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Review

Protection Systems for DC Shipboard Microgrids

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Abstract: In recent years, shipboard microgrids (MGs) have become more flexible, efficient, and reliable. The next generations of future shipboards are required to be equipped with more focuses on energy storage systems to provide all-electric shipboards. Therefore, the shipboards must be very reliable to ensure the operation of all parts of the system. A reliable shipboard MG should be protected from system faults through protection selectivity to minimize the impact of faults and facilitate detection and location of faulty zones with the highest accuracy and speed. It is necessary to have an across-the-board overview of the protection systems in DC shipboards. This paper provides a comprehensive review of the issues and challenges faced in the protection of shipboard MGs. Furthermore, given the different types of components utilized in shipboard MGs, the fault behavior analysis of these components is provided to highlight the requirements for their protection. The protection system of DC shipboards is divided into three sub-systems, namely, fault detection, location, and isolation. Therefore, a comprehensive comparison of different existing fault detection, location, and isolation schemes, from traditional to modern techniques, on shipboard MGs is presented to highlight the advantages and disadvantages of each scheme.

Keywords: shipboard; protection; fault; microgrids

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1. Introduction

The demand for more durable and higher quality shipboard power systems has increased due to the widespread application of power electronic devices, increase in high-power electrical loads, and development of integrated electrical propulsion [1,2]. With the advent of energy storage systems (ESSs) and power electronic converters in the DC Microgrids (MGs), significant developments have been attained to improve the reliability and performance of the electrical systems [3]. A DC shipboard system is a type of DC MG that should be self-reconfiguring, self-healing, and self-diagnosing [4]. The DC voltage zonal MG structure has been proposed as a new electrical system architecture for all-electric shipboards, in which the utilization of power electronic converters is pervasive [5–7]. These converters can widely simplify the system by providing higher efficiency, cutting costs, and requiring a smaller space [8].

One of the main challenges encountered in the designing of DC shipboard MGs is the lack of guidelines, standards, and comprehensive solutions on the implementation of the protection system within such systems [9]. The fault protection system of a DC MG system typically includes fault detection, location, and isolation [10]. The protection system is essential to de-energize the faulty point from the healthy parts of the system and modify the system structure to guarantee that the unnecessary interruptions of the critical loads are avoided. The challenges of fault detection and location in DC shipboard MGs can be compared with terrestrial DC MGs. However, these systems require different protection systems compared to terrestrial DC MGs since the reconfiguration of DC shipboard MGs is highly affected by the criticality of propulsion loads in marine systems and the significant differences in the load profiles. The propulsion loads in these systems are variable and consume approximately 80% of the generation capacity. Therefore, these systems require different protection systems from terrestrial DC MGs [11]. Although some fault protection systems have already been developed for DC MGs [12], the protection systems for DC systems in shipboards are still in the developing stage, given the higher safety requirement and smaller scale.

An overview of protection systems for DC shipboard MGs is presented in Figure 1. As shown in Figure 1, the protection systems include fault detection, location, and isolation. Moreover, due to the recent development of DC shipboards, the fault location and detection methods can be categorized into traditional and modern techniques, which the traditional methods are mainly designed for AC systems. Short-circuit fault in DC systems causes a fast decrease in voltage and an increase in the current [13]. This fast-rise current is injected by discharging of DC-link capacitors, introducing challenges in the design of a suitable fault detection scheme [14]. Due to the very low rise time of the fault current in DC shipboard MGs, the protection system must detect and isolate the faulty section within a very short operation time. Furthermore, this rapid fault current results in difficult coordination of primary and backup protection units [15]. In addition to the fault detection challenges, fault isolation devices face some challenges. The faulty point should be de-energized by using a circuit breaker (CB), fuse, or switch. Due to the lack of zero-crossing point in DC currents, the AC CBs cannot be installed directly in DC systems. Therefore, hybrid CBs and DC CBs are alternatively proposed and developed, but these are still limited by cost and size. During the fault, a large fault current flows through the freewheeling diodes of converters, causing possible damages to them [16]. The withstand threshold of diodes in fault conditions is determined by the thermal limit of diodes, which is defined as I^2t [17].

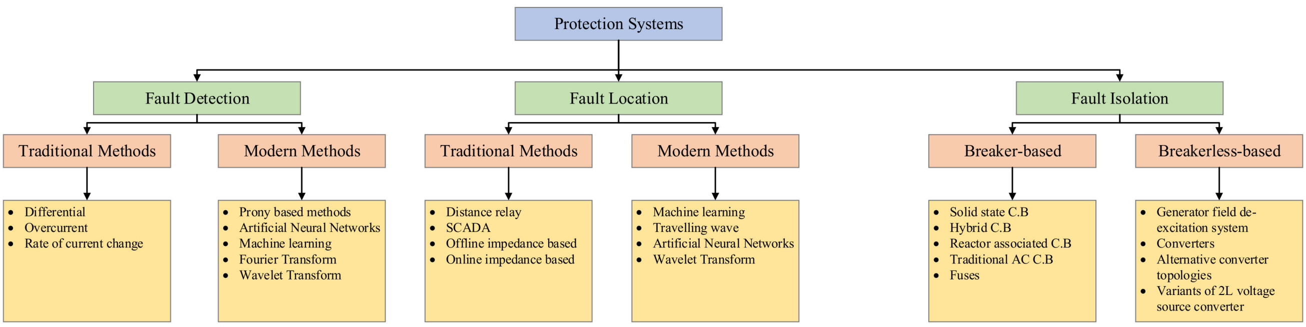

Figure 1. Overview of the protection system of DC shipboard MGs.

The main objective of this paper is to review all protection methods suggested for DC shipboards to understand future challenges and requirements of DC shipboards. This paper includes seven sections. The detailed structure of the DC shipboard and the comparison of protection requirements of DC shipboards and terrestrial DC MGs are covered in Section 2. Section 3 discusses the characteristics of each component during the fault and the challenges and requirements of the protection system in DC shipboard MGs. In Section 4, different types of fault detection methods, including overcurrent, current waveform, distance, and modern schemes, are reviewed. The limitations, advantages, and applications of each protection method are discussed. Section 5 presents and compares different types of fault location approaches, including impedance, converter, and signal processing-based methods. Section 6 introduces and compares different protective devices, including breaker-based and breakerless devices, in terms of their structure, application, and limitations. The conclusions and future potential research are presented in Section 7.

2. DC Shipboard Structure

The DC systems have better performance than AC systems in terms of energy losses, weight, efficiency, reliability, and power quality. Furthermore, they avoid the problems of AC systems caused by frequency and phase angle differences and variations [18]. By utilization of DC structure in shipboards, the classical marine engines can be operated at an optimal operation point for minimization of emission and fuel consumption. Moreover, the DC structure in maritime systems offers easier connections of the produced power of alternative energy resources, such as supercapacitors, fuel cells, and battery banks [19]. The large low-frequency transformers and phase synchronization requirement can be eliminated in DC shipboard MGs [20]. However, there are still some concerns about the reliability and safety of the DC shipboards, particularly on the ESS and converter sides.

The DC power systems widely use power converters, mainly to rectify the output voltage of generators (AC/DC converters), support the AC motors (e.g., pumps, thruster, propulsion motors) input-voltage inversion (inverters), regulate voltage level (DC/DC converters), and interface ESSs and DC buses at different voltage levels (full-bridge DC/DC converters) [21]. Figure 2 represents the application of converters in a DC shipboard MG consisting of ESS, fuel cell, AC and DC loads, motors, and generators. DC/DC converters take care of the voltage level differences between the main DC bus and ESS and fuel cell. AC/DC converters are connected to the generator to convert the AC output power to DC for connection to the DC bus. Moreover, the AC/DC converters are installed to change the voltage and speed of the propulsion motors. On the other hand, some DC/DC and DC/AC converters reduce the voltage level ratings for load applications. Typical electrical ratings of such DC shipboard MG are presented in Table 1 [22].

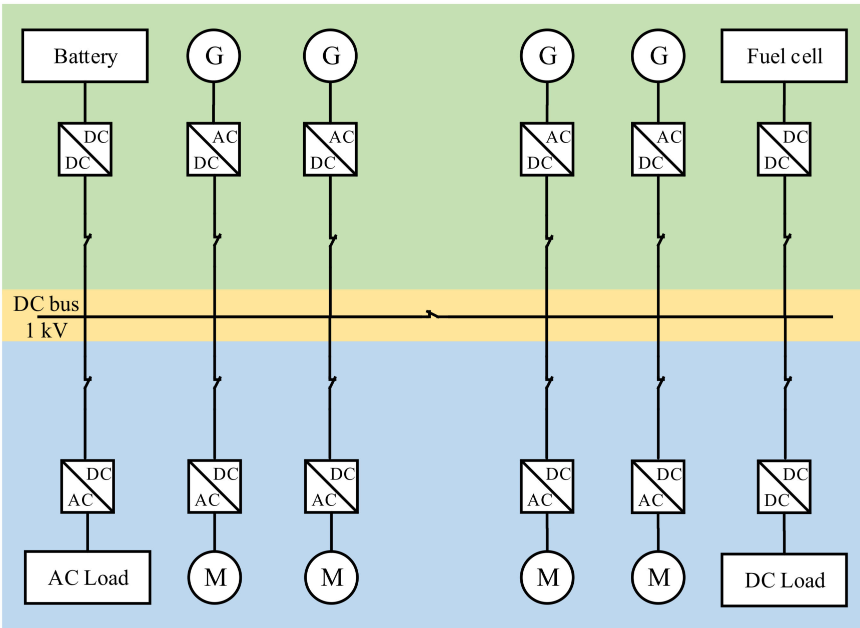

Figure 2. Single-bus structure of a DC shipboard MG, M: motor, G: generator.

Table 1. Typical electrical ratings of a DC shipboard, adapted from [22].

Component	Capacity
Main switchboard	1 kV
Propulsion motor 2 and 3	2000 kW
Propulsion motor 1 and 4	500 kW
Fuel cell	300 kW
Battery	1 kV, 300 kWh
Generators	690 V, 3000 kVA

Figure 3 shows the multi-voltage level DC shipboard structure. The output of AC generators is converted by AC/DC converter to DC power by the rating of 10 kV. The distribution DC/DC converters reduce the voltage level for connection to 1 kV DC bus. Propulsion motors are connected to different voltage levels by DC/AC converters, and loads, fuel cells, and ESSs are connected to the lower voltage level DC bus.

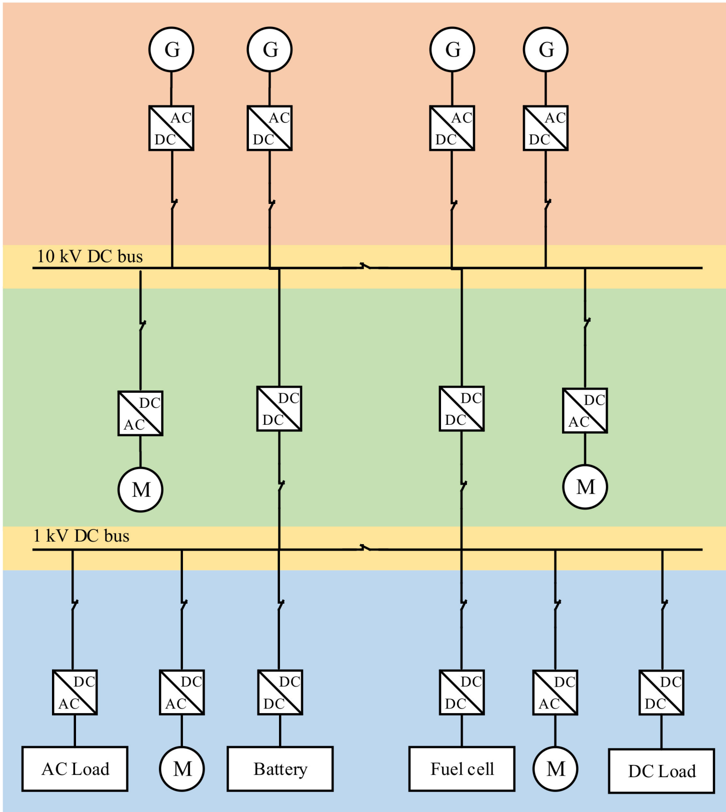

Figure 3. Multi-voltage structure of a DC shipboard MG, M: motor, G: generator.

Comparison with Terrestrial DC MGs

The DC shipboard MGs can be compared with terrestrial DC MGs since both having a high penetration of converters and are isolated finite inertia power systems. Based on the applications, the terrestrial DC MGs have different distribution topologies, namely, ring or radial. However, depending on the operational requirements, the DC shipboard MGs have different configurations. The ferries have a simple topology in which loads and generation sources are connected to a single DC bus [23]. The warships use a zonal distribution system due to the higher survivability and reliability requirements compared to the ferries [24]. In case of failure in the generation, the terrestrial DC MGs can be operated in grid-connected mode by connecting to a stable grid [25]. However, the DC shipboard power systems can be operated only in ship-to-shore mode when they are in dock [26]; otherwise, they can only be operated in islanded mode. Therefore, the DC shipboard MGs should be designed to be more reliable than terrestrial DC MGs to provide more safety for the crew and passengers. The terrestrial DC MGs can accommodate the penetration of many RESs, whereas due to the weight and space constraints, the DC shipboards mainly operate using variable speed diesel or gas turbines [27]. The load demands in the terrestrial DC MGs are typically predictable, continuous, and conventional based on the recorded past data and events. On the other hand, loads in DC shipboards are mainly unpredictable and dependent on the weather conditions and operation modes [28]. During generation loss, a load-shedding algorithm is necessary for both shipboard and islanded terrestrial systems to prevent unintentional blackout conditions. However, the load shedding and prioritization are generally performed in the case of terrestrial power systems [29], and the load prioritization in shipboards depends on the operation mode of the ship power system [30]. Another main difference of these two power systems is the grounding requirements. Practically, the terrestrial MGs use solid grounding to detect earth faults, whereas a high-resistance grounding is preferred in the shipboard MGs which are expected to continue the service with a single earth fault [31]. The performance of different grounding structures is presented in Table 2 [32]. The cable insulation level can be categorized into 100% and 173% levels. At the 100% level, cables may be applied to a system where ground faults are cleared rapidly, but at the 173% level, cables are applied to systems where clearing time is indefinite.

Table 2. Characteristics of different grounding structures, adapted from [32].

Characteristics	Terrestrial MGs	Shipboards
Cable insulation requirement	100%	173%
Transient over-voltage	2.5	2.7
Continuity of service	No	Yes
Arc risk level	High	Very low
High ground-fault current	Yes	No

3. DC Fault Features and Protection Requirements

Despite significant benefits achieved by the DC shipboards, the lack of an efficient protection system to mitigate the faults is one of the main obstacles of critical maritime systems. The main challenges of designing a protection system for such systems are as follows:

- System grounding: the grounding solutions of DC shipboards are comparable with the terrestrial AC systems; however, the grounding place is different. Because the DC ships are expected to continue electrical services during single earth faults, a high resistance DC-link grounding scheme is conceived to be implemented [33].
- Output filter effects: during a fault, the converter's output filter (L-filter for current source converters and C-filter for voltage source converters (VSC)) is charged by considerable energy, which should be dissipated [34].
- Dependency on the topology of converters: the fault current is dependent on the topology of converters [35]. The current can reach zero in the current-controlled thyristor bridge topology and block the generator from injected current to the faulty point [36]. However, the generator can continue to inject current to faulty points through the freewheeling diodes in IGBT-based VSCs until activation of its own AC protection [37].
- Lack of zero-crossing point: the arc blocking is a difficult stage in DC systems due to the lack of zero-crossing point. Therefore, the traditional AC CBs cannot be installed directly in DC systems, and new fault isolation devices should be developed [38].
- High-rise transient discharge: in DC shipboards, due to the low Ohmic resistance, the fault current is raised to a high value, and the whole system is impacted by approximately the same severity of fault current [39]; this challenges the operation time and selectivity of the protection system.

3.1. Fault Contributions from Sources

In DC shipboard MGs, synchronous generators are connected to a VSC, as depicted in Figures 2 and 3. Moreover, other components, such as propulsion motors and ESSs, are also connected with an interface converter. Therefore, the fault current in DC shipboards can be categorized into two different responses: (1) transient DC-link capacitors discharge current of converters; (2) steady-state fault current from generator, motor, and ESSs [40]. The high-rise discharge current may cause damages to the conductors by magnetic forces, thermal damages to the components in the current path, and overvoltage damages to diodes [41]. The most severe type of fault in DC shipboards is low impedance faults, which cause a high magnitude of fault current. As represented in Figure 4, the response of VSC in the DC systems during external faults generally includes three different stages as follows [42]:

Stage 1: Instantaneous DC-link capacitor discharge current, which starts immediately after the fault and reduces the DC-link voltage.

Stage 2: Freewheeling diodes conduct, and the generator, motor, or ESS are essentially moved to short-circuit condition. Therefore, the sub-transient of components is started at this stage with a high level of fault current.

Stage 3: Steady-state fault current flows from the generator, motor, or ESS to the faulty point. At this stage, the sub-transient of components are finished, and generators are in the transient stage with a lower fault current.

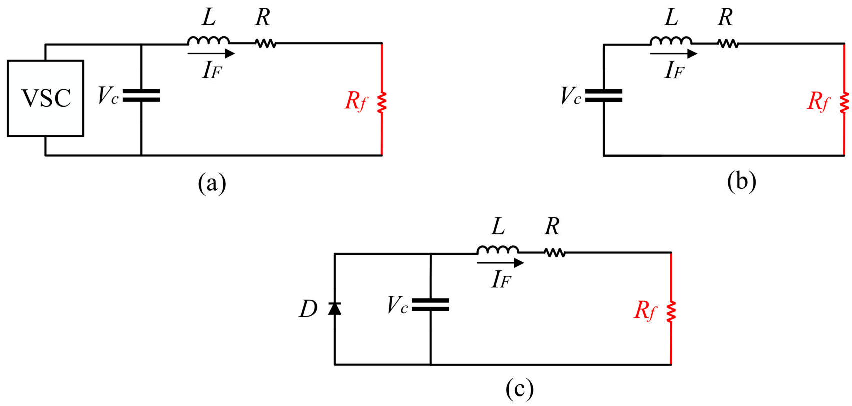

Figure 4. (**a**) Faulted network. (**b**) *Stage 1* and (**c**) *Stage 2*.

During *Stage 1*, the fault current injected to the faulty point exponentially decayed, as shown in the equation below [43]:

$$I_f = -\frac{I_0\omega_0}{\omega} e^{-\lambda t} \sin(\omega t - \delta) + \frac{V_0}{\omega L} e^{-\lambda t} \sin(\omega t) \tag{1}$$

where

$$\lambda = \frac{R}{2L} \tag{2}$$

$$\omega = \sqrt{\frac{1}{LC} - \lambda^2} \tag{3}$$

$$\delta = \tan^{-1}(\frac{\omega}{\lambda}) \tag{4}$$

$$\omega_0 = \sqrt{\lambda^2 + \omega^2} \tag{5}$$

where I_0 and V_0 are pre-fault current and voltage, respectively, C is the capacitance of VSC, and L and R are the equivalent inductance and resistance of the cable from the VSC to the faulty point, including fault resistance, respectively.

Then, after the reduction of DC-link capacitor voltage to zero, the fault current will go to the second stage, which is discharging of the cable inductor. In Stage 2, the inductor current flows through the VSC freewheel diodes. Therefore, the fault current in *Stage 2* can be defined by [44]:

$$I_f = I_1 e^{-(\frac{R}{L} t)} \tag{6}$$

where I_1 is the initial current, which is calculated by (1) when the DC-link capacitor voltage reaches zero.

Figure 5 shows the characteristic of fault current magnitude in terms of variations resistances (R) and VSC capacitances (C) of a DC shipboard with a nominal current of 5 A. As can be seen from Figure 5, decreasing the fault resistance or location will increase the fault current magnitude, which causes hazardous damages to the system's components. On the other hand, in a situation with higher fault resistance, the fault current will have a low value, which cannot be detected with traditional fault detection techniques. Therefore, it can cause some ignition in the shipboard.

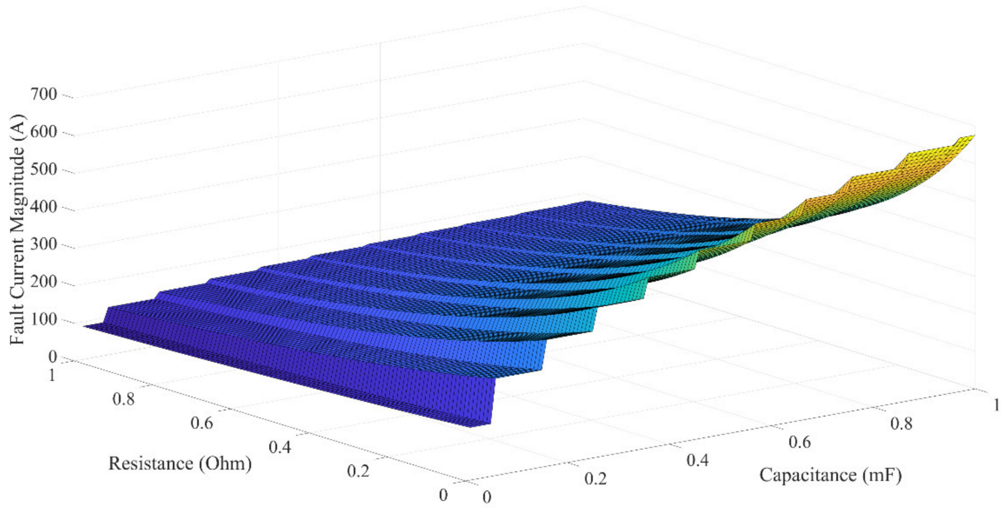

Figure 5. Fault current magnitude for different resistances (R) and VSC capacitances (C).

Stage 2 is the most hazardous stage for freewheeling diodes due to the high initial value of current, which can immediately damage the diodes [45]. *Stage 3* of fault current must be defined separately for each component as presented in Sections 3.1.1 and 3.1.2.

3.1.1. Electrical Machines

AC generators inject the fault current through the diode path of the connected AC/DC converters. The DC fault current appears with the envelope of the three-phase AC fault current. Therefore, during the near-end faults, the first peak of DC fault is defined by generator fault peak, which arises around half cycle of generator operation frequency. Afterwards, the DC fault current oscillates at the transient stage of the AC generator and then settles down to a steady-state fault current condition [46].

The fault current contribution from the AC generator can be determined by (7) [47]. In (7), the I_1 represents the current waveform during rising to reach the maximum value of fault current, and I_2 represents the current waveform after the rise time to reach a steady-state value, as shown in Figure 6, for a system with I_p = 27.1 kA, I_k = 25.1 kA, t_p = 14.6 ms, τ_d = 6.3 ms, and τ_a = 3.6 ms.

$$\begin{cases} I_1 = I_p \frac{1-e^{-t/\tau_d}}{1-e^{-t_p/\tau_d}} \; 0 \le t \le t_p \\ I_2 = I_p\left[(1-\alpha)e^{-(t-t_p)/\tau_a} + \alpha\right] \; t \ge t_p \\ \alpha = \frac{I_k}{I_p} \end{cases} \tag{7}$$

where I_p is the peak of fault current, t_p is rise time, I_k is the quasi-steady-state fault current, τ_a is the decay-time constant, and τ_d is rise time constant.

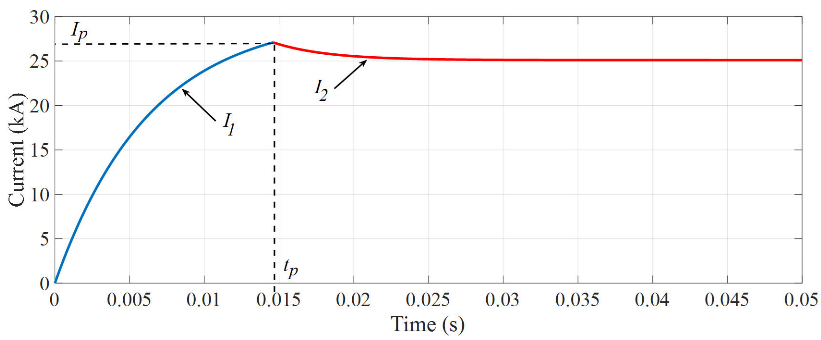

Figure 6. Fault current behavior of an AC generator based on Equation (7).

As with AC generators, the AC motors can also contribute to fault current before the remaining flux of the motor disappears [47]. The final DC current is a summation of fault current contributions from all energy sources in the DC shipboard. However, calculation of (7) is for uncontrolled fault currents; therefore, the fault current control and limiting can also impact the fault current peak and time.

3.1.2. ESSs

In terms of lifetime operation, the battery ESS is the most expensive component of DC shipboard MGs. Thus, faults in ESSs are very costly. The fault current of ESS is typically very high, and it can initiate an explosion. During a fault at the terminal of the ESS, the control system forces the DC/DC converter to be permanently in the path and the complimentary switch to be off, to move the value of I_B to zero, as depicted in Figure 7. The ESS response to a fault will be a first-order differential equation, and the ESS fault current can be determined by [48]

$$I_B = \frac{V_B}{R_B + R_{cable}}(1 - e^{-t/\tau}) \tag{8}$$

where R_{cable} is the cable resistance, R_B is the internal resistance of ESS, V_B is the ESS voltage, and τ is the transient time constant which depends on the system parameters, and can be determined as follows

$$\tau = \frac{L_{cable} + L_{conv}}{R_{cable} + R_B} \tag{9}$$

where L_{cable} and L_{conv} are the cable and converter inductance, respectively.

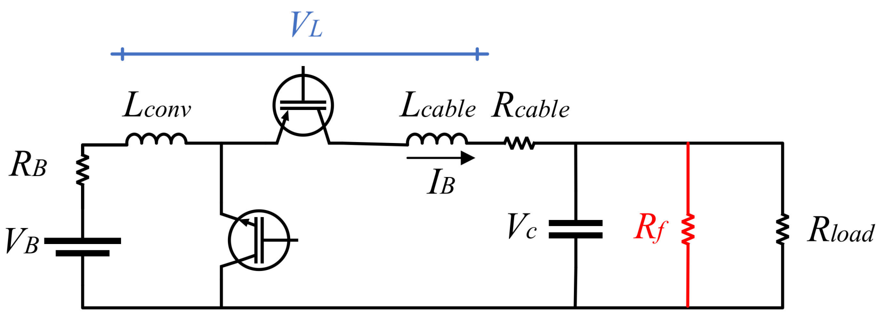

Figure 7. Equivalent ESS circuit during fault.

It should be noted that the fault current magnitude of ESS depends on the internal resistance and battery voltage. Additionally, as presented in (8), the cable resistance has a non-negligible effect. Moreover, during faults, the fault resistance changes the ESS response to a second-order differential equation as follows [49]

$$\frac{d^2V_L}{dt^2} + \frac{1}{R_fC}\frac{dV_L}{dt} + \frac{1}{LC}V_L = 0 \tag{10}$$

where V_L is the total inductive voltage, C is the DC-link capacitor, R_f is the fault resistance, and L is the summation of L_{cable} and L_{conv}.

By solving (10), the poles will be determined as follows:

$$P_{1,2} = -\frac{1}{2RC} \pm \sqrt{(\frac{1}{2RC})^2 - \frac{1}{LC}} \tag{11}$$

Then, the resonant frequency, ω_0, and neper frequency, α, are obtained by

$$\begin{cases} \omega_0 = \frac{1}{\sqrt{LC}} \\ \alpha = \frac{1}{2RC} \end{cases} \tag{12}$$

Based on the values of ω_0 and α, the response can be over-damped, under-damped, or critically damped. Therefore, the value of fault resistance can change the response of fault current contribution from the ESS side [50].

As an example, for practical systems, an ESS with R_B = 0.019029 Ω, L_{conv} = 0.00417 H, and V_B = 800 V, the maximum value of fault current can reach 20 kA, with a rise time of approximately 215 ms [46].

3.2. DC Shipboard Protection Challenges and Requirements

3.2.1. Sensor Requirements

One of the pivotal components of protection systems is the current sensor [51]. A suitable sensor must track and measure the current waveform during fault conditions accurately. There is a wide range of current sensors for measuring the fault current, such as Rogowski coils, Hall-effect sensors, and shunt resistors. Among these current sensors, the Rogowski coil is able to measure the fast high-frequency AC and pulsed loads. Furthermore, it has a low cost and negligible DC offset and saturation problems. Therefore, it is an appropriate sensor for fault detection applications in DC shipboard MGs, in which DC fault current rises instantaneously. However, one of the main drawbacks of the Rogowski coils is the need for translation of voltage induced across the coil to a current value. Therefore, it needs an additional power supply. Moreover, although this sensor is useful for monitoring the change of DC current, it cannot be used during steady-state conditions. Therefore, a more detailed study on current sensors and accurate modeling of them is essential to design sensors applicable in DC shipboard systems [52].

3.2.2. Timing Requirements

The fault current in DC systems rises quickly due to the low impedance of the system. Typically, the steady-state value of fault currents is used for relay settings in AC systems [53]. However, in DC shipboards, the transient value of fault current may damage the converters [54]. Therefore, it is necessary to detect and isolate the faults in the DC system within 10 ms [55].

3.2.3. Selectivity Challenges and Requirements

The fault detection unit should operate by selective coordination, and in AC systems, the unit and non-unit protection systems are used to achieve selective operation. The unit protection uses the measured values of current and voltage at both ends of the system, while the non-unit protection uses only the signals at the local point, and the selective operation of the system is guaranteed by using an intentional time delay [56]. However, due to the fast-rising fault current in DC shipboard MGs, using an intentional time delay is impossible [57]. Furthermore, the distance protection units are also useful for long-distance transmission lines, which make them non-applicable DC shipboard MGs which are compact in nature. The selectivity of unit-based protection systems is ensured by differential operations. However, in DC shipboards, it may require the transmission of time-stamped voltage or current signals through a high-bandwidth communication link, and it is costly and may cause some delay and noise on the transmitted data of the protection system.

3.2.4. Communication Requirements

In AC substations, the data are transferred based on IEC 61850 standard by generic object-oriented substation event (GOOSE) messages. The GOOSE packets in AC systems cause around 3 ms delay, and obviously, it cannot be acceptable in DC systems, in which the communication delay should be limited to 1 ms [58]. Consequently, proposing the localized protection method can solve the challenges of communication requirements.

3.2.5. Standardization Requirements

DC shipboards typically have different characteristics. Despite the existence of standards for power electronic systems of DC shipboards, there is a lack of communication protocols, isolation guidelines, and protection standards [59].

4. Fault Detection in DC Shipboards

The fault detection methods in DC shipboards can be designed by modification of the schemes used in terrestrial DC MGs. However, more caution is required in designing fault detection schemes for DC shipboard MGs. In recent years, many studies have been carried out on quick fault detection of terrestrial DC MGs in different voltage levels, such as low-voltage [60], medium-voltage [61], and high-voltage [62] DC systems.

Fault detection methods in DC shipboards requires more developments due to a more complex multiterminal power system, higher safety requirements, and the compact nature of these systems. The existing fault detection methods for DC shipboard MGs are summarized as follows:

4.1. Overcurrent Schemes

The overcurrent fault detection method is among the most conventional schemes. This method operates when the current flowing in the protected system exceeds a threshold [63]. In DC shipboards, the generator's CBs are equipped with an overcurrent relay, and due to the multiple generators in the shipboard, the coordination of relays is challenging and requires proper protection selectivity. In [64], the selectivity of relays is carried out by using a centralized protection management system, which severely depends on the communication links. In [65], a method using an additional bus capacitor as a solution for extending protection selectivity of DC shipboards is suggested. Moreover, this technique can support the operational management of the system by mitigating the voltage drop of the healthy section of the system. In [66], it is suggested to involve the VSCs themselves to act similar to crowbars in series with overcurrent relay to improve their effectivity in DC shipboards and isolate the fault from the AC side of generators; however, this cannot be used for other components.

Unlike the traditional overcurrent relays, the direction of fault current is considered in directional overcurrent relays. A directional fault detection method is presented in [67] based on the magnitude and direction of the current and DC bus voltage amplitude by utilizing intelligent electronic devices (IEDs). It concluded that the presented method operates independently for the load and generator sides and requires only a low-bandwidth communication link.

4.2. Current Waveform-Based Schemes

In these methods, the current or voltage signals are decomposed into specific time-frequency resolutions [68]. Wavelet Transform (WT) and Fast Fourier Transform (FFT) can then be utilized to determine the sudden variations in features of current and voltage signals. In [69], a WT-based multiresolution analysis approach is used to determine the features of different fault types in a DC shipboard MG with wavelet in an optimal decomposition level. However, one of the difficulties of such fault detection methods is high impedance fault detection, which causes a small change in current magnitude compared to the normal operation of the system. In [70], the high impedance faults in DC shipboards are detected by using WT and through proper coordination between fault detection devices and converters. Due to the low operating speed of this method, it may prevent thermal damages to the electrical system due to the low current magnitude of high impedance faults. On the other hand, to provide a combined monitoring and fault detection method, [71] suggests the use of short-time Fourier Transform (STFT) to design a data clustering-based method to extract features for different load conditions and transients such as arcing and shunt faults.

4.3. Artificial Neural Network (ANN)-Based Schemes

In ANN-based fault detection schemes, the fault is detected by utilization of the transient current and voltage waveform signals [72]. This approach is effective in the detection of different fault types, especially in DC systems. The main disadvantages of this technique are long training and significant calculation burden; it also requires a feature extraction method to provide required inputs of ANN [73]. In DC shipboard MGs, it is essential to detect the faulty point within a few milliseconds to ensure the reliability of the system. In [74], a fault detection technique based on WT multiresolution analysis method and ANNs is proposed. In this method, first, the features of faults are extracted by using WT multiresolution analysis as the input of ANN; then, ANN is adopted to automatically detect faults according to the extracted features. Moreover, another application of ANN for fault detection of DC shipboards is reported in [75]. In this study, long short-term memory recurrent ANN-based autoencoder networks are used to detect DC faults and provide load monitoring, and it is concluded that the suggested method is immune against noise.

4.4. Other Schemes

Apart from the aforementioned fault detection techniques, some other effective techniques have been reported for DC shipboard fault detection. In [76], a novel machine learning method is presented to detect faults in DC shipboards by extracting time-scaled features of current by WT. The results show the high accuracy of the suggested method by 99.8%. Moreover, as another application of machine learning in fault detection, in [77], the empirical mode decomposition is used as a feature extraction method for machine learning, and the training time of machine learning is reduced by more than 50%. On the other hand, [78] proposes an active foldback controller for DC shipboards to design a fault detection and postfault recovery method in a DC shipboard MG. The proposed method uses the AC/DC converter to detect faults in the DC line.

The existing fault detection techniques, along with suitable references, have been presented in Table 3.

Table 3. Summary of fault detection methods.

Category	Method	Advantages	Disadvantages
Overcurrent	[65]	• Extending selectivity • No need for communication link • Fast • Compensate voltage drop	• Requires additional equipment • Increases the weight of protection system • Costly
	[66]	• Uses the existing system components • Low cost • No need for new settings for overcurrent relays	• Slow (detects fault within 20 ms) • Only fault detection on loads
	[67]	• Increased redundancy by using backup protection method • Fast	• Requires communication link • Sensitive to system topology
Current waveform-based	[69]	• Local • Bi-directional fault detection	• Sensitive to noise • Requires high sampling rate
	[70]	• High impedance fault detection • Local • Detect faults in different components	• Slow • Sensitive to grounding system
	[71]	• Detecting different types of faults • Monitoring of transients in loads • Fast	• Requires communication link • Requires fault detection system in all load terminals

Table 3. *Cont.*

Category	Method	Advantages	Disadvantages
ANN-based	[74]	• Local • Low cost • Detect faults in different components	• Requires a feature extraction method • High computational time
	[75]	• Detects different disturbances • Load monitoring • Fast	• High training time • Costly
Other schemes	[76]	• Immune against noise • Load monitoring • Accurate	• High training time • Requires a lot of offline data
	[77]	• Low cost • Low training time • Fast	• Sensitive to fault resistance • Sensitive to operating condition • Sensitive to system topology
	[78]	• Lack of additional component installation • Fast • Low cost • Postfault recovery ability	• Only for AC/DC converters • Cannot protect ESSs

5. Fault Location in DC Shipboards

Locating different faults in DC shipboards is a challenging topic in the design of a protection system. When the fault is detected in the electrical system of a DC shipboard, it is vital to accurately locate the distance of fault as quickly as possible to ensure the reliability of the system by isolating the only faulty segment. Only a few studies, which are presented below, addressed the fault locating in DC shipboard MGs; therefore, this issue is a subject for future research works.

5.1. Impedance-Based Schemes

After fault events, the system impedance will change. Thus, by monitoring the system impedance, seen from the relay locations, it is possible to locate the fault distance. In [79], an active impedance estimation technique is suggested, which uses a power converter at the bus location to measure the system impedance; then, it injects a short-duration current into the power system of the DC shipboard. Afterward, the impedance of the system and fault location will be estimated by measuring the current and voltage responses. Additionally, similar fault location methods using the injection of a short-duration current to the system are presented in [80–82]. However, such fault location methods require additional equipment and high sampling rate sensors.

5.2. Converter-Based Schemes

Due to the connection of converters to components and line segments, the available data and measured values in converters can be used to locate the fault distance. A new fault location scheme in [83] is suggested by using the background noise in the voltage and current signals to locate the high impedance faults. The mid-point voltage of AC/DC converters is used in this method due to the significant change in this point during faults, and WT is accordingly utilized to locate the high impedance fault distances accurately. In [84], the current characteristic of the DC/DC converter is used, and by applying filtering at the input terminal, the fault location is estimated. The current characteristic of the AC/DC converter and WT is used in [85] to locate the fault.

5.3. Other Schemes

Apart from the abovementioned schemes, some other techniques are proposed in recent years for the protection of DC shipboards. In [86], a fault location method is presented by using ANN. In this method, the faults are classified and located by using the transient features of current and voltage waveforms of relay location as inputs of ANN.

Additionally, in [87], the transient features of local fault current and machine learning are used to locate faults in power electronic converters. However, these methods require high numbers of data and high training time. In [88], a graph traversal-based algorithm is proposed for fault location and recovery of the system. In this method, as an online fault location technique, the isolation zones are minimized to ensure the redundancy of the system during and after the fault.

In Table 4, the existing fault location schemes for DC shipboard MGs have been presented.

Table 4. Summary of fault location techniques.

Category	Method	Advantages	Disadvantages
Impedance-based	[79–82]	• Accurate • Fast • Local	• Requires additional equipment • Costly • Sensitive to fault impedance • Offline
Converter-based	[83]	• Locate high impedance faults • Lack of communication link • Only requires converter sensors • Low cost • Fast	• High sensitivity to grounding system • Requires reconfiguration of converters • Only locate cable faults
	[84]	• Fast • Low cost • Lack of communication link	• Only locate cable faults • Only for DC/DC converters
	[85]	• Fast • Low cost • Lack of communication link	• Only locate cable faults • Only for AC/DC converters
Other schemes	[86]	• Fault location and classification • Fast • Low cost	• High training time • Requires high sampling rate sensors
	[87]	• Immune against noise • Low cost • Accurate	• High training time • Requires much offline data
	[88]	• Online • Recovery of system • Minimum isolation zones • Fast	• Only for AC/DC converters • Requiring communication link • Only can locate in DC cables

6. Fault Isolation in DC Shipboards

A fast fault isolation technique is essential to prevent any damages to system components due to the high-rising fault current in DC shipboards. After fault detection, the protection system requires preventing further damages to system components by disconnection of faulty point of the DC shipboard [89]. The isolation of faulty sections is enabled by the converter's switches and CBs. Due to the short length of cables and heavy dependency among the various components in the system, the DC shipboard MGs is a tightly coupled system. Thus, more components are influences by the fault, and the fault isolation is more challenging in DC shipboards compared to other electrical systems. The fault isolation in DC shipboards should be sensitive, secure, and fast, and can be categorized into breaker-based and breaker-less schemes.

6.1. Breaker-Based Schemes

In breaker-based schemes, CBs are utilized to isolate the system during fault. In DC shipboards, the fault current requires to be extinguished by additional units due to the lack of a zero-crossing point [90]. However, in small-scale DC shipboards, due to the limited current and voltage ranges, the DC CBs can de-energize the arc faults. These CBs have different systems to cool and dissipate the fault energy so that the fault voltage surpasses the voltage of the system and forces the current to reach the zero value [91]. However, the application of DC CBs on large-scale DC shipboards with higher fault current levels are more challenging.

One of the DC shipboard isolation systems is solid-state CBs (SSCB), which includes solid-state switches such as IGBTs, IGCT thyristors, and a snubber circuit. The SSCBs are composed of Metal Oxide Varistors (MOVs), capacitors, and resistances to disintegrate energy during fault [92]. In Figure 8, a typical SSCB is depicted. The mechanical isolation, programmable coordination, and fast fault interruption are the key features of SSCBs in DC shipboard MGs. The design of an SSCB for DC shipboard is suggested in [93]. It provides high reliability and fast isolation for DC shipboards. However, these types of CBs have high losses.

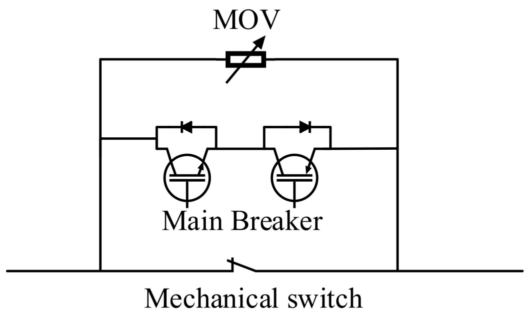

Figure 8. Structure of typical SSCBs.

Another type of CBs is Z-source breakers, as shown in Figure 9 [94]. This CB is composed of resistors, diodes, a crossed L-C connection, and a Silicon-Controlled Rectifier (SCR). The current flows through the inductors and SCR from the source to the load during normal operation mode. During a fault, the transient fault current flows through the capacitor in opposition to the SCR current. Consequently, the fault current drives the SCR current to zero and makes the SCR switch off. In DC shipboards, these types of CBs can effectively isolate the DC faults [94]. In [95], the modified Z-source CBs are proposed for DC shipboards to maintain common ground connection during the problem of reflected fault current at the source. Moreover, the Z-source CB is designed to handle the overload conditions instead of mistaking a large change in load current for a fault. In [96], an improved Z-source CB is suggested for the DC shipboard, and a recloser unit is also added to the fault isolator. The Z-source CB presented in [97] can be implemented in the systems without any additional fault detection units, and therefore, it can isolate the faulty line after exceeding the current threshold. The advantages of Z-source breakers are easy installation, lower cost, and low power loss.

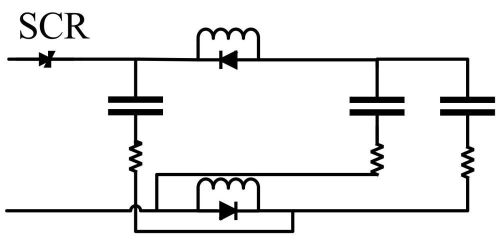

Figure 9. Structure of typical Z-source CB.

6.2. Breaker-Less Schemes

Figure 10 presents fault management steps for the DC shipboard breaker-less system [64]. *Step 1* starts after fault inception on the system, and the protection system detects a fault current surge. After fault detection, converters enter the current limiting mode for restricting the current magnitude and keeping the fault current around the normal rating to facilitate the fault point localization. In *step 2*, after identifying the faulted point, converters will reduce the current to zero and de-energize the shipboard system. Then, in *step 3*, the corresponding no-load disconnectors in converters are activated to physically isolate the faulty point from the healthy part of the system. Finally, in *step 4*, the shipboard system restores to normal operation mode after fault clearance.

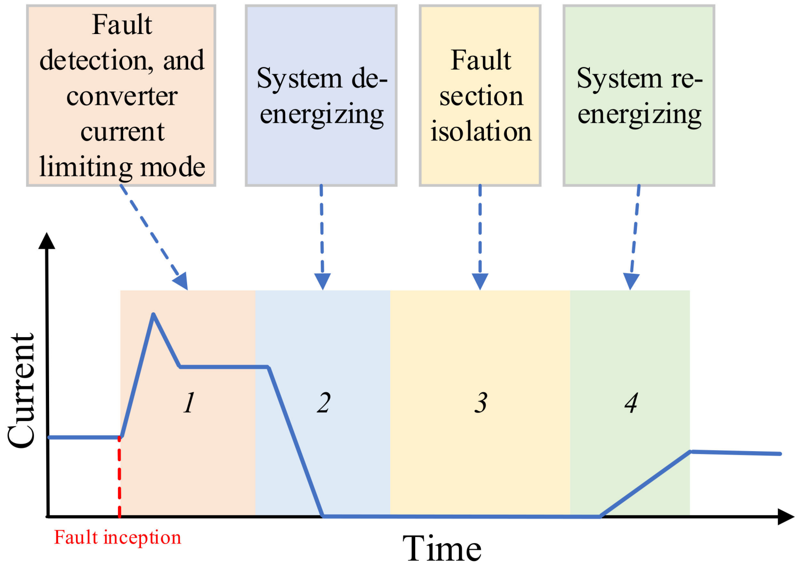

Figure 10. Converter control steps for fault mitigation.

The converters, by using self-turn-off power electronic devices, can be utilized for fault current isolation in breaker-less fault interruption methods [98]. In these methods, the fault detection unit is inside of the power converters, and during faults, the VSC switches to block mode for preventing the fault damages in the system. A fault isolation technique for DC shipboard MGs based on the coordination of power supply converters and bus switches is presented in [99]. In [100], a control technique is developed for a DC/DC converter as an isolation device in a breaker-less DC shipboard system. The results show the lack of need for any fast fault detection methods or no need for mode transition in normal and fault operation modes.

In Table 5, the comparison of existing fault isolation schemes for DC shipboard MGs has been represented.

Table 5. Summary of fault isolation techniques.

Method	References	Advantages	Disadvantages
Breaker-based	[90–97]	• Lack of control requirement • Fast • Local	• More requirements of components monitoring • Longer switching response • Larger components • Ineffective at higher voltages
Breaker-less	[64,98–100]	• Operation speed • Lower cost • Current-limiting performance	• Possible impact on all sections, when fed by the DC bus, not only the faulty section • The risk that fault isolation converters cannot tolerate the fault currents, which can lead to cascading failures • The need for additional series switches • Not effective for interrupting all types of faults because some parasitic paths might be present in systems and converters

7. Conclusions, Solutions, and Future Recommendations

In this paper, the DC fault protection schemes for DC shipboard MGs have been reviewed, and the limitations, advantages, and challenges of these schemes are discussed. It is observed that the different aspects of protection systems, such as fault detection, location, and isolation, are necessary for developing and designing a comprehensive and robust DC shipboard system. The requirements of DC shipboard MGs are different from terrestrial DC MGs, and they depend on different shipboard operation parameters, such as load conditions, system configuration, and installed components. In new DC shipboards systems, novel fault detection, location, and isolation methods are implemented to solve the limitations of the traditional schemes. Consequently, the possible practical solutions, concluded from the abovementioned comparisons, for protection systems of DC shipboards, can be presented as follows:

- Fault detection scheme: due to the limitations of traditional methods, the ANN-based methods can be implemented in new all-electric DC shipboards to detect faults more accurately, quickly, and reliably than existing current waveform-based techniques.
- Fault location and isolation scheme: due to the recent developments on the converters and high penetration of DC/DC and AC/DC converters in DC shipboards, the fault location and isolation techniques can be carried out by installed converters to reduce the cost and size of the system. Moreover, the converter-based solution will have higher operation speed and functionality with the help of new control and fault-current-limiting methods in novel converters.

Therefore, the following recommendations have been made for future research:

- The DC shipboard MGs operation is different from terrestrial DC MGs. Therefore, before designing a protection system, detailed modeling of the DC shipboard MG is essential to consider its various operation requirements and modes.
- Most fault detection schemes consider the voltage and current sensors as ideal devices. Due to the rapid high-rise fault current in DC shipboards, these sensors could be saturated or damaged. These sensors also have some delays and may not arcuately replicate the fault current waveform. Moreover, designing local fault detection methods can reduce the cost of the fault detection unit, requiring sensors in both ends of the line, and avoid more delays.
- The fault isolators are another important challenge in the implementation of protection systems in DC shipboard MGs. The breaker-based CBs have larger components, higher weights, and are ineffective at higher fault current rates. Since the DC shipboards have weight and space limitations, the breaker-less schemes might be a better solution. However, these schemes also have some limitations, such as less survivability, inability to be implemented in all lines, and limited fault current tolerance.

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