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Advantages of using a DC power system on board ship

Abstract

This article is structured to present an overview of a DC ship power system. The main DC grid configurations will be presented and a difference to the AC system configuration will be highlighted. Compared to the AC power system used on board ships, DC has some obvious benefits which will be explored in this paper. These benefits include: improvement of prime mover efficiency and reduction of fuel costs, weight and space savings, unity power factor operation of generators, lower transmission losses, faster and simpler parallel connection of generators and simpler implementation of energy storage. Finally, some of the challenges introduced with the DC technology will also be explored. These include: high short-circuit currents, DC protection concept and expensive and possibly non-profitable energy storage system solutions.

Keywords: ship; DC grid; electric power system; dynamic positioning; specific fuel oil consumption

1. Introduction

The first commercial use of electricity on board ships begins in 1880 on the SS Columbia for powering lighting circuits, then it moves on with hybrid propulsion systems with steam turbines and diesel engines and finally transitions to the present with the first fully electric marine vessel powered only by batteries in 2015. In the period 1956-1985, the discovery and rapid advancement of the power semiconductor technology opened a new path for marine vessels, where electric propulsion and standard AC loads were joined in a concept called Integrated Full Electric Propulsion (IFEP).

In January 2015, the world's first battery-driven ferry Ampere was commissioned and is now regularly operated in Norway [1, 2].

In general, the advancements in the power electronic technology steered the development of ships in direction of hybrid AC/DC and full DC power systems. Of course, that opened new challenges of power and voltage stability, harmonic pollution and power quality in marine vessel power systems. The role of energy storage systems, inclusion of renewable energy sources (RES) and the emission free operation are especially important in the design of modern ship power systems.

Generally speaking, the electrical load of today's vessels is constantly increasing. The propulsion systems and auxiliary loads, such as hotel and service loads in cruise vessels, and DP (Dynamic Positioning) systems for subsea operations, are all powered by electrical energy. The electrical power system must promptly respond to any change in vessel's operation, it must be reliable and should have a high level of survivability. From an economical point of view, fuel consumption must be efficient, since it directly translates to the minimisation of fuel costs and emission of air pollutants. The International Maritime Organization's (IMO) MARPOL air pollution regulations serve as a tool for keeping those emissions minimal, and all ship owners must comply with them.

2. Basic principle and configuration of a DC ship power system

Ship's DC grid can be observed as an extension of multiple DC-links which are an integral part of frequency converters in propulsion and thruster drives of IFEP vessels. Since those drives make up for more than 80% of the electrical power consumption on electric propulsion vessels, the idea was to unite all DC-links in a common DC bus. This new concept keeps most of the very well-known components like AC generators, inverter modules, AC motors, etc., but the main AC switchboard and propulsion transformers are left out [3].

In an AC grid, a frequency converter consisting of a rectifier and an inverter is used to control the speed of an induction or a synchronous motor (AC/DC/AC frequency conversion). The AC voltage is first converted to DC in the rectifier and then inverted back to AC. In the case of a DC grid, at the motor side only the inverter is needed, while the rectifier is then relocated at the synchronous generator output. This means that irrespective of the distribution system, both of these power electronic devices are needed, but the location of the rectifiers has changed in the DC concept. Although propulsion transformers are omitted, the HV/LV transformers are kept for low voltage networks and are fed via inverters located on a common DC bus. Alternatively, LVAC could be obtained from DC by means of a dedicated high power step-down DC-DC converter followed by an inverter. Yet, there is a certain lack of technologies that make this choice difficult at the time, especially considering the large voltage ratio resulting in the need for standard transformers to be used for galvanic isolation. This basically means that other AC loads (e.g. "hotel load") which require constant frequency (60 Hz) and low voltage in the ship are usually supplied by the power transformer. As a consequence, the DC system will require two inverters more than the AC system.

The power transformers are heavier than DC/DC converters, but have a greater efficiency (> 98 %), require less maintenance and their price range is much lower. Also, their inductance improves the electric power quality and suppresses the high order harmonics.

There are several ways of configuring a DC ship power network. In **Figure 1,** the typical AC IFEP system is displayed, which will serve as the basis for later comparison. The generators are connected on MV[1] Switchboards and the energy is transformed via MV/LV transformers to the LV consumers. Electromotive drives used for the propulsion are fed via propulsion transformers and variable frequency drives (VFDs).

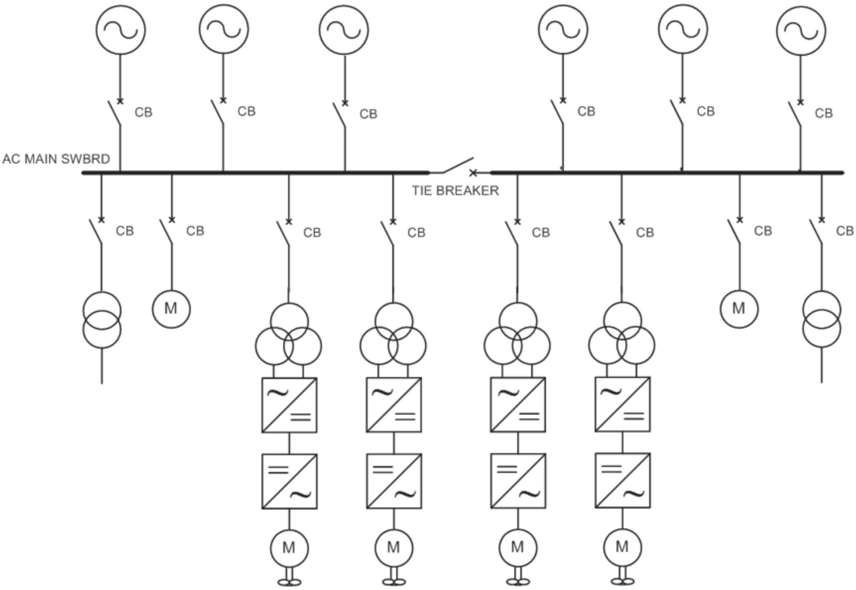

Figure 1 The typical AC IFEP configuration

The concept of Onboard DC Grid has two configurations. The first is a multidrive approach (**Figure 2**) and the second one is a fully distributed system (**Figure 3**) [4].

In a multidrive configuration, all converter modules are located within the same space layout which was occupied by the omitted main AC switchboard. That simply means that the power cables from generators to the DC bus carry AC current, and the same applies to power cables from DC bus to the AC consumers.

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[1] In the maritime industry, voltage > 1000 V is referred to as High Voltage, and on land based systems, voltage > 1000 V is considered as Medium Voltage. On board vessels HV and MV have the same meaning, since voltages over 20 kV are not present on ships.

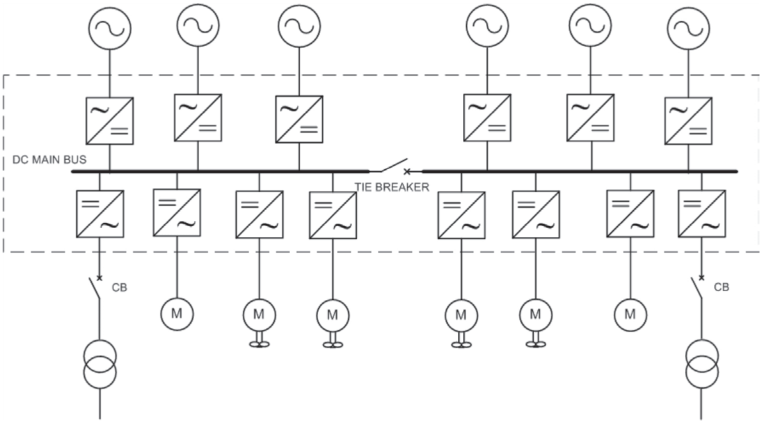

Figure 2 Onboard DC grid – Multidrive power system scheme

In the distributed configuration, each converter component is located as near as possible to the respective power source or load. In other words, each production unit has the possibility of an integrated rectifier mounted either directly on the unit itself or alternatively in a separate cabinet close by. Consequently, power cables carry DC current from generators' rectifiers to the DC bus. Also, the inverters are located near AC loads (mounted or in a separate cabinet close by) and power cables carry DC current from the DC bus to the AC consumers' inverters.

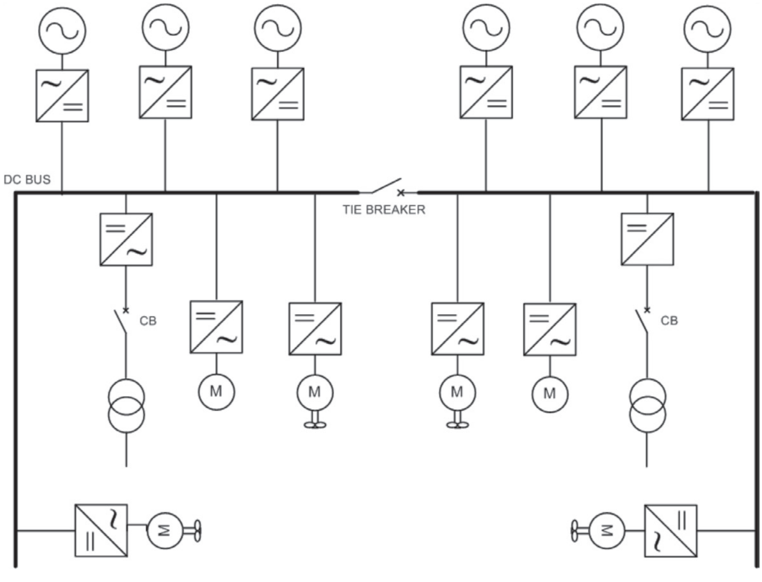

Figure 3 Onboard DC grid – Distributed power system scheme

As said above, irrespective of the DC network configuration, electrical elements like the main AC switchboard and all thruster transformers are omitted in the new concept. Instead, voltages and currents of all the generators are rectified and the active power is sent into a common DC bus. That DC bus distributes the electrical energy towards the main consumers, and each of them is fed by a separate inverter unit. As a result, the volume of components that must be installed in the main switchboard room is drastically reduced, since there are no AC circuit breakers and their respective relays.

The DC design enables upgrading of the system with energy storage or renewable energy sources (like photovoltaic panels), which can now be connected directly to the grid or via DC/DC converters.

The main benefits of this approach are space and weight savings and flexibility of placement of electrical equipment. This significantly provides more cargo space and enables a more functional vessel layout, where the electrical system is designed around vessel's functions and not vice-versa.

3. Benefits of using a DC ship power system

One of the reasons why the AC system has prevailed over the DC one lies in the use of a transformer, which can shift the voltage level up or down (but not the frequency), depending on the ratio of primary and secondary coil turns. DC systems required rotating devices to accomplish the same task, and that was uneconomical and also unreliable from the maintenance point of view [5]. However, beginning from the mid-20th century, rapid development of modern power electronics is today paving the road to DC ship power systems for the following reasons:

- Improvement of prime mover efficiency and reduction of fuel costs,
- Weight and space savings,
- Generators operating with a unity power factor,
- Lower transmission losses,
- Faster and simpler parallel connection of generators,
- Simpler implementation of energy storage.

3.1. Improvement in the prime mover efficiency and reduction of fuel costs

In AC power systems, prime movers are connected to fixed speed generators in order to maintain the designated power system frequency (50/60 Hz) within allowable limits. Since the prime movers' speeds are fixed due to frequency control, the loading of each prime mover determines its fuel efficiency in terms of amount of fuel per delivered amount of useful energy - Specific Fuel Oil Consumption (SFOC) in g/kWh. In case a large consumer connects to the system and the online prime movers are not able to meet this increased load demand, vessel's PMS (Power Management System) will first shed non-essential loads (preference trip). In case available power is still low, PMS will order the idle prime movers to spin up, and after synchronization it will connect them to the power system. In that case, after (usually equal) load sharing between the generators, the situation where prime movers are running at low (non-optimal) loading conditions can occur. This is often the case with shipboard AC power systems.

There is another problem that regularly arises in vessels for DP (Dynamic Positioning) operations. Almost all classification societies impose strict regulations for redundancy in order to avoid total loss of DP vessels' manoeuvrability. The International Marine Contractors Association (IMCA) states (for an offshore vessel) that if there is a realistic chance of the bus-ties not opening or not opening fast enough then the main switchboard should be split for the work (two-split), and if so the power system must include an independent power system (Power/Energy Management System – PMS/EMS) for each individual split [6]. Furthermore, IMCA and DNV-GL (earlier DNV) have almost the same requirements which are based on risk assessments (Failure Modes and Effect Analysis – FMEA) and fault tolerance (isolation of faults) analysis [7]. The idea is that the DP vessel's power system should be divisible into two or more systems so that in the event of failure of one system, at least the other one will remain operational [8]. However, closed bus-tie DP operations have economical, technical, operational and environmental benefits since the PMS in that way controls more generators and thus can efficiently adjust the total generation to the total consumption. In other words, there will be fewer online generators but they will be more loaded, resulting in lower fuel consumption and pollutant emissions. For that reason, some DP operators run the power system with closed bus-ties for as large periods of operation as possible. On the other hand, a split power system increases the number of less loaded online prime movers, which results in lower efficiency (higher fuel consumption) and increased emissions.

One alternative which does not require closing bus-ties is using a DC ship power system. Since the frequency of the main bus is 0 Hz, the speed of the prime movers does not have to be locked to 50/60 Hz. In this case, the prime movers can run at optimized speed in order to meet the power demand [9]. The grid voltage will be maintained by controlling the generators' excitation current (and consequently the magnetic field), which is similar to the AC systems. Today, almost all energy producers on electric ships are combustion engines, most operating on liquid oil (HFO/MDO), some on gas (mainly from LNG), and some even with Dual Fuel capability (liquid fuel or gas). If these engines are operated at constant speed, the fuel consumption will be lowest at a very small operating window of around 85% of the rated load. However, if the prime movers' speed can be adjusted, this operating window can be extended down to 50% without any fuel consumption increase (**Figure 4**).

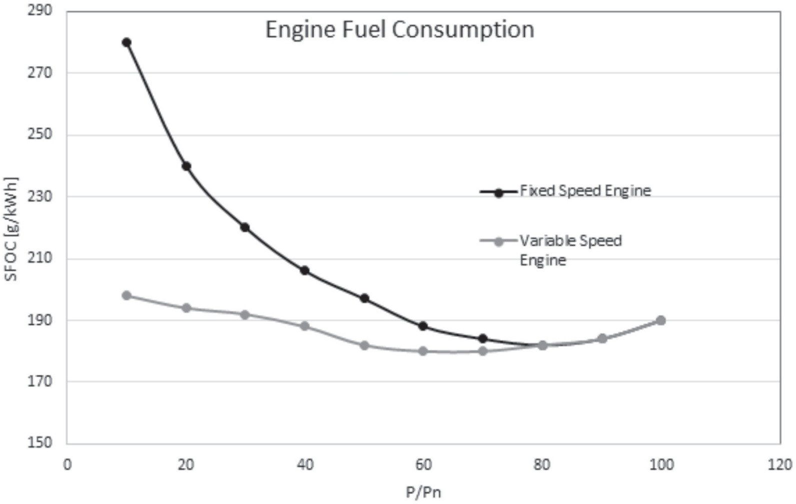

Figure 4 The comparison of Specific Fuel Oil Consumption (SFOC) in respect to the load percentage between fixed and variable speed diesel engine

This can be very beneficial for DP vessels, where the average electric thruster loads are usually low due to low propeller speeds and normal weather conditions, but the number of online generators is higher than really needed because of safety reasons.

This flexibility offers improvements in efficiency on the generation side, but also changes profoundly the overall distribution system on the ship. It offers the possibility to use high-speed generators connected to the DC distribution system through rectifiers, allowing for a reduction in size, as smaller machines with higher rotational speed, lower torque and higher power density can replace the existing 50/60 Hz generators.

3.2. Weight and space savings

As previously stated, in DC systems high-speed gas turbines coupled with high-speed generators can be used, since their speed is not locked to match the 50/60 Hz grid frequency. In AC systems, this type of prime mover has to be used with reduction gears in order to decrease the rotor shaft speed for frequency control, which seriously limits their wider usage on board ships. Since high speed turbo generators weigh less and occupy less space than hydro generators (and do not require the reduction gear), their use in DC systems can seriously contribute to financial savings for the vessel owner.

Also, unlike the AC network which requires three conductors for power transmission, the DC network requires only two of them. Thus, removing one conductor not only saves weight but in addition it saves space for the corridor reserved for power distribution. The alternative to DC cables is the use of DC bus ducts throughout the ship. Although the use of bus ducts is a relatively new type of installation work for many ship yards, there are several benefits that arise from using this concept: reduced cross section, no bending radius and drastic improvement in the fire damage resistance compared to traditional cables.

In the second chapter, it was explained that in a DC system the main AC switchboard together with circuit breakers and relays is left out. Also, propulsion transformers are omitted and in [4] a case study was conducted with the goal to weight the comparison between the DC and the AC system electrical equipment. The results showed that the weight of the installed electrical equipment would be reduced from 115 tonnes for an AC system to 85 tonnes for a DC system with a particularly big reduction in the weight of the propulsion and thruster drives.

3.3. Generators are operating with a unity power factor

In case that diode rectifiers are used for generators' AC to DC voltage/current conversion, than the reactive power flows can be cancelled. That of course means that the cables running from generators' stator coils to the rectifiers will not contain the reactive power. Thus, the generators' operating power factor can be set to unity ($\cos\varphi = 1$). This economically implies that, since the generators do not produce any reactive power, their size can be reduced due to the reduction of the excitation system size [10]. However, even when reduced in size, they will still supply the same active power for the ship's network. In other words, generator's current will be smaller due to the lack of the reactive power transmission, meaning that the cables between the generators and rectifiers can have substantially smaller cross sections. Smaller cross section of stator windings further lowers the generator's size.

However, the cables between the inverters and electric motors will have both active and reactive power flows, since all motors require a magnetic field for transformation of the electrical into mechanical energy. Their reactive power will be supplied via inverters by changing the control signal of semiconductors (IGBT or IGCT) in order to create lagging between the voltage and the current sine wave.

In AC systems, the AVR is used for the voltage and reactive power regulation. But, in a DC system, the AVR will be used not only for the DC bus voltage regulation, but also for load sharing between online generators.

3.4. Lower transmission losses

The DC cable distribution does not experience skin effect problems like the AC transmission, because the frequency of the DC grid is 0 Hz. That, however, does not apply to the parts of the network which carry AC currents. The other benefit is that the DC network does not transport the reactive power and, depending on voltage levels, the weight of cables may decrease for a given power level. In other words, since the generators and the DC network do not transfer the reactive power, their currents are lower and, as a consequence, the Joule losses associated to power cables are also lower. The reactive power and power losses may considerably reduce the energy transportation capability in AC networks. That is the main reason why the HVDC (High Voltage Direct Current) transmission was introduced on land based power systems.

Additionally, cables operated on the DC current do not have any inductive reactance, since it is equal to zero at the frequency of 0 Hz. In an AC system, cable impedance causes a current-dependent voltage drop along the cable or the overhead line. On land based power systems, on transmission networks (≥ 110 kV) the R/X ratio is << 1, which means that the reactive current is responsible for the voltage drop and the ohmic resistance can be neglected. That is why the power electronics controlled reactive compensators (FACTS devices – Flexible Alternating Current Transmission System**)** are used by the ITO (Independent Transmission Operator). On distribution networks (< 110 kV), the R/X ratio is closer to 1, but there is a difference between the Medium Voltage networks (1 kV ≤ Un < 110 kV) where R/X ≈ 1 and Low Voltage networks (< 1 kV) where the ohmic resistance is dominant. That is why the DSO (Distribution System Operator) does not usually use FACTS for power factor control. Instead, every Substation has condenser batteries which are connected to the grid without the power converter interface. When using a DC grid, the voltage drop associated with the cable inductive reactance can be neglected, which is important in designing the electrical system.

3.5. Faster and simpler parallel connection of generators

In AC systems, paralleled power sources must be frequency, voltage and phase matched before connected to the power system (synchronization). In a DC system, the phase and frequency matching is not needed since all rectifiers convert the AC generator voltage to the DC main bus voltage, resulting in a faster power generation response time. However, the voltage regulation via generator's AVR (Automatic Voltage Regulation) is still necessary. Also, as previously mentioned, the AVR's task is not only to regulate the voltage, but also to share active loads between online generators.

The time constants in the speed regulation circuit are much higher than in the voltage regulation circuit, which is beneficial for voltage stability reasons. As already well known, the generator output voltage depends on its speed, number of stator turns, rotor magnetic flux, etc. If the rotor speed drops, than the AVR has to quickly compensate with the DC excitation current (and flux) in order to maintain the output voltage. Due to the lower time constants in the voltage regulation circuit, the speed drop will not affect the generator's output voltage because the AVR will indeed react promptly by increasing the DC excitation current.

Shortening of the synchronization time is a very important feature, and it is of essential importance for conserving the power system stability during heavy load variations in the ship power system [11].

3.6. Simpler implementation of energy storage systems (ESS)

Some of the ESS technologies that are technologically viable today are the Battery Energy Storage System (BESS), flywheels, the Superconducting Magnetic Energy Storage (SMES), the Compressed Air Energy Storage (CAES), the Super Capacitors and Pumped Hydro Storage (PHS), the last one being exclusively used on land power systems. Whether the power system is the AC or the DC one, most ESS technologies will require power converters as an interface to the network for charging and discharging purposes. A broadly used application of an ESS is the Uninterruptible Power Supply (UPS), with batteries serving as a backup power source [12]. This type of application is used on board many vessels and for different types of marine operations.

Most power consumers on board ship do not have a flat load profile. Propulsion systems, while conducting station-keeping, have a load profile which correlates with waves and ocean currents. Weapons systems aboard a naval vessel may give a pulsed load profile at irregular time instants, which would be more or less impossible to predict. Because of the vessel's dynamic load profile, the PMS/EMS must constantly perform calculations of available power and often for safety reasons more prime movers are running than actually needed. One application of the ESS, particularly well suited for a shipboard power system, is the load shaving or peak shaving. By using the ESS to flatten the vessel's total load profile, the PMS would have to perform less operations in terms of starting and stopping the generators. Additionally, fewer prime movers would have to be online to meet a potentially high and instant power demand, resulting in greater fuel savings.

The optimal usage of the ESS would be achieved by charging it under low non-ideal loading conditions, and discharging it while the load demand exceeds the power generation capabilities. In other words, while the system's electric load is light and the ESS (battery pack, for example) is almost empty, the best way to increase fuel efficiency of the online generators is to connect the ESS to the network as a load. In that way, not only does the system efficiency rise, but at the same time the energy is stored for future use. When the power demand almost surpasses the power generation (available power is low) and the ESS (battery pack, for example) is full, the best way to maintain high fuel efficiency of the online generators is to connect the ESS to the network as a power source. In that way, the PMS will not activate another production unit, which would result in lowering the total fuel efficiency of prime movers. Peak shaving is a very interesting feature of the ESS and, apart from fuel efficiency, it contributes to the lower emission of air pollutants due to the need for fewer running gensets [13].

The ESS can be used as a spinning reserve, meaning that during a ship's manoeuvre, where multiple generators must be online in order to compensate possible load variations, using the ESS can lower the number of the online generators. This also cuts fuel costs.

Finally, the ESS can serve as a support to the generators during network transient states. In case of a sudden and large load variation, generators may not react as fast as required by the PMS due to their rotating mass inertia. This power difference can be rapidly compensated by using the ESS, thus eliminating the need for load shedding. With regard to the dynamic positioning, batteries can be used to provide the power for propulsion until the additional main engine is started and accelerated to provide the long-term power for propulsion.

Possibly the biggest ESS advantage is emission free operation. In future, shipboard power systems ESS may be part of a larger green system coupled with renewable sources, whose goal it would be to keep the air pollution in harbours at the minimum. That, of course, depends on the capacity of the ESS which is not yet high and requires often charging. Renewable sources like photovoltaic cells can be connected to the vessel DC system and can store their excess power to the batteries. In any case, using the ESS lowers the emission of CO_x, SO_x and NO_x compounds and the acoustic signature of the engine room.

4. The challenges of using a DC ship power system

Standards for DC distribution systems on offshore drilling platforms exist, but according to the DNV these systems are based on the old technology and thus the standards are not applicable to the upcoming DC distribution systems. Consequently, there are no standards regarding a DC distribution system on board ships and thus no given limits. The main reason for this is that the emerging solutions from Siemens, ABB, and other manufacturers all have different approaches using different technologies and solutions both between each other and compared to previous installations. The lack of standardised systems and components makes definite limits regarding voltage variations, THD etc almost impossible to obtain.

In any case, the DC power distribution is not yet a standard solution regulated by the classification societies, and before it does become one, there are some challenges that need to be addressed:

- High short-circuit currents
- DC protection concept
- Expensive and possibly non-profitable energy storage system solutions

4.1. High short-circuit currents

A positive side of using an AC power system with reactive power flows is that the impedance of the cable (inductive reactance) automatically limits the short circuit currents, which have a dominant influence on the selection of power system elements. In AC systems, cable impedance consists of ohmic resistance and inductive reactance, and the latter of course is not the case in DC networks. In DC systems, only the (very low) ohmic resistance of the cables limits the short-circuit currents, and for that reason all parts of the power system are equally effected by a short-circuit at an arbitrary position

[14]. A switchboard that can withstand a 24 kA short circuit current (for a predefined period) weighs and costs less than a switchboard that can withstand 50 kA. This effect combined with the fact that the DC current does not have a natural zero-crossing, results in a situation where it is hard to break a connection (bus-tie/circuit breaker) or even limit the DC current, which may endanger the power equipment.

4.2. The DC protection coordination

The main traditional challenges with the DC distribution have addressed in general the achievement of full selectivity and equipment protection in a way similar to the one for the AC distribution. AC currents are by nature far simpler to break because of their natural zero crossing every half cycle. DC circuit breakers do exists to some extent but are more complex, larger and more expensive than the comparable AC circuit breakers. The DC grid protection faces serious challenges in comparison with the AC system which effectively uses its main switchboard with AC circuit breakers and protection relays.

The idea concerning the DC system is to ensure selectivity and equipment protection while at the same time minimizing the use of expensive and space consuming DC circuit breakers, although they can be used as tie-breakers for the connection of DC main bus sections. Proper protection of the DC Grid can be achieved by a combination of fuses and controlled turn-off semiconductor power devices. If the energy producing units' rectifiers are equipped with controllable switching devices, the fault currents can be blocked much faster than it is possible with traditional circuit breakers with associated protection relays. Fuses can be used to protect and isolate inverter modules in case of serious module faults. This is no different with today's frequency converters. In the event of severe faults on the DC bus, the system is protected from the generator's short-circuit current by means of controllable turn-off semiconductors in the rectifier, which also doubles as a protection device for the generator.

By using a combination of fuses and fully controllable converters, in [15] it is claimed that any fault current can be cleared within maximum 40 ms. This results in a drastic reduction in the DC Grid fault energy levels as compared with traditional AC protection circuits where fault durations can reach up to 1 s. These low energy fault protection schemes enable the DC system to be used for the installed power up to at least 20 MW.

4.3. Expensive and possibly non-profitable energy storage system solutions

Even though using the ESS in shipboard power systems has many advantages, there are some unsolved challenges that have yet to be addressed. Many of the available ESS technologies are actually very expensive solutions with a limited capacity. As for the BESS, the available battery technology may be a problem, since the battery packs are heavy (relative to power capacity) and in many cases have a large footprint. Another exceptionally important issue is the battery packs' lifetime. Rapid charging and discharging of the battery is widely used on land power systems as a standard service provided by charging stations for electrical vehicles. But rapid charging generates a lot of heat and draws a lot of power, which makes it much more expensive and less efficient than slow charging. Also, rapid charging and discharging has a critical effect on the battery's life [16]. Thus, a possible realistic outcome of using the BESS on board ships is the battery pack death occurring before the installation costs are paid back by the reduced fuel consumption. In some applications, supercapacitors or fuel cells can switch places with the battery pack, improving the energy storage system properties such as the increased lifetime, charge/discharge speed, energy density relative to footprint and weight, etc. Hybrid energy storage systems, including different types of energy storage devices, may also be an interesting possibility, thus increasing applications and the system flexibility.

5. Conclusion

It is already obvious that more and more equipment on board ships is of an electrical type, and the future of maritime industry is moving towards an All-Electric Ship (AES). The proof is in the fact that the shipboard electrical power demand continues to increase and in some cases it even exceeds 100 MW. The concept of the Medium Voltage DC grid is also being explored (MVDC) for marine applications [17, 18] and this implies that the research and development of power systems will continue at a fast pace to accommodate the ever increasing electric demand.

Even though the DC concept has many benefits which were explained in this paper, this new technology introduces challenges that must be quickly addressed and solved. It is already certain that for some vessels with characteristic operational profiles the DC systems will not be an optimal solution anytime soon. On other vessel types, the transition from the AC to DC will move gradually via hybrid solutions, which will simultaneously contain an AC main bus and a DC main bus, each with its associated type of load. Finally, some vessels which require a DC system are already either in service, or in the commissioning phase or in a design phase.

The choice between the AC or DC ship power system will be strongly dependent on available technology and different components developed by different manufacturers. Advancements in the energy storage technology and the DC circuit breaker technology may tip the scales in favour of DC systems, but that remains yet to be seen. Finally, the benefits and challenges described in this paper, along with the fact that only the most feasible solutions will be chosen, will determine whether a DC marine power system is only a trend or a permanent solution.

References

1. E. Skjong, R. Volden, E. Rødskar, M. Molinas, T. A. Johansen, and J. Cunningham, "Past, Present and Future Challenges of the Marine Vessel's Electrical Power System", IEEE Transactions On Transportation Electrification, vol. PP, issue: 99, Apr 2016
2. E. Skjong, E. Rødskar, M. Molinas, T. Johansen, and J. Cunningham, "The Marine Vessel's Electrical Power System: From its Birth to Present Day," Proceedings of the IEEE, vol. 103, no. 12, pp. 2410–2424, Dec 2015
3. ABB, "Onboard DC Grid. The step forward in Power Generation and Propulsion," 2011. [Online]. Available: http://www04.abb.com/global/seitp/seitp202.nsf/0/292d42e87306453dc12579ad0050a457/$file/12_10_OnboardDCGrid_Technical-Information.pdf.
4. J. F. Hansen, J. O. Lindtjørn, U.U. Ødegaard, T.A. Myklebust; Increased operational performance of OSVs by Onboard DC Grid; 4th International Conference on Technology and Operation of Offshore Support Vessels; Singapore August 2011
5. M. Patel, "Shipboard Electrical Power Systems", ser. Shipboard Electrical Power Systems. Taylor & Francis, 2011
6. IMCA, http://www.imca-int.com/
7. DNV-GL, https://www.dnvgl.com/
8. IMO, http://www.imo.org/.
9. B. Zahedi and L.E. Norum, "Efficiency analysis of shipboard DC power systems," in Proc. of IECON 2013, pp. 689-694.
10. N. H. Doerry and D. H. Clayton, "Shipboard electrical power quality of service," in Electric Ship Technologies Symposium, 2005 IEEE. IEEE, 2005, pp. 274–279.
11. G. Reed, B. Grainger, A. Sparacino, and Z.-H. Mao, "Ship to grid: Medium-voltage DC concepts in theory and practice," IEEE Power and Energy Magazine, vol. 10, no. 6, pp. 70–79, Nov 2012
12. S. Kim, S. Choe, S. Ko, and S. Sul, "A naval integrated power system with a battery energy storage system: Fuel efficiency, reliability, and quality of power." IEEE Electrification Magazine, vol. 3, no. 2, pp. 22–33, June 2015
13. A. Oudalov, R. Cherkaoui, and A. Beguin, "Sizing and optimal operation of battery energy storage system for peak shaving application," in IEEE Lausanne Power Tech, 2007, July 2007, pp. 621–625.44
14. M. Baran and N. Mahajan, "DC distribution for industrial systems: opportunities and challenges," IEEE Trans. Ind. Appl., vol. 39, no. 6, pp. 1596–1601, Nov 2003
15. J. F. Hansen, J. O. Lindtjørn, and K. Vanska, "Onboard DC grid for enhanced DP operations in ships," in Proc. of MTS Dynamic Positioning Conf., 2011, pp. 1-8.
16. Z. Zhou, M. Benbouzid, J. F. Charpentier, F. Scuiller, and T. Tang, "A review of energy storage technologies for marine current energy systems," Renewable and Sustainable Energy Reviews, vol. 18, pp. 390–400, 2013
17. U. Javaid, D. Dujić and W. van der Merwe,"MVDC Marine Electrical Distribution: Are we ready?", Industrial Electronics Society, IECON 2015 - 41st Annual Conference of the IEEE
18. A. Tessarolo, S. Castellan, R. Menis, and G. Sulligoi, "Electric generation technologies for all-electric ships with Medium-Voltage DC power distribution systems," in Electric Ship Tech. Symp. (ESTS), 2013, pp. 275-281.

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Prednosti korištenja DC brodskog elektroenergetskog sustava

Sažetak

Ovaj je članak strukturiran na način da prezentira prednosti i mane korištenja DC brodskog elektroenergetskog sustava. DC električni sustav nije novost i originalno je korišten za napajanje električnih krugova rasvjete na brodovima krajem 19-tog stoljeća. Ali s vremenom je napušten i zamijenjen sa AC elektroenergetskim sustavom, koji se danas koristi širom svijeta (za potrebe kopnenih i brodskih elektroenergetskih sustava). Međutim, ponajviše zbog naglog razvitka poluvodičke tehnologije, danas se DC sustavi sve više koriste na kopnu (HVDC prijenos) i na brodovima. U usporedbi sa AC sustavom, DC ima brojnih prednosti poput redukcije potrošnje goriva, smanjenja težine elektroenergetskih komponenti i redukcije gubitaka energije. Ovaj članak će detaljnije prikazati navedene prednosti, ali će istražiti i mane koje donosi DC tehnologija.

Ključne riječi: DC brodski elektroenergetski sustav; redukcija potrošnje goriva; težina elektroenergetskih komponenti; zaštita elektroenergetskog sustava; kvaliteta opskrbe električnom energijom