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A Review of Power Converters for Ships Electrification

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LIST OF ABBREVIATIONS

3L-NPC	Three-Level Neutral-Point Clamped
AES	All-Electric Ships
APF	Active Power Filter
CPT	Capacitive Power Transfer
CSC	Current Source Converter
DAB	Dual Active Bridge
EMI	Electromagnetic Interference
ESS	Energy Storage Systems
EV	Electrical Vehicles
GaN	Gallium Nitride
GTO	Gate turn-off thyristor
IEGT	Injection Enhancement Insulated Gate Bipolar Transistors
IGBT	Insulated Gate Bipolar Transistors
IGCT	Integrated Gate Commutated Thyristors
IMO	International Maritime Organization
IPT	Inductive Power Transfer
JBS	Junction Barrier Schottky
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single-Output
MMC	Modular Multilevel Converters
MOSFET	Metal Oxide Semiconductor Field-Effect Transistors
MVDC	Medium-Voltage DC
PEI	Power Electronics Interface
PFC	power factor correction
PV	Photovoltaic
PWM	Pulse Width Modulation
SiC	Silicon-Carbide
SIMO	Single-Input Multiple-Output
SM	Submodules
THD	Total Harmonic Distortion
VSC	Voltage Source Converter
WBG	Wide-Bandgap
WPT	Wireless Power Transfer

Abstract—**Fully-electric ships have become popular to meet the demand for emission-free transportation and improve ships' functionality, reliability, and efficiency. Previous studies reviewed the shipboard power systems, the different types of shipboard energy storage devices, and the influences of the shore-to-ship connection on ports' electrical grid. However, the converter topologies used in the electrification of ships have received very little attention. This paper presents a comprehensive topological review of currently available shore-to-ship and shipboard power converters in the literature and on the market. The main goal is to anticipate future trends and potential challenges to stimulate research to accelerate more efficient and reliable electric ships.**

I. INTRODUCTION

The transportation sector exerts considerable effort to phase out fossil fuels because of the scarcity of their resources, price volatility, and the negative impacts on human health and the environment. Although the share of shipping emissions in global air emissions is only 2.89%, the International Maritime Organization (IMO) plans to reduce the emissions by 50% of 2008 emissions in 2050 [1]. Integrating more renewable energy resources in the shipping industry is one way toward the modest goal of decarbonization.

Electrification of ships has a long history, back to the early 1800s, resulting in the development of today's all-electric and hybrid ships [2]. Reusser et al. [3] classified the shipboards propulsion systems according to energy source into (1) thermal, which includes diesel engines, gas turbines, and combined engines; (2) fully electric, in which a direct connection is between the prime mover and a motor with or without a gearbox; and (3) hybrid system which is a combination of diesel engines or gas turbines with electric motors.

Fang et al. [4] categorized the electrification of ships by considering the connections between the propellers and prime motor in (1) conventional mechanical-driven ships in which the connection between the prime motor and the propeller is via a gearbox; (2) electric-driven ships in which there is no connection between the propeller and the prime motor; and (3) All-Electric Ships (AES) in which the onboard generators meet the propulsion and service loads via the integrated power system. By combining the previous two classifications, we can sub-categorize AES down considering the shipboard power systems into hybrid power systems in which thermal energy source is part of the systems and fully-electric in which Energy Storage Systems (ESS) and renewable energy resources are the primary sources of power onboard, as illustrated in Fig. 1.

In the literature, several studies have reviewed different aspects related to the electrification of ships. Jafarzadeh et al. [5] identified the types of ships that can benefit from electric

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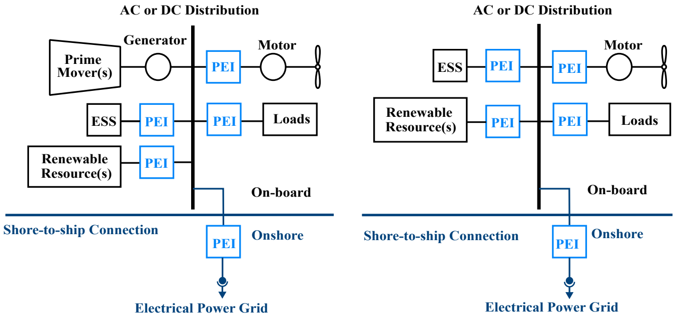

(a) (b)

Fig. 1. Single-line diagram overview of the power converters as Power Electronics Interface (PEI) in a shipboard AES power system: (a) Hybrid power system. (b) Fully-electric power system.

and hybrid solutions. Geertsma et al. [6] also reviewed shipboard electric and hybrid power supplies, propulsion system architectures, and their associated control strategies. Kumar et al. [7] classified ships and their power systems and elaborated on energy efficiency and power quality in these systems.

The main characteristic of the emerging shipboard power systems is an increasing load variability and pulsation, which require more power than the available at steady-state [8]. In other words, the shipboard loads may be intermittent, operating on time scales down to milliseconds or less, and can require from kW to MW or even GW power ranges. Shipboard ESS can provide the extra power needed during load variation and pulsation. Mutarraf et al. [9] reviewed several types of ESS and the critical challenges of integrating them into shipboard power systems. They found that Li-ion batteries are the most common for shipboard power applications, specifically for ferries.

The major players in marine battery applications on the market are ABB, ZEM Energy, Siemens, and Corvus Energy. For instance, Corvus Energy has already developed maritime ESS for fully-electric fish farm supporting vessels (200 kW h to 500 kW h), 15 car ferries (500 kW h to 3000 kW h), three passenger vessels (2000 kW h to 3000 kW h), and 96 hybrid ships [10]. Table I lists some examples of ships with onboard battery systems in Norway.

A shore-to-ship connection should provide cleaner power to ships during docking or charging the shipboard batteries. Kumar et al. [15] reviewed three alternative battery-charge scenarios: onshore slow charging, onboard fast charging, and a hybrid charging category. Khersonsky et al. [16] and Karimi et al. [17] reviewed the current state of shore connection and applicable standards for shore-to-ship interconnections, and proven techniques for shore power interconnections. Sciberras et al. [18] studied the electrical characteristics of the shore connection installations and their influence on electrical network characteristics. In addition, Kumar et al. [19] surveyed the technical aspects, the existing standards, and the critical challenges in designing and modeling a harbor grid for the shore-to-ship power supply.

Thus far, however, power converter topologies have received much less attention than shipboard power systems, ESS, and shore connections. Power converters are the key players in the electrification of ships. As a Power Electronics Interface (PEI), converters have a vital role in integrating ESS, speed control of electric propulsion, and as an interface between the shore power installation and ships, as illustrated in Fig.1. The extent of electric ship development depends on the utilized converters' reliability, efficiency, and cost-effectiveness. This paper thoroughly reviews the converters' topologies used in the electrification of ships found in the literature and on the market. It also gives instructions for designing, analyzing, and selecting a suitable converter for ships. Moreover, the paper tries to anticipate future trends and potential challenges.

The organization of the rest of the paper is as follows: Section II presents the shore-to-ship converters. Section III investigates the shipboard converters. Section IV overviews the most common solid-state device technologies available for ships. Section V gives instructions and requirements for selections of topologies. Section VI addresses the future trends that need more research and investigation. Finally, section VII concludes the paper.

II. SHORE-TO-SHIP CONVERTERS

Although some shore-to-ship connections are simple plug-ins with no power electronics, this section focuses on the PEI in the shore connections. Conductive (wired) and wireless connections are the two main approaches to shore-to-ship electrical connections.

A. Conductive Connection

GloMEEP [20] [1] categorized the ships based on the shore power installation requirements into small ships with moderate power requirements (less than 50 kW to 100 kW) and large ships with high power requirements (100 kW up to 10 MW or 15 MW). Kumar et al. [19] sub-categorized the ships based on the connection of the voltage level to medium and low-voltage: the shore-side medium-voltage level is 6.6 or/and 11 kV, while the low-voltage range is 380 V to 460 V and 50 and/or 60 Hz. The two categorizations can help in designing and operating the converters used in the conductive shore-to-ship connection. Nevertheless, the categorization based on the voltage level suits this paper better.

1) Medium-voltage converters: The world's first commercial shore-to-ship 10 kV and 1 MW to 1.5 MW power installations were at the Swedish port of Gothenburg in 2000 [16]. Since then, many ports around the world have implemented shore power installations. The shore conductive connection (also known as "the cold ironing") provides power to ships at berth while its main and auxiliary engines are off to reduce engine emissions. With the wide variety of the ships' voltages and frequencies, some ports have the following electrical infrastructure [21]: (1) a frequency converter: to adapt the frequency of electricity from the local grid to match the ship's frequency, (2) protections equipment: to provide electrical protections such as breakers and disconnectors, an automated earthing switch, a transformer, protection equipment such as

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[1] It is a GEF-UNDP-IMO project that supports the uptake and implementation of energy efficiency measures for shipping to reduce emissions.

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TABLE I
SUMMARY OF BATTERY BASED SHIP.

Year	Vessel's Name	Vessel's Type	Fuel Type	Battery's Provider	Capacity [kWh]
2015	Karoline [10]	Fishing Boat	Diesel	Corvus Energy	195
2015	Viking Ship [11]	Supply Vessel	LNG	ZEM Energy	653
2015	MF Ampire [10]	Car Ferry	Fully Electric	Corvus Energy	1090
2015	MF Folgefonn [10]	Car Ferry	Diesel	Corvus Energy	1000
2017	GMV Zero [10]	Fish-farming Support	Fully Electric	Corvus Energy	340
2018	Future of The Fjords [12]	Ferry	Fully Electric	ZEM Energy	1800
2018	Forsea [13]	Ferries	Fully Electric	ABB	4160
2019	Color line [14]	Cruise Ferry	Diesel	Siemens	5000

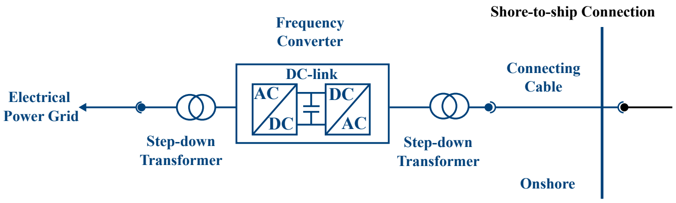

Fig. 2. The generic architecture for medium-voltage shore-to-ship connection.

transformer and feeder protection relays, and (3) communications equipment: to link ship and shore.

Fig. 2 shows the generic architecture for medium-voltage shore-to-ship connection. The transformers step up or down the voltages and provide galvanic isolation. The frequency converter is a prominent part of the system that supplies ships with the required operational frequency. In addition to the converter and transformers, IEC/IEEE 80005 standard [22], [23] set out requirements for circuit breakers, earthing switches, and fiber optic connection for data communication, but the figure does not illustrate them as they are out of the scope of the paper.

The conventional frequency converter is a three-phase front-end diode bridge rectifier followed by a three-phase inverter, as shown in Fig. 3 (a). This topology suffers from high input Total Harmonic Distortion (THD) and electromagnetic interference issues. Sciberras et al. [18], Zhu et al. [24], and Anurag et al. [25] proposed a front-end active bridge rectifier to replace the diode bridge rectifier and achieve low THD and high power factor. Six-pulse, 12-pulse, 18-pulse, or 24-pulse rectifiers are alternatives to reduce the harmonics further [3], [18], [26], [28]. Fig. 3 (b) to (d) shows 12-pulse and 24-pulse rectifiers as examples that are used in shore-to-ship connections. These converters minimize harmonic distortion but increase the switching losses. Higher pulses converters like a 36-pulse inverter can be used to further reduce the THD [29], but the complexity, size, and weight of the transformer will increase.

As an alternative, Strzelecki et al. [27] investigated an 8 MVA cascaded diode bridge rectifier followed by Three-Level Neutral-Point Clamped (3L-NPC) inverters to achieve high voltage and power capability. Fig. 4 (a) shows the rectifiers are connected in parallel to convert the voltage from the coupled coils of the transformer into 7 kV dc, and then the parallel-connected 3L-NPC inverters convert the dc voltage back to 50 or 60 Hz ac voltage. In contrast, Fig. 4 (b) illustrates the rectifier pairs are connected in series to achieve 14 kV dc at the bus, which is followed by the series-connected 3L-NPC inverters convert the dc voltage into 50 or 60 Hz ac voltage [27].

In [27], the authors suggested twelve pulse diode rectifiers to achieve twenty-four pulse rectifications in parallel connection or twelve pulse rectifications in the series connection. The twenty-four pulse parallel-connected rectifiers are more favorable as they reduce the harmonic content and hence require either a simple and small separate filter or an integrated filter with the secondary winding of the star/delta transformer. However, the main limitation of the rectifiers is the high conduction losses due to the diode conductive and reverse recovery losses. One way to tackle this issue is by using Silicon-Carbide (SiC) based Schottky diodes. However, it would increase the overall cost of the converter.

The three-level inverters have a high output power capability, relatively simple control, and a positively verified compact structure with high packing density. The inverters can also balance the voltage on the DC capacitors of the rectifiers. Packaging technologies of power converters also called "modularization," can increase production volume, reduce price, and enhance performance by integrating single or multiple packaging technologies. Fig. 5 (a) illustrates the generic topology of the modular-based frequency converter. The filters on both sides eliminate harmonics in ships and the grid. The dc-link in these converters keeps independent grid- and ship-side control without impact from one side to the other. At the same time, the dynamic braking chopper provides low-voltage ride-through during a significant grid disturbance and safe shipboard disconnection with a lost grid.

Yang et al. [30] investigated a modular type three-level four-quadrant converter FCS 6000 technology by ABB for shore-to-ship connections. The converter topology is similar to the three-level active front-end topology proposed in [31]. However, as the previous topology suffers from switching losses, network interaction limits the operation, especially by Gate turn-off thyristor (GTO) switches. The proposed topology utilizes Integrated Gate Commutated Thyristors (IGCT) based rectifiers and inverters, as illustrated in Fig. 5 (b). The IGCT combines both the advantages of a common GTO and

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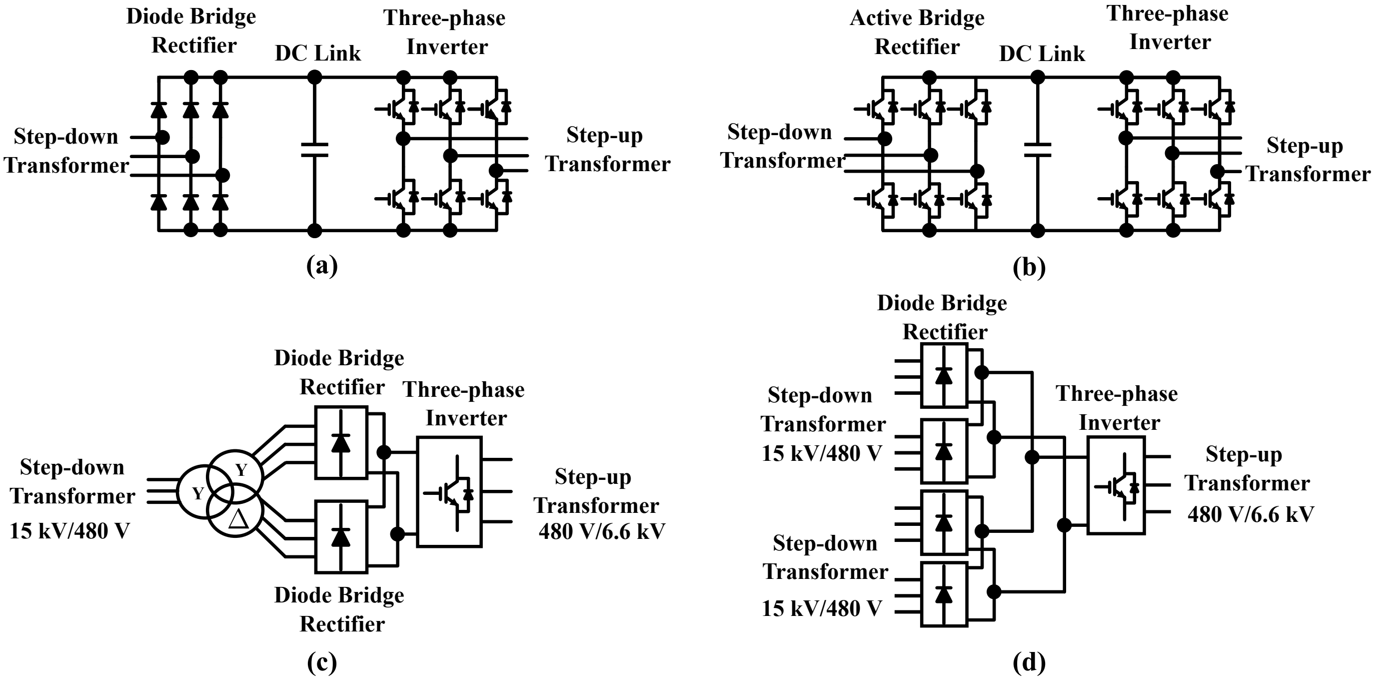

Fig. 3. Frequency converters: (a) Three-phase diode bridge rectifier. (b) Three-phase active bridge rectifier [18], [24], [25]. (c) Twelve pulse rectifier [3], [18], [26]. (d) Twenty-four pulse converter [3], [18], [26].

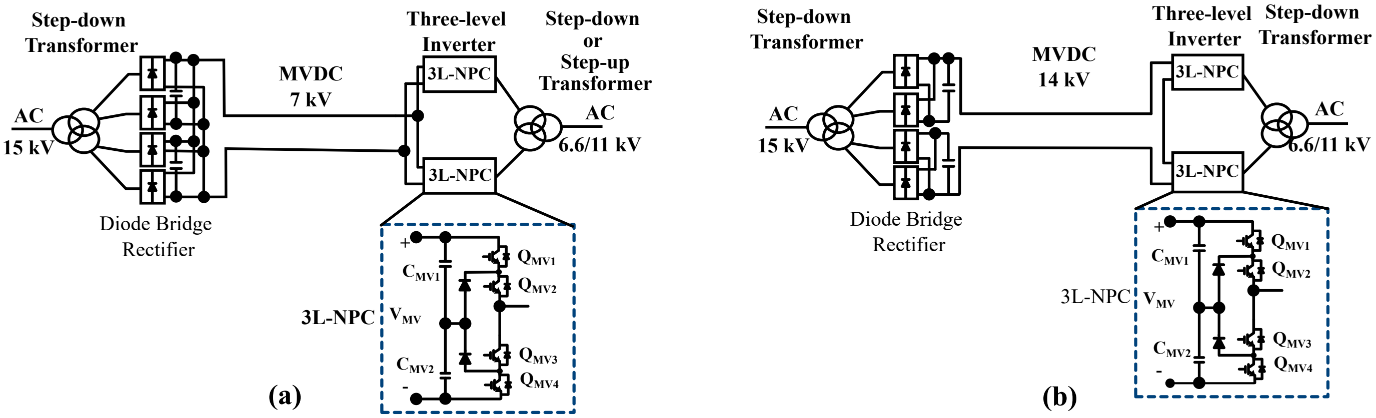

Fig. 4. High-power frequency converters: (a) Parallel connected diode bridge rectifier 3L-NPC rectifier [27]. (b) Series connected diode bridge rectifier 3L-NPC rectifier [27].

TABLE II
A COMPARISON BETWEEN DIFFERENT FREQUENCY CONVERTER SOLUTIONS.

Frequency converter	Diode bridge	Active bridge	12 and 24 pulse	Modular three-level
Design and control complexity	Low	Low	Moderate	High
Harmonic distortion	High	Moderate	Low	Low
Semiconductor losses	Low	Low	High	Moderate
Converter cost	Low	Low	High	Moderate
Bidirectional power flow	No	Yes	No	Yes
Active and reactive control	No	Yes	No	Yes
Voltage- or current-source converter	No	Yes	No	Yes

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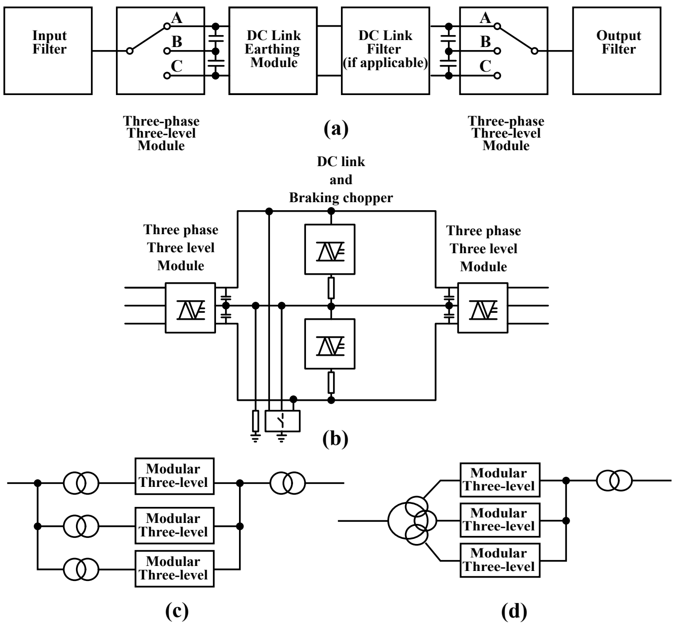

Fig. 5. Modular frequency converters: (a) The generic topology of modular three-level frequency converters. (b) Scheme of modular three-level frequency converter [30]. (c) Parallel connection of modular converters with multiple step-down transformer [30]. (d) Parallel connection of modular converters with one multi-winding transformer [30].

the Insulated Gate Bipolar Transistors (IGBT) (i.e., the low conducting losses and very fast transition). As an alternative, Jiao et al. [32] proposed the same topology based on IGBT devices.

The back-to-back connection in these converters gives them the advantage of controlling both active and reactive power. The converters can then be connected in parallel or series to achieve the required voltage level, as shown in Fig. 5 (c) and (d), respectively. Table II lists a comparison between the onshore frequency converters mentioned earlier. Some key players for shore-to-ship connections are Cavotec, Wärtsilä, Schneider-Electric, Siemens, Sweden's Processkontroll EL, Danfoss, and ABB. Table III lists some of these players and the converter topologies they offer for shore-to-ship connection applications.

2) Low-voltage converters: Small-size ships operate at a low-voltage range of 380 V to 460 V and power level less than 100 kW. Thus, the shore-to-ship connection can directly be connected to the low-voltage grid, which might disturb the shore-side grid's voltage. Front-end ac-dc converters provide power factor correction (PFC) and avoid harmonic distortion. The conventional PFC boost converter, as shown in Fig. 6 (a), can solve this problem. Due to their simple design and control, the PFC boost converters are solutions in several grid connection applications.

For shore-to-ship connections, Kim et al. [33] studied and tested a 3 kW prototype to operate at universal input mains and 400 V output voltage. The maximum efficiency of the topology reached 99.2 % at 1 kW load for 0.99 PF and 100 kHz switching frequency. The main limitation of the conventional PFC boost converters is the limited operation frequency, which in tens kHz ranges, resulting in large passive components. Besides, the converters suffer from high switch-voltage derivative (dv/dt), which results in Electromagnetic Interference (EMI) issues.

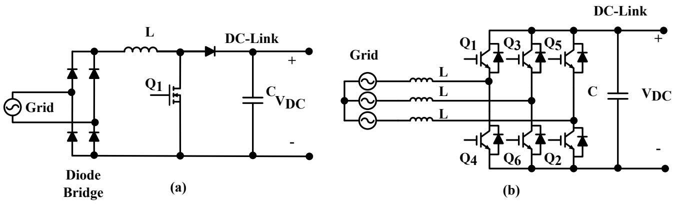

Fig. 6. PFC converter topologies for small-size ships: (a) Boost converter [33]. (b) Three-phase APF converter [34].

Interleaved boost converters can be a good alternative for a high rating power. The sizes of the indicators in these converters are small due to the 180° phase shift between the interleaved parallel boost converters. Moreover, the size of the dc-link filter is smaller due to the small ripple current. If the required power increases, multiple phases interleaved converters are another option. Qiao et al. [34] proposed a three-phase Active Power Filter (APF) for shore-to-ship connection applications to eliminate the power line harmonics and achieve unity PF, shown in Fig.6 (b) [34].

Similar to Electrical Vehicles (EV) charging applications, the topologies contain a boost converter for active PFC and can be single- or three-phase, and two- or multi-level converters [35]. These converters offer alternative solutions for shore-to-ship low-voltage connections. Other types of nonisolated PFC topologies proposed for EV charging applications can be an option for shore-to-ship connections such as Buck-boost, SEPIC, Ćuk, Zeta, or Luo derived converters [36]. For onshore fast charging, Takamasa et al. [37], and Hiroyasu et al. [38] investigated an on-road EV quick charger to charge a 25 kW electric boat. The converter managed to charge up to 80% of the full charge battery within 30 minutes. Other EVs' fast charging approaches can offer a charging solution for small ships [39], [40], although electrical ships can require higher charging power than EV.

The conductive shore connections suffer from some disadvantages, such as (1) the challenges of connection and disconnection of the charging equipment, specifically during rough weather conditions; (2) the mechanical contacts and plugs' exposure to wear, tear, and corrosion; and (3) the electric and fire hazards during connecting and disconnecting [41]. As a result, Wireless Power Transfer (WPT) has recently attracted more attention as an alternative to conductive shore connections. It provides galvanic isolation and an autonomous charging possibility. However, it has a lower power transfer capability than its conductive counterparts.

B. Wireless Connection

Wireless Power Transfer (WPT) technologies use electromagnetic fields to transfer energy and are applied to many electric charging applications. The three main groups of these technologies are: near-field, mid-range, and far-field [42]. The classification depends on the size of the transmitter, the receiver, and the transfer distance. Near-field WPT, namely

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TABLE III
MARKET OVERVIEW OF A FREQUENCY CONVERTER FOR HIGH-POWER SHORE-TO-SHIP CONNECTIONS.

Product	**Topology**	**Manufacturer**	**Power (MVA)**	**Voltage (V)**
SINAMICS SM120	Diode bridge	Siemens	4 - 13.3	3300 - 7200
SFC	Diode bridge or Active bridge rectifier	Greencisco	0.06 - 0.4	380 - 400
OVYPHASE GPC	Active bridge rectifier	Wärtsilä	0.6-1.5	3x260 - 458
MGE Galaxy 7000	Active bridge rectifier	Schneide	0.45 - 0.5	380 - 440
PCS 6000	Modular frequency converter	ABB	4 - 9	3300 - 4160

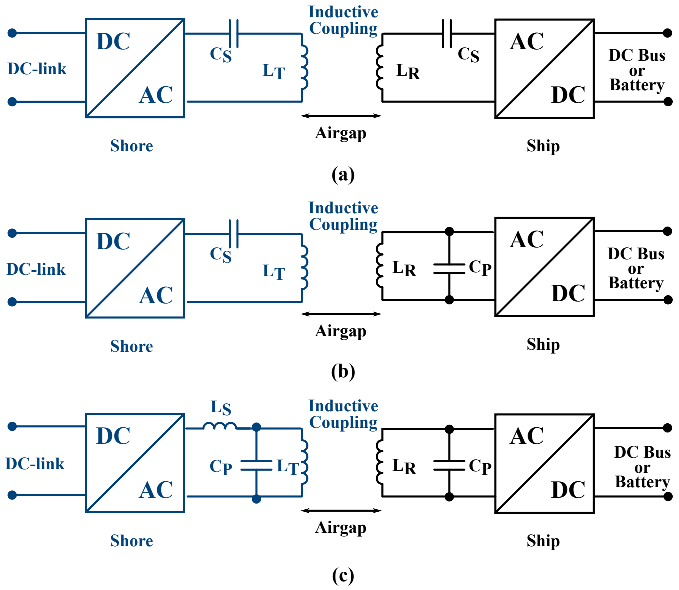

Fig. 7. IPT compensation topologies for ships: (a) series-series, (b) series-parallel, and (c) hybrid combination.

TABLE IV
COMMERCIAL IPT CHARGING SYSTEMS FOR EV AND SHIPS.

Provider	**Air-gap** (cm)	**Power** (kW)	**Applications**
Plugless Power [52]	15	3.3 & 7.2	EV
WiTricity [53]	N/A	3.6 & 11	EV
Momentum-Dynamics [54]	19	450	EV
Mojo Mobility [55]	20	20	EV
Hevo [56]	N/A	8	EV
TGood [57]	up to 20	60	EV
Toshiba [58]	up to 16	7	EV
INTIS [59]	up to 20	50 & 100	EV
Wärtsilä [60]	up to 50	2000	ships
IPT technologies [61]	up to 25	100	ships and EV

Inductive Power Transfer (IPT) and Capacitive Power Transfer (CPT), are the most common techniques proposed for ship charging applications.

Inductive charging, or IPT, operates based on loosely-coupled magnetic fields between transmitter and receiver coils. It has begun to receive more attention for charging electric cars, buses, and trains [43], [44]. For shore-to-ship connection applications, several papers [41], [45]–[47] proposed IPT transfer power from shore, while other suggested offshore connections from tugboat [48].

The series-connected compensation capacitors are added to the transmitter and receiver coils to improve the coupling between the coils. The converters can achieve soft-switching and transfer more power using the resonant principle. Besides, they can operate at high switching frequencies, improving their energy density. Kumar et al. [48] and Guidi et al. [49] proposed converters with series-series compensation circuits to achieve shore-to-ship IPT, as shown in Fig. 7 (a). The operation frequency depends on the load and the coupling conditions between the two coils in the case of the series-compensated transmitter side. It also suffers from higher voltage stress on the compensation resonant capacitor compared with parallel compensation [50]. Zhang et al. [45] proposed other compensating circuits such as series, parallel, and hybrid combinations, as shown in Fig. 7 (b) and (c), respectively. They also investigated inductor-capacitor-inductor (LCL) and inductor-capacitor-capacitor (LCC) compensations to achieve more freedom in designing WPT systems. However, the complexity of the design will also increase with increasing numbers of resonant components.

The difference between the series and parallel components of the secondary side compensation is that the receiver side acts as a voltage source in the series compensation and as a current source in the parallel one. The series-parallel configuration can provide a high charging current to ships for the same coil sizes. Zhang et al. [51] reviewed and evaluated the most popular IPT compensation topologies based on their basic and advanced functions.

On the market, many manufacturers have recently started to provide IPT-based charging stations for EV. For electrical ships, IPT technology offers a 100 kW wireless charging option for electric and hybrid ferries, yachts, fishing vessels, tugboats, and research vessels [61]. Wärtsilä Norway has also been able to transfer more than 2 MW with a distance up to 50 cm using the series-series compensation [60]. Table IV lists the manufacturers that provide IPT solutions for both EV and ship charging applications. However, IPT suffers from eddy current losses, which may result in a fire hazard. The IPT system also comprises expensive and bulky parts, such as ferrite iron plates and Litz-wires.

Capacitive charging, or CPT, can provide an attractive alternative for shore-to-ship connection [62]–[64]. It is cheaper and lighter, with negligible eddy current and misalignment

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TABLE V
A COMPARISON BETWEEN IPT AND CPT FOR SHIP-TO-SHORE CONNECTION.

	IPT	CPT
Power Density	High	Low
Eddy Current Losses	High	Negligible
Misalignment Performance	Bad	Good
Cost	High	Low
Weight	Heavy	Light
Efficiency	High	Low
Leakage Fields Shielded Capability	Easy	Difficult

losses compared to IPT [65]. Table V lists a comparison of both CPT and IPT technologies for shore-to-ship. Submerged CPT system underwater can improve the capacitive coupling [62], [64], [66], [67]. Yang et al. [62] proposed a bidirectional LCL compensation converter to transfer $100\,\mathrm{W}$ over $15\,\mathrm{cm}$ distance and over 80% efficiency. However, the conductivity of seawater could result in degrading the overall efficiency of the system [66], [67].

III. SHIPBOARD CONVERTERS

The shipboard power converters facilitate the integration of ESS, renewable energy resources, loads, or propulsion systems with the shipboard system, as previously illustrated in Fig. 1. Kumar et al. [7] previously reviewed the topologies proposed for adjustable speed propulsion systems; hence, this paper will not consider them in further discussion. Similar to Section II, the paper categorizes the shipboard converters into medium- and low-voltage converters based on their voltage level.

A. Medium-Voltage Converters

Currently, the AC shipboard distributed systems are either low-voltage systems (with $400\,\mathrm{V}$, $50\,\mathrm{Hz}$ or $440\,\mathrm{V}$, $60\,\mathrm{Hz}$) or medium-voltage systems (with $3.3\,\mathrm{kV}$, $6.6\,\mathrm{kV}$, or $11\,\mathrm{kV}$ and $60\,\mathrm{Hz}$ or $50\,\mathrm{Hz}$) [68]. The shipboard power system architectures have many similarities and differences compared to the terrestrial ones. Understanding the overlap between terrestrial and shipboard grids can aid in their design and operation [8].

Yang et al. [69] anticipated that the future shipboard distribution systems of large ships would be Medium-Voltage DC (MVDC) since they offer significant operational and economic merits. The dc shipboard architectures can provide better survivability, limitation of fault current, and reconfiguration capability [70]. The advancement of power converters makes the transition to shipboard MVDC possible. On the market, ABB offers a modular shipboard DC power system platform for simple, flexible, and functional integration of energy sources and loads [71].

For a ship's MVDC distribution system, power converters become an essential topic as they provide the ability to adapt ESS, control bidirectional power flows in transient or emergency conditions, and limit fault currents [72]. The literature proposed various topologies of two-level (2L) Dual Active Bridge (DAB) Voltage Source Converter (VSC) for shipboard MVDC distribution systems. The DAB converters have mainly three merits: galvanic isolation, soft-switching, and bidirectional power flow capabilities.

Wang et al. [73] investigated a resonant DAB hybrid dc-dc converter for inland or all-electric shipboard MVDC systems, as shown in Fig. 8 (a). The topology can achieve zero voltage switching turn on at the primary side and zero current switching turn off at the secondary side. However, this converter has a half-bridge configuration that can suffer from high voltage and current stresses, resulting in significant losses and limiting the power conduction capability.

As an alternative, Din et al. [74] examined a three-phase DAB as a step-down voltage stage between the generators and the MVDC bus, as presented in Fig. 8 (b). The converter may need a large magnetic core in high input voltage and light-load conditions resulting in increased cost and weight. Besides, the excessive current stress operation conditions can degrade the overall efficiency or even damage the converter.

Zahedia et al. [75] examined a full-bridge VSC on the medium voltage side and a Current Source Converter (CSC) on the low voltage side as a shipboard dc-dc converter, as shown in Fig. 8 (c). This topology requires an active clamping circuit (S_c and C_c) to avoid excessive voltage stress across the switches, which increases the number of components and complexity of the controller. Fig. 8 (d) shows a three-phase current-fed bidirectional dc-dc converter that achieves soft-switching conditions over a wide operation range [76]. Nag et al. proposed an isolated bipolar current-fed converter that can restrict the power flow from the low-voltage in case of a short circuit bus fault [83].

Integrated multilevel configurations, namely, 3L-NPC, provide the necessary power and may meet the dimensions, weights, and protection constraints [77]. These configurations are composed of two conventional 2L converters that stack over each other. The papers [77], [84] used full-bridge 3L-NPC to achieve higher power capability compared with the half-bridge 3L-FC converter, as illustrated in Fig. 8 (e). However, 3L-NPC suffers from a neutral-point voltage balancing problem and a low-frequency ripple of the neutral point caused by certain loading conditions [85]. Moreover, these configurations still have power conduction limitations and unidirectional power flow.

To further increase the operating voltage and power capability, Agamy et al. [78] proposed six series-connected switches on the high voltage side to build a resonant dual active bridge LLC converter, as illustrated in Fig. 9(a). The topology combines the merits of the high efficiency of resonant converters and the control flexibility of dual active bridges. However, the series-connected switches may experience an uneven share of the total voltage during blocking and transient mode, and their gate driver may not exhibit similar performance [86].

Alternatively, You et al. [79] proposed cascaded topology for shipboard systems, in which cascaded low power Submodules (SM) are connected to operate at medium-voltage ranges, as shown in Fig. 9 (b). The MVDC side is connected in series to divide the voltage over the cascaded converters, while the low-voltage side is connected in parallel to provide the required voltage level. The configuration has many switches

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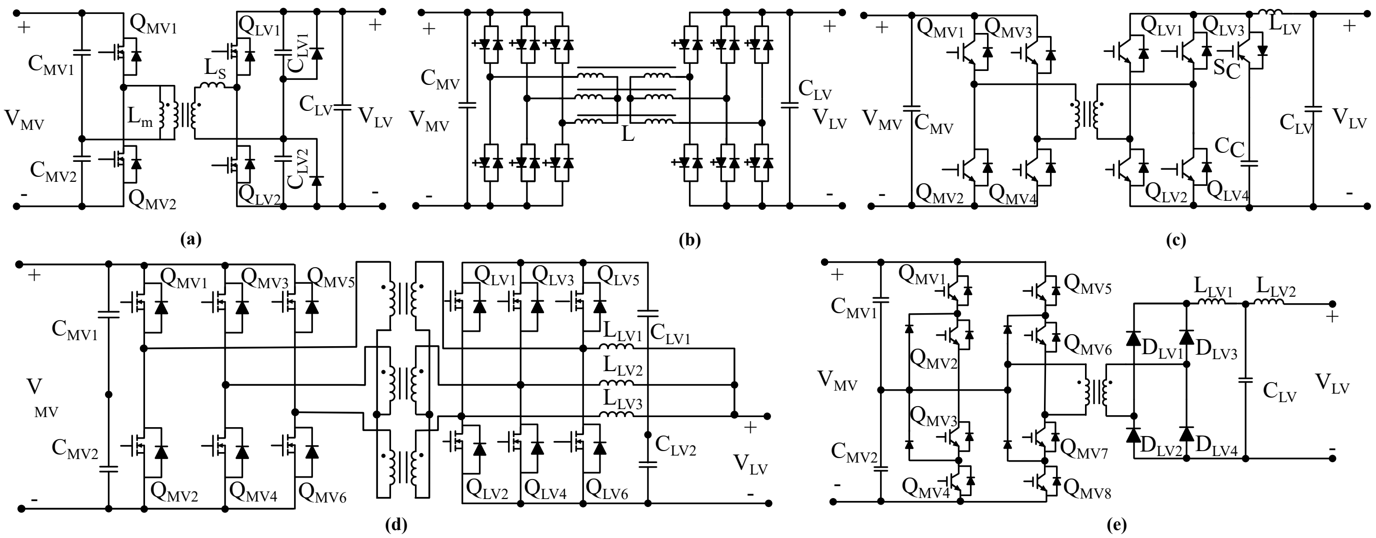

Fig. 8. The 2L and 3L MVDC shipboard converters: (a) A resonant DAB hybrid dc-dc converter [73]. (b) A three-phase dual-active bridge [74]. (c) A CSC-based DAB [75]. (d) A three-phase current-fed DAB [76]. (e) A full-bridge 3L-FC converter [77].

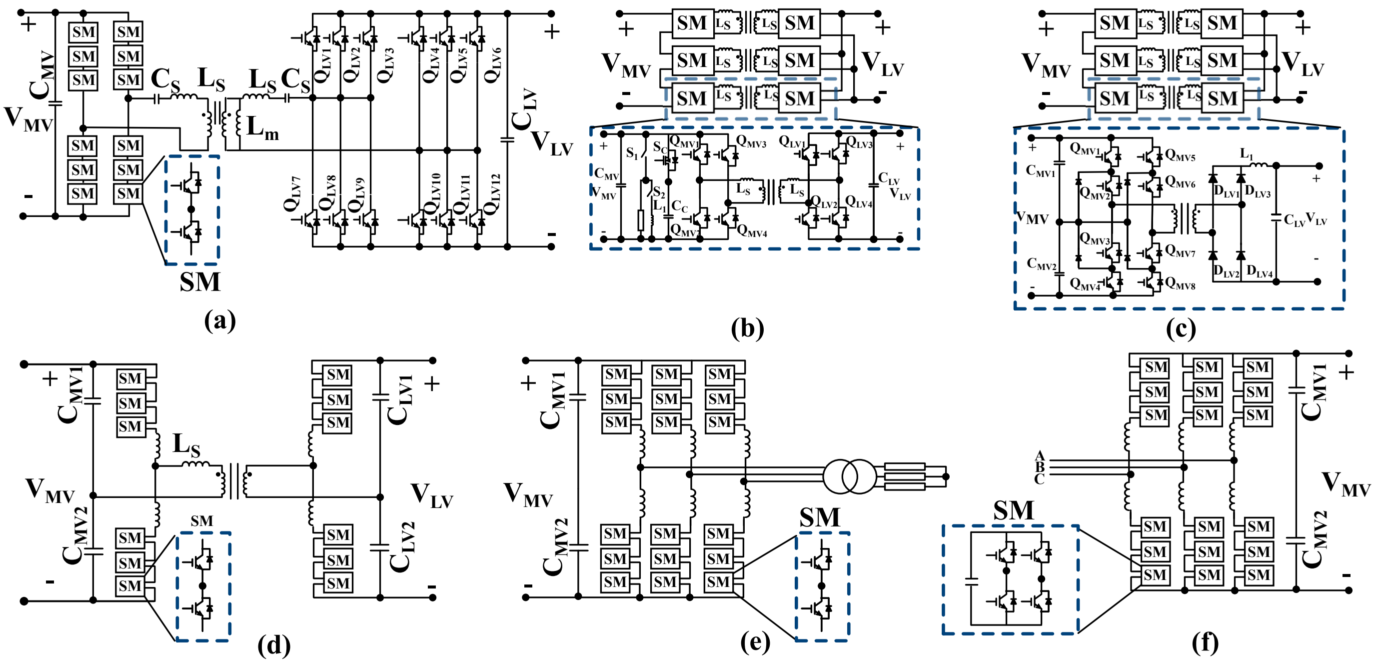

Fig. 9. High-power shipboard topologies: (a) Series-connected switches DAB LLC bus-tie [78]. (b) Cascaded DAB [79]. (c) 3L-SM based MMC converter [69]. (d) Half-bridge-SM dc-dc converter [80]. (e) Half-bridge-SM based dc-ac converter [81]. (f) Full-bridge-SM based ac-dc converter [82].

and components, which increase the losses, cost, and degradation of the overall efficiency. Besides, the switch S_1 may short-circuit the MVDC side. Another approach is a cascaded 3L-NPC SM converters, as shown in Fig. 9 (c) [69]. Like the previous counterparts, these converters might suffer high losses, high costs, and low efficiency.

In contrast to previous topologies, Modular Multilevel Converters (MMC) have high reliability, modularity, and redundancy [87]. Besides, they provide a cost-effective solution since they are composed of low-voltage, low-cost semiconductor technologies [86]. The MMC can be categorized based on the SM into half-bridge [80], full-bridge [79], [82], and three-level SM. In [80], an isolated configuration based on half-bridge SM is proposed, as shown in Fig. 9(d). The leakage current can be alleviated in MMC converters with the low SM ground parasitic capacitance. MMC can be used in dc-ac [81] or ac-dc [87] power stage for electric ship, as illustrated in Fig. 9 (e) and (f) respectively.

Chen et al. [81] designed DC-AC half-bridge SM based MMC as a load side converter with four-, five- and six-levels MMC. Steurer et al. [87] controlled a $5\,\mathrm{MW}$ four MMC at a dc voltage range from $6\,\mathrm{kV_{ac}}$ to $24\,\mathrm{kV_{ac}}$. Table VI compares some of the presented dc-dc converters proposed for MVDC shipboard power systems in terms of the rated power, switching frequency, conversion voltage, numbers and types of switches, and overall efficiency.

TABLE VI
A COMPARISON BETWEEN SHIPBOARD DC-DC CONVERTERS.

Topology	**Power** [kW]	**Frequency** [kHz]	**Voltage** [kV]	**No. of Switches**	**Type of Switches**	η **[%]**
Resonant & DAB [73]	10	40	0.4-6	4	MOSFET	> 98
Three-phase DAB [74]	8000	1	8.9-6	12	IEGRs^1	N/A
Three-phase current-fed DAB [76]	6	40	0.024/0.048-0.288	12	MOSFET	96.4
Full-bridge 3L-NPC [77]	750	1	4-0.71	8	IGBT	N/A
LLC DAB [78]	1000	2.5-5	1-5	36	IGBT	97.5
Cascaded DAB [79]	200	N/A	10-0.38	4	MOSFET	N/A
				8	IGBT	
Half-bridge MMC [80]	250	1	200-100	14	IGBT	N/A
3L-SM MMC [69]	>2000	7	4 - 0.71	24	IGBT	96.1

[2] Injected-Enhance Gate Transistor

Previous MVDC shipboard dc-dc converters have galvanic protection capability; hence a fault on either side does not severely affect the components on the other side. The suitable adjustment of the turn ratio of the transformers in these converters gives them the flexibility to choose the voltage levels on both sides. The conventional 2L DAB converters have many merits, including inherent soft-switching, bidirectional power flow, high power density, and modular structure capability. However, they suffer from extremely high voltage and current stress during overload and start-up operation conditions [88]. The resonant DAB converter has tackled the voltage and current stress problem by working in hybrid operation mode. Nevertheless, the converter requires large resonant capacitors to keep the voltage ripple lower than half the low side voltage level under normal operation. Besides, it needs two extra diodes parallel to the resonant capacitors for current overload protection.

The three-phase DAB converter has low voltage and current stress per phase under regular operation and better transformer utilization [89]. Besides, the transformer has low kVA ratings and high-frequency losses, making it suitable for high-power applications. However, the practical realization of a three-phase symmetrical transformer with identical leakage inductance in each phase adds extra design challenges. Moreover, it has more components which can result in additional losses and is more costly than its single-phase DAB counterparts. In addition, the transformer connection possibilities can negatively affect the performance of the converter [90].

The voltage-fed DAB, in general, has some disadvantages, including difficulty in achieving soft-switching conditions when the input and output voltage ratio is not close to the transformer turns ratio. The voltage mismatches on both sides result in large RMS and peak current stress in the transformer and switches [76]. The current-fed DAB converters can tackle these problems by improving the performance for the wide operating range. However, these converters require a high dc inductor to reduce the ripple in the input current, which will affect and complicate the soft-switching condition. Although the active climbing circuit offers a solution for the hard-switching operation and turn-off voltage spikes problems, it increases the design complexity and the number of components. The three-phase current-fed DAB also suffers from the same challenges that face the three-phase voltage-fed DAB, namely, the practical realization of a three-phase symmetrical transformer, more losses, and high cost due to the increasing components numbers.

Full-bridge 3L-NPC converters offer a good alternative to the previous 2L converters. The switching devices configuration in the 3L-NPC topology operates under low voltage stress, which doubles the converter's power rating and improves the quality of the output waveform [85]. Nevertheless, these converters suffer from a neutral-point voltage balancing problem, a low-frequency ripple of the neutral point under certain load conditions, and a high complicity of the controlling techniques.

The MMC converters have exceptional waveform quality, compact modular design, and high power density. However, these converters have complex designs and control. Besides, although they compose cost-effective and low-voltage switches, they have higher overall cost than other 2L converters and 3L 3L-NPC topologies [91]. Table IX lists a summary of some advantages and disadvantages of 2L DAB, 3L 3L-NPC, and MMC shipboard converters.

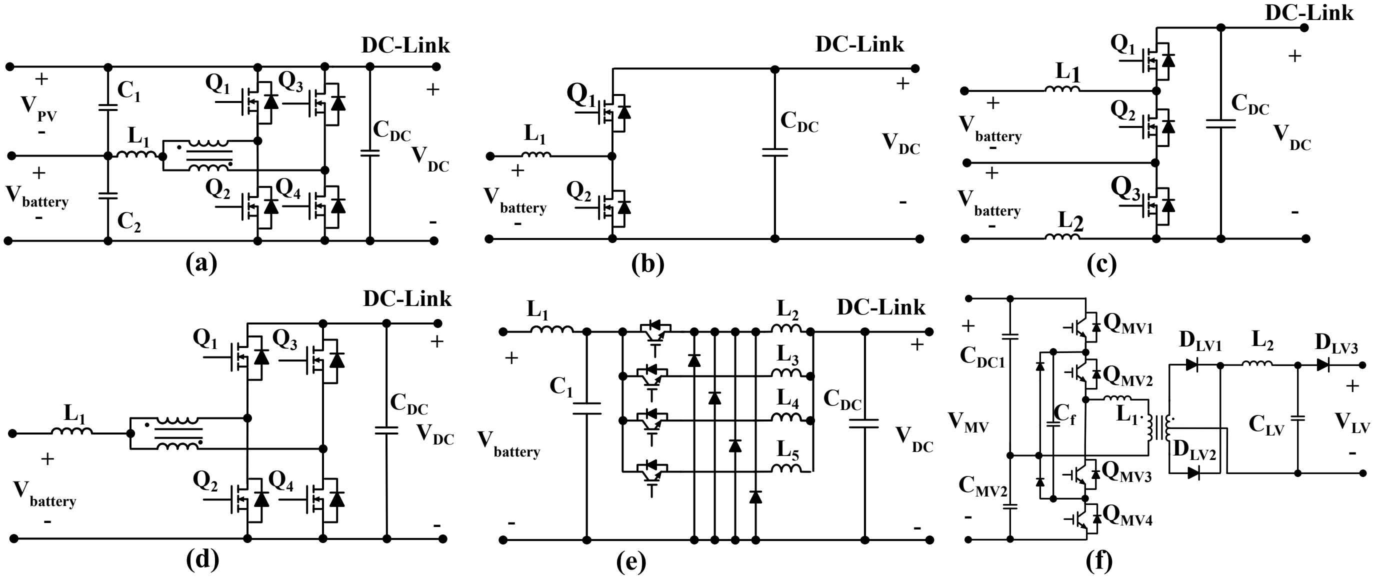

Fig. 10. dc-dc converters for small ships: (a) Two-stage buck-boost [92]. (b) Conventional buck-boost [93]–[95]. (c) Double input buck-boost [96]. (d) Interleave boost [97]. (e) Interleave buck converter [98]. (f) Half-bridge 3L-NPC converter [99].

B. Low-Voltage Converters

In small ships, many papers proposed various Pulse Width Modulation (PWM) dc-dc converters to integrate renewable energy [92], [100], [101] or ESS [93], [94], [96]–[98] on ships. A conventional boost converter, similar to the one shown in Fig. 6 (a), connects between Photovoltaic (PV) system, battery system, and adjustable speed propulsion converter in [100]. Khooban et al. [93] also used a boost converter to connect fuel cells to a shipboard dc bus. Fig. 10 (a) shows an alternative approach, in which a two-stage bidirectional buck-boost converter connects between PV system, batteries, shipboard system, and the grid-connected PFC interface [92]. Researches [93]–[95] also utilized conventional buck-boost to couple between battery systems and dc bus, as shown in Fig. 10 (b). Barabino et al. [96] used a double input buck-boost, as shown in 10 (c), to connect a battery to a dc system.

Interleaved PWM converters are good options to improve the power conduction density on ships. The phase-shifted between the interleaved converters reduces the output ripple and minimizes the output capacitor's size. Postiglione et al. [97] studied a loosely coupled inductors interleaving boost converter that is illustrated in Fig. 10 (d). Bairachtaris et al. [98] investigated a four-interleaved buck converter, shown in Fig. 10 (e), between the battery system and loads.

Song et al. [99] proposed a $7\,\mathrm{kW}$ half-bridge 3L-FC converter with flying capacitor (C_f) for shipboard systems, as illustrated in Fig. 10 (f). They designed the converter to step down the wide range of input voltages of $850\,\mathrm{V}{\sim}1.25\,\mathrm{kV}$ to $68\,\mathrm{V}$ with $96\,\%$ efficiency. The converter requires a bulky flying capacitor to keep the voltage ripple within the limit by increasing the load current, and the switches in the half-bridge configuration experience high stress.

Table VII lists a comparison between the PWM dc-dc converters proposed for small ships in terms of rated power, switching frequency, conversion voltage, type of switching, soft-switching capability, and the type of power source. Convectional transformerless PWM converters were used as single-phase inverters in grid-connected PV applications [102]. These converters have few components, simplifying the design and control. Researchers [103]–[105] proposed different soft-switching techniques to minimize switching losses, offer high-frequency operation, and improve power density. However, operating these converters at high switching might make the design of magnetic components and other required circuitry more difficult.

The two-stage and double buck-boost converters, shown in Fig. 10(a) and (c), are Multiple-Input Single-Output (MISO) converters. The MISO converters have attracted attention in interfacing fuel cells, batteries, and ultra-capacitors to traction drive in electric and hybrid-electric vehicles [106]–[108]. When the number of input ports increases, then the number of components and hence the size and weight of the overall converter will increase. The single inductor MISO converters that deal with this problem are shown in [109], [110]. Single-Input Multiple-Output (SIMO) [111] and Multiple-Input Multiple-Output (MIMO) [112] converters can also be attractive solutions for shipboard low voltage systems.

When the PWM converters operate with continuous current mode, it results in hard switching and hence high losses. In contrast, discontinuous or critical current mode operation has a soft-switching characteristic that leads to low switching losses. Nevertheless, operating in these two modes results in high voltage and current ripples, which require high rating switches, bulky inductors, and EMI filters [113]. Interleaved converters can tackle this problem by connecting multiple converters in parallel to reduce the input and output current ripples. Hence sizes and weights of the inductors and filters will also decrease.

The interleaved boost and the buck converter, shown in Fig. 10 (d) and (e), respectively, can operate in the critical mode to

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TABLE VII
A COMPARISON BETWEEN DC-DC CONVERTERS FOR SMALL SHIPS.

Topology	**Power** [W]	**Frequency** [kHz]	**Voltage** [V]	**No. of Switches**	**Type of Switches**	**Soft-Switching**	**Source**
Boost [100]	300	N/A	48-300	1	IGBT	No	PV
Two-stage buck-boost [92]	450-850	250	15-50	4	MOSFET	No	PV/Battery
Forward type [101]	1000	50	24-56	3	MOSFET	Yes	PV
Buck-boost [94]	N/A	2	14-42	2	IGBT	No	Battery
Boost [93]	500	N/A	(45∼54)-110	1	IGBT	No	Fuel Cells
Buck-boost				2	IGBT		Battery
Interleaved boost [97]	14000	20	(75∼127)-160	4	MOSFET	No	Battery
Interleaved Buck [98]	2000	20	36-14.7	4	IGBT	No	Battery

TABLE VIII
MARKET OVERVIEW OF SHIPBOARD CONVERTERS.

Product	**Topology**	**Manufacturer**	**Power (MW)**	**Voltage (V)**
ACS 6000	3L-NPC	ABB	up to 100,000	13,800
SINAMINS GM150	3L-NPC	Siemens	3,400-5,800	3,300 - 4,160
Benshaw M2L 3000	MMC	Benshaw	746	up to 4,160
DY400-DD400-12	Isolated dc-dc	DWE	450 - 500	12 - 400
Maxi,Mini,Micro	Isolated dc-dc	Vicor	Up to 1300	24 - 425

achieve soft-switching capability. Unlike the interleave boost converter, the interleave buck converter has a unidirectional power flow, making it unsuitable for charging battery applications. As an alternative, interleave converter with a matrix inductor utilizes flux cancellation and sharing, resulting in lower core loss and size [114].

On the market, many manufacturers provide shipboard converters. Table VIII lists the manufacturers that provide some of the previously mentioned topologies for shipboard power systems. Table IX summarizes the pros and cons of some of the shipboard converters.

IV. SOLID-STATE DEVICE TECHNOLOGIES

Developing semiconductor devices increases shore-to-ship and shipboard converters' efficiency and power density. Moreover, introducing the concept of power electronics building blocks to marine electrical systems reduces the cost, losses, weight, size, and maintenance of the converters [115]. Power diodes, thyristors, and transistors are the three primary semiconductor devices used in shipboard converters.

Conventional silicon power diodes are a standard option in the rectification stage [18], [27], [33], [77], [98], [99], [116] in both the onshore connections and on shipboard topologies. However, these diodes suffer from a high surge of reverse recovery current. Recently, SiC based diodes can be an alternative, as they have negligible reverse-recovery current. Junction Barrier Schottky (JBS) diodes are another option that provides low-voltage drop, high-voltage blocking, and low reverse leakage current. Kim et al. [33] used JBS diodes in PFC shore-to-ship applications, while Wang et al. [73] utilized them in shipboard dc-dc conversion systems. Diodes, however, have unidirectional power flow capability as they can only operate in forwarding operation mode.

Thyristors have an advantage over power diodes with the controlled turn-on gate capability. Thus, converters with thyristors provide power control capability by controlling the gates firing signals. ABB built PCS 6000 frequency converter utilizing IGCT. These types of thyristors combine low conducting losses and very fast transition. Thyristors are more suitable for MVDC shore-to-ship connections and other applications when the current crosses zero, such as inline commutated converters, cyclo-converters, and motor drive inverters.

As an alternative, Insulated Gate Bipolar Transistors (IGBT) and Metal Oxide Semiconductor Field-Effect Transistors (MOSFET) have faster switching capability than the thyristors, as transistors operate in forwarding conduction mode only when a gate signal is applied. The IGBT have lower frequency switching capability but higher power conduction

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TABLE IX
SUMMARY OF ADVANTAGES AND DISADVANTAGES OF SOME OF THE SHIPBOARD CONVERTERS.

Configuration	Advantages	disadvantages
Conventional buck-boost converter	1) Low number of components. 2) Bidirectional power flow capability. 3) Simple design and control. 4) Soft-switching capability under specific operation conditions. 5) Low-cost.	1) Bulky inductors under specific operation condition conditions. 2) Hard-switching losses in continuous current operation mode. 3) No galvanic isolation. 4) High harmonic and EMI noises.
MISO	1) Bidirectional power flow capability. 2) Moderate design and control. 3) Soft-switching capability under specific operation conditions. 4) Medium-cost.	1) Hard-switching losses in continuous current operation mode. 2) Increase number of components compared to conventional converters. 3) No galvanic isolation. 4) High harmonic and EMI noises.
2L DAB	1) Relatively low number of components. 2) Bidirectional power flow and galvanic isolation capability. 3) Simple design and control. 4) Low harmonic noises if resonant tanks are used. 5) Soft-switching capability. 6) Different transformer connection possibilities if three phases DAB is used. 7) Relatively low-cost	1) High number of the components and high losses if three-phase or cascaded DAB is used. 2) High voltage and current stress under particular operation conditions. 3) Hard to achieve high efficiency over wide input and output voltage ranges. 4) The complexity of the design and control increases with the number of switches, phases, and resonant components in the resonant tanks 5) The transformer connection might negatively affect the performance in the three-phase DAB. 6) The cost increases if three-phase or cascaded DAB is used.
3L-NPC	1) Bidirectional power flow and galvanic isolation capability 2) Moderate design and control. 3) Low harmonic noise. 4) Medium input voltage ranges and power capability. 5) Moderate cost.	1) Neutral-point voltage balance issue. 2) High to a very high number of the components and high losses if cascaded 3L-NPC is used. 3) Complex control techniques to balance the neutral-point voltage. 4) The complexity of the design and control increases with the number of switches. 5) The cost increases if cascaded 3L-NPC is used.
MMC	1) High reliability, modularity, and redundancy. 2) Bidirectional power flow and galvanic isolation capability 3) Low harmonic noise. 4) Medium to high input voltage ranges and power capability.	1) High number of the components and high losses. 2) High total cost. 3) Complex design and control.

ability compared to MOSFET. They are utilized in both the shore-to-ship connection [27], [30], [34], [41] and shipboard applications [69], [78], [80], [87]. Injection Enhancement Insulated Gate Bipolar Transistors (IEGT) are another option to replace thyristors in high-power applications. With keeping the advantages of IGBT, Din et al. [74] utilized IEGT in dc-dc converters for MVDC shipboard applications.

In contrast, MOSFET have better switching capability, better temperature, and lower current tail than IGBT. Thus, they are used in both shore-to-ship applications [33] as well as in shipboard systems [99], [117]. The superiority of properties of Wide-Bandgap (WBG) materials, namely, SiC and Gallium Nitride (GaN), give the WGB-based devices the capability to operate at a high switching frequency and high temperature. SiC- and GaN-based devices are both used in shore-to-ship PFC applications [33] and on shipboard converters [73], [82].

Currently, shore-to-ship connections utilize diodes in medium-voltage diode bridge rectifiers and low-voltage PFC converters. In the future, switching devices, such as IEGT, IGBT, and MOSFET might replace the diodes in the shore connections. Rolan et al. [118] anticipated that smart ports are the future and more the integration of ships in microgrids on the ports. Thus, converters with bidirectional power transfer capabilities will be more attractive than unidirectional ones to provide the required energy exchange between ships and smart port grids. Likewise, switching devices, especially the WBG-based ones, will offer good options for shipboard converters to achieve bidirectional and low power density advantages.

V. INSTRUCTIONS AND REQUIREMENTS

Up to this point, sections II and III presented various topologies for different functions, characteristics, voltage levels, and power levels. This section provides detailed instructions for design and analysis for suitable selections of topologies. Besides, it presents some of the specific requirements that the power converters for ships should comply with by overviewing the standards.

A. Design instructions

The electrical system structures and architectures onshore or onboard determine the design, analysis, and selection of power converters. Thus, the first step is to determine the system architecture and design synthesis. Once the system's architecture and design are analyzed, the second step is deciding whether the converter will provide power conversion or power conditioning. For power conversion, converters can behave as sourcing (i.e., primary voltage control) or loading (i.e., passive concerning voltage control). For power conditioning, converters can perform protection, active filtering, or power quality management.

The third step is determining the required voltage and power ranges, operating frequency and duty ratio, maximum losses and minimum efficiency, the impact of system grounding on the converters, components stress limits, and required protections. Then, the fourth step is to determine the design requirements, such as the size and weight of the converters, solid-state devices, and other components selections, controllers, communications, heat dissipation and cooling options, protections, and any other mechanical, environmental, and electromagnetic compatibility requirements. The fifth and last step is to perform different assessments and analyses for integrating the converters in the system, including harmonic analysis, electrical load analysis, current hull analysis, life cycle cost analysis, expandability and survivability analysis, and risk assessment. IEEE Std 1662 [119] gives more details about each step.

B. Analysis and suitable selections

Selecting an appropriate model is vital for converters analysis. For instance, the behavior model considers the converters as black boxes representing the converters' behavior seen from the port or shipboard systems. It is simple and reasonably accurate over a range of operating conditions. In contrast, the physical-based model describes the converters using the physical laws based on the topologies' architectures, characteristics, or other external influences. Thus, it is more detailed, complex, and accurate over a wide operation range.

The shore or shipboard power system architecture, DC or AC voltage ranges, frequency levels, hierarchical control levels, converter's application, characteristics, and costs are criteria for suitable selection of converter's topology. Table X provides a guide to selecting an appropriate topology.

C. Specific requirements

The IEC/IEEE International Standard [22], [23] and IMO [120] describe the requirements for shore-to-ship synchronization. According to the standards, blackout or automatic synchronization are two approaches that can provide a load transfer in shore-to-ship connections. For the load connection via blackout, the shore supply can only be connected to a dead switchboard through interlocking. This approach is more suitable for a low-voltage shore supple. In contrast, automatic synchronization is suitable for high voltage shore supple in which the load transfer shall be completed in the shortest time by maintaining continuity of supply onboard.

One option is using the ship power management system for synchronization with the shore power system. However, the synchronization might take seconds to minutes, depending on the engines/generators' time constant. As an alternative, power converters provide automatic synchronization in microseconds [121] using the shore-side infrastructure, which includes automation and communication systems. Future research should investigate different synchronization strategies, control arrangements, and data transmission protocols.

Other requirements by the standards [22], [23] are that all shore-to-ship connections should also comply with IEC 60146-1 [123]. This standard specifies the general requirements for converters, especially concerning EMC, harmonic distortion, and insulation coordination. IEEE Std 1162 [119] gives requirements for the design and applications of power electronics in onshore and offshore electrical power systems. Onboard, IEC 60092 [122] gives general constructional requirements and test methods for shipboard electrical installations.

IEEE Std 1709 [125], IEEE Std 1162 [119], IEEE Std 45.1 [127] and IEEE Std 1826 [126] also provide recommendations for MVDC shipboard power converters. All power converters for ships should have electromagnetic compatibility and comply with IEC 61000 standard [124]. Table XI summarizes the power electronics standards for ships and their main scope.

VI. FUTURE TRENDS AND CHALLENGES

A. Shore-to-ship converters

Transformers and frequency converters are the main equipment of the conventional port electrical infrastructure. The transformers supply the required voltage range with galvanic separation from the shore electrical systems to ships whose operating voltages vary differently. On the other hand, static frequency converters provide the required operating frequency and can give the capability to control the voltage droop. The current trend of frequency converters is multi-pulse diode bridges, active front-end bridges, and modular rectifiers to imply with the IEC/IEEE 80005-1:2019 standard. The standard limits the total harmonic distortion of the shore connections to 5% [22].

The research has raised the shipboard DC power system architectures as an alternative to the current onboard AC power systems. ABB, one of the leading players in the marine industry, has built an onboard DC microgrid designed for marine power generation and propulsion drive applications. Hence dc-dc converters can gain more attention for shore connection with the required voltage. Transformer-based converters provide galvanic isolation. The high-frequency transformers in these converters can be considerably smaller than their low-frequency counterparts to improve the energy density. Three-phase modular converters are also attractive options

TABLE X
GUIDELINES IN SELECTING SUITABLE TOPOLOGY.

Converters	**Application & Function**	**Characteristic**	**Volt. & freq.**	**Examples**
Frequency Converters	power conversion (sourcing)	control harmonics and power factor, uni- or bidirectional power, regulate voltage & frequency	MV & 50/60 Hz	Multi-pulse diode bridge or active front-end rectifier with VSC, back-to-back ac-dc-ac VSC or CSC, matrix converters, cycloconverters, 3L-NPC, MMC
AC Rectifiers	power conditioning (PFC, active filtering) or power conversion (sourcing or loading)	control harmonics and power factor, uni- or bidirectional power, regulate voltage with limited ripple	universal main & 50/60 Hz	Diode bridge or bridgeless PWM-based voltage- or current-fed converters, resonant-based converters, 3L-NPC, MMC
DC inverters	power conversion (sourcing or loading)	uni- or bidirectional power, regulate voltage & frequency, regulate power & current	up to MV & 100s Hz	conventional voltage- or current-fed converters, SIMO, MISO, MIMO, 3L-NPC, MMC
dc-dc inverters	power conversion (sourcing or loading)	uni- or bidirectional power, isolated or non-isolated, regulate voltage & or/& current	up to MV & 100s Hz	conventional voltage- or current-fed converters, SIMO, MISO, MIMO, 3L-NPC, MMC

TABLE XI
SUMMARY OF THE POWER ELECTRONICS STANDARDS FOR SHIPS.

Standard	**Scope**
IEC/IEEE 80005 [22], [23]	low- and high-voltage shore connection
IEC 60092 [122]	Electrical installations in ships
IEC 60146 [123]	Semiconductor converters & Commutated Converters
IEC 61000 [124]	Electromagnetic compatibility
IEEE Std 1662 [119]	Onshore & offshore electrical power systems
IEEE Std 1709 [125]	Power distribution and dc power-delivery systems on ships
IEEE Std 1826 [126]	High-power electronics equipment used in zonal electrical distribution systems
IEEE Std 45 [127]	Electrical generation, distribution, and propulsion system design for use on shipboard

for high-power or fast-charging connections. Thus, future research might focus more on designing and controlling dc-dc topologies for shore-to-ship connections.

The two-level converters will remain the dominant topologies in the literature for small ships' shore-to-ship connections because they have simple structures and controls. Nowadays, the dc-link voltage is around $400\,\mathrm{V}$ to $600\,\mathrm{V}$ and the maximum dc-link voltage can reach $870\,\mathrm{V}$ as in the on-road vehicles applications [128]. Thus, the multilevel converters could become an attractive alternative with increased dc-link voltages. The front-end PFC converters are essential in connecting ships to the port's electrical grids. Single and three-phase interleave PFC converters could be a suitable option for shore connection applications in the future. Nevertheless, PFC converters need thorough investigations.

Resonant converters have recently attracted more attention in EV charging applications [129]. These converters have soft-switching capability, high power density, high efficiency, and low EMI mitigation. The transformer-based resonant converters can realize galvanic isolation and achieve soft-switching using the leakage inductance of the transformer resonating as a part of the resonant circuits. Furthermore, they have high step-up or down and bidirectional capabilities. But these converters require more investigation for shore-to-ship connection applications.

Finally, WPT technologies are promising options compared to conventional conductive connection approaches. At present, IPT attracts more attention as a WPT approach for shore connections than CPT. Table IV shows that a number of manufacturers have already started offering wireless charging solutions for both EV and ships. However, future research should investigate how to improve the WPT efficiency and power transfer ability, mitigate the EMI problems, and keep the fields within the safety limits.

B. Shipboard converters

Currently, ac-dc converters are interfacing between the generation units and the shipboard systems. In contrast, dc-dc converters operate as solid-state transformers to connect ESS, renewable resources, and loads to the shipboard systems. As the literature anticipated that the future systems would operate at medium dc voltage, converters will operate under such voltage levels to achieve the required integrity of different system units.

For low-power applications, DAB converters are the most common shipboard converters as they offer galvanic isolation, soft-switching, and bidirectional power flow capabilities. In contrast, modular converters are more suitable for high-power applications as they have high reliability, modularity, and redundancy. The shipboard dc-dc converters provide a step-down voltage from a medium-voltage range to a low-voltage range of $100\,\mathrm{V}$ to $400\,\mathrm{V}$. Shipboard converters with high power density are better options than conventional ones due to the limited available spaces.

Although the PWM-based converters are the most common topologies proposed for ESS charging applications, they suffer from low power density and the EMI problem. Besides, these converters operate in hundreds of kHz to tens MHz frequency which could increase the complexity of the design. High-frequency power converters can be good candidates, but they suffer from thermal and EMI problems and hence require a thorough investigation. Moreover, common noise issues, circulating leakage current, and thermal problems need further research in shore-to-ship connections and shipboard.

C. Solid-State Devices

The advancement of semiconductor devices has paved the way for higher power conduction capability, power density, and conduction efficiency. For instance, IEGR devices show a good operating capacity in multilevel converters for increased power and voltage systems. In contrast, conventional IGBT are the primary devices used in MMC configurations. WBG-based devices have superiority over traditional Si-based switches, making them attractive for the electrification of ships. Similar to EV applications, SiC and GaN might experience intensive deployment in both shipboard and shore-to-ship topologies. MOSFET might replace diodes in the smart port connections to achieve bidirectional power flow. Significantly, the researchers anticipated the integration of ships in microgrids on the ports.

VII. CONCLUSION

The paper thoroughly reviewed shore-to-ship connections and onboard converters to help facilitate and accelerate renewable energies and ESS. The shore-to-ship converters and shipboard converters are the main categories in this paper. The paper also subcategorized the converters into medium- or low-voltage converters. In shore-to-ship connections, the conductive connection is the primary approach for large ships where diode bridges, active front-end bridges, and modular rectifiers-based frequency converters are the most common topologies. In contrast, small ship connections received very little attention in the literature, and only off-the-shelf solutions are available on the markets suitable for EV charging applications. WPT has recently attracted more attention as a safe and automatic alternative for the conductive approach.

In the shipboard power converters, the nature of the onboard power systems directly affects the design or selection of the power converter topologies. Previous research intensively investigated MVDC systems and proposed several topologies. Modular converters were most common in large ships. Small ship converters received little attention where PWM-based dc-dc converters were the common solutions. Future research should examine shipboard converters' power density, noise, and thermal issues.

Regarding semiconductor devices, IGBT are the most common devices used in shipboard modular converters. The investigation of the WBG devices (SiC and GaN) has recently increased for both shore-to-ship and shipboard applications. The deployment of WBG devices might increase due to their superiority in operating at a higher switching frequency, breakdown voltage, and better thermal conductivity than conventional Si-based switches.

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