smart cities

Review

State-of-the-Art Review on Shipboard Microgrids: Architecture, Control, Management, Protection, and Future Perspectives

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Abstract: Shipboard microgrids (SBMGs) are becoming increasingly popular in the power industry due to their potential for reducing fossil-fuel usage and increasing power production. However, operating SBMGs poses significant challenges due to operational and environmental constraints. To address these challenges, intelligent control, management, and protection strategies are necessary to ensure safe operation under complex and uncertain conditions. This paper provides a comprehensive review of SBMGs, including their classifications, control, management, and protection, as well as the most recent research statistics in these areas. The state-of-the-art SBMG types, propulsion systems, and power system architectures are discussed, along with a comparison of recent research contributions and issues related to control, uncertainties, management, and protection in SBMGs. In addition, a bibliometric analysis is performed to examine recent trends in SBMG research. This paper concludes with a discussion of research gaps and recommendations for further investigation in the field of SBMGs, highlighting the need for more research on the optimization of SBMGs in terms of efficiency, reliability, and cost-effectiveness, as well as the development of advanced control and protection strategies to ensure safe and stable operation.

Keywords: shipboard microgrid; shipboard microgrid control; shipboard microgrid uncertainties; shipboard microgrid management; shipboard microgrid fault management; shipboard microgrid protection

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1. Introduction

1.1. Background

Nowadays, the shipping industry has a significant impact on our environment. It is estimated that by 2050 the shipping industry will account for 12–18% of global anthropogenic carbon dioxide (CO_2) emissions [1]. Pollutants released by ships in coastal areas may lead to serious health problems for the populations nearby [2,3]. Therefore, the International Maritime Organization (IMO) has created effective regulations to limit ship emissions and protect the environment [1]. Such restrictions are designed to reduce emissions from ships and help the shipping industry significantly reduce its carbon footprint in the future [4]. However, 95% of vessels use diesel-fueled engines, making it difficult to meet the IMO's targets [5]. However, the evolution of the power electronics used in electrical power systems has led to developments in ship power systems [6]. Hence, the shipboard microgrid (SBMG) concept has been developed. Since alternative energy and electrical propulsion systems have evolved in the ship power system, warships have been equipped with electric-drive propulsion systems to maximize fuel efficiency and minimize noise pollution [7–10]. Such innovations have led to a growing variety of power and propulsion architectures that make it complex to balance efficiency with the ability to operate in a wide range of operating profiles. The combination of energy sources and the propulsion system formed the novel SBMG, which is defined as an independent electric power system installed on a ship to provide electricity to different loads, including propulsion motors and many other service loads [11]. The SBMG is a local system suited to operate in small areas, where loads are placed very close to generation resources. The main components of the SBMG are the generating units, the distribution system, and the loads. The generation units include conventional units, such as synchronous and diesel-engine generators, and RES units, such as solar panels, wind turbines, fuel cells, and batteries. The function of the distribution stage is to distribute the power to all the loads by utilizing network devices, including transformers and switchboards. The shipboard loads are divided into propulsion and service loads. Although propulsion loads are the main loads in vessels, several loads must be considered, such as lighting systems, navigation, radar, and controls. These loads are variable, and they need to be adequately controlled given load disturbances and uncertainties. The SBMG has many benefits compared to conventional systems, including high reliability, reduced greenhouse gases (GHGs), fuel consumption and cost savings, increased use of clean energy, and the ability of fuel cells and/or batteries to supply peak and partial loads for optimal operation [12,13]. However, it also presents many challenges, such as the need for solar panels with high-efficiency conversion stages; strong designs for PV arrays and wind turbines; optimal arrangements to limit ship deck space; poor power quality and energy efficiency; the necessity for advanced control strategies to maximize efficiency, improve power quality, and ensure reliability; choosing and matching suitable energy sources; the complex protection of DC SBMGs; the vulnerability of the ship's DC grid insulation to temperature, humidity, and vibration; the high capital costs of installing new energy technology; high-frequency disturbances due to the resonance of the power distribution cables; and the uncertain effects of severe environmental conditions on SBMGs, such as PV, wind, and time-varying load uncertainties [1,14,15].

Marine vessels are categorized into various types based on their usage, including passenger vessels, such as small passenger ships and large passenger ships such as cruise ships; commercial vessels, such as offshore vessels and cargo vessels; tanker vessels for transporting bulk amounts of gases or liquids; and military vessels, including naval vessels and coast guard ships. The voltage required for these vessels varies based on their usage, ranging from 690V for small passenger ships and offshore vessels to 11 kV for cargo vessels. Tanker vessels and military vessels typically operate at 6.6 kV [15,16].

1.2. Related Work

There are different structures for the SBMG according to its usage and importance. So, different control, management, and protection strategies are used. As the system becomes more complex, the number of variables considered in control increases. The design of advanced propulsion systems still relies on traditional control techniques, yet SBMG research has proved that conventional control systems do not significantly reduce the impact of fuel consumption or emissions, despite increased costs and system complexity [17–20]. Therefore, intelligent control strategies are proposed to improve SBMG performance. However, these strategies still have many issues that need to be resolved.

Moreover, there are special loads in shipboard power systems, such as electromagnetic guns, electromagnetic launch systems, and free-electron lasers, which intermittently draw very high short-time current, also known as pulsed loads, which may affect SBMG stability. Energy storage systems (ESSs) add flexibility to SBMGs, provide the potential to improve efficiency, and reduce emissions from hybrid ship power systems. These hybrid power systems include traditional gensets and new equipment, such as gas capture systems and alternative energy sources, e.g., solar panels, fuel cells, and ESSs. However, for hybrid ship power systems, compatibility issues exist, such as the coordination between multiple energy sources, such as wind, water, and solar, and the potential for improving fuel efficiency and total costs. This requires a group of functions and algorithms that determine power distribution to keep the power supply continuous with respect to an objective function which is referred to as the Power Management System (PMS) [21–24]. Many optimization tools exist to solve such issues from many studies considering uncertainties.

Furthermore, SBMG protection systems are dependent on marine vessels' class. In the last few years, battery-operated ferries which work on DC power systems have become an important option for short-distance travel. Ferries are vulnerable to power loss, leading to immediate stalling. Blackouts caused by ineffective protection algorithms could cause changes to the ship's position. Moreover, critical activities, such as oil exploration, make these ships prone to accidents and collisions. A collision with a spilled oil tanker can result in dire consequences; it would not only affect the environment and destroy marine life, but it might also lead to financial loss from fines or lawsuits. Therefore, a low-cost and low-complexity protection solution can easily defend against such threats, saving time and money. To ensure an uninterrupted power supply, a robust and comprehensive protection system is required. This will also enable the system manager to correct any faults and disconnect faulty equipment only [25].

From the above, it can be concluded that the control, management, and protection of SBMGs are not straightforwardly achieved. The more complex the system, the more challenges the SBMG faces. To solve such challenges, robust techniques and strategies in the protection, control, and management of SBMGs are required, along with consideration of uncertainties. Design criteria and control, management, and protection methods must be investigated to ensure smart, reliable, flexible, and robust future ships. A comparative analysis of these techniques must be performed to establish a smart strategy to achieve high performance [4]. Many research works have investigated SBMG control, uncertainties, management, and protection.

Many review papers have been published related to SBMG features. Table 1 compares some of those features according to ten different aspects from 2016 until 2021. The following factors are important when reviewing the main features: (1) the energy management system (EMS); (2) the operation of the SBMG; (3) the protection of the SBMG; (4) the architecture of the SBMG; (5) the control of the SBMG; (6) the challenges of the SBMG; (7) the propulsion system; (8) uncertainties; (9) bibliometric analysis (BA); and (10) research gaps. Based on Table 1, it can be concluded that most of the reviewed literature focuses on the EMSs, operation, protection, architectures, and propulsion systems of SBMGs. However, there is a lack of research on uncertainties and challenges in designing and implementing SBMGs. This paper contributes to the existing literature by addressing these gaps and presenting a comprehensive approach to overcome these challenges.

Table 1. Comparison of aspects of the existing literature reviews in the SBMG field.

Ref.	Year	EMS	Operation	Protection	Architecture	Control	Challenges	Propulsion System	Uncertainties	BA	Research Gap
[26–29]	2016	-	✓		✓	✓	-	-	-	-	-
[4,30–34]	2017	-	✓	✓	✓	✓	✓	✓	-	-	✓
[35–38]	2018	✓	✓	✓	✓	✓	-	-	-	-	✓
[39–43]	2019	✓	✓		✓		✓	-	-	-	✓
[1,12,44–49]	2020	✓	✓	✓	✓	✓	-	✓	✓	-	-
[14,21,50,51]	2021	✓	-	✓	✓	-	✓	-	-	-	✓
[52,53]	2022	✓	-	-	✓	✓	-	-	-	-	✓
[54]	2023	✓	-	-	-	-	-	-	-	-	-
This paper		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

1.3. Contribution

In this paper, a comparison of SBMGs and land-based microgrids is first introduced. A review of the SBMG is presented based on classifying SBMGs in terms of their distribution system types, propulsion systems, and power system architectures, along with their developments. The review includes a detailed discussion of AC, DC, and hybrid AC/DC distribution systems. It also includes a detailed comparison of mechanical propulsion, electric propulsion, and hybrid propulsion systems and of radial, integrated, and zonal architectures. Moreover, a review of the most recent research in terms of the control, management, and protection of SBMGs is presented with a comparison of the contributions and issues of each study, and a co-occurrence analysis of these recent research works is performed to study the most recent trends concerning SBMGs. Finally, a review of uncertainties and issues relating to SBMGs is presented to compare the contributions of and issues considered in the most recent research. The main contributions of this research are as follows:

- A comparison of SBMGs and land-based MGs;
- An exploration of the classification of SBMGs based on distribution types, propulsion system types, and architecture types;
- A comparison of the most recent studies on the control, management, and protection of SBMGs based on the contributions and shortcomings of each study;
- A bibliometric analysis to study the most recent trends concerning SBMGs in terms of control, management, and protection;
- An investigation of the uncertainties that may be encountered with SBMGs;
- A presentation of the most recent new trends related to SBMGs.

The rest of the paper is organized as follows: Section 2 introduces the paper's motivation and a bibliometric study for the most recent research concerning SBMGs. Section 3 compares shipboard and land-based microgrids' IEEE/IEC standards. Section 4 discusses the structure and design of the SBMG and outlines a quest for a future integrated SBMG. Section 5 represents and differentiates between control methods applied for SBMGs. Section 6 discusses the uncertainties related to the SBMG, while Section 7 investigates the management techniques for the SBMG. Section 8 discusses the protection techniques for the SBMG, Section 9 represents examples of real ships worldwide, and Section 10 investigates the research gaps and recommendations concerning the SBMG. Finally, Section 11 concludes the paper.

2. Motivation

A systematic review of the Scopus database was performed to study the research progress concerning SBMGs to effectively employ the tightly coupled power components in SBMGs. SBMGs have to deal with many variable load demands caused by propulsion motors. In addition, a high pulsed power is required in naval ships due to the high-power weapons used. Therefore, it is essential to achieve an efficient and reliable power supply by properly coordinating different power sources with each other. Such coordinated control prevents voltages in SBMGs from falling below acceptable limits, and it distributes power between sources based on their characteristics. SBMGs allow for a 10% voltage tolerance, as defined in IEEE Standard 1709-2010 [55]. Thus, the main goals for SBMGs are not just to maintain the steady bus voltage but rather to ensure system reliability and survivability. Additionally, in modern ships, more than one source ensures power-supply reliability (e.g., diesel generators and batteries). Thus, coordinated control is required to prevent generators from overloading and to extend the ESS to avoid overloading. Ref. [56] aims to optimize and control ESSs to support critical mission loads and improve energy efficiency for multi-mission activities. It also involves developing real-time control algorithms for this purpose. Furthermore, maintaining the ship's degree of freedom is also essential to maintain its position during maneuvering under severe environmental conditions to maintain its destination. Moreover, it is essential to provide reliability and survivability for SBMGs under fault conditions to maintain the crews and keep people safe. So, a protection layer is very important for SBMGs, and ensuring one could be complex due to the existence of pulsed power loads (PPLs) that are characterized by power change rates and a large peak power which make it difficult to distinguish between fault currents and normal faults caused by PPLs. A shipboard power and cooling system model with a PPL (electromagnetic railgun) is presented in [57] which implemented traditional and exergy-based control schemes. Moreover, it is difficult to design a grounding system for an SBMG because it is considered an isolated power system. Furthermore, designing an EMS to achieve an optimization objective considering the system constraints is mandatory to coordinate different power components with different time scales. The objective of the optimization problem can be minimizing operation cost, minimizing fuel consumption, or minimizing the power losses. The challenges of multi-objective EMSs can be found in [58]. Therefore, the control, management, and protection of SBMGs are essential issues that should be reviewed. Figure 1 shows the statistics of the papers published in the last ten years on control, uncertainties, management, and protection in IEEE and Elsevier's magazines and journals.

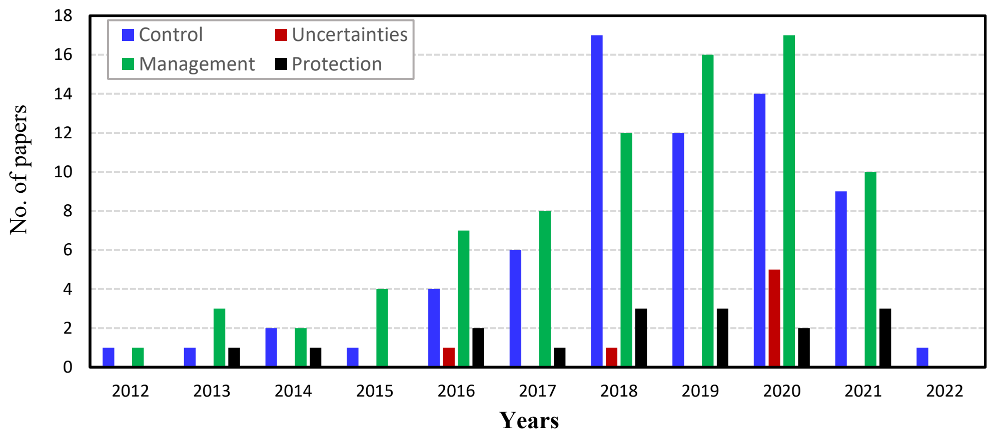


Figure 1. Statistics of the published papers in the SBMG field.

Therefore, one of the main objectives of this research was to classify and analyze the SBMG integration projects that are widely cited to fully understand their developments. To this end, we categorized and analyzed keywords used in a selection process consisting of the ship power system (SPS), control, protection, and energy management. Throughout the process, numerous publications were found but only those that passed the criteria were chosen by analyzing each publication's title, focus, and contributions.

The primary research identified 1815 articles in the Scopus database. The number of articles decreased to 1341 by selecting the year range of 2010 to 2021. Then, by selecting article papers only, the number of articles decreased to 473. These were then reduced to 390 by selecting English-language publications only. Thus, 327 papers were collected by selecting Engineering and Energy subject areas. The collected data were analyzed by determining the number of articles in each year from 2010 to 2021, as shown in Figure 2. Based on the provided data, we can see that the number of articles related to the research topic has been steadily increasing over the years. In 2010, there were only 5 articles published, but this number increased to 76 in 2021. The highest number of articles (57) was published in 2020, followed closely by 2021, with 76 articles. This suggests that research interest in the topic is growing and that more researchers are working on it. Article numbers for different journal publishers are shown in Figure 3. It was concluded that IEEE has the highest frequency of publication, with 177 articles, followed by Elsevier, with 53 articles. MDPI, IET, Springer, and Taylor and Francis Online have relatively lower publication frequencies, with 25, 13, 12, and 9 articles, respectively. The bibliometric analysis suggests a growing interest in the field of study, as well as the importance of choosing reputable journals and publishers for disseminating research findings. The distribution of the top 15 keywords from 2021 to 2010 is shown in Figure 4. The keyword "Energy efficiency" was the most frequently used keyword in 2021 (57 articles), followed by "Ships" (51 articles) and "SPS" (24 articles). In 2020, "Ships" was the most frequently used keyword (47 articles), followed by "ESS" (22 articles) and "Ship propulsion" (13 articles). Similarly, "Ships" was the most frequently used keyword in 2019 (35 articles), followed by "Electric ship equipment" (15 articles) and "Ship propulsion" (11 articles). Overall, "Ships" was the most frequently used keyword from 2021 to 2010, indicating that the maritime industry is a significant area of research. Other popular keywords included "Energy efficiency", "Ship propulsion", and "ESS", suggesting a focus on sustainable energy solutions in the industry. Additionally, there was a noticeable increase in the number of articles related to "SPS" in 2021 compared to previous years, indicating growing interest in this area of research. The ten authors with the most publications concerning SBMGs are shown in Figure 5. It can be concluded that Guerrero, J.M. and Khooban, M.H. are the top two most productive authors, with 21 and 19 publications, respectively. This suggests that they are likely experts in their respective fields and have significantly contributed to the literature. Additionally, the fact that the remaining eight authors have published between 9 and 13 articles indicates that they too are prolific and influential researchers. Overall, this analysis suggests that these ten authors are important figures in the field and that their research has significantly impacted the academic community.

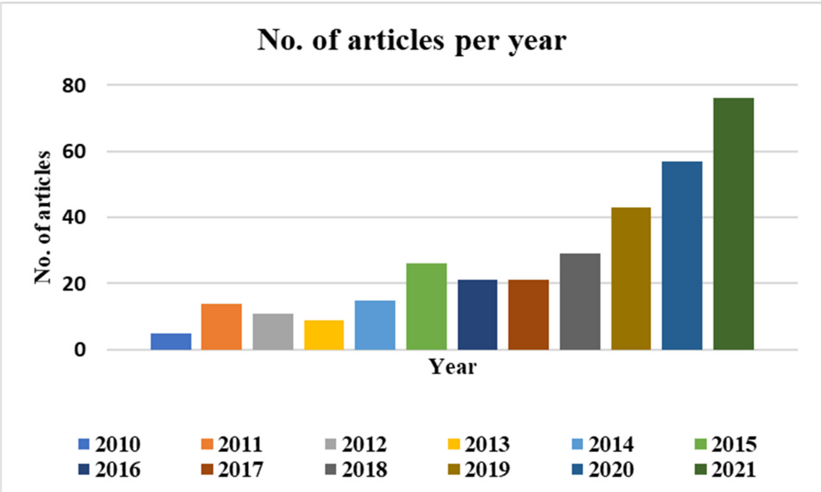


Figure 2. Research trend from 2010 to 2021.

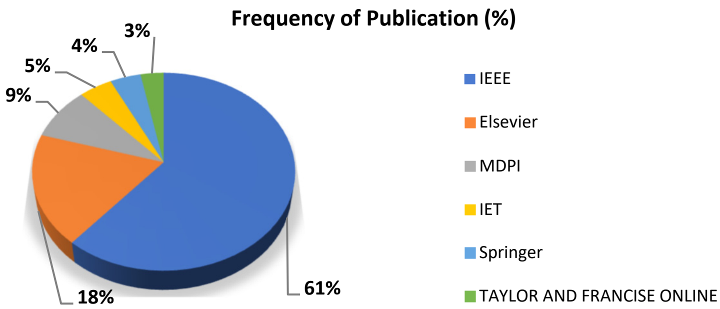


Figure 3. Article numbers based on different journal publishers.

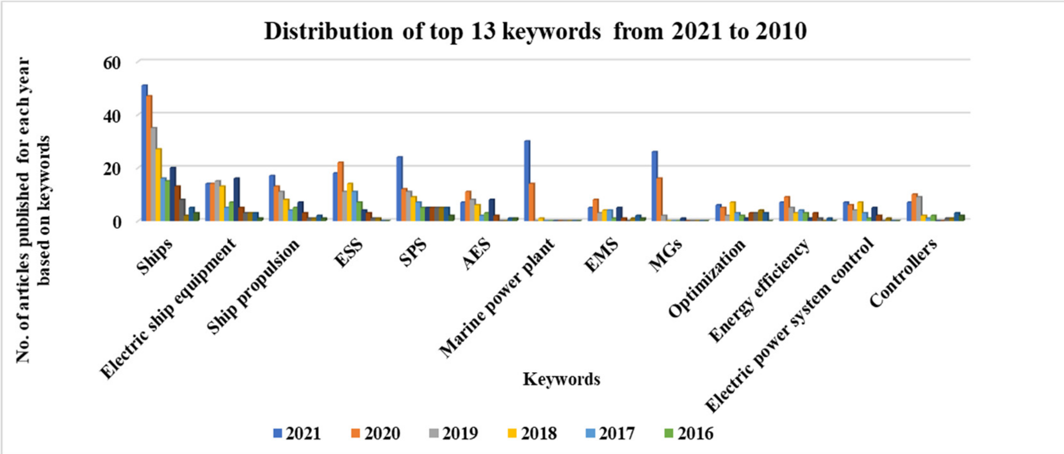


Figure 4. Distribution of top 15 keywords from 2021 to 2010.

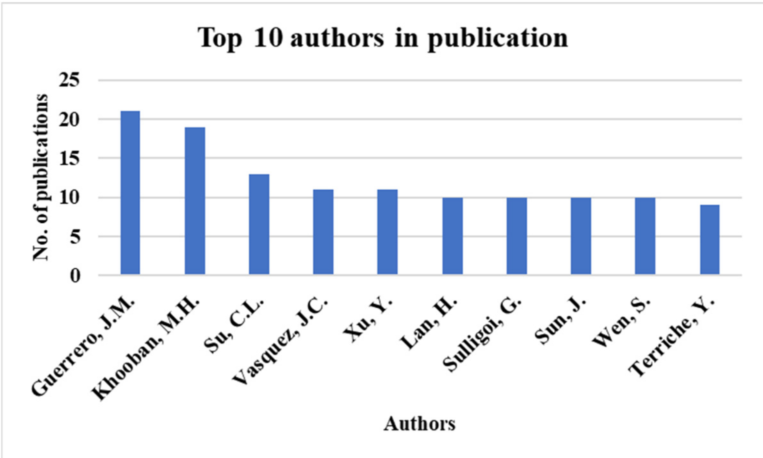


Figure 5. Ten authors with the most publications.

The recent research papers on control, management, and protection from the year 2021 to the year 2016 were compared in terms of their contributions and shortcomings and analyzed using VOS viewer software, as described in the sections below. This analysis was performed only for the authors' keywords, as they have the greatest analytical value because they represent the author's preferences.

3. SBMG Versus Land-Based MG IEC/IEEE Standards

The standards for shipboard microgrids, such as IEC/IEEE 80005-1 and IEEE 2030.8, have several unique requirements and considerations compared to standards for land-based microgrids. Some of these differences include:

- Environmental considerations: Shipboard microgrids are exposed to harsh environmental conditions, such as high humidity, saltwater, and vibrations, which can affect the performance of electrical components. The standards for shipboard microgrids consider these environmental factors and provide guidance for equipment selection and testing to ensure reliable operation [59].
- Safety requirements: Shipboard microgrids must adhere to stringent safety requirements, particularly regarding shock and fire hazards. Standards such as IEC/IEEE 80005-1 provide guidance for the design and testing of shipboard electrical systems to ensure they meet these safety requirements [60].
- Power quality considerations: Due to the sensitive electrical equipment on board ships, power quality is of the utmost importance. Standards for shipboard

microgrids, such as IEEE 2030.8, provide guidelines for maintaining stable power quality in the presence of variable loads and power sources [61].

- Operational considerations: Shipboard microgrids have unique operational considerations compared to land-based microgrids. For example, shipboard microgrids may need to operate in the islanded mode for extended periods, and there may be limited access to maintenance resources during operation. Standards for shipboard microgrids provide guidance for these operational considerations to ensure reliable and safe operation [61].

Overall, while there may be some overlap between standards for shipboard and land-based microgrids, the unique environmental, safety, and operational considerations of shipboard microgrids require specific guidance and requirements. The applicable IEC/IEEE standards for SBMGs versus land-based MGs are shown in Table 2.

Table 2. SBMG versus land-based MG IEC/IEEE standards [62–65].

Standard	SBMG	Land-Based MG
IEC 61850	Not applicable, as shipboard microgrids are not interconnected	Applies to land-based microgrids, used for communication and interoperability between different devices
IEEE 1547	Not applicable, as it applies to the interconnection of distributed resources with the grid	Applies to land-based microgrids and sets requirements for the connection of distributed energy resources to the utility grid
IEC 60780	Applies to shipboard microgrids and sets requirements for insulation monitoring	Not applicable to land-based microgrids
IEEE 930	Applies to shipboard microgrids and sets requirements for the design and operation of shipboard power systems	Not applicable to land-based microgrids
IEC 60092	Applies to shipboard microgrids and sets requirements for electrical installations in ships	Not applicable to land-based microgrids
IEEE 2030.1	Not applicable, as it applies to the smart grid interoperability of energy storage systems	Applies to land-based microgrids and sets guidelines for integrating distributed energy resources, including energy storage, into microgrids

4. Classification of SBMGs

SBMGs can be classified according to their types, propulsion systems, and architectures. SBMG types may be AC, DC, or hybrid AC/DC. SBMGs have a variety of propulsion systems: the mechanical system was the first propulsion system, then it was developed to the electrical propulsion system, and, finally, the hybrid propulsion system was developed. SBMG networks can be gathered into various power system architectures, including radial, integrated, and zonal systems [66,67]. A comparison of SBMGs for each classification will be discussed in the following subsections.

4.1. SBMG Classification According to Distribution System Types

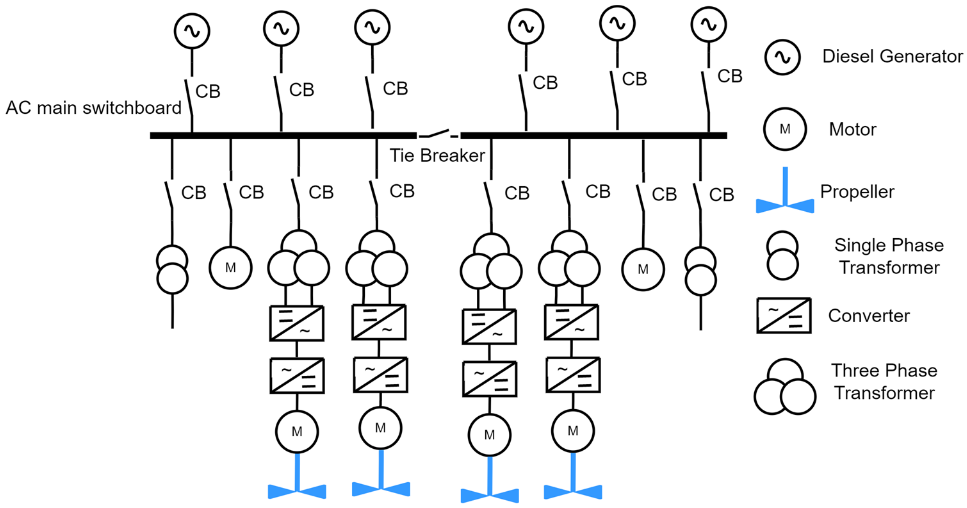
The SBMG can be classified according to its distribution system types as follows.

4.1.1. AC Shipboard Microgrid

The AC-SBMG was used when ships began to be electrified. In this type, the diesel generator is connected to the AC bus through breakers to deliver the power to the propulsion load and 50/60 Hz transformers are used to integrate the service loads, as shown in Figure 6a. The AC-SBMG ensures system continuity and improves fuel efficiency. However, there are many power quality issues, such as harmonic currents, frequency deviation, and unbalanced voltages due to high-power and propulsion load existence, making the frequency and voltage control of generators a vital issue. So, such a distribution system type is not a good solution for SBMGs compared to other types [68].

4.1.2. DC Shipboard Microgrid

The DC-SBMG has become more prevalent in recent years due to the existence of various new energy resources. They are compatible with the prime movers operating at their optimal speed, reducing fuel consumption and increasing fuel efficiency. The DC system might be pivotal for ensuring ships' electrical supply continuity, which is required for various marine operations [69]. In DC-SBMGs, all the sources are connected to AC/DC converters connected to the DC bus, which delivers the power to the load, as shown in Figure 6b. This configuration allows the high-speed generators and high-speed gas turbines to be used, making it possible to regulate generator speed without causing frequency issues [70]. However, SBMGs present the challenge of designing their protection systems. The lack of zero-crossing current makes the DC breaker disconnection more complex for large currents than the AC breakers. Though the DC-SBMG has protection challenges, it has a lot of merits over the AC-SBMG, as shown in Table 3. The table illustrates a comparison of DC and AC shipboard microgrids. Based on the information provided in the table, a potential novel criterion could be "Scalability", which refers to the ability of the shipboard microgrid to expand or contract its capacity and accommodate additional loads or sources. This criterion could be relevant for both AC and DC shipboard microgrids and could impact their suitability for future needs and expansion. AC shipboard microgrids typically use a centralized architecture with a large AC bus that distributes power throughout the ship. This makes them well-suited to handling large loads and accommodating additional loads as needed. However, adding additional generation sources can be more challenging, as the AC power must be synchronized with the existing system. This can require additional control systems and can limit the flexibility of the microgrid. DC shipboard microgrids, on the other hand, typically use a decentralized architecture, with multiple smaller DC buses distributed throughout the ship. This makes them more flexible and easier to expand as additional loads or generation sources are added. In addition, DC power does not require synchronization, which simplifies the control system and reduces the need for additional equipment. Overall, both AC and DC shipboard microgrids can be scalable, but the specific advantages and challenges will depend on the design of the microgrid and the ship's power needs.



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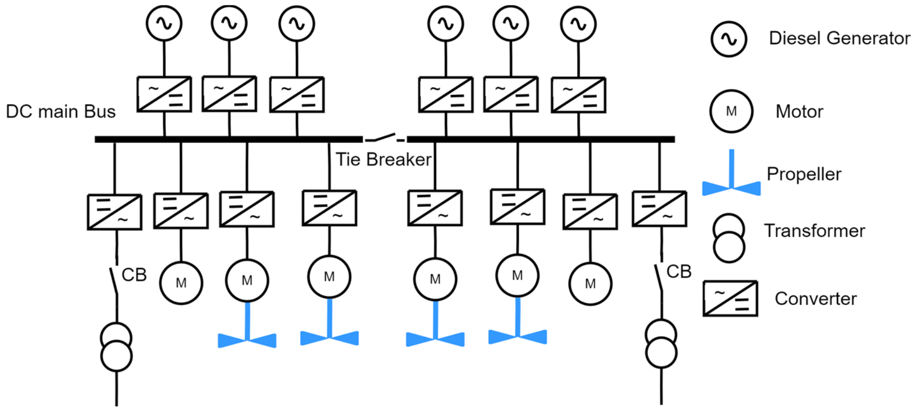


(**b**)

Figure 6. AC and DC shipboard microgrids: (**a**) AC shipboard microgrid; (**b**) DC shipboard microgrid (multi-drive power system scheme) [71].

Table 3. AC **versus** DC shipboard microgrids [72–77].

Factors	AC Shipboard Microgrid	DC Shipboard Microgrid
Conversion Efficiency	Low	High
Cost of Converters	High	Low
Transmission Efficiency	Low	High
Power-Supply Reliability	Difficult to maintain a successful transition after faults	Smooth transition
Controllability	Difficult	Simple
Power Converter	More components for converters in the three-phase system Requires heavier low-frequency transformers	Fewer components for converters in the DC lines Requires smaller and lighter high-frequency transformers
Load Availability	High	Low
Protection System	Cheap, better protection and less complicated circuit breaker systems, all of which are due to the help of natural current zero	Costly components that are not always straightforward to use
Stability	It is affected by the operation mode, types of DERs, and control topology	It is affected by power electronics interfaces for satisfactorily integrating sources, loads, and storage devices
Suitability	AC electrical loads	DC electrical loads
Calculation Procedure	Numbers can be complex	Numbers can be real
Power Quality	Lower	Higher power quality
Synchronization	Requires synchronization	No synchronization issues
Life Span	Shorter lifespan	Maximum lifespan
Frequency	50 Hz	There is no need to regulate the frequency
Operational Cost	More operational costs	Huge savings are available with operational costs
Size of SBMG	High	Small
Scalability	Difficult	Flexible and easier

4.1.3. Hybrid AC/DC Shipboard Microgrid

The advancements in power distribution technology, with its ability to tap power from shore-based sources and RESs, have created more efficient and clean power systems onboard ships and vessels. RESs (such as wind and solar) and traditional energy sources (such as gas and oil) can be combined in a hybrid system to create a more sustainable maritime industry. A multi-energy hybrid power system can provide economical and eco-friendly energy for ships. Such a system provides an alternative energy source with the potential to overcome the limitations of using a single source [4]. In a hybrid system, there are two buses, a DC bus connected to a fuel cell or any other DC energy source and an AC bus connected to distributed generators, as shown in Figure 7, which represents the power system structure of the Viking Lady after the integration of a fuel cell by Wärtsilä [35].

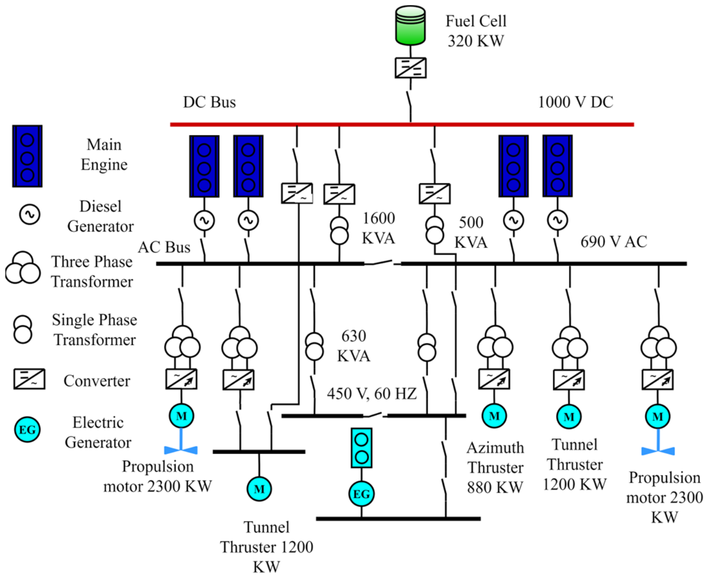


Figure 7. Hybrid shipboard microgrid in the Viking Lady [35].

4.2. SBMG Classification According to Propulsion Systems

As explained before, the propulsion systems used in ships are classified as mechanical, electrical, and hybrid propulsion systems. A description of each type and its main advantages and challenges will be presented in the following.

4.2.1. Mechanical Propulsion System

From oars and sails to mechanical propulsion, ships have significantly developed in the last two centuries. The primary way that ships were propelled was by steam engines, but this method was not always the most popular. Reciprocal engines and turbines were also used for air and water travel up until the early part of the 20th century.

A mechanical propulsion system highly affects the design speed. The most efficient operating range of the diesel engine (DE) is between 80 and 100 percent of the top speed [4]. In this range, the fuel cost is reduced, and the engine emissions are minimized. This technology comes with only three power conversion stages: an engine, a gearbox, and a propeller, leading to lower conversion losses. Despite its benefits, mechanical propulsion faces several challenges, including limited maneuverability due to the engine's operating profile, increased stress on the engine leading to higher maintenance requirements, inefficiency and high emissions at low speeds, and lower dependability compared to electrical propulsion due to the risk of a breakdown in the drive train components. While different control strategies can mitigate some of these challenges, they cannot be entirely eliminated [4].

4.2.2. Electrical Propulsion System

Since the evolution of solid-state power electronics and digital controllers in the 1980s, it has become possible to electrify a ship with an electric propulsion system. Along with variable speed drives, field-oriented control and direct torque control have led to modern shipboard propulsion. In 1988, electric propulsion was introduced on the Queen

Elizabeth II to improve emissions reductions and fuel efficiency and give excellent maneuverability [78]. Since then, the trend has begun to move from mechanical to electric propulsion in many vessels. The electric propulsion system offers several benefits over traditional mechanical propulsion systems, including improved fuel efficiency and reduced noise emissions. Electric motors are simpler than mechanical engines, resulting in a longer lifespan and less maintenance. Additionally, with the proper control system, electric propulsion systems have high availability [4,79,80]. However, there are also challenges associated with electrical propulsion systems, such as lower energy efficiency and higher losses in conversion stages compared to mechanical systems [12,81].

In uncontrolled SBMGs, voltage and frequency swings can often occur under fault conditions, which may cause the switching off of the electrical systems and hence affect the system's reliability and availability.

4.2.3. Hybrid Propulsion System

Electric propulsion systems can reduce fuel consumption, but they are not cost-effective for smaller vessels because of the extra costs required for electrical equipment and power conversion components. Ships powered by a hybrid propulsion system have the benefits of both electrical and mechanical propulsion. This improves the efficiency of electric power at low speeds and saves the fuel in diesel engines at high speed because electrical propulsion is used for low and intermediate speeds, while mechanical propulsion is used for higher speeds. The generator's mechanical drive engine allows the capacity to be generated either by the electric generator or generator sets. Hybrid designs often require trade-offs between electrical power output and physical size, or between durability and fuel efficiency.

The overall system structure of the ship can be divided into three different types: series, parallel, and hybrid series–parallel. In the series SBMG, the power from a combination of sources is transferred to the system load through a bus bar, as shown in Figure 8a. It has a variety of modes, such as a fuel-cell working mode, a generator-set working mode, and a combined power-supply working mode. A parallel power system, shown in Figure 8b, is a mechanical and electrical propulsion mix. Mechanical and electrical propulsion are combined through a coupling device to either operate independently or couple the operation of their components. A coupler can transfer mechanical power from the main engine to an operating motor/generator. On the electric propulsion side, energy is provided by various energy sources, such as wind, hydro, solar, wastewater heaters, and batteries, through a DC bus that delivers power to the load. Hybrid series–parallel SBMGs, shown in Figure 8c, provide an opportunity to get the best of both series and parallel SBMGs. Since the two different kinds of coupling devices exist for mechanical and electrical propulsion, they can be parallelized so that the main engine can drive the generator [1]. Hybrid propulsion systems are always a challenge. They require an optimal power management strategy to transfer electrical energy between mechanical drive motors and battery storage units. While implementing the control strategy, the main challenge is to balance all the system components.

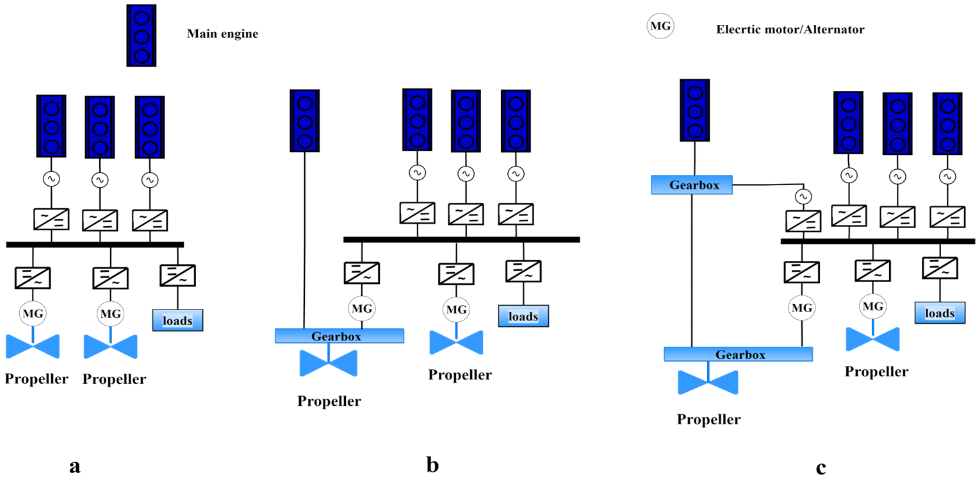


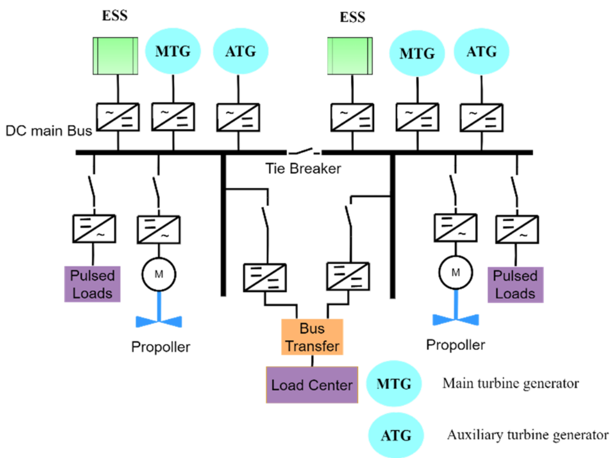
Figure 8. Hybrid propulsion system structure: (**a**) series power system of an SBMG; (**b**) parallel power system of an SBMG; (**c**) hybrid series–parallel power system of an SBMG [1].

4.3. SBMG Classification According to Power System Architectures

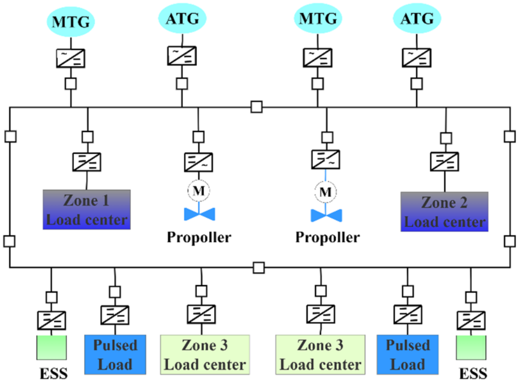
Radial, ring, and zonal systems are the main architectures related to the SBMG, as described in the following subsections.

4.3.1. Radial Architecture

Traditional SBMGs have radial structures that are recommended by IEEE Std. 1709-2010 [77], and they are designed to provide both propulsion and service loads by using separate generators for each load type (segregated architecture) [34]. However, with the evolution of power electronics, it is becoming more common to integrate propulsion and service loads into a single power system [35], as shown in Figure 9a. On the other hand, when the ship is stopped or moving slowly, the propulsion power system generates excess unusable power. Therefore, the overall system efficiency is very low, as the service loads require immense power in modern ships. In general, this structure is uneconomical and has less efficiency.



(**a**)



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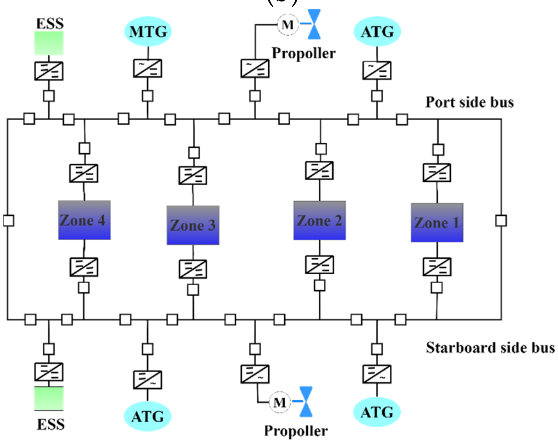

(**c**)

Figure 9. Architecture classifications of the SBMG: (**a**) radial architecture; (**b**) ring architecture; (**c**) zonal architecture [77].

4.3.2. Ring Architecture

The ring distribution system, shown in Figure 9b, is also used in a few cases for SBMGs. It consists of the bus-tie switches that connect multiple DC buses that are closed in normal operation. This configuration has higher reconfigurability and survivability than the radial configuration. When a fault in the distribution bus occurs, the nearest circuit breakers are automatically disconnected, and the rest of the load centers keep working as normal. In this configuration, the loads have only one link to the bus, making it more susceptible to faults in critical loads. The ring architecture is a transition between radial and zonal distribution, and fewer power systems use it.

4.3.3. Zonal Architecture

The extreme physical and electrical separation, the limitations of the generator's output, and its inertia have made the system inherently fragile, causing it to fail when exposed to high loads and strain. A reconfiguration strategy called zonal structure was developed to address the ship's key risks and vulnerabilities and maintain it in readiness to fulfill its mission, as shown in Figure 9c. This reconfiguration is more complex when the zonal distribution structure saves weight and space [82].

5. Control Techniques in SBMGs

The control techniques in the SBMG are mainly classified as dynamic positioning control (DPC) techniques and converter control techniques. Figure 10 illustrates the classification of control techniques applied to the SBMG. The following subsections discuss the control methods for the SBMG and present a comparison of the contributions and shortcomings of the most recent research works.

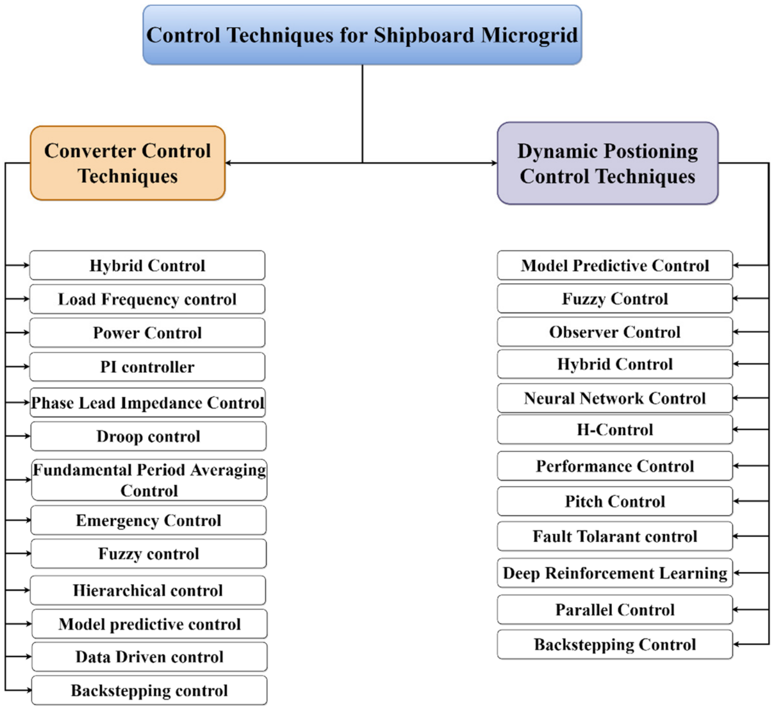

Figure 10. Control techniques of the SBMG.

5.1. Dynamic Positioning Control (DPC)

A DPC system is used in marine engineering to maintain a ship's position and heading. In the presence of storm waterspouts or hurricane hits, the ship's position may be altered from its desired position. A DPC system can adjust the ship's positioning regardless of the influence of waves or current conditions. It automatically compensates for these forces and keeps the ship in a stable position with the help of the propulsion systems. DPCs have fantastic propulsion systems, such as the thruster subsystem. This part of the ship comprises four principal propellers, two in the front and two in the back, and eight bow and stern thrusters, all controlled by the DPC. All of these thrusters move water such that it provides forward movement for the ships [48]. In case of the worst single failure, it is essential to check if there is enough thruster capacity and power to maintain the desired ship position [83]. Additionally, estimating the sea state parameters is necessary to help control methods and the decision-making process [84]. The DPC uses both feed-forward and closed control loops to achieve the best performance possible. The recent research related to DPC methods is shown in Table 4. Based on the table, it can be concluded that there are several shortcomings and limitations associated with the proposed control schemes for autonomous surface vessels. These limitations include the lack of handling of input saturation problems, the use of only position and heading measurements for control, and the failure to consider actuator losses and thruster saturation constraints. Other limitations include not considering stochastic disturbances and environmental disturbances in trajectory tracking. Additionally, some of the proposed control schemes require complex calculations, which may be challenging to implement in practice. Despite these limitations, it is important to note that developing autonomous surface vessel control schemes is a rapidly evolving field, and researchers are continually exploring new methods to address these challenges. Thus, future research may lead to the development of more robust and effective control schemes that can overcome the current limitations and shortcomings associated with autonomous surface vessel control. Figure 11 represents the co-occurrence analysis for these studies. The analysis combines the author's keywords in a single group called "dynamic positioning system" which contains the main keywords, namely, "vectorial backstepping", "dynamical system", "environmental disturbance", "fuzzy control", "ship handling", "control allocation", and "uncertainty analysis". Based on the given set of keywords, it appears that the main focus of the analysis is on the dynamic positioning of marine surface vessels, with a strong emphasis on control systems, optimization, and performance assessment. The keywords also suggest the use of various learning algorithms and techniques, such as reinforcement learning, deep learning, and neural networks, to enhance the performance of the control systems. There is also a significant emphasis on uncertainty analysis, fault detection, and fault tolerance in the design of control systems. The keywords suggest that there is ongoing research in the field of marine surface vessel control systems and that there is a need to improve their energy efficiency and environmental impact.

Table 4. Contributions and shortcomings of the most recent research related to DPC methods [85–103].

Ref.	Algorithm	Contributions	Shortcomings
[85]	Fuzzy Control	- Use an adaptive fuzzy controller by incorporating the backstepping control method to solve the tracking control problem in dynamic positioning of ships - Ensure that all signals are bounded and that any performance metric is met considering uncertain models and a time-changing environment - Predict unmeasurable velocity	- The input saturation problem is not handled
[86]	Fuzzy Control	- Develop a nonlinear adaptive fuzzy output feedback controller for DPC of ships against different uncertainties - Increase the system accuracy while guaranteeing that every closed-loop signal eventually becomes bounded - Reduce the position error - Combine auxiliary dynamic systems and adaptive fuzzy systems	- The proposed control scheme only uses measurements of the ship's position and heading to operate - Ship's unavailable velocities are not measured - Actuator losses are not considered
[87]	Fuzzy Control	- Apply Takagi–Sugeno (T-S) fuzzy DPC for unmanned marine vehicles - Provide good performance for dynamic positioning - Stabilize the unmanned marine vehicle - Reduce the negative effects of wave disturbances by using an observer-based controller	- Network-based filtering for the system is not used
[88]	Deep Reinforcement Learning (DRL)	- Develop a DRL control scheme to solve the problem of low-speed control, such as DPC - Increase accuracy and energy efficiency - Eliminate steady-state deviations - Detect location with high accuracy	- The dynamics of the system and the actuator characteristics are not considered
[89]	H_∞ Optimal Control	- Composite hierarchical control approach based on H_∞ optimal control and disturbance observer for DPC of ships against uncertainties - Stabilize the closed-loop control - Keep the heading and vessel's position at the reference point	- Stochastic disturbances are not considered - Saturation constraints of thrusters are not taken into consideration
[90]	Model Predictive Control (MPC)	- Introduce robust DPC based on MPC and Luenberger observer for autonomous surface vessels when full and partial states are available	- Estimation only occurs with available vessel poses

		- Ensure that the vessel stays within a certain distance of the designated destination point - Predict the system states at whole unavailable conditions - Ensure convergence of the position and heading to their desired values	- The problems of trajectory tracking of autonomous surface vessels (ASVs) with respect to environmental disturbances are not considered
[91]	Performance Control	- Apply DPC for ships exposed to unknown time-varying disturbances based on prescribed performance control - Provide a desired position and direction for the ship - Consider rate constraints and input magnitude	- Actuator losses are not considered
[92]	Neural Network (NN)	- Implement deep-learning techniques for the dynamic positioning system to be employed in economic dispatch and operational planning based on a nonlinear recurrent neural network - Predict the power consumption in the thruster accurately - Improve the operational planning for different sea conditions - Allow power management solutions to predict short-term load and plan operations more accurately	- Saturation constraints of thrusters are not taken into consideration
[93]	Neural Network (NN)	- Provides a DPC for vessels against unknown dynamics based on an optimal NN scheme - Minimize positioning errors - All signals in the closed-loop system are uniformly ultimately bounded - Keep the heading and vessel's position at the desired reference - Reduce emissions - Solve energy conservation problems	- Loss of robustness - Input rate restriction and input saturation are not considered
[94]	Neural Network (NN)	- Control ship's degree of freedom in the three directions by controlling the actuators based on NN and PID - Control the over-actuated ship movement	- Power minimization and the thruster's forbidden zones are not considered
[95]	Observer Control	- Design an observer-based robust controller to accurately model the ship's damping and mooring forces against uncertainties - Reduce susceptibility to high-frequency vessel vibration	- Perturbation in mass matrix related to thruster dynamics is not considered
[96]	Backstepping Control	- Combine command-filtered back-stepping and MLP (minimal learning parameter) techniques for dynamic positioning vessels in case of rate saturations and input amplitude - Reduce tracking errors by considering the rate and amplitude of saturation	- Unknown time-varying disturbances are not estimated
[97]	Backstepping Control	- Propose an adaptive DPC scheme based on the projection algorithm, the vectorial backstepping, and the observer against time-varying disturbances, such as unknown waves and noises	- The rate and amplitude of saturation are not considered - Actuator losses are not considered

		- Make positioning errors asymptotic to zero in the presence of unknown ship model parameters and time-varying disturbances	
[98]	Backstepping Control	- Develop a DPC method for the over-actuated vessels considering uncertainties and thruster faults - Ensure convergence of the position and heading to their desired values in the presence of partial loss of actuator effectiveness - Provide adaptive control by combining the backstepping method and sequential quadratic programming	- Applying the proposed methodology requires complex calculations
[99]	Backstepping Control	- Design DP robust nonlinear control based on command filtered vectorial backstepping, a disturbance observer, and an auxiliary dynamic system to solve the problem of the thruster's dynamics - Minimize the errors in positioning vessels - Consider saturation constraints of thrusters - All signals in the closed-loop system are uniformly ultimately bounded - Address the dynamics of a marine vessel thruster with an unknown time-varying ocean disturbance - Simplifying the computations and improving the performance by compensation for filter errors of intermediate control vectors is included in the DPC law	- Actuator losses are not considered
[100]	Hybrid Control	- Present a hybrid control strategy for the maneuvering and station-keeping of the vessels. The strategy is based on the model-based observer, signal-based observer, and the controller candidate - Improve the vessel's transient response	- Saturation constraints of thrusters are not considered
[101]	Fault-Tolerant Control (FTC)	- Apply the FTC scheme based on fault-state observer and dynamic surface control for dynamic positioning in case of thruster fault - Estimate the states in the presence of system faults - All signals in the closed-loop system are uniformly ultimately bounded - Keep the heading and vessel's position at the reference point	- Saturation constraints of thrusters are not considered
[102]	Pitch Control	- Prevent engines from overloading using measures of performance that quantify engine thermal loading - Achieve more conservative maneuverability, cavitation behavior, and acceleration - Predict the behavior of the propulsion system	- Reduction in fuel consumption, emissions, and cavitation noise is not considered - Poor maneuverability

[103]	Parallel Control	- Control both diesel engines and electric motors that work in parallel by applying a parallel control method - Increase the ship's speed and improve acceleration - Reduce engine thermal load - Highly mitigate fluctuating engine performance	- The load dynamics effect is not investigated

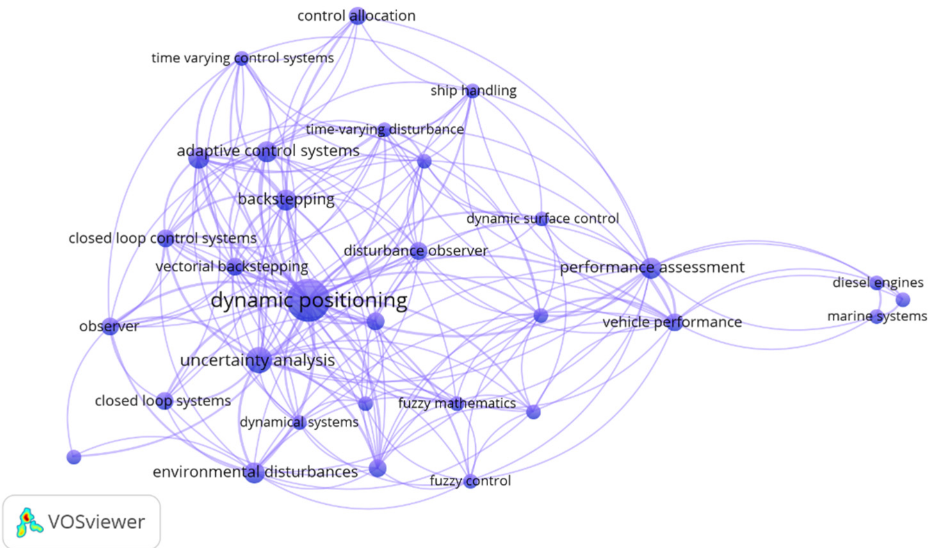

Figure 11. Co-occurrence analysis for dynamic positioning control articles.

5.2. Converter Control Methods

Due to the developments in power electronics, two types of converters are used in SBMGs: DC/DC and AC/DC converters. There are many types of AC/DC converters, such as pulse width modulation (PWM) force-commutated rectifiers, diode rectifiers, DC/DC converters cascaded to diode rectifiers, and thyristor phase-controlled rectifiers [104]. They can interface with different energy sources, provide power flow control, and regulate the SBMG's voltage and current. This ensures the stability, reliability, and efficiency of any DC SBMG. Several challenges are encountered while controlling the bidirectional DC-DC converters in DC-SBMGs. Some of these difficulties are constant power load (CPL), pulsed power load (PPL), and power quality [105]. Static var compensators solve these problems by using fixed capacitors-thyristor-controlled reactors and thyristor-switched capacitors [106]. They can effectively reduce power quality issues but need an appropriate control method for this. Many researchers have solved such problems by providing different control methods, as shown in Table 5. Based on the table, it can be concluded that model predictive control (MPC) and load frequency control (LFC) are the two most commonly used algorithms in power system control. These algorithms offer various advantages, such as improving power reliability and efficiency, mitigating the negative effects of pulsed power loads, and minimizing frequency and power oscillations. Additionally, MPC has been used to dampen steady-state deviations, reduce HESS losses, and provide stability for DC SBMGs. LFC, on the other hand, has shown better transient and steady-state performance than all other control methods.

Table 5. Contributions and issues of the most recent research related to the converter control methods [6,107–138].

Ref.	Algorithm	Contributions	Shortcomings
[107]	Model Predictive Control (MPC)	- Compute the frequency and voltage deviations with higher bandwidth based on MPC with a fuzzy logic (FL) controller - Damp steady-state deviations	- The problem of network degradation is not solved - Load fluctuations are not considered - PPL effects are not investigated
[108]	MPC	- Reduce the hybrid energy storage system (HESS) losses, power tracking errors, and load fluctuations by combining MPC and flywheel state-of-charge (SoC) reference planning - Improve power reliability and efficiency	- Frequency and voltage deviations are not explored - PPL effects are not investigated
[109]	MPC	- Minimize unknown PPL effect by using nonlinear MPC - Consider the source and battery's current constraints - Provide stability for DC SBMG	- Uses a lot of sensors - The powers and states are not predicted - Charging and discharging actions are not taken into consideration - Load fluctuations are not considered
[110]	MPC	- Mitigate the negative effects of pulsed power loads and give converters a break based on MPC - Both transient and steady-state performance are better than all other control methods	- Load fluctuations are not considered
[111]	MPC	- Minimize the extremes of frequency and power oscillations - Attain smoothed frequency	- Load fluctuations are not considered
[112]	MPC	- Stabilize the voltage - Provide optimal power sharing between sources	- Load fluctuations are not considered - Frequency deviations are not investigated
[113]	MPC	- Guarantee synchronization - Mitigate load fluctuations - Reduce the voltage deviation - Reduce HESS losses, RMS currents, and battery peak	- Frequency deviation is not investigated
[114]	MPC	- Predict the propulsion load torque - Improve system efficiency - Enhance system reliability - Mitigate load fluctuations - Use adaptive model predictive control (AMPC)	- Voltage and frequency deviations are not investigated - PPL effect is not investigated
[115]	Load Frequency Control (LFC)	- Accurately mitigate frequency deviations arising by the loads based on a linear matrix inequality technique and the Lyapunov stability theory - Resist system uncertainty - Consider communication delay time	- Uncertainty and unavailability manipulators are not taken into consideration - Load fluctuations are not considered

[116]	LFC	- Investigate the use of fifth-generation (5G) technology in shipboard power systems by employing the concept of the JAYA algorithm in LFC - Model the degradation factor's effects related to the communication infrastructure, such as packet loss and time delay - Improve the system's stability and efficiency	- Voltage and frequency deviations are not investigated - PPL effect is not investigated
[117]	LFC	- Increases system stabilization - Minimize the voltage deviation - Reduce frequency deviations in terms of peak undershoot and overshoot by applying the grasshopper optimization algorithm (GOA)	- The dynamic system model is not explored - PPL effect is not investigated - Load fluctuations are not considered
[6]	LFC	- Tracking the reference frequency with less load variation by applying a fuzzy PD+I controller and modified black-hole optimization algorithm (MBHA) - Enhance the robustness against uncertainties	- Voltage deviation is not investigated
[118]	LFC	- Apply LFC for an independent hybrid shipboard microgrid based on the PI-(1 + PD) controller - Improve the power quality and reduce the frequency deviation - Consider the dynamics of the SBMG - Maximize utilization by adjusting the unit's output power	- Load fluctuations are not considered - PPL effect is not investigated
[119]	LFC	- Apply LFC based on sliding mode controllers - Balance between consumption and power generation - Improve deviation of power and frequency to be within limits	- The dynamic response is taken into consideration - PPL effect is not investigated
[120]	LFC	- Propose an intelligent controller for secondary load frequency control (SLFC) based on fuzzy control - Reduce energy storage costs - Integrate the use of the Sine Cosine algorithm	- Time delay effect on the system performance is not considered - Dynamic system model is not considered
[121]	Hybrid Control	- Enhance the stability of power electronics equipment used in the system - Maintain the voltage at the desired level - Reduce the CPL's effect - Use two FL controllers based on sliding mode control	- Frequency deviations are not investigated - Converter dynamics are not considered
[122]	Hierarchical Control	- Lowering of the capacity of diesel generators and batteries - Improve fuel efficiency - Utilize the hybrid ESS to absorb the braking energy - Smoothing out power fluctuations - Apply V-I droop control and high-/low-pass filters for the primary controller	- Power sharing is dependent on the characteristics of the energy storage system. This is determined by the charge/discharge capabilities, not the rated power or capacity - The SBMG dynamics are not considered - Voltage and frequency deviations are not investigated

[123]	Hierarchical Control	- Increase fuel efficiency - Regulate bus voltage - Optimally share power between sources	- Load fluctuations are not considered - The dynamic system model is not investigated - PPLs effect is not investigated
[124]	PI Control	- Excellently predict the variations in load and energy for various voltage and frequency levels - Reduce fluctuations caused by sea and weather conditions - Increase battery lifetime	- The effect of partial shading is not taken into consideration - The source and battery's current constraints are not taken into consideration
[125]	Droop Control	- Reduce frequency and voltage deviations - Improve system dynamics and power quality during short periods of high-power demand	- The SBMG dynamics are not considered - Load fluctuations are not considered
[126]	Droop Control	- Improve the voltage, frequency, and efficiency based on droop control - Provide seamless transitions between different operation scenarios - Optimize the converter capacity - Increase fuel efficiency	- Load fluctuations are not considered - The SBMG dynamics are not considered - PPL effect is not investigated
[127]	Droop Control	- Provide a decentralized control method to integrate multiple SBMGs to form a seaport microgrid - Enable optimal power sharing between multiple SBMGs	- The economic and technical challenges are not investigated
[128]	Droop Control	- Reduce the deep discharge of battery energy storage - Apply an adjustable droop control based on the variations in voltage - Improve the stability of the voltage and lower the risk of fluctuations - Improve the quality of power - Balance the SoC of the ESS	- The SBMG dynamics are not considered - Load fluctuations are not considered
[129]	Droop Control	- Stabilize the voltage - Regulate the batteries' state of charge	- PPL effect is not investigated - Load fluctuations are not considered - The dynamic system model is not investigated
[130]	Droop Control	- Regulate the bus voltage deviation caused by SoC by applying a control method based on the droop control as a primary and the dynamic SoC balancing control strategy as a secondary control - Equalize SoC - Control the distributed ESS in case of communication failure - Proper sharing for currents among distributed energy storage systems	- Load fluctuations are not considered - PPL effect is not investigated

[131]	Fuzzy Control	- Apply combined fuzzy and MPC to fix the transients among multiple operation scenarios in DC SPSs - Reduce the injecting current - Estimate uncertain CPL for optimal power sharing - Increase battery life	- The voltage drops in the DC bus are not improved - Load fluctuations are not considered
[132]	Fuzzy Control	- Regulate the MVDC bus voltage - Provide load-generation balance and enhance the optimal power sharing between the energy storage devices - Propose an intelligent decentralized controller	- The SBMG dynamics are not considered - PPL effect is not investigated
[133]	Backstepping Control	- Propose an ellipse-optimized composite backstepping control and Kalman filter estimation for point-of-load inverters - Achieve the optimal system damping - Maximized dynamic response - Minimize the total harmonic distortion (THD) - Improve the voltage deviations	- PPL effect is not investigated - Load fluctuations are not considered
[134]	Data-Driven Control	- Improve the voltage and frequency of the system	- Dynamic system model is not examined - PPL effect is not investigated - Load fluctuations are not considered
[135]	Emergency Control	- Apply a method that enhances the system reliability and quality of the control - Apply a genetic algorithm (GA) to obtain optimal control system parameters - Apply a hierarchical emergency control	- Dynamic system model is not investigated
[136]	Power Control	- Reduce the terminal voltage oscillation and eliminate the torque and power angle oscillation - Reduce fuel consumption	- Load fluctuations are not considered - Dynamic system model is not investigated - PPL effect is not investigated
[137]	Phase-Lead Impedance Control	- Mitigate the DC voltage oscillations without affecting the performance of the load - Correct the rectifier's output impedance to exhibit damping characteristics - Improve the system stability	- Load fluctuations are not considered - PPL effect is not investigated
[138]	Fundamental Period Averaging Control (FPA)	- Regulate the voltage and limit the current	- Transient states are not taken into consideration - Load fluctuations are not considered

Figure 12 represents the co-occurrence analysis for these studies. The analysis divides the author's keywords into six clusters with the main keywords for each cluster. We can conclude that the topics of energy storage, control and optimization, transportation, emissions and pollution, and miscellaneous topics are the most common research areas from the given keywords. Furthermore, it is clear that these topics are highly interrelated, and advancements in one area can have a significant impact on others. From Figure 12, it can be concluded that the integration of RESs and ESSs in ship power systems increases the complexity of the control systems, and there are various methods used to control SBMGs, as shown in Table 5.

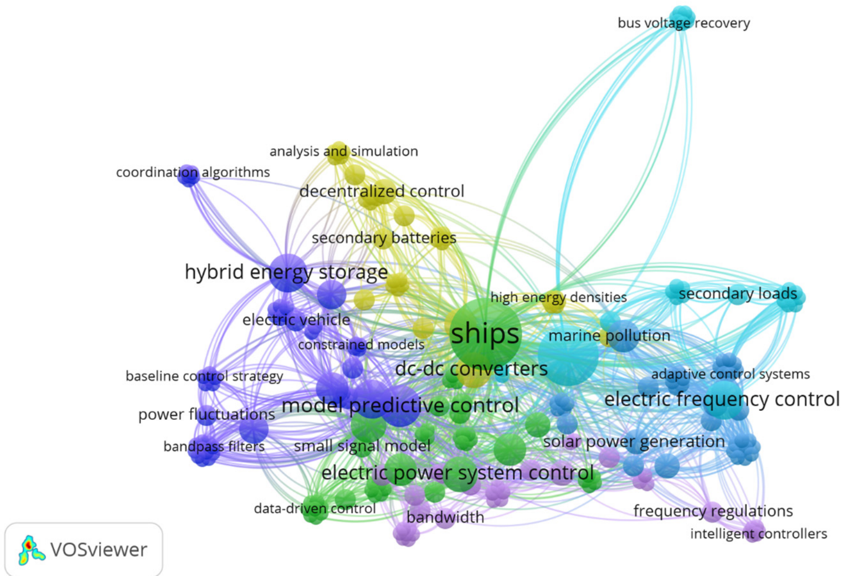

Figure 12. Co-occurrence analysis for converter control articles.

6. Uncertainties in SBMGs

Ships are exposed to different unexpected problems, including severe environmental conditions, change in position according to the movement of the waves, the condition of the sea and the wind, and the existence of time-varying uncertain CPL in SBMG. Due to such uncertainty problems, SBMGs face many stability issues that are discussed below:

Weather-condition uncertainties: Uncertainties during the navigation route due to weather conditions, such as wind (speed and direction) and waves (height and length), lead to uncertain navigation resistance. The ship is exposed to different propulsion loads under various navigation uncertainties [139,140].

PV system uncertainty: The PV output varies with ship movement even if the solar radiation is constant, such that the PV system may undergo partial shading, lessening its efficiency [141].

Wind uncertainty: The wind output varies with the change in weather conditions faced by the ship.

Uncertain time-varying loads: DC SBMGs have active loads, such as actuators and ESSs, that are interconnected. These loads are usually controlled by converters. If the loads have high bandwidth and control performance, they consume power that is independent of the bus voltage. These loads are classified as CPL and behave like incremental negative impedances. Hence, the existence of time-varying uncertain CPL in SBMGs can threaten the stability of SBMGs [142,143].

Dynamic interactions of power converters: The complex interactions between power converters in SBMGs cause dynamic changes in ship performance in terms of voltage, frequency, and power fluctuations.

Table 6 illustrates the most recent research that discusses the uncertainty problems and the techniques used to solve them.

Table 6. Contributions and issues of the most recent research related to the uncertainties associated with SBMGs [139,142,144–152].

Ref.	Considered Uncertainties	Contributions
[144]	PV System Uncertainty	- Determine the best size in the hybrid ship for the ESS due to the PV uncertainty and ship swinging - Reduce fuel costs, capital costs, and emissions based on the interval method
[145]	PV Uncertainties	- Control the short-term noise caused by dynamic shading based on the maximum power point tracking method - Help in minimizing the disturbances due to environmental variations
[146]	PV Uncertainties	- Smooth the PV power (decreasing fluctuations) results with respect to uncertainties based on discrete Fourier transformation and the particle swarm optimization (PSO) technique - Optimally size the energy storage systems
[147]	Dynamic Interactions of Power Converters	- Explore the dynamics of complex interconnected power converters systems and assess their compliance with standards - Predict system behavior based on black-box models
[139]	Navigation Uncertainties	- Reduce the uncertainty in navigation before and during a voyage based on a two-stage robust scheduling method and a multi-battery ESS management method - Managing the batteries' operation to increase their lifetime
[148]	RES Uncertainties	- Minimize the operation cost - Reduce emissions - Optimally coordinate scheduling between RESs in case of uncertainties in both RESs and load demand
[149]	RES Uncertainties	- Minimize the operating cost of a ship for the worst-case uncertainties of RES based on two-stage robust optimization
[150]	RES Uncertainties	- Manage the variation in wind velocity and solar irradiance - Provide optimal power flow based on FL controllers
[142]	Uncertain Time-Varying Loads	- Track the desired DC voltage of the bus bar resulting in the uncertainty behavior of CPLs in the DC power system based on an adaptive backstepping controller - Ensure the system's stability
[151]	Uncertain Time-Varying Loads	- Reduce frequency fluctuation based on a fuzzy control strategy - Regulate the rotating speed of diesel generators
[152]	Uncertain Time-Varying Loads	- Increase the use of load in the DC zonal system while satisfying the power capacity - Regulate the loads

7. Energy Management Systems (EMSs) in SBMGs

The main purpose of the energy management methods applied to the SBMG is to reduce fuel consumption, minimize running costs, ensure safety and sustainability, reduce downtime, improve efficiency, and provide fuel savings. A ship's EMS can save energy, control propulsion machinery and generators, perform load shedding, and provide a secure environment for the crew, which results in increasing the SBMG's reliability [37]. An EMS requires a good forecasting approach that addresses the energy demand and supply needed to optimize performance and costs while reducing the environmental impact [43]. Using RESs in SBMGs has many benefits, such as decreasing the amount of required energy, reducing gas emissions, and lowering the noise compared to conventional power plants. They can positively affect some other factors, such as climate change, due to the lack of heat production by RESs and wastewater due to the lack of water for cooling [153–157].

Smart EMSs communicate between the different sources and customer demands to achieve the best power matching and/or reduce the cost considering multiple constraints. Energy management techniques can be broadly classified into three categories based on the control architecture used: centralized, decentralized, or hierarchical. In centralized control, a single entity manages the entire microgrid, including generation, storage, and consumption. This approach provides a high level of control but can be costly and complex to implement. Decentralized control involves dividing the microgrid into smaller subsystems, each with its own control mechanism. This approach is less complex and more flexible than centralized control but may not provide optimal performance. Hierarchical control combines the advantages of both centralized and decentralized control, where each subsystem has its own control mechanism but there is also a higher-level control that coordinates the actions of the subsystems. This approach provides flexibility and scalability while ensuring optimal performance. The hierarchical control scheme consists of three layers: primary, secondary, and tertiary. The primary layer handles local control and maintains the balance between generation and consumption within individual microgrid components. The secondary layer coordinates microgrid components to optimize the system's performance. The tertiary layer focuses on global control and optimization of the entire microgrid system. Hierarchical control offers a flexible and scalable solution that integrates multiple energy sources and enables decision making at different levels of the microgrid system [158]. These classifications are explained in Figure 13.

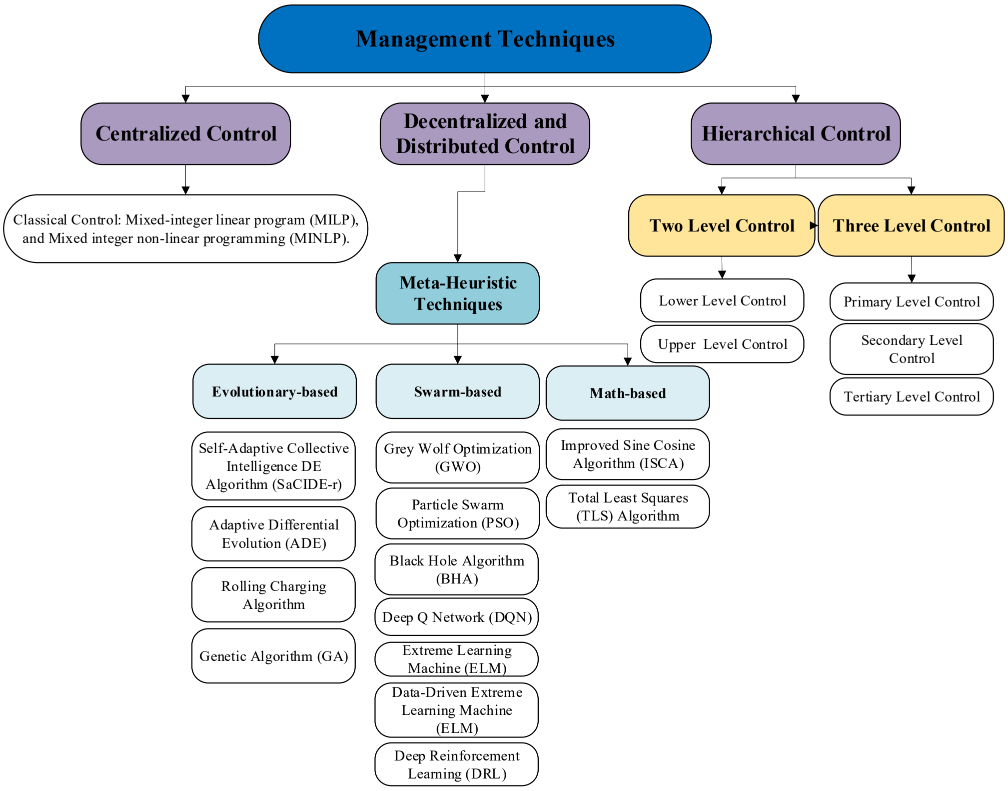

Figure 13. Classification of management methods.

Table 7 gives a comparison of the most recent studies that represent and employ the EMS in the SBMG in terms of the contributions, the objectives and constraints of each paper, and the shortcomings that indicate the objective functions that have not been taken into consideration, besides the shortcomings of the contributions of each piece of research. Table 7 mentions using different energy storage systems, such as batteries, fuel cells, and cold ironing, to reduce emissions and increase efficiency. Additionally, the text highlights the importance of analyzing load profiles and implementing real-time energy management systems to ensure the safe and efficient operation of ships. The listed articles have various shortcomings, such as not investigating the impacts of integrating renewable energy sources with conventional sources, not considering power losses and battery lifetime, not including optimal sizing of energy storage systems, and not investigating uncertainties in wind and wave energy. Other common issues include not considering energy efficiency indicators, regulatory constraints, and system costs and not investigating the behavior of microgrids and fuel cells.

Table 7. Contributions and shortcomings of the most recent studies related to the energy management methods [159–206].

Ref.	Contributions	Objectives and Constraints	Shortcomings
[159]	- Apply information-gap decision theory (IGDT) to reduce the total cost to optimally schedule the diesel generators, electrical boilers, electric heat pumps, and energy storage systems - Economically fulfill electricity and thermal demands, taking into account uncertain hybrid cruise ship load	Objectives: - Minimize the total hybrid cruise ship cost in terms of fuel, emissions, and maintenance costs by considering economic and technical constraints Constraints: - Diesel generator constraints - Electrical heat pump and electrical boiler system constraints - ESS constraints	- Impacts of integrating RESs with conventional sources are not investigated - Fuel consumption and power losses are not included in the objective functions
[160]	- Apply the Improved Sine Cosine Algorithm (ISCA) to obtain efficient power management and optimal sizing of components in a zero-emission vessel supplied by a hybrid system consisting of fuel cells, batteries, and cold ironing	Objectives: - Minimize the total system cost, including both the investment and the operating costs Constraints: - Power-supply constraints - Battery operation constraints - Fuel-cell operation constraints	- Security challenges, such as cyber-attack detection, are not investigated - Power losses and battery lifetime are not considered
[161]	- Proposing and analyzing a zero-emission electric hybrid energy system composed of a fuel cell, battery, and cold ironing - Apply the ISCA to solve the problem of scheduling the power of an electric ferry ship to optimally manage the energy of the proposed hybrid energy system in a cost-effective way	Objectives: - Minimize the system's hourly operation cost for a period of 24 h - Determine the best amount of hourly generated/stored power of each energy source to feed the loads Constraints: - Power-supply constraints - Battery constraints - Fuel-cell constraints - Dynamics of loads and fuel-cell constraints - H_2 tank constraints	- No RES is included - Wind and wave uncertainties are not considered

[162]	- Apply a Self-Adaptive Collective Intelligence Differential Evolution Algorithm (SaCIDE-r) to reduce fuel and battery costs and minimize the cost of degrading batteries to manage the energy storage sources	Objectives: - Minimize both fuel-consumption and emission costs - Minimize the total life losses of batteries, considering their degradation costs Constraints: - Diesel generator constraints - Battery constraints - Load demand constraints	- The system uncertainties and power losses are not investigated - The optimal sizing of the ESS is not included in the objective functions
[163]	- Apply a constraint decomposition algorithm to provide a robust joint scheduling method with high-quality solutions to reduce fuel consumption and energy efficiency operation indicators considering uncertain scenarios	Objectives: - Minimize fuel consumption for generation and start-up - Improve energy efficiency operation indicators - Reduce gas emissions during ship voyages Constraints: - Diesel generator constraints - ESS constraints - Cruising speed constraints - Energy efficiency operation indicator constraints	- Power losses are not included in the objective functions
[164]	- Apply augmented $\epsilon-$constraint lexicographic optimization to balance the operational point - Apply a generation and voyage scheduling method to address the HESS operational characteristics, considering uncertainties in forecasting the electric propulsion load	Objectives: - Minimize GHG emissions - Minimize fuel consumption and cold-ironing costs and decrease the degradation of lithium-ion batteries for generation scheduling - Adjust the power of propulsion load for optimal load profile by forecasting the sea state for voyage schedule Constraints: - Diesel generator constraints - Cruising speed constraints - Distance coverage constraint - ESS constraints - Cold-ironing constraints	- Optimal sizing of ESS composition is not investigated
[165]	- Hybridizes two types of ESS by applying a two-step multi-objective optimization method - A normal boundary intersection method combined with the column-and-constraint generation algorithm is applied to solve the proposed multi-objective optimization model to increase both power density storage and extend the battery lifetime	Objectives: - Minimize fuel consumption for generation and start-up - Minimize gas emissions during ship voyages - Minimize battery lifetime degradation Constraints: - Diesel generator constraints - ESS constraints - Cruising speed constraints	- Power losses and operational costs are not considered

[166]	- Study the power system of the SBMG by applying an ESS and a tailored EMS to optimally control the integrated battery storage device with the onboard power system - Apply a power flow approach to the EMS of the SBMG to integrate hybrid AC and DC sources - Reduce pollution near offshore platforms and ports - Increase the efficiency of the generator during voyages by managing the batteries' charging	Objectives: - Minimize the fuel consumption of generators Constraints: - Grid operating constraints - Synchronous generator operating constraints - Battery energy storage system (BESS) operating constraints - AC/DC converter constraints	- Power loss impacts are not considered - Optimal sizing of the ESS is not investigated
[167]	- Propose an operation task-aware EMS for managing the power of a ship consisting of an ESS, main engines, and a diesel–electric engine to optimally dispatch the storage and generation units - Apply a real general EMS for the SBMG under different operation scenarios, such as DP, transit, and emergency scenarios	Objectives: - Minimize fuel consumption - Keep the ship positions while satisfying the operational requirements Constraints: - Operating power-supply constraints - Load demand constraint - ESS discharging constraints	- ESS degradation and the probability of service interruption are not investigated
[168]	- Perform a two-stage joint scheduling model to optimally coordinate the voyage scheduling and power generation of an all-electric ship (AES) to address the variation in the electricity price of the side during the navigation route - Apply a mixed-integer linear program (MILP) with multi-objective differential evolution (MODE) to coordinate the generation and voyage scheduling for AES and improve the reliability and energy efficiency of the SBMG	Objectives: - Minimize GHG emissions and cost Constraints: - Service load constraints - SoC constraint - Reserve constraints - AES speed constraint - Voyage constraint - ESS output constraint	- Regulatory constraints, such as transmission limits, are not taken into consideration
[169]	- Apply MILP to optimally size and manage an ESS integrated with the SBMG based on the load profile of the SBMG to minimize the management cost, GHG emissions, and fuel oil consumption	Objectives: - Minimize the total cost in terms of the management and installation costs of the ESS and power converters Constraints: - Power balance constraint - Reserve constraints - Inequality constraints	- The impact of system losses is not examined

[170]	- Analyze the load profile of a seismic survey vessel, a ferry, and a platform supply vessel during their operations - Apply MILP to find optimal scheduling by implementing an optimal unit commitment for the generation - Compare three different configurations, including a fixed-speed DE generator, variable-speed gensets, and ESS implementation - Increase operational efficiency to save on fuel and reduce the amount of time the generator runs	Objectives: - Minimize the running time for each generator - Minimize fuel consumption, maintenance costs, GHG emissions, and fuel consumption Constraints: - Generator constraints, such as the number of running hours and the number of start/stops	- Optimum sizing of the ESS and battery lifetime are not included in the objective functions
[171]	- Apply hierarchical ESS management to determine the distributed location and the capacity of an ESS in the SBMG multi-battery ESS and extend the battery lifetime	Objectives: - Minimize the operating cost - Minimize GHG emissions Constraints: - Power-supply constraint - ESS charging/discharging constraints - Diesel generator constraints - Cruising speed constraints	- Power losses are not included in the objective functions - Wind and wave uncertainties are not investigated
[172]	- Apply a DRL scheme to optimally schedule the power of a ferry boat that uses a fuel-cell and battery ESS to solve the EMS-problem - Improve loss of load expectation and reliability index	Objectives: - Minimize energy resource costs in terms of investment cost and operation cost Constraints: - Batteries discharging and charging constraints - Fuel-cell constraints - Fuel-cell and load dynamics constraints - H_2 tank constraints	- Energy efficiency indicators are not investigated - Wind and wave uncertainties are not included - Optimal sizing of the ESS is not discussed
[173]	- Apply an Adaptive Differential Evolution (ADE)-based SoC estimation technique to minimize the hysteresis effect and accurately estimate the SoC of lead-acid batteries with ship thruster load - Form a dynamic charge and discharge model to ensure a safe operation for batteries and extend battery life	Objectives: - Minimize the SoC of batteries Constraints: - Providing a penalty function to the objective function (inequality constraints)	- Cost minimization is not included in the objective functions - Optimal sizing of batteries is not investigated

[174]	- Apply EMS to manage the electrical power system of a yacht under fault and overload conditions to reduce fuel consumption. The power system consists of two diesel engines to drive permanent magnet synchronous generators - Decrease the power variations and instantaneous speed of the diesel engine by exploiting li-ion batteries back in regular conditions - Analyze the power system configuration of SBMG	Objectives: - Minimize the diesel engine (DE) speed and power fluctuation - Minimize fuel consumption - Minimize GHG emissions Constraints: - Power balance constraint - Power and voltage limits	- Uncertainties of both wave and wind are not investigated
[175]	- Apply a data-driven extreme learning machine (ELM) to coordinate the generation and demand side to address PV uncertainties in AES considering the swinging and moving of ships and the temperature variation - Reduce prediction error PV certainties forecasting	Objectives: - Minimize fuel cost in terms of start-up fees and fuel consumption Constraints: - Generation constraints - Voyage constraints	- Energy efficiency indicators are not investigated
[176]	- Apply a decentralized EMS using the alternating direction method of multipliers (ADMM) algorithm to provide a cost-effective, privacy-preserved, and resilient operation for the SBMG	Objectives: - Minimize the cost - Maximize the stored energy in the ESS Constraints: - Power limits of each generator - Power balance constraint - Virtual ESS charging and discharging constraint - Upper and lower constraints of the virtual ESS	- Battery's lifetime and power losses are not included in the objective functions - Sizing of the cloud ESS is not investigated
[177]	- Apply a low-complexity near-optimal algorithm based on benders decomposition (LNBD) to optimally manage the power for failure mode considering the mid-time scheduling and the faults at bus and generators to improve the system performance for supplying the demand power	Objectives: - Minimize the total operating cost in terms of ESS and generation costs Constraints: - ESS constraints - Diesel generator constraints - Load constraints	- RES is not considered - Wind and wave uncertainties are not investigated

[178]	- Investigate the distributed generation (DG) technology applications on a naval energy system to determine the optimal energy management strategy - Examine different operational strategies for energy management throughout an annual load profile	Objectives: - Minimize the annual variable cost Constraints: - Electrical and thermal demand constraints	- The impact of system losses is not examined - No ESS is included within the proposed system
[179]	- Examine the impacts of using hybrid power systems with battery energy storage for short-haul ferries - Apply Grey Wolf Optimization (GWO) and a rule-based control method to optimally exploit and manage the power generation of the hybrid power system to reduce fuel consumption	Objectives: - Minimize fuel consumption - Minimize GHG emissions and noise Constraints: - Power balance constraints - Diesel generator power constraints - BESS constraints - GHG emissions constraints - Blackout prevention constraints	- Wind and wave uncertainties are not investigated
[180]	- Apply a GA to adjust the air and fuel flow to manage fuel cells to improve their performance without the employment of a DC/DC converter	Objectives: - Reduce fuel consumption - Maintain the fuel-cell voltage within a safe operating limit Constraints: - Fuel flow constraints	- Uncertainties are not considered - Cost reduction and power losses reduction are not included in the objective functions
[181]	- Apply fuzzy-based particle swarm optimization (FPSO) for an AES with full-electric propulsion, energy storage, and a shore power-supply facility to coordinate the generation and demand load management to minimize the costs and emissions	Objectives: - Minimize the operating costs - Minimize GHG emissions Constraints: - Power balance constraints - Generator constraints - ESS operation constraints - Blackout-prevention constraints - GHG emissions constraints - Ship speed constraints	- The optimal sizing of the ESS and extending the batteries' lifetime are not investigated - Wave and wind uncertainties are not considered
[182]	- Apply a rolling charging algorithm to manage multiple energy storage devices, including lead-acid and lithium-ion batteries and supercapacitors for various pulsed loads	Objectives: - Minimize the total operating costs Constraints: - ESS charging constraints - Transmission power flow	- The optimal sizing of the ESS and power losses are not investigated
[183]	- Apply a primal-dual method of multipliers (PDMM) to optimally schedule the power of an MVDC-SBMG consisting of two types of turbo generators that are single- and twin-shaft turbogenerators and an ESS to improve the speed and accuracy of the turbo generators	Objectives: - Minimize the total cost in terms of generation cost and ESS cost Constraints: - Generator constraints - ESS constraints	- Energy efficiency indicators are not investigated - The optimal sizing of the ESS and battery lifetime are not investigated

[184]	- Apply the augmented ε-constraint method (AUGMECON) to achieve a coordinated voyage scheduling and energy dispatch for a multi-energy SBMG consisting of a diesel generator, ESS, PV, and combined cooling heat and power to optimally operate multiple sources in the SBMG to optimize the costs and emissions	Objectives: - Minimize operating costs - Minimize GHG emissions Constraints: - Ship speed constraints - Cruising distance constraints - Propulsion motor power constraints - Generator constraints - Power balance constraints	- Wave and wind uncertainties are not investigated - Optimal sizing of both the ESS and PV is not considered - Energy efficiency indicators are not investigated
[185]	- Apply a power flow approach based on a resistive and capacitive droop controller to achieve an optimal operating range under different operating conditions - Manage the energy between multiple storage units for the SBMG with an HESS consisting of a BESS system and conventional generation units	Objectives: - Minimize the cost in terms of storage-device costs and generation-unit costs - Minimize power fluctuation Constraints: - Generator constraints - Voltage characteristics of supercapacitors - BESS constraints - Bus voltage limits	- Small-signal analyses for the system with capacitive droop control are not investigated - Power loss reduction is not included in the objective functions - Optimal sizing of the ESS is not considered
[186]	- Apply a multi-agent power management scheme based on droop control to regulate the voltage and economically share the power of diesel generators to achieve optimal fuel efficiency for a DC SBMG - Increase the resilience and flexibility of the DC SBMG	Objectives: - Minimize fuel consumption - Optimally share the power of distributed generators Constraints: - Diesel generator constraints - Power balance constraints	- RES is not investigated - Power losses are not included in the objective functions
[187]	- Apply optimal power generation scheduling based on dynamic programming methods to manage the propulsion load by regulating the cruise speed of the ship - Analyze several ship power-generating and propulsion configurations	Objectives: - Minimize the operational costs in terms of maintenance cost, fuel cost, and start-up cost - Minimize GHG emissions Constraints: - Load constraints - Generator constraints - Power balance constraints	- ESSs and RESs are not considered - The ship's uncertainty effects on propulsion loads are not considered
[188]	- Apply a nondominated sorting genetic algorithm (NSGA-II) to solve a bi-objective optimization problem considering GHG emissions and fuel consumption to detect the size of the major components in a hybrid-electric propulsion system including a gearbox, battery, diesel engines, and motors	Objectives: - Minimize fuel consumption and GHG emissions Constraints: - Power balance constraint - Generator set constraints - Battery constraints - Ship speed constraint	- Energy efficiency indicators are not investigated - Power losses are not included in the objective functions - Battery sizing and lifetime are not investigated

[189]	- Apply an EMS for an HESS consisting of batteries and supercapacitors to reduce battery charging and discharging peak current - Optimally size supercapacitors and batteries	Objectives: - Maximize battery lifetime related to charging and discharging peak current considering uncertainties Constraints: - Supercapacitor voltage constraints - Supercapacitor current constraints	- The system costs are not included in the objective functions - Energy efficiency indicators are not investigated - Batteries sizing is not investigated
[190]	- Apply nonlinear robust tube-based model predictive control (NRTP-MPC) to compute the energy of the propulsion load and control the ship's speed - Apply conventional MPC to track the demanded energy and optimally share the power between multiple sources	Objectives: - Minimize tracking error of demanded energy and surge speed - Minimize fuel consumption and energy losses Constraints: - Ultra-capacitor voltage constraints - Ship speed limitations	- Energy management during a failure is not investigated - The ship's uncertainties are not considered
[191]	- Apply mixed-integer nonlinear programming (MINLP) to model a two-stage planning problem that calculates the optimal size of a shipboard carbon capture system (CCS) - First determining the capacity of the CCS and then applying demand-side and generation management to solve the shortage of power caused by the CCS	Objectives: - Minimize the operating costs in terms of start-up fees and fuel consumption, besides minimizing the investment cost of the fuel cell, ESS and CSS Constraints: - Capacity and space of ESS and CCS constraints - ESS constraints - GHG emissions constraints - Power balance constraints - DG constraints - Battery constraints - Output power limits - Spinning reserve constraints	- Energy efficiency indicators are not investigated
[192]	- Apply adaptive multi-context cooperatively coevolving particle swarm optimization (AM-CCPSO) to provide a solution for the shipping company's operational cost control considering the emission regulation and upcoming tighter emissions regulations - Investigate the optimal operation and cooperation of a hybrid energy system and on-land shore power to achieve cost savings	Objectives: - Minimize the total cost in terms of fuel consumption, shore power service, and battery degradation costs Constraints: - Port regulation constraints - Power boundary constraint - Battery discharging and charging constraints - Diesel output constraints - SoC boundary constraints - PV output constraints - SoC terminate state constraints	- The ship's uncertainties are not investigated - Optimal sizing of PV and batteries is not investigated - Power losses are not included in the objective functions

[193]	- Optimally supply the shipboard electrical demand by scheduling the generation of hybrid power systems consisting of PV, ESS, cold ironing, and diesel generators - Calculate PV output along the navigation route based on the solar radiation density - Evaluate the cold-ironing effect on the output power	Objectives: - Minimize the total cost in terms of fuel-consumption cost, maintenance cost, and cold-ironing service cost - Minimize GHG emissions Constraints: - Power balance constraint - GHG emissions constraints	- Power losses are not included in the objective functions - Sizing of the PV and ESS is not investigated - Impact of wave and wind uncertainties is not included
[194]	- Apply the PSO method to achieve optimal power flow dispatching for a hybrid SBMG consisting of PV, a diesel generator, a battery, and cold ironing, considering different objectives and constraints to minimize electricity cost and explore solar energy	Objectives: - Minimize the operating cost - Minimize GHG emissions Constraints: - Power balance constraint - Generator constraints - Blackout-prevention constraint - GHG emissions constraints - Ship speed constraint	- Energy efficiency parameters are not investigated - Sizing of PV is not investigated
[195]	- Apply an Adaptive Multi-Context Cooperatively Coevolving PSO (AM-CCPSO) algorithm to achieve optimum EMS and optimal power flow dispatch of maritime HESS	Objectives: - Minimize the total cost in terms of fuel-consumption cost, the cost of battery charging and discharging, and cold-ironing service cost Constraints: - Port's regulation constraint - Diesel generator output constraints - SoC constraints - Power-flow boundary constraint - SoC boundary constraints - PV output constraint	- Wind and fuel cells are not investigated - Power losses are not included in the objective functions
[196]	- Apply stochastic MPC to optimally operate an SBMG consisting of an ESS/cold-ironing/fuel-cell hybrid ship considering the uncertainties of weather and waves - Examine the impact of aging factors of the fuel cells and the ESS on their optimal scheduling	Objectives: - Minimize the total operating cost under different uncertainty scenarios Constraints: - Traveling timetable constraints - Fuel-cell constraints - ESS constraints - Cold-ironing constraints - H2 tank constraints - Demand–supply constraints	- The degradation of equipment is not investigated - The fuel-cell dynamics are not investigated - Energy efficiency indicators are not investigated

[197]	- Propose a hierarchical framework of an energy management model for multi-microgrids - Apply MPC to efficiently control the proposed model to minimize the system operating costs and reduce the average unplanned daily power exchange	Objectives: - Minimize the total cost in terms of operating cost and penalty cost Constraints: - SoC boundaries - System frequency constraints - Voltage and current constraints of each bus	- The behavior of MGs under uncertainties is not investigated
[198]	- Apply an optimal control strategy to optimize an SBMG consisting of a battery/PV/cold-ironing/diesel HESS considering emission constraints and cold-ironing prices - Apply MPC to dispatch the power flow in the proposed system - Provide accurate estimation of PV output	Objectives: - Minimize the total cost of ships at ports Constraints: - Power balance constraints - PV output constraints - GHG emission constraints - Battery capacity constraints	- Wind and fuel cells are not investigated - Sizing of PV and batteries is not investigated
[199]	- Apply MPC within an energy management system to control the output power of a ship power system consisting of an ESS and generators in order to satisfy the load demand and optimally achieve the set points for the ESS that satisfy the load in case of generator failure	Objectives: - Maintain the desired SoC of the ESS while satisfying the load demand Constraints: - Generator output constraints - Generator ramp rate constraints	- Power losses are not included in the objective functions - ESS sizing is not investigated
[200]	- Present a new configuration made of batteries combined with flywheels to reduce the propulsion load fluctuations and save energy - Apply MPC to facilitate the proposed configuration in real-time implementation	Objectives: - Minimize HESS losses - Minimize the cost in terms of power losses and battery usage Constraints: - SoC boundaries of batteries and flywheels - Battery current constraints - Flywheel torque constraints	- Energy efficiency indicators are not investigated
[201]	- Apply MPC to energy management model consisting of a hybrid fuel cell and battery to increase the efficiency and forecast the load demand - Propose a linear model for fuel cell operation and a nonlinear operating model for batteries - Study six operating scenarios for batteries and fuel-cell settings	Objectives: - Minimize the operating costs, including cold-ironing cost, battery discharging cost, and liquid consumption cost Constraints: - Fuel-cell constraints - Battery constraints - Cold-ironing constraints - Demand–supply constraints - H2 tank constraint	- Optimal charging and discharging times of batteries are not investigated - The demand fluctuations are not investigated

[202]	- Apply a hybrid MPC for an EMS to optimally coordinate between the generator and ESS to meet propulsion loads under high-power ramp rate conditions	Objectives: - Minimize the operating cost - Maintain the SOC of the ESS at the desired level Constraints: - Ramp rate constraints - Power balance constraints	- ESS ramp rate constraints are not considered - Energy efficiency indicators are not investigated - Power losses are not included in the objective functions
[203]	- Apply an EMS to a proposed HESS system consisting of ultracapacitors and batteries in order to coordinate the ultracapacitors' and batteries' operations and decrease the load fluctuations - Apply MPC to control ultracapacitors to make them operate at their efficient point to track the power - Apply PI motor speed control to reduce load fluctuations	Objectives: - Minimize HESS loss - Minimize the tracking error of power - Minimize the operational cost in terms of power losses Constraints: - SoC boundaries of batteries and ultracapacitors - Batteries' and ultracapacitors' current constraints	- Uncertainties are not considered
[204]	- Improve the system performance and fuel efficiency by applying the Input–Output Feedback Linearization (IOFL) method to bridge the gap between energy management, maneuvering control, and power and propulsion system control - Predict the energy required for the ship's operation - Apply EMS to optimally divide the predicted power between energy resources	Objectives: - Maximize fuel-consumption efficiency - Minimize fuel-consumption cost Constraints: - Battery constraints - Power balance constraints - Charging and discharging constraints	- Uncertainties and power stability problems are not investigated - Power losses are not included in the objective functions
[205]	- Apply model predictive energy management based on a modified black-hole algorithm (BHA) for a hybrid-electric ferry with multiple batteries and generators to satisfy the varying load power	Objectives: - Minimize the fuel-consumption cost and operational cost of the shipboard generators - Optimize the fuel cell's operation Constraints: - Generator output constraint - Generator ramp rate constraints - Battery output constraints	- RES is not considered - Power losses are not included in the objective functions - Optimal sizing of the energy storage system is not investigated
[206]	- Apply adaptive MPC for EMS to estimate the uncertainty of battery/flywheel HESS and battery/ultracapacitor HESS parameters - Optimize the system performance by mitigating the load fluctuations and improving the system reliability and efficiency	Objectives: - Minimize HESS losses - Minimize the tracking error of power Constraints: - HESS constraints - SoC boundaries	- RES is not considered

Figure 14 represents the co-occurrence analysis for these studies. The analysis divides the author's keywords into ten clusters, with the main keywords in each cluster. From Figure 14, it can be concluded that the existence of multiple power sources in SBMGs increases the need for optimization problems with constraints to achieve the objective functions, the main one being minimizing the cost. One of the most prominent themes is related to energy management and efficiency, which includes sub-topics such as demand-side management, renewable energy resources, energy storage systems, and energy efficiency. Another important topic is emission control, which includes sub-topics such as greenhouse gases, emissions regulation, and carbon capture. Electric ship equipment and all-electric ships are other significant topics that emerged from the analysis. These topics include sub-topics such as electric propulsion, energy storage systems, hybrid energy storage systems, and energy management systems. Additionally, there are some other sub-topics, such as fuel consumption, energy generation, and power generation, which are also relevant to the analysis. In conclusion, the co-occurrence analysis shows that there are several interrelated topics that are important for the research and development of efficient and environmentally friendly ship propulsion systems.

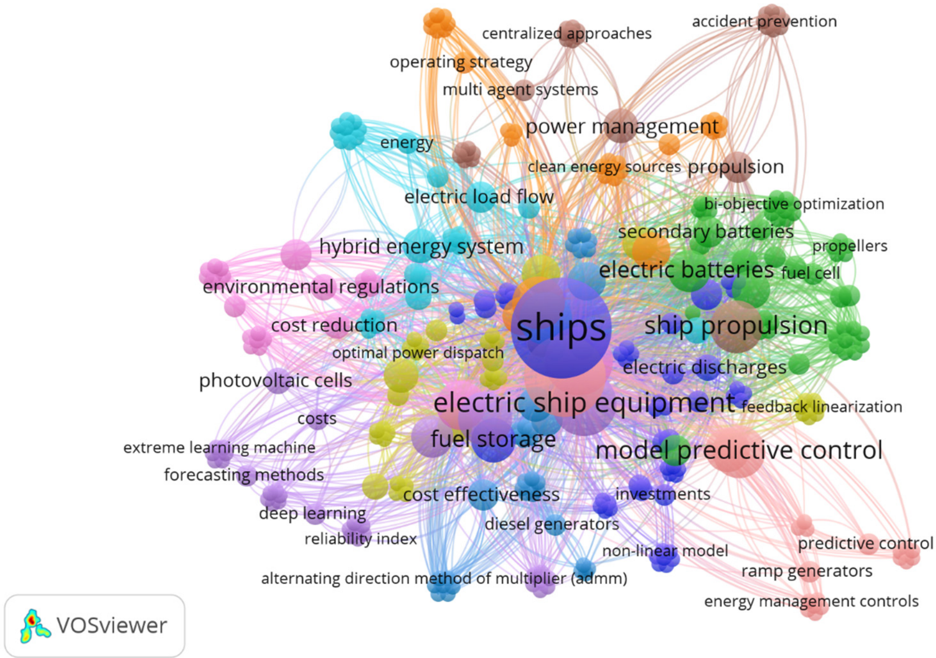

Figure 14. Co-occurrence analysis for energy management articles.

8. Protection of SBMGs

Protection systems in maritime applications are important to keep people and property safe. If a protection system fails, it can lead to disastrous consequences, such as electrical faults, blackouts, or general hassle. A maritime system is usually well-equipped with a protection system to avoid these undesirable effects. An effective protection system should be sensitive, selective, quick-operating, reliable, simply constructed, and economical [39]. However, the DC-SBMG's protection system has a lot of challenges, including [33,207–211]:

- Lack of natural zero-crossing current;
- The nature and direction of the fault current;
- Incoordination of current-based relays;
- The effect of the output filter;
- Dependence on converter topology;
- Severe transient discharge;

- The grounding system;
- The occurrence of miscoordination between the primary and secondary protection due to the short time required for fault clearing and the circuit breaker used in the DC-SBMG.

AC circuit breakers often cannot be used in DC circuits because they require current zero crossing. The emerging hybrid circuit breaker has been proposed to solve this problem but still provides a low protection level. If the fault current is large enough, it can damage the freewheeling diodes. The ability of a diode to withstand these faults is defined by the amount of adiabatic heating that occurs during the fault. Solid-state circuit breakers and intelligent electronic devices (IEDs) were used in [25]. The IED is a crucial device used in electrical networks where fault currents are detected and localized using the direction of the current and the differences between IEDs. Once a fault has been detected, a solid-state circuit breaker isolates it to prevent high voltage from being released. Therefore, IEDs and solid-state circuit breakers are necessities to protect DC circuits [33].

However, the DC zonal SBMG may require small time-coordinating protection measures among its various components. This is because the semiconductors in the power converters, such as diodes, IGBTs, and thyristors, have low thermal capabilities, i.e., there is a lag time between fault detection and clearance [212]. Therefore, the DC protection has to take place within a few seconds.

In designing a DC-SBMG, one of the main constraints is the lack of standards and guidance on implementing comprehensive fault management. Fault management is the ability of the SBMG to perform system reconfiguration to deliver the power to the critical loads instead of interrupting these loads. One of the significant differences between marine systems and land-based ones is the load profiles. Marine engines are sensitive to power outages, causing their loads to be more critical; hence, they need to be reconfigured quickly [38]. In this context, SBMG fault management consists of three stages. The first is the detection and localization of the fault. The second stage is the isolation of the fault. The third stage is the reconfiguration of the isolated system to feed the critical load. Power converters need to avoid a complete failure until the fault clearance occurs using an appropriate FTC approach. Figure 15 illustrates the fault-management methods in DC-SBMGs. Table 8 presents the most recent techniques used in DC protection for SBMGs for fault management. Based on the contributions presented in Table 8, it can be concluded that various fault-detection, diagnosis, isolation, and protection techniques have been proposed for DC SBMGs. Most of the contributions focus on fault detection and isolation methods, with some proposing fault-localization and reconfiguration solutions. However, fault reconfiguration is not investigated in most of the contributions, which can lead to prolonged downtime in the event of a fault. Additionally, the system's dynamics are not investigated in some of the contributions, which can impact the effectiveness of the fault-detection and diagnosis techniques. Overall, further research is needed to address the issues identified in the contributions and improve the fault management of DC SBMGs.

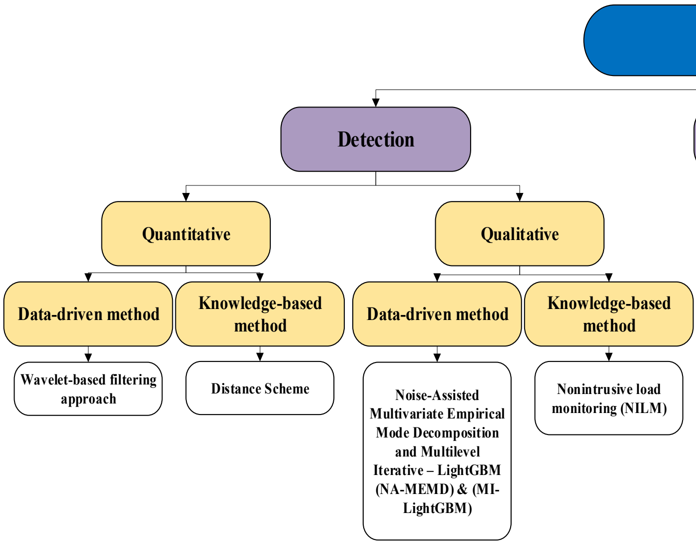

Figure 15. DC-SBMG fault-management methods.

Table 8. Comparison of the contributions and issues of the most recent research related to fault-management techniques [213–223].

Ref.	Contributions	Issues
[213]	Presents fault diagnosis based on machine-learning Noise-Assisted Multi-variate Empirical Mode Decomposition and Multi-level Iterative—LightGBM (NA-MEMD) and (MI-LightGBM)	Fault reconfiguration is not investigated
[214]	Presents static and dynamic protection systems Discusses the short-term dynamics for a zonal SBMG after fault occurrence considering load-shedding actions Models the propulsion power converter's electro-mechanics	The system's dynamic is not investigated
[215]	Presents fault detection and isolation based on nonintrusive load monitoring (NILM)	Fault reconfiguration is not investigated
[216]	Presents a fault diagnosis method based on the wavelet-based filtering approach Minimizes the probability of misdetection	Fault reconfiguration is not investigated
[217]	Presents a scalable solid-state bus-tie Switch that can be easily scaled for current and voltage Investigates fault-detection methods Reduces the electrical and thermal stresses by using multiple units rather than a single unit	Fault localization and reconfiguration are not investigated
[218]	Presents a new solid-state bus-tie switch (SSBTS) Parallel connecting multiple units of the topology to increase power and voltage ratings	Fault localization and reconfiguration are not investigated
[219]	Presents a solid-state DC circuit breaker Detects and isolates the fault in significantly less time	Fault reconfiguration is not investigated
[220]	Explores three different protection schemes for DC faults in SBMGs, namely, a six-pulse thyristor rectifier, a six-pulse diode rectifier, and a two-level active rectifier	Fault reconfiguration is not investigated
[221]	Presents a fault-detection algorithm based on overcurrent Recloses the Z-source breaker after the fault if necessary by control Integrates Z-source DC circuit breakers into a zonal MVDC SBMG Provides solutions for two Z-source breakers to work in parallel and supply current for the same load center Explores the SCR's gate control	Fault localization is not detected
[222,223]	Presents a fault-detection and -localization method based on a distance scheme Locates different types of faults in both forward and reverse directions	Fault reconfiguration is not investigated

Figure 16 represents the co-occurrence analysis for these studies. The analysis divides the author's keywords into four clusters, with the main keywords in each cluster. Based on the co-occurrence analysis of the provided keywords, it can be observed that the majority of the keywords are related to fault detection and protection in electric power distribution systems, particularly in shipboard applications. Techniques such as distance-protection schemes, fault localization, and fault-detection algorithms are commonly mentioned, along with advanced monitoring and diagnostic methods, such as machine learning and signal processing. Other relevant topics include power system protection, load management, and reconfiguration, as well as the challenges and practical problems associated with implementing these techniques in complicated structures, such as marine power plants and shipboard microgrids. Overall, the analysis highlights the importance of reliable and high-performance electric distribution systems in ensuring the safe and efficient operation of ships and other marine vessels.

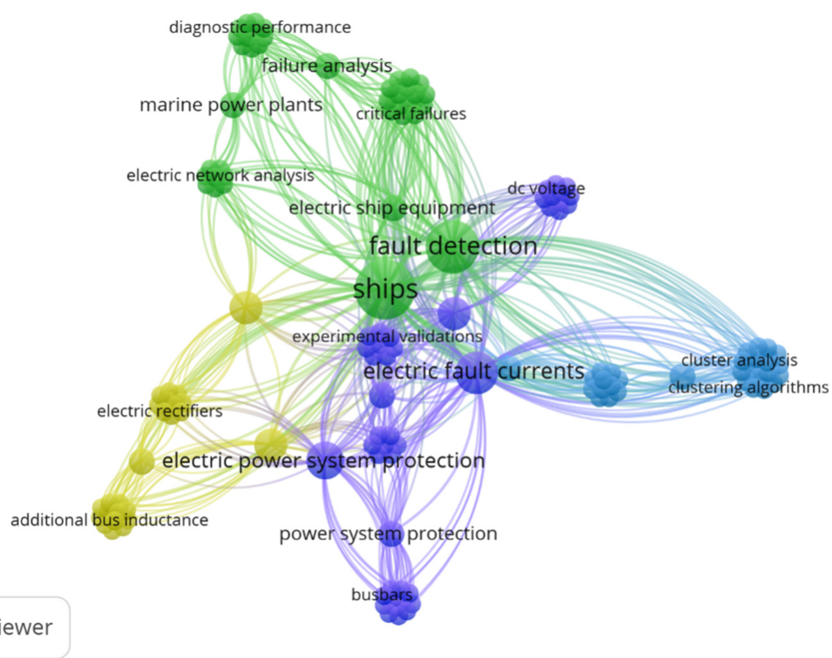

Figure 16. Co-occurrence analysis for protection articles.

9. Real Ships in The World

There are many types of ships which vary in their features and functionalities. Ships have been electrified to minimize GHG emissions. Table 9 shows the shipboard microgrids implemented across the world, with their names, types, available power supplies, storage systems, and the years in which they started sailing.

Table 9. Examples of the existing real ships in the world [14,36].

Ship Name	Ship Type	Sources of Power Supply	Storage System	Year
Suntech	Yacht	PV panels with 19.6 kW Diesel generators	Batteries	2001
Sun 21	Catamaran yacht	PV panels	Batteries	2007
Auriga Leader	Car carrier	PV panels with 40 kW	Batteries	2008
MS Viking Legend	Car ferry	Asynchronous generators	Unknown	2009
Truanor Planet Solar	Catamaran yacht	PV panels with 93 kW	Li-ion batteries	2010
COSCO Tengfei	Ocean-going car carrier	PV panels with 143.1 kW Diesel generators	Li-ion batteries with 750 kW	2011
Hornblower Hybrid	Ferry ship	Wind turbines with 5 kW Diesel generators PV panels with 20 kW	Hydrogen fuel cells	2011

Solar Sailor	Ferry ship	PV panels Wind Diesel generators	Batteries	2012
Emerald Ace	Car carrier	PV panels with 160 kW diesel generators	Li-ion batteries	2012
Anji204 Inland River	Ro-ro car ship	PV panels with 37.12 kW	Li-ion batteries with 128 kW	2015
Harvey Stone	Multi-purpose field support vessel	2 × 3350 kW main generators 3120 kW emergency generator	Unknown	2016
Vision of the Fjords	Car ferry	Diesel genset	600 kWh Batteries	2016
Texel Stroom	Car ferry	4 × 2000 kW diesel generators	Compressed natural gas (CNG)	2016
NKT Victoria	Cable-laying vessel	2240 kW main generator	Batteries	2017
Van Oords' Nexus	Cable-laying vessel	2 × 2666 kW and 2 × 2000 kW main generator engines 1 × 1432 kW aux generator engine	Unknown	2017
Tycho Brahe and Aurora of HH ferries	Car ferry	4 × 2.6 MW Wärtsila diesel gensets	Batteries	2017
Happiness	Ferry	Diesel generator	Lithium-iron phosphate battery	2017
E-ferry	Car ferry	Batteries	4.3 MWh lithium-ion batteries	2018
Australian Research Vessel	ASRV	Diesel generator with an emergency diesel generator set	Unknown	2020

10. Research Trends and Recommendations

Despite the many research papers in the SBMG field, there is still a significant need for further research. The research gaps regarding the control, uncertainties, management, and protection of SBMGs can be summarized as follows:

In terms of SBMG control: The problems of voltage and frequency deviations are investigated using different control methods. However, most of these methods are not accurate enough to give the desired voltage and frequency levels; voltage deviation represents a vital issue in SBMGs due to the presence of PPLs and CPLs. So, employing artificial-intelligence techniques with such control schemes would be an excellent solution for the future. Moreover, applying machine-learning and deep-learning approaches with the control methods can enhance their performance in achieving optimal voltage and frequency levels. In addition, performing appropriate efficient control methods while eliminating the effect of packet losses is a new future research trend.

In terms of SBMG uncertainties: The unknown loads and the uncertain output powers of both PV and wind due to severe environmental conditions facing ships are significant issues. The investigated research focused on solving only one problem regarding uncertainties. In the future, it is recommended to apply methods and techniques that use intermittent platforms for data processing, analysis, and storage, such as cloud computing, Fog, and the Internet of Things (IoT). These methods can help in solving different uncertainty problems simultaneously.

In terms of SBMG energy management: In order to optimally share the power to the demand load, ensuring high system stability, it is recommended to incorporate the IoT with energy management strategies to facilitate communication between each element in the SBMG. Applying new artificial intelligence techniques can improve the system's performance and they can be used to optimally manage the system while considering the effect of demand response.

In terms of SBMG protection: Fault management is a big issue for SBMGs, as PPLs affect fault-detection and -localization methods. So, it is recommended to use smart protection strategies depending on deep-learning strategies to detect faults, in addition to using IoT to communicate between detection and isolation processes. Designing an efficient protection scheme based on artificial intelligence and optimization algorithms while using a communication channel with the minimum delay time is a new trend for SBMGs. Moreover, coordinated protection and reconfiguration are necessary to achieve higher survivability.

Additionally, in the future, it will be possible to form combined sea microgrids by integrating multiple SBMGs using wireless technology.

11. Conclusions

This paper has provided a comprehensive literature review of the classifications, control, uncertainties, management, and protection of SBMGs. It has explored the developments of the distribution, propulsion, and power system architectures. Dynamic positioning and converter control techniques have also been discussed, along with uncertainty issues and management optimization techniques. Fault detection, isolation, and reconfiguration techniques have also been presented, and a co-occurrence analysis was performed to identify the most recent trends in control, management, and protection. The main conclusions of this review are:

- Dynamic modeling of SBMGs, considering all uncertainty issues, is essential for their operation.
- A hybrid AC/DC distribution system with an integrated power system in a zonal structure is recommended for a more reliable and flexible power system.
- A hierarchical control framework is better suited for regulating voltage and frequency deviations in complex SBMGs.
- Particle swarm optimization (PSO) and genetic algorithms (GAs) are more effective for multi-objective optimization with multiple constraints using machine learning.
- Machine-learning methods with communication for fault diagnosis and breakerless topologies for fault isolation are recommended for better protection systems.
- Fifth-generation wireless communication is suggested to reduce delay time and sensor losses in control, management, and protection processes.

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