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DC Microgrid Islands on Ships

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***Abstract*—Since shipboard power systems are inherently islanded and consist of energy intensive sources and loads, it is an interesting application for dc microgrids. The object of this paper is to explore the merits of dc based shipboard power distribution as compared to conventional ac solutions. A survey of current initiatives, emerging concepts and design challenges is carried out. Based on the review, insight is offered on different aspects like efficiency, safety, and reliability and their relevant trade-offs. It will be discussed how the interplay of reliability and availability, driven by the computational cost of optimization and restoration goals, forms the heart of reconfigurability.**

I. Introduction

The penetration of dc based grid power transfer at medium and low voltage distribution level is currently confined to applications with microgrids pocketed within the existing ac infrastructure (hybrid ac-dc microgrids) or at remote locations where the reach of conventional grid is difficult. This is because the already installed ac grid infrastructure is costly to refurbish. Furthermore, the distribution grid operators (DNOs) are disinclined to embark an operational risk of opting for a universal dc distribution grid.

However, an emerging application of dc distribution is finding traction in the shipping industry [1]. The fact that shipboard power system is inherently islanded from the main grid and the components are compatible for operation with dc supply gives designers the scope to develop dc microgrid based vessels.

DC distribution is more compact than ac for the same operating power. Cable cross-section is lower due to enhanced operating voltage rating, while most loads can be connected to main bus using reduced conversion steps. For conventional generator systems, lack of synchronization and frequency constraint leads to reduced size at higher operating speeds. In ships, where on board space is limited, floor saving can be a vital driving force. Furthermore, reduced weight of power system would imply transportation savings as well. An illustration of dc microgrid island on ship in accordance with standard recommendation by [3] is shown in Fig. 1.

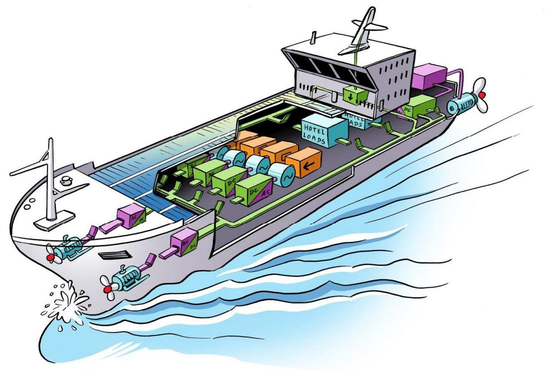


Fig. 1: An illustration of dc microgrid island on an all electric ship.

The concept of all electric ship (AES) allows for the possibility of flexibly routing energy where it is required instead of using dedicated internal combustion engines [4]. This reconfigurability of the system and inherent redundancies are added advantages of dc apart from efficient and compact power distribution. Nevertheless, the adoption of dc distribution is not without its own complexity and trade-offs. The three performance aspects of a distribution grid are depicted in the Venn diagram of Fig. 2. Structurally, the efficiency, reliability and protection of the dc system are interrelated and intimately connected with the incurred installation cost. Designers should, however, be mindful that the choices are different for land based power grid as compared to shipboard power system. For example, it is pointed out in [2] that as compared to land based system, greater premium is placed on reliability of ship power system considering the safety of the passengers.

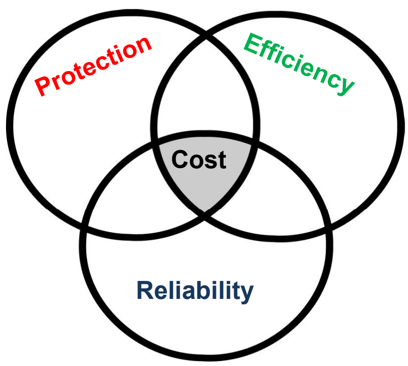
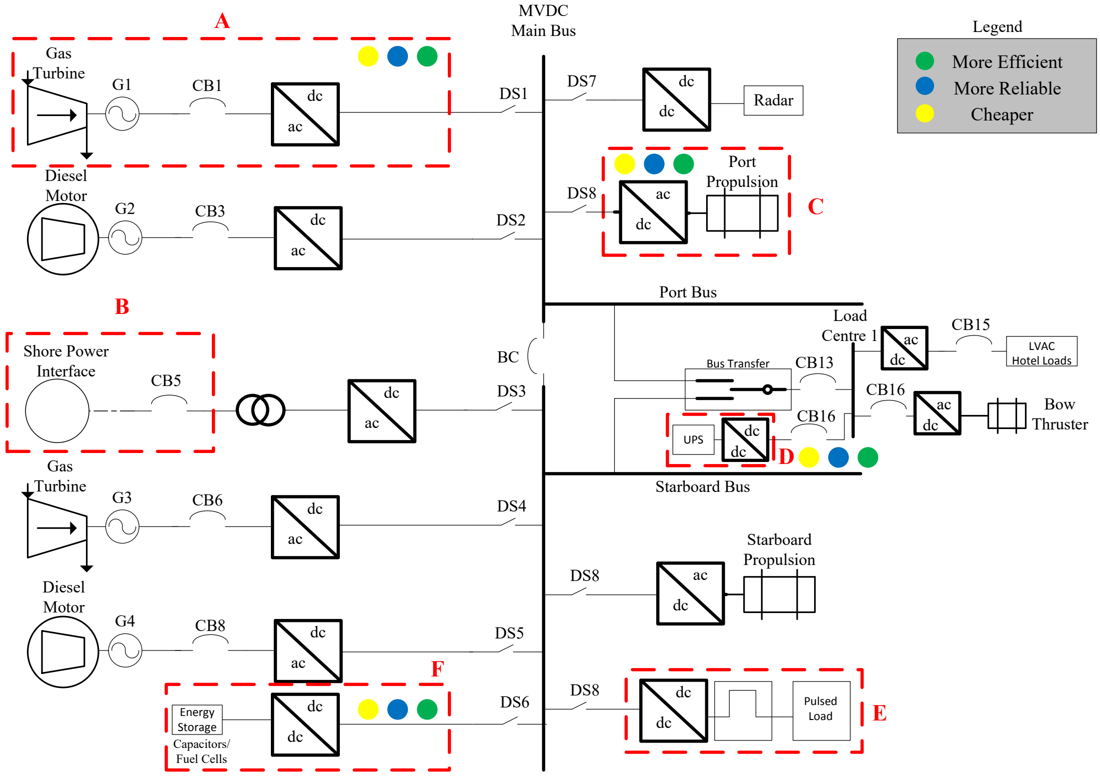


Fig. 2: The three domains influencing the choice between ac and dc microgrids.

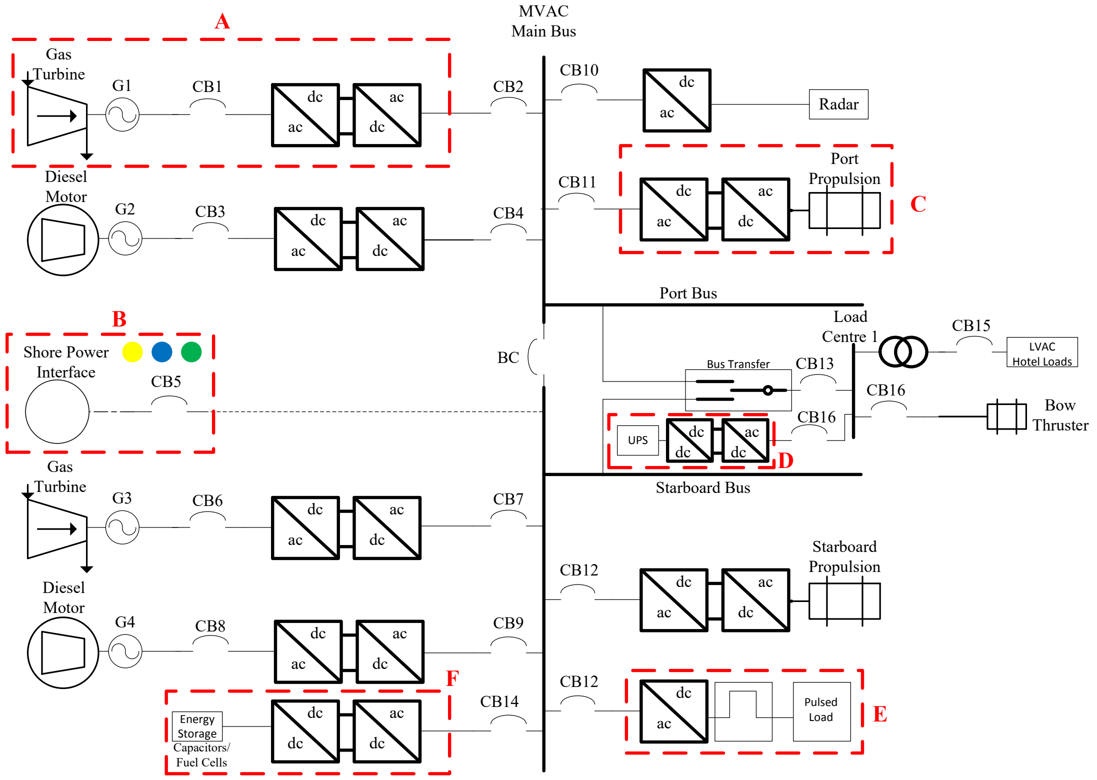
The object of this paper is to holistically explore the merits of dc based shipboard power distribution. A survey of current initiatives and emerging concepts is carried out and the existing opportunities and challenges are highlighted.

II. AES Power System Structure

Fig. 3a shows the AES power system structure adapted from IEEE recommended notional design of MVDC ship system [3]. The system consists of two buses running longitudinally along the ship (port and starboard) that supply different



(a) Main distribution bus is medium voltage dc.



(b) Main distribution bus is medium voltage ac.

Fig. 3: Single line diagram of a typical all electric ship.

load centers through a bus transfer switch for adequate redundancy. The port bus and starboard buses are interconnected in ring structure using bus coupler BC. Each side has at least two generators, one main and one auxiliary. Interface of one of them is highlighted as block 'A'. A connection point is possible from the on-shore grid to the ship main bus marked as 'B'. Each side has a high powered ship propulsion motor marked as 'C'. Other components include UPS (block D), pulsed loads (block E) and storage (block F).

An equivalent ac system design for achieving similar operability and component integration is shown in Fig 3b. Traditionally, power converters are not applied for generator systems [4], while for adequate motor controllability, particularly for high powered propulsion, an ac-dc-ac conversion step is employed. Nevertheless, the interface is so chosen for each component so that the design choices for each component operational requirements is similar and a critical comparison of ac and dc ship distribution system can be offered. The power electronics (PE) interface between different energy generating and consuming components effectively decouples most of their operational design choices from the distribution grid itself [5].

The conversion interface for component specific integration is inherently different for a dc and ac based distribution system [6]. Therefore, the efficiency (green), reliability (blue) and costs (yellow) will be different when the main bus is dc as compared to ac. This intuitive representation, considering a single ac-dc conversion stage as one unit in efficiency, reliability and cost, is shown in Fig. 3 for each component integration. In reality, the dependencies of the aspects illustrated in the venn diagram of Fig. 2 are more complicated. The nuances of ship component integration in terns of operational benefits with ac and dc grid will be discussed in subsequent sections.

III. AES Component Integration

In this section, discussion is presented on component specific comparision between a MVac and MVdc all electric ship. The highlighted aspects are not limited to the electrical system layout itself, but the consequences of adapting a MVdc system on conventional design choices and a critical review therein as opposed to an ac distribution.

A. Generator System

Conventional Interface: Traditionally, the gas turbine based as well as diesel generators which supply power to the entire ship are interfaced to the ship ac distribution grid without a power electronic interface [4], as shown in Fig. 4.

Limited by the power frequency interface, a synchronous machine (SM) is a favourable choice, connected to the high speed turbine using a gear box. As a consequence, for the same power capability, the floor area, volume and therefore the weight of the machine increases due to reduced speed operation [8]. The rated power of the machine is proportional to the product of the operating torque and speed, wherein, the torque depends directly on the machine radius r and length l. Therefore, for the same rated power operation, the floor area of the machine varies inversely with the speed and the volume V_{m} varies inversely with its square.

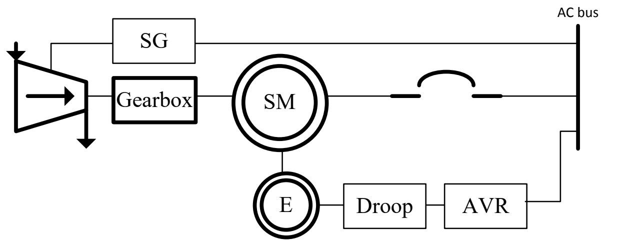


Fig. 4: Conventional generator integration and control with the AES ac distribution system.

Power quality control is also an important aspect from generator integration point of view [4]. The speed governor (SG) controls the frequency and hence the active power injected by the SM, while the automatic voltage controller (AVR) regulates the voltage and the reactive power flow at the coupling point. Droop control maybe required to impose a virtual impedance to make possible the parallel operation of generators while avoiding reactive power exchange between the gensets.

PE-Based Interface: Having a PE interface between the generator and the grid makes it possible to run the machine at variable speeds independent of the power frequency. High speed machines interfaced with the prime mover are also possible [7], [8], thereby reducing the size and weight. The interfacing converters can handle the frequency and voltage control requirements instead of SG and AVR. Without need for a controlled excitation, permanent magnet machines can be employed, which can directly be connected to the prime mover shaft, eliminating the need for gear-box and AVR. Rotor copper losses can also be reduced but it must be noted that high speed operation increases the core losses. Furthermore, the ability to run the machine at variable speeds based on the engine load enables gains in specific fuel consumption as seen for a 300 kW diesel generator in Fig. 5. About 10 % fuel savings can be achieved when the generator is lightly loaded.

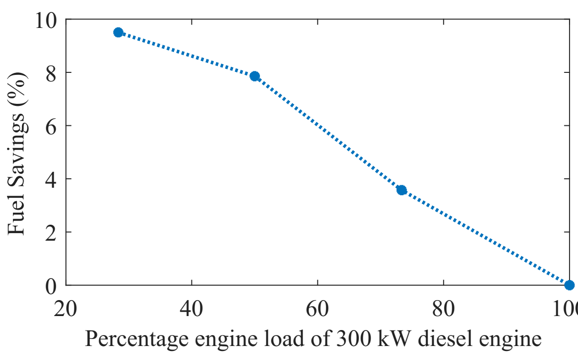


Fig. 5: Fuel savings due to variable speed operation of a 300 kW diesel generator([9]).

For these reasons, power electronic interface is increasingly being adopted even for ac distribution system. The optimized efficiency of all electric ships with quantified system level comparison of ac and dc shipboard power system is carried out in [9].

DC Grid Interface: Comparatively, a common dc bus would reduce the conversion stage [5], [6], thereby improving the efficiency and reliability of the system. Further, the converter control would not need to cater for the grid frequency requirements. A theoretical and experimental study on the dc integrated generator system was carried out in [7]. Herein, the fully rated uncontrolled rectifier was interfaced between the generator terminals and the dc bus, while the control was achieved using a lower rating variable frequency PWM inverter as shown in Fig. 6. The benefit of this scheme is that a fully rated controllable rectifier would increase the complexity of regulation and cost, while reducing the efficiency.

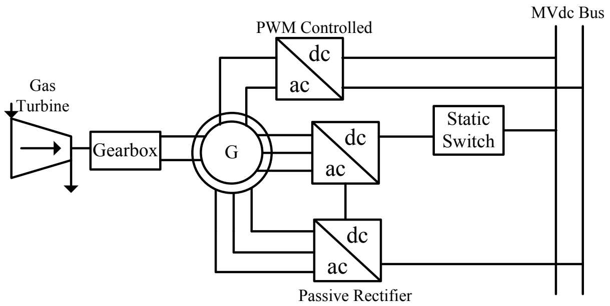


Fig. 6: Interface of shipboard generator system with MVdc bus (adapted from [7]).

In this system, a dual three phase high speed 6300 r.p.m generator was compared in terms of power quality and reliability with a single three phase generator. The dc side current and voltage waveforms had lower ripple in case of the dual alternator. Further, when a faulty diode was simulated, the presence of two rectifiers allowed a deteriorated, but continued operation, unlike the one with a single rectifier. However, the trade-off of this increased reliability was cost and space requirements with the additional rectifier unit. The decision on improved reliability towards faulty converter should be considered keeping in mind that back-up generators are generally available in shipboard power systems. Therefore, (n-1) contingency may not be effected by this strategy.

Protection from 3 kV dc bus faults was achieved using a solid state switch. Extremely short operating time was reported which helped the designers to downsize the equipment protected by this switch. Apart from reduced space requirements, the additional cost of the protection switch could be compensated by the savings in downsizing the protected power electronics. The trade-off therefore, is the reduced efficiency due to the conduction losses in this normally closed, series connected semiconductor.

The second generation of the MVdc interfaced generator system is shown in Fig. 7. In this work [8], a 12 phase, 2 MVA permanent magnet generator was directly interfaced with the high speed, 22500 rpm prime mover. The system reliability increased from the point of view of removal of gearbox which was vulnerable to mechanical wear and tear. Since the control of field was not possible, the responsibility of voltage regulation fell on IGBT controlled dc-dc choppers. As compared to the previous generator of 5300 kg, the weight of this quad-pole generator was reduced to 2300 kg. Other advantages included reduced bearing span of the short rotor with larger diameter, reduced volume and better vibration performance. However, the key design challenge in was managing the increased core losses due to ultra high speed operation. Experimental test results showed that the compact design had high power density and met the expected operational requirements.

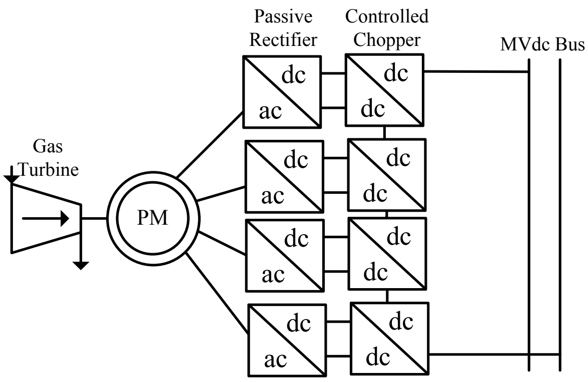


Fig. 7: Direct interface of generator set with prime mover (adapted from [8]).

Placement of the Turbine-Generator System: Reiterating the premium on small, light and energy efficient components for the economics of ship, the on-board electrical distribution is envisioned as a power train [10]. This paper highlights an interesting opportunity in placement of compact turbine generators higher in a ship. It was argued that the higher they are placed, lesser is the volume needed for intake and exhaust ducting for the turbine. The trade-off is the greater power cabling requirements, which can be minimized by use of dc. More on cabling requirements under ac and dc will be discussed latter in this section.

B. Shore Power

Considering the market inertia of ac based power distribution, it would be logical to assume that the shore power grid would be ac. Therefore, appropriate interfacing infrastructure would be needed. Without a standard operating voltage level for all ships, a customized ac-dc converter would be required on-board each ship. The amount of energy exchange with the shore grid should be minimized to make dc a favourable option in terms of efficiency as compared to ac.

C. Propulsion System

The superiority of electric propulsion over mechanical alternatives lies in the potential fuel savings and high maneuverability in cruise vessels which run at a fraction of their rated load most of the time [11]. It was recognized that rapid and precise torque response, as well as high over-torque capability were particularly advantageous in ice-breaking applications and dynamic positioning in drilling vessels.

Conventionally however, a dedicated prime mover was interfaced with the propeller [4], [11]. For high propulsion power requirements, this may be favourable even today. Nevertheless, the efficiency benefits of optimally running the turbine [12], [13] has led to the realization of hybrid solutions [4], [11]. The advantage of using the electric machine in both generator and motor mode in combination with dedicated combustion engine is suggested to improve the ship functionality in various operation modes [11]. Such concepts mark the evolving attempts of realizing fully integrated shipboard power systems where various sources and loads can exchange energy [14].

Other interesting studies look into the time constants of different ship components [13] and suggest smart load management by rapid shift of power to pulsed loads of lower time constant without effecting the propulsion motors of high time constant [12], [18].

It was highlighted that the benefits are dependent on the operational duties of the ship and the interaction between mechanical system during propulsion and the larger electrical network were poorly understood [13]. For instance, an easy observation made during the design of hybrid system was that prime mover speed couldn't be fixed and it varied due to hydrodynamic interactions between the ship's hull, propeller and water [4]. In this case, the converter interface proved to be inevitable to mitigate the problem, but there are instances where the dynamics of propulsion system can strongly influence the power quality of the ship microgrid [12].

For example, when a low frequency thrust disturbance of 10 % of its steady state magnitude was introduced to represent the effects of high seas, the ship's speed was unaffected due to its high inertia, but impacted the supply current [13]. A study on the impact of such low frequency propulsion loads on an ac system showed a resonance behaviour with the maxima in grid frequency and voltage magnitude variation occurring around 1 Hz [15]. This variation increased when number of prime movers were lowered from 4 to 3, owing to the decreased inertia of the system. Even though the variation remained within standard limits, it was discouraged to reduce the system inertia by switching off prime movers when 1 Hz variation in propulsion load is expected.

Even though there are more studies on integrated ac power systems coupled to hydrodynamics, such as the one looking into the surge motion of electric ship [16], it was noted in [17] that limited knowledge was developed on problems related with dynamic interaction of propeller emergence with shipboard MVdc microgrid. The schematic of the MVdc system studied in relation to random wave dynamics and ship motion is shown in Fig. 8 [17].

The study showed that propeller emergence, that can suddenly reduce the thrust due to effective disk area reduction, had no significant influence on the dc bus voltage. It did influence, however, the fuel flow and demand on the gas turbine.

Stability issues due to large, constant power loads such as ship propulsion cannot be less emphasized, particularly in dc microgrids. Interesting perspective and possible mitigation methods is discussed in [19], [20].

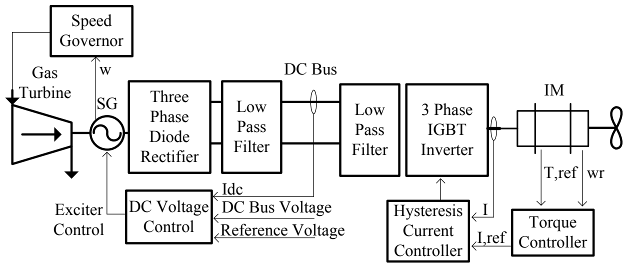


Fig. 8: Propeller Interface with an MVdc Bus (adapted from [17]).

Clear efficiency benefits of operating dynamic positioning with on-board dc grid is shown with actual demonstrations, such as the one with Dina Star recently [21], [22]. Fuel savings as much as 27 % have been reported in this case [11].

D. Uninterrupted Power Supply (UPS)

Sensitive loads to which the power is routed through a UPS have proved to be more efficient and reliable when dc is used [23]. This study on datacenters claimed a measured efficiency enhancement of 4 % solely due to the UPS unit when used with dc as compared to ac. It can be inferred that similar benefits can be obtained on dc shipboard UPS.

E. Pulsed Loads

Since the expected operational lifetime of shipboard power system is lower than land-based power systems, the cabling infrastructure, particularly connecting pulsed loads, are imposed with voltages for only a small amount of time. It was argued in [26], that therefore, for pulsed loads the cable insulation could be significantly downsized. Another study showed that the same can be done for conductor area. Considering that thermal time constant is in minutes, cables can be imposed with 30 % higher current than its rated value for a short time, without breaching its thermal limit [27].

Other opportunities related to pulsed loads lie in smart load management using the differences in time constants of shipboard elements [18] and storage optimization in downsizing the generation capacity [24].

F. Energy Storage

Shipboard storage is responsible for several applications such as optimizing fuel consumption of gas turbine [9], mitigating power quality and stability issues [12], [19] and bridging the supply power gap to pulsed loads [24], among others. A good insight into the role of storage in designing a smaller and better performing ship power system is offered in [24]. A study in [9] shows how a dc microgrid on ship could save upto 7 % energy as compared to one without.

Application requirements indicate that combination of energy dense storage like batteries and significantly power dense storage like flywheels and ultracapacitors maybe required. The integration of these storage components with dc interconnection would benefit more, as is shown to have 15 % fuel savings compared to conventional ac system [9].

IV. Protection, Reliability and Reconfiguration

Persistent efforts towards compact, energy dense shipboard power system has implications on its protection elements, both in context of physical layer insulation, as well as operational layer devices, coordination and reconfiguration. The design choices are intimately linked with reliability, efficiency and cost of the system, which we will explore in this section.

A. Electric Insulation

From insulation reliability point of view, it is cautioned in [25] that the experience from the land based grid may not be completely applicable on shipboard environment. For instance, the latter could be less vulnerable to lightning impulses as it can be seen to be present imperfectly within a grounded Faraday cage. On the hand, it could have different switching surge response due to its tightly coupled nature.

Cables: Considering the high power requirements, medium voltage distribution level is recommended in order to keep the bus current levels low [3]. In this voltage range, experience with insulation performance of dc cables is limited [26]. This work attempts to explore the possibility of reducing the cable size while understanding the lifetime reliability of its insulation. For instance, it was argued that while electric treeing is typically not a serious issue at medium voltage, it could be a concern while downsizing the cabling requirements for pulsed loads in case the thermal expansion causes interfacial voids.

Compact bus and cable distribution system is a requirement in shipping applications due to limited space availability. It has been suggested that significant capacity gains can be achieved by opting for dc as compared to ac [28]. Insulation lifetime performance maybe similar or better even when voltage is enhanced by a significant factor [28]–[30]. This is because of lower partial discharges for dc under similar operating conditions as ac [30]. Nevertheless, a rigorous experimental validation of this concept, particularly from the context of ship environment with varying temperature and insulation conditions is required [29].

Machines: It was discussed in a previous section how high speed electric machines are being preferred for minimizing the size and direct integration with the prime mover. While some design necessities were followed in [8] to minimized the core losses that are dependent on square of the speed, the focus was power quality and efficiency issues. The detrimental consequences on insulation life without aggressive cooling was cautioned in [25]. Here, the role of the phenomenon of 'rotor growth' at high tip speeds in compromising the insulation system was also highlighted. Further, even though emerging semiconductor technologies such as SiC IGBT can offer high frequency operation at medium voltage level with its higher blocking capacity and efficiency, the negative impact of high dv/dt on the machine insulation and bearings should be managed [31].

B. Grounding System

A comparitive study on different grounding methods for shipboard MVdc power system was carried out in [32]. With the focus on minimizing the over-voltage and over-current during monopole to ground fault, aspects such as cost, reliability, relay coordination, power losses and fault ride-through were also studied. Due to high over-voltage, ungrounded system was not favoured. Similarly, solidly grounded system suffered from high over-currents. Resistive grounding was found to be most favourable considering that it limited the voltage and current to moderate values at low cost with high reliability. When neutral point is not available, grounding with high magnitude resistors in parallel were studied, but these suffered from power loss during normal operating conditions and were costly. In context of a typical shipboard MVdc network, grounding with resistance of 400-800 Ω was recommended.

C. Series Arcs

Series arcing is particularly an issue with dc due to the absence of zero crossing [33]. In fact, sustained series arcs were obtained for dc circuits operating loads as low as 100 V, 5 A [34]. These kinds of faults do not show over-currents and over-voltages that the monitoring devices can detect. Clearly, for a compactly designed medium voltage, high powered shipboard dc system, series arcs could pose serious problems. Some efforts have been carried out in experimental test beds with systems closely representing ship power systems [35]. A robust mechanism should be in place to detect and eliminate series arc fault to guarantee safe and reliable operation.

D. Protection Devices

A great premium is placed on solid state circuit breakers (SSCB) for coordinated protection of interconnected dc ring system proposed for shipboard power system [1]. Considering that the cost of the switch and on-state resistance is proportional to the blocking voltage, this trade-off should be kept in mind. It is recommended to combine the SSCB with fast acting no-load isolating mechanical switches [1]. As higher and higher dc voltage is preferred for efficiency reasons, it is also pointed out that SSCBs at this voltage level are still in developmental stage. A novel design and analysis of SiC based DC SSCB with low on-state resistance and high voltage rating is presented in [36].

A demonstrated shipboard dc protection system using power electronics in combination with fuses on ABB's Dina Star [22] claims successful interruption within 20 ms, thereby ensuring significantly lower fault power as compared to its ac counterpart and offering possibility of downsizing the protected equipments. Another study used hardware in the loop testbed aiming to showcase a breaker-free fault management scheme using modular multilevel converter to recover from pole to pole dc faults in 8 ms [37].

For the devices to quickly eliminate faults, proper detection and selectivity is important. Some initiatives in this direction for dc distribution systems are presented in [38]–[41].

E. Reconfiguration and Zonal Redundancy

With dc based distribution, a more interconnected system can be envisioned. This is favourable because multiple paths exist between the sources and loads, thus increasing the availability of the system by finding useful reconfigurations during contingencies [42]. However, more number of protection devices are required to isolate the fault at any location. This increases the installation and maintenance cost. Moreover, greater number of devices will increase the complexity of the system and the failure rate. Further, greater communication and coordination will be required to ensure expected operation [1]. One could argue that this is in fact detrimental to the reliability of the system. A good differentiation between reliability and availability is offered in [43].

The interplay between reliability and availability, driven by computational cost of the optimization and restoration goals forms the heart of reconfigurability. This is observed in [44] which shows how the computational time increases and the percentage global optimal solution decreases as the number of switches increase.

An example of shipboard electrical service restoration [1] is shown in the schematic of Fig. 9. Herein, when the no load switches S1, S2, S3 isolate the fault, the power converters re-energize the bus. Intercommunication was important between switches and converters in order to effectively isolate the fault.

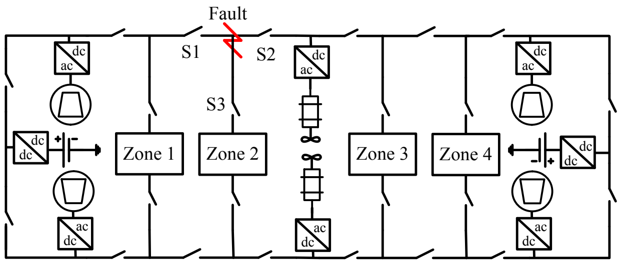


Fig. 9: Zonal fault isolation in an interconnected shipboard power system (adapted from [1]).

A more complicated dual ring dc bus system was proposed in [1] in order to improve the efficiency of operation. Another method based on zonal redundancy was proposed in [11]. Here, different redundancy groups were created responsible for protection within individual zones.

V. CONCLUSION

DC microgrid for shipboard power distribution is emerging as a workable concept. The opportunity of energy dense, compact dc power train solution is attractive as it can save significant amount of space and weight while exchanging energy more efficiently than conventional ac system. Component reduction makes the system more reliable, considering that in many cases a conversion step is reduced.

The review on design choices of individual shipboard components for miniaturization, efficiency, safety, reliability, stability, power quality and costs was carried out. Many interdependencies and opportunities were highlighted; and at the same time challenges and hidden influences were cautioned. It maybe concluded that dc microgrids islands on ships hold significant potential.

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