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## A Review of DC Shipboard Microgrids

*Part I: Power Architectures, Energy Storage and Power Converters*

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# A Review of DC Shipboard Microgrids – Part I: Power Architectures, Energy Storage and Power Converters

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**Abstract-** Integrated power systems (IPSs) are popular in the shipbuilding industry. DC shipboard microgrids (DC-SMGs) have many advantages compared with AC ones in terms of system efficiency, operation flexibility, component size, and fault protection performance. Being in the exploring stage, DC-SMGs have several potential configurations with different system architectures and voltage levels. In a DC-SMG, functional blocks integrated include power generation modules (PGMs), propulsion system, high power loads, and pulsed loads specifically in naval ships. In modern ships, the PGMs include not only generators and fuel cells (FCs) but also energy storage systems (ESSs), which cooperate with generators to improve the overall efficiency and reliability. High power electric converters are vital interfaces between the functional blocks and the DC distribution system. Rectifiers for generators take the tasks of DC bus voltage regulation and power sharing. Inverters for propulsion motors are responsible for the motor drive in different operating conditions. Bidirectional DC/DC converters for ESSs are used to provide supply-demand balance and voltage fluctuation mitigation. This paper makes a comprehensive review of power architecture, functional blocks including electrical machines and energy storage, as well as power converters in DC shipboard power systems.<sup>1</sup>

## I. INTRODUCTION

The modern maritime industry has developed for almost two decades. In this process, shipboard power systems (SPSs) are evolving to overcome the challenges of optimal use of energy sources and minimizing the environmental impacts, particularly concerning pollutants and greenhouse gas emissions [1]. Increasing vessel developments are aiming to offer superior energy efficiency by means of deploying

technologies for improving propulsive efficiency, equipping hybrid power generation systems with energy storage systems (ESSs) to optimize performance, and adopting smart and lightweight materials to enhance switching performance and improve power density [2], [3], [4]. In this context, the integrated power system (IPS) is presented, which provides power to all-electric loads via a number of power sources. By incorporating electrical propulsion techniques, IPS could provide an efficient, flexible, and environment-friendly power supply. Furthermore, the development of energy storage unit materials makes all-electric ships (AESs) possible, with huge advantages in operational efficiency and costs [5], [6]. In recent years, some companies, e.g., Rolls-Royce marine and Kongsberg, proposed the idea of an unmanned autonomous ship that permits reducing the risk of human error on board, which has been the main cause of accidents at sea. The unmanned ships require advances in not only autonomous ships, but also digitalization and communication technologies such as cloud technology, blockchain technology, augmented reality, and smart speakers. It is predicted that the future trend of the maritime industry might be more risk-informed and data-based, and these are the main challenges in building smart ships. Besides in commercial ship applications, IPS also gains popularity in naval vessels [7]. Except in the case of charging at the dock, also named cold ironing, the SPS operates in islanded mode most of the time, and this is the reason why it is also defined as a shipboard microgrid (SMG).

The electrification of SPS experiences the changes between AC and DC systems. The SPSs in their infancy are DC distribution networks without advanced power electronics. With the need for AC propulsion motors, the AC SPSs emerged and became popular. In AC SPSs, both generators and propulsion motors are directly connected to the AC bus through breakers, and the service loads are integrated through 50/60 Hz transformers [8]. Therefore, the voltage and frequency control of generators, which supports the AC bus, is vital for the system operation. In recent decades, the development of power electronics, concerns about fuels and the demands on compact SPSs drive the progress of shipboard generation systems, and research focuses switch to the full electrification of DC ships. Compared with AC distribution, the DC SPS presents a DC bus, and the shipboard power components connect through power converters as the interface to the DC bus. This configuration allows the use of high-speed

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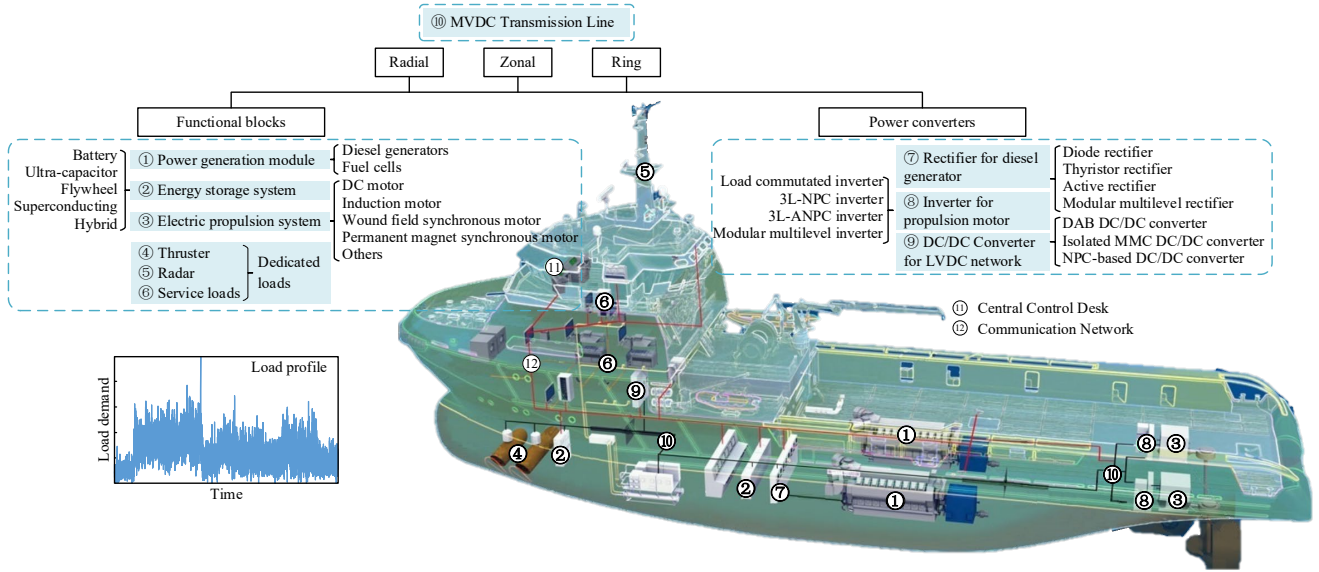


Fig. 1. Overview of a typical DC-SMG

gas turbines and high-speed generators, and makes it possible to regulate the generator speed without frequency issues [9]. Therefore, the volume and size of SPS, as well as the fuel consumption of generators can be reduced [10]. Besides, the DC-SMGs simplify the generator connection without the need of synchronization of phase angle and frequency. Another advantage of DC-SMGs is replacing the bulky 50/60 Hz transformers by compact solid-state transformers, which further improve the power density [11]. Though with these benefits, the DC-SMGs have the challenge in protection system design. Lacking of zero crossing of the current, DC breakers with the capability of disconnecting large current are more complex than AC breakers.

Assuring the quality of service (QoS) in SMGs is more difficult than that in terrestrial microgrids (MGs) [12]. Being islanded, a DC-SMG is endowed with limited power which is mainly generated by synchronous generators and FCs as the PGMs to feed the entire system. In the load side, the electric propulsion system accounts for around 80% of the total power demand with large fluctuations, which is one of the main causes of SPS instability issues. Besides, dedicated loads in ships such as thrusters and radar may bring the voltage oscillation as well. Therefore, the DC-SMGs are weak and the magnitude of perturbations might be high. To improve the QoS, modern ships are usually equipped with ESS as backup of PGMs to suppress the voltage oscillation. An overview of SPS is shown in Fig. 1. All the functional blocks in both generation side and load side are arranged in radial, zonal, or ring architecture. Power converters, including the rectifiers, inverters, and DC/DC converters, as the interfaces between functional blocks and the DC network are controlled properly to ensure the system operate steadily. On the other hand, regulations and standards on SPSs are immature. Even though there are some recommendations and rules enacted by IEEE and International Maritime Organization (IMO) [13], DC-SMG as an emerging technology still requires a suitable standardization when being deployed in the shipbuilding

TABLE I. RECOMMENDED MVDC VOLTAGE CLASSES (KV)

	MVDC Class	Nominal MVDC Class Rated Voltage	Maximum MVDC Class Rated Voltage
Already Established	1.5	1.5 or $\pm 0.75$	2 or $\pm 1$
	3	3 or $\pm 1.5$	5 or $\pm 2.5$
Future Design	6	6 or $\pm 3$	10 or $\pm 5$
	12	12 or $\pm 6$	16 or $\pm 8$
	18	18 or $\pm 9$	22 or $\pm 11$
	24	24 or $\pm 12$	28 or $\pm 14$
	30	30 or $\pm 15$	34 or $\pm 17$

industry.

In comparison, there are many difference between DC-SMGs and general DC MGs. The load profile in DC-SMGs, of which an example is shown in Fig. 1, is more unpredictable than terrestrial DC MGs due to the variable and harsh operation conditions; on the contrary, the generated power in terrestrial DC MGs with high penetration of renewable energy sources may fluctuate depending on the weather conditions. These differences lead to different requirement on ESS in each applications. Furthermore, the specific structure of DC-SMGs brings the challenge in grounding system design.

This paper aims at providing and making a summary of current solutions on above challenges. This paper is organized as follows. Section II provides the review on DC-SMG configuration, including the bus architecture, voltage level, and system configuration. Section III presents functional blocks in DC-SMGs. In section IV, the general information of power converters and their adoption into DC-SMG are studied. Finally, concluding remarks are given in the last section.

## II. POWER ARCHITECTURES OF DC-SMGs

Power demand in a ship is usually up to megawatt (MW)-

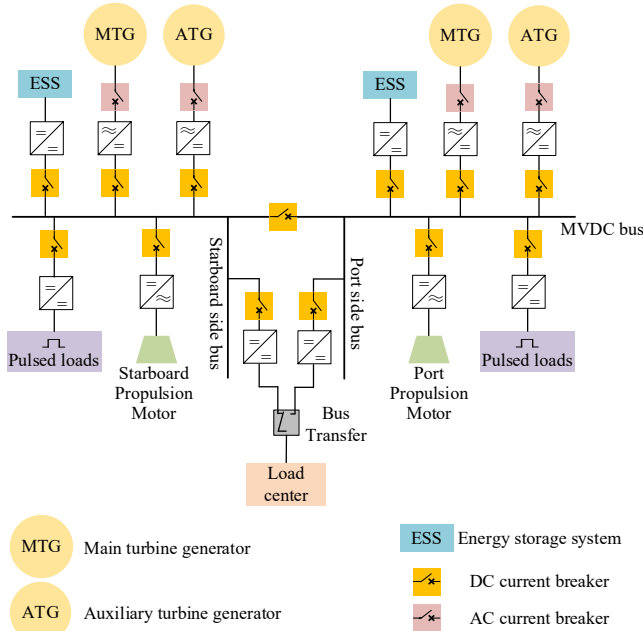


Fig. 2. IPS based on radial distribution

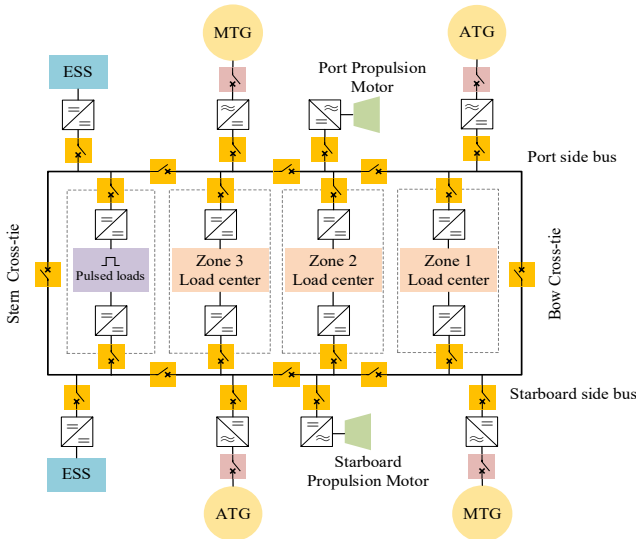


Fig. 3. IPS based on zonal distribution

class, which cannot be met by low voltage SPSs. Furthermore, different types of ships have various power supply requirements in terms of reliability, energy density, flexibility, etc. Therefore, it is necessary to study the bus architecture and voltage levels, as well as system configuration of SPSs.

**A. Bus Architecture and Voltage Levels**

For DC networks, there are two types of DC bus architectures: unipolar and bipolar bus topology [14], [15]. In unipolar systems, all the elements are connected to a two-wire, i.e. positive and negative, DC bus through converters. The unipolar system is simple, but it cannot provide redundancy and is weak to defend even a single fault [14]. On the other hand, the bipolar configuration has three wires, i.e. positive, negative, and neutral ones. Compared with the unipolar system, the bipolar one has the advantages of higher power

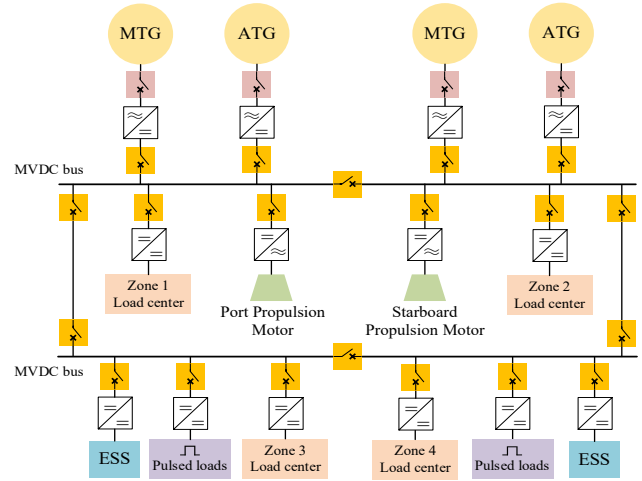


Fig. 4. IPS based on ring distribution

capacity, increased reliability, lower transmission losses due to lower current in the return wire, and flexibility in the connections between loads and distributed generation [15]. However, since the bipolar architecture can provide different voltage levels, unequal distribution of loads may result in voltage unbalance, which requires a voltage balancer circuit to stabilize the DC bus voltage. Nevertheless, most of the existing DC-SMGs deploy bipolar architecture.

Up to now, there is no existing standard specifically for DC-SMGs determining the DC voltage levels. The system voltage should be determined by the cost, desired generator and propulsion motor drive voltage, converter design, load requirements, cable and bus-bar rating, and the fault energy [16]. Practically, voltage levels of the distribution system vary depending on the power level and the types of vessels. For example, a large liquefied natural gas (LNG) tanker may utilize a 6.6-11kV medium voltage distribution system, while an offshore supply vessel may utilize a 480V or 690V low voltage system. Generally, low voltage DC (LVDC) systems are lower than 1kV, with power system capacity in the range of 1-20MW, while medium voltage DC (MVDC) systems are higher than 1kV, with 20-100MW. Recommended MVDC voltage levels for SMG are shown in TABLE I, with  $\pm 10\%$  DC bus voltage tolerance.

**B. System Architecture**

**1) Radial distribution**

Radial distribution is a conventional architecture that is recommended by IEEE Std. 1709-2010 and has been applied in SMGs. The system configuration is depicted in Fig. 2. Generally, two DC buses distribute the power to consumers. Power sources, including generators and ESSs, are distributed symmetrically and feed each DC bus. The port and starboard propellers are powered via two DC buses separately, while two DC buses supply the onboard service loads for higher reliability.

The radial scheme has the advantages of being simple and cost-efficient. Furthermore, since it has been used in traditional mechanically driven ships and AC ships, it is easier and more practical to redesign the system from the traditional

ones to modern DC alternatives [10]. For example, the cruise ship ‘Royal Princess’ is designed as MVDC AES using a radial distribution network [10]. However, this solution becomes bulky when the number of loads increases and is not flexible when a fault occurs in DC bus [17].

### 2) Zonal distribution

Zonal distribution is another potential configuration according to IEEE Std. 1709-2010 [16]. This configuration has become the US navy standard [18]. As shown in Fig. 3 [19], in zonal network, the shipboard loads are divided into  $n$  zones, each of which is fed by two connections from the buses and managed independently. The zonal distribution is typically arranged in the port and starboard sides along with the ship, and these two buses are connected at the stern and bow [20]. This design enables redundant feedings for loads from two longitudinal DC buses. Each load center has connections with both the port and starboard buses, and when a fault occurs in one side, vital loads within the zones will autonomously shift their power sources to the healthy opposite bus [21]. In naval vessels, specific high power loads like radars are set independently as the only equipment in one zone [16]. Currently, few cases are using zonal architecture, while most study works are based on notional models [19].

There are many benefits in zonal networks. The survivability can be greatly enhanced for marine loads by feeding power from both port and starboard side DC buses. Upon sensing loss of the primary power source, the vital loads can switch to the alternative one automatically or manually. The longitudinal bus architecture allows isolating faults with the minimum affected areas using coordinated protection systems via a communication network. Besides, partitioning of the loads from bow to stern along the ship reduces the cable needed, and thus lowers the cost and impact from the cables. Further information for designing the zonal distribution system is accessible in IEEE Std. 1826-2012.

### 3) Ring distribution

In few cases, ring distribution is also used. A typical ring-bus-based DC power architecture is depicted in Fig. 4 [8]. In ring distribution, the bus-tie switches connecting DC buses keep closed in normal operation, making the DC bus a loop. Similar to the zonal architecture, the ring configuration has higher survivability and reconfigurability than radial ones. When a single fault occurs in DC bus, ring distribution enables the fault isolated by disconnecting the nearest circuit breakers and keeps the rest parts working as normal. However, different from zonal distribution, each load center in ring distribution has only one link to the bus, which is susceptible to faults in vital loads. The ring architecture is more like a transition between the radial and zonal ones, and is rarely used in SMGs.

A qualitative comparison on radial, zonal, and ring distribution architecture and the key performances are shown in TABLE II from the aspects of typical bus schemes, key performances of reliability, survivability, reconfigurability, and complexity. The radial scheme requires least breaker and its structure is the simplest, while correspondingly, the reliability, survivability, and reconfigurability are worst. Zonal

TABLE II. COMPARISON OF RADIAL, ZONAL, AND RING DISTRIBUTION

	<b>Radial</b>	<b>Zonal</b>	<b>Ring</b>
<b>Bus scheme</b>	Two buses connected by one breaker.	One ring bus with $2n+2$ breakers.	One ring bus with six breakers.
<b>Reliability</b>	Low	High	Medium
<b>Survivability</b>	Low	High	Medium
<b>Reconfigurability</b>	Low	High	Medium
<b>Complexity</b>	Low	High	Medium
<b>Number of applied cases</b>	Most	Medium	Least

scheme has the best performance in these three performance items, while the price is high system complexity and large numbers of breakers, especially for big ships. Ring scheme has the medium level in these comparison items. From these comparison, it can be concluded that radial scheme is can be used for small ships with few components, such as short-distance ferries, and the cases in which requirement on system reliability is not very high. While for large ships with high requirement on system reliability and survivability, such as vessels, cruises and cargoes, zonal and ring schemes may preferable for better personal and good safety. Up to now, the radial scheme is mostly used in practical cases, since current electric ships are refitted from old ships, keeping the radial scheme still popular.

## III. FUNCTIONAL BLOCKS IN SHIPS

From the perspective of functionality, as mentioned in section II, power devices in DC ships generally include power generation modules, ESSs, propulsion systems, and loads. Detailed information about these blocks is described in the following.

### A. Power Generation Modules

Power generation components in ships are required to be efficient and environment-friendly. Presently, the main sources in ships are diesel generators, while deploying FCs for marine applications is under development. Besides, with the introduction of energy storage techniques, AESs with increasing capacity are just around the corner.

#### 1) Generators

Generally, the marine generation module in DC power system consists of prime movers, generators, and rectifiers. Usually, the prime mover, known as a combustion engine, is fueled with diesel or heavy fuel oil [22]. While in military ships and some auxiliary generator sets in commercial vessels, the prime movers can be gas turbines for their reliability, efficiency, high energy density, and wide speed range [23]. Some industrial products of diesel engines and gas turbines from Wärtsilä, MAN, GE, and Rolls Royce are presented in [24]. Of particular interest to the US Navy is developing a fuel-efficient, power-dense marine gas turbine rating of about 10MW [20]. With the shipboard electrical power demand tend to continuously increase from tens of MW and in some cases even greater than 100 MW are expected to be developed in the future [21].

The optimal machine type mainly depends on the power and

speed requirements of the marine application. Generally, two types of generators can be employed in the marine applications, namely the wound-rotor synchronous machine (WRSM) and the permanent-magnet synchronous machine (PMSM). The existing cases of marine generators are represented in TABLE III. Compared with that in AC systems, the integration of gensets in DC systems do not require gearboxes and low-frequency transformers anymore, and the alternator is directly driven by the prime mover being able to operate at variable speed. The comparison structure is shown in Fig. 5.

The output of generators is converted by rectifiers from AC to DC to fit in the SMGs. The converter power rating matches with the genset. In high power applications, the scalable modular converters are popular. The rectifier types suitable for maritime applications will be clarified in section IV.

2) Fuel cells

Functionally, FCs work as power sources without greenhouse gas emissions. Instead of burning fuels, FCs have various techniques including alkaline fuel cell (AFC), proton exchange membrane FC (PEMFC), direct methanol FC (DMFC), and solid oxide FC (SOFC) to transfer chemical energy to electric energy [25]. The DC output of FCs is converted to the required voltage through DC/DC converters to fit the DC-SMGs. In high power applications, SOFC is

appealing due to its high power density and high efficiency up to 85% [26]. The fuel in FC can be methanol, diesel, hydrogen, LNG, and so on. Different technologies, might have specific requirements. For instance, AFC requires hydrogen with high purity, while SOFC can use various fuels including methanol, diesel, hydrogen, and LNG.

FCs have the advantage of a long lifetime, which is attractive in marine applications. For instance, a Siemens-Westinghouse CHP-100 SOFC achieved a lifetime of 30,000 hours and up to 70000 hours in lab test [25]. However, the slow dynamic response is the main barrier of using FCs in SMGs, due to their slow internal electrochemical and thermodynamic responses [27]. Therefore, hybrid ESS (HESS) combining FCs and other energy storage units is a good option to achieve fast-response operation. The main requirement for this hybrid system is efficient and intelligent power management between the two systems. To implement FCs in SMGs, studies on efficiency, load change behavior, and fuel flexibility are needed.

Up to now, there are more than twenty FC projects in the maritime sector, with capacity ranging from tens to more than 320kW. For example, the fuel cell project ‘SchiBZ’ in 2016, the *Oel-Waerme-Institut gmbH* (OWI), and four other institutions enabled the transformation of diesel fuel and water to a fuel gas with high hydrogen content, integrating into fuel cell systems to generate electricity [28]. The world’s first liquid hydrogen FC (3.2MW) cruise ship is scheduled by 2023 for Norway’s fjords [29]. ABB presents FC solutions that based on hydrogen PEMFC for marine use, and the system can be fully hydrogen-electric or integrated as part of a hybrid SPS [30].

B. Energy Storage System

In order to facilitate a more economical and reliable operation in marine vessels, energy storage techniques are necessary and have been widely applied in ships. The ESS can bring five benefits: spinning reserve, peak shaving, network resilience and stability, shaft generator load transfer, and harbor operation. Due to the large inertia of the generation system, fast dynamics cannot be regulated by the prime mover of genset, while ESS can quickly meet the load demands and to flatten the vessel’s total load profile by coordinating with genset via an energy management algorithm [31],[32]. In case the generation system fails, or during the short period of fault isolation of the uninterruptible parts, ESS can supply as a backup power source. Moreover, for naval ships, voltage instability caused by pulsed loads with a considerable high power ramp rate can be suppressed by high power density ESS.

ESSs in SMG can be based on a host of technologies including battery, ultra-capacitor (UC), flywheel, and superconductors. The choice of ESS technology depends on the requirements on power range, power density, charge/discharge time, cost, etc. The batteries and UCs are integrated into the DC-SMGs with the interface of DC/DC converters, while the flywheels and superconductors are connected through ac/DC converters. Note that, the broad operation range of marine applications has a big impact on the

TABLE III. EXISTING CASES OF MARINE GENERATOR

Gen. type	WRSM		PMSM	
Cases	6-phase WRSM NP [23]	4-pole WRSM (main generator) [116]	12-phase PMSM NP2 [117]	8-pole PMSM (auxiliary generator) [116]
Power rating	2.15 MVA	59kW	2 MVA	9 kW
Rated voltage (V)	2×1200	750	4×620	750
Rotational speed (rpm)	6300	1800	22500	3600
Gas turbine rotational speed (rpm)	22500	1800	22500	3600
Gear-box need	Yes	No	No	No

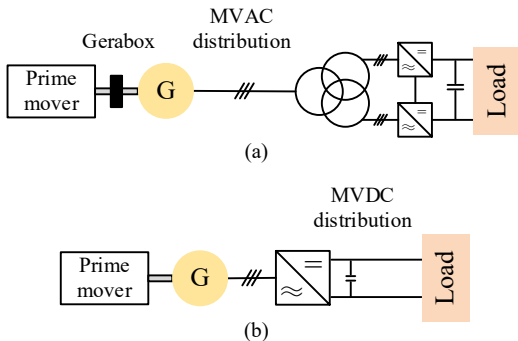


Fig. 5. Simplified generation module in (a) MVAC distribution with gearbox interfacing prime mover, and (b) MVDC distribution

performance of ESS, and the optimum location of the ESS within the ship plays an important role in its stability [33]. To improve the ESS performance, strategies for sizing and siting of ESS is studied as well [34], [35].

1) Battery energy storage system

Due to the scalability in batteries, the battery ESS (BESS) is popular in SMG for high-power and long-term demands. Normally, lithium-ion (Li-ion) battery is a good option due to its high energy density, low self-discharge rate, and long lifetime.

A BESS can be integrated into the DC-SMG distribution through a bidirectional converter. Conventionally, batteries are integrated by arranging multiple battery cells in series and parallel to build a storage unit in a matrix. A centralized battery management system (BMS) is used to monitor battery cell parameters such as state of charge (SoC), temperature, and voltage, and manage the power flow. However, this centralized configuration has problems in voltage sharing, over charge/discharge, and efficiency issues. To solve the problems in centralized BESS, the concept of distributed BESS is proposed in recent years, in which each battery cell has one converter module to switch on/off and regulate the output power. The simplified configurations of the centralized and the distributed BESS are depicted in Fig. 6 [36].

The research topics in BESS include SoC balance among battery cells [37], coordination with other types of power sources [38], reliability and efficiency analysis [39], fault management [40], etc. Accurate SoC estimation is a challenge for system coordination, and different SoC estimation methods are summarized in [41].

2) Ultra-capacitor energy storage system

UCs fill the gap between batteries and conventional capacitors; therefore, they can be used as energy storage devices in ships. Due to its low internal resistance, UC has a small time constant, enabling it to deliver a high charge/discharge ramp rate and resulting in high power density [42]. However, the energy density in the UC is relatively low, while batteries have benefits in energy density. Consequently, HESS combining UCs and batteries not only

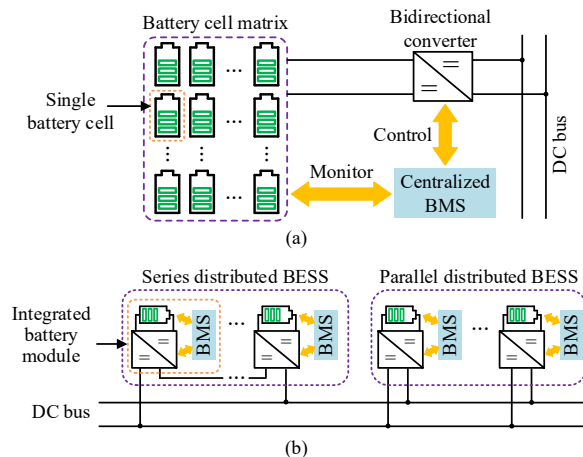


Fig. 6. Simplified configurations of (a) centralized and (b) distributed BESS

can meet the long-term load demand but also reduce peak power stresses on the battery packs, and it is particularly suitable to satisfy peak power demand in military ships for pulsed loads and transient load variations.

To manage the hybrid UC and battery ESS in MVDC SMG, different control strategies are studied. In [43], a PI controller based energy storage management system is designed to generate instantaneous storage reference according to the bus voltage and load demand, and power references of batteries and UCs separated by a low pass filter are sent to DC/DC converter controller to regulate the power exchange. Another fuzzy logic controller presented in [44], [45], [46] regulates the instantaneous power flow to improve the system efficiency.

3) Flywheel energy storage system

Since ships operate in various operating conditions and the network power quality changes frequently in a wide range, fast response high power ESS is required. Flywheel ESS (FESS) not only can meet this requirement, but also has the advantages of high energy efficiency, low maintenance, long lifetime, and being environment-friendly without chemical hazards. FESS combined with UCs can provide power for military ships requiring power in less than 10 $\mu$ s [47]. However, it cannot be ignored that FESS has the drawback of high self-discharge rates [48]. The most common applications of FESS are for uninterruptible power supplies (UPS) and power quality improvement [47]. Currently, FESS is becoming widely applied in various applications including the marine industry [49]. Typically, FESS is a kind of electric supply device that stores energy in the form of kinetic energy in a rotating flywheel connected to the shaft of an electric machine. The FESS structure is depicted in Fig. 7, containing rotor (flywheel), shaft, motor/generator, and power electronic interface. The amount of stored energy depends on the form, mass, and rotation speed of the flywheel [50]. In charging mode, the flywheel speeds up and store the kinetic energy in the high-speed rotational disk; while in discharging mode, the stored kinetic energy will be released by slowing down the rotating flywheel.

In DC marine power system, FESS can be used for voltage sag correction, power smoothing, power leveling, and voltage

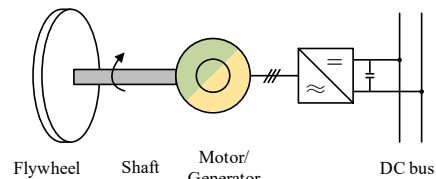


Fig. 7. Structure of the flywheel ESS

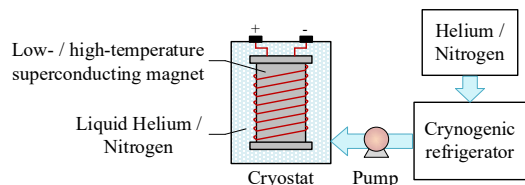


Fig. 8. Superconducting magnetic ESS

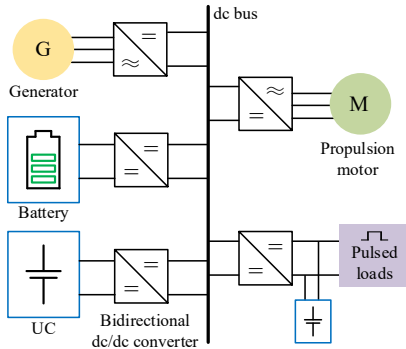


Fig. 9. Block diagram of dc-SMG with battery/UC HESS

restoring [50]. A series voltage injection type of flywheel is presented in [51] to correct voltage sags caused by faults and pulsed loads in naval ships. Reference [52] compares the operation performance with and without FESS in an electric ship power system with pulsed loads, and the results highlight the importance of FESS in maintaining system stability in the event of pulsed loads.

4) Superconducting magnetic energy storage system

Superconducting magnetic ESS (SMESS) is an attractive technology that stores energy within the magnetic field generated by the DC current flowing through a coil comprised of superconducting wire with near-zero loss of energy [53]. Similar to UC ESS and FESS, SMESS also has the capability of frequent and rapid charging and discharging (within milliseconds) with high efficiency over 95% and it is potentially suitable for the military marine system. A typical SMESS consists of a cryogenically cooled superconducting coil and power conditioning system, as depicted in Fig. 8. Due to the cooling system required, the initial cost of SMESS is relatively high, and a large amount of power is needed to keep the coil at cryogenic temperature. Besides, mechanical instability is another problem in SMESS [53].

There is still a long way to go before implementing SMESS in ships before this technology becomes mature, and some research projects under development become completed. In [54], a hybrid ESS consisting of SMESS and lithium-ion batteries in AES are studied. SMESS is used to ensure system stability during the transient periods, while lithium-ion batteries are implemented to deal with long-term energy deficiency.

5) Hybrid energy storage system

By analyzing features of various energy storage unit types, it is obvious that there is no perfect option being able to meet

all the requirements in marine applications. Different types of energy storage units have various response characteristics and are suitable for compensating different power fluctuation range [55]. A comparison of above four energy storage techniques applied in SPSs is presented in TABLE IV. Quantitative comparison of ESSs among existing commercial and notional ship cases shows that the BESS has relative high energy rating, while the maximum power is smaller and response time is longer than the other techniques. On the contrary, the UC, FESS, and SMESS have the capability of providing high power in a very short time, and the efficiency are higher than BESS, but the energy rating is lower. Among these ESS techniques, BESSs have already been widely used in commercial ships, UCs and FESSs in a few cases, while SMESS is quite new in maritime application and there is few notional study cases.

HESS is usually adopted to fulfill various needs in ships. The most commonly used HESS is the combination of batteries and UCs, which has been clarified before, providing both high energy density from batteries and high power density from UCs. In [56], a hybrid battery/UC ESS, as shown in Fig. 9, for the propulsion system and pulsed loads in MVDC SMG is studied, in which the batteries and UCs can support generators with high power (15MW) for 60 seconds, or individual batteries can support the propulsion system in low speed for more than 3 hours as the backup of the generators. A comparative study on the optimal combination of battery, UC, and flywheel is determined with the objective of minimizing the voltage and frequency fluctuations caused by pulsed loads [57]. The comparison results show that the battery and flywheel combination can achieve better performance over other combinations, while the combination of flywheel and UC will cause frequency oscillation.

C. Electric Propulsion System

Electric propulsion system in ships, emerged as an efficient propulsion arrangement, is a fast-growing research area driven by the rapid growth in power electronics and advanced machine manufacturing [58]. Having an electric motor that drive the ship propeller directly, the mechanical structure can be simplified by eliminating the gearbox. Variable speed electric drive motors have proven to be superior to the mechanical alternatives, especially in ice and dynamic positioning (DP) operation, which requires high power capacity and fast and accurate torque response. Moreover, electric propulsion can achieve higher efficiency, lower noise and vibration compared to the conventional engine system.

TABLE IV. COMPARISON OF SHIPBOARD ESS [118], [119], [120], [121]

Technique	Power range (MW)	Energy rating (MWh)	Response time	Charging time	Discharge time	Power density (kW/kg)	Efficiency	Cases
BESS	0.9-2	0.3-10	Few to 40ms	Tens of minutes to hours	Minutes to hours	0.05-2	60%-80%	MF Herjólfur ferry, AIDAperla cruise
UC	Up to 50	0.02-0.3	10-20ms	Few to tens of minutes	Milliseconds to 1 hour	0.5-10	>95%	Notional catamaran
FESS	0.03-100	Up to 5	<=4ms	Few to tens of minutes	Up to 15 minutes	0.4-1.5	80%-95%	Demonstrator electric ship at Alstom
SMESS	Up to 10	0.07-5	Milliseconds	Seconds	Few to minutes	Up to 100	>95%	Notional cases



Typically, 80% of the loads in ship installations will be electrical motors including thrusters, pumps, and other onboard loads [22].

The propulsion motor and associated drive control system are two core parts in the propulsion system. This section focuses on the practical propulsion motors used in ships, while the inverters will be explained in section IV. The characteristics of various propulsion motors and their application in both commercial and demonstrative ships are presented.

#### 1) DC motor (commutator motors)

The DC motors were used in hydrodynamic survey vessels in the past. The main advantage of DC motor is being capable of providing flexible and efficient propulsion for ships. The flexibility of accurate torque control with low ripple leads DC motor to be used in icebreakers, since it is necessary to have rapid control for effective operation. Besides, the DC motor speed can be controlled relatively easy. However, the commutators of the DC motor wear down over the time and need maintenance. Even though brushless DC motors exist, the size and weight are increased, and few are used in marine applications [59], [60]. What is worse, the power range of DC motor is around 5MW, which limits the use of DC motors in modern large ship propulsion. Therefore, more interest in propulsion motors is on AC machine design.

#### 2) Induction (Asynchronous) motors

The induction motor (IM) is the workhorse of the marine industry. Compared with DC motor, the IM eliminates the commutators nor slip rings, reducing the maintenance cost. Besides, the IM is superior in robustness and long lifetime thanks to its simple construction. However, a large starting current is required if implementing the IM as the propulsion motor of a ship. To overcome this, a cycloconverter can be used, and provides a good speed control in the meantime.

In high-power marine applications, the multi-phase IM emerges as well. A six-phase IM is studied in [61] and [62] to achieve higher torque and efficiency. The IM is usually controlled as a variable speed motor fed from a constant speed motor. The IM for medium-speed geared propulsion/thruster applications can achieve up to 10MW, while for higher power applications, synchronous motors are preferred.

#### 3) Wound field synchronous motors

The design of a synchronous motor is similar to that of a synchronous generator. Generally, wound field synchronous motors (WFSMs) are often a bit more efficient than IMs [63]. Since WFSM needs a DC power supply, which requires slip rings and brushes, the maintenance is a challenge. Indeed, this issue exists in DC motor as well. The benefit of the WFSM is

that the cost of the drive motor can be reduced by using load commutated inverters via regulating the voltage and power factor [63]. Furthermore, there is no power limitation in WFSM, even an output of 100MW is possible. But practically, the ship propulsion WFSMs are generally not that high, e.g. the Rolls-Royce's podded propulsor developed by Kamewa and Alstom are available from 5 to 25MW, the Azipod propulsion units from ABB are up to 17MW.

#### 4) Permanent magnet synchronous motors

PMSM is suitable for advanced shipboard applications. Since permanent magnets provide flux, there is no dissipation in the rotor, resulting in a higher power density and higher efficiency in PMSM than the WFSM and IM. Furthermore, the allowed flux dissipation in the stator can be higher than the WFSM for the same temperature, which increases the shear stress, making the motor more compact. However, since PMSM is always excited, there is a potential safety issue if the motor cannot be disconnected from either the propeller or the fault when a drive system fault occurs [63].

Some kW-class drives using PMSM are studied in the literature. Two 12kW PMSMs in a propulsion system of an AES powered by lithium-ion batteries were presented in [64]. PMSM in higher power marine applications is in progress. In addition, PMSM has been implemented in podded propulsion applications where the dimensions should be as small as possible, benefiting from its high efficiency, high torque density, and compact design. Siemens offers a solution in the power range from 5-23MW electric pod system SISHIP SiPOD-M/-T with high overall efficiency and compact design.

#### 5) Others

A range of other motor types are used in experimental applications. A low-speed 3.6MW high temperatures superconducting (HTS) synchronous motor (SM) was operated in a US navy ship [65]. Siemens also aims at developing low-speed, high-torque HTS motors. The HTS motors operate at the temperature of 20-77K, therefore requiring a high cost. Besides, superconducting homopolar DC motor (SHDCM) which has HTS armature and field coils is used for a purpose of ship propulsion. Compared with HTSSM, SHDCM can reduce superconductor by using magnetic materials in rotor. Therefore, the cost of SHDCM can be reduced, and the mechanical robustness is enhanced than HTSSM [66]. A summary and comparison of motor types for ship propulsion is presented in TABLE V. It can be concluded that the WFSM and PMSM have good quality for ship propulsion with high power range and high efficiency, while the IM has better reliability and lower cost. Superconducting technique for propulsion motor is applied in HTSSM and SHDCM, which can improve the efficiency and

TABLE V. COMPARISON OF SHIP PROPULSION MOTORS [122], [123], [124]

Motor type	Power range	Efficiency	Reliability	Power density	Controllability	Cost	Cases
DC motor	<5MW	80%-95%	Low	Low	High	Medium	SINAVY DC-PROP (Siemens)
IM	<10MW	91%-92%	High	Medium	High	Low	Converteam (GE)
WFSM	5-30MW	~95%	Medium	Medium	Medium	Medium	Mermaid (Rolls-Royce), Azipod (ABB)
PMSM	5-23MW	94%-97%	Medium	High	Medium	High	SISHIP SiPOD-M/-T (Siemens)
HTSSM	4-40MW	>98%	Low	High	Low	High	Factory testing (AMSC)
SHDCM	<19MW	~97%	Medium	High	Low	High	Demonstration project (General Atomics)

power density significantly than conventional motor types. However, due to the need on relative low temperature of coils and armatures, the controllability and reliability of HTSSM and SHDCM are weakened, and the cost is much higher than the conventional ones. These are the main obstacles need to overcome for wider implementation of HTS techniques in ship propulsion motors.

In the future, there might be more new concepts for variable speed drives with high efficiency, or special design for certain applications.

Podded propulsion is another type of propulsion system, in which the electric motor is directly connected to the propeller shaft integrated with the thrust bearing and propeller bearing. It is originally designed for the icebreaking purpose, and currently has dominated icebreaker and cruise vessel. In the industrial community, companies include ABB, Rolls Royce-Converteam, Siemens-Schottel, and SAM Electronics-Wartsila Propulsion are working on podded propulsion and have their specific products.

#### D. Dedicated High-power Loads and Pulsed Loads

Besides propellers, there are some dedicated high-power loads in ships, such as the bow and stern thrusters, compressors for air conditioning, heating and ventilation, etc. These loads, typically requiring several MW of operating power, are supplied directly from the DC distribution bus via DC/DC converters. While the remaining consumers including hotel loads, communications, auxiliaries, electronics, etc. are supplied by low-voltage switchboards.

Compared with commercial vessels, some special devices are deployed in navy ships. The US Navy is moving to electromechanical devices and all-electric ships. The electromechanical devices, which require high power pulse power, include electromagnetic aircraft launch system (EMALS) and all the electric weapons such as electromagnetic railguns (EMRGs), high-energy lasers and radars. To drive these devices, the stored energy should range from tens of kilojoules to several gigajoules and should be capable of providing instantaneous power exceeding 20 gigawatts [67].

Due to the integration of pulsed loads, coordinated control and system stability are two crucial issues to study [68]. To meet the power supply requirement of pulsed loads, coordination of large pulsed loads and sufficient power supply with a rapid response is of vital importance. In addition, voltage dip at point of common coupling caused by pulsed loads should be compensated to ensure power quality and system stability.

## IV. POWER ELECTRONIC CONVERTERS FOR DC-SMG

Power electronic converters are of great importance in interfacing functional blocks to DC-SMGs. In this section, power converters in DC-SMGs including rectifiers for generators, inverters for propulsion motors, and DC/DC converters for ESS and DC loads are reviewed. The power converters are employed depending on the application in hand and aimed functionality. Compared to power converters in

electric vehicles, aircraft power systems, and general terrestrial DC MGs, the converters in DC-SMGs require much higher voltage rating, and the power density constraints in maritime application is less limited than that in aircraft power systems but higher than terrestrial DC MGs. Besides, reliability in ships and aircrafts has super high priority. Except these differences, power converters in both maritime and other applications have requirements of high efficiency and low cost. As high power and high voltage is the developing trend of future DC-SMGs, this paper focuses on the power converters in this category. The summary and comparison of these converters are presented in TABLE VI and TABLE VII. There are more power converters, e.g. Vienna rectifier, and hybrid modular multilevel converter (MMC), which are not discussed in this paper due to their limited availability in maritime application.

### A. Rectifiers

In DC-SMGs, all generators will be available for providing energy through rectifiers, which convert AC to DC, and take the responsibility of stabilizing the DC bus voltage. Therefore, rectifiers directly affect the quality of DC supply. Essentially, unidirectional AC/DC conversion can realize the function since generators are only supposed to supply power to the system.

Various rectifier topologies for marine applications are available in present, which can be categorized into two-level and multi-level rectifiers according to the output voltage level.

#### 1) Two-level rectifier

Classical two-level voltage source converters (VSCs) are commercially available in medium voltage applications. The converter topology together with three-phase generator is shown in Fig. 10, in which the switches can be diode (uncontrolled), thyristor (half-controlled), and IGBT (fully-controlled), as shown in Fig. 10 (a), (b), and (c), respectively.

##### a. Diode rectifier

Diode rectifiers are the most popular type of ac/DC conversion in SMGs, thanks to its simple, reliable, and cost-efficient. However, the DC-side voltage or the AC-side current cannot be actively regulated by rectifiers, in which case the voltage regulation of PGM is achieved by regulating the excitation system of generators. Besides, diode rectifier may inject current harmonics into the system, and additional filters are necessary to improve the power factor.

Multi-phase multi-pulse rectifier (e.g. 12-pulse, 18-pulse, 24-pulse) depending on the voltage and power requirements of the system are preferred as an interface of the three-phase AC generators, by parallel or series connecting multiple 6-pulse diode rectifier units, as shown in Fig. 11 (a) and (b), respectively [24], [69]. The benefits of this multi-pulse rectifier are: 1) Reducing the voltage or current stress on switching devices, allowing the utilization of present semiconductor technologies efficiently while reducing the input current harmonics. 2) Achieving medium voltage in a scalable way, which adds flexibility in determining voltage class of generators. 3) Providing better fault tolerance by bypassing the faulty unit or faulty winding and operating in a

de-rate mode. However, the fault performance in an uncontrolled diode rectifier is limited. For a series multi-pulse diode rectifier, when a short circuit happens in one 6-pulse diode rectifier unit, the other unfaulty ones cannot output power as well due to the demagnetizing action of the short circuit current [70].

There are some practical cases of marine generation system using diode rectifiers. A marine generation system in MVDC AES consisting of a 21MW synchronous generator, a three-phase passive diode rectifier with an output low-pass filter is presented in [71]. A demonstrative program commissioned by the Italian Navy, named Naval Package (NP), developed a shipboard 2.15MVA generation system in 2006, in which a dual-star alternator with two stator three-phase windings feeding two series 6-pulse diode rectifiers [72]. To improve the voltage controllability and fault performance, an advanced NP2 based on previous NP version is developed in [73], consisting of a permanent magnetic quadruple-star alternator with four sets of three-phase stator windings, four series-connected 6-pulse diode rectifiers and choppers fed by each set of windings.

Furthermore, to enhance the output voltage control and fault current limit capability, an ac/DC converter composed of a DC/DC converter cascaded to a diode rectifier is a potential solution. In [74], a 12-phase wound-field synchronous generator along with control rectifiers (diode rectifiers with choppers) is presented for marine generation systems.

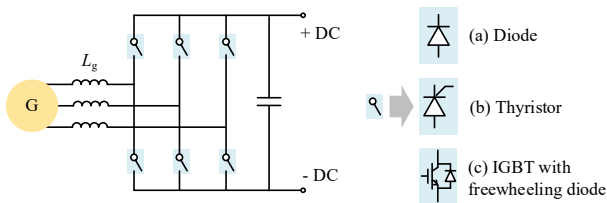


Fig. 10. Two-level rectifiers

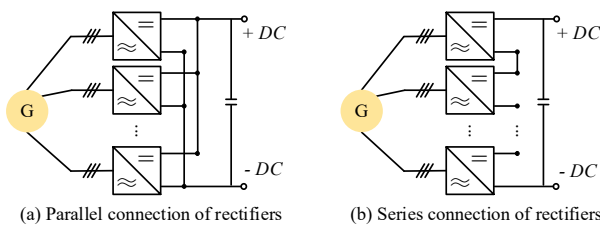


Fig. 11. Multi-phase generator with multiple 6-pulse diode rectifier units, (a) parallel connection of rectifiers, and (b) series connection of rectifiers.

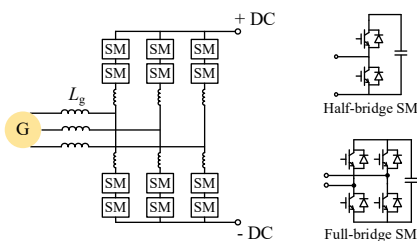


Fig. 12. MMC.

b. Thyristor rectifier

The thyristor rectifiers are used in LVDC marine networks, and the research is in the process of the extension to utilization in MVDC systems. Besides the advantages in diode rectifiers, thyristor rectifiers have output voltage control in a narrow range and fault current control capabilities, which is suitable in breaker-less shipboard architecture [75]. However, the control circuit makes the converter construction more complicated than diode rectifier.

To meet the high power and high voltage requirements, thyristor rectifier is widely studied. A 12-pulse thyristor rectifier, in which a phase-shift transformer is used to produce two sets of three-phase windings, is studied in [76]. In the applications where generators are three-phase, low-frequency (60Hz) transformers are required to get several sets of windings so that the multi-pulse thyristors rectifiers can be implemented. In [77], a 50MW shipboard system adopts a 3 to 12 phase transformer and a 24-pulse thyristor controlled rectifier to convert source energy from AC to DC distribution. In this case, the size and weight of the low-frequency transformer are obstacles if applied in practical ships. Furthermore, an extra device of reactive power generator is required when the thyristor rectifier is supplied by a PMSM or an induction generator [78]. If so, the diode rectifier can also satisfy the voltage conversion needs, which makes it unnecessary to implement the thyristor rectifier.

c. IGBT rectifier

The semiconductor switches in IGBT rectifiers are IGBTs with freewheeling diodes. With controllable switches, IGBT rectifier is able to generate a controllable DC voltage, which is preferable in stabilizing the DC bus voltage in SMGs. Besides, improved dynamic performance, extended operating range, and ride through capability can be achieved. However, the adoption of active semiconductor devices increases the cost and control complexity. Furthermore, the bidirectional power flow regulation capability brought by IGBT rectifier is not desired in SMG generation set application. Thus, the active rectifier is just implemented in study cases and not widely used yet for the generator in practical marine applications at present.

2) Multi-level rectifier

In order to match the high power ratings, the design of power converters in SMGs is oriented toward modular topologies. MMC is a promising topology in high-voltage DC transmission systems, and is receiving increasing attention in medium voltage applications as well. Some experimental platforms of MVDC SMGs based on MMC are built and tested [79], [80]. The topology of MMC rectifier is shown in Fig. 12. Each arm consists of cascaded submodules (SMs), which can be half-bridge or full-bridge. With  $N$  SMs in each arm, the output voltage could reach  $2N-1$  levels. With the modular structure, MMC has the advantages of voltage and current scalability, high efficiency, redundancy in case of module failure, and reduced voltage rating of single switching devices. In addition, compared with the aforementioned rectifier topologies, normally no output filter is needed in

MMCs, which helps limit short circuit current and shorten the recovery time. However, the modular design also leads to bulky size and weight, which is not preferable in SMGs. A 5MW 6-24kV MVDC power hardware-in-the-loop platform is built in Florida State University, which contains four MMCs composed of 36 full-bridge SMs [81], and further studies on fault management are taken based on this setup [79].

3) Comparison and analysis

Analysis on the comparison are taken from the aspects of power density, converter reliability, and efficiency. In terms of power density, two-level topologies are more compact due to fewer semiconductor switches and DC capacitors than MMC rectifier, as shown in TABLE VI. In terms of reliability, the passive diode rectifier is simple in structure and does not need controller, making it highly robust. On the contrary, numerous switching devices and capacitors and high control complexity of MMC weaken its reliability, although it can achieve partial fault ride-through capability with redundant SMs [82]. In terms of efficiency, two-level rectifiers generally have higher operating efficiency than MMC, due to less switching and conduction losses. Diode rectifier has the highest efficiency since it has no switching losses and power losses in gate driver circuit.

To sum up, for large ships that have high requirement of power capacity and have sufficient space to accommodate a ring or zonal power system, as shown in Fig. 3 and Fig. 4, to improve its system reliability, MMC is preferred due to its high output performances. For small ships with limited space, where radial power system is usually used, diode rectifier and thyristor rectifier are preferred to achieve better reliability and economy.

B. Inverters

Inverters are a vital interface for propulsion motors, which consume nearly 80% of the total energy in ships. Electric propulsion system requires variable frequency drives in multi-megawatt range, which features high overall efficiency, fast system response, precise speed and torque control, wide speed control range, soft starting, speed reversal and regenerative braking [83]. Significant challenges in designing medium voltage drive in DC systems are in the motor-side, e.g.,  $dv/dt$ , common mode voltage, harmonics, resonance, and semiconductor devices, e.g., switching losses and reliability

[84]. To meet the marine propulsion requirements and overcome those challenges, normally multilevel inverters are employed. This section reviews the state-of-the-art on high power drives in marine applications, which can be evaluated by the key aspects mentioned in [85], including output voltage level, fault tolerance, and efficiency.

Medium-voltage AC drives are available in a variety of arrangements, depending on the motor types. Generally, 1) DC motors require DC converters or silicon-controlled rectifiers (SCRs), 2) asynchronous motors require voltage source inverters (VSIs), 3) synchronous motors require VSIs, current source inverters (CSIs), cycloconverters, 4) PMSM's require VSIs [83], [86].

Typical topologies of inverters for electric propulsion in DC-SMGs are shown in Fig. 13. Presently, neutral point clamped (NPC) inverters and MMC are popular in commercial propulsion drive. Even though there are two-level VSIs for industrial high power drives, most of them are used in high power traction applications. Furthermore, two-level VSIs cannot provide redundancy under faulty conditions. Thus, multilevel inverter topologies are mainly focused here.

1) Two-level inverter

Two-level inverters mainly include two types: two-level VSI and CSI. Since the topology and operating principles of are very similar to two-level voltage source rectifiers mentioned in IV.A, this topology will not be repeated here.

The load-commutated inverter (LCI), as one typical topology of CSIs, is widespread in the speed controller of synchronous motors for large ship propulsion [87], [88]. The configuration of LCI-fed drive system is shown in Fig. 14. The switching devices of LCI are low cost thyristors compared with transistors. For high power propulsion drives, dual three-phase LCI-fed synchronous motor, is suitable with the benefit

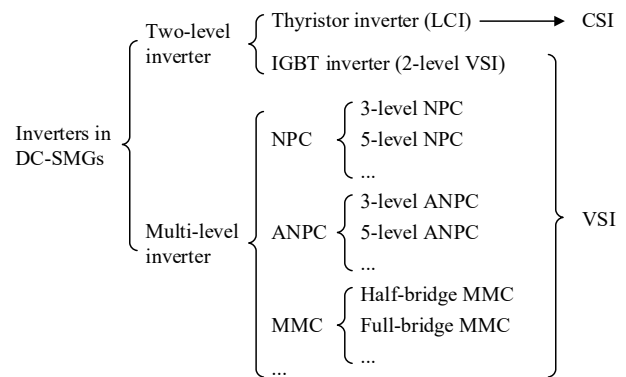


Fig. 13. Classification of inverters for propulsion motors in DC-SMGs.

TABLE VI. COMPARISON OF R

	Diode rectifier*	Thyristor rectifier / LCI	IGBT rectifier*				
Output voltage levels	-	-	2				
Voltage stress		$v_{dc}$		$v_{dc}/N$ [126]		$v_{dc}/2$ [93]	
Filter Inductor size		High		Low		Medium [127]	
Capacitor number		1		$6N$		2	
Switching frequency	-	Several to tens kHz		Hundreds Hz [128]		Hundreds to thousands Hz [93]	
Number of switches	6 diodes	6 thyristors	6 IGBTs	$12N$ IGBTs	$24N$ IGBTs	$12$ IGBTs and $6$ diodes	$18$ IGBTs
Control complexity	No control needed		Simple		Complex		Medium
Fault tolerance		×			$\sqrt{}$ [129]		×
Fault ride-through capability		×		×	$\sqrt{}$ [131]		×

\* represents only for rectifiers; \*\* represents only for inverters; otherwise, the topologies are suitable for both rectifiers and inverters.

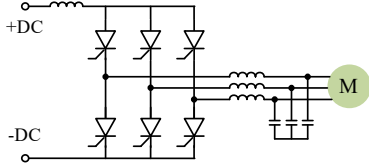


Fig. 14. Simplified equivalent circuit of three-phase WFSM connected to LCI

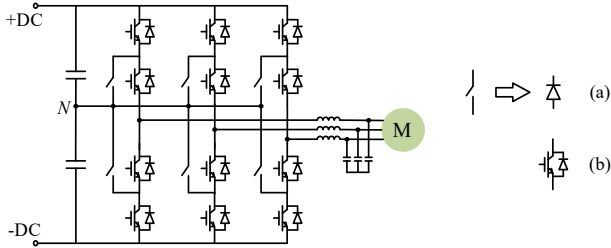


Fig. 15. Three-phase three-level NPC inverter

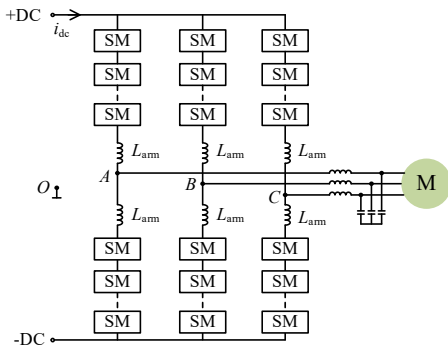


Fig. 16. Scheme of MMC drive

of low dominant torque harmonic components [87]. To meet power quality requirements, 24- or 48-pulse configuration can be employed as well. The architecture for LCI drives depends on the number of LCIs, DC-link connection, and the number of synchronous motor phases [89]. It should be noted that LCIs for marine propulsion in literature are generally used in AC systems, and when adopting this converter in DC systems, a proper adjustment in converter connection should be considered.

LCI-based medium-voltage marine electric propulsion is available in the industry [90]. Siemens has the product of SINAMICS GL150 with the power range 6-85MVA [91], and it has the advantages of control redundancy and being almost maintenance-free.

2) Three-level inverter

Three-level NPC inverters are typical three-level inverters and widely used in high-power drive applications with the power level of several megawatts. The configuration of three-level NPC drive is shown in Fig. 15 (a). Compared with traditional two-level inverters, three-level NPC inverters present advantages in terms of lower semiconductor stresses, better output voltage and current quality and reduced voltage peak transient at the motor terminals. While compared with other multilevel converter topologies, three-level NPC has a

simpler circuit structure, leading to a smaller footprint [92]. However, three-level NPC inverters have the drawback of an unsymmetrical temperature distribution of semiconductor junction resulting from the unequal loss distribution, especially when the converter operates at low fundamental frequency [93].

The marine propulsion drive based on three-level NPC has been produced by ABB and Siemens. ABB has ACS 6000 [94], which can drive propulsion motors up to 36MW, and Siemens has SINAMICS GM150 [95], [96] for IMs and synchronous motors.

To overcome the drawbacks of unequal loss distribution in three-level NPC inverters, active NPC (ANPC) inverter is used in some cases. In three-level ANPC, the clamping diodes in NPC are replaced by the two series IGBTs and freewheeling diodes, as shown in Fig. 15 (b), achieving active clamping. Different commutations and switching states can be used to distribute losses more evenly by selecting the circuit loop, and proper active loss balancing methods are presented in [93], [97].

GE has developed the three-level ANPC based marine drive system, MV7000 [98], with the capacity up to 81MW, suitable for IMs, synchronous motors, and PMSMs. A three-level ANPC/H-bridge hybrid inverter suitable for ship propulsion is presented in [99]. By replacing the clamp IGBT of SiC MOSFET, the switching losses can be reduced, hence system efficiency and harmonic performance are improved.

3) Multi-level inverter

MMC topology is a promising candidate for high power propulsion, and the topology is shown in Fig. 16. This configuration has the advantages of fault-tolerant capability, modularity, and voltage scalability features. Furthermore, it has the benefits of reduced requirements on switch voltage ratings, allowing a filter-less connection to the grid with low harmonics, fault current limitation capability, fast recovery after AC or DC short circuit faults.

Though MMC inverters are originally used in high power grid systems, they are becoming increasingly popular in propulsion drive applications. It should be noted that the benefits of MMC inverter is not significant if the DC bus voltage is not high, and filters are needed if there is only a few SMs in each arm.

The operation principle of MMC for marine propulsion is studied in [100]. In the industrial community, Siemens develops the SINAMICS SH150 [91] and H-Compact Plus, which consists of 17L full-bridge MMC topology [101], [102] for marine propulsion.

4) Comparison and analysis

Comparison of above four inverter topologies is shown in TABLE VI. Similar with that in rectifier section, analysis on the comparison are taken from the aspects of power density, converter reliability, and efficiency. To avoid repetition, the analysis on LCI and MMC inverter is simplified in this subsection. In terms of power density, two-level inverter has the highest power density, NPC and ANPC are the next, and the power density of MMC is the lowest because of its

numerous number of switching devices and energy storage elements. In terms of reliability, similar to the analysis of rectifiers, two-level inverters with simple power circuit and control system have higher reliability than MMC topology. The advantage of MMC is its higher control flexibility and better output performance. In terms of efficiency, NPC/ANPC have higher conduction losses and switching losses than two-level LCI due to more switches [103]. Similarly, MMC inverter has even higher losses.

In summary, the principle of inverter topology selection is similar to that of rectifiers. Large ships that require high drive power supply can choose NPC/ANPC or MMC to obtain higher output power and better control performance, at the cost of occupying more cabin space and hardware cost. For small-power ships, it is recommended to choose a two-level inverter to improve the economy of the SPS.

C. DC/DC Converters

In DC-SMGs, many interfaces are requiring DC/DC converters, including the interfaces of DC ESS sources and the connections between MVDC and LVDC buses. In low power applications, buck and boost converters are enough for converting the voltage, while this section focuses on the high power and medium voltage SMGs, in which both the power conversion capacity and operation safety are required [104], [105], [106]. Thus, high power galvanic isolated DC/DC converters for DC-SMGs are presented as follows.

1) Dual-active bridge DC/DC converter

Dual active bridge (DAB) DC/DC converters catch much attention in high power applications for the merits of inherent soft-switching capability, galvanic isolation, high power density, and bidirectional power flow [107].

A typical DAB converter topology is depicted in Fig. 17, as

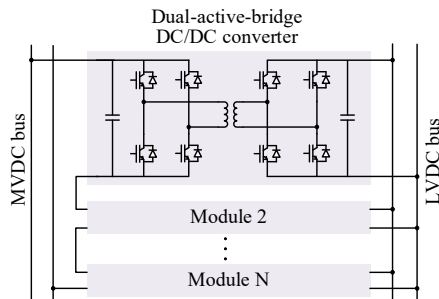


Fig. 17. Input-series-output-parallel dual-active-bridge DC/DC converter

a module of the whole converter configuration. It consists of two full-bridge converters with DC capacitors and a high/medium-frequency transformer. Two active H-bridge converter make bidirectional power flow possible. The transformer is applied for voltage matching and galvanic isolation. The medium/high-frequency operation significantly reduces the size and weight of passive components, enabling a high power density [108]. To increase the power rating, input-series-output-parallel (ISOP) DAB can be used. However, due to the DC-link capacitors, the DAB converter cannot completely control the fault current. In addition, for ISOP DAB in high power applications, power balancing among different modules is a challenge to suppress the circulating current and balance the capacitor voltage in each module.

At present, the research topics of DAB mainly focus on topology operation, the basic characteristics, expanding the soft-switching range, redundancy design, and control methods [109]. In [110], a 10kV/380V ISOP DAB in MVDC SMG is studied in terms of ISOP balancing with parameter mismatch, and fault state control.

2) NPC-based DC/DC Converter

Three-level NPC-based DC/DC converter is another option for DC-SMGs. A typical three-level NPC-based DC/DC topology is shown in the frame of Fig. 18. The benefits of NPC are clarified in inverter section. Even though three-level converter has the advantages of low switch voltage stress, low electromagnetic interference (EMI), and good power quality [111], when it comes to medium-voltage high-power applications, semiconductor switches and diodes are exposed to considerable current stress. To fit the high power rating requirement in SMGs, a multi-phase NPC-based DC/DC converter (4000V/710V) for DC-SMGs is presented in [112]. In addition, the ANPC DC/DC converter for MVDC grid is

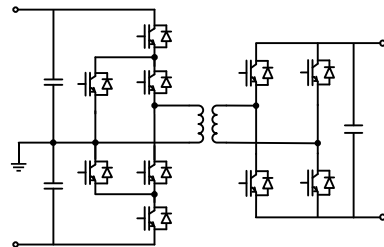


Fig. 18. Three-level NPC-based DC/DC converter

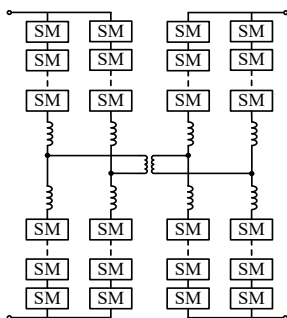


Fig. 19. Single-phase isolated modular multilevel DC/DC converter

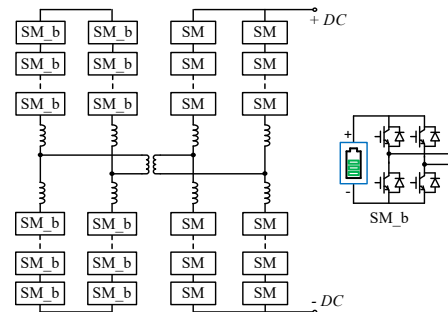


Fig. 20. iM2DC integrated with battery

TABLE VII. COMPARISON OF DC/DC CONVERTERS

	ISOP DAB	iM2DC		NPC-based dc/dc converter
		Half bridge	Full bridge	
Voltage stress	$v_{dc}/N$ and $v_{dc}$	$v_{dc}/N$		$v_{dc}/2$ and $v_{dc}$
Inductor and transformer number	$N$ transformers	12 inductors and one transformer		One transformer
Capacitor number	$2N$	$12N$		3
Switching frequency	Hundreds Hz to kHz [133]	Hundreds Hz to kHz [134]		Hundreds Hz [112]
Number of switches	$8N$	$16N$	$32N$	10
Control complexity	High	High		Medium
Fault tolerance	$\times$	$\sqrt{[135]}$		$\times$
Fault ride-through capability	$\sqrt{[134]}$	$\times [136]$	$\sqrt{[108]}$	$\times$

$N$  in this table represents the number of modules in each modular power converter.

studied in [111] to achieve better thermal performance in semiconductor devices and lower losses.

### 3) Isolated MMC DC/DC converter

Isolated MMC DC/DC converter (iM2DC), as shown in Fig. 19, is relatively a new technique in medium voltage applications, which is firstly proposed and used in HVDC power transmission systems. A typical iM2DC consists of cascaded SMs, as mentioned in multi-level rectifier section, and an isolated medium-/high-frequency transformer. The advantages of iM2DC partly come from the modular scheme. Therefore, being the same as those in MMC rectifier, including flexibility in interfacing different voltage levels, fault-tolerant ability, and easy maintenance, the transformer provides galvanic isolation between the high voltage side and the low voltage side. However, due to the relative low voltage of SMGs, the number of SMs in MVDC systems is much less than that in HVDC systems, while the compact design onboard do not allow much redundancy equipped, therefore resulting in the deterioration of fault tolerance performance. In addition, the transformer frequency is a tradeoff between transformer size and converter switching losses. Besides, capacitor voltage balancing among SMs, circulating current, and redundancy design are important issues to consider in iM2DC.

The iM2DC for MVDC zonal SMGs is studied in [113], and the operation principle and control of the 5kV/2kV iM2DC, with six and three SMs in each arm of medium- and low-voltage side, respectively, are analyzed. In [114], the fault performance of an iM2DC in SMGs is studied, in which the LVDC bus voltage is 1kV and there are 4 SMs in each arm, with 2.25kV cell capacitor voltage reference.

A variation of iM2DC in which the BESS is integrated into MVDC SMG is emerging. In the primary side of high frequency transformer, the capacitor in each SM of typical iM2DC is replaced by battery packs, while in the secondary side, full-bridge SMs are deployed, as shown in Fig. 20 [115]. This converter provides DC active power filter (APF) function to smooth out the MVDC bus current via the SM capacitors in the medium-voltage side, and the battery ESS in the low-voltage side is responsible for providing active power.

### 4) Comparison and analysis

Comparison among above DC/DC converters are presented in TABLE VII. With modular structure, ISOP DAB and iM2DC can support relative high voltage easily, and have good fault management capability. Therefore, they are suitable

for large ships with high power demands. Especially, iM2DC achieves good performances in high voltage SMGs, in which more SMs can be implemented in each arm so that the power quality is improved. However, these two converter types require numbers of inductors, transformers, and capacitors in the meantime, resulting in the converters being bulky and the control being complex. While NPC-based DC/DC converter is simpler in structure and more efficient than ISOP DAB and iM2DC converters, but it has problems in fault tolerance. Therefore, NPC-based DC/DC converters suit for medium-sized and short voyage-distance ships of which the SMG voltage is not high and the fault tolerance requirement is not highly strict.

## V. CONCLUSIONS AND FUTURE DIRECTIONS

Presently, DC-SMGs have become one of the major research directions in the marine industry for their benefits in terms of efficiency and resiliency. This paper presents an overview of the state of the art of the techniques in DC-SMGs, including the power architecture, functional blocks, and power converters.

Power architecture in DC-SMGs includes the DC bus configuration and system scheme. In terms of power configuration of DC-SMGs, bipolar bus architecture is more widely used than unipolar ones. The DC bus voltage ranges from less than 1kV in LVDC systems to 1.5kV and 3kV or even higher in MVDC systems depending on the ship type and load demands. Power components in DC-SMGs can be arranged in radial, ring, or zonal structure. Radial architecture is the most widely used among these three types by borrowing from general DC MGs. In order to actively manage the power flow and improve fault performance, ring distribution system is studied in some cases. Zonal distribution further ensures reliability and power supply continuity on the basis of ring architecture, as all the low voltage loads are separated into several load centers, and each load center can be fed by DC buses on both sides of the ships.

Functional blocks in DC-SMGs include PGMs, ESSs, propulsion systems, dedicated high power loads, and pulsed loads. PGMs mainly include synchronous generators and FCs, and both of them have the problem of slow dynamics due to large inertia and internal electrochemical responses, respectively. To overcome this drawback, ESSs are used to provide fast power supply and achieve transient generation-demand balance. Besides, ESSs help to improve the generator efficiency with specific optimization algorithms. ESSs with

different characteristics are reviewed, including batteries, UCs, flywheels, and superconducting magnet. Among these, battery packs have large power capacity, while UCs, flywheels, and superconducting magnet ESSs have fast charging and discharging rates, which is suitable for compensating step power demand caused by pulsed loads. Propulsion motors in ships can be IMs, WRSMs, or PMSMs. Multi-phase motors are usually used in high power marine applications. Besides propulsion loads, which take nearly 80% of total power demand, there are specific high power loads, service loads, and pulsed loads for military ships.

In order to manage functional blocks, proper controlled power converters are vital parts of the systems. Existing rectifiers, inverters, and DC/DC converters interfacing PGMs, propulsion motors, ESSs, and load centers in the DC-SMGs, are discussed. For rectifiers, two-level full-bridge rectifiers are common in relative low power SMGs. Among them, diode rectifiers are currently mostly used due to the high reliability, simple structure and low cost. With more controllability in semiconductor switches, thyristor and IGBT based two-level rectifiers have better performances in voltage regulation and power quality. MMC rectifiers suit for high power SMGs with relative high voltage. Inverter topologies for inductance motors can be LCI, three-level NPC/ANPC, and MMC inverters, depending on the requirement of power level and power quality. The commercial products using these topologies are introduced in this paper. In addition, isolated DC/DC converters for ESSs and DC load centers are discussed. To meet high power demands in future ships, modular converter structures are preferred, such as DAB and iM2DC.

Though much work has done on DC-SMGs, there are still some challenges need to overcome on the way to make the electric ships prevalent:

- 1) High requirement on system reliability. The reliability may be affected by various factors. From the perspective of system architecture, there is a tradeoff between system reliability and system complexity. From the perspective of shipboard loads, more numbers and types of loads with different characteristics are integrated and the system control becomes complicated.
- 2) High requirement on system power density. One of the main barrier of developing all-electric ships is the insufficiency of ESS capacity. Though it can be solved by parallel and cascaded connecting multi energy storage units, the compact design cannot achieved in this way. Thus, it is a tradeoff between ESS capacity and its volume and weight.
- 3) High requirement on system stability. Considering numerous power converters, shipboard load types, e.g., the pulsed load, and the harsh onboard operation conditions, ensuring the stability of SMG is still a challenge.
- 4) The protection of DC-SMGs. The presence of pulsed loads may cause malfunction of fault detection. Besides, general challenges in DC power systems also exist in DC-SMGs, such as lacking of high voltage DC breakers.

With above technical challenges, proper solutions have to be studied and developed. Besides, potential research

directions are identified as follows: 1) With the objective of high capacity and high energy density, improvement on existing ESS and novel energy storage techniques are desired. Currently, all-electric ships are only for short-distance voyage due to the limited power capacity. Fuel cells and superconducting magnetic ESS are briefly introduced in this paper, and they have much potentials in SMGs if the drawbacks are overcome. Besides, proper allocation and organization of different types of power sources is needed in practice to avoid the system being bulky and weighty. 2) In military ships, specific power supply for pulsed loads is far from mature and needs extensive study. The pulsed loads require power supply with high power ramp and high peak power, and this demand may cause stability issues on the system. 3) Fast charging from onshore power system is another research trend. At present, electric ship charging relies on proper scheduling between ship and harbor in order to set aside more time for charging. However, from the perspective of ship operation, it may be not cost-efficient. The fast charging techniques for electric vehicles need modifications if using in ships, since the voltage and power ratings are different in these two applications.

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