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Bipolar DC grids on ships: possibilities and challenges

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1 Introduction

Climate change is one of the major issues that humanity is facing. The International Panel on Climate Change (IPCC) recommends system transitions in different industries around the globe to limit the global temperature rise to 1.5°C [20]. Electrification The maritime industry is responsible for around 3% of the GHG emissions in the world [42]. The International Maritime Organization (IMO) has adopted several measures to reduce GHG emissions from international shipping. These measures include the mandatory Energy Efficiency Design Index (EEDI) for new ships and Ship Energy Efficiency Management Plan (SEEMP) [29, 49].

Electrification is considered as an important way for reducing GHG emissions on ships [7]. Currently, alternating current (AC) grids are employed on ships. However, there is a clear trend of moving towards direct current (DC) grids on ships. This is because of their higher power density, ease of integration of alternative fuels, higher power quality, and lower losses [21]. A recent real case study demonstrated fuel savings of around 6% during the entire voyage [12]. Moreover, the area occupied and weight of the equipment in the dc are reduced by 41% and 56% respectively when compared with ac grid [12].

The dc grids on the ships can be either unipolar (UDC) or bipolar (BiDC). The UDC grids uses two conductors (+ and – poles) for power transfer. On the other hand, a BiDC grid can have either two (+ and – poles) or three conductors (+, neutral and – poles).

The BiDC grids have a higher power density and flexibility compared to UDC grids. This is because of the availability of multiple point of connection of the loads. Many examples of UDC grids on ships are available. However, BiDC grids are still in nascent stages of development. Hence, there is a dearth of knowledge about their implementation on ships. This article is an attempt to reduce that gap.

The structure of the paper is as follows. In Sect. 2, the methods and components for implementing a BiDC grid is discussed. The discussion is mainly focused upon the generation technologies (Sect. 2.1) and methods along with the load connection methods (Sect. 2.2). The issue of power balancing in BiDC grids are also discussed in Sect. 2.3. Thereafter, the challenges of implementing BiDC grids on ships are discussed in Sect. 3. Conclusions are given in Sect. 4.

2 Implementation of BiDC grids on ships

2.1 Generation

The generation of power in marine vessels usually comprises of a prime mover and a generator in case of electric propulsion system. Traditionally, the prime movers are combustion engines fueled with Diesel or heavy fuel oil, gas turbines, steam turbines, combined cycle turbines, and nuclear engine [3]. The IMO has put new limits on the fuel sulfur content (FSC) of ships to 0.5% (0.1% in sulfur emission control areas). This is considerably lower than the previous limit of 3.5% [18]. Therefore, the ship manufacturers are considering much cleaner fuels like liquefied natural gas (LNG) for the prime mover [18]. Contrarily, unburnt methane (methane slip) is a big issue when using LNG in ships. Methane slip can be more severe for the climate due to its high carbon dioxide equivalence [18]. Moving forward, the shipping industry is considering

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Power-to-X (PtX) strategy to produce fuels like green hydrogen [51]. The green hydrogen produced can be used as fuel for the solid oxide fuel cells (SOFC) on ships [48]. A detailed discussion on the fuels for the prime mover is beyond the scope of this article.

The generators installed on the ships are usually 3-phase synchronous generators [22, 35]. The armature windings are arranged in Y so as to reduce the phase to ground insulation requirements [35]. The neutral of the generator is kept open to improve the resilience of the grid as it will remain unaffected in case of single phase to ground fault. According to IEEE Standard 45.1 and 1709-2018, there are standard voltages defined for generation and distribution on ships. These are summarized in Table 1 [1, 2]. Due to the various voltage and power levels of ships, it is pertinent to have a discussion on the various types in which the generation units are arranged in a ship.

Any voltage below 1500V is considered low voltage (LV) in ships. According to IEEE Std 45.1, LVAC (480V and 690V) and LVDC are used when the total installed generation capacity is lower than 4 MW and any single load has a power rating of no more than 400 kW [1, 3]. The examples of such ships would consist of ferry, yacht, platform supply vessel, anchor handling vessel etc.

An example platform supply vehicle with prospective BiDC grid is shown in Fig. 1. Here, the service loads are low power loads and hence their converters

are connected between a single pole and neutral. The thruster and propulsion motors are high power loads. Hence, their drives are connected between the + and - poles.

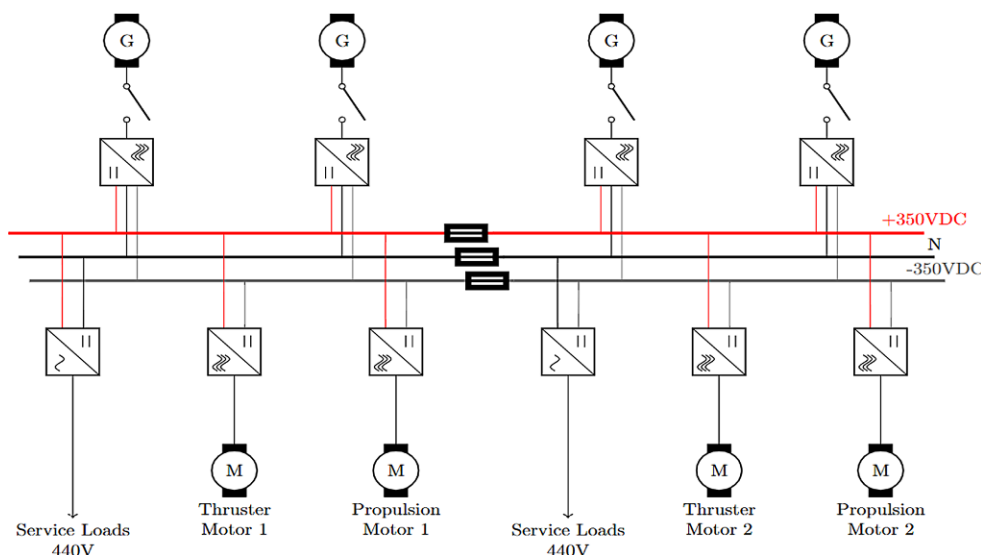
There are several topologies of the three phase AC-DC rectifiers that can be used to form the BiDC voltage. The commonly known topologies can be divided into two parts: unregulated ac-dc rectifiers and active pwm rectifiers. The unregulated ac-dc rectifiers consist of diode bridge rectifiers and multiple pulse rectifiers. They can be only used when there is a possibility of voltage regulation at the generator side [11]. Hence, they cannot be used with permanent magnet synchronous generators. Keeping that in mind, below are shown some of the ways in which a BiDC grid can be created with three winding wound rotor synchronous generator.

In Fig. 2, a three phase synchronous generator is used to create a BiDC grid. The synchronous generator is interfaced with the BiDC grid using a three winding transformer and a 12 pulse rectifier [4, 32]. The three winding transformer adds weight to the ship and also consumes space. This leads to additional weight and hence increases costs and reduces efficiency of ships [36]. To circumvent these issues, a dual stator synchronous generator can be used [11, 44]. Dual stator machines are usually used for MVDC systems and when higher fault tolerance is required [11, 44]. For a wound rotor synchronous generator, multi-winding

Tab. 1 System voltages for AC and DC ships

Power Utilization	IEEE Std 45	IEEE Std 1709	Remarks
Generation	AC: 120V, 208V, 230V, 240V, 380V, 450V, 480V, 600V, 690V, 2400V, 3300V, 4160V, 6600V, 11 kV, 13.8 kV DC: 120, 240	DC: 1.5 kV, 3 kV, 6 kV, 12 kV, 18 kV, 24 kV, 30 kV	The IEEE Std 45 only defines low voltage dc
Distribution	AC: 115V, 200V, 220V, 230V, 350V, 440V, 460V, 575V, 660V, 2.3 kV, 3.15 kV, 4 kV, 6.3 kV, 10.6 kV, 13.2 kV DC: 12V, 24V, 28V, 115V, 230V, 270V, 380V	-	The IEEE Std 1709 does not explicitly define voltages for generation and distribution

Fig. 1 Example of Platform Supply Vessel BiDC power system



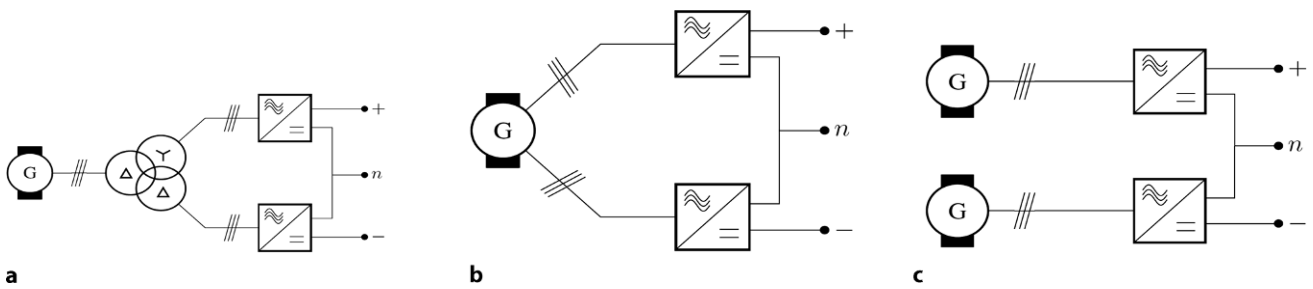
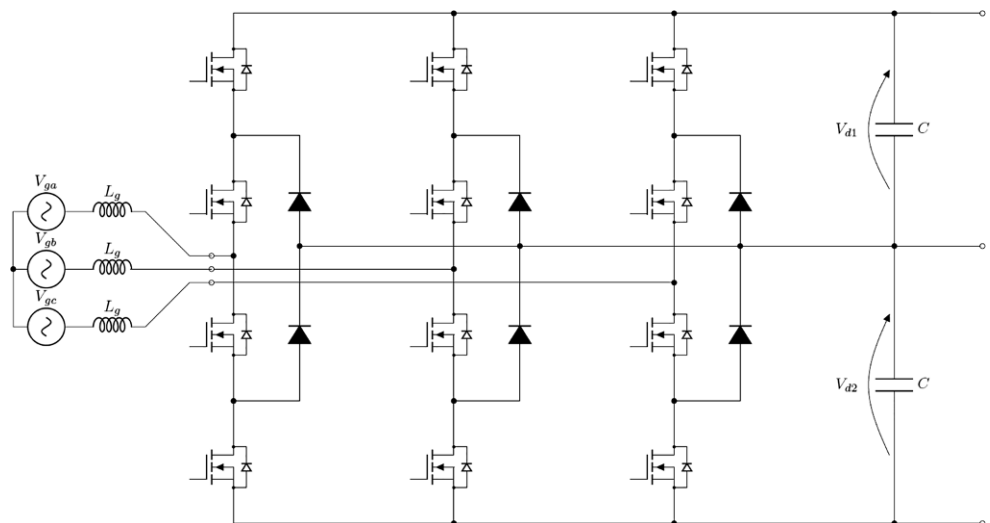


Fig. 2 Different ways of creating BiDC grids on ships. **a** Creation of BiDC from single 3-phase synchronous generator, **b** Creation of BiDC from dual stator synchronous generator, **c** Creation of BiDC from two synchronous generator

Fig. 3 3-level neutral point clamped converter



transformer is not necessary. This scheme is shown in Fig. 2b.

In this topology, the power imbalance between a pole and neutral can lead to harmonics which in turn lead to higher copper losses and torque pulsations [30]. Damper windings can be used to dampen the oscillation but they increase the losses in the generator [30]. The 12 pulse rectifier used in the above methods shall have characteristic harmonics at $12k \pm 1$ times the fundamental frequency of the generator [34]. These harmonics usually get canceled when the dc load at the output are balanced. Alternatively, additional negative sequence voltage are induced on the ac side when the dc loads are unbalanced [34].

When multiple generators are available aboard a ship then two generators can be used to form a BiDC grid as shown in Fig. 2c. In this scheme, the redundancy provided by the two generators, when used otherwise, is sacrificed.

As discussed above, the uncontrolled rectifier cannot be used when there are unbalances in the grid. There have been several catastrophic incidents on ships due to harmonics [22]. To mitigate these issues, controlled/active rectifier technologies become necessary. There are several topologies of the converters that can be utilized for creating a BiDC grid on a ship. The three level topologies are the most

prominent and mature technologies. These consist of the 3 Level Neutral Point Clamped (3LNPC) converter and 3 Level T-Type (3LTT) converter. Figure 3 shows a NPC converter interfacing an ac system with BiDC system.

A comparison of all the three BiDC grid generation method are compared in Table 2.

In case of unbalanced loads on the dc side, the 3LNPC converter can balance the voltage. The balancing of capacitor voltages in a NPC converter is an active area of research [40]. One of the major issues of NPC converter is the unequal power losses in the different semiconductors [8, 24].

Moving forward, as the power levels are increasing aboard a ship, the requirement of power converter topologies also keep on changing. To satisfy the requirement of high voltage on a ship, multilevel converter topologies are also being utilized.

2.2 Loads

The loads on a ship primarily consist of propulsion motors and hotel loads. In a BiDC grid, there are several ways of connecting them. The higher power loads can be connected between the poles; the lower power loads can be connected between a pole and neutral. These connections are also shown in Fig. 1. This has

Tab. 2 Comparison of various BiDC generation methods

Parameter	Single Sync Generator	Dual Stator Generator	Dual Sync Generator
Cost	Low	Medium	High
Space	Medium	Low	High
Weight	High	Low	Medium
Fault tolerance	Low	Low	High

the added advantage that the cost of power converters for low power loads can be kept lower as the semiconductor of lower voltage will be needed.

2.3 Power balancing

The issue of imbalance in power is inherent to BiDC grids. Unbalanced power flow between poles and neutral can lead to the shift in voltage of the neutral line. This can lead to tripping of critical equipment relays and reduced overall efficiency of operation [14]. Power balancing can be done in three ways. The 3 level converters shown in Fig. 2a and 2c can be controlled appropriately to supply the required power by the different poles. The power converter connected to the dual stator machine in Fig. 2b can be controlled in the synchronous reference frame to balance the BiDC grid [13].

Other methods of balancing the BiDC include installing dc-dc converters on the dc grid side. Various suitable power converters for balancing a BiDC grid are shown in Fig. 5 [23, 50]. These topology have several advantages. They can be installed in a distributed manner in the grid. Also, the power levels can be much smaller as they are intended for handling limited power unbalance. Other strategies include using the power converters already installed in the grid to balance the power flow [26]. The features of the different topology are summarized in Table 3.

3 Challenges of BiDC implementation

Although the BiDC grids on ships seems desirable, there are still several challenges to be solved to make them feasible. These are discussed in this section.

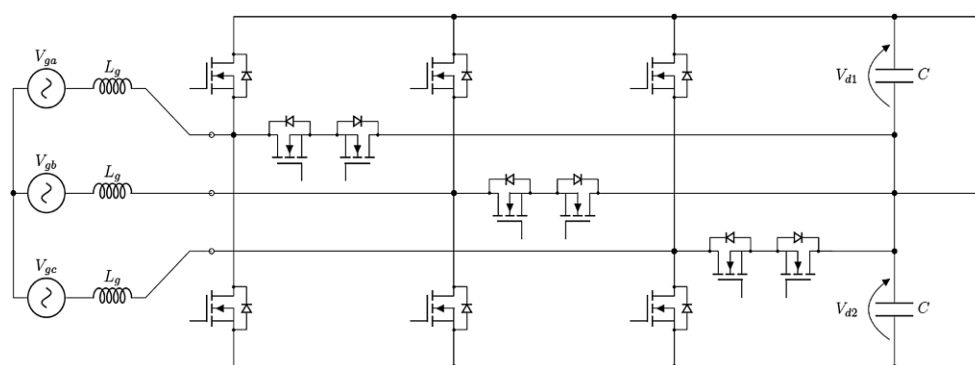
3.1 Stability

In a dc ship, the propulsion motors and other loads are interfaced through power electronic converters with the grid. When the converters are tightly regulated (having large bandwidth), the loads behave as constant power loads (CPL) [16, 45]. Due to the presence of CPL, the shipboard power system can become unstable as they can lead to oscillations and even collapse of the dc bus [45]. Therefore, before realizing a dc shipboard, it is necessary to perform stability analysis of the system.

A BiDC ship would inherently consists of several power electronics converters for the generation and consumption of power. A power electronic dominated grid also brings more challenges to the stability of the grid. When power electronic converters are used to interface prime movers to the grid, the inertia of the grid decreases [6]. The power electronic interface usually consists of converters which uses phase locked loop (PLL) to synchronize with the grid (in this case it is the synchronous generator). However, these converter are not suitable for forming the grid and also are unable to share power if several generators are present. To mitigate these issues, droop control and virtual synchronous generator algorithms are used [25]. However, there is still a considerable research which is required to understand the issues in shipboard power systems.

Power grids on ships are inherently weak. This is because the installed generation capacity is not significantly higher than the highest total load demand. The weak grids can become easily unstable when there is a sudden change in the load requirements [46]. The system to be studied is divided into several subsystems of sources and loads [39]. Thereafter, several methods are available to study the effect of passive components size on the system stability. Two of

Fig. 4 3 level T-Type converter



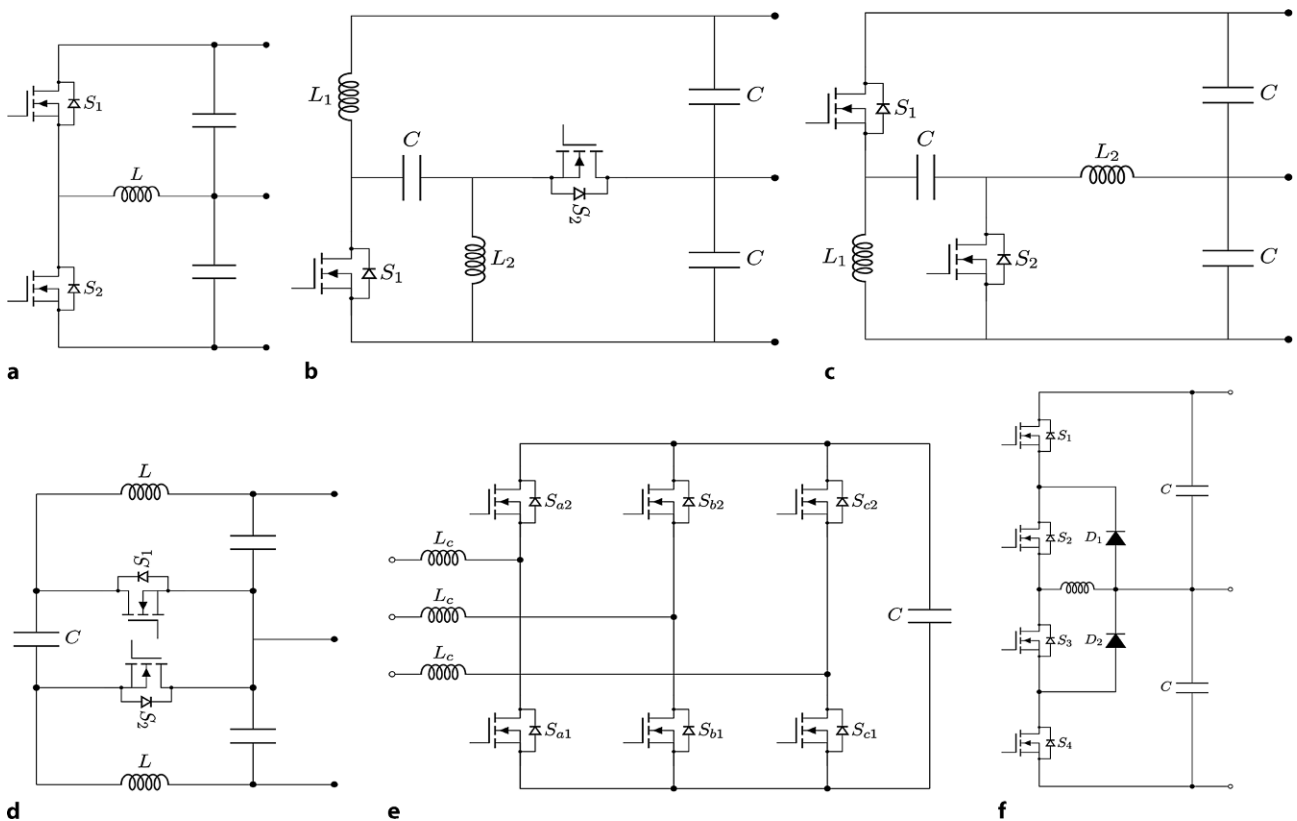


Fig. 5 Different topologies for a balancing converter. **a** Boost converter, **b** Sepic converter, **c** Zeta converter, **d** Cuk converter, **e** B6 converter, **f** 3 level converter

the most used methods are eigenvalue analysis and nyquist stability criterion [17]. These methods have been extensively used to study stability of UDC grids. However, in BiDC grids there are additional factors which can lead to instability in the grid. In [47], the author depicted a BiDC grid as a multi input multi output (MIMO) system. Gershgorin Band Theorem was used to quantify the interactions between the input-output pairs. The authors also concluded that the stability is greatly influenced by the imbalance of power flow between the poles of the grid. The authors, did not however, include the parameters of distribution lines in their analysis. More general method of modeling and stability analysis of a BiDC grid involving the line parameters (resistance, self and mutual inductance, capacitance) are given in [6, 52].

3.2 Protection

Protection is one of the most important criteria for successful operation of a power grid. The protection in a dc grid is much more challenging than an ac grid because of the reasons as follows [12, 15, 19, 37, 41, 43].

- Contrary to an ac grid, a dc grid does not have zero current crossing. When a fault occurs in ac grid, the current interruption can be done during or around the zero current crossing. Due to the current being near or equal to zero, the arc formed can be quenched easily. This however, is not possible in a dc grid. When a fault occurs in a dc grid, the current do not decrease and hence a formidable arc is formed when the contacts try to open. This can lead to the erosion of the circuit breaker's contacts and

Tab. 3 Qualitative assessment of different balancing converters [23, 50]

Balancing Converter	Switch Voltage	Passive component amount	Symmetric switch loading
Buck/Boost	High	Low	Yes
Cuk	Low	High	Yes
Sepic	High	High	No
Zeta	High	High	No
3 Level converter	Low	Low	Yes
B6 converter	Low	High	Yes

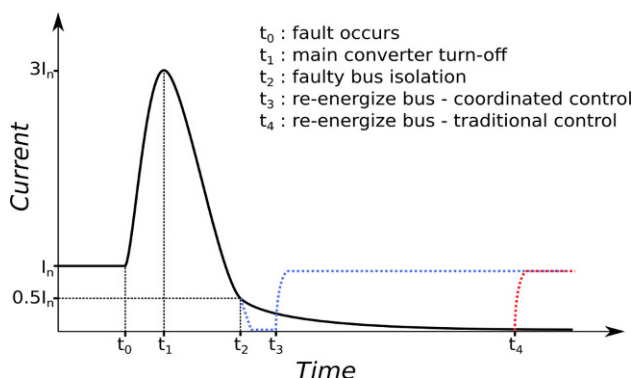


Fig. 6 De-energizing protection scheme for dc grids

in severe cases, the arc cannot be quenched at all thus leading to catastrophic situations.

- The dc grids are usually fed with power electronic converters. When a fault occurs anywhere in the grid, the converters are shut down first to break the supply for the whole grid. Hence, there is limited selectivity in the detection and isolation of faults.
- During a fault on the dc side, the filter capacitors and cable capacitance dump all their energy into the fault in a very short time period. This leads to higher rate of rise of current during the fault. This is not the case in ac grid as the fault current is limited by the transformer and cable impedance.
- The dc grids are usually made with power electronic converters which do not provide sustained high currents when a fault occurs. Due to this, the detection and selectivity in isolation becomes problematic.

There are several schemes for designing the protection system for dc microgrids. One of the schemes is based on de-energizing the whole grid [9]. In this approach,

first the main converter is turned off and the current is reduced. When the current is below a predefined value, the contactors are operated to isolate the faulty power supplies. Lastly, the bus is re-energized. The process is illustrated by Fig. 6. Traditionally, faulty power supply is isolated when the current in the bus is close to zero. However, the authors in [10] suggest that the contactor of the faulty supply can be operated at much lower current (in Fig. 6, this is 0.5 times nominal current I_n) for isolation. In this way, the bus outage time can be significantly decreased which improves the power quality on a ship [9, 10].

Another scheme of protection in an LVDC grid is given by the NPR 9090:2018 standard [31]. In DC grids, some power sources have very high short circuit currents and therefore portray risks for other equipment in the system. In this standard, the generation and load units are distributed in different zones based upon their fault characteristics, short circuit (SC) & nominal current limits, and current flow direction. The characteristics of different zones are summarized in Fig. 7a. A notional distribution system for a ferry ship showing the protection zones is shown in Fig. 7b. The ferry uses batteries as the main power source. The loads are distributed in different zones depending upon their power limits. For instance, propulsion motors have much higher power rating than the service motors. Hence, the propulsion motors are assigned to zone 2 and service motors are assigned to zone 3. In zone 4, low voltage and low power loads are kept which have only unidirectional power flow. Due this distribution of power sources and sinks in different, the risks due to faults in the grid can be lowered.

Grounding is also critical for power systems. The selection of inappropriate grounding methods can lead to corrosion issues in ships. The issue of cor-

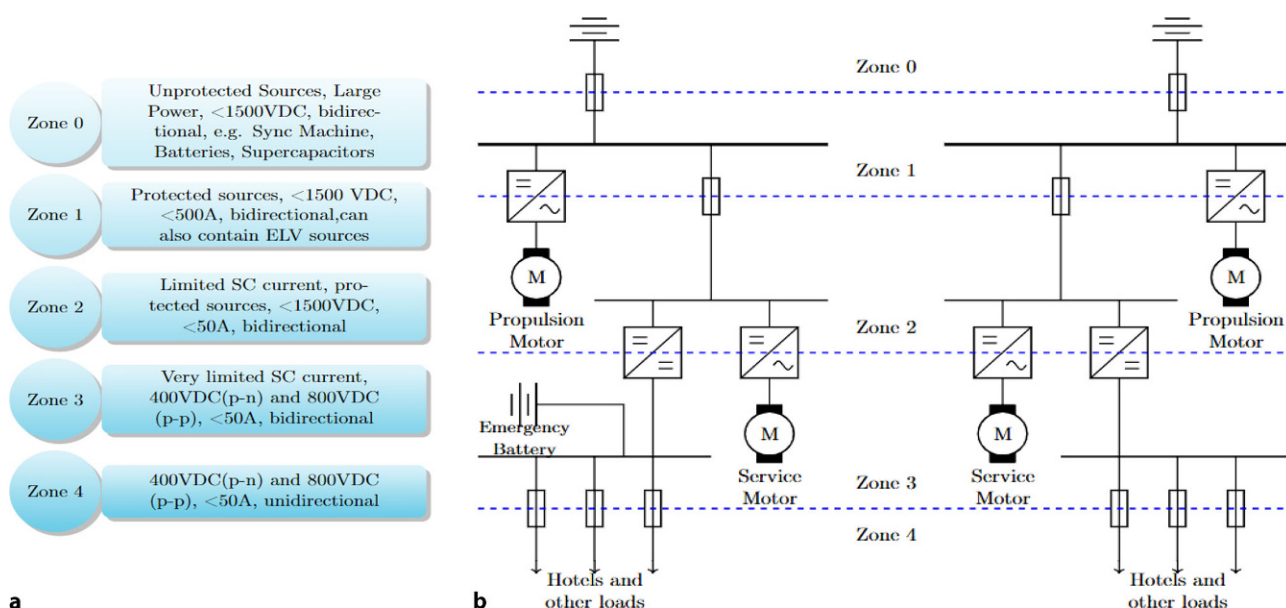


Fig. 7 Protection concepts on LVDC ships. a Description of protection zones according to NPR 9090:2018 standard, b Example of protection zones in ferry ship

rosion is more severe in dc systems compared to an ac system with the effect decreasing with increasing frequency [38]. This is because of the non-oscillatory current and voltage magnitude in dc. The direct grounding of the negative terminals leads to the corrosion of metal parts [28, 33]. This happens due to the electrochemical reactions taking place on the metal surface because of stray currents through the ground electrode. This subsequently leads to higher operation and maintenance costs as the corroded metal parts are sometimes invisible to the naked eye [5].

The study of grounding is even more important in the BiDC grids with several power sources. In such grids, when there are multiple points of grounding, there is a possibility of the flow of circulating currents between them. This is because of the voltage unbalance in the grid which leads to different potential of neutral line at various nodes. The extent of the effect is dependent upon the type of grounding connection and the grid architecture [27]. This can eventually increase the rate of corrosion on a ship. Hence, designing a proper grounding scheme is essential to ensure safe operation of a ship.

3.3 Standardization

BiDC grids is an emerging technology with limited real world applications. One of the reasons for the limited adoption of BiDC technology is the limited number of standards. The Netherlands is the first country to publish guidelines for LVDC (350–1400 VDC) grids [31]. The standard segregates a dc system into several safety zones. Each zone has its own risks and measures for protection.

For a BiDC grid on ship, IEEE Standard 1709:2018 provides guidelines for MVDC systems (1–35 kV) [2]. However, as illustrated in Table 1, there are no standards for generation of LVDC on ships. Hence, it becomes difficult for manufacturers to build devices suitable for the purpose. Therefore, standardization remains a challenge for BiDC grids on ships.

4 Conclusion

The recent regulations by the IMO have become the key drivers for the changing infrastructure on ships. The industry is now gradually moving towards the concept of more electric ships to increase the efficiency of operation and reduction of GHG emissions. BiDC grids have several advantages compared to three phase ac and UDC grids. A ship is nothing but a microgrid floating on sea. Hence, there is a great potential for BiDC grids to be implemented and utilized on them.

In this article, the methods and challenges of implementing BiDC grids on ships are discussed. There are several ways of forming a BiDC grid on ships. The choice of an appropriate technology is constrained by the power quality requirements, costs, and space. Bal-

ancing converters are an integral part of a BiDC grid. However, the choice of the type of balancing converter can vary depending upon the size of ships. For small ships, a single balancing converter might suffice. On the other hand for large ships like cruise ships, multiple balancing converters might be needed. More research is required to find the optimal placement of these converters on large ships.

Although seemingly beneficial, the implementation of BiDC grids on ships still have several challenges. First limitation is ascertaining the stability of operation when large amount of power electronic components are used. There is parity between the total installed generation and load capacity. Hence, the BiDC grid becomes weak leading to instability. Secondly, the biggest challenge is the unavailability of cost effective and reliable protection systems for BiDC grids. The unavailability of standards for LV BiDC grids on ships is also a challenge. Availability of such standard would lead to greater acceptance of the technology in the market. All the above challenges must be solved concurrently to make BiDC grids feasible on ships in the coming future.

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