfiguration of shipboard power system. In: International conference on information science & technology. IEEE; 2015. p. 131–5.
[78] Sixin LSL, Jianmei XJX, Xihuai WXW. Network reconfiguration of shipboard power system based on improved differential evolution. In: control conference, vol. 52. IEEE; 2010. p. 42–6.
[79] Kong Young-Mo, Choi Su H. Proceedings of the 1st world congress on engineering asset management. In: Proceedings of the 1st world congress on engineering asset management. WCEAM; 2006. p. 1043–9.
[80] Wang C, Guo X. A hybrid algorithm based on genetic algorithm and ant colony optimization for Traveling Salesman Problems. International conference on information science & engineering. IEEE; 2011. p. 4257–60.
[81] Hai L, Wen S, Hong YY, Yu DC, Zhang L. Optimal sizing of hybrid pv/diesel/battery in ship power system. Appl Energy 2015;158:26–34.
[82] Barsoum N, Vasant P. Balancing cost, operation and performance in integrated hydrogen hybrid energy system. In: First asia international conference on modelling and simulation (AMS 2007), 27-30 march 2007, phuket, Thailand. IEEE Computer Society; 2007. p. 14–8.
[83] Alam MS, Gao DW. Modeling and analysis of a wind/PV/fuel cell hybrid power system in HOMER. In: IEEE conference on industrial electronics & applications. IEEE; 2017. p. 1594–9.
[84] Vieira GTT, Peralta CO, Salles MBC, Carmo BS. Reduction of CO2 emissions in ships with advanced energy storage systems. In: 2017 6th international conference on clean electrical power (ICCEP). IEEE; 2017. p. 564–71.
[85] Doerry N, Amy J, Krolick C. History and the status of electric ship propulsion, integrated power systems, and future trends in the u.s. navy. Proc IEEE 2015;103(12):2243–51.
[86] Mccoy TJ. Integrated power systems—an outline of requirements and functionalities for ships. Proc IEEE 2015;103(12):2276–84.
[87] Sudhoff SD. Currents of change. IEEE Power Energy Mag 2011;9(4):30–7.
[88] Jin Z, Sulligoi G, Cuzner R, Meng L, Vasquez JC, Guerrero JM. Next-generation shipboard dc power system: introduction smart grid and dc microgrid technologies into maritime electrical netowrks. IEEE Electrific Mag 2016;4(2):45–57.
[89] Cheetham Peter, Kim, Chul, Graber, Lukas, Pamidi. Implementation of superconducting cables in medium voltage DC integrated power systems on all electric ships. In: IECON 2018 - 44th annual conference of the IEEE industrial electronics society; 2018. p. 3425–30.
[90] Su Chun-Lien, Lin Kun-Liang, Chen Ching-Jin. Power flow and generator-converter schemes studies in ship MVDC distribution systems. IEEE Trans Ind Appl 2015;52(1):50–9.
[91] Bi K, An Q, Duan J, Li S, Gai K. Fast diagnostic method of open circuit fault for modular multilevel dc/dc converter applied in energy storage system. IEEE Trans Power Electron 2017;32(5):3292–6.
[92] Zhang QY, Yue JF. Study of voltage level sequence of distribution network in Zhengzhou new district based on AHP. Power Electronics & Motion Control Conference. IEEE 2012;4:2699–703.
[93] IEEE Industry Applications Society. In: IEEE recommended practice for 1 kV to 35 kV medium-voltage DC power systems on ships. IEEE; 2010. p. 1–54.
[94] Doerry, Norbert. Naval power systems: integrated power systems for the continuity of the electrical power supply. IEEE Electrific Mag 2015;3(2):12–21.
[95] Kanellos FD, Prousalidis J, Tsekouras GJ. Onboard dc grid employing smart grid technology: challenges, state of the art and future prospects. IET Electr Syst Transp 2015;5(1):1–11.
[96] Huhman BM, Neri JM, Wetz DA. Design of a battery intermediate storage system for rep-rated pulsed power loads. Electric ship technologies symposium. 2013. p. 1–5.
[97] Sinha K, Tapre PC. Impact of ramp and gust in wind farm distributed generation using power system stabilizer in PSCAD simulation. Electrical, electronics & computer science. IEEE; 2014.
[98] Vahedi H, Perkins D, Gonsoulin D, Vu T, Edrington CS. Optimal sensor placement for MVDC ship power system. 2017 IEEE Electric Ship Technologies Symposium (ESTS); 2017. p. 207–11.
[99] Kanellos FD, Tsekouras GJ, Prousalidis J. Onboard dc grid employing smart grid technology: challenges, state of the art and future prospects. Electric Syst Transport Iet 2015;5(1):1–11.
[100] Briant L. Demand for greener, more efficient propulsion systems : a look at the siemens blue drive plus c system. Mar Log 2012;117.
[101] Yazaki Y, Ishidate K, Hagita K, Kondo Y. Embedded planar power inductor in an organic interposer for package-level dc power grid. Magnet IEEE Trans 2014;50(11):1–4.
[102] http://www.csic-cse.com.
[103] Cupelli M, Ponci F, Sulligoi G, Vicenzutti A. Power flow control and network stability in an all-electric ship. Proc IEEE 2015;103(12):2355–80.
[104] Javaid U, Freijedo FD, Dujic D, Wim VDM. Dynamic assessment of source-load interactions in marine mvdc distribution. IEEE Trans Ind Electron 2017;64(6):4372–81.
[105] Lesage JR, Longoria RG, Shutt W. Power system stability analysis of synthesized complex impedance loads on an electric ship. In: IEEE electric ship technologies symposium. IEEE; 2011. p. 34–7.
[106] Hajian M, Lu Z, Jovcic D. Dc transmission grid with low-speed protection using mechanical dc circuit breakers. IEEE Trans Power Deliv 2015;30(3):1383–91.
[107] Suttell N, Vargas JVC, Ordonez J. Transient thermal analysis of hts dc cables cooled with gaseous helium using a volume element method transactions on applied superconductivity. IEEE Trans Appl Supercond 2017;27(4):1–5.
[108] Gomes D, Barbi I, Lazzarin TB. High voltage power supply using t-type parallel resonant dc-dc converter. IEEE Trans Ind Appl 2018;54(3):2459–70.
[109] Elserougi AA, Massoud AM, Ahmed S. Arrester-less dc fault current limiter based on pre-charged external capacitors for half-bridge modular multilevel converters. IET Gener, Transm Distrib 2017;11(1):93–101.
[110] Sano K, Takasaki M. A surgeless solid-state dc circuit breaker for voltage-source-converter-based hvdc systems. IEEE Trans Ind Appl 2014;50(4):2690–9.
[111] Mokhberdoran A, Carvalho A, Silva N, Leite H, Carrapatoso A. Design and implementation of fast current releasing dc circuit breaker. Elec Power Syst Res 2017;151:218–32.
[112] Jovcic D, Taherbaneh M, Taisne JP, Nguefeu S. Offshore dc grids as an interconnection of radial systems: protection and control aspects. IEEE Trans Smart Grid 2015;6(2):903–10.
[113] Sarlette A, Dai J, Phulpin Y, Ernst D. Cooperative frequency control with a multi-terminal high-voltage dc network. Automatica 2012;48(12):3128–34.
[114] Eriksson R. Coordinated control of multiterminal dc grid power injections for improved rotor-angle stability based on lyapunov theory. IEEE Trans Power Deliv 2014;29(4):1789–97.
[115] Peltoniemi P, Nuutinen P, Pyrhonen J. Observer-based output voltage control for dc power distribution purposes. IEEE Trans Power Electron 2013;28(4):1914–26.
[116] Saad Ahmed A, Faddel Samy, Youssef Tarek, Mohammed Osama. Small-signal model predictive control based resilient energy storage management strategy for all electric ship MVDC voltage stabilization. J Energy Storage 2019;21:370–82.
[117] Balsamo F, Capasso C, Miccione G, Veneri O. Hybrid storage system control strategy for all-electric powered ships. Energy Procedia 2017;126:1083–90.
[118] Tribioli L, Onori S. Analysis of energy management strategies in plug-in hybrid electric vehicles: application to the GM Chevrolet Volt. American Control Conference (ACC). IEEE 2013:5966–71.
[119] Da Rù D, Morandin M, Bolognani S, Castiello M. A threshold logic control strategy for parallel light hybrid electric vehicle implementation. In: Iet international conference on power electronics; 2016.
[120] Nelson D, Nehrir M, Wang C. Unit sizing and cost analysis of stand-alone hybrid wind/PV/fuel cell power generation systems. Renew Energy 2006;31(10):1641–56.
[121] Torreglosa JP, García P, Fernández LM, Jurado F. Hierarchical energy management system for stand-alone hybrid system based on generation costs and cascade control. Energy Convers Manag 2014;77:514–26.
[122] Thounthong P, Chunkag V, Sethakul P, Sikkabut S, Pierfederici S, Davat B. Energy management of fuel cell/solar cell/supercapacitor hybrid power source. J Power Sources 2011;196(1):313–24.
[123] Tang D, Zio EnricoYuan Y. The energy management and optimization strategy for fuel cell hybrid ships. In: 2017 2nd international conference on system reliability and safety, ICSRS 2017; 2018. p. 277–81.
[124] Yan Xinping, Xu Li, Yuan Chengqing. Ship clean energy technology. second ed. National Defense Industry Press; 2015 [In Chinese].
[125] Zhang Minmin, Kang Wei. Design of a hybrid electric ship energy management system. China Water Transp Monthly 2011;12:73–5 [In Chinese].
[126] Khan MMS, Faruque MO, Newaz A. Fuzzy logic based energy storage management system for mvdc power system of all electric ship. IEEE Trans Energy Convers 2017;PP(99):1. https://doi.org/10.1109/TEC.2017.2657327.

[127] Yupeng Y, Tianding Z, Boyang S, Xinping Y, Teng L. (2018). A fuzzy logic energy management strategy for a photovoltaic/diesel/battery hybrid ship based on experimental database. Energies 2018;11(9):2211.
[128] Zhu L, Han J, Peng D, Wang T, Charpentier JF. Fuzzy logic based energy management strategy for a fuel cell/battery/ultra-capacitor hybrid ship. In: 2014 international conference on green energy. IEEE; 2014. p. 107–12.
[129] Wang J, Wang QN, Wang PY, Wang JN, Zou NW. Hybrid electric vehicle modeling accuracy verification and global optimal control algorithm research. Int J Automot Technol 2015;16(3):513–24.
[130] Xinxin F, Xing H, Junjian H. A strategy to optimize the multi-energy system in microgrid based on neurodynamic algorithm. Appl Soft Comput 2019;75:588–95.
[131] Moreno J, Ortuzar ME, Dixon JW. Energy-management system for a hybrid electric vehicle, using ultracapacitors and neural networks. IEEE Trans Ind Electron 2006;53(2):614–23.
[132] Herrera VI, Gaztanaga H, Milo A, Saez-De-Ibarra A, Nieva T. Optimal energy management of a battery-supercapacitor based light rail vehicle using genetic algorithms. In: 2015 IEEE energy conversion congress and exposition. IEEE; 2015. p. 1359–66.
[133] Gianni C, Fabrizio P, Giuditta P, Giuseppe SG. Distribution energy storage investment prioritization with a real coded multi-objective genetic algorithm. Elec Power Syst Res 2018;163:154–63.
[134] Jordan Radosavljević, Miroljub Jevtić, Klimenta D. Energy and operation management of a microgrid using particle swarm optimization. Eng Optim 2016; 48(5):811–30.
[135] S., M. M. A. M. Pourhashemi AP. Ant colony optimization applied to optimal energy management of fuel cell hybrid electric vehicle. In: Ultra modern telecommunications and control systems and workshops (ICUMT), 2012 4th international congress on. IEEE; 2012. p. 497–503.
[136] Wang B, Xu J, Cao B, Bo N. Adaptive mode switch strategy based on simulated annealing optimization of a multi-mode hybrid energy storage system for electric vehicles. Appl Energy 2017;194:596–608.
[137] Wu L, Wang Y, Yuan X, Chen Z. Multiobjective optimization of hev fuel economy and emissions using the self-adaptive differential evolution algorithm. IEEE Trans Veh Technol 2011;60(6):2458–70.
[138] Kanellos FD, Tsekouras GJ, Hatziargyriou ND. Optimal demand-side management and power generation scheduling in an all-electric ship. IEEE Trans Sustain Energy 2014;5(4):1166–75.
[139] Chen C, Wang X, Xiao J. An energy allocation strategy for hybrid ship dc power system based on genetic algorithm. IETE J Res 2016;62(3):301–6.
[140] Tashakori Abkenar A, Nazari A, Jayasinghe SDG, Kapoor A, Negnevitsky M. Fuel cell power management using genetic expression programming in all-electric ships. IEEE Trans Energy Convers 2017;32:779–87.
[141] Jialin W, Li X, Zhengguo WU, Xuanfang Y. Multiobjective optimal network reconfiguration of shipboard power system based on non-dominated sorting genetic algorithm-II. Power System Technology; 2012. p. 58–64.
[142] Divyajot, Kumar R, Fozdar M. Optimal sizing of hybrid ship power system using variants of particle swarm optimization. In: 2017 recent developments in control, automation & power engineering (RDCAPE). IEEE; 2018. p. 527–32.
[143] Ruoli T, Xin L, Jingang L. A novel optimal energy-management strategy for a maritime hybrid energy system based on large-scale global optimization. Appl Energy 2018;228:254–64.
[144] Zhang W, Shi W, Zhuo J. (2017). Shipboard power system stabilizer optimization using ga and qpso algorithm. Int J Comput Intell Appl 2017;16(3):50–65.
[145] Yang Z, Xiao J, Wang X, Deng J. Ship energy management system optimization strategy based on differential evolution algorithms. China Ship Res 2018;75(4): 136–43 [In Chinese].
[146] Zhang N, X M, L J. Energy management for parallel HEV based on PMP algorithm. Shanghai(CN). In: International conference on robotics & automation engineering; 2017. p. 177–82.
[147] Ameur I, Benalia A. In: PMP based optimal power management of a PV-Fuel-Cell-Battery hybrid power source. Algiers(DZA): 2019 international conference on advanced electrical engineering. ICAEE; 2019.
[148] Ou K, Yuan WW, Choi M, et al. Optimized power management based on adaptive-PMP algorithm for a stationary PEM fuel cell/battery hybrid system. Int J Hydrogen Energy 2018;43(32):15433–44.
[149] Geertsma R, Kalikatzarakis M, Boonen EJ, Visser K, Negenborn RR. Ship energy management for hybrid propulsion and power supply with shore charging. Contr Eng Pract 2018;76:133–54.
[150] Zahedi B, Norum LE, Ludvigsen KB. Optimized efficiency of all-electric ships by dc hybrid power systems. J Power Sources 2014;255:341–54.
[151] Bassam AM, Phillips AB, Turnock SR, Wilson PA. Development of a multi-scheme energy management strategy for a hybrid fuel cell driven passenger ship. Int J Hydrogen Energy 2016;42:623–35.
[152] Tianheng F, Lin Y, Qing G, Yanqing H, Ting Y, Bin Y. A supervisory control strategy for plug-in hybrid electric vehicles based on energy demand prediction and route preview. IEEE Trans Veh Technol 2015;64(5):1691–700.
[153] Zhang C, Vahid A. Real-time optimal control of plug-in hybrid vehicles with trip preview. In: American control conference. IEEE; 2010. p. 6917–22.
[154] Hou J, Sun J, Hofmann H. Adaptive model predictive control with propulsion load estimation and prediction for all-electric ship energy management. Energy 2018;150:877–89.
[155] Meyer Richard T, DeCarlo Raymond A. Hybrid optimal power management of a ship. In: ASME international mechanical engineering congress and exposition, proceedings (IMECE), vol. 4; 2014.
[156] Diju G, Xuyang W, Tianzhen W, Yide W, Xiaobin X. An energy optimization strategy for hybrid power ships under load uncertainty based on load power prediction and improved NSGA-II algorithm. Energies 2018;11:7.
[157] Haseltalab A, Negenborn RR, Lodewijks G. Multi-level predictive control for energy management of hybrid ships in the presence of uncertainty and environmental disturbances. Ifac Papersonline 2016;49(3):90–5.
[158] Saad Ahmed A, Faddel Samy, Youssef Tarek, Mohammed Osama. Small-signal model predictive control based resilient energy storage management strategy for all electric ship MVDC voltage stabilization. J Energy Storage 2019;21:370–82.
[159] Raziei SA, Jiang Z. FPGA implementation of a real-time model predictive controller for hybrid power systems. In: Energy conversion congress & exposition. IEEE; 2017. p. 3090–7.
[160] Hu X, Zou C, Tang X, Liu T, Hu L. In: Cost-optimal energy management of hybrid electric vehicles using fuel cell/battery health-aware predictive control, vol. 35. IEEE Transactions on Power Electronics; 2020. p. 382–92.
[161] Liu Teng, Tang Xiaolin, Wang Hong, Yu Huilong, Hu Xiaosong. Adaptive hierarchical energy management design for a plug-in hybrid electric vehicle. IEEE Trans Veh Technol 2019;68(12):11513–22.
[162] Garbatov Y, Sisci F. Sensitivity analysis of risk-based conceptual ship design. In: Guedes Soares C, Santos TA, editors. Progress in Maritime technology and engineering; 2018. p. 499–510.
[163] Lee S, Kim S, Jeong Y, Jung SY. Power system modeling and analysis of electric ship propulsion system. In: International telecommunications energy conference. IEEE; 2009.
[164] Ferdous R, Khan FI, Veitch B. Methodology for computer-aided fault tree analysis [J]. Process Saf Environ Protect 2007;85(1):70–80.
[165] Khan F, Rathnayaka S, Ahmed S. Methods and models in process safety and risk management: past, present and future. Process Saf Environ Protect 2015;98: 116–47.
[166] Marhavilas PK, Koulouriotis DE, Mitrakas C. On the development of a new hybrid risk assessment process using occupational accidents'data: application on the Greek public electric power provider. J Loss Prev Process Ind 2011;24(5):671–87.
[167] Jiang H, Wang X, Wang L. Failure analysis of ship power system based on improved fuzzy analytic hierarchy process. In: IEEE international conference on cyber technology in automation. IEEE; 2015. p. 213–6.
[168] Zhang W, Yan X. Fire risk assessment of battery powered ship using entropy cloud method. In: 2017 4th international conference on transportation information and safety, ICTIS 2017 – proceedings; 2017. p. 331–6.
[169] Alafnan H, Min Z, Yuan W, Zhu J, Li J, Elshiekh M, et al. Stability improvement of dc power systems in an all-electric ship using hybrid smes/battery. IEEE Transactions on Applied Superconductivity; 2018. p. 1–6. 5700306.
[170] Shih NC, Weng BJ, Lee JY, Hsiao YC. Development of a 20kw generic hybrid fuel cell power system for small ships and underwater vehicles. Int J Hydrogen Energy 2014;39(25):13894–901.
[171] Alho J, Lana A, Lindh T, Pyrhonen O. Analysis on short-circuit protection in a battery-powered marine vessel with a DC distribution system. In: 20th European conference on power electronics and applications; 2018.