DC-grid system for ships: a study of benefits and technical considerations

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ABSTRACT
The primary electric power system of ships has been based on the alternating current (AC) system for a long time. However, marine engineers started to question the efficiency of the AC-grid system, which was previously taken for granted. Also, important environmental benefits of the DC-grid system for marine applications were highlighted. In this regard, this paper presents the technical, economic, and environmental benefits of the DC-grid system in ships. Ships that have already applied or plan to apply the DC-grid system are categorized into several types. Additionally, some technical considerations focused on the fault protection topology, the power-sharing (balancing) topology, power quality/stability issues, power source control methods, DC arc flash hazard, and international regulations/standards regarding DC-grid ships are reviewed. Lastly, the prospects of the DC-grid system in ships are addressed with a conclusion.

Introduction

Although the alternating current (AC)-grid system has been in use for a long time, the direct current (DC)-grid system also has a long history. The first electric power transmission was made by the DC system, which was invented by Thomas Edison. However, it was difficult to transfer electric power over long distances. Thus the AC system, which can transfer high voltages easily using transformers, was selected as a standard power system.

In the marine industry as well, most ships have used the AC system for a long time, except for small boats. However, the first attempt to use the electricity in a ship was made by the DC for lightings of the steamship “SS Columbia” in 1880 (Skjong et al. 2015, 1–5; Skrabec Q. R. 2007, 92). The first naval electric ship, “HMS Adventure,” also used DC generators and DC motors for its propulsion in 1922 (Simmonds 2015, 37; BMT Defense Services 2015, 5).

Recently, after a long-term break, the DC made a comeback both on land and in the marine industry. Developments in power electronics, renewable energy, and energy storage systems (ESSs) have supported the growth of the DC-grid. And it is also affected by market demands for cleaner and more efficient electric power against stricter environmental regulations.

For example, the GW-class DC system is drawing attention as a promising solution for transferring a large amount of the electric power. This HVDC (high voltage direct current) transmission system can transmit more electrical power over long distances than a similar AC one because it has no reactive power losses. And small-scale DC-grids have also been used in spacecraft, space stations, aircraft, electric vehicles, and ships recently (Mahmoud 2017, 73–76).

In case of ships, the DC-grid system has been attempted to naval vessels including submarines at the beginning, and related researches have been performed with some specific subjects: Simmonds (2015) proposed to adopt the DC-grid system for naval vessels, and Santoso et al. (2013) made a reliability assessment through failure mode and effects analysis regarding the naval power distribution system. Furthermore, Wang (2012) undertook a review of DC circuit breakers for submarine applications. For merchandise ships, Staudt et al. (2013) analyzed fault scenarios in DC-grids with special short-circuit protection system, and Kanellos et al. (2017) suggested an optimal active power management system (PMS) for DC-grid ships.

Following this recent wave of interest in research on the DC-grid, this paper made a comprehensive review of the DC-grid system to expand its application in the marine industry. First, several significant benefits of the DC-grid system compared to the AC system highlighted in “benefits of DC-grid” section. And various ships that have already applied or plan to apply the DC-grid system are categorized into several types in “types of the DC-grid” section. Also, important technical considerations to motivate the DC-grid system in ships are discussed in “technical considerations” section. Finally, the prospect of the DC-grid system in the marine industry is addressed along with a conclusion.
Beneﬁts of DC-grid

Benefits of the DC-grid system in ships could be explained in two aspects. One is the power stability and quality aspect, and the other is the economic and environmental aspect as below.

Power stability and quality beneﬁts

In the AC-grid system, both voltage and frequency are required to be monitored and controlled for maintaining the power stability. However, in the DC-grid system, there are no reactive power interactions, and then the system control is oriented to the voltage only. Therefore, the DC-grid has advantages of keeping the power stability than that of the AC-grid.

In addition, the synchronization of generators is simpler than the AC-grid. In the AC-grid system, it is necessary to consider the voltage, frequency, phase angle during synchronizing more than two generators. However, in the DC-grid system, only the voltage is a crucial factor.

In the view of the power quality in the AC-grid, the main troublesome is the harmonic distortion (Jayasinghe et al. 2017, 1–12). Especially, electric propulsion ships with many variable frequency drives (VFDs) have suffered from the harmonic distortion issue. In a VFD, a rectifier converts a constant voltage from an AC, and an inverter recreates the AC at the required speed for the road; this might arise the harmonic distortion issues (Bossert, et al. 2017, 487). To solve this problem, the harmonic filters had been installed additionally in the past, and then, the phase-shifting transformer has been commonly installed in front of the VFD for generating 12 or 24 pulses. Even though the advanced VFD such as an active front end converter could reduce the harmonics significantly, its price is rather higher than others.

However, in the DC-grid system, it is unnecessary to transfer an AC to a constant voltage (DC), and thereby the rectifier part in the VFD could be eliminated. Thereby, power losses and harmonic distortions into the connecting load could be reduced. Consequently, the DC-grid is well suitable for ships with many VFDs to control motors such as heavy-lifting cranes, propulsion or thruster motors, pumps, compressors, etc. (Geertsma et al. 2017, 47).

To summarize, the DC-grid system has following beneﬁts compared to the AC-grid in terms of the power stability and quality aspect.

- Freedom of the reactive power (increasing power stability)
- Freedom of the frequency (easy synchronizing of power sources)
- DC-based power distribution (reducing harmonic distortions and increasing power quality)

Economic and environmental beneﬁts

In the AC-grid system, a genset (generator and prime-mover) has to run at the given fixed frequency of 50 or 60 Hz. However, the speciﬁc fuel oil consumption (SFOC) of a genset is different depending on its load, and it is designed to optimize around 75–85% load factor typically (ABB 2017a). When operating at low load, the SFOC becomes higher as shown in Figure 1. However, in the DC-grid system, gensets can operate with variable frequencies, so it has a wider operating window with high fuel efficiency. It is known that the DC-grid system could reduce the fuel consumption and emissions by up to around 20% depending on the ship type (ABB 2011; Settemsdal et al. 2014, 18).

As mentioned above, most electric propulsion ships have been equipped with additional equipment to mitigate harmonic distortions such as harmonic filters or phase-shifting transformers, whereas these are no longer necessary for the DC-grid. Also, the rectiﬁer part (AC/DC) in the VFD can be removed. Thereby, it can make more cargo spaces on a ship.

In addition, it is effortless to integrate DC power sources (e.g., fuel cells, lithium-ion batteries, supercapacitors, etc.) into a DC-bus. Especially, the ESS could be used for various purposes: peak shaving, load leveling, absorbing regenerative power, etc. Therefore, the ESS can reduce gensets’ running time and improve energy efficiency. Besides, it can also contribute to reducing the maintenance cost of gensets.
Lastly, large ships with several MW-class generators may encounter a problem with power supply when harboring at a port. Sometimes, a smaller additional generator has to be installed only for power supply at the port. On the contrary, an additional generator for harbor use is not necessary anymore in the DC-grid system, because the variable speed generator has low fuel consumption even when operating at low load such as harbor operations (Kokkila 2012).

To summarize, the DC-grid system has following benefits compared to the AC-grid in terms of the economic and environmental aspects.

- Variable speed/frequency operation of gensets (reducing fuel consumptions, emissions)
- Removing a rectifier in a VFD for motor controls (reducing weight and volume)
- Eliminating harmonic mitigation equipment (reducing weight and volume)
- Easy integration of DC power sources to a DC-bus (improving energy efficiency)
- Unnecessary for an additional small generator for power supply at a harbor in case of MW-class large ships (saving the cost of a small genset)

To sum all benefits up, the DC-grid system would be preferable to two cases. One case is the ships that employ DC power sources as the primary power source. And the preferred ship types for this case might be ferries, cruises, small feeder vessels, etc. Besides, the autonomous or unmanned ship has also high possibility to install the full-battery power system with the DC-grid due to low maintenance cost; for example, Fjord1’s upcoming semi-autonomous ferries, YARA’s upcoming autonomous container feeder vessel (120TEU) (Kongsberg 2017; NorwayToday 2017).

The other case is the ship that requires variable speed motors with VFDs such as dynamic positioning (DP) thrusters, pump motors, or crane motors. And the preferred ship types for this case might be offshore service vessels, platform supply vessels, multi-purpose support vessels, anchor handling tug supply vessels, research vessels, shuttle tankers, product carriers, drill ships, drilling rigs, dredgers, etc. – some proposed concept systems of the DC-grid are shown in Figures 2–4. For a product oil carrier (Figure 2), the part of cargo pump motors with each VFD could be simpler by applying the DC-grid system. Similarly, the thruster motor part of a pipelayer ship (Figure 3) and winch motor part of a cutter dredger ship (Figure 4) could also be simpler by applying the DC-grid system.

Types of the DC-grid

The DC-grid system has been applied to various types of ships, particularly, ferries, tugs, DP ships, naval ships, etc. as shown in Table 1. Applying the DC-grid system does not mean that the entire electric system must be distributed by only the DC. The DC could be used as a main or sub-distribution system as follows.

- Main-bus type (two-split type, zonal type)
- Sub-bus type (radial type, common DC-bus type)

First, the DC can be used as a main-bus type as shown in Figure 5. The two-split type is the most common and simple solution, and it could be divided into two types depending on the main power sources as shown in Figure 5(a,b). In the zonal type (Figure 5(c)), all loads in a compartment receive power from a “zone” of one or both of the buses directly in that compartment (Sarar 2006, 5). This type ensures survivability as it can prevent the spread of damages via fire or flooding (Doerry, 2007, 6). Therefore, the system is highly redundant and has been applied to some naval ships in combination with battery packs or fuel cells as air-independent propulsion system (Geertsma et al. 2017, 47). However, this complicated power architecture requires much more sophisticated control and coordination.

Figure 2. Comparison between the conventional AC-grid and proposed DC-grid of a product oil carrier (Kim 2017; Siemens 2017, 73–80).
strategies, which needs to be carefully evaluated during early-stage design (Jin et al. 2016, 3–4).

Second, the DC can be used as a sub-bus type as shown in Figure 6. The radial type (Figure 6(a)) is preferred for ships that need to control many electric motors for specific purposes. In a drilling rig, for example, drill strings need to maintain stationary relative to the seabed. To ensure this operation, winch motors raise and lower the string to compensate for the ocean waves (Kilberg 2012); this is called as “Active Heave Compensation.” This particular part consisting of many electric motors could be a DC-grid system. And other possible applications would be some special-purpose load parts such as thruster motors, crane motors, pump motors, etc.

There is another sub-bus type which is located between two power converters (Figure 6(b,c)). This type is usually applied to ships equipped with electric propulsion motors or shaft generator/motors. If the ESS is installed to this type, it is easy to obtain the regenerative electric power when the motor is stopped or rotated in the opposite direction acting as a generator (e.g., thrust motors, shaft generators, crane motors, winch motors, etc). In other words, the ESS can absorb the regenerative power rather than eliminate it through a dynamic braking resistor.

**Technical considerations**

Though the DC-grid system has many benefits compared to the AC-grid system, it is not a common solution in the marine industry. Therefore, there are several technical considerations as below.

**Fault protection strategy**

In the DC system, the current has to be forced to zero for interrupting a fault current, whereas, in the AC system, the current naturally crosses zero twice in each period. Therefore, DC breakers use complicated mechanisms to extinguish the large fault current and arc safely, resulting in more expensive and bigger space than the AC one.

In this regard, the hybrid protection system has been applied as an alternative method. It is a Figure 3. Comparison between the conventional AC-grid and proposed DC-grid of a pipelayer ship (Kim 2017; Siemens 2017, 73–80).

Figure 4. Comparison between the conventional AC-grid and proposed DC-grid of a cutter dredger ship (Kim 2017; Siemens 2008, 132).
Table 1. References of the DC-grid system in ships.

| Type                        | References (ship name, type, delivery year)                                                                 |
|-----------------------------|-------------------------------------------------------------------------------------------------------------|
| Main-bus type Two-split type| Generator main power                                                                                      |
|                             | MS Viking Legend (car ferry, 2009) (Andersen 2011, 6–7)                                                   |
|                             | MS Viking Prestige (car ferry, 2011) (Andersen 2011, 6–7)                                                 |
|                             | MV Jaguar (general cargo ship, 2012) (World Maritime News 2012)                                           |
|                             | Absis Dover (MPSV, 2012) (MarineLink 2012)                                                                  |
|                             | Dina Star (PSV, 2013) (ABB website 2017b)                                                                  |
|                             | Edda Ferd (PSV, 2013) (Motorship 2013)                                                                     |
|                             | BB Green (ferry, 2015) (BB Green 2015, 34)                                                                  |
|                             | Damen Eco Liner (tanker, 2015) (Dijkstra 2016)                                                             |
|                             | Edda Freya (OSV, 2016) (Corvus Energy 2017; Rederi 2017)                                                   |
|                             | Harvey Stone (MPSV, 2016) (ESG 2016)                                                                       |
|                             | Vision of the Fjords (car ferry, 2016) (SMM 2016)                                                          |
|                             | U I Ferry 60, 61 (passenger ferry, 2016–17) (Danfoss drive 2017)                                           |
|                             | NKT Victoria (cable laying vessel, 2017) (OSJ 2017)                                                        |
|                             | Van Oord’s Nexus (cable laying vessel, 2017) (OSJ [Offshore Support Journal 2017)                         |
|                             | Aker ARC 124 Port (icebreaker, in 2018) (Aker Arctic 2016)                                                 |
|                             | Australian Research Vessel (ASRV, in 2020) (Subsea World News 2017)                                       |
| Battery main power          |                                                                                                             |
|                             | FCS Alstenwater† (ferry, 2012) (Bassam 2016)                                                                |
|                             | Ampere (car ferry, 2014) (Ship technology 2017)                                                             |
|                             | Tycho Brahe and Aurora of HH ferries (car ferry, 2017) (ABB 2016)                                         |
|                             | Elektra (ferry, 2017) (EE publishers 2017)                                                                  |
|                             | Guangzhou Shipyard International (cargo ship, 2017)† (ChinaDaily 2017)                                    |
|                             | E-ferry (car ferry, in 2018) (E-ferry 2017)                                                                 |
| Supercapacitor main power   |                                                                                                             |
|                             | Ar Vag Tredan (ferry, 2013) (Deyrieux 2013)                                                                 |
| Zonal type                  |                                                                                                             |
|                             | DDG 1000 (guided missile destroyer, 2008) (Electric Ships Office 2013, 55)                                 |
|                             | F125 (frigates, 2011) (Thysen Knup 2016)                                                                    |
|                             | Some types of submarines (Siemens 2016)                                                                    |
| Sub-bus type Radial type    |                                                                                                             |
|                             | GSP Magellan (offshore rig, 1992) (GSP Offshore 2017)                                                       |
|                             | GSP Jupiter (offshore rig, rebuilt 2007) (GSP Offshore 2017)                                               |
|                             | Viking lady† (PSV, retrofit 2009) (J.J. de-Troya, et al. 2016)                                              |
|                             | North Star Shipping’s TBN No. 1, 2 (PSV, 2013) (Siemens 2012)                                              |
|                             | Tidewater’s TBM (MMC879 LH polar class) (PSV, 2013) (Siemens Marine Solution 2012)                        |
|                             | Tidewater’s TBM (MMC879) (PSV, 2013) (Siemens Marine Solution 2012)                                       |
|                             | Deepwater Thalassa (drillship, 2015) (Transocean 2017a)                                                   |
|                             | Deepwater Proteus (drillship, 2015) (Transocean website 2017b)                                             |
|                             | Deepwater Pontus (drillship, 2015) (Transocean website 2017c)                                              |
|                             | Texel Stroom (car ferry, 2016) (Cresco 2016)                                                                |
|                             | Happiness (ferry, 2017) (Greenport 2017)                                                                    |
| DC common-bus type Electric propulsion application |                                                                                             |
| Shaft motor/generator application | Simon Møkster Shipping’s Stril Merkur (stand-by, rescue and guard vessel, 2011) (Siemens 2008, 29)       |
|                             | Ib Hallaig (ferry, 2012) (Anderson 2012)                                                                    |
|                             | Ib lb-class B Urho (icebreaker, retrofit 2016) (PR Newswire 2012)                                           |

†Antarctic Supply Research Vessel, ‡installed fuel cell power system with batteries, §powered by li-ion batteries and supercapacitors.

Note: This list has not covered the whole reference ships for each type.

Figure 5. Main-bus types of the DC-grid system.
(a) Two-split type (generator main power), (b) two-split type (ESS main power), (c) zonal type.
combined protection system involving fuses, isolating switches, disconnectors, and controlled turn-off of semiconductor power devices (Hansen, Lindtjørn, and Vanska 2011, 1–8). It is known that this kind of a virtual DC circuit breaker could interrupt an amount of fault current quickly or limit the fault current permitted to flow (Bossert, Rozine, and Ockerman 2017, 487). In order to perform this function, power converters should have the capability to ensure the transient stability and limit potential over-voltages during transients (Doerry 2007). In other words, short-circuit conditions in the DC-grid strongly depend on the chosen converter topologies and the surge current capability of the power electronics.

However, at critical parts that have potentials to flow high short-circuit currents and endanger a ship’s safety and propulsion, DC circuit breakers should be installed in real. In this regard, major electric companies have been developing the DC breaking topology to interrupt high currents during a fault. Previously, electromechanical circuit breakers were mostly used to interrupt current flow by opening an electromechanical contact and utilizing the relatively high insulation strength of substances such as air, vacuum, and sulfur hexafluoride (SF6). And its current zero-crossing point is generated by an oscillating current through a passive or an active circuit as shown in Figure 7(a).

Recently, the solid-state circuit breaker (SSCB) which replaces the electromechanical contact with semiconductor switches has been adopted as shown in Figure 7(b). It has the required open-circuit disconnecting capability, high current carrying capacity with the high switching speed (Wang 2012, 2–40). Furthermore, the hybrid DC circuit breaker that combines the SSCB and the traditional mechanical switch has been developed as shown in Figure 7(c). However, both the SSCB and the hybrid circuit breaker are required to control the semiconductor switches inside, and they are expensive and complicated in the current state (Wang Xiang, et al. 2014, 31).

Additionally, galvanic isolations should be considered to prevent potential circulating currents in the distribution system. And the grounding is also an essential factor for human safety; therefore, the touch voltage should be limited to acceptable levels (Satpathi, et al. 2015, 2).

Lastly, the supervision diagnosis system based on intelligent fault detection methods is to be developed.

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**Figure 6.** Sub-bus types of the DC-grid system.
(a) Radial type, (b) DC common-bus type (electric propulsion application), (c) DC common-bus type (shaft motor/generator application).

**Figure 7.** Simple schematics of the typical DC circuit breakers (Gu et al. 2017, 8–9).
(a) Electromechanical circuit breaker, (b) solid-state circuit breaker, (c) hybrid circuit breaker.
to achieve faster and more perfect protection (Jin et al. 2016, 3–4).

**Power balancing strategy**

The power balancing topology is essential for both the AC and the DC-grid. However, unlike the AC-grid system, the DC-grid system does not have reactive power, and the voltage is the only primary indicator of the active power control. On that basis, the PMS should be designed differently compared to the AC one.

In the AC grid, the active power ($P$) can be calculated as follows (Mahmoud 2017, 73–76).

$$P = \frac{V_s \times V_r}{X_{ac}} \times \sin(\delta)$$

(1)

where $V_s$ is a sending-end voltage, $V_r$ is a receiving-end voltage, and $X_{ac}$ is a line inductance. Therefore, the active power can be controlled by the frequency because the voltage angle ($\delta$) is also proportional to the frequency.

In the DC-grid, however, the active power flow is proportional to the DC voltage ($V_{dc}$) and the active power can be controlled by the DC link voltage as below.

$$P = \frac{V_{dc} \times \Delta V_{dc}}{R_{dc}}$$

(2)

where $\Delta V_{dc}$ is a voltage drop over the line resistance ($R_{dc}$).

In this regard, the voltage-power (V-P) or voltage-current (V-I) droop scheme can be employed as the primary-level power controller in the DC-grid, rather than the frequency-power (F-P) droop in the AC-grid as shown in Figure 8. If load changes, a DC-bus voltage varies, and the droop controller adjusts the output power of each converter connected to each power source in response to the voltage variation. In order words, this control is achieved by simultaneously using local control of the power electronic interfaces as well as the entire coordination among all the power system.

And the droop ratio (droop gain) must be determined such that it guarantees the overall stability of the system. In this regard, the maximum allowable voltage variations is an essential factor that must be taken into account when selecting the droop ratio. Furthermore, a secondary-level power controller might be applied to compensate for any voltage deviations that is caused by the primary-level controller to improve power quality.

If the ESS that has bidirectional power flow (charge or discharge) is integrated into the DC-grid, it is important to consider the drooping characteristic of its converter which has two control regions as shown in Figure 9. Besides, the SoC range of the ESS should be considered during charging or discharging operations. For example, if the SoC is below the lowest limit (about 10–20%), the batteries cannot be used as a power source and should be stopped the discharging operation.

**Power stability/quality strategy**

In the DC-grid system, the fundamental frequency is zero, and the harmonic distortion issue arisen in AC-grid systems is not under consideration. However, the majority of power quality issues could be attributed to voltage changes which occur due to cyclic or non-cyclic load transients (Jayasinghe et al. 2017, 1–12).

Also, the voltage ripple ($\text{AC}_{\text{rms}}$ over steady DC voltage) from power converters consisting of controllable switching devices might cause the power quality issue. Regarding the voltage quality, there is a standard in Unified Requirement No. ES imposed by the IACS (International Association of Classification Societies) as below (IACS 2005, 1).

As shown in Table 2, the voltage tolerance limitation is ±10%, and the DC voltage ripple should be kept under 10%. In addition, the voltage deviation depending on cyclic loads is limited below 5%. In order to meet these requirements, the role of converters connected to a DC-bus is significant.

Of course, from a whole system point of view which consists of the AC-grids as well as the DC-grids, the harmonics caused by power converters should be limited to the specified requirements. In
IACS, the limitation of the total voltage harmonic distortion is under 8% (IACS 2016, 1), and the limitation of single order voltage harmonics is different depending on classification societies.

Moreover, the fault ride-through capability is also essential to maintain the power stability. When one unit in a branch fails, it is necessary to bypass shortly to maintain the healthy units and ensure the essential services available. To cope with this emergency situation, the ESS could be an option because of its rapid response capability (Settemsdal et al. 2014, 18). Especially, the ESS with high power density (e.g., supercapacitors or lithium-ion batteries with high C-rate) is highly recommended for the quick reaction.

**Power source control strategy**

First, in case of gensets in the AC-grid using the fixed frequency of 50 or 60 Hz, a governor has to control the speed of the genset to maintain the frequency within the limited operating range (Figure 10(a)). On the contrary, in the DC-grid, the governor can allow the genset to operate at variable speeds with a given criterion; this criterion could be the minimized fuel consumptions (emissions) or optimal engine loading (Geertsm et al. 2017, 47). In this regard, a lookup table with optimal speed reference with respect to engine power could be applied to obtain optimal speed control for minimizing fuel consumption (Figure 10(b)), and the data for the lookup table are retrieved from manufacturers such as Figure 1 (Syverud 2016, 18).

And, if the conventional governor of the AC-grid is applied to the DC-grid, it could worsen the power stability because gensets have their own limited load acceptance for sudden load disturbances (Choe, Son, and Sul 2016, 1284). Particularly, the gas engine has limited over-boosting capability due to misfiring at lean mixtures, i.e., at high air/fuel ratios (CIMAC 2011, 4). Therefore, the improved transient control method of the governor during dynamic load disturbances should be considered unless the ESS installs to support some amount of power mismatches during the load disturbances.

Also, DC-based power sources, such as fuel cells, solar cells, lithium–ion batteries, and supercapacitors, have high possibilities to be adopted as a main or sub-power source in the DC-grid ship. Therefore, it is important to recognize each power sources’ characteristic and each power control topology. For example, in case of solar cells, its maximum power varies with solar radiation, ambient temperature, and solar cell temperature. Therefore, its power is mostly controlled by the maximum power point tracking system and integrated with the ESS. Besides, the top-level integrated power control system should cooperate each power control system appropriately considering the overall power stability.

**DC arc flash hazard**

Arc flash is a dangerous condition associated with the release of energy caused by an electrical fault. Therefore, it is recommended to minimize the dangerous effects of the arc flash on personnel in both AC and DC-grid. In this regard, IEEE standard 1584 (2002) provides techniques for designers and facility operators to apply in determining the AC arc flash hazard distance and the incident energy to which employees could be exposed during their work on or near electrical equipment. However, there are no unified standards or guidelines for the DC arc flash yet.

A method of estimating DC arc flash incident energy that follows was published in the IEEE (Doan, D.R 2010). This method is based on the concept that the maximum power possible in a DC arc will occur when the arcing voltage is one-half the system voltage. Testing completed for Bruce Power (Kinectrics Inc 2007) has shown that this calculation is conservatively high in estimating the arc flash value. This method applies to DC systems rated up to 1000 V (NFPA 2018, 65–66). Therefore, the higher DC arc calculation method has to be studied to prevent HVDC arc flash accident. And some methods for detecting, eliminating, or mitigating of the DC arc flash have to be considered at the design stage. The arc flash mitigation options are mentioned in Annex B of IEEE standard 1709 (2010) for reference.
Lastly, appropriate international standards or guidelines have to be provided to the industry. Though the DC-grid system is not widely used than the AC-grid, there are some standards/guidelines available as shown in Table 3. IEEE Std. 1709 was released for the medium voltage DC (MVDC)-grid system. And the IEC 63108 was just released as a publicly available specification in May 2017. Also, the calculating method for short-circuit currents in a DC system is covered in IEC 61660.

Also, the Naval Sea Systems Command (NAVSEA) in the United States began to develop new MIL-STD-1399 sections for low voltage DC (LVDC) and MVDC distribution. NAVSEA also released a request

Table 3. Standards or guidelines of the DC-grid system in ships.

| Organization | No.     | Title                                                                 | Publication year (edition) | Remarks                                      |
|--------------|---------|----------------------------------------------------------------------|----------------------------|----------------------------------------------|
| IEEE         | 1709    | IEEE Recommended Practice for 1–35 kV Medium-Voltage DC Power Systems on Ships | 2010 (ed. 1)               | General guideline (>1 and ≤35 kVdc)          |
| ISO          | 16315   | Small craft – Electric propulsion system (some parts for the DC distribution) | 2016 (ed. 1)               | For small ships (<1 kVdc and <24 m in length) |
| IEC          | 63108 (PAS) | Electrical installation in ships – Primary DC distribution – System design architecture | 2017 (ed. 1)               | General standard                            |
|              | 61660-1 | Short-circuit currents in DC auxiliary installations in power plants and substations – Part 1: Calculation of short-circuit currents | 1997 (ed. 1)               | Short-circuit calculation in DC-grid         |
|              | 60092-507 | Electrical installations in ships – Part 507: Small vessels (some parts for the DC distribution) | 2014 (ed. 3)               | For small vessels (<50 m in length, and ≤500 GT) |
|              | 60092-201 | Electrical installations in ships – Part 201: System design – General | 1994 (ed. 4)               | In chapter 4 (DC distribution systems)       |
|              | 61892-1 | Mobile and fixed offshore units – Electrical installations – Part 1: General requirements and conditions | 2015 (ed. 3)               | For offshore units in chapter 4.6, annex D (≤1.5 kVdc) |
| NAVSEA       | STD-1399 (navy) | Electric Power – Low Voltage and 1000 V Direct Current (draft) | 2016 (draft)               | US DoD standard (≤1 kVdc)                    |
|              | STD-1399 (navy) | Electric Power – High Voltage Direct Current (draft) | 2016 (draft)               | US DoD standard (>1 kVdc)                    |
| IACS         | UR² E5  | Voltage and frequency variations | 2005 (rev. 1) | Voltage variations for DC-grid calculation |
| NFPA⁴        | 70E     | Standard for Electrical Safety in the Workplace – Annex D | 2018 | DC arc flash calculation |

¹GT: Gloss tonnes in a ship, ²DoD: Department of Defense, ³UR: unified requirements of the IACS, ⁴NFPA: National Fire Protection Association.

Note: This list might not be covered the whole standards/guidelines.
for information to obtain feedback from the industry, academia, and government on the early draft of the standards (Doery 2016, 2). And classification societies have some parts or an additional preliminary rule for the DC-grid system on ships.

Future prospects

The LVDC system is easily available on the market, and its improved efficiency and reliability have been demonstrated through many references as shown in Table 1. On the other hand, it would be difficult to apply the HVDC system for large ships. The biggest reason is that high power converters and HVDC breakers are not yet widely available, and they are expensive in the current state.

However, it is expected that the global DC system market will grow at a CAGR of 4.98% during the period 2017–2021, especially the HVDC market is highly positive (at a CAGR of 8.4%) (PR Newswire 2017). Main drivers for its growth are growing needs of renewable energy sources due to environmental problems and needs of more efficient electricity due to increasing electric demands. Following this trends, it could further propel the growth of the DC-related equipment. And it would give positive effects to the HVDC system in the marine industry as well.

Although it could be possible to apply the HVDC system in ships soon, the loads would be based on conventional AC machines because the DC rotating machine has higher maintenance costs compared to AC machines. Therefore, it is necessary to coordinate the AC and DC system appropriately to make more efficient and safe.

Conclusion

With recent interests in more reliable and economic power distribution, the DC-grid has been entered in the marine industry and combined with the conventional AC-grid. This paper reviews the benefits of the DC-grid system compared to the AC one. The main benefits are the freedom of the frequency (reactive power), easy integration of DC power sources, simplification of the VFD for motor controls, etc. And these benefits enable DC-grid ships to be more efficient, economic, and eco-friendly than before. And various ships that have already applied or plan to apply the DC-grid system are addressed depending on the type.

In addition, some technical considerations are reviewed to improve the reliability of the DC-grid system in ships. Especially, the highly reliable protection and power-sharing topology should be specialized for the DC-grid system, and the control method for each power source should also be considered.

Although the DC-grid system still has some challenges to be a standard on a similar level of the AC-grid system, its prospect in the marine industry is positive because of the strong demands for the efficient or eco-friendly power system according to the stricter environmental regulations. In the meantime, all relatives including ship designers, manufacturers, ship owners, and operators on-board are recommended to be familiar with this new system.

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