PROTECTION COORDINATION IN DC SHIPBOARD POWER SYSTEMS: CHALLENGES, CURRENT STATUS AND NEW TECHNOLOGIES

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ABSTRACT

In the maritime domain, the efforts to reduce the emission of greenhouse gases move industry towards highly efficient vessels with DC distribution technologies. These new power systems, however, come with technical challenges in protection coordination which is necessary to minimise the impact of the system fault. This paper presents benefits and protection difficulties of DC shipboard power systems, and current protection schemes, commercially available, with three different classification: bus protection with solid-state bus-tie breakers, feeder protection with high-speed fuses and generator-rectifier fault blocking functions. In addition, two new protection methods recently proposed are introduced: additional bus capacitance for the bus protection and artificial short-circuit for the generator-rectifier protection. Lastly, possibility of a modular multi-level converter for the DC shipboard power systems is discussed with its pros and cons.

INTRODUCTION

The maritime sector is a major contributor to global warming and environmental pollution. In order to reduce the environmental impact associated with shipping, IMO (International Maritime Organization) adopted mandatory regulations on energy efficiency for ships, e.g., EEDI (Energy Efficiency Design Index) and SEEMP (Ship Energy Efficiency Management Plan) [1]. According to EEDI, by 2025, all new ships have to consume 30 percent less energy than those built in 2004.

The shipboard power system (SPS) is an off-grid stand-alone system which allows for the flexibility to employ new

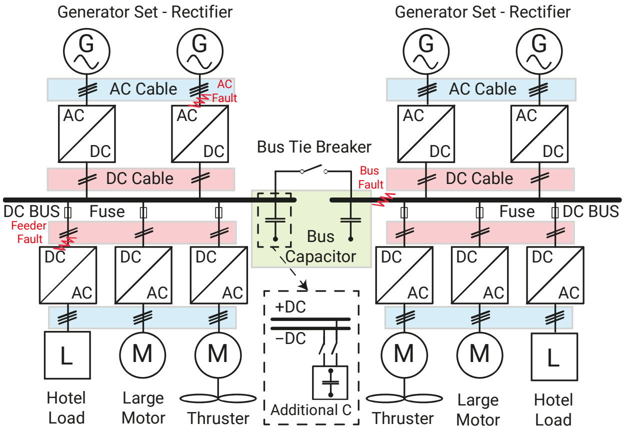


Fig. 1: Simplified schematic of DC SPS. Additional bus capacitor introduced in this paper is also illustrated.

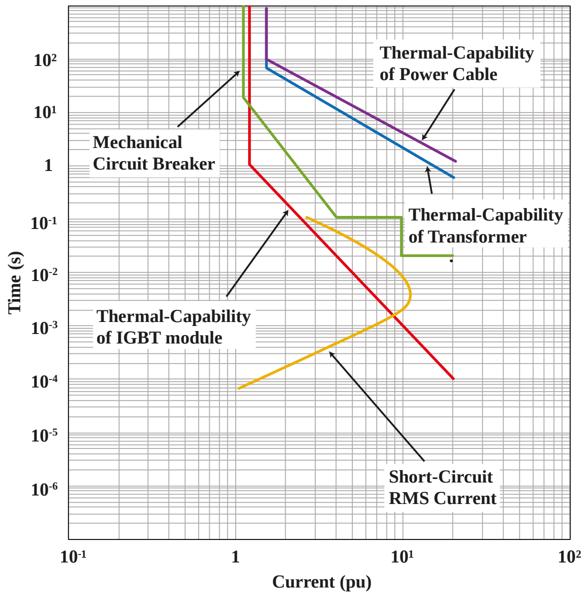


Fig. 2: Time-current characteristics of IGBT module, transformer, power cable and mechanical circuit breaker against short-circuit current.

concepts of power systems if the new technologies fulfil ship's mission. With this flexibility, in 2011, DC distribution systems shown in Fig. 1 were introduced [2] as a promising solution for dynamic positioning (DP) vessels and have commercially been applied to these vessels with power levels up to 20 MW and voltage levels of around 1 kV. This is because the DC solution is a feasible way to comply with the energy efficient regulations with its advantages in the marine applications: fuel savings with variable-speed engines, running engine optimisation by the closed-bus operation during the DP mode, weight/footprint reduction in electrical installation and easy integration of energy storage systems.

These new power systems, however, also carry with technical challenges in protection coordination which is necessary to minimise the impact of the system fault. First of all, power converters, which are core components in DC distribution systems, have very low-thermal capability. Whilst power transformers and cables can sustain fault currents for several seconds, the fault in the DC distribution systems has to be cleared within several milliseconds to several tens of milliseconds for preventing converter failures, as shown in Fig. 2 [3]. In addition, there is no zero-crossing of DC fault currents. This makes the development of fast DC circuit breakers difficult and costly compared to that of AC circuit breakers.

In order to take the benefits of the DC distribution systems, several protection schemes for the DC SPS were introduced and a method of three-level protection [2], [4] has been accepted more and more for the low-voltage marine applications. But, the protection coordination for the DC SPS is still an early stage technology. There are technological gaps to be filled and no well-defined standards. In addition, there can be innovative ways having better performances and other solutions for different SPS configurations.

This paper presents the three-level protection with technical descriptions. Moreover, new technologies on the protection coordination to improve or fill technological gaps are discussed with their operational principles: additional bus capacitance to improve protection selectivity and sensitivity of the feeder protection by the high-speed fuses, and artificial short-circuit to effectively block the fault current for active rectifiers. Lastly, advantages and disadvantages of a modular multi-level converters (MMC) are discussed as a future source-side converter for medium-voltage marine applications.

CURRENT PROTECTION SCHEMES

Protection schemes which are adopted for the commercial DP vessels are based on the three-level protection in common [2], [4]: first level (fast action) – bus protection with solid-state technologies (the bus-tie breaker in Fig. 1), second level (medium action) – feeder protection with fuse technologies (the fuses in Fig. 1) and third level – generator-rectifier fault blocking functions. The time coordination between the protection methods are provided by different time frames as depicted in Fig. 3. Note that zonal protection schemes [5] which are well-known methods for ring bus configuration-based military applications are not considered in this paper.

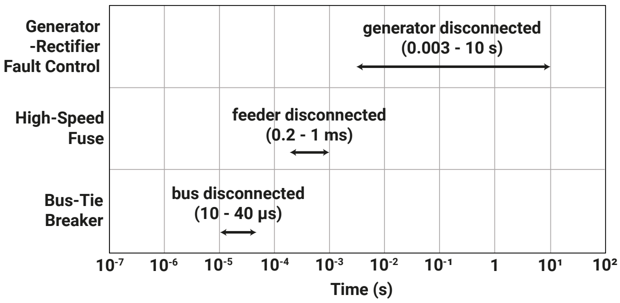
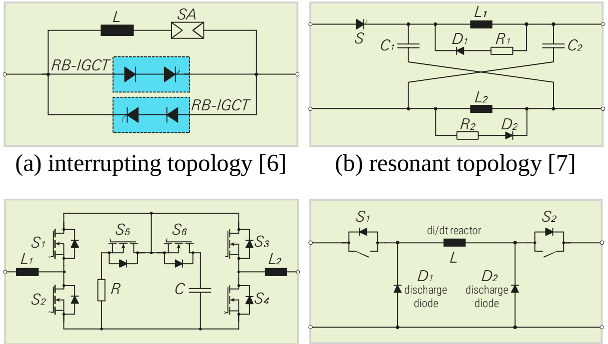


Fig. 3: Time frames of three-level protection method.

Bus protection with solid-state bus-tie breakers

As aforementioned, the bus protection is the fastest operation, and allows for minimising the impact from system faults by isolating the healthy buses from the fault. By using the solid-state technologies, the bus-tie breakers can interrupt the fault within several tens of microseconds, and then the voltage at the healthy part is ramped up to be back to normal. There are several topologies proposed for the DC distribution systems: interrupting, limiting, resistive and resonant topologies, as shown in Fig. 4.



(a) interrupting topology [6] (b) resonant topology [7]

(c) resistive topology [8] (d) limiting topology [9]

Fig. 4. Solid-state bus-tie breakers for DC distribution systems.

They 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.

Feeder protection with high-speed fuses

After the bus isolation, the faulty feeder has to be disconnected from other healthy feeders in the same bus. With the benefit in cost, the high-speed fuses are widely applied for the feeder protection in the DC SPS, and provide the fault clearing performance within a short time. During a millisecond range of the feeder protection (Fig. 3), the fault energy is mainly contributed by the system capacitance in the DC networks which has much faster response than the AC generators.

In order to achieve the safe operation of the fuse, the DC SPS should have sufficiently high energy installed in DC bus capacitances which can melt the fuse elements within a given time. But, this is not always under control of system designers because it is dependent on commercial rectifiers designed by manufacturers. Furthermore, two technical aspects in the system protection, selectivity and sensitivity, should be considered for the fuse selection. It means that the fuse on the faulty feeder clears the fault not only without the pre-arcing of other fuses on the healthy feeders, but also under any system conditions like the maximum and minimum loading conditions. One approach to achieve the protection selectivity and sensitivity by use of additional bus capacitance will be described in the section of new protection methods.

Generator-rectifier fault blocking functions

For the primary electrical power source, power generation systems of the DC SPS consist of synchronous generators (driven by diesel engines) and source-side converters (e.g., diode, thyristor and active rectifiers). For the main bus fault and the feeder protection failure, the fault current contribution from the power generation systems has to be blocked by the generator itself or the rectifier.

Diode rectifier

The protection method for the diode rectifier described in [4], [9] is composed of high subtransient reactance and excitation removal of the synchronous generator. When the fault clearance time of the DC fault (milliseconds range) is considered, the magnitude of the fault current, i_{DC}, is mainly governed by the subtransient reactance, X_d'', and can be calculated by (in case of the six-pulse diode rectifier):

$$i_{DC} = \frac{3\sqrt{2}}{\pi} \frac{V_{LN}}{\sqrt{R_S^2 + \left(X_d'' + X_f\right)^2}}$$

where, V_{LN} is the RMS value of line-to-ground AC voltage, R_S is the source resistance, and X_f is the AC-side reactance. In other words, the fault energy contributed by the generator is significantly decreased with the increased subtransient reactance.

The fault current is completely eliminated by the excitation removal function of a generator protection unit. A direct (or static) excitation system including a thyristor rectifier inside the system can immediately remove the excitation, but it has some issues like frequent maintenance, carbon dust and firing harzards. The brushless excitation system, on the other hand, has slow discharging characteristics of the flux linkage in the field winding. In order to rapidly discharge the flux linkage, the damping circuit is additionally necessary in the brushless excitation system.

Thyristor rectifier

The thyristor rectifier can handle the DC fault by adjusting the DC link voltage with the firing angle control. During the normal state, the firing angle is maintained with 0 degree to operate it as the diode rectifier or below 30 degree to regulate the DC voltage. Once the fault is detected, a controller of the rectifier forces the angle into 110-120 degrees to extinguish the fault current by reversing the DC voltage polarity, called fold-back protection control [10].

Fig. 5 shows an example of the fold-back protection control. The fault at 10 second results in a significant increase in the DC current and a decrease in the DC voltage. After the delay with 1 millisecond to coordinate the feeder protection and to decide the fault occurrence, the fault blocking function is activated at 10.001 second (the firing angle is changed from 9 degree to 120 degree at that time), and then the fault current is finally limited due to the reversed DC voltage.

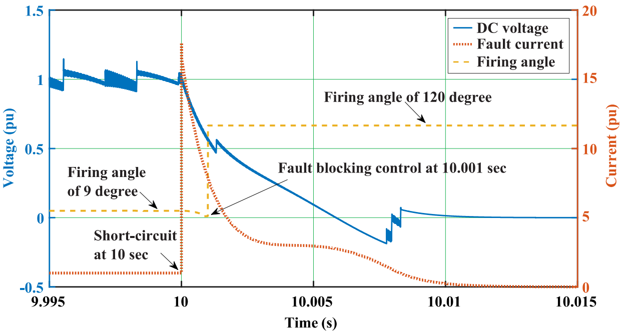


Fig. 5. Fold-back protection control of thyristor rectifier. The voltage shown is the terminal voltage of the rectifier before the LC filter (right after the six-pulse thyristors).

With this function, the source-side converter based on the thyristor has a competitive advantage in the system protection than the diode and active rectifiers, and it allows for establishing "breaker-less" DC distribution systems.

NEW PROTECTION METHODS

There are recent research activities to develop more reliable protection schemes and to fill the technology gaps which are still needed to be examined. Apart from the above protection technologies, two new protection methods are introduced with their operation principles: additional bus capacitance [11] and artificial short-circuit [12].

Additional bus capacitance

To achieve the protection selectivity and sensitivity with one specific fuse is a challenging issue. This is due to different fault energies under different fault locations and loading conditions. For example, in Fig. 6(a), the fault at the large motor should be cleared by the fault currents from the two rectifiers, the thruster motor and the hotel load under the operation mode 1 (OM1, the maximum loading condition). In this case, the pre-arcing of other fuses on the healthy feeders has not to be started before the total clearing of the fuse on the faulty feeder to achieve the protection selectivity. On the other hand, the fuse on the faulty feeder should be melt by the fault current under the

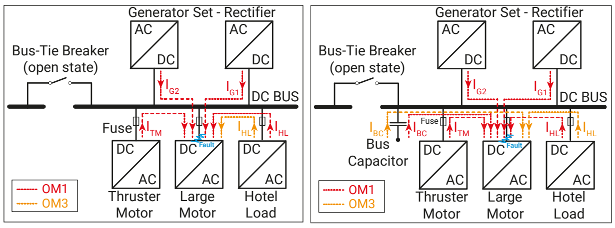


Fig. 6. Fault current flows depending on ship operation modes: (a) without (w/o) and (b) with (w/) additional bus capacitance.

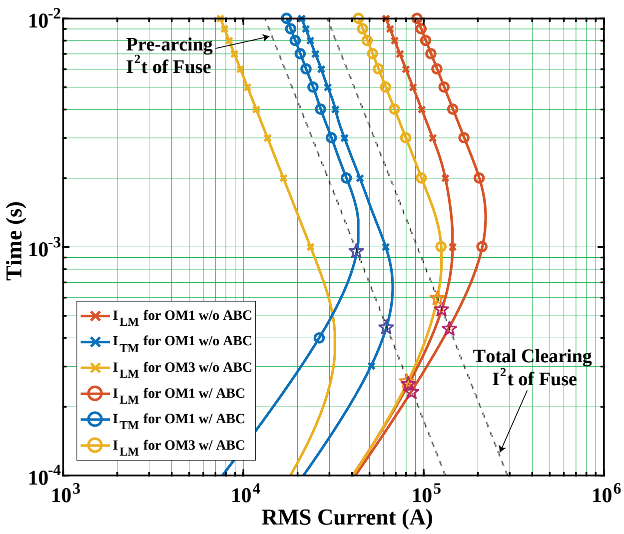
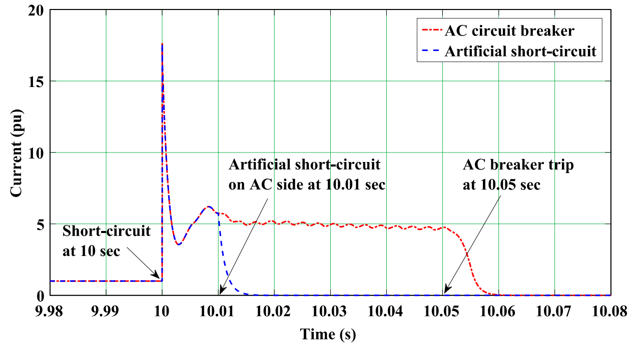


Fig. 7. Selectivity and sensitivity analysis without (w/o) and with (w/) additional bus capacitance (ABC in figure).

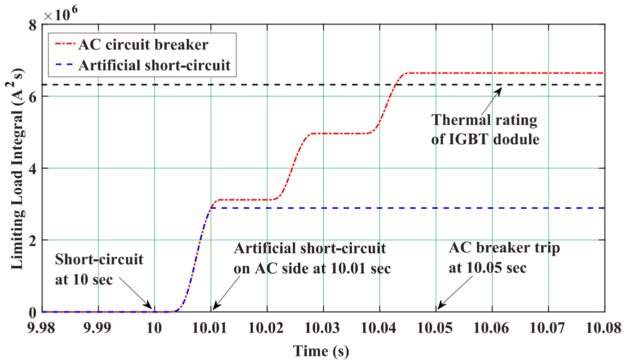
operation mode 1 as well as the operation mode 3 (OM3, the minimum loading condition) which is related to the protection sensitivity. But, during the OM3, the fault energy only provided by the hotel load might not be enough to blow up the fuse. A new method proposed in [11] provides a feasible solution for these technical difficulties by employing the additional bus capacitance into DC buses (the bus capacitor in Fig 1). The additional bus capacitance directly contributes the additional energy to the fuse on the faulty feeder, and it helps to achieve the protection selectivity and sensitivity, as illustrated in Fig. 7. Without the additional bus capacitance in Fig. 7 (cross makers), the fault current (a blue line with cross makers) passing through the fuse on the thruster motor (healthy feeder) starts to melt the fuse (pre-arcing) before the total clearing of the fuse on the large motor (faulty feeder). Moreover, the protection selectivity is not available under OM1 (a red line with cross makers) and OM3 (a yellow line with cross makers) loading conditions. By employing the additional bus capacitance (circle markers), the protection selectivity and sensitivity can be achieved.

Artificial short-circuit

For the low-voltage marine applications, the active rectifier has a disadvantage in the thermal capability because it is based on IGBT modules which have lower short-circuit withstand capability than press-packed diodes and thyristors. In addition, the fault current passing through the active rectifier has to be blocked by external protection devices due to lack of a fault blocking function. In order to overcome the drawbacks of the active rectifier, the artificial short-circuit method is proposed in [12], and it can interrupt the fault current passing through the rectifier by developing artificial low-impedance path between the source and the rectifier, as shown in Fig. 8. It means the methods can change the fault current flow from the green-dotted lines to the orange-dotted lines in Fig. 8. Finally, the AC circuit breaker disconnects the generator from the artificial short-circuit. The operation time of the artificial short-circuit is dependent on the devices, e.g., a high-speed mechanical earthing switch – 4 ms [13] and a semiconductor switch based on thyristor – below 1 ms.
The short-circuit analysis with the high-speed mechanical earthing switch is provided in Fig. 9, and the proposed method is compared with the conventional AC circuit breaker solution. The artificial short-circuit on the AC-side is generated at 10 ms after the fault, and then it limits the fault contribution from the source to the fault. On the other hand, the AC breaker could interrupt the fault current with 50 ms (the fastest trip time in mechanical). Fig. 9(b) shows that the artificial short-circuit method can handle the fault energy passing through the rectifier under the IGBT thermal rating, while the AC circuit breaker has a slow fault interrupting performance and this is not enough to protect the IGBT module.



(a) short-circuit currents for the two protection methods



(b) short-circuit energies for the two protection methods

Fig. 9. Short-circuit analysis with thermal capability comparison.

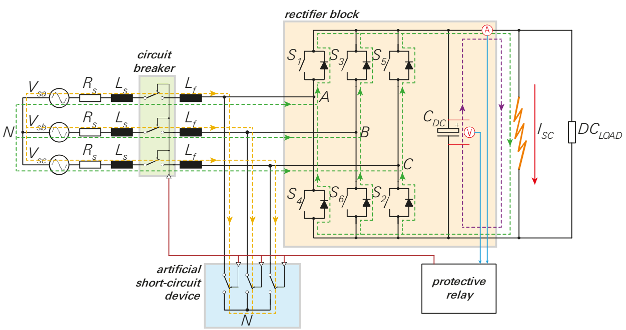


Fig. 8. Schematic diagram of artificial short-circuit method.

MODULAR MULTI-LEVEL CONVERTERS

The MMC has increasingly become more popular because of its high controllability and dynamics in high-voltage applications. With the same reason, this is also considered as a promising candidate of the source-side converter for the medium-voltage marine applications [14]-[16].

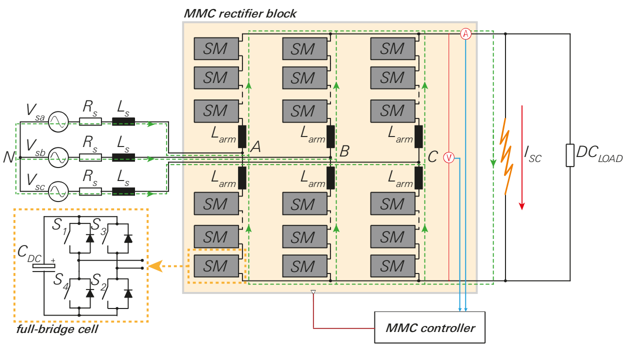


Fig. 10. Schematic diagram of DC short-circuit in MMC.

There are two types of the MMC: half-bridge (HF-MMC) and full-bridge (FB-MMC, Fig. 10). Differently with the HF-MMC, the FB-MMC consists of four IGBT modules and a capacitor in one cell, and this cell allows for adjusting the cell voltage of zero, positive and negative depending on switch states [17]. With this capability, the FB-MMC can be operated with reduced DC voltage as well as positive or negative DC voltage. This implies that the FB-MMC can rapidly extinguish the fault current with the reversed DC voltage. Otherwise, this is not available by the HF-MMC.

As above mentioned, the FB-MMC has attractive functions, especially the fault management function. However, this converter needs twice more semiconductors as the HB-MMC requires. When the FB-MMC is compared with other source-side converters, it shows much lower competitiveness in cost and switching losses. Therefore, it is expected that the FB-MMC solution is suitable for the medium-voltage high-power marine applications in which high reliability against faults is very important and DC circuit breakers are not available or extremely expensive.

CONCLUSION

This paper has presented and discussed the benefits and the challenges of the DC SPS as well as the current and new technologies on the protection coordination for this application. The three level protection has successfully been applied for the commercial DC-based DP vessels. But, there are still technological gaps like a way to achieve the protection selectivity and sensitivity for the feeder protection with the high-speed fuses and a method to limit the fault current through the active rectifier. The new methods, the additional bus capacitance and the artificial short-circuit, have been introduced in this paper, and they can be considered as promising protection methods because both the methods are easy to implement and require only simple devices (relatively cheap), the additional bus capacitor and the artificial short-circuit device. Moreover, the FB-MMC is discussed with its pros and cons as the potential source-side converter for the medium-voltage marine application. Although the FB-MMC is not an economical solution than other multi-pulse converters or a half-bridge MMC, its fault management function is enough to consider it to be a future solution.

Several discussions in this paper provides the importance of the DC SPS to comply with the energy regulations and current protection technologies. And also, the discussions help to connect the existing technological gaps and the new technologies recently introduced.

ACKNOWLEDGEMENT

This work has been supported by Hyundai Electric & Energy Systems Co., Ltd., Republic of Korea.

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