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Shipboard DC Systems—A Critical Overview: Challenges in Primary Distribution, Power-Electronics-Based Protection, and Power Scalability

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ABSTRACT This article gives an overview of challenges in primary distribution, protections, and power scalability for shipboard dc systems. Given that dc technology is in development, several aspects of shipboard systems have not yet been sufficiently devised to ensure the protection and efficiency demanded. Several issues in dc systems arise from the lack of complete relevant standardization from different regulation bodies. Unipolar and bipolar bus architectures have application-specific advantages that are discussed and compared. The placement of power electronics in dc systems creates opportunities for switchboard design, and this article compares the centralized and distributed approaches. Likewise, protection architectures for shipboard dc systems have challenges. Breaker-based protection utilizes slow fuses, mechanical circuit breakers, and solid-state circuit breakers. In addition, power-electronics-based protection embeds the protective circuit in the power converters, but its development lags. This article compares the state-of-the-art technologies, reviewing their main features. Finally, the power requirement of various applications and the low production rate of vessels force the designers to utilize commercial off-the-shelf converters to scale up power. The misuse of such converters, the modular topologies, and power electronics building blocks are exposed highlighting challenges and opportunities toward the mass adoption of dc systems onboard maritime vessels.

INDEX TERMS DC circuit breakers, dc systems, power-electronics-based protection, power electronics building blocks (PEBBs), power scalability, shipboard dc systems.

NOMENCLATURE

APU	Auxiliary power unit.	JFET	Junction-gate field-effect transistor.
COTS	Commercial off-the-shelf.	LVDC	Low voltage direct current.
DAB	Dual-active bridge converter.	MCB	Mechanical circuit breaker.
EP	Electrical propulsion.	MMC	Modular multilevel converter.
ESS	Energy storage system.	MOSFET	Metal-oxide-semiconductor field-effect transistor.
HCB	Hybrid circuit breaker.	MOV	Metal-oxide varistor.
HP	Hybrid propulsion.	MP	Mechanical propulsion.
ICE	Internal combustion engine.	MVDC	Medium voltage direct current.
IGBT	Insulated gate bipolar transistor.	SSCB	Solid-state circuit breaker.
IGCT	Integrated gate-commutated thyristor.	TRL	Technology readiness level.

I. INTRODUCTION

Climate change is propelling humanity to reshape the shipping industry toward more sustainable operations and fewer emissions. Maritime transportation is responsible for 3.1% of total CO₂ emissions [1], [2], and the estimations show a rising of 12–18% of total CO₂ emissions by 2050 if no effective countermeasures are enforced [3], thus projecting a pessimistic outlook for the future. As a reaction, the European Commission is implementing a CO₂ emission reduction policy of at least 40% by 2030 for the sector, boosting the energy transition actions in the continent [4]. This energy transition is fundamental to achieving the carbon reduction objectives in an industry heavily dependent on fossil fuels and low-efficiency engines, as low as 42% at nominal load and 20% at low-load regime [5]. Hence, the research and development efforts are focused on three main areas: 1) ICE modifications for enhanced efficiency and fuel flexibility [1]; 2) system hybridization and alternative power supplies, such as fuel cells and storage systems [3]; and 3) integrated power system development [6], [7]. The latter is based on ship electrification to merge the power train (propulsion, power plant, power system, and loads) into a single system based on EP or HP [8].

The motivation to opt for electric propulsion instead of MP lies in several advantages as follows. In EP, ICEs can be used frequently at rated power, reducing off-design load efficiency drops that affect mechanical drives [6]. The engines generate electricity only, allowing fuel-efficient and flexible operation with lower emissions [3]. EP is more efficient at low speeds and for highly variable load profile vessels than MP, enabled by variable-speed drives [9]. A multiengine centralized power system has high availability and survivability. A single ICE failure has a reduced impact on the operation [10]. However, the convenience of adopting electric propulsion is normally application specific, e.g., a cargo ship could not benefit from electric propulsion as the electric motors currently do not match the cruising speed from ICEs, whereas a cruise ship gets substantial benefit given that their operation focuses on consumption at lower speeds [8].

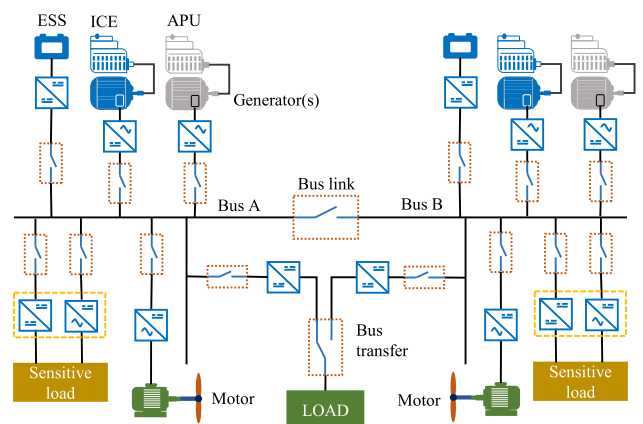
Nevertheless, EP is the most suitable option for the integrated power system. The integrated approach enables global optimization of the system for a more cost-effective operation, refreshing the interest in efficient onboard power system development, in which dc distribution is considered the backbone for future vessel electrification [8].

Fig. 1(a) shows a simplified representation of a generic shipboard dc integrated power system. The system has a dual dc bus configuration with a main ICE, an ESS, and an auxiliary power unit attached to the loads. The illustration features EP only. However, the concepts discussed in this article are also compatible with HP drives.

Shipboard dc systems are flexible, scalable, and controllable, have increased volumetric power density, and have simpler ESS integration compared to ac systems [11], [12], [13], [14]. Synchronization requirements and speed restrictions



(a)



(b)

FIGURE 1. Referential case study for shipboard dc systems. (a) Moonrise superyacht manufactured by Feadship in 2022. Credit to Feadship [Online] <https://www.feadship.nl/>. (b) Referential shipboard dc integrated power system with EP, suitable for the superyacht. Dots: dc switches.

from ac technology are no longer necessary, allowing optimal design and operation of ICEs and generators [8], [15], [16]. In addition, the shipboard system scalability can simplify the redundancy scheme and increase the reliability onboard, potentially enhancing survivability and reducing maintenance requirements [15]. Although these advantages are valuable for the shipping industry and the emission reduction objectives, the extent of such benefits is application specific, and new challenges are arising from the dc technology. These are frequently related to protections, scalability, control, stability, distribution, and power electronics, highlighting the importance of current development efforts.

The dc protection systems required a redesign from the ac technology, and multiple works, such as [17], [18], [19], [20], [21], and [22], show progress on the matter, frequently focusing on grounding schemes, protection devices, and reconfiguration. Some shipboard dc system scalability challenges are discussed in [20], [23], [24], [25], and [26], where the research is usually focused on power modules, MMCs, and PEBBs to

scale up power and voltage levels in different vessels. Control strategies and architectures are investigated in [17], [22], and [27], proposing a similar hierarchical control approach from the ac case for the general control architecture, droop controllers on the primary level, centralized, decentralized, and distributed controllers for the secondary level, and energy management placed at the tertiary control level. Some stability issues for shipboard applications and land dc microgrids are discussed in [10], [17], [19], and [27], covering voltage stability problems, pulsed and constant load limitations, and stability enhancement methods. Multiple scholars are also working on distribution architectures, giving special attention to grid reconfiguration and zonal distribution [11], [19], [22], [28]. Finally, the work on power electronics for shipboard dc systems is gaining popularity, where the discussion focuses on converter topologies for generation, propulsion, loads, and modular converters [20], [23], [24], [28].

Despite the extensive effort placed on the dc system investigation, multiple research opportunities require attention to support the development. This review explores challenges regarding primary distribution, protection devices, and power scalability that are not entirely covered in previous works available in the literature and are paramount for massive technology adoption. Addressing the subsequent matters does not disregard the existence of other relevant topics, such as stability, EMI, and quality of service, investigated by various scholars. The three key challenges are the following.

- 1) Shipboard dc systems lack a common framework to guarantee a suitable protection performance from the primary distribution and the protection coordination.
- 2) The breaker-based protection commonly used in shipboard dc systems utilizes dc breakers based on ac breakers that have limited performance and compromised protection requirements.
- 3) Ship manufacturers rely on COTS converters to reach the power level requirements of the system.

First, considering that dc systems are emerging for shipboard applications, gradual evolution of rules and regulations is expected, and some scholars are discussing the standardization issues [11], [19], [29]. However, ship design includes an extensive decision-making process involving variables that can affect the protection performance and the volumetric power density. As the regulation is still evolving, the baseline for protection and coordination is missing, allowing ship designers to prioritize other variables. The effect of such decisions is uncertain given that some of the studies required to obtain the information are not defined completely. This article explores some of the issues inherited from the emerging condition of dc systems from the protection perspective: 1) a possible standardization delay that could facilitate undesirable behavior in the event of faults; 2) the bus architectures available and their main characteristics and protection approach; and 3) the power converters placing considering general characteristics, and a superyacht as illustrative use case comparing the centralized and distributed approaches.

Second, dc systems have two characteristics that constrain the applicability of protection measures from ac: 1) dc systems lack the natural zero crossing of the current and the inverse impedance of ac [30]; and 2) dc systems are based on power converters that utilize filtering components that remain charged [8]. As the ac circuit breakers rely on the zero crossing to separate the contacts, they are ineffective for dc applications. Passive components can store a nonnegligible amount of energy capable of quickly feeding a short-circuit fault [8]. Therefore, scholars developed dc protections based on solid-state switches, mechanical and hybrid dc circuit breakers, high-speed fuses, and control actions for an integral protection system [21]. Despite some performance limitations, this protection approach is widely accepted and has allowed a relatively established market for dc circuit breakers. However, such shortcomings frequently involve time response, efficiency, and size, especially for MVDC applications, and more suitable solutions are needed [8], [17], [18]. To contribute in the development of shipboard dc protection systems, this article investigates the breaker-based and the power-electronics-based protection. The study includes the protection mechanisms, their operation principle, a survey of marine-certified products, and the development of SSCB considering arising challenges, and a downscaled SSCB prototype to study a breaker control strategy.

Finally, COTS converters allow building block utilization during system design, which is desirable to simplify the process and cut design costs while obtaining reliable operation and robust components. Nevertheless, the COTS converter components are unknown and often require characterization for proper controller design, energy management, and certification [31], [32], [33]. These parts are not necessarily designed for shipboard applications nor tailored for the specific vessel. Hence, the misuse and excessive oversizing of components are frequent, compromising the volumetric power density and the overall efficiency and limiting the power scalability.

This article provides a simplified comparison among modular power converters for shipboard dc systems for various purposes within the vessel. The comparison allows a high-level comparison that can partially justify the deployment of building blocks for certain applications. In addition, this article points out the design obstacles of PEBBs, where the thermal management can become challenging especially in a distributed switchboard.

This article presents an overview of the causes and consequences of each challenge and highlights the fundamental gaps to address, contributing to the shipboard dc systems development, all from a critical perspective. The rest of this article is organized as follows. Section II describes the main dc primary distribution challenges. Section III presents the main dc protection technologies. Section IV introduces power scalability for dc ships. Finally, Section V concludes this article.

II. PRIMARY DISTRIBUTION IN SHIPBOARD DC SYSTEMS

Shipboard dc distribution is an emerging technology and despite the existence of IEEE, IEC, and NPR standards applicable to the industry, the rules and regulations have not reached the required maturity [28]. Furthermore, a methodology for the decision-making process during design is not yet complete because the knowledge from ac grids is not directly applicable in dc.

This section shows an overview of the standardization issues in shipboard dc systems, the dc bus architecture options and challenges, converter placing, and compares the centralized and distributed switchboard in a realistic use case. The section highlights the challenges to overcome in the widespread of dc systems onboard.

In addition, notwithstanding the research popularity of zonal architecture, their industrial adoption is delayed. A system with zonal configuration is complex and requires a complex control architecture and a high number of circuit breakers and disconnectors. Most of the current systems are demonstrators, whereas the research frequently relies on notional models [10], [28]. Furthermore, the ring architecture is occasionally used in sensitive applications, such as offshore supply vessels and drillers [17]. An additional bus-tie switch operates as redundancy in a dual-bus architecture, but some cases could feature more. Considering the tendency to retrofit vessels using radial architecture as in [34], and the aforementioned arguments, the analysis in the current section studies the radial architecture only.

A. STANDARDIZATION

The IEEE Standard 1709-2018 [35] is a set of recommendations that proposes a zonal distribution architecture as the best practice while ignoring the converter placement and overlooking the protection requirements. The IEC 63108 is limited to a selection of brief definitions for primary dc distribution and control systems that require further information [36]. The IEEE Standard 45 series [37], [38], the US standard for shipboard system design, does not cover dc systems. The NPR-9090 [39] focuses on residential applications, limited in the approach of protections, power levels, and architecture. However, it is the completest framework for system design applicable in the European Union. Consequently, the rules and regulations for shipboard dc systems require further investigation to incorporate newer technologies.

1) DC PROTECTION ARCHITECTURES

Not all sections of a power system require the same level of protection. Critical parts of the system (e.g., propulsion system) need special protection measures, while nonfundamental load or low-power equipment requires much less sensitive protection. From this, an upgrade of the NPR-9090 to onboard dc grids is a practical solution and a missing requirement for the dc system design in LVDC systems. A complete framework is required, similar to the

proposed case in [40] for residential LVDC grids, where protection zones and frontiers are well defined and have specific requirements. For shipboard MVDC systems, the situation is more complicated, IEEE Standard 1709-2018 does not include a well-defined protection structure, and the IEEE Standard 45 series barely mentions voltage classes in IEEE Standard 45.1-2017 [37]. DC systems are completely disregarded by IEEE Standard 45.5-2014 [38], which is intended for safety considerations in shipboard power systems.

As a result, designers and manufacturers rely on the experience from ac systems during grid design, which can originate various unidentified limitations. Some of the necessary studies for the identification of limitations are also missing, thus restricting the possibility of providing best practices from standardization bodies. Scholars are showing multiple studies to overcome the shortcomings, allowing regulators to expand the knowledge and recommendations about bus architectures and converter placing. However, studies about fault propagation, essential in dc protection development, are scarce in the literature.

B. BUS ARCHITECTURE

In the current standard of ac distribution, most of the distribution utilizes three-phase systems, and only the low power loads are single phase. In contrast, dc distribution can feature unipolar or bipolar arrays, and both architectures can provide full power to the loads and propulsion, as depicted in Fig. 2.

The voltage levels in dc systems are more flexible than ac cases. Hence, the selection of the voltage class is essential for the performance. An increased voltage level facilitates higher power capabilities, smaller cabling cross section and lower losses for the same power level. However, medium-voltage classes require additional certifications from designers and certification entities given the increased insulation and safety concerns. Furthermore, a higher voltage gain ratio in the power converters might need modular power converters in parallel and/or series connections to match the requirements [8], [19]. In addition, utilizing low-voltage levels for the same power can decrease the complexity of power converters. The semiconductor variety and availability improves in lower voltages, allowing the usage of more efficient modules. The usage of parallel power converters is relatively simple to achieve to cope with the higher current needs in low voltage [8], [19].

Consequently, the availability of distinct bus architectures makes the decision-making process more challenging. The unipolar and the bipolar bus architectures are the most frequently mentioned in shipboard dc grids and are affected in a different way by the previously mentioned arguments. This section discusses the benefits and challenges of both choices, including the protection approach and a simplified comparison.

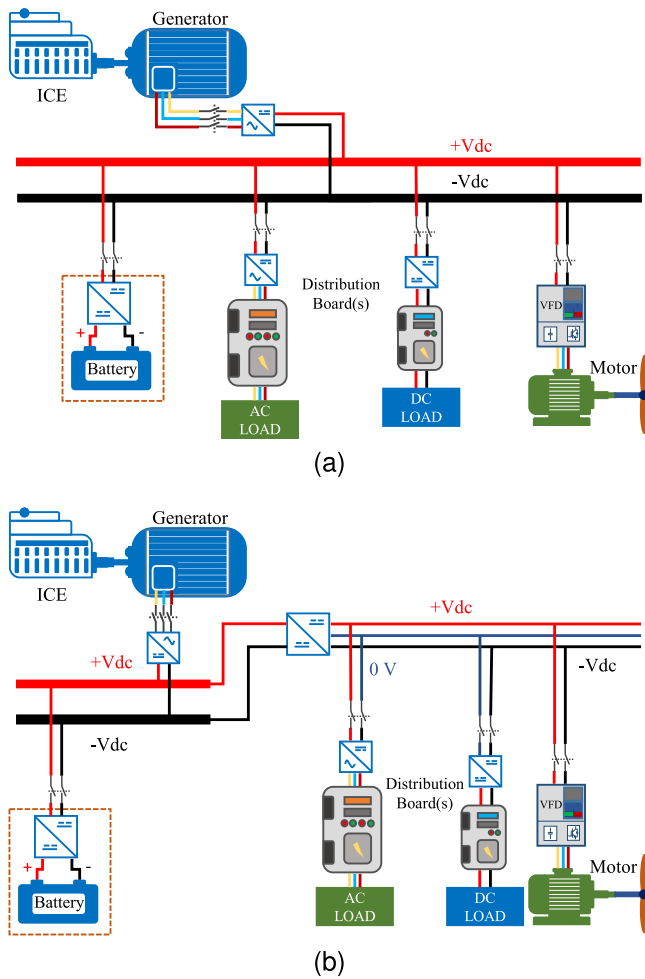


FIGURE 2. Unipolar and bipolar bus architectures for onboard dc systems. (a) Unipolar dc system, reported for various applications, such as superyachts and cable layers. (b) Bipolar dc system, recommended in the IEEE Standard 1709-2018 for high survivability. Dash: optional.

1) UNIPOLAR BUS

The unipolar dc system uses only two conductors for distribution. The sources and loads are connected to a single level of dc using the positive (+Vdc) and negative (-Vdc) ports of the bus [28], as shown Fig. 2(a). These systems are simple to implement and maintain, and the cabling load is balanced. However, the single voltage system reduces flexibility, and no backup power line is available in the case of a fault [19], [28].

2) BIPOLAR BUS

The bipolar bus architecture, also known as the three-wire dc bus system, utilizes one additional conductor as the “neutral” (0 V), as shown in Fig. 2(b). The additional conductor creates two complementary power lines with two voltage levels in the same bus. The efficiency improves because the return wire reduces the current carried by the pole wires. Thus, bipolar systems can supply higher power than unipolar systems, and the positive and negative buses can operate independently, increasing flexibility and reliability [19], [22], [28]. Furthermore, bipolar dc systems may require a voltage balance circuit

TABLE 1. Bus Architecture Comparison for Unipolar and Bipolar DC Systems

Unipolar	Bipolar
<ul style="list-style-type: none"> Simple to design and deploy Based on two conductors Can become vulnerable when a fault occurs Preferred for most applications Controlled by the converter of the main power supply Better controllability and limited reconfiguration options 	<ul style="list-style-type: none"> Design based on balancing the load between the poles Based on three conductors and a voltage balancer Fault-tolerant, losing one pole does not mean losing the bus Preferred for warships considering the increased survivability Require an additional voltage balancer for stable and efficient operation Enhanced reliability and reconfiguration options.

to avoid stability and efficiency issues created during voltage unbalance scenarios. This circuit also requires a well-tuned control system to operate properly, which can also include a complex control strategy [16], [19], [22], [28], [41].

3) PROTECTION APPROACH

Table 1 summarizes the main differences between the two bus architectures discussed. This overview suggests that the protection approach shall be different in both cases. For instance, the voltage balance power converter can become a critical component to protect from a short circuit. Moreover, the available grounding scheme regulation for bipolar systems is best introduced in IEEE 1709-2018 [35]. Nevertheless, the fuse is an essential protection component [42], regardless of the bus architecture or whether the system is ac or dc, and despite their limited time response. Extensive research is required to provide an alternative solution to the fuses, protection systems for unipolar and bipolar systems, and the grounding scheme for each case.

C. POWER CONVERTER PLACING

As there is no consensus about the physical location of the power converters, the stakeholders have proposed different approaches. Depending on the application and the manufacturer, two general dispositions are frequently used. The converter disposition close to generators and loads and the placement embedded into the switchboard are designated distributed and centralized approaches, respectively [15], [34]. In the vessels from Wärtsilä, different placings are available [43]. The disposition and integration of frequency drives, switchboards, and energy storage vary significantly according to the application.

1) CENTRALIZED

The centralized or multidrive approach shares qualities with a generic ac switchboard. Converter modules are placed within the same space as the protection, control, and connection devices [34], as illustrated in Fig. 3.

The switchboard contains all the components framed by the dashed red rectangle in Fig. 3. The power distribution is

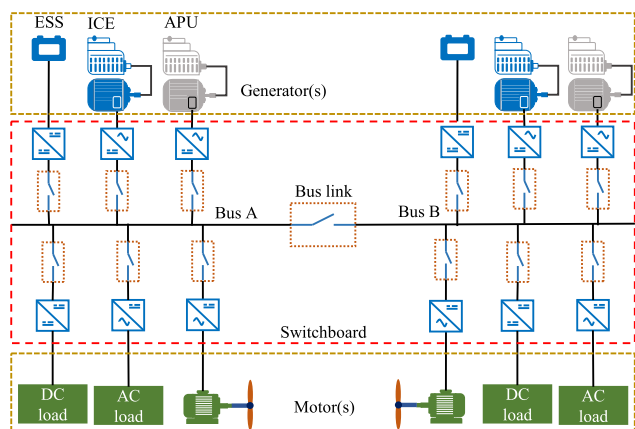


FIGURE 3. Centralized disposition of conversion stages for onboard dc systems. Dots: dc switches; red dash: switchboard components normally placed close together; and dark yellow dash: components normally placed away from the switchboard.

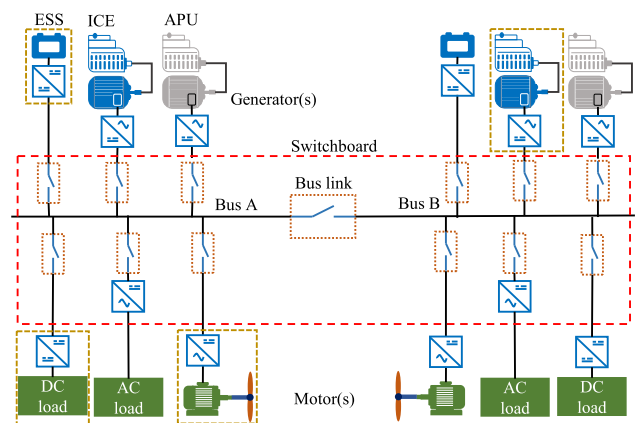


FIGURE 4. Distributed disposition of conversion stages for onboard dc systems. Dots: dc switches; red dash: switchboard components normally placed close together; and dark yellow dash: components normally placed close to their respective drives and far from the switchboard.

then centralized, or pseudo-centralized, from the switchboard to the load, requiring extensive ac cabling in the vessel.

2) DISTRIBUTED

For this case, as the name suggests, the power conversion stages are placed as near as possible to the load or the generator and away from the switchboard, as shown in Fig. 4.

The generated power can be fed directly to the dc bus for distribution from the rectified ac generator or the dc storage. The main load supply utilizes dedicated inverters (dc–ac converters) and dc–dc converters, and normal ac distribution requires island converters [34]. Such a configuration can significantly reduce the ac cabling for the bus circuits compared with the centralized placing.

3) OTHER PHYSICAL DISPOSITIONS

The centralized and distributed dispositions are the extreme cases where the components are contained within the same

TABLE 2. Switchboard Approach Comparison for Shipboard DC Systems

Centralised	Distributed
<ul style="list-style-type: none"> Power converters and systems are close to each other <ul style="list-style-type: none"> Require extensive use of ac cabling Communications and instrumentation are closely connected and centralised <ul style="list-style-type: none"> Extended VFD cables increase the losses and EMI Baseline of the system volume 	<ul style="list-style-type: none"> Power converters are close to generators and loads <ul style="list-style-type: none"> DC cabling is extended as close to the load as possible Communications and instrumentation are centralised in the switchboard and distributed in the system <ul style="list-style-type: none"> Short VFD cables reduce the conduction losses and localise the EMI A considerable volume reduction is possible

space or placed all over the ship. However, the dc systems enable mixed dispositions without matching the previous cases [28], [43], including the complete removal of the switchboard. The advantages need identification in any case and specify the disposition according to the requirements at the design level.

Table 2 shows a simplified comparison between the centralized and distributed placing. In the case of the switchboardless approach, the empirical information is limited, and the implications are mostly conjectures that require further studies .

D. SWITCHBOARD APPROACH COMPARISON IN A SUPERYACHT

A primary switchboard cabling estimation is valuable to quantify the centralized and distributed approach differences. The system of a Superyacht [Fig. 1(a)] allows an estimation considering a multimewatt calculation with relative complexity. Hence, an inference about various seagoing vessels is possible based on the current use case. The operation modes, existence of multiple generators, variable loads, and EP enable the comparison at certain extent. The dc primary switchboard features a twin system with one main diesel generator, one secondary diesel generator, one ESS, one main propulsor, and ac loads on each side (Figs. 3 and 4). An additional bow thruster is attached to one side of the switchboard, which is mainly required for maneuvering.

The parameters of the real system are implicit for confidentiality purposes. Some referential values provide sufficient information for the comparison. The main generators have 30% more power than the secondary diesel generators, and the thruster has 15% of the power of the main propulsors. As the switchboard is dc, the cabling of the ESS remains unchanged in the two approaches; their influence is disregarded. The voltage level of the ac components is 600 V (except for the bow thruster, which is 360 V), and the voltage level of the dc bus and the dc components is 1000 V. The generators and the motors are 64 m away from the switchboard, and the minimum cabling cross section is calculated using (1) and (2), as recommended in [44]. The cabling selection uses the power and control marine cables from the Prysmian Group [45], where the inner grid necessary current rating is the defining

TABLE 3. Switchboard Approach Cabling Comparison for a Superyacht

Component	Connection	Cables per line	Circuits	Cabling count	Cable type
Primary generator	Three-phase	10	1	33	150 mm ²
	Unipolar dc	8	2	32	70 mm ²
Secondary generator	Three-phase	8	1	24	95 mm ²
	Unipolar dc	9	1	18	70 mm ²
Main propulsor	Three-phase	8	2	48	95 mm ²
	Unipolar dc	9	2	32	95 mm ²
Bow thruster	Three-phase	5	1	15	70 mm ²
	Unipolar dc	8	1	16	50 mm ²

factor for selecting the number of parallel off-shelf cables

$$A_{csDC} = \frac{L \cdot I \cdot \rho}{\Delta V} \quad (1)$$

$$A_{csAC} = \frac{\sqrt{3} \cdot L \cdot I \cdot \cos \varphi \cdot \rho}{\Delta V - \sqrt{3} \cdot 10^{-3} \cdot \frac{x}{c} \cdot L \cdot I \cdot \sin \varphi} \quad (2)$$

where L is the cable length, I is the nominal current rating, ρ is the cable resistivity, ΔV is the acceptable or target voltage drop, x is the cable reactance per kilometer, and c is the number of conductors per phase. Equations (1) and (2) are frequently reported for minimum cross-sectional calculations despite the fact that they do not consider the thermal limits, acceptable losses, and have direct proportionality with the power line length. Additional parameters required to improve the calculations are not usually explicit in the procedures. Table 3 shows the summary of the cabling calculation for the Superyacht.

The column *component* considers one of the installed in the vessel. *Connection* refers to the connection type of the component or its drive. *Cables per line* account for the parallel cabling required in the installation, depending on the current rating. *Circuits* include double connections and/or parallel drives. *Cabling count* reflects the total number of cables required for the component. *Cable type* indicates the cable type selected from the marine cabling catalogue [45].

1) WEIGHT

The weight estimation utilizes information in Table 3 and the cable length for each case. In the centralized switchboard, the weight of the dc cable is neglected because the connection occurs inside the switchboard, whereas ac cables extend from the switchboard to the generators and loads. In contrast, the distributed switchboard requires extended dc cables from the switchboard to the power converters, neglecting the ac cabling.

The outcome of the weight calculation shows approximately 15.000 kg for the ac cabling in the centralized switchboard, while the dc cabling in the distributed case shows about 10.000 kg, which indicates a 35% difference. Consequently, the cabling reduction implies a volume reduction, which is close to 36% for the current use case.

Losses comparison for DC vs AC Cabling

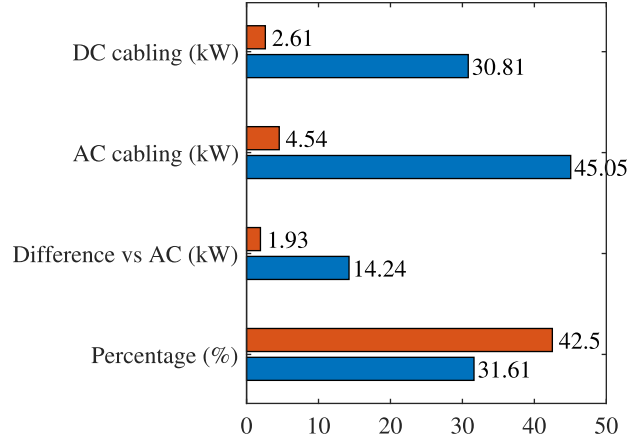


FIGURE 5. Estimated loss comparison of the primary power system for distributed (dc cabling) and centralized (ac cabling) switchboards in a dc-equipped Superyacht. Blue: cruising (high load); orange: maneuvering.

2) LOSSES

The calculation of the losses is a relatively straightforward process built upon the cabling selection. The cabling cross section, the length, the resistivity, and the number of parallel cables are the factors considered in the calculation. The carried-out estimations include two operation modes of the Superyacht: full-speed cruising and maneuvering.

- 1) *Full-speed cruising*: 96% of the installed power is necessary during this operation mode. All the generators operate at equal load, the main propulsors run at full speed, and the bow thruster has minimum consumption.
- 2) *Maneuvering*: Only the main generators operate at 45% of their capacity, while the secondary generators are OFF. The main propulsors run at 15%, and the bow thruster runs at 75% of their nominal speed.

Fig. 5 summarizes the results considering the losses for the main components in the system. The losses in the cabling for the distributed switchboard are significantly lower than in the centralized case for both operation modes. The loss reduction in the cabling in cruising mode is about 32%, whereas the loss reduction in maneuvering rises up to 42.5%. Nevertheless, the number of parallel cables in the system increases the current rating of the lines while reducing the losses. When considering that dc cabling losses in cruising mode are 14.2 kW lower than with ac cabling, and 1.93 kW lower in maneuvering

mode, it is unclear whether such difference could create a noticeable impact for the application and the specific use case. However, the difference is not negligible and could increase with the evolution of dc systems.

E. KEY CHALLENGES

As the system design does not have a common-structured process, manufacturers and stakeholders propose their solutions to fulfill their business objectives. However, the outcome of such decisions is frequently contradictory, and some basic concepts have no explicit consideration. Among the existing gaps, the absence of guidelines on control and coordination of protections to limit the impact of a fault is considered an exciting research opportunity.

Fault propagation and characterization studies in shipboard dc systems are required to characterize the behavior of possible faults onboard. These studies can be used in support of the control and protection coordination design to limit fault propagation. The result of that work should serve as input for a structured decision-making process to properly define protection and coordination requirements in shipboard dc systems considering the final application. In the future, this could also serve to expand the rules and regulations that are currently incomplete.

Considering the Superyacht under study, the system power density could increase substantially in the distributed switchboard following the cabling layout. The volume and weight savings discussed in this document are valuable for design of future dc systems and require expansion to other parts of the vessel and applications. The loss calculation in this document are a starting point to quantify the potential savings acquired by deploying a distributed switchboard.

III. PROTECTION STRATEGIES IN SHIPBOARD DC SYSTEMS

Some challenges behind the missing dc protection guidelines hinted at in Section II rely on technical differences from ac technology because of the natural characteristics of dc [18]. These characteristics make ac protections ineffective for dc systems, forcing intensive research on dc circuit breakers and power electronics for protection systems [8]. However, these protection systems have limitations that affect their feasibility for shipboard dc systems, such as time response, efficiency, and cost-effectiveness. This section introduces some of the natural characteristics of dc systems that affect protection effectiveness. An overview of the typical faults onboard, the general protection requirements, and the recommendations from the standards are also presented. The breaker-based protection for dc systems and some identified challenges are covered, including a brief survey of marine-certified components. Power-electronics-based protection, or breakerless protection, is introduced, showing the current limitations and challenges. The section concludes with a comparison of technologies from the perspective of shipboard dc systems.

A. DC SYSTEMS NATURAL CHARACTERISTICS

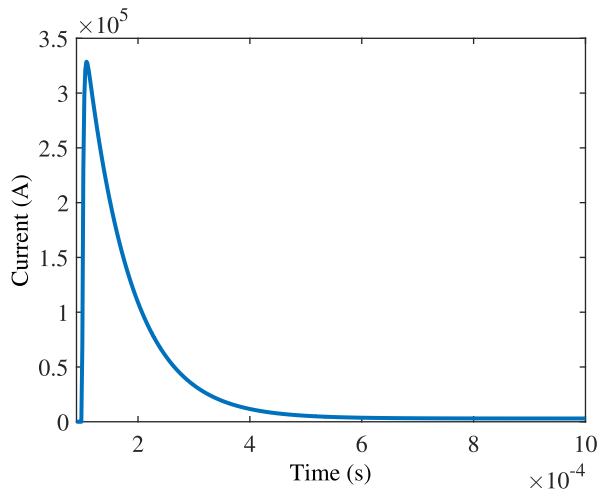
DC protection systems and design are trending topics of research. The intrinsic characteristics of dc make the protection systems more challenging than in ac [8], creating a broad selection of research opportunities to exploit. Scholars are mainly focusing on the following matters.

- 1) *Current zero crossing*: The lack of natural zero-crossing behavior in dc creates two challenges in protection systems.
 - a) Circuit breakers require a forced high-amplitude counter voltage to allow the mechanical contact separation [18], [40], [46], [47].
 - b) Reactive components utilized for filtering power converters and other functionalities in the system remain charged in normal circumstances [8], [18], [23].
- 2) *High-speed high-current rising interruption*: DC systems have a relatively low impedance, which requires high-speed high-current interruptions. That is, to avoid the rapid growth of faulty current (e.g., a short circuit) that could reach the current interruption capacity of circuit breakers [18], [40], [46], [47].
- 3) *High thermal stress and losses*: Fast SSCB protection devices produce higher conduction resistance than MCBs. The device has conduction losses during steady-state operation, whereas the rising currents can lead to overheating and damage of the device during transients [46].
- 4) *Fault location*: As no information about phasor and frequency is available, detecting the fault location can be more challenging for reliable power distribution [48].

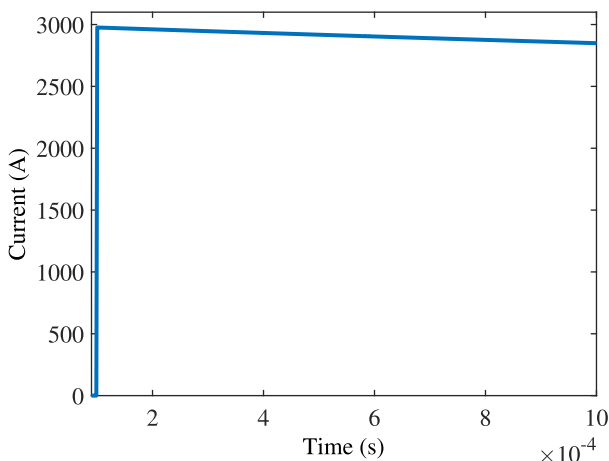
Additional challenges have been identified, such as the high-current turn-OFF for solid-state devices, arc extinction, grounding scheme, superconducting current limiters, cybersecurity, integration of multiple renewable energy sources, or mode change. Those challenges apply to a certain extent in shipboard dc systems and are under investigation for conventional (inland) dc grids [48], which are beyond the scope of this article.

B. FAULTS IN SHIPBOARD DC SYSTEMS

Shipboard dc systems faults studies are reasonably similar to ac systems and other dc application studies. For instance, most relevant studies focus on different kinds of short circuits and their detection, whereas the standards propose related exploratory studies [18], [35], [49], [50]. As power electronics can limit the impact of open-circuit and overvoltage faults, their study is scarce in the literature for shipboard dc grids. The work in [48] categorizes the short circuits for generic dc microgrids into transient and steady-state faults. The transient considers the energy stored in capacitors, inductances, and cables. The steady-state considers long-lasting faults facilitated by power supplies, e.g., distributed energy resources. In shipboard dc systems, the transient response has essentially the same origin, whereas the steady state could also come from the motors [18].



(a)



(b)

FIGURE 6. Simulation of a short circuit in a 1.5-MW shipboard dc systems at 1000 V, considering output filters and parasitic inductances. (a) Pole-to-pole event. (b) Pole-to-ground event.

Different types of short circuit and their effects have been extensively investigated for various applications. In shipping, the short-circuit capacity lies mainly on the dc filters of the drives and the impedance of the circuit [51], [52]. The time response follows the lumped RC circuit as $\tau = RC$, whereas the current variation is guided by $di/dt = V_0/L$. In general, the output capacity varies from several millifarads up to hundreds of millifarads according to the application and the number of drives, whereas the impedance mainly depends on the parasitic inductance of the system. For instance, in a multimegawatt dc system, the capacity could reach about 300 mF, and the parasitic inductance will vary with the cabling arrangement, the bus bars, and the drive connection. Scholars find the pole-to-pole and pole-to-ground short circuits the most relevant to study [18], [50], [53]. The simulation in Fig. 6(a) shows the behavior of a pole-to-pole short circuit in a 1.5-MW system, whereas the simulation in Fig. 6(b) shows

the pole-to-ground case. The simulation model includes the parasitic effect of the cabling and the drives, an equivalent capacity of 50 mF and a dc bus voltage of 1000 V. In addition, the model considers a floating ground scheme commonly utilized in maritime applications [17], [35].

The results in Fig. 6(a) exhibit a peak current close to 330 kA in about 8 μ s. Meanwhile, the pole-to-ground fault in Fig. 6(b) has a similar di/dt , but the maximum current reaches close to double the nominal current before starting to decrease. Consequently, this article reviews those short circuits and the protection requirements inherited from their characteristics.

1) POLE-TO-POLE SHORT CIRCUIT

The pole-to-pole short circuit is a low-impedance fault and is the most dangerous onboard [54]. During the transient event, the capacitors discharge into the fault, creating a high di/dt condition, where the current can reach tens of thousands of amperes if not interrupted [54]. The transient and steady-state effects of the pole-to-pole fault applied to the ac generator are studied in [18] and [48].

2) POLE-TO-GROUND SHORT CIRCUIT

The pole-to-ground short circuit is a high-impedance fault, and the impact is generally less severe than the pole-to-pole case [48]. Generally, the severity of the short circuit depends on the grounding impedance, which varies with the grounding scheme [55]. Shipboard dc grids usually feature a floating ground, and further development on the high-impedance grounding is expected [56]. Despite the potential loss of the dc bus, the current overshoot in a pole-to-ground fault is limited or nonexistent because of the ground impedance, as shown in [48].

3) PROTECTION REQUIREMENTS

The design of the protection system of a dc system must protect all entities interacting with it, and the service availability should not be compromised [40]. The premise of the protection system is to comply with the following directives.

- 1) *Safety*: All systems and individuals are working/operating safely with the system.
- 2) *Sensitivity*: The protection systems can detect different types of faults in the system.
- 3) *Security*: The protection devices act when required only, avoiding false tripping.
- 4) *Selectivity*: Constrained by the distribution architecture, only the faulty region/component should be isolated.
- 5) *Speed*: Usage of high-speed protection systems to prevent blackouts and extended damage.
- 6) *Cost-effectiveness*: Compared to the protected systems, the cost of the protection system must justify the investment.

Furthermore, the recommendations provided by some standards facilitate the overview of protective measures to consider. The IEEE Standard 1709-2018 recommends a series

TABLE 4. Definition of Protection Levels in Marine DC Power Grids [58]

Protection	Action	Protection component	response time
1	Fast	Solid-state bus-tie switches	up to 10s of μ s
2	Medium	Solid-state circuit breakers and high-speed fuses	up to a few ms
3	Slow	Generator deexcitation, fold-back protection control, high-speed fuses, solid-state circuit breakers	up to several seconds

of studies intended to ensure the compliance of the dc system with some basic definitions of protection and survivability [35]. The standard recommends pole-to-pole, pole-to-ground, and pole-to-pole-to-ground fault studies caused by component failure, power converters, and subsystems attached to the dc bus. In addition, the document includes communication and sensor failures, cooling system malfunctions, and fault management studies for postfault restoration.

The IEEE Standard 45.1-2017 includes additional recommendations to consider despite the limitation regarding specific dc protection measures. The fault classification includes overcurrent, ground, line-to-line, internal equipment, loss of phase, and others [37]. Additional information about fault management and some protection design guidelines is also available. Nevertheless, the recommendation of dc systems is limited to a maximum short-circuit current calculation.

In order to tackle the directives, two types of protection architectures for shipboard dc systems have been proposed in [8]: the *breaker-based* protective architecture and the *power-electronics-based* protective architecture also known as breakerless or unit-based protection [30], [57]. The remaining of this section investigates the protective architectures and their technology, the current panorama of dc circuit breakers, and the development of SSCBs.

4) SHIPBOARD PROTECTION ZONES

DC protection systems normally includes zones of protection for the different parts of the grid that change with the requirements [58]. One common approach is segregating in zones based on fault clearance time in a three-level protection scheme, summarized in Table 4.

Such an approach is considered cost-effective for radial architectures onboard ships because of the simplicity and the lack of (complex) communication requirements. Therefore, manufacturers rely on similar schemes during protections designs [59].

The three-level protection in scheme in Table 4 has disadvantages in two types of fault. Bus separation failure and limited selectivity and sensitivity of the feeder protection [59]. The first challenge is addressed in the literature by enhancing the reliability, protection performance, and added features of the bus separation component. The selectivity issue requires the adjustment of the dc capacitance and high-speed fuses and circuit breakers [47], [49], [59]. In contrast, an intelligent-electronic-device-based differential and directional

protection can identify and isolate a fault with minimum system loss. However, the system features a relatively high cost, relies on special communication systems, and requires a device with a circuit breaker in every feeder, which limits their cost-effectiveness [59].

C. BREAKER-BASED PROTECTION

As the name suggests, breaker-based protection systems utilize several circuit breakers installed and coordinated to protect the system. Circuit breakers are the first component for short circuit and overload protection in any MVDC system. An extensive classification, description, and discussion regarding circuit breakers, including mechanical and solid-state components, is available in [46]. Another comparison is presented in [17], discussing the advantages and drawbacks of different circuit breaker technology. Future trends for SSCB are examined and discussed in [60]. The comparison presented in [47] includes dc-dc converters in the analysis and discussion to highlight the potential benefits of breaker-based and breakerless protection architectures. Finally, the work in [61] shows the design and protection scheme and testing of SSCBs for shipboard power systems, highlighting the need for further development.

There are several circuit breaker technologies to consider. The following sections briefly introduce the fundamentals of: 1) MCBs; 2) SSCBs; 3) hybrid circuit breakers (HCBs); and 4) solid-state bus-tie switches, which are the most relevant technologies, and shows a brief selection of commercially available dc circuit breakers with marine certification.

1) MECHANICAL CIRCUIT BREAKERS

Circuit breakers need to build up a counter voltage at least equal to, but preferably higher than, the bus voltage to force the current to drop to zero ampere to interrupt the circuit [62]. For MCBs, there are two operation technologies to consider: the passive resonant circuit breaker [see Fig. 7(a)] and the active resonant circuit breaker [see Fig. 7(b)] [17], [46], [58].

Both active and passive circuit breakers use the same principle to operate. The use of an *LC* resonant branch to reach the fault current and extinguish the arc and an MOV to clamp the voltage to a maximum permissible value [46]. The difference between the two circuit breakers lies in the inclusion of auxiliary switches to enhance the breaker performance [46], [47].

2) SOLID-STATE CIRCUIT BREAKERS

In SSCBs, power semiconductors controlled by gate drivers are utilized instead of mechanical switches [46], [62]. The wide variety of semiconductors enables a variety of SSCB topologies with specific advantages. Some typically employed technologies, which are used according to the current rating requirements, are the insulated gate bipolar transistors (IGBTs), the reversing block IGBTs, the integrated

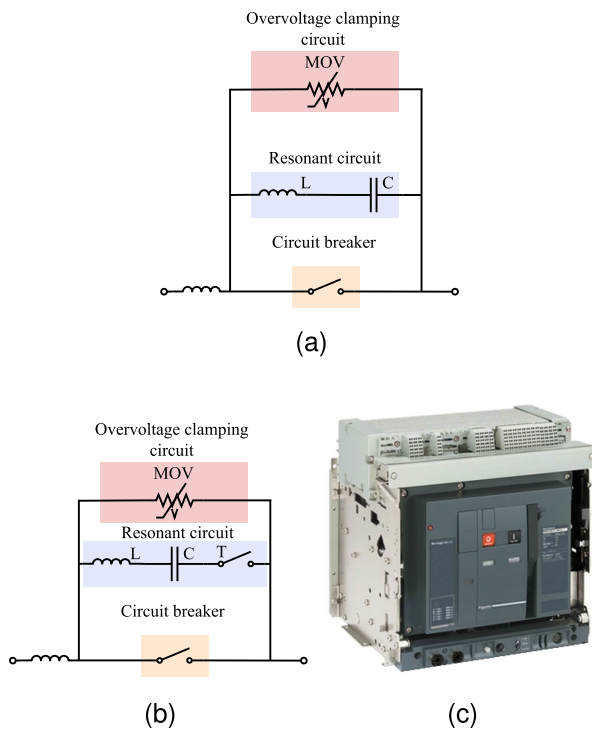


FIGURE 7. Referential schematic diagram of MCBs. (a) Passive configuration. (b) Active configuration. (c) Commercially available mechanical dc circuit breaker from Schneider Electric [63].

gate-commutated thyristor (IGCT), the power metal–oxide–semiconductor field-effect transistors (MOSFET), the power JFET and the power diodes.

This section presents a typical categorization of SSCBs as follows: 1) *unidirectional* [see Fig. 7(a)]; 2) *bidirectional* [see Fig. 7(b)]; and 3) *thyristor-based* [see Fig. 7(c)]. The latter technology (thyristor) is mostly used in ac SSCBs because the commutation requires the current zero-crossing behavior to impress a high impedance into the circuit, while the other technologies depicted in Fig. 8(a) and (b) can impress a high-impedance behavior independently of the flowing current magnitude, thus being well suited for dc SSCBs. Extended relevant information available in [17], [24], [46], [47], and [64].

a) Unidirectional: Unidirectional SSCBs use single or series-connected arrays of controlled switches (JFET, MOSFET). The circuit allows bidirectional current flow but unidirectional current interruption because the voltage interruption is possible in one direction only [17], [46].

b) Bidirectional: Bidirectional SSCBs use antiseres power semiconductors e.g., IGBTs, to realise bidirectional voltage blocking. The disposition of the power semiconductors is variable and frequently placed in series arrays and/or in parallel to achieve the voltage rating and power level required. These are typically enhanced with passive components and varistors to facilitate commutation and voltage clamping [46], [47].

c) Thyristor-based: Thyristors have high commercial readiness, a mature manufacturing process, and the highest voltage

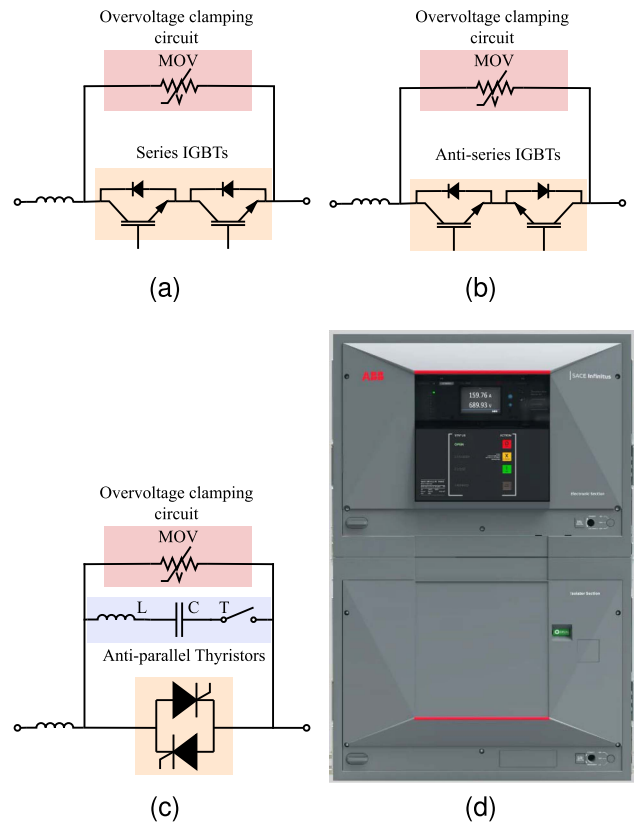


FIGURE 8. Referential schematic diagram of (some) SSCBs. (a) Unidirectional configuration. (b) Bidirectional configuration. (c) Thyristor-based configuration. (d) Commercially available SSCB from ABB based on reverse-blocked IGCTs [65].

and current ratings in single-package devices [46], [66]. Nevertheless, thyristors require resonant parallel circuits to create the zero-crossing current needed for dc SSCB [46], which can also limit the protection performance of the device. IGCTs are preferred over thyristors in dc SSCBs, because of their nonzero current blocking capability. In addition, IGCTs in antiparallel configuration do not require the resonant branches shown in Fig. 8(c). The commercial SSCB in Fig. 8(d) is based on reverse-blocked IGCTs, which enable high-speed protection with limited losses [67].

3) HYBRID CIRCUIT BREAKERS

The HCB is a combination of the SSCB and the MCB to exploit the advantages of both technologies [17], [46], [47], [68]; one of many available examples is depicted in Fig. 9.

In HCBs, normal current conduction is achieved with the mechanical switch, while the high-speed protection is achieved by the power semiconductors [46]. Such a configuration allows the device to break the current arc-free (possibly enhancing the mechanical switch lifetime) at high speed with low conduction losses [62], [67]. As a result, the thermal management of the semiconductor can become less complicated than the devices depicted in Fig. 8. The HCB topologies are also varied, allowing designers to enhance the specific characteristic of the component [46].

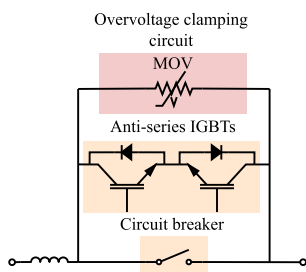


FIGURE 9. Referential schematic diagram of one (of many) HCB.

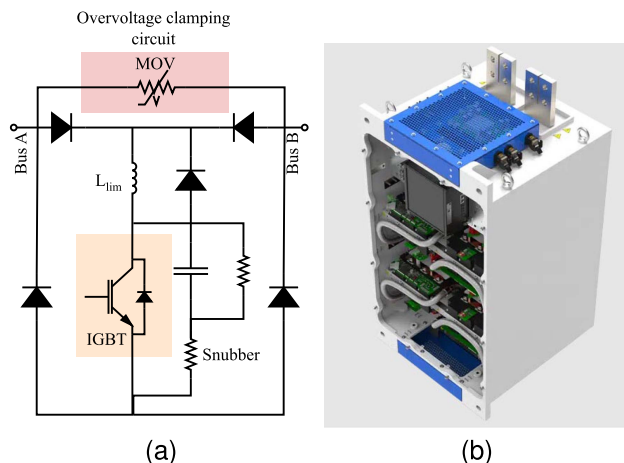


FIGURE 10. Example of a solid-state bus-tie switch (a) Referential schematic diagram of one (of many) solid-state bus-tie switch. (b) Commercially available IGBT-based solid-state bus-tie switch from KWx [73]. *Disclaimer: the product from KWx does not necessarily has internal configuration of the schematic in (a).*

The works in [69] and [70] show extensive dedication to improving the response time of the HCB by using wide-bandgap emitter turn-OFF thyristors and fast mechanical switches in a 7-V lab dc system, close to the MVDC class 6 (6 kV), triggering a 100-A fault in the dc bus with a clearance time of around 1.75 ms, which is not a fast response time for dc systems. The work in [71] shows a different HCB design using current injection to reach fast zero current with a setup of 400 V and fault current of around 90 A, cleared in about 310 μ s. The described system requires adjustment to match the HVDC or MVDC levels that the author claims.

4) SOLID-STATE BUS-TIE SWITCH

The bus-tie switch is a special circuit breaker that shares multiple characteristics with the SSCB. These switches are specially adapted to connect two bus bars as part of the onboard dc power system [15]. The device is designed for ultrafast and safe operation in coordination with other protection components [72]. Fig. 10(a) shows one of the proposed topologies designed and tested in [58] for reference.

The solid-state bus-tie switch is the first protection device to act when a fault occurs. Hence, the device should achieve a clearance time within a few microseconds, low conduction

losses, bidirectional operation (current and voltage), and independent fault detection functionality [74].

Different scholars propose using integrated procedures to enhance several characteristics, such as response time, thermal dissipation, and voltage balance for bus connections [58], [72], [74]. The complexity of the device is generally high, leading to an expected high cost that can restrict the implementation feasibility for various applications. Furthermore, the quantity of bus-tie switches in a shipboard dc system is not high, so it would be necessary to evaluate against the design requirements.

D. DEVELOPMENT OF SSCBS

Modern SSCBs include various protection capabilities besides the breaker functionality, such as inrush current limiter and overload protection [18]. SSCB technology requires additional design considerations to ensure the proper operation of the breaker. This section reviews: 1) popular control strategies; 2) thermal management; and 3) current research in SSCBs.

1) BREAKER CONTROL

The control strategy applied to the SSCB and the solid-state bus-tie switches is fundamental for the protection performance. The switch-ON limiting inrush current, the current limiter, the overload protection, and the short-circuit protection are a few of the most significant functionalities embedded into an SSCB controller [75].

- 1) *Switch-ON limiting inrush current:* The functionality aims to enable a safe start of the power converters by limiting the current to slowly charge the output capacitors [76], [77]. The procedure described similarly to a rule-based controller in [75] and [78] is summarized as follows. During the turn-ON, the SSCB closes in a short-circuit condition that limits the current charging the parallel capacitors. The capacitors charge without current overshoot, and the SSCB changes to ON-mode when complete, allowing the normal load supply.
- 2) *Current limiter:* Current saturation is a basic protective functionality for SSCBs [77]. The circuit maintains a predefined maximum current during a short circuit and avoids current oscillations when the fault is removed [75], [79]. The current saturation includes a latching timer that avoids prolongation of the faulty condition beyond limits.
- 3) *Overload protection:* The overload implies demanding more current than the maximum defined during a relatively long period, which is not necessarily triggered by a short circuit [77], [79]. The SSCB acts as current limiter throughout an overload, activating the latch timer. Once the latch timer expires, the SSCB disconnects the load and remains locked until a manual reset is activated [75].
- 4) *Short-circuit protection:* The short circuit is the worst case scenario for a protection system [79]. The transient

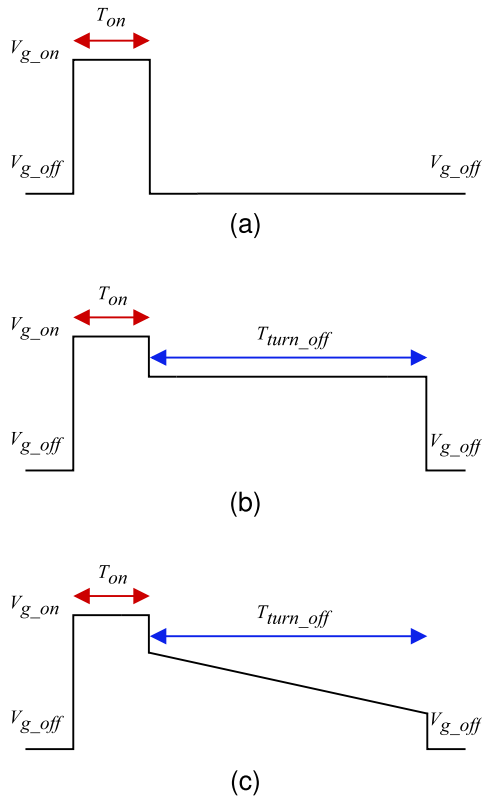


FIGURE 11. Gate signal modulation waveforms for SSCB control. (a) Conventional two-level waveform. (b) Three-level waveform with intermediate turn-off level. (c) Three-level waveform with ramp turn-off transition.

current overshoot is processed by the control unit, which triggers the OFF-mode of the SSCB [76], [80]. After the transient state, the SSCB operates as a current limiter and disconnects the load, requiring a manual reset [77].

Different control strategies applicable in SSCBs enable such protection functionalities. The gate signal modulation is utilized for transient overvoltage reduction (see Section II-D1a), whereas the di/dt control is suitable for current transient protection (see Section III-D1b) [76]. Investigating these techniques is relevant to this work, and these techniques are reviewed in the following sections. The latched protection action and the voltage overshoot suppression are basic complementary strategies exploited in SSCB control [81], [82].

a) *Gate signal modulation:* The investigation in [81] shows the gate signal modulation for protection purposes in the following three ways:

- 1) conventional two-level gate waveform [see Fig. 11(a)];
- 2) gate waveform with intermediate level during turn-OFF [see Fig. 11(b)];
- 3) gate waveform with slope transition during turn-OFF [see Fig. 11(c)].

The normal gate modulation in Fig. 11(a) could cause resonance considering the circuit inductance and the parasitic capacitance in the switch [81]. The overvoltage created throughout the resonance can affect the operation of nearby

SSCBs, potentially reducing the performance of the protection device. For the three-level modulation in Fig. 11(b), the resonance overvoltage could decrease by reducing the gate voltage [81]. However, such modulation does not enable zero-current switch, which can trigger a resonance behavior during part of the turn-OFF process. In the ramp turn-OFF modulation in Fig. 11(c), the gate voltage decreases linearly, allowing a “soft” interruption of the current [81]. The resonance could attenuate its magnitude by allowing a slow reduction of the gate voltage.

Considering an adequate tuning of the pulsewidth modulation signal, the SSCB performance could remain within the design requirements, while the resonant behavior could attenuate significantly, especially during turn-OFF. Nevertheless, the utilization of resistor–capacitor–diode snubbers is common to mitigate resonance and overvoltage issues in SSCBs [83]. The snubber design requires a careful parasitic impedance estimation. However, the solution is relatively simple and does not affect the performance of the SSCB [84]. The convenience of one of those solutions is not evident for every application. A performance benchmark is then required to justify a selection and obtain a cost-effective solution.

b) *di/dt control:* As discussed previously, most of the protection functionalities in SSCB are directly related to current control. Hence, current variation rate is an expected variable to monitor during active protection. The current sensing usually requires shunt resistors, current limiting inductances, Hall effect current sensors, or Rogowski coils [82], [85], [86]. In general, SSCBs demand high-speed detection subsystems to cope with the short-circuit current of dc systems [83].

Consequently, the fault detection circuit demands a relatively short response time that outperforms most digital controllers. Hence, scholars rely on high-bandwidth comparators to implement analog high-performance fault detection circuits [83], [85]. Different control circuits are applicable depending on the application and the installed sensor [82], [83], [85]. An example of the detection circuit designed for the desaturation functionality of SiC MOSFET drivers is depicted in Fig. 12(a). The desaturation action normally applies to switch devices as a protection mechanism against semiconductor short circuits [87]. The diagram in Fig. 12(a) is applicable for Rogowski coil measurement, which requires an integration stage. The high-speed protection system allows fault detection and protection within 400 ns and a clearance time of around 700 ns [85].

Fig. 12(b) depicts a di/dt control circuit for a GaN SSCB with a high-speed Hall effect sensor (500 ns). The circuit includes a resistive divider with a variable resistor to adjust the threshold current. The high-speed comparators (4.5 ns) and logic gates (9 ns) allow fast fault detection and latching of the breaker [83].

A relatively small external inductor, e.g., $L_{didt} = 500$ nH, can be added to the SSCB to sense the di/dt of the flowing current by measuring the voltage across this inductor with a high-bandwidth differential strategy. An SSCB prototype has been designed to verify this functionality with the main

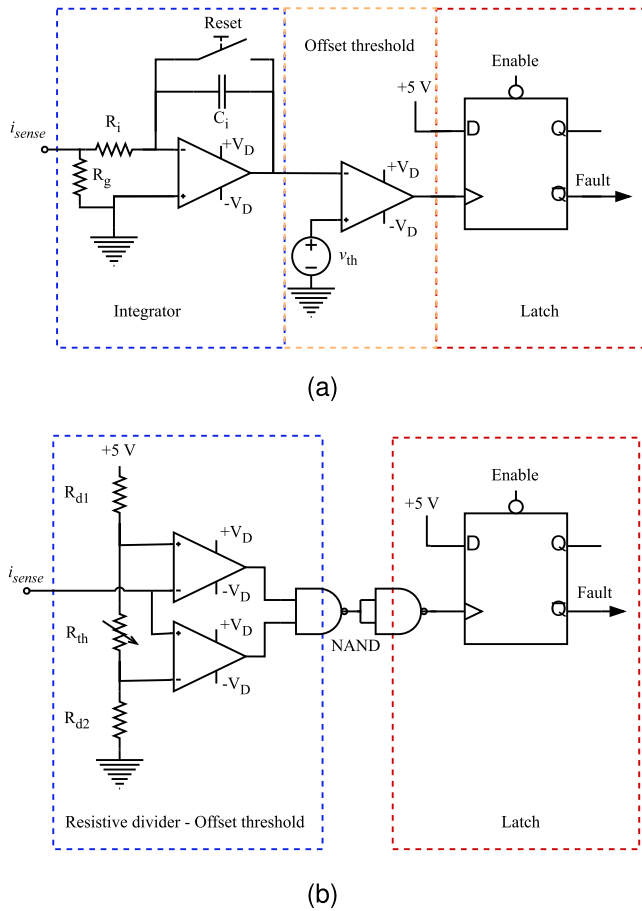


FIGURE 12. Schematic of analog di/dt control circuits. (a) Latched di/dt control circuit for SiC MOSFET drive desaturation. (b) Latched di/dt control for a wide-bandgap SSCB.

schematic and final circuit shown in Fig. 13. Therein, external di/dt inductors (L_{didt}) are used to fast detect low-impedance short circuits, and Hall effect current sensors complement the protection as these are effective to detect short circuits with much lower di/dt (or high-impedance short circuits). In addition, to protect the SSCB against overvoltages, varistors are placed across the upper and lower side common-source bidirectional switches, and small shunt capacitors C_f are used for improving protection selectivity. The fault detection logic is similar to the one shown in Fig. 12(b). More detail about this SSCB can be found in [40] and [82].

Fig. 14 shows the experimental results of the SSCB prototype in Fig. 13, where a 350-V dc voltage source is connected between the terminals a and n , and a resistive load is connected between the terminals b and N . After a certain time, a contactor is used to apply a low-impedance short circuit between the terminals b and N . The differential voltage measurement obtains a signal proportional to the flowing current di/dt . If the di/dt is high, then the existence of a low-impedance short circuit is detected, and the voltage across the inductor will be proportional to the rise of the fault current.

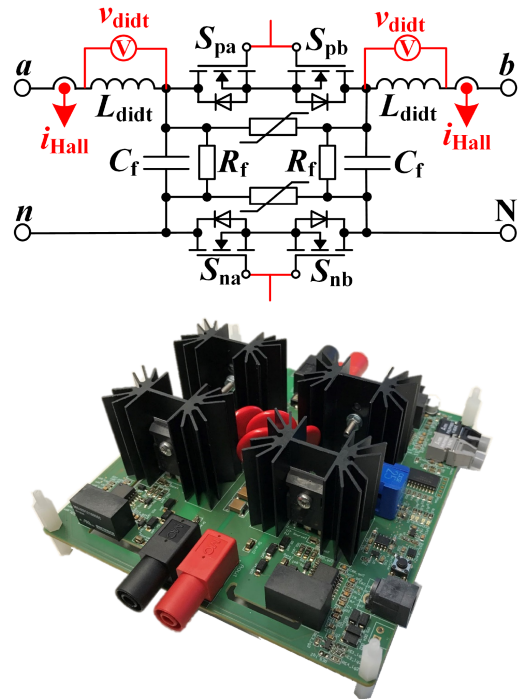


FIGURE 13. Basic schematic and prototype of a downscaled SSCB implementing di/dt .

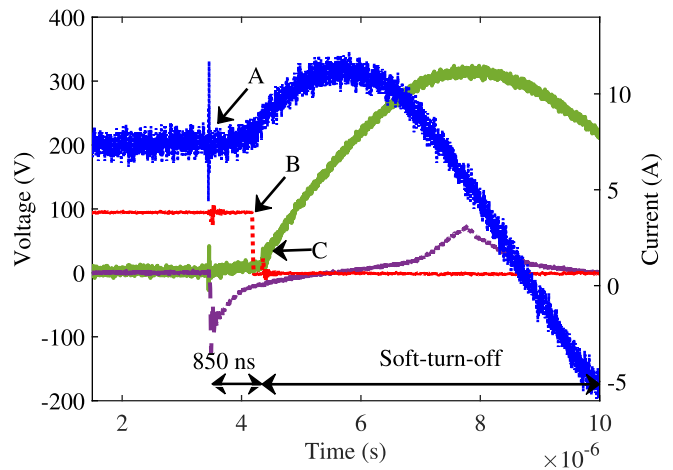


FIGURE 14. Experimental results of the SSCB depicted in Fig. 13 with di/dt protection showing the three main operation steps. “A” is the short-circuit instant, “B” is the instant of fault detection that creates a signal to turn OFF all SSCB’s switches, and “C” is the instant where the soft turn-OFF of the SSCB starts. Blue: input current measured at the terminal a ; red: fault logic signal; green: voltage across the upper SSCB switches (S_{pa} and S_{pb}); and purple: voltage across one of the di/dt inductor.

In Fig. 14, it is also possible to identify the detection and response time of the designed SSCB. The short circuit occurs in A, which has a delay in the comparator detection of about 850 ns. Then, the short circuit is detected in B, where the gate command for all the switches (S_{pa} , S_{pb} , S_{na} , and S_{nb}) is set to OFF, whereas the clearance of the short circuit starts with the voltage increase across the SSCB switches in C. Herein, the switch impedance is increased according to the slow drop

of gate voltages, as shown in Fig. 11(c). All in all, the low-power prototype available is valuable for the development of maritime certified SSCBs and for foresee the evolution of the technology.

Nevertheless, the studies about feasible and adequate control strategies in SSCB for shipboard dc systems are not common, and further investigation is needed to achieve the performance requirements without penalizing the cost-effectiveness of the device. SSCBs offer a wide selection of functionalities for circuit protection embedded in the controller. Gate modulation strategies and damping circuits are convenient to mitigate the impact of a hard breaking.

The convenience of the gate modulation or the damping circuit could require an application-specific assessment. High-speed analog circuits are suitable for SSCB control for different applications and sensors. Given that Hall effect current sensors may have a slower response than the Rogowski coils but are less vulnerable to EMI and noise, the characterization of specific dc systems could facilitate the selection, design, and calibration of current sensors. In future developments, a selection of controllers and functionalities for shipboard dc applications is necessary to improve system safety while reducing the hardware required to comply with protection requirements.

2) THERMAL MANAGEMENT

The efficiency, power density, and reliability of SSCBs, HCBs, and solid-state bus-tie switches are closely related to the thermal stability of the utilized semiconductors [88]. Fast heat removal is especially relevant in dc systems because the high-current variations created by a fault can easily damage the semiconductor and possibly affect the equipment connected [23].

In SSCB and HCB, steady-state and transient operation conditions have different cooling requirements [46], [89]. In the event of a fault, the rapidly rising current increases the temperature in the semiconductor. The heat transfer still requires a few additional milliseconds to dissipate the power, which means that the effectiveness of the cooling solution drops during transient events [90]. The heat sink may have a small influence on dynamic performance because of its thermal capacitance.

Fig. 15 shows the simulation of an SSCB based on the IPB200N25N3 semiconductor, which has a maximum current of 50 A at 100 °C. To highlight the effect of various heat sinks in transient response, the SSCB is opened and closed at different intervals, allowing thermal stabilization after each event.

The ambient temperature is defined as 45 °C to consider the effect of other equipment placed in the switchboard. The thermal resistance of the heat sink in Fig. 15 is reduced in steps by 10% to account for various oversizing cases. Such variations have limited effect during the transient as the temperature variation is similar in all cases, with a significantly slow dynamic response. Although the steady-state junction

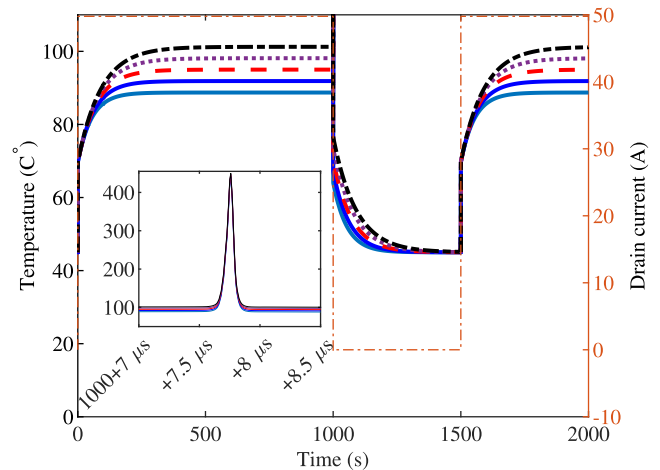


FIGURE 15. Dynamic response of the junction temperature in a MOSFET-based SSCB for various heat sink sizings at 45 °C ambient temperature. The base case considers the maximum current of 50 A at 100 °C (dash black), the current transitions from 0 to 50 A and back (dash/dot light red), and four cases of thermal resistance. Inset: Detail of the junction temperature overshoot after disconnection, in microsecond scale.

temperature decreases when oversizing the heat sink, the transient performance is different.

In the breaking event, the junction temperature drops about 24 °C in approximately 220 ms for all cases, while the fall time of the transistor is around 12 ns. When the switch is closed, the junction temperature rises an average of 24 °C in about 50 ms regardless of the thermal resistance. After the sharp increase, the junction temperature increases by 9 °C on average for more than 30 s before the effect of the heat sink is partially visible. Such results suggest that the sizing of the heat sink has a minimal impact during transient operation and maximum effect in steady state. Therefore, the semiconductor packaging and its maximal thermal limits will define the maximal protection current of the device (microsecond dynamics), whereas the size of the heat sink (millisecond to second dynamics) will have little impact on this matter. In subsequent breaking events, where the thermal stabilization is not achieved, the heat sink oversizing may not avoid the overheat protection triggering.

Nevertheless, the protection devices often feature oversized cooling solutions, such as high-volume heat sinks and water-cooling systems. The power density, the cost, and the reliability of the protection device can be consequently affected, which is considerably undesirable in ship applications, resulting in a mismatch with the market requirements [91].

3) TRENDING RESEARCH

The investigation in [79] shows low-power SSCB for enhanced time response without considering other design variables. The work in [90] is focused on an integrated design methodology of SSCB considering clearance speed, reliability, cost, and efficiency. The LVDC SSCB design shown

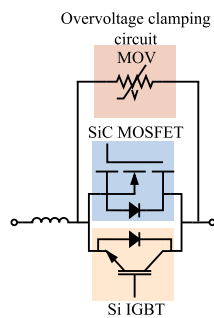


FIGURE 16. Referential schematic of a hybrid SSCB.

in [92] has an integral approach considering overload, short-circuit detection, and load step changes as part of the SSCB design. The time response from 5 to 10 μ s suggests a good starting point to improve the SSCB for LVDC circuits of the shipboard dc system, where the efficiency needs further enhancement.

Power efficiency is also essential to facilitate the semiconductor thermal management and, therefore, the complexity, cost, and power density of the SSCB.

For instance, hybrid semiconductor switches could facilitate the implementation of more efficient SSCBs [93]. The concept involves a combination of at least two different technologies of semiconductor functioning as a single component. The parallel Si IGBT–SiC MOSFET hybrid switch is under study in various applications, such as residential, traction, and aircraft electrification [94], [95], [96]. Several hybrid SSCBs have been proposed and patented, exploiting the advantages of different semiconductor switches [97]. The short-circuit failure mechanisms of Si/SiC hybrid switches are studied in [98], showing the thermal runaway and the gate dielectric breakdown as the main failure modes for different short-circuit scenarios.

Considering the relative novelty of the hybrid Si/SiC switch, the background for SSCBs is scarce. A comparison of Si IGBT-, SiC MOSFET-, and hybrid Si/SiC-switch-based SSCBs was conducted in [93]. The Si/SiC hybrid SSCB prototype tested in [93] is similar to the schematic in Fig. 16, which is considered intrinsically fault tolerant [99]. The research concludes that the HCB is more efficient and cost-effective than the SiC-based SSCB, showing higher current limit and overload capacity, lower surge voltage, better gate voltage stability, and lower cost. However, additional research and testing is required to assess the short-circuit current withstanding capabilities, the conduction losses quantification, the overall complexity increase, and the effect of the high-speed turn-OFF from the MOSFET in the reliability of the IGBT.

Further development on SSCB technologies is required to cope with the drawbacks compared to MCBs, such as cost, form factor, and size of the complete device.

The development of marine-certified SSCBs requires an integral approach to consider the previously mentioned research topics, and the intensive testing program that the device

must undertake. Under such premises, it could be possible to develop a family of technologies that fulfill the technical requirements in ship applications.

E. COMMERCIALY AVAILABLE DC CIRCUIT BREAKERS

There are several solutions of dc circuit breakers and their availability changes with the application and the technology they use. The options for marine-certified products required for dc systems is relatively limited compared to residential applications. For instance, the information regarding SSCBs is extensive for academic purposes; commercially available products are scarce when considering the certification. In contrast, certified mechanical solutions are more common, mainly because some vendors could provide an upgrade for already existing products.

Table 5 briefly describes some dc circuit breakers available in the market. The mechanical product is a suitable option for the application among different vendors and has negligible power losses. The SSCB is a recently launched product by ABB, and further information is required to create a complete assessment.

The loss estimation of the solid-state bus-tie switch at 1 kA comes from the nominal current losses in the datasheet. Such a calculation allows a rough comparison with other products, and a detailed benchmark is necessary in the near future. At the time of writing, no marine-certified HCB had been identified.

From the commercial products in Table 5, the following characteristics are identified and discussed:

- 1) market choices;
- 2) breaking time;
- 3) conduction losses;
- 4) cooling solution;
- 5) volume.

1) MARKET CHOICES

The availability of MCBs is substantially broader than that of solid-state products; several major manufacturers (ABB, Schneider Electric, Siemens, and Eaton) offer complete portfolios for different marine applications.

2) BREAKING TIME

The breaking time of solid-state components is, on average, three orders of magnitude faster than the mechanical device. The performance of the protection system is affected by the time response of the circuit breakers, given that dc short circuits are relatively fast events. The MCB action may not be quick enough for protection against severe short circuits.

3) CONDUCTION LOSSES

Solid-state devices have relatively high conduction losses, and their characterization is essential for solid-state devices. On the contrary, mechanical components have negligible conduction losses. More efficient semiconductors are needed and

TABLE 5. Example of Commercially Available DC Circuit Breakers With Marine Certification [63], [65], [73]

Type	Vendor	Reference	Rated voltage (V)	Breaking current (A)	Breaking time	Power losses (kW)	Cooling solution	Dimensions HxWxD mm
MCB	Schneider Electric	NW20HDC-C	1000	2000	30 ms	Not reported	Air	352x422x427
SSCB	ABB	SACE Infnitus	1000	2500	$\leq 25 \mu\text{s}$	1,3 @ 1 kA	Liquid	Not reported
Solid-state bus-tie switch	KWx	AA-10411-203	1000	3000	15-21 μs	6 @ 3 kA 0,67 @ 1 kA est.	Liquid	507x207x912

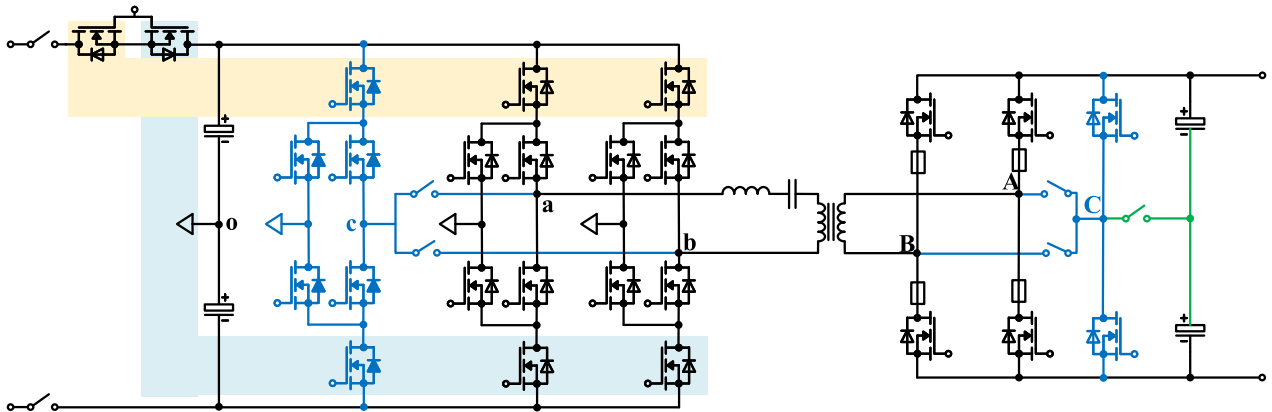


FIGURE 17. Representation of fault-tolerant power converter (active-neutral-point-clamped series-resonant converter) with embedded protection, part of a power-electronics-based protection concept.

expected in the future to increase the system efficiency. However, the conductors used in the mechanical devices should remain more efficient, and faster mechanical solution could be developed.

4) COOLING SOLUTION

The device cooling is especially relevant for solid-state components. The liquid solution allows the downsizing of the heat sink for solid-state devices, whereas MCBs normally do not require additional components. Solid-state products require more complex solutions than the air-cooled heat sinks to operate adequately, potentially increasing the cost of the overall system. Nevertheless, in maritime applications, utilizing liquid cooling is well known, which can benefit the implementation of this technology in centralized switchboards.

5) VOLUME

The volume of MCBs is substantially smaller than the solid-state counterparts, which is an advantage for installation. The solid-state units require space for additional components and other supplemental functionalities not considered for this analysis. Despite the absence of information on the dimensions of the SSCB (from ABB), a form factor similar to the solid-state bus-tie switch could be possible.

The diversification of the SSCB solutions portfolio is necessary for the development of breaker-based protections. Such a scenario can improve the cost-effectiveness of the overall solution and possibly facilitate improvements in efficiency, cooling solutions, and volumetric power density.

F. POWER-ELECTRONICS-BASED PROTECTION AND FAULT-TOLERANT CONVERTERS

Contrary to breaker-based protection, the power-electronics-based protective architecture dispenses the circuit breakers and embeds the protection functionalities in the power converters, while employing fault-tolerant topologies, as illustrated in Fig. 17. The idea highlighted in this schematic is that the solid-state blocking capability is directly provided by the converter itself, e.g., by the upper and bottom switches of the active neutral-point-clamped converter. Therefore, the power converters provide short circuit, overload and overvoltage protections, galvanic isolation, and, logically, the power conversions [58]. However, the successful implementation of all the SSCB functionalities is yet to be demonstrated in power-electronics-based protection. Nevertheless, the technology requires only disconnectors and switches for circuit segmentation and bus transfer, which reduces the number of necessary components and system complexity. Fig. 17 shows an illustrative representation of a power-electronics-based protection converter, which could replace, e.g., the battery converters in Fig. 3 and their protection components.

The fault-tolerant topologies in Fig. 17 are based on reconfiguration capabilities after a component failure and redundancies [100], [101]. The converter allows several reconfiguration actions depending on the fault location and its severity. A mechanism allows the connection of the redundant “c” legs (*in blue*) to replace the malfunctioning of legs “a” or “b”, maintaining the power level of the converter [102]. The three-level structure on the primary side allows several alternative current paths depending on the position of the faulty semiconductor, enabling partial power operations. The three-level topology

can then be considered a single-failure tolerant architecture for the semiconductors and does not require the incorporation of fuses within the semiconductor bridge legs. In addition, the series semiconductors can be used as redundancy in the case of a partial failure. The faulty switch is short circuited, and the remaining switch provides the control [103]. Likewise, the full bridge on the secondary side can operate as a voltage doubler to maintain the operation voltage. This can be provided by the auxiliary switch drawn in green, which can interconnect one of the transformer terminals to the capacitor midpoint. These reconfigurations are extensively studied in [100], [101], and [102], where a survey about power converter topologies and prone-to-fail components is presented.

In addition, the protection circuit in Fig. 17 hints to a necessity of developing compact protection strategies, close to the converter or part of the topology to fulfill the safety requirements of maritime applications. The existence of conduction losses and the high relative cost of SSCBs can compromise the cost-effectiveness of the protection solution. Hence, the mechanical switch in Fig. 17 provides additional galvanic isolation of the converter with negligible losses. Nevertheless, the complete protection strategy is missing, and the technology requires development and a validation, which are not in the scope of research from this article.

The fault detection strategy and the (coordinated) control system lead the protection performance in the converter [104]. Isolated power converters with bidirectional current control are being utilized for fault isolation (using the switches to handle the fault current) [17], [18], [30]. Additional transistors can be placed as part of the power converters to increase the protection performance and reduce losses during steady-state operation [105]. Those designs result in converters with increased complexity compared to breaker-based protection [18]. However, the complete protection solution should have less complexity and more volumetric power density than those of the breaker-based system [8], [58].

The DAB converter and the MMC are commonly researched topologies to use in dc–dc protection and fault-tolerant dc power grids for different applications (including onboard dc power grids) [18], [20], [106], [107], [108], [109], [110], [111], [112].

Both the converters have a flexible design process, extensive development background, controllable bidirectional power flow, galvanic isolation, and modular capabilities. Both the DAB and the MMC have benefits and challenges. Both the converters can be downsized by adjusting the switching frequency but are susceptible to thermal management issues and control complexity [18], [20], [112].

Scholars are working on improving different characteristics in breakerless systems. For instance, the dc bus capacitor discharge is proposed in [49] to enhance the selectivity of the protection system. A capacitor filtering approach is explored in [58], for line-to-line short-circuit detection in residential bipolar dc grids. Modifications of the DAB are investigated

in [49] to obtain highly efficient energy conversion and bidirectional fault handling. The installation of energy storage embedded in an MMC is simulated in [113] to enhance bidirectional fault isolation. The work in [114] shows a diagnosis strategy used to improve the efficiency and reliability of the DAB. Furthermore, the performance assessment in [115] shows a diagnosis strategy used to enhance the efficiency and reliability of the DAB; the performance assessment in [116] compares the DAB and an isolated MMC for breakerless protection with experimental validation. The generator-side protection is studied in [21], assessing the time response in a simulated voltage-source converter.

Currently, breakerless system protection in the use case of onboard power grids is scarce. Identification of a commercial solution has not been possible, suggesting that the development of the system is falling behind. In addition, the reported implementations include laboratory setups or demonstrators, where the proof of concept (fault isolation) occurs under power and voltage-downscaled environments. The power and voltage scaling-up process relies on parallel module implementations, which also needs a complete testing process in experimental facilities [18].

G. ANALYSIS AND COMPARISON

Breaker-based and power-electronics-based protections have several features and challenges discussed in this section. Table 6 includes a simplified summary of the main characteristics as an overview to facilitate the comparison. This section investigates some relevant characteristics to visualize the current status of the technologies.

Several features and challenges of the breaker-based and power-electronics-based protections are discussed in [8], [30], [57], [66], and [118], basing the discussion on the premise of an available zonal distribution architecture. The development of protection architectures in this context is not realistic because of the limited number of vessels featuring that architecture. The survivability and reconfiguration options depend mostly on the distribution architecture, not the protection architecture. A definition of protection features in the framework of architecture may not be applicable in current use cases. Hence, the massive adoption of the zonal distribution architecture is essential to validate the studies. Nevertheless, current works provide important contributions into the field that should not be disregarded despite the limitations.

The scope of other works, such as [18], [47], [58], and [59], has a more realistic use case definition by proposing the radial architecture, partially aligned with the information shown by ABB [34] and Wärsilä [43]. The survivability and reconfiguration limitations are considerable challenges that require more engagement, and the protection system should contribute in their mitigation. An adaptation closer to a ring architecture or the double feeding of sensitive loads could partially mitigate some limitations of the radial architecture, which can also enhance the performance of the protection system or reduce their complexity.

TABLE 6. Protection Architecture Comparison for Breaker-Based and Power-Electronics-Based Systems

Breaker-based	Power electronics-based
<ul style="list-style-type: none"> Relieve the power converters of fault location and current limiting functionalities [8]. Reduction of converter complexity and communications requirements compared to the breakerless architecture [57]. Current limiting, fault isolation and galvanic isolation are achieved by using external SSCBs and HCB [8], [57]. Preferred for high survivability because of the distributed approach of the protection devices [66]. Different algorithms can be deployed to detect and locate faults [54], [66]. <ul style="list-style-type: none"> Snubbers and filters are embedded in the device to improve the transient response of SSCB and switches [66]. Adequate for high peak current mitigation coming from a fast discharging dc bus capacitor [30]. <ul style="list-style-type: none"> Multiple types and architectures of SSCB and HCBs are used for unidirectional and bidirectional current limitation, and fault isolation [8]. <ul style="list-style-type: none"> The technology readiness level of MVDC HCBs and SSCBs is considered low at the time of this writing [8], [17], [117]. Relatively established market with availability of commercial products 	<ul style="list-style-type: none"> Voltage transformation, galvanic isolation and current limiting are handled directly by the power converters [8], [30], [57], [66]. Fault detection and location methods are embedded in the power converter acting as load feeders [66]. Current limiting can be used to inhibit the effect of line-line, line-ground, and line-line-ground short circuits [8], [57]. Distributed communications among the generator, the energy storage and the switches are required for coordination and fault isolation [8]. <ul style="list-style-type: none"> Low impedance faults are also handled by the power converters by controlling and blocking the current flow into the system [8]. Expected to have relatively lower risk and cost than the breaker-based architectures (fewer multi-functional components) [57]. High power density compared to the breaker-based architecture, fewer components and embedded functions could enable this feature [30], [57]. Support for digitalisation-related functionalities and prediction or ageing models. Conduction losses from SSCB are removed, better efficiency than breaker-based protections is therefore expected. Product and market on development, no commercially available options.

The diversification of the architecture options (distribution and protection) is a significant challenge in the context of protection systems. An integral approach is missing, considering both technologies without the current bias in favor of the breaker-based protective architecture. Having a common framework for distribution and protection architectures may be useful for multiple applications in the shipping industry, potentially easing the iterative process of defining protection strategies, protection requirements, and devices while designing the primary distribution system.

In protection systems, most of the research efforts are focused on fault detection, location, and prediction algorithms, MCB, HCB, and SSCB. Several fault detection and localization methods are compared in [17], [18], and [53], such as active impedance estimation, traveling waves, neural networks, and wavelets. Noise pattern analysis is investigated in [119] to detect pole-to-ground short circuits. The directional protection algorithm in [120] uses the current direction for detection purposes. Furthermore, extensive work is done on instrumentation, algorithms, and devices to improve the speed and sensitivity of detection [18], [47], [59]. The variety of techniques under investigation shows significant interest in the topic. Nevertheless, the detection algorithms usually require assumptions of ideal protection devices to enable real-time operation.

Furthermore, the circuit breaker technologies are still under development, especially for MVDC. The MCBs have a slow dynamic response, SSCBs have conduction losses, and the HCBs still have a slow dynamic response for the requirements.

The evolution of solutions using power-electronics-based protection is delayed upon the arguments of expensive development and low performance with little evidence and business decisions. In the future, empirical evidence about power-electronics-based protection performance is expected. A benchmark against breaker-based protection is required to

conclude whether the efficiency and response time limitations are surpassed.

IV. POWER SCALABILITY IN SHIPBOARD DC SYSTEMS

After considering the emerging challenges for shipboard dc systems in Sections II and III, identifying implementation obstacles for real applications is of primary importance for the mass adoption of dc systems. For instance, the power levels of different ships diversify among applications; the power level for different ships varies greatly among applications, from 40 kW to 190 MW. However, most of the semiconductors utilized for power converters can withstand a fraction of that power, making power scalability essential. Usually, ship manufacturers harness COTS converters for simplicity, making compromises on performance and volumetric power density. This section explores the power requirements for the propulsion of different vessels and the misuse of COTS converters in shipboard power systems. A discussion about modular power converters and PEBB is also present for power scalability, with an overview of benefits and challenges. A design challenges analysis for modular converters placed in the PEBB framework finalizes this section.

A. POWER LEVELS IN SHIP APPLICATIONS

In most applications, propulsion power is the highest load on the ship. Thus, propulsion power is a reference of the total power level, except for cruise ships and large warships, in which the hotel and other loads are higher [8]. The use of EP, HP, and MP is application specific. When considering the same application, EP ships have the largest electric power systems, followed by HP vessels and MP ships. This review focuses on EP vessels as power converter scalability is critical for such vessels.

The information summarized in Table 7 includes an estimated range of propulsion power for different applications in contexts with the propulsion architecture. The information of

TABLE 7. Propulsion Type and Power for Different Vessels

Ship type	Power train	Propulsion power (MW)
Ferries	EP, HP	0.04-40
Tugs	EP, HP	0.5-2.5
Fishing	EP, HP, MP	0.2-6
Yachts	EP, HP, MP	1-19.2
Cruise ships	EP	20-60
Drilling Vessels	EP	18-25
Cable layers	EP	13.4-22
Icebreakers	EP	4.3-18
Offshore vessels	HP	1-10
Cargo ships	HP, MP	5-100
Inland cargo	EP, HP	2-5
Tankers	HP, MP	3-50
Dredging vessels	HP, MP	4-22.5
Naval frigates	HP	36-40
Naval destroyers	HP	40-75
Capital naval vessels	EP	72-190

propulsion power was extracted from [8], [34], [43], [121], [122], and [123], and the references for propulsion architecture are [1], [9], [124], [125], [126], [127], [128], and [129].

From Table 7, it is visible that multiple applications use EP and HP in standard operation. Sensitive applications, such as drilling vessels and cable layers, require additional thrusters to improve maneuverability, usually by using EP. Electric motors can provide full torque at low speeds and better controllability than ICE, which is desirable for those applications [125]. It is also visible in Table 7 that the power levels for the different applications are broad, increasing the challenges for scalability in dc systems.

B. COTS SOLUTIONS

Power scalability challenges for power converters are especially relevant for shipboard dc systems. Manufacturers rely on mature and closed COTS converters mainly because they can obtain reliable performance and robust components and systems. However, these components are not necessarily designed for shipboard applications nor tailored for the specific application, possibly compromising volumetric power density and efficiency and limiting modularity and maintenance schemes. In addition, the deficit of valuable information about the equipment can affect the control design and the energy management strategies, possibly limiting the performance. For that reason, closed systems enforce additional tests for control design and certification [31], [32], [33].

A black box strategy is indicated in [31] to foresee the dynamic response of COTS converters for integrated power systems on ships. A similar method is investigated in [32], extended with parameter-varying transfer functions to account for severe nonlinearities in COTS converter characterization for dc microgrids. And the work in [33] shows the frequency deviation of a COTS uninterruptible power supply for ship applications for EMI certification. The referenced investigations point out the convenience of COTS converters for easy integration and agree on the imposed challenge of additional

assessments required to identify the dynamic performance of the components.

The COTS converters for shipboard dc systems mentioned by ABB, Siemens, and Danfoss are complete ecosystems provided by the manufacturers. In such products, the components are closed and protected, the interoperability is not guaranteed, the backward compatibility is explicitly limited, and the modularity is restrictive to their family of products [34], [130], [131]. The design standardization and regulation issues discussed in Section II are also contributing factors. The detailed information about closed systems from major manufacturers is difficult to obtain, and the integration flexibility of their products is not always clear. Hence, the system design has constraints linked to technical limitations already surpassed in other applications (e.g., inland LVDC grids).

C. MODULAR POWER CONVERTERS

As an alternative to the COTS converters, modular power converters are advantageous to reach the power level of generators, motors, and high-power loads in different vessels without losing functionalities. Shipboard dc systems require converters for rectification, propulsion, energy storage integration, load supply, and bus interfaces. Several benefits and challenges are present in various modular converter topologies utilized for multiple purposes within the dc system. Table 8 shows a characteristics summary for the most relevant converters.

From Table 8, it is clear that MMC converters have the flexibility to operate in different parts of the power system. However, the extent of the benefits is constrained by the vessel application, given that the voltage and power levels are variable within a wide range, compromising the power density, fault tolerance, and the feasibility of such converters for the extensive development process. For multiphase generators, the arrays of multipulse rectifiers are preferred instead of MMC rectifiers because of their simplicity and power density [16]. The array configurations can fulfill the design requirements, providing the proper power balance functionalities for the semiconductors and voltage balance for the rectifiers.

The DAB arrays can offer flexible solutions for a wide range of ship applications, providing the control strategy that allows power balance while reducing the circulating current, a wide soft-switching operation range for the semiconductors, and avoiding transformer saturation [132], [133]. Nevertheless, series input DAB configurations require controllability improvements for fault currents that affect the dynamic response of the converter. Furthermore, parallel DAB can suffer from controllability issues when using a high number of modules to scale up power, creating power unbalances and circulating currents.

Some modifications of the neutral point clamped converters are candidates for relatively low-power MVDC–LVDC interfaces and propulsion. The active version of such converters is mentioned in [28] and can be used to compensate for the

TABLE 8. Definitions of Modular Power Converters for Shipboard DC Systems [8], [17], [20], [24], [28], [29]

Application	Configuration	Benefits	Challenges
Three-phase generator	MMC rectifier [16]	<ul style="list-style-type: none"> • Suitable for MVDC applications • Voltage scalability • High efficiency 	<ul style="list-style-type: none"> • Unnecessarily complex • Extensive development process
Multi-phase generator	<ul style="list-style-type: none"> • Multi-pulse parallel rectifier [16] • Multi-pulse series rectifier [16] 	<ul style="list-style-type: none"> • All rectifiers rated at the full dc side voltage • Current is divided by the number of rectifiers • Natural redundant configuration • Reduce the voltage requirements for the semiconductors and the rectifiers • Flexible for voltage class selection 	<ul style="list-style-type: none"> • It might require series semiconductor devices to reach the voltage requirements • Series switches and snubbers require voltage balance circuits • The rated current flows through each of the rectifiers • It might require to balance the voltage amongst the rectifiers
Three-phase ac machines	<ul style="list-style-type: none"> • Neutral point clamped inverter (three-level) [24], [28] • MMC inverter [24], [28] 	<ul style="list-style-type: none"> • Reduced semiconductor stress • Enhanced power quality • Fault tolerance capabilities • Suitable for high-power propulsion • Modular and scalable 	<ul style="list-style-type: none"> • Asymmetrical losses distribution • Uneven heat dissipation • Lacks efficiency when the input voltage is low • Extensive development process
MVDC-LVDC interfaces	<ul style="list-style-type: none"> • Input series output parallel DAB [28] • Input parallel output parallel DAB [8], [24] • Neutral point clamped based dc-dc [24], [28] • MMC dc-dc [24], [28] 	<ul style="list-style-type: none"> • High power density • Scalability for high-power interfaces • High power density • Scalability for high-power interfaces • Fault tolerance capabilities • Reduced voltage stress • Enhanced power quality • Reduced electromagnetic interference • Fault tolerance capabilities • Simplified maintenance requirements • Modular and scalable 	<ul style="list-style-type: none"> • Low fault current controllability • Power balance is required to suppress the circulating current • Asymmetrical current distribution • Controllability limitations when having several power converters • Increased current stress for high-power MVDC applications • Uneven heat dissipation • Reduced number of sub-modules can affect the performance for shipboard applications • Capacitor voltage balance and circulating current among sub-modules is a major challenge

asymmetrical heat dissipation, increasing the converter complexity and the control scheme.

D. POWER ELECTRONICS BUILDING BLOCKS

First introduced by the office of the U.S. Office of Naval Research, the PEBB is a generic framework to include semiconductors, gate drivers, signal conditioning, communications, controllers, filters, sensors, protections, and thermal management into standard scalable blocks to achieve high-power converters [8], [24], [134], [135].

Power levels on ships can vary from less than 1 MW to hundreds of megawatts (see Table 7), ac bus voltage from 690 V up to 11 kV [29], and dc bus voltage from 700 V to 6 kV [29], [39]; for commercially available converters, higher levels can be achieved in the future [8]. The outcome of PEBB, in theory, is cost reduction, improved reliability, and reduction in design and operation complexity within those operation ranges. Moreover, the product development and maintenance processes can be simplified as well [24], [134], [135], [136].

Furthermore, recent works point out that the use of PEBBs presents limits on power density, especially for ship power grids due to discrete components and the power density of silicon IGBTs. Several scholars propose the integrated PEBBs

based on SiC MOSFETs and integrated multipurpose substrates as a solution [137], [138], [139]. Such technology could provide volume and weight reductions [137], and further development is necessary to assess its feasibility and technology readiness level (TRL) improvement to ease mass adoption.

The simplified architecture depicted in Fig. 18 includes the modules required in general for a PEBB based on the DAB converter. The generic architecture features the power switches packed in half-bridge or H-bridge disposition, the gate drivers, the control and sensors units capable of locally controlling power and temperature, and the passive components [136].

The external power supply placed for the gate drivers is not only a consideration of redundancy and reliability but also a matter of safety. It is fundamental for the proper operation of the PEBB that the gate drivers are always powered before the power stage to avoid incidents led by controller unavailability [134], [136].

The start-up and the connection with charged power stages procedures require closed-loop control for correct operation. During start-up, the voltage builds up from zero, and an activation delay in the drivers and controllers is necessary for transient protection [135], [136]. The charged stage connection requires voltage balance to avoid circulating current

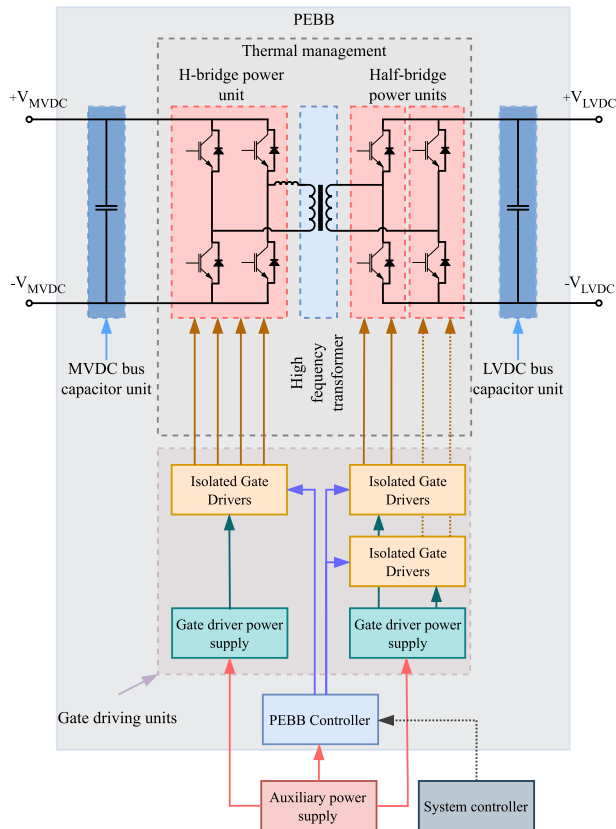


FIGURE 18. Concept architecture of PEBB for a DAB dc-dc converter.

and voltage dips. Finally, the PEBB coupled to the system controller allows the integration into the power grid and the interaction with other PEBB modules, providing the proper control and communication architectures [140].

E. DESIGN OBSTACLES

When considering series and parallel arrays and modular power converters, any variation of the device characteristics, namely module, gate driver, circuit impedance, filter, or cooling solution, can cause asymmetrical power distribution, which also increases with power [29]. The rest of this section includes an overview of the following obstacles: 1) voltage balance and circulating current; 2) thermal management; and 3) emerging challenges to overcome.

1) VOLTAGE BALANCE AND CIRCULATING CURRENT

Parallel-connected converters and modules can present circulating current when the operation point or utilized components (with their intrinsic features) are slightly different. Hence, additional circuits for balance and control compensations are required [8]. In addition, controlling multiple parallel converters can become challenging, potentially compromising their dynamic response within the system.

For series-connected converters, the current flows through all the converters avoiding circulating currents. In this case, the voltage can be different for the converters and an advanced

modulation strategy, e.g., sorting algorithms in MMC, and a voltage balance, with the proper control strategy, is mandatory [16].

In MMCs, both the series and parallel modules can be present. Cascaded modules create series configurations with a potential voltage unbalance. In that case, the capacitors of the modules will cause a circulating current among the modules, increasing the losses [28]. Hence, additional control strategies are required to perform compensations. The intra-arm voltage balancing control, the capacitor voltage balancing controller, the circulating current elimination control, and the circulating current injection controller are a few of the preferred strategies. The added control strategy must operate in addition to the regular controller to mitigate the unbalance and circulating currents, thus increasing the system complexity [141], [142].

In practice, no converter is equal to others, parameter variations are unavoidable, and integrated solutions for circulating current for parallel modules and voltage balance for series modules are required. In order to exploit the advantages of modular converters, those solutions should be placed at the circuit and the control level. Furthermore, PEBBs approach the modular power converter concepts from an integral perspective. Therein, it is advisable to use the component screening method to match the parasitic elements of the parallel PEBBs, i.e., to provide means to equalize the ON-state characteristics of semiconductors and passive elements. However, the suppliers providing the screening services will most likely increase the cost of the components when considering off-shelf devices, but this will be relative to the purchase volume of each item.

2) THERMAL MANAGEMENT

Thermal management in shipboard power converters and PEBB is considered essential and challenging. For instance, the high-power requirement in a relatively power-dense converter can dissipate a considerable amount of heat despite the converter efficiency [25]. The *thermal management zone* in Fig. 18 aims to highlight the components inside the PEBB that dissipate more heat, where the effect of thermal management is critical.

Traditional cooling strategies employed in shipboard PEBB include heat sinks, heat pipes, and liquid cooling. The work in [143] thoroughly discusses different cooling approaches. Therein, most techniques are not currently applicable for shipboard PEBBs, given the distinctive operation and environmental requirements for those systems, along with maintenance complexity and safety concerns [25].

- 1) For the heat sinks, forced air cooling is feasible in shipboard PEBB, and most of the heat is removed by convection [143]. The humidity and air saltiness conditions constrain the performance of such a solution.
- 2) Direct liquid cooling utilizes flexible hoses inside the PEBB to circulate liquids, such as deionized water or dielectric substances, for removing heat [25].

- 3) External liquid cooling harnesses liquid circulation to remove heat from a plate in contact with the PEBB. The same liquid selection for direct cooling is applicable [25], [144].
- 4) Heat pipes employ a contained fluid that evaporates in the presence of heat (evaporation), producing internal pressure changes that move the vapor to the section of the duct that is in contact with a heat sink. The steam is then condensed, causing a pressure change that forces the liquid back into the evaporation section [143].

Both the heat pipes and the liquid cooling solutions can be more compact than a forced-air heat sink, especially in the case of liquid cooling [25]. However, liquid solutions are more complex to design and maintain than heat sinks or heat pipes [143]. Heat pipes, on the other hand, have the flexibility to remove heat from components located in different places, which is not the case for the simple forced-air heat sink. Nevertheless, both technologies are frequently combined to enhance cooling performance. Depending on the sizing (power and voltage), the PEBB can rely on one or another thermal solution, and the approach of a more complex solution needs to be justified.

3) CHALLENGES TO OVERCOME

The framework of power electronics for shipboard dc systems is complex, where voltage and power scalabilities are challenges during development. For instance, the power ratings of power semiconductors are limited, and highly complex converters are expensive and difficult to maintain. Current solutions utilize COTS converters, which can limit the system capabilities, especially regarding volumetric power density, specific power, and dynamic response.

Framing the development of power converters within the PEBB concept could accelerate the acceptance of newly developed technology. However, the process is also complex and extensive, and an approach based on high TRL designs could accelerate the development while reaching the performance and power level requirements.

In addition, the switchboard approach can also affect the cooling solution available for the power converters. The liquid cooling utilized in some centralized switchboards may become unsuitable for distributed systems as the cooling circuit is centralized. The addition of liquid cooling components into the building blocks may affect their form factor and reliability. Consequently, the distributed switchboard approach requires an extensive development of the cooling solution for the PEBBs.

V. CONCLUSION

Shipboard dc systems have remarkable properties that make them suitable replacements for the current ac systems. In doing so, many opportunities will be available to possibly contribute to meet emissions targets in the maritime sector. Enhanced volumetric power density and controllability are part of the value promise of dc systems, in addition to the

flexible engine operation, modular integration of dc sources and storage, and potential reduction of conversion stages. This article introduces a critical overview of the missing developments in primary distribution, dc protections, and power scalability. By addressing all the identified gaps, shipboard dc systems can become safer and more robust, easing the technology acceptance. The main topics addressed in this article are presented in the following subsections.

A. PRIMARY DISTRIBUTION

The selection of unipolar or bipolar bus architectures affects the protection design. For instance, the voltage balance converter becomes critical for protection in bipolar systems. The unipolar system has fewer protection zone reconfiguration options, which demands better protection performance. The definition of a distributed or centralized switchboard concerns the entire distribution system, including protection architecture. The effect of this decision-making process is not well studied in the literature. The opinion from the industry is divergent, and further studies are necessary to improve the regulation and the design process shortly.

The use case studied in this article suggests that the power density of the primary system in a superyacht could increase substantially in the distributed switchboard. The results also show a reduction in the cabling losses, which varies with the operation mode of the vessel. Additional benefits of the distributed switchboard regarding EMI and layout flexibility are possible. Such advantages require further investigation to quantify the benefit for the use case and other use cases. Despite the positive results, additional challenges for the distributed disposition require identification and solving processes. For instance, the required cooling solution modification needs to be investigated as part of the research to adopt the distributed approach.

Fault-propagation studies and protection coordination guidelines can support a future common framework for system design. The fault-propagation characterization can help to rewrite the protection requirements to obtain a more suitable solution for the dc technology. The basis of testing and validation stages requires further investigation for dc technology, given that fundamental concepts regarding fault propagation and protection are missing. Consequently, the basics of dc system design come from ac systems, which can compromise reliability, safety, or efficiency.

B. DC PROTECTIONS

In breaker-based protections, MCBs have considerably low losses and slow response. Solid-state devices have a fast response but relatively high losses. Hybrid breakers are quicker than MCB and more efficient than SSCB but noticeably slow for shipboard applications. Hence, multiple research efforts focus on lossless solid-state and faster hybrid technologies, while other protection devices, less reliant on the circuit breaker performance, are frequently disregarded. The power-electronics-based protection investigated in this article can be appropriate to overcome some of the performance limitations

of the dc breaker technology. Additional benefits regarding volumetric power density and system complexity are possible, enforcing the motivation for its development.

As the power-electronics-based protection technology requires further development, some technical limitations require identification. However, a protection system based on well-known reliable power converter topologies can ease the development cycle, and a rapid transition from a prototype to a product could be possible. Despite the limited access to marine-certified solid-state protection components, this article provides a theoretical background valuable for dc protection system development. The analysis covers the advantages of the considered technologies, the key challenges to overcome in their development, and their operating principle.

C. POWER SCALABILITY

Matching voltage and power levels in dc systems is challenging for the maritime sector. The high power and mobility preconditions force shipyards into making fast and practical decisions, frequently resulting in misused and oversized COTS converters. Meanwhile, the acceptance of PEBBs is growing, creating a diversity of products that might reshape the future of dc technology. However, some major ship manufacturers can still prefer a solution provided by reputed converter vendors, such as ABB, Siemens, and Danfoss.

It is unclear whether shipyards or COTS converters manufacturers will adopt the PEBBs for dc systems in the future. However, by utilizing a power scalability scheme based on PEBBs, it is possible to overcome some limitations of COTS converters in shipboard dc systems, especially regarding volumetric power density and system characterization, which is nonexistent in closed product families. In addition, the development of power-electronics-based protection within the framework of PEBB could enable cost-effective power scalability while maintaining protective properties. Such a product could be advantageous for multiple applications in the section, potentially increasing their value in the future.

This article highlights some of the most urgent challenges of shipboard dc PEBB development as a suitable candidate for modular shipboard dc systems. The scalable architecture of the building block requires voltage balance and circulating current countermeasures to ensure efficiency. A proper thermal management concept will ensure the efficient operation of the building block for different switchboard concepts. The form factor of the PEBB may require adjustments to comply with the requirements of ship designers. By addressing those challenges, the massive implementation of shipboard dc systems could take a step forward into becoming a reality.

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