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Marine DC Power Ditribution Networks

S. Kim, G. Ulissi, S. Kim, *et al.*

POWER ELECTRONICS LABORATORY
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Marine DC Power Distribution Networks

Seongil Kim[1], Gabriele Ulissi[1], Soo-Nam Kim[2], Drazen Dujic[1]
[1]Power Electronics Laboratory, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland
[2]Power System Research Department, Hyundai Electric & Energy Systems (HE), Republic of Korea
Corresponding author: Seongil Kim, seongil.kim@epfl.ch
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Abstract

Power distribution networks for marine applications have experienced significant changes in recent years with the evolution of DC technologies. Some low-voltage DC solutions have already been employed for low power ships with their main benefits and there are a lot of research activities to adopt these technologies to high power ships. This paper presents current technologies on marine DC power distribution networks in terms of system architectures, power equipment and system protection. In addition, several developments for marine applications which may be needed in future are discussed.

1. Introduction

In the commercial sector, ships should be built with high energy efficiency not only to minimise fuel cost, but also to comply with strict environmental regulations [1]. DC power distribution networks (PDNs) have attracted a lot of attention from marine industry as a promising solution to achieve those. The DC PDNs allow for employing variable-speed generators that consume less fuel under low and medium loading conditions, compared to fixed-speed generators (fuel savings: $15-20\,\%$) [2]–[4]. In addition, electrical equipment weight and footprint can be reduced by removing AC switchgear and bulky transformers.

For DC PDN-based dynamic positioning (DP) vessels, the closed-bus operation during the DP mode, which is not permitted in the AC PDN, is allowed by means of bus-tie switches based on solid-state technology [6]–[8]. The closed-bus operation enables fewer running engines and their operation at an optimal point. Moreover, batteries can be integrated into the DC PDNs with reduced number of conversion stages or directly due to their DC nature. These benefits described above together with the increased battery integration in ships (see Fig. 1) have moved the marine PDN from AC towards DC with commercially available low-voltage DC (LVDC) PDN solutions. Fig. 2 depicts the numbers of LVDC ships built by two vendors since 2013 [9], [10].

The motivations to employ the DC PDNs into the military applications are related to navy ships' requirements. For some types of submarines (like a non-nuclear air-independent-propulsion submarine), the batteries are used as a main power source during the submerged operation (or the stealth operation), as shown in Fig. 3. When the state of charge of the battery drops to a low level, multi-phase generator-fed multi-pulse rectifier sys-

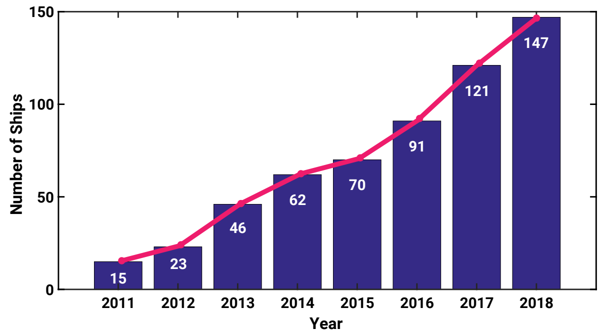

Fig. 1: Number of ships with installed battery energy storage system [5].

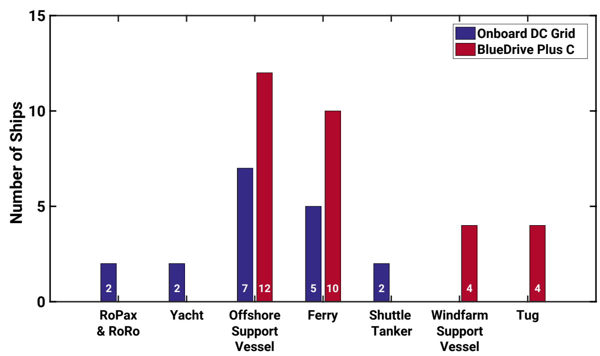

Fig. 2: Low-voltage DC ships built since 2013 [9], [10].

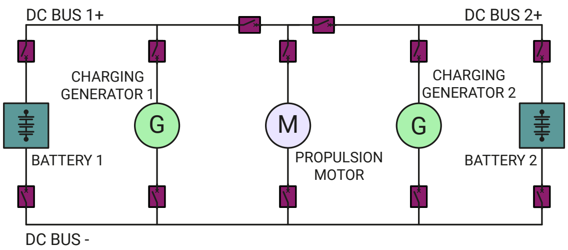

Fig. 3: Submarine's simplified electrical diagram [12].

tems (Fig. 7) produce the DC power to charge the battery (the snorkel operation) [11], [12].

In surface navy ships, an electromagnetic railgun has been developed in some countries for a future weapon system. This weapon essentially uses electromagnetic energy to accelerate the projectile to hypersonic velocity. In the electrical system point of view, it is an ultra-high pulse power load (tens of megawatts) and the power supply capable of this pulse load is one of the biggest technical challenges for the ship PDN design. Medium-voltage DC (MVDC) PDNs including energy storage systems have actively been investigated as a prospective solution to accommodate it with less system impact than the AC PDN [13].

As briefly described above, both the commercial and military ships are the applications that have actively employed the DC solutions into their PDNs. For this emerging topic, this paper presents the overview of currently available marine DC PDN technologies in terms of system architectures, power equipment and system protection. Additionally, future developments for marine applications are discussed.

2. System Architecture

System architecture of the marine DC PDN is basically dependent on the design philosophy and the requirement to carry out ship's missions. The marine DC PDNs having different system architectures can be implemented by different bus configurations and cable layouts.

Bus Configuration

Most commercial ships have been built to perform limited number of functions as well as to minimise electrical installation and operation cost. The latter is the reason why the radial bus configuration (Fig. 4(a)) is widely used in commercial ships. It is the simplest bus scheme and requires less installation area with minimum numbers of circuit breakers.

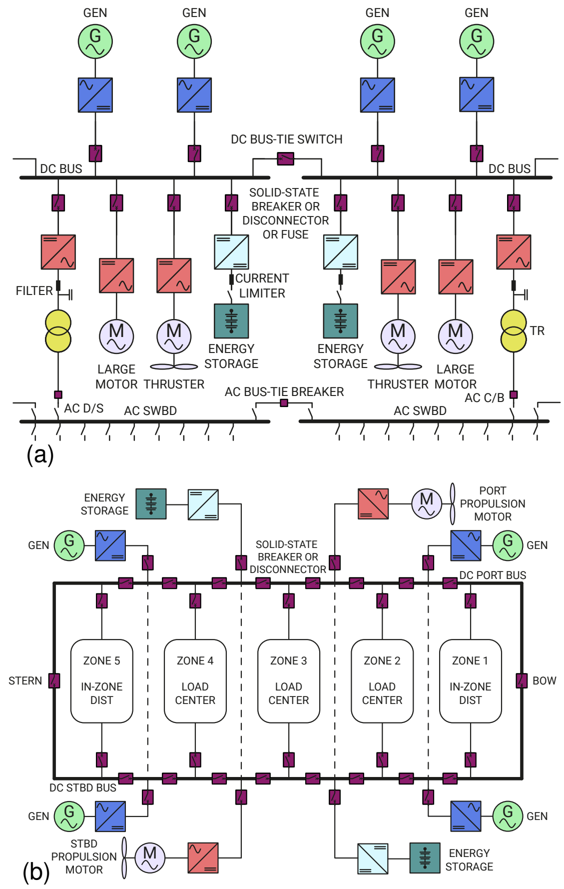

Fig. 4: Bus configurations of marine DC PDNs: (a) radial and (b) ring [14].

Higher degree of safety and redundancy in this configuration can be achieved by the main switchboard sectionalised by a bus-tie switch. This sectionalised switchboard not only can reduce the maximum fault current level, but also allows healthy parts to be operated independently (stand-alone operation).

On the contrary, the ring bus configuration (Fig. 4(b)) is often used in military ships since this configuration provides better reconfigurability and greater survivability. In this configuration, a system fault can be isolated by tripping the two circuit breakers on both sides of the fault (the minimum power outage). However, a complicated protection scheme and a large number of switching devices (breakers or isolators) are necessary in this configuration, making it costly for commercial ships.

Cable Layout

There are two cable layouts to establish the marine DC PDNs: centralised and distributed layouts, as depicted in Fig. 5. In the centralised layout (or a multidrive approach in [15]), the DC network is limited in the cabinets and all DC parts (recti-

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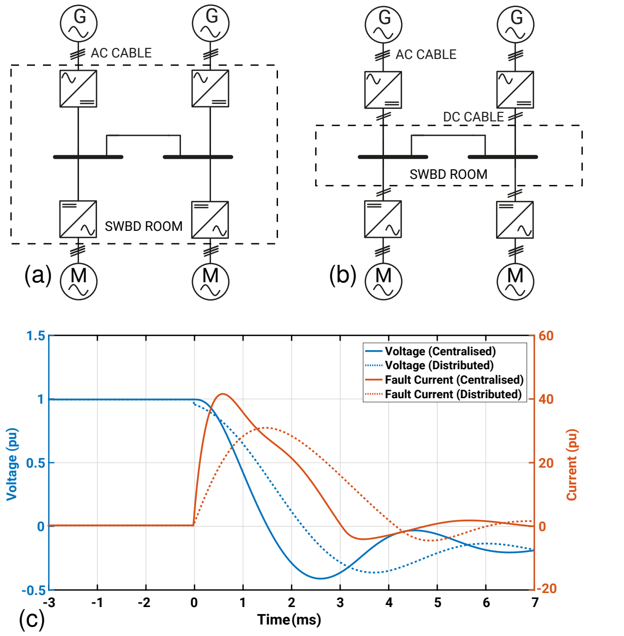

Fig. 5: Cable layouts: (a) centralised, (b) distributed and (c) voltage and current waveforms during a DC fault.

fiers, inverters, isolators and bus-tie switches) are connected to the DC bus through metallic busbars. While AC cables are used to connect generator-rectifier and inverter-load, DC cables are not used in this layout, as shown in Fig. 5(a). Contrary to that, the DC cables are mainly used to integrate the converters into the DC bus in the distributed layout (or a fully distributed approach in [15]). The distributed layout allows for installing the power converters next to the machines and can achieve high energy efficiency by using the DC cables which have lower power losses than the AC cables. In this layout the DC faults are more likely to occur compared to the centralised layout.

The presence or absence of the DC cable in the DC network can have an important impact on system protection. As an example, Fig. 5(c) illustrates the voltage and current waveforms during a DC fault for the centralised and distributed layouts.

3. Power Equipment

Marine PDNs are, in essence, microgrids composed of power generation, distribution, loads, protection devices and energy storage systems. As the PDMs are changing from AC to DC, there are big changes in the power equipment and its applications. In addition, there are problems of complexity to select and combine power equipment due to lack of standardised and typical DC PDNs.

Power Generation

Generators driven by prime movers are commonly used in the marine power system as a primary electrical power source. Unlike AC ships, there is no need to keep the constant power frequency in DC ships, e.g., $50\,\mathrm{Hz}$ or $60\,\mathrm{Hz}$. This provides freedom to optimise engine speed depending on system loading condition and its control can be implemented as the power controller in Fig. 6.

Various rectifiers are currently available to provide the DC power to the system, as shown in Fig. 6. When the diode rectifier is used, the DC voltage should be adjusted by the exciter of the synchronous generator. The voltage dynamics of the diode rectifier-based network relies on the exciter performance and its response is relatively slow, compared to converter controllers. The thyristor rectifier can be operated with two ways: 1) uncontrolled manner ($0\,\mathrm{deg}$ of firing angle, same as the diode rectifier) and 2) controlled manner (adjust-

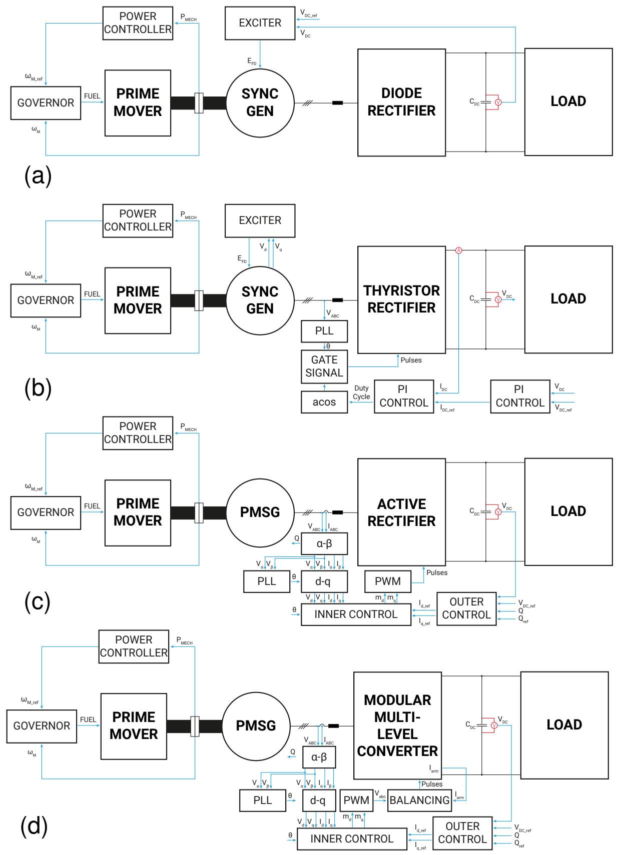

Fig. 6: Generator-rectifier systems: (a) synchronous generator (SG) with diode rectifier, (b) SG with thyristor rectifier, (c) permanent magnet synchronous generator (PMSG) with active rectifier and (d) PMSG with modular multilevel converter.

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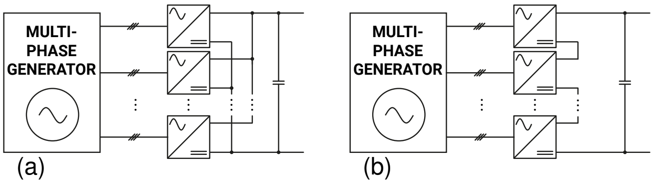

Fig. 7: Multi-phase multi-pulse supply: (a) parallel configuration and (b) series configuration.

ing DC voltage by firing angle control (Fig. 6(b)). The active rectifier and the MMC use fully controllable semiconductors and provide fast dynamic response with their high switching frequency. This allows for the use of the synchronous generator as well as the permanent magnet synchronous generator (PMSG), as shown in Fig. 6(c) and 6(d).

A multi-phase generator interfaced with a multi-pulse rectifier in parallel (Fig. 7(a)) can provide higher power quality on the DC side (less DC voltage ripple) [16]. Additionally, parallel configuration provides improved fault tolerance in case of the failure in one of the rectifiers or machine's winding sets. For the series connection of several six-pulse rectifiers to the multi-phase generator (Fig. 7(b)), it also improves the power quality on the DC side. Furthermore, higher DC voltages could be achieved by available generators without transformers.

DC Circuit Breakers

Whilst faults in the AC PDNs, consisted of AC equipment having relatively high thermal capability, are usually managed in the range of seconds, DC faults in the DC PDNs have to be cleared within several milliseconds due to very low thermal capability of power converters. It implies that mechanical circuit breakers are not suited for the DC PDNs. Hybrid circuit breakers having mechanical and solid-state switches in parallel provide faster fault interruption, but their interruption speed is still slow to coordinate protection measures. Thus, solid-state circuit breakers (SSCBs) have been proposed and developed for the marine DC PDNs [17]–[20].

The SSCBs suitable for ultra-fast fault clearing commonly include semiconductors to interrupt the current, inductors to limit the rate of rise of fault current, and protection circuits to dissipate inductive energy and mitigate overvoltage. These SSCBs can be classified by ways to interrupt the current and dissipate inductive energy stored in the system during their interruption: interrupting, resonant, resistive and limiting topologies.

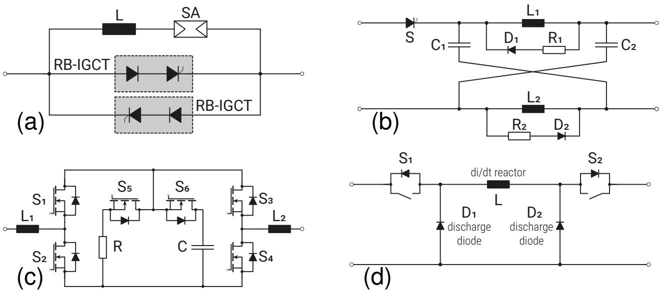

Fig. 8: SSCBs: (a) interrupting topology [17], (b) resonant topology [18], (c) resistive topology [19] and (d) limiting topology [20].

- Interrupting topology (Fig. 8(a)): The current in the circuit is interrupted by reverse blocking semiconductors (e.g., RB-IGCT) and the stored energy is dissipated by a surge arrester (SA) installed in parallel that can also reduce overvoltage on the semiconductors.
- Resonant topology (Fig. 8(b)): When the fault current flows through the SSCB, the resonant circuit creates an artificial zero current without any active circuits. During this zero current, the thyristor (S) is turned off and the energy in inductances L_1 and L_2 is dissipated in the respective anti-parallel diode and resistor.
- Resistive topology (Fig. 8(c)): When the main current path is interrupted by turning off S_2 and S_3, the current is directed to the capacitor (C). If the voltage on the capacitor exceeds a threshold level, the stored fault energy is discharged by the resistor (R) with turning on S_5 and S_6. The capacitor charge and the discharge by the resistor is repeated until the current is driven to zero.
- Limiting topology (Fig. 8(d)): The current can be interrupted by S_1 or S_2 depending on current direction. The freewheeling diode D_1 or D_2 allows the fault current present in the di/dt limiting reactor to freewheel through one of the two discharge diodes, depending on current direction. The inductive energy is therefore dissipated in the circuit and the fault resistance.

Energy Storage Systems

There are several energy storage systems that can be applicable to the marine DC PDNs: compressed air energy storage, rotational kinetic energy (flywheels), capacitive and super-capacitive systems, electrochemical energy storage (batteries) and energy storage based on hydrogen. Among those, the battery storage systems have already proven

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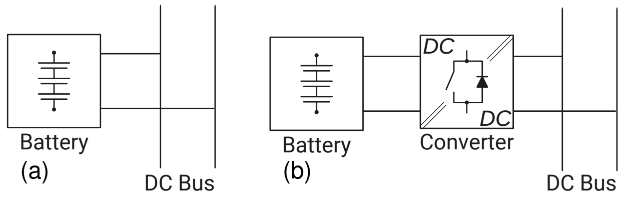

Fig. 9: Battery connections: (a) direct and (b) converter.

their performances along with continued technological developments and decreased costs in the marine applications (Fig. 1).
The battery integration into the marine PDNs helps to increase the energy efficiency with its own functions, e.g., spinning reserve, peak shaving, improved dynamic performance and optimal generation scheduling [21]. Additionally, plug-in hybrid and pure electric ships allow operation from battery power only to eliminate environmentally harmful emissions when the ships enter and leave a port (zero emission operation).
The battery can be connected to the DC line directly or through DC-DC converters. The direct connection of the battery (Fig. 9(a)) is a simple way and can reduce the cost, weight and power loss by avoiding the DC-DC converter. However, the energy stored in the battery cannot be controlled independently from the DC-link voltage. In other words, the optimum use of them is limited in this way. Furthermore, the DC-link voltage varies depending on the state-of-charge because the voltage of the battery connected to the DC-link is increased during charge and decreased during discharging. Despite all of these disadvantages, these systems have been used in practice because those are cost effective and simple. When the storage systems are segregated from the DC-link by the bidirectional DC-DC converter (Fig. 9(b)), all the benefits of the integrated energy storage systems can be achieved with the fixed DC-link voltage.

4. System Protection

Protection methods are dependent on system architectures, desired reliability requirements and system earthing. Thus, different protection methods have been proposed for different DC PDNs.

Zonal Protection

Zonal protection is a protection measure for the ring-configured military ships and there are two approaches: unit-based and breaker-based. In the unit-based protection, rectifiers interfacing with electric sources play an important role [22], [23]. The current contribution of the source is limited by the rectifiers with their DC fault handling capabilities, e.g., thyristor rectifier or full-bridge MMC [24], [25]. For this protection, mechanical bus-tie switches between the port and starboard buses should be normally open. If a DC fault occurs in one area, the current is blocked by the rectifiers (an example shown in Fig. 10(a)) and mechanical disconnectors isolate the fault and reconfigured the system (Fig. 10(b)). However, for this operation complex communication is necessary [19] and the system restoration is relatively slow due to the mechanical disconnectors.
On the other hand, the breaker-based protection allows for normally closing solid-state bus-ties switches. In addition, the fault can be isolated with the minimum power outage [26], [27] (Fig. 10(b)). But, this approach requires the installation of a large number of the SSCBs.

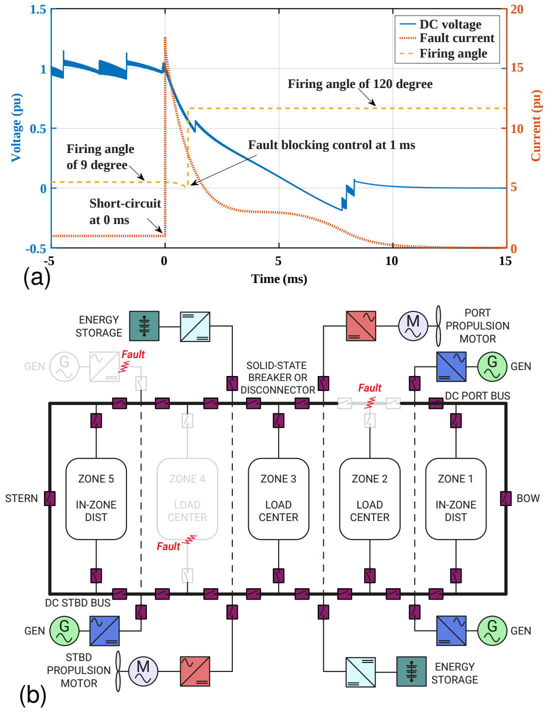

Fig. 10: Zonal protection: (a) rectifier fault blocking and (b) system re-configuration.

Differential & Directional Protections

For radial-configured DC SPSs, differential and directional protections combined with an intelligent electronic device (IED) and a SSCB are possible solutions for bus protection and/or other protections [28], [29]. The principle of the differential protec-

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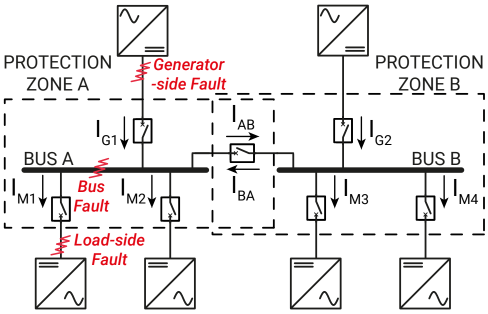

Fig. 11: Principle of differential & directional protections.

tion is based on the difference between the sums of currents flowing into and out from the protection zone. During normal operation and the external faults (the generator- and load-side faults in Fig. 11), their current sums are equal theoretically ($I_{G1} = I_{M1} + I_{M2} + I_{AB}$). Otherwise, for the internal fault (the bus fault in Fig. 11), all currents flow into the zone and the difference between the sums is not zero ($I_{G1} \neq I_{M1} + I_{M2} + I_{AB}$) that may be very high, indicating fault conditions.

The directional protection is based on the comparison of all the current directions as well as current amplitudes. For the generator-side fault in Fig. 11, the current direction of I_{G1} is negative, assuming that the positive direction is the current flowing from generator to bus and bus to load, and it stands for the fault between the bus and the generator. In case of the bus fault, the current directions of the generator and load sides are positive and negative, respectively. Similar to the differential protection, the current directions and some more information (e.g., current amplitudes and bus voltages) provide enough information to detect the bus fault.

Three-Level Protection

A three-level protection is one of the economic solutions for the LVDC PDNs [6], [7], [20]. This protection consists of three different actions with different operation time frames:

- fast action (1st level) - bus separation with solid-state DC bus-tie switch (several tens of microseconds)
- medium action (2nd level) - feeder protection with high-speed fuse (a few milliseconds)
- slow action (3rd level) - generator-rectifier fault control (up to several seconds)

For the generator-rectifier fault control, several methods are available depending on rectifier type, e.g., excitation removal and high subtransient reactance of a synchronous generator for the diode

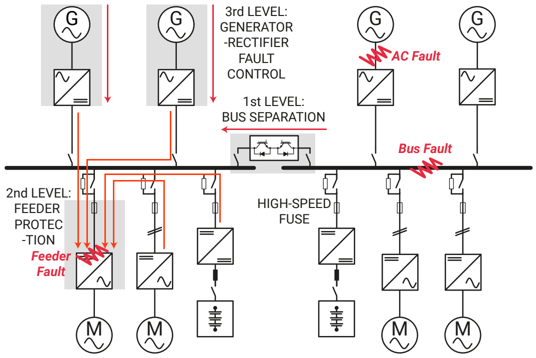

Fig. 12: Operational scheme of three-level protection.

rectifier [20], a fold-back fault control for the thyristor rectifier [24] and an artificial short-circuit method for the active rectifier [30].

When the feeder fault (Fig. 12) occurs, the DC bus-tie switch rapidly separates the DC buses. After that, the high-speed fuse on the faulty feeder isolates the fault from the system. As the last level, the generator-rectifier fault control eliminates the fault contribution of the generator for the feeder protection failure or the DC bus fault. The conventional generator protection can manage the AC fault.

Earth Fault Protection

System earthing is an important aspect in the DC PDNs because it is essential to ensure equipment protection as well as human safety. In the marine DC PDNs, a continuous power supply is a critical issue on the safety. Therefore, among several system earthings, the unearthed system (the IT DC system) is mainly recommended for both the commercial and military ships to increase the availability of the system by preventing a power interruption from a single-pole-to-earth fault, which may be the most common type of faults [31]. In the unearthed system, there is no current path for the single-pole-to-earth fault and it can be detected, localised and cleared without big system impacts.

In the unearthed system, the insulation resistance between pole to ground is a good indicator to detect the earth fault [32]. The insulation resistance is very high under normal condition (> $1\,\mathrm{M\Omega}$). If the earth fault occurs, it may decrease below certain threshold value. The resistance can be measured by applying test voltage and analysing returning current (I_R in Fig. 13). The test voltage is superposed to the system voltage and this voltage generates the returning current if the earth fault occurs.

When the earth fault is detected, the fault should be cleared before the second earth fault occurs, which

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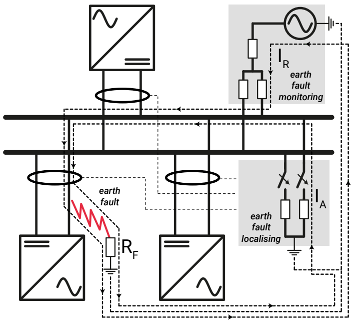

Fig. 13: Earth fault detection and localisation.

can have a huge impact on the system. A current tracing method can be applicable to find a fault location. In this method, a high value of resistor is connected and it generates an artificial current (I_A in Fig. 13) from the resistor to the earth fault. The fault can be localised by tracing the current flow.

5. Future Developments

The LVDC ships are already a reality and have been successfully deployed. It is also expected that more and more ships will be built with the LVDC or MVDC PDNs due to their distinctive advantages. Despite of such bright start and perspective, the DC solutions in the marine domain are still the early stage and lots of developments are necessary to transform the AC to DC technologies.

To begin with, the lack of a standardisation has led to diverse architectures and to make equipment selection complex. When general standards are issued, more standardised architectures and equipment combination are available. It may accelerate the development of generators, rectifiers, cables, inverters, motors suitable for the DC PDNs. With the availability of suitable industrial equipment, system engineers have freedom to design their own ships with lots of available equipment, whilst current LVDC PDNs are almost fixed by DC solutions provided by industrial vendors.

In addition, any kind of ESSs, mentioned in the paper, does not produce environmentally harmful emissions when those systems provide or discharge energy to systems. With the request on eco-friendly ships and the dramatic fall in ESS cost, the shift from diesel engines to plug-in hybrid or all-electric vessels is unstoppable, similarly to car industry. This trend has encouraged the use of the DC PDNs in marine applications that are more favourable to integrate the ESSs.

Furthermore, the installation of a shore power supply in port has been increased to minimise the impacts of air pollution from ships by shutting down the main and auxiliary engines when ships are approaching a port or while docked. Due to the lack of DC power supply function in the current shore power supply, every DC ship should be equipped with DC/AC inverters and transformers in the PDNs. Once the shore power supply provides the DC power to the ships, such inverters and transformers can be removed or replaced to DC/DC converters. This makes DC ships lighter and cheaper. For battery-powered ships, inductive power transfer battery charging of $1\,\mathrm{MW}$ is already introduced [33], it allows for significantly reducing the size of onboard battery. As a next step, the inductive battery charging system with higher power ratings and less system impacts may be developed.

Lastly, a connected smart ship is a future ship that is equipped with digital technologies to increase asset utilisation and reduce operational cost. This ship collects real-time data and exchanges those with a ship owner, other ships, a port terminal, logistics and a shipbuilder. All the data collected are analysed to provide new services and improve operational efficiency. The DC PDNs are more controllable and flexible systems than the AC PDNs, and those allow the ships with real-time communication as well as fast control through the power converters installed in every feeder. Thus, the DC PDNs are better suited systems for the connected smart ship.

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