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Control Architectures, Stability Analysis and Protection Schemes

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A Review of DC Shipboard Microgrids – Part II: Control Architectures, Stability Analysis and Protection Schemes

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Abstract- **This paper presents a review of coordinated control strategies, stability analysis, and fault management for DC shipboard microgrids (DC-SMGs). As an emerging application, the DC-SMG lacks a comprehensive summary of the control schemes. Considering the specific load profile in ships, this paper discusses the coordinated control strategies of diesel generators and energy storage system (ESS). Depending on the maritime conditions, different operation modes are switched by the energy management system (EMS). Due to the presence of high-bandwidth controlled constant power load (CPL) converters, negative impedance instability is induced. Meanwhile, the pulsed loads in DC-SMG may affect the voltage stability significantly. Small-signal and large-signal stability analysis can be used to evaluate the effect of these two types of loads. In the aspect of shipboard protection system, this paper presents the specific requirements of DC-SMG based on the standards. Lacking of 'ground' in ships, solutions in designing the grounding system for DC-SMG is described. Besides, the short-circuit fault management consisting of fault detection, fault isolation, and reconfiguration in DC-SMGs are summarized. Finally, existing commercial DC ships are presented and compared to demonstrate the developing trends.**[1]

I. INTRODUCTION

Environmental concerns in transportation give rise to the development of electrification in the marine industry. The integrated power system (IPS) is conceived to improve system efficiency and reduce fuel consumption by providing electric power to the entire system including electric propulsion drives and service loads [1]. Since the shipboard power system (SPS) operates in stand-alone mode when the ship is sailing, it can be defined as a shipboard microgrid (SMG).

In recent years, DC distribution attracts much attention in the SMG community. Compared with AC-SMGs, DC-SMGs have many benefits, including: 1) facilitating the connection of power components without phase angle synchronization; 2) reducing the size and weight by eliminating large low-frequency transformers; 3) reducing fuel consumption due to variable speed prime movers; 4) managing power flow and enabling reconfiguration after faults; 5) enhancing the survivability by simplifying the connection and disconnection of different types of power sources and reducing the number of prime movers [2], [3], [4].

To assess an electric ship, evaluations from the aspects of technology, environment, economy, and society should be taken. In terms of technical evaluation, reliability, energy efficiency, maneuverability, speed, distance, etc. are the main considerations in designing a ship. Since a number of electric devices and mechanical machines are tightly coupled in SMG, and the system lacks support from a strong grid, the SMG contains a wide range of dynamics and is susceptible to disturbances with limited generation capacities. Specifically, for military ships, due to the harsh operation conditions, it is vital to consider the system survivability, which represents the capability of fulfilling its mission in a timely manner in the presence of attacks, failures, or accidents [5], [6]. Therefore, the goal of designing SMGs is to enhance reliability, stability, and survivability at minimal additional costs.

In order to ensure system reliability, it is important to manage optimal cooperative operation among paralleled generation, storage, and consumption in DC-SMGs. For power generation modules (PGMs) in DC-SMGs, two control objectives are considered, namely keeping DC bus voltage in the stable region and sharing power among PGMs with different characteristics as commanded by the energy management system (EMS) [7], [8]. Although DC-SMGs share some similarities with general DC MGs, implying existing methods can be transferred to the SMGs, there are still several differences in terms of reliability requirement, power density, and load prioritization [9]. The overview of control strategies for general DC MGs is presented in [10], [11], [12]. However, these papers only summarized the general control schemes without the specific concerns on the characteristics of power sources in ships.

In terms of stability, the specific issues in DC-SMGs include the CPLs, pulsed loads, and typical system architectures. The tightly regulated converters in SMGs induce

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Coordinated control

- Local control of shipboard generation set
- Local control of shipboard ESS
- Coordination between generators and ESS
- Energy management system in DC-SMG

Stability analysis and issues

- Stability analysis on constant power loads
- Stability analysis on pulsed loads
- Stability analysis on system architectures

Protection system for DC-SMG

- Grounding system
- Short-circuit fault management
  - Fault detection and localization
  - Fault isolation
  - Post-fault reconfiguration
- Leakage protection

Fig. 1. Control issues in DC-SMG.

a negative impedance characteristic within the bandwidth of their control loops, which weaken the system stability. Several research works have studied methods to alleviate CPL instability, mainly in small-signal analysis aspects [13], [14], [15]. Besides, in naval ships, pulsed loads, e.g. laser weapons and electromagnetic railguns, require a special power supply and cause bus voltage drop, thus affecting the system dynamics. The research on stability caused by pulsed loads is limited in existing literature and is highly needed. Most of existing works focus on providing solutions in mitigating the impact of pulsed loads by providing a high power ramp [16], [17], [18]. This paper will present current studies on instability issues caused by pulsed loads. In addition, due to the harsh operating conditions in maritime application, system architecture may affect the stability by changing the line impedance and system network after reconfigurating.

Fault management is a challenging topic for DC-SMGs. Due to the nature of network independence from the main grids, as well as rough operation environment in ships such as vibration, moistness, and salinity, SMGs are fragile and prone to fault [19], [20]. To ensure personnel and equipment safety, the grounding system in DC-SMGs is important yet difficult due to the lacking of the 'ground'. Currently, studies and standards on grounding systems in DC-SMGs are limited. On the other hand, due to the presence of pulsed loads, conventional DC MGs fault detection approaches presented in [21], [22], [23] have to be modified to fit the DC-SMGs. Without a zero-crossing point in DC fault current, DC breaker is still a barrier in high power applications, leading to the popularity of converters with fault isolation capability [24], [25], [26]. To improve the system survivability and ensure power supply for vital loads in ships, reconfiguration after faults is considered in the protection system [27]. Besides, the leakage protection for crew safety is rarely discussed, but it worths researching to fit in the maritime application. An introduction on this topic is presented in this paper.

Fig.1 shows a general representation of control issues, including the coordinated control, stability issues, survivability, and protection system in a DC-SMG. This paper aims at providing a comprehensive review of these issues. Section II provides coordinated control in DC-SMGs. Section

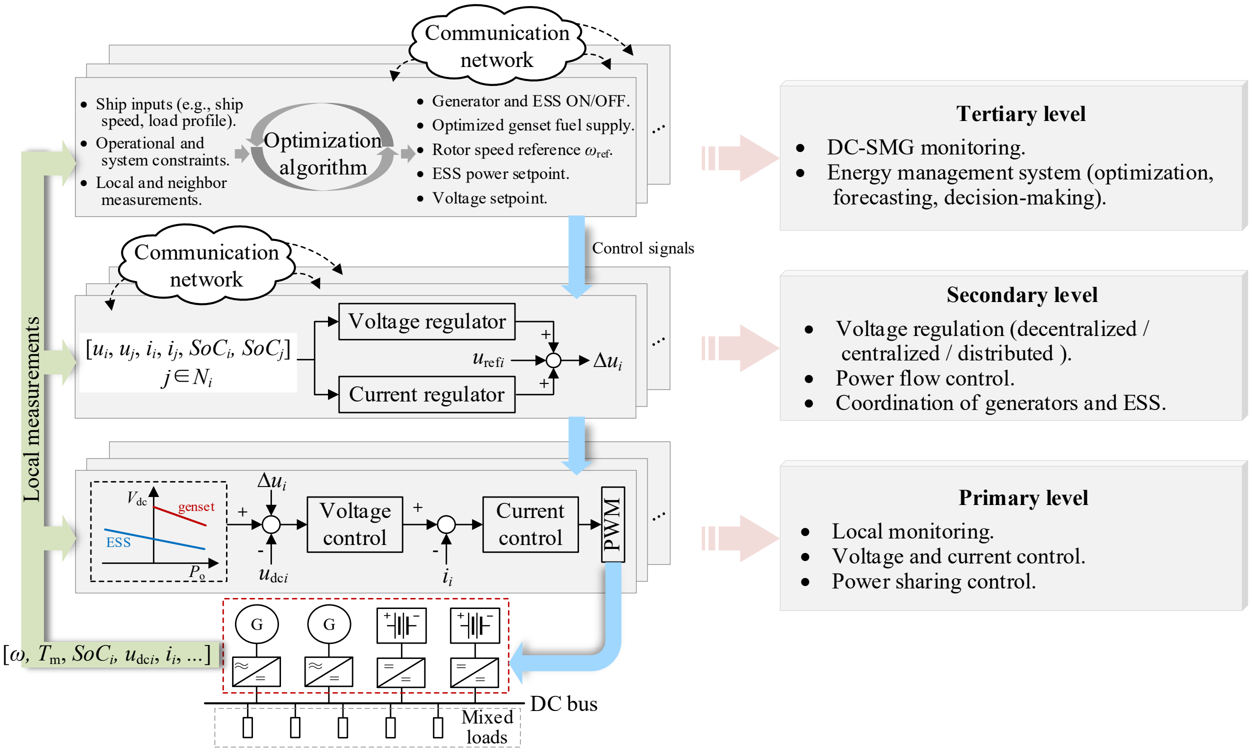


Fig. 2. Hierarchical control scheme in DC-SMGs.

III presents the stability analysis. In Section IV, the protection schemes of DC-SMG are described. Industrial cases implementing DC distribution in ships are presented in Section V. Finally, concluding remarks are given in the last section.

II. CONTROL ARCHITECTURES IN DC-SMGS

To enable the effective employment of the tightly coupled power components in SMGs, a proper coordination control system is essential. Due to lacking of operation standards, there are various coordination methods presented in academia depending on the power system schemes. The specific concerns in DC-SMGs are the frequent variable load demands caused by the startup/brake operation of propulsion motors, and high power weapons in naval ships, in which conditions high pulsed power is demanded. Therefore, power sources with different output characteristics have to be cooperated properly to achieve reliable and efficient power supply.

A. Basic principles

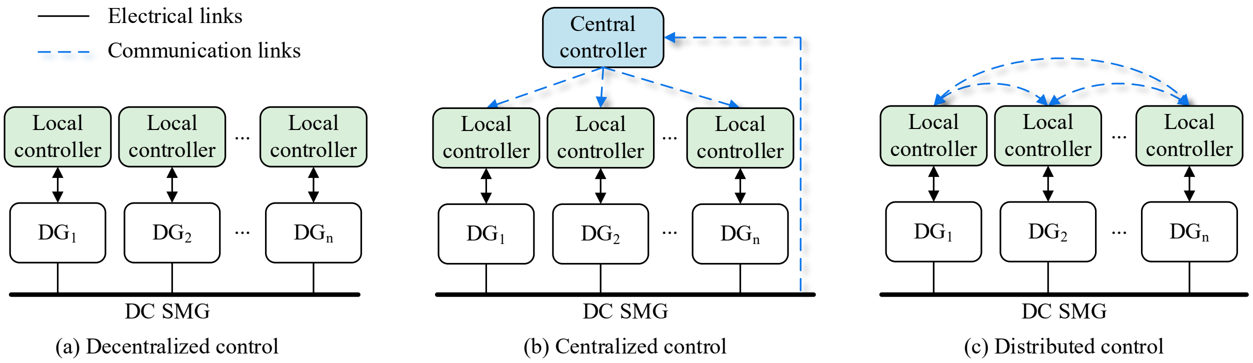
The objectives of coordinated control in DC-SMGs are to ensure the DC bus voltage is within the acceptable range and to share power according to the sources' characteristics. For the first objective, in contrast to terrestrial MGs, shipboard DC distribution allows ±10% voltage tolerance according to IEEE Std. 1709-2010 [28]. Thus, maintaining the steady bus voltage is no longer the only objective in DC-SMGs. On the contrary, ensuring system reliability and survivability are the main goals. For the second objective, in modern DC ships, there are at least two types of sources to ensure the reliability of the power supply (e.g. diesel generator and battery, or diesel generator, ultra-capacitor (UC) and battery). In order to extend the lifetime of ESS units and prevent the generators from being overloaded, coordinated control is necessary to be studied.

To achieve above control objectives, different control methods are studied. The hierarchical control scheme is popular in terrestrial DC MGs, and can be adopted in DC-SMGs as well. The basic operation principle of hierarchical control in DC-SMGs is shown in Fig. 2. The primary level control consists of the inner current and voltage control loops and the virtual output-impedance loop, which is designed according to the characteristics of the power source, aiming at sharing the load. One basic principle of power sharing is the rated capacity of power sources, while with the increasing demand for fast load response and the integration of hybrid ESS (HESS), power sharing according to the sources' characteristics become popular [29], [30]. The secondary level control focuses on the DC bus voltage restoration with or without communicating with neighbor converters. By regulating the terminal voltage of converters for generators and ESS, the coordination between them is achieved. Besides, ESS states, such as state of charge (SoC), can be regulated at this control level. In the tertiary level control, an EMS considering system constraints is designed to achieve specific optimization objectives [31], [32]. The generated optimized commands, including the generator and ESS ON/OFF states, their power setpoints, and voltage references for both generator and ESS sides' controllers, are sent to the lower control levels. In addition, the optimized fuel supply for generators and rotational speed of engines are generated by EMS for generator excitation control to achieve efficient operation [33]. The information of converter output voltage u_{dci}, converter current i_i, rotational speed of generator rotor ω, mechanical torque T_m, and SoC of ESS are used locally and globally in different levels.

According to the requirement on communication networks, the control methods used in the hierarchical control architecture can be categorized into three types: decentralized, centralized, and distributed control. The basic control schemes of these three control types are shown in Fig. 3. The decentralized control focuses on the local level, while the other two types need the information of other distributed generations (DGs) in the system [34]. In the centralized control scheme, a central controller collects the information from all the DGs to achieve global optimization and regulation, and then sends the references to each local controller [35], [36]. The distributed control, by contrast, can reduce the dependence on communication links, in which there is no central controller and each local controller only communicates with several neighbors [37].

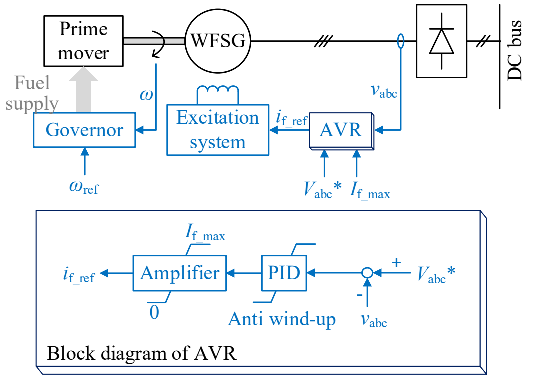
B. Local control of shipboard generation set

There are two control schemes for gensets in DC-SMGs. The first one is regulating the DC voltage by excitation control [38], [39]. It suits in the case of wound field synchronous generators (WFSGs). With the excitation control, the

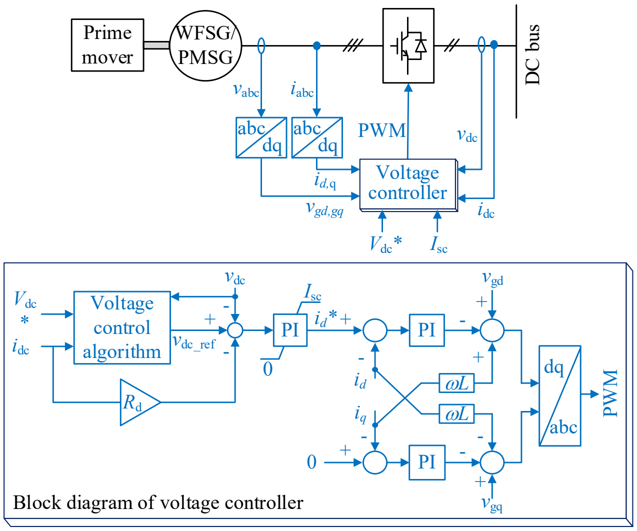


(a) Decentralized control (b) Centralized control (c) Distributed control

Fig. 3. Block diagram of coordinated control schemes.



(a) Generation system with excitation control



(b) Generation system with converter control

Fig. 4. Two control schemes of shipboard gensets.

converters can be simplified by using passive rectifiers. A typical control scheme is shown in Fig. 4 (a). The DC bus voltage is regulated by controlling the terminal voltage of the generator [40]. The automatic voltage regulator (AVR) controls the generator terminal voltage by adjusting the excitation current, whose reference is $i_{\mathrm{f\_ref}}$, of the generator [41]. The governor regulates the rotational speed of the generator by adjusting the fuel amount to the prime mover [42]. It should be noted that the excitation control is slow to respond to fast transient loads. To ensure the DC bus voltage constant, the second control scheme is introduced, which is regulating the output voltage by controlling the active rectifiers, as shown in Fig. 4 (b). This method is suitable for gensets with permanent magnet synchronous generators (PMSGs) besides WFSGs [43], [44]. As there are usually more than one power source in a ship, droop control is a common method to share the power, with which the power sharing ratio is inverse proportional to the droop coefficient R_{d}. The voltage reference $v_{\mathrm{dc\_ref}}$ is generated by secondary and tertiary level control as clarified in Fig. 2. Several simple and effective methods for the voltage control algorithm block in Fig. 4(b) are presented in [45], and this figure presents the decentralized control method as an example.

Both two control schemes have been implemented in practical cases. The naval package (NP) [46] features a 6-phase WFSG and feeds the DC load through two cascaded diode bridges. For brushless synchronous generators in the marine DC system, a flux estimation-based DC bus voltage control can be used [47]. Actually, for the synchronous generator system, introducing flux deviation is preferred by avoiding changing the mechanical operation point of the diesel engine. However, the dynamic response of the excitation control is a big problem, especially during fast transients. Due to the large inertia of the generators, AVR plays the role of driving the generator to a steady-state relatively slow. Moreover, the measured error in practical cases may lead to overload and instability issues [48]. While the second control scheme can solve the problems in excitation control. The NP2 [49] implemented a 12-phase PMSG, driven by four ac/dc converters, each composed of a three-phase diode bridge and a chopper (3 level neutral point clamped (NPC) converter in this case) in series, to the output voltage of the generation modules, and the DC voltage is controlled by the voltage regulator acts on choppers. A modular multilevel converter (MMC) rectifier for the generator is used in a 12kV medium voltage DC (MVDC) power system of an all-electric ship (AES) in [50] to control the DC bus voltage and manage the power flow.

A comparison between these two methods is presented in [51], in which both excitation current control of the generator and the active ac/dc converter control are used to regulate the output DC voltage. The simulation results show that voltage regulation by AVR requires almost 30s to reach the steady-state, while the voltage response of active-controlled converter is much faster. Considering the frequent fluctuant load profile in SMGs, controllable converters are preferred, on which the following coordinated control methods are based.

Above approaches are based on the model-based control, which requires detailed knowledge of plant dynamics, while for SPS, the system parameters and state variables are changeable depending on the operation conditions. Thus, model-free methods, e.g., fuzzy logic control, may provide solutions to stabilize the shipboard converters. Further studies can be taken on this topic.

C. Local control of shipboard ESS

ESS in SMG is responsible for generation-demand balance and maintain bus voltage. In addition, modern ships are on the way to become AES, in which ESS is the main power source during offshore operation. Therefore, intelligent coordinated control for ESS in SMGs is an important field to study. When operating as a power source, the ESS should ensure the DC bus voltage and power sharing among power storage devices. While when operating as a load, the ESS is regulated to store power.

There are several energy storage types in SMGs, such as lithium batteries, UCs, and flywheels. Among these, lithium battery is the most common one due to its merit of high energy density; while UC and flywheel are usually integrated as a part of HESS and coordinate with battery packs since these two types have high power density.

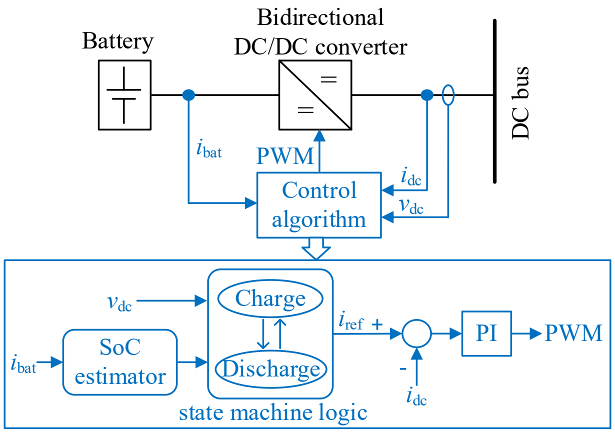


Fig. 5. BESS controller block diagram.

The coordinated control of ESS should consider the characteristics of energy storage units. For battery ESS (BESS), two constraints should be considered to increase the battery lifetime. One is limiting the state of charge (SoC) within an acceptable range, while the other is limiting the charging and discharging current within the maximum values. In [52], [53], a decentralized controller for BESS in a DC-SMG is studied. Based on the local voltage measurement and SoC estimator, the DC bus voltage can be maintained when the load changes. The controller is shown in Fig. 5. A state machine logic is implemented to limit the SoC and avoid unnecessary charge and discharge of the batteries.

As the marine applications have high requirements on peak power and power change rate, and the load demands are relatively unpredictable, HESS which combines UCs and flywheels with batteries provide a solution to meet the dynamic load demand. The concern on UCs is limiting the equivalent SoC in acceptable range when charging and discharging. While for flywheel, the energy is adjusted by regulating its speed [17], [54]. The coordination of different energy storage units depends on their characteristics. Since UCs and flywheels have good performance in short-term intensive charging and discharging, a frequency-based power sharing method can be used to allocate the power of HESS [29], [30]. A HESS in a 12kV DC AES uses a low-pass filter (LPF) and a high-pass filter (HPF) to allocate the storage reference power between the batteries and the UCs. The batteries provide the low-frequency component of the total storage reference power and the UCs provide high-frequency component [50]. The allocation ways of HESS for pulsed loads, which can be connecting the HESS to the DC bus, and connecting the HESS in the pulsed load side, still need further studies to fit the system.

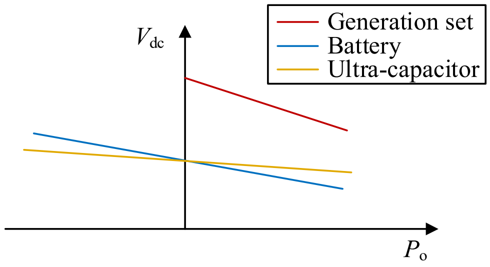


Fig. 6. Illustration of the coordinated control among different power sources.

D. Coordination between generators and ESS

Coordination among generators and ESS has a considerable effect on system efficiency and stability. In large ships, both generators and ESS are usually integrated to cope with different operating situations. Compared with the rated power of diesel generators, the capacity of ESS is usually much smaller. Thus, ESS acts as the complement of generators when the load demand increases, and store the energy when load demand decreases.

Numerous studies have present the coordinated control methods of generators and ESS. Decentralized control, e.g., droop control, is a common method to realize the control objectives of DC bus voltage control and power sharing. The principle of hierarchical coordination using droop control for different power sources is shown in Fig. 6. The droop coefficient is inversely proportional to the power source capacity. Another coordination principle is based on centralized control. In [48], a master-slave power sharing method for generators and ESS on DC ships is implemented. The DC bus voltage is stabilized by ESS with P-V droop control in normal operating conditions, and the operating point of the excitation-controlled generators is constant. While in emergency conditions, the ESS operates in maximum output. The drawback of this control configuration lies in the lifetime degradation of the batteries since the DC bus voltage fluctuations need to be suppressed by the batteries. In [44], [55], the coordination between generators and HESS in a radial 12kV DC-SMG consisting of two generators and two load zones (including HESS) is studied. An adaptive centralized control scheme with sparse-feedback, multi-rate linear quadratic regulator controller is presented to regulate the DC bus voltage after the system is linearized. However, the inherent drawback of being susceptible to single-point failure in the centralized controller cannot be avoided in this control scheme.

E. Energy management in DC-SMGs

The DC-SMG is a highly integrated system with complicated system scheme and dynamics, including electromagnetic transients of semiconductor switches with milliseconds, electromechanical transients of pulsed loads, and motors within microseconds, ESS charging and discharging within seconds, and mechanical dynamics within minutes, even the long-term ship operation within hours. To coordinate these power components with different time scales, proper EMS is necessary to schedule ship operation at a higher control level. Besides, the EMS has several regulation objectives, which can be minimizing the fuel consumption and emission [56], minimizing the operation cost [57], minimizing the power losses [58], etc.

A multi-objectives multi-timescale EMS may have many considerations and challenges, including:

1) Considering various operation conditions of ships, the optimization objectives are different. For instance, in

normal conditions, maximum operation efficiency may be the main objective, while in an emergency condition, power supply continuity has the highest priority.

2) Transient dynamics and seamless switching between different operation modes, including the fault isolation and post-fault reconfiguration processes.

3) To feed the pulsed loads in ships, fast dynamics and accurate power management is required. Not only the general power regulation on generators and ESS in relative long timescale but the pulsed loads in ultra-short timescale.

Besides the power source management, demand response can also be implemented to achieve power balance. Different from load management for terrestrial power systems, of which the managing objects more focus on economical operation, the load management of SPSs is responsible for enhancing system stability by avoiding the sources being overloaded [59]. To achieve this object, the shipboard loads are classified into three types depending on their priority: particularly vital, vital, and non-vital loads [60]. Note that the priority may vary according to ship missions [61]. With this classification, load shedding can be implemented properly without affecting the basic operation when power sources are overloaded or system fault occurs. A multi-agent system (MAS) model can be used with the consideration of load priority to balance generation and load demand while satisfying system constraints [62], [63].

Many researches have been done to enhance the superiority of DC-SMGs. This section just introduces such a topic and more details about shipboard EMS are out of range of this paper.

III. STABILITY ANALYSIS AND ISSUES IN DC-SMGS

Ensuring system stability is a challenging task in DC-SMGs since these islanded full power electronics power systems have limited power generation capacity, significant nonlinear propeller loads and continuously changing the load demands, especially in naval ships with pulsed loads [64]. Stability issues in DC-SMGs include the rotor angle of the synchronous machines and the DC bus voltage stabilities [2]. The first category relates to the mechanical characteristics of the synchronous machines, while the second one concerns the bus voltage on both voltage magnitude and duration of the disturbance. This section focus on voltage stability, which is challenged by the increasing amount of power electronic converters in the SMG.

The specific stability issues in DC-SMGs are from the presence of the high-power motor drives that show CPL behavior, and the high-power pulsed loads that absorb power with high magnitude and ramp rate. The numerous nonlinear power converters regulated with high bandwidth tend to absorb constant power regardless of the DC bus voltage variations [2]. The mismatch between such negative impedance behavior of CPL and the impedance of SPS with cascaded power converters leads to the system being unstable [65], [66]. While the pulsed loads may cause the generators' rotor angle instability and further the DC bus voltage instability. Taking the dynamics and interactions of different interface converters into account, the stability analysis should be extended [67]. The impact of system transient instability caused by pulsed loads depends on not only the pulse magnitude and its duration but also the system configuration and the controller parameters [68].

Besides these specific loads, other factors may also affect the stability of DC-SMGs. From the system architecture viewpoint, the typical DC-SMGs have multiple buses, leading to a complex line impedance network. Furthermore, due to the harsh operating conditions in ships, the aging process may result in the cable impedance deviating from the nominal value, which further causes severe stability issues [69]. From the generation side, diesel generators and ESS are the main power sources in current DC-SMGs, while these two components are not specific in maritime applications. To avoid repetition, the stability issues on the generation side are not discussed in this section.

A. Stability analysis on constant power loads

The impacts of CPL on general MGs have been widely studied [70]. Nevertheless, this instability problem also exists in DC-SMGs due to the inverter-fed motor drive loads, dc/dc converter loads, and other inverter loads.

1) Stability issues induced by CPLs

The CPLs refer to the loads consuming constant power regardless of the input voltage. The incremental impedance of the CPL can be calculated as:

$$R_{CPL} = \frac{\partial v_{load}}{\partial i_{load}}\Big|_{(V_0,I_0)} = -\frac{V_0^2}{P_{\mathrm{CPL}}} \tag{1}$$

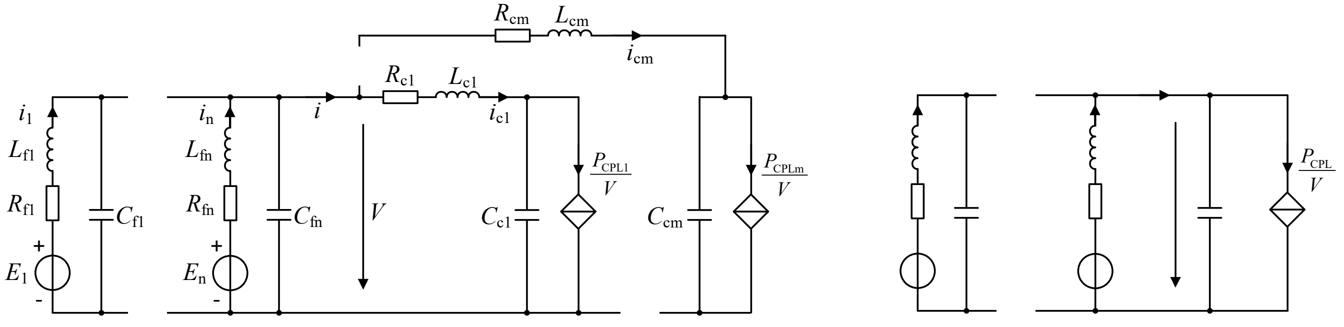
where V_0, I_0, and P_{CPL} are the steady-state load voltage, current, and CPL power at a given operating point. It can be found that the CPL has negative incremental impedance. The interaction of CPLs with the source converters makes the system less damped and affecting stability [71].

To overcome instability caused by CPLs, passive damping methods using passive elements such as RC filters, active damping methods by modifying the control loops to emulate the passive elements, such as feedback control based methods [72] and virtual impedance dampers [73], are widely studied. Besides, nonlinear methods such as sliding-mode control are also used to overcome the CPL instability [74].

2) Small-signal modelling

The general circuit model of a DC-SMG system with n power sources and m CPLs can be represented as Fig. 7(a) [75], [76]. In this model, E_{n} represents the output DC voltage of the converters on the source side employing state-space averaging, R_{fn}, L_{fn}, and C_{fn} are parameters of LC filter connected to the source converter. The CPL is represented with the power of P_{CPLm}. The cable is represented with the parameters of R_{cm}, L_{cm}, and C_{cm}. To simplify the model, the line impedance can be neglected, and the simplified model is shown as Fig. 7(b), in which C_{eq} is the equivalent capacitor of all the capacitors and P_{CPL} is the sum of all the CPL power. The dynamic model is represented by

$$\begin{cases} C_{eq}\dfrac{dV}{dt}=\sum\limits_{k=1}^{n} i_k-\dfrac{P_{CPL}}{V} \\ L_{fk}\dfrac{di_k}{dt}=E_k-R_{fk}\cdot i_k-V \quad \forall k=1,\dots,n \end{cases} \tag{2}$$



(a) Circuit model of a DC-SMG with n sources and m CPLs.

(b) Simplified circuit model of a DC-SMG.

Fig. 7. Circuit model of a DC-SMG.

Linearize (2) by a Taylor series expansion, using only the first two terms, as follows:

$$\begin{aligned} \frac{dV}{dt} &= f(V,i_1,\dots,i_n) \\ &\approx f(V_0,i_{10},\dots,i_{n0})+\frac{\partial f}{\partial V}\Big|_{V_0,i_{k0}}\cdot(V-V_0)+\sum_{k=1}^{n}\left[\frac{\partial f}{\partial i_k}\Big|_{V_0,i_{k0}}\cdot(i_k-i_{k0})\right] \end{aligned} \tag{3}$$

$$\begin{aligned} \frac{di_k}{dt} &= g(V,i_k,E_k) \\ &\approx g(V_0,i_{k0})+\frac{\partial g}{\partial V}\Big|_{V_0,i_{k0},E_{k0}}\cdot(V-V_0)+\frac{\partial g}{\partial i_k}\Big|_{V_0,i_{k0},E_{k0}}\cdot(i_k-i_{k0}) \\ &\quad +\frac{\partial g}{\partial E_k}\Big|_{V_0,i_{k0},E_{k0}}\cdot(E_k-E_{k0}) \end{aligned} \tag{4}$$

In (3) and (4), V_0, i_{k0}, and E_{k0} (k=1, …, n) are chosen at steady-state conditions. From (3) and (4), the small-signal model is obtained as (5).

$$\begin{aligned} \begin{bmatrix} \dfrac{d\Delta V}{dt} \\ \dfrac{d\Delta i_1}{dt} \\ \dfrac{d\Delta i_2}{dt} \\ \vdots \\ \dfrac{d\Delta i_n}{dt} \end{bmatrix} &= \begin{bmatrix} \dfrac{1}{C_{eq}R_{CPL}} & \dfrac{1}{C_{eq}} & \dfrac{1}{C_{eq}} & \cdots & \dfrac{1}{C_{eq}} \\ -\dfrac{1}{L_{f1}} & -\dfrac{R_{f1}}{L_{f1}} & 0 & \cdots & 0 \\ -\dfrac{1}{L_{f2}} & 0 & -\dfrac{R_{f2}}{L_{f2}} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -\dfrac{1}{L_{fn}} & 0 & 0 & \cdots & -\dfrac{R_{fn}}{L_{fn}} \end{bmatrix} \cdot \begin{bmatrix} \Delta V \\ \Delta i_1 \\ \Delta i_2 \\ \vdots \\ \Delta i_n \end{bmatrix} \\ &+ \begin{bmatrix} 0 & 0 & 0 & \cdots & 0 \\ 0 & \dfrac{1}{L_{f1}} & 0 & \cdots & 0 \\ 0 & 0 & \dfrac{1}{L_{f2}} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & \dfrac{1}{L_{fn}} \end{bmatrix} \cdot \begin{bmatrix} 0 \\ \Delta E_1 \\ \Delta E_2 \\ \vdots \\ \Delta E_n \end{bmatrix} \end{aligned} \tag{5}$$

Based on the small-signal model, stability analysis can be accomplished by using Nyquist or Bode diagrams [77].

3) Stability enhancement methods

To enhance the small-signal stability, proper control techniques can be imposed on the generation side. Active damping is a simple yet effective method to improve system stability. The principle of active damping is emulating a virtual impedance by control to compensate for the negative impedance on CPL. By adding the information of the DC bus voltage into the power reference, the system stability can be improved [78]. Another technique is linearization via state feedback (LSF), which implements a gain directly to compensate for the nonlinear term in CPL and cancels the instability with a good performance. After the system nonlinearity is compensated, conventional linear control techniques can be applied for the desired pole placement [76], [75]. It should be noted that LSF can only be applied to converters with enough regulation bandwidth. A comparison between active damping and LSF can be found in [14]. A decentralized linear-quadratic Gaussian (LQG) control approach for generator-side converters in MVDC SMG is studied in [34]. In this approach, the multi-generator system is modeled by the state space average model, and the nonlinear CPL is modeled as a virtual disturbance and considered as an additional state to be estimated, then the stable operating point can be obtained and applied in the linear quadratic regulator.

B. Stability analysis on pulsed loads

In military ships, there are special load types equipped, such as radars, electromagnetic launch systems, free electron lasers, aircraft launchers, and rail guns. These loads require the periodical power from hundreds of kilowatts to tens of gigawatts with the durations varying from several microseconds to a few seconds [79], [80], [81]. These types of loads are categorized as pulsed loads. Pulsed loads feature not only large peak power but also high power ramp rate, therefore, resulting in significant impacts on the DC bus voltage and system stability.

The ideal power profile of the pulsed load within one period features as (6) [82].

$$P_p(t)=\begin{cases} P_{p\max}, & t_0<t\le t_0+t_p \\ 0, & \text{others} \end{cases} \tag{6}$$

in which, P_{pmax} is the power amplitude of the pulsed load, t_{p} is the pulse signal duration.

1) Large-signal modeling and stability analysis

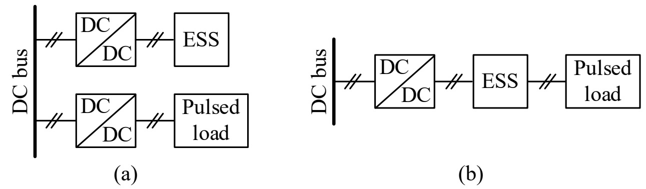
Large-signal stability analysis suits for analyzing the conditions with large disturbances, such as large load variations, loss of sources, and line faults [83]. Therefore, it can be used for studying the stability of pulsed loads in DC-SMGs to capture the large-signal effects. This technique employs nonlinear models and estimates the domain of asymptotic stability through Lyapunov-based methods [84]. In [85] and [86], the DC-SMG with pulsed loads is formulated as a Hamiltonian surface based on Hamiltonian surface shaping and power flow control (HSSPFC), which can predict the stability boundary at a wide time range. A meta-stability is defined that when the pulsed load is active, the system can be in an unstable state, while when the pulsed load is inactive, the system damps back to the stable state. Nevertheless, the boundaries of instability during the active state of pulsed load are not clarified. In [87], a sum-of-squares optimization is used to analyze the nonlinear dynamics of the system with pulsed loads. From a system-level viewpoint, the stability can be achieved by ensuring each subsystem being stable. This idea is adopted in [88], in which the system gain matrix is formed by evaluating the input-output gains of each subsystem.

The stability analysis of SMG with pulsed loads refers to two aspects. The first one is analyzing the stability of system variables in the entire pulse duration time. Here, the pulse shape is not considered and the pulsed load duration is seen as a unit. From this viewpoint, during the entire pulse time, in which case the pulsed loads iteratively charging and discharging, the shipboard power system variables should have a periodic alternating process rather than merely equilibrium points to keep stable. Thus, the system stability can be studied by periodic-orbit stability method and state-space averaging method [89], [90].

The second aspect focuses on the change of system variable status in one pulse period. As the shipboard pulsed loads usually require large power demand within a short time, it may cause the overcurrent of power sources and voltage sag in DC bus. From this aspect, to some extent, the pulsed load demand is like a large disturbance in general MGs. Thus, the transient stability analysis is necessary to study the impact of pulsed load in one pulse period. Besides, the pulse shape may affect the system variables. A demonstration of the system variables under triangular and rectangular wave pulsed loads is presented to show the difference [89].

2) Stability enhancement methods

Currently, most studies about the effect of pulsed loads on the SMGs focus on the ways of mitigating the potential instability. There are two ways to balance the generation-demand during the pulsed load operation. One approach is activating load shedding and reduce the power consumption of less important during pulsed load operation [91]. The other method, which is more general, is using the ESS to regulate power balance. The HESS consists of UCs, flywheels, and batteries is a common solution to meet the pulsed load demand and ensure system stability. There are mainly two architectures of integrating the ESS to mitigate the impact of pulsed loads. One is that the ESS feeds directly to the DC bus, as recommended in IEEE Std. 1709-2010 [92], as shown in Fig. 8(a) [93], and the other is that the ESS acts as a buffer for pulsed loads by connecting through the dc/dc converter in pulsed load side, in which way the ESS absorb energy from DC bus then supplies to the pulsed load, as shown in Fig. 8(b) [90], [94]. Both architectures can fit well. Detailed control strategies on ESS can be found in [16], [53], [94], [95], [96].



(a) (b)

Fig. 8. Two architectures of integrating ESS to mitigate the impact of pulsed loads.

C. Stability analysis on system architectures

Typical DC-SMG architecture includes radial, zonal, and ring configurations, in which multiple buses are designed in order to enhance system survivability [92]. Therefore, the line impedance network of the DC-SMG is complex and may cause severe stability issues. When analyzing system stability, the DC bus is represented by the cables with parameters of line impedance, and the state-space representation is obtained through Kirchhoff current law [65], [97].

The system architecture may induce some challenges in analyzing stability from two aspects. One is line impedance challenge caused by the cable aging process, which is inevitable in ships due to the salty and humid operation environment and is severer than terrestrial applications [69]. In this case, the line impedance may deviate from the nominal value gradually, and affect the stability of the originally designed steady-state operating point. The cable length in ships is typically from tens to a few hundred meters, so the impedance variation can be seen as a small disturbance to the system. Therefore, in the early stage of controller design and small-signal stability analysis, this characteristic has to be taken into consideration.

The other stability issue related to system architecture is shown in the post-fault reconfiguration process. In case of a fault occurring and the system reconfiguration being activated, the system architecture may change from one type to another. This change requires a large-signal stabilizer to ensure system stability. Currently, the effect of typical DC-SMG architecture on system stability and their comparison, as well as corresponding stabilizers are rarely studied in existing literature, and it could be a future research direction.

IV. PROTECTION SYSTEMS FOR DC-SMG

Due to the high requirements for reliability, survivability, and robust power distribution in DC-SMGs, a well-designed protection system is necessary. Key design criteria for the protection system are reliability, speed, performance, economics, and simplicity [98].

Fault types that potentially happen in DC-SMGs are short circuit faults, open circuit faults, and communication malfunction. In stand-alone SMGs, open-circuit is more of a control strategy issue after faults, while communication malfunction is more about sensor devices and data management. Therefore, this section mainly discusses the short-circuit faults in DC-SMGs.

There are many challenges in designing the protection system for DC-SMG. The presence of shipboard pulsed loads, which feature a large peak power and power change rate, makes it difficult in fault management that the shipboard protection system has to distinguish the normal current caused by pulsed loads and the fault current. Besides, since the SMG is a mobile islanded power system without 'ground', it is difficult to design the grounding system. Also, the common challenges in DC power systems still exist in DC-SMGs, such as lacking zero-crossing of current, which results in arc flash in the circuit breaker.

Besides ensuring the safety of power systems in SPSs, the security of the crew has to be considered as a part of protection system design. Thus, there is a strong demand for monitoring the health of shipboard electrical appliances by detecting the leakage current flowing from the live part of the installation to the ground [99].

A. Requirement for protection of DC-SMGs

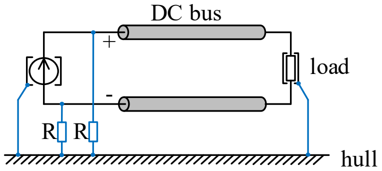
For the SMG, regardless of the system topology, the system must be able to survive after faults with minimum energy feeding the faults [100]. The general requirements for ship protection system design should comply with IEC 60092-101:2018 [101]. IEEE Std. 1709-2010 [92] also presents protection and survivability requirements on circuit breakers (CBs), voltage limiters, sensors, and surge arresters for DC-SMGs. In [19], more detailed requirements of fault management are overviewed, including requirements on current sensors, timing and fault isolation, selectivity (relay coordination), communication and automation infrastructure, as well as standardization and interoperability.

To ensure the secure operation of maritime systems, the protection system needs to fulfill the requirements of sensibility in fault detection, selectivity, and fast speed in fault isolation, reliability, simplicity, and economy.

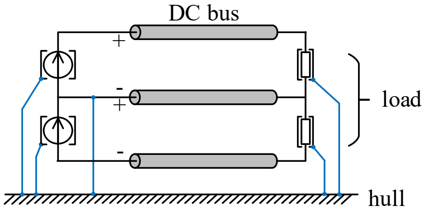
B. Grounding system

A significant feature of SMG is lacking the ground, making the grounding system of DC-SMG a big challenge. If adopting ungrounded in DC-SMGs, the leakage current and the line-to-ground fault current can be small, making the power supply continuity in case of a single line-to-ground fault [102]. However, just due to the low current, it is difficult to detect and locate this fault. Furthermore, the small leakage current leads to large common-mode voltage, making a high requirement on shipboard equipment insulation level and high risk to the person.

In some cases, the hull is regarded as the ground. According to IEEE Std. 1709-2010 [92], there are two feasible grounding options for bipolar DC-SMGs: grounding with high resistance, and grounding with a solidly grounded neutral point, as shown in Fig. 9 [103]. In a bipolar DC bus with a high resistance ground architecture, each pole has to withstand the full bipolar DC voltage during unbalanced voltage conditions. In maritime applications, the DC-SMGs are expected to run even with a single line-to-ground fault, so grounding with a high resistance is preferred [19]. On the other hand, in DC bipolar arrangement with a solidly grounded neutral point architecture, the insulation level is half that of voltage to ground and can work in an emergency at half power with one of the two poles out of service. However, all load feeders require a neutral cable to return the unbalanced and fault current back to the solid DC ground.



(a) Bipolar arrangement with resistance ground



(b) Bipolar arrangement with a solidly grounded neutral point

Fig. 9. Grounding systems of DC-SMGs.

C. Short-circuit fault management in DC-SMGs

Extremely high fault current is a problem in DC-SMGs, resulting from the increasing generation capacity and low impedance network in modern electric ships. However, the pulsed loads with large peak power and power change rate bring challenges in fault detection, while it is required to detect faults within several or a few tens of milliseconds [104]. A typical DC fault current in DC-SMG is the sum of the capacitive discharge current which is contributed by the DC-link capacitors followed by the fault current supplied by the interfaced power sources. The fault management process includes fault detection and localization, fault isolation, and post-fault reconfiguration.

1) Fault detection and localization

In DC-SMGs, two facts make the fault detection and location a challenge: 1) Due to the presence of pulsed loads, which require high transient power, the normal current of pulsed load may be difficult to distinguish from fault current within a very short time. 2) The scale of SMGs is much smaller than terrestrial MGs, resulting in the differences of short-circuit impedances in different locations among the DC-SMG are not significant, and the fault current magnitude is similar wherever the fault occurs. Therefore, extra precautions must be taken to detect the fault accurately and fast. In [105], a data clustering-based fault detection approach that extracts unique feature vectors of the pulsed loads by using short-time Fourier transform analysis is presented to identify the pulsed load transient in naval SMG, thereby distinguishing from the real faults.

Depending on the characteristics of different fault types, various fault detection methods are required. For instance, a single-point grounding fault in cascade BESS is detected by monitoring the system neutral point voltage, while a two-point grounding fault requires overcurrent protection [106]. The existing fault detection and localization methods for DC-SMGs in literature are overviewed in TABLE I. It can be found that overcurrent protection and directional protection are relatively simple and mature, but since they need the current information to trigger the protection, they may not be suitable for ships with large pulsed loads. On the other hand, wavelet transform- (WT-) based, artificial neural networks- (ANN-) based, and active impedance estimation- (AIE-) based methods can fast and accurately detect the faults, but might have difficulty in computation.

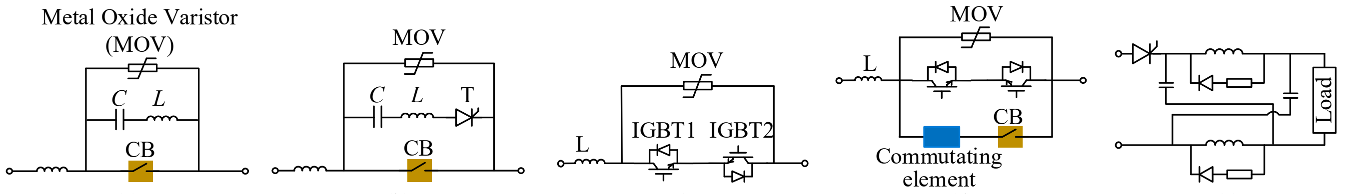
2) Fault isolation

After detecting and localizing the fault, selective tripping has to be operated to isolate the faulty area. A general classification of fault isolation in DC-SMGs is breaker-based and breaker-less approaches. In the first category, the challenge lies in lacking zero-crossing current yet high voltage in DC-SMGs. Currently, the fuse for DC networks can sustain voltage up to 4.2kV, which can meet the need in many commercial ships, such as ferries and vessels. As the fuses are one-time devices, which need to be replaced after being successfully operated, reusable breakers are necessary to facilitate the operation.

There are several CBs suitable for DC-SMGs, as summarized in TABLE II. The most simple and mature solutions are the DC CBs with passive/active resonating circuits, as shown in Fig. 10 (a) and (b). The fault clearing time of passive resonance DC CB is in the range of tens of milliseconds, which cannot meet the requirement of DC-SMG (less than 8ms [107]). While ABB has developed an active injection resonance DC CB which can interrupt up to 10kA fault current in a 80kV system within 5ms in 2014 [108]. Besides, the solid-state CBs (SS CBs), shown in Fig. 10 (c), are becoming popular in DC-SMGs in recent years due to their fast time response. A high current SS CB developed by ABB can detect a fault current within 10µs, limits the fault current to 20µs, and dissipates the fault energy within 500µs [109]. The adoption of SS CBs in zonal DC-SMGs is studied in [25], [26]. The hybrid CB shown in Fig. 10 (d) combining the advantages and overcome the disadvantages of the mechanical and SS CBs is an option for DC-SMG as well. In hybrid CBs, the commutating element can be an inductor or a superconductor coil to aid commutation [110]. In [111], a study case of integrating Z-source breakers into zonal DC-SMG is presented. The structure of Z-source CB is shown in Fig. 10 (e). From the comparison of these DC CBs presented in TABLE II, it can be found that passive and active resonance DC CBs have a simple structure, even the active ones can interrupt fault current within 5ms, while their biggest problem is the risk of arc when disconnecting the fault. Therefore, there are only suitable for small-size ships with low voltage and current. For large ships with high safety requirements, the SS

TABLE I. COMPARISON OF DIFFERENT FAULT DETECTION METHODS

Method	**Operation**	**Advantages**	**Limitation**
Overcurrent protection [129], [130], [131]	Triggers the relays when the current exceeds the predefined threshold within several ms.	1) Low cost. 2) Simple, no communication needed. 3) Limit the instantaneous overcurrent to avoid power converter damage.	1) Malfunction in the presence of pulsed loads. 2) Malfunction when reconfiguring the propulsion motors. 3) Long fault clearance time in complex architecture.
Directional overcurrent protection [132]	Triggers the relays by estimating the current direction and overcurrent.	1) Requiring only low-bandwidth communication.	1) Malfunction in zonal and ring networks with normal bidirectional current. 2) Long sampling time. 3) Communication required.
WT-based method [133], [134]	Extracts the signal feature of fault current in time and frequency domain.	1) Suitable for analyzing pulse signal 2) Fast and effective. 3) Can be used as a hybrid method with other methods.	1) Difficulty in wavelets selection. 2) Significant computational burden.
ANN-based method [135], [136]	Feeds the extracted features of fault into the ANN for fault detection.	1) Accurate and robust.	1) Requires a huge data of faulty system for training the neural network. 2) Incapable of online fault localization. 3) Only specific to the trained network.
AIE-based method [137], [138]	Triggers the relay when the real bus impedance is not equal to the pre-calibrated value.	1) Accurate and fast.	1) Difficulty in obtaining the accurate system impedance during the system operation.



(a) (b) (c) (d) (e)

Fig. 10. Schematic of DC CBs: (a) passive resonance DC CB; (b) active resonance DC CB; (c) IGBT-based solid-state CB; (d) hybrid CB; (e) Z-source CB.

TABLE II. COMPARISON OF DC CIRCUIT BREAKERS

	Advantages	Drawbacks
Passive resonance dc CB [21]	1) Simple design.	1) Long fault interruption time (tens of ms). 2) Risk of arc. 3) Requiring a large inductance.
Active resonance dc CB [21]	1) Fast interruption time (<5ms). 2) Simple design.	1) Risk of arc. 2) Requiring reliable injection switch. 3) Requiring to charge the capacitor.
SS CB [25]	1) Ultra-fast protection speed ranging from several μs to less than 1ms. 2) No risk of arc.	1) High cost of semiconductor switches. 2) High ON-state losses. 3) Requiring strict fault detection and timing.
Hybrid CB [139]	1) Fast interruption time (few ms). 2) Low operating losses. 3) No risk of arc.	1) The commutating element may lead to additional losses or other requirement, e.g., needing cryogenic system. 2) Increased cost and size.
Z-source CB [140]	1) Natural commutation. 2) Lower cost than SS CB. 3) No risk of arc.	1) Insensitive to small transient fault. 2) Could not provide prolonged protection.

CBs are preferable due to the capability of fast interruption without arc, even though the cost and losses are higher. In case of fast fault interruption and high-efficiency requirement, hybrid CBs that combining the benefits of mechanical CBs and SS CBs can provide a solution. Z-source CBs can also interrupt the fault current without arcing, and the cost is lower than SS CBs. However, because of the commutation principle, Z-source CBs cannot operate for less severe fault.

The breaker-less protection is based on the coordination of converters and contactors. An overview of fault isolation methods in component level for DC-SMGs is presented in [19]. Besides, a system-level fault isolation scheme for DC-SMG is studied in [104], in which three protection levels consisting of fast action by SS DC bus-tie switch, medium action of feeder protection by fuse, and slow action by generator-rectifier fault control are adopted. In practical applications, to coordinate multiple converters and contactors, the breakerless protection system complexity associated with fault detection and localization is increased, and the fault isolation time is generally longer than that of DC breaker approaches. To ensure the safety of power electronic converters, a combination of different isolation methods can be used. For instance, the active-controlled internal semiconductor switches can block the module or entire converter in case of faults, and the DC breakers are set as backup protection.

3) Post-fault reconfiguration

When the fault is isolated, a proper reconfiguration strategy has to be implemented to ensure power supply continuity to vital shipboard loads, and the settings of the protection devices should be updated. The DC-SMG reconfiguration is governed by selecting bus architecture and load shedding [19]. The bus architectures for DC-SMGs include radial [112], ring [113], and zonal ones [114], among which the zonal architecture has the highest reliability level. A zonal system can be reconfigured to a ring scheme, and further to a radial one when necessary. The port and the starboard buses in a DC-SMG are separated in normal condition; while when a fault occurs in one bus, the bus breakers act to isolate the fault and re-energize the healthy part, and the network is reconfigured. Besides, another strategy is the self-healing reconfiguration method that subdivides the zonal system into several zones and then reconfigures after clearing the fault. Load shedding provides a way to ensure a continuous power supply for vital loads and maintains the critical marine mission when faults occur. The loads in ships are classified into three groups according to their priority, namely vital, semi-vital, and non-vital loads. The objectives in designing load shedding algorithms are to update the load priority in real-time, and minimize the number of loads disconnected [61]. In some cases, advanced algorithms are used to achieve reconfiguration objectives. Common reconfiguration objectives in the literature include the system loss minimization [115], delivery power maximum [116], preserving the stability margin [117], and load service quality maximum [118]. In addition, there are some approaches to ensure power continuity during the interruption, such as providing battery supplied power to critical loads, and implementing ride-through on downstream inverter-fed motors.

D. Leakage Protection

Leakage protection refers to personal protection against faulty situations. It requires monitoring and protection measures that can send alarm signals and disconnect the sources if the leakage current of the facilities exceeds the preset values.

The protection of DC leakage current requires specific residual current devices (RCDs) [119]. In the application of DC-SMGs, in which the residual current contains a smooth DC component, a type B RCD complying with the International Standard IEC 62423 is required [120]. The type B RCDs can detect the leakage current containing dc, high-frequency AC components, and 50/60Hz AC components. The tripping threshold of the RCDs is designed below the personal safety threshold to ensure the protection of humans and higher than the capacitive earth leakage current to avoid unwanted tripping.

The main challenge in designing the RCDs lies in the

TABLE III. PRACTICAL CASES OF DC-SMG

Case (Year)	Type	Company	Power	Capacity	Voltage	Detail information
Royal Princess (2012) [1]	Cruise ship	Fincantieri Shipyard Italy	78 MVA	N/A	11 kV	Generators: 2×21MW+2×18MW.
Dina Star (2013) [141]	PSV	Kleven Maritime Norway	10 MW	N/A	1 kV	Generators: 4×2.35MW+1×0.97MW.
Edda Ferd (2013) [142],[143]	PSV	Østensjø Rederi AS Norway	11MW	338 kWh	700V	Generators: 2×2.2MW+2×3.3MW+158kW; Batteries: 52×6.5kWh.
Fannefjord (2014) [144], [145]	Ferry	Fjord1, Norway	2.8MW	410kWh	1050V	Two LNG engines (2×900kW), one diesel engine (1000kW) and battery hybrid system.
ReVolt (2014) [146]	Short-sea vessel	DNV GL	N/A	3MWh	N/A	Autonomous and unmanned, fully battery powered.
Ampere (2015) [147]	Car ferry	Norwegian Shipyard Fjellstrand	900kW	1MWh	810-1050V	All-electric-ship. Batteries: 2×520kWh.
M/F Tycho Brahe, M/F Aurora (2017) [148], [149]	Ferry	HH Ferries Group Denmark	11MW	4160 kWh	1kV	Gensets: 4×2.6MW; Lithium batteries: 640×6.5kWh.
Future of The Fjords (2018) [150]	Catamaran	The Fjords DA	1.8MW	1.8MWh	1kV	All-electric-ship. Batteries: 2×900kWh.
USS Zumwalt DDG-1000 destroyer (2008) [151]	Destroyer	US Navy	78 MW	N/A	4160V	Prime movers: 2×35.4MW+2×3.8MW.

detection of leakage current. Conventional leakage current detection methods include balanced bridge method [121], unbalanced bridge method [122], and AC signal source injection method [123]. However, these methods are incapable of automatic real-time detection and warning. Besides, the RCDs can only act to the total imbalance between the phase line and the neutral line, and cannot act to an individual appliance [99].

Advanced techniques provide solutions for leakage current monitoring that can overcome the drawbacks of conventional methods. The event-based non-intrusive current measurement can measure the real-time currents on wires by extracting information from appliance states captured by the sensor array [124]. Another non-instructive load monitoring (NILM) for fault detection and isolation in the shipboard application is demonstrated in [125] and shows its effectiveness.

V. CASE STUDIES

Up to now, the concept of DC-SMGs has been utilized in a few commercial products. ABB and Siemens have developed DC-SMG solutions for customers. The Onboard DC Grid developed by ABB is a modular power system platform comprising modules of power sources (e.g., variable speed generators, energy storage, and fuel cells), propulsion, automation, and advisory systems, and has been installed on a wide range of vessel types including ferries, platform supply vessel (PSV), offshore service vessels (OSVs), and a cable layer [126]. This integrated system has benefits in efficiency, weight and space arrangement, operation flexibility, and safety [127]. The first delivery of the Onboard DC Grid system was to the PSV ‘Dina Star’ in 2013. Siemens also developed the Blue Drive PlusC electric propulsion system [128], which enables flexible shore connection, as well as the common benefits in DC systems. Both the Onboard DC Grid system and the Blue Drive PlusC system are arranged in radial architecture.

Practical cases using DC-SMG in real ships are listed in TABLE III. Some of these are retrofitted from the traditional structure, keeping the original diesel-powered engines and adding batteries, e.g., M/F Tycho Brahe and M/F Aurora, so that the ships can run on a full battery, full diesel or a hybrid set-up. Norway and Italy lead the pack in DC-SMGs studying and commercialization. For small ships, such as ferries, short-sea vessels, and some platform supply vessels (PSVs), the system voltage is around 1kV, and AES commercial products are already existing. While higher power (>10MW) ships still need diesel generators or LNG generators to supply as the main power source, of which the rated power is usually different, namely main and auxiliary generators. In these high power ships, medium voltage (>3kV) power system is adopted.

VI. CONCLUSIONS AND FUTURE DIRECTIONS

In this paper, the cutting edge of DC-SMG coordinated control, dynamic stability analysis, and fault management are reviewed. Besides, commercial prototypes applying DC power architecture are presented to indicate the developing trend.

Coordinated control methods in DC-SMGs will continue to evolve in the coming years. The control schemes are deducted from those used in terrestrial DC MGs. However, we need to consider the limitations in vessels, such as very weak grid conditions, lack of inertia, larger transient frequency and control deviations, limitations on communications since compartments and engine rooms are often built on steel, electromagnetic interference (EMI) issues, and so on. Hierarchical control architecture is used in many study cases. Adaptive droop control strategies are commonly designed in the primary control level of the power converters to achieve proper power sharing among power generators and ESS. The power sharing of HESS depends on the load profile and characteristics of energy storage units. The secondary control focuses on voltage regulation that compensating for the voltage deviations caused by droop control. While the tertiary control is implemented with the EMS in which various control objectives are achieved by advanced algorithms.

In order to achieve more stable control performance and a longer lifetime of ESS, the coordinated control among different ESS types has to consider the character of each energy storage unit. As the capacity of ESS is increasing in DC-SMGs, in the system with numerous parallel- and series-connected batteries, the states of batteries, including battery capacity, state of charge, temperature, and state of health, has to be balanced or managed properly. To achieve this object, all this information has to be considered in coordinated control. In addition, ultra-capacitors, flywheels, and other advanced ESS techniques are utilized to achieve fast response to the specific shipboard load profile, in which case, the principle of coordinating different ESS types need further studies. Besides, advanced algorithms may be used to achieve more efficient operations.

The voltage stability in DC-SMGs, including small-signal and large-signal analysis, is a vital issue in marine applications, due to the presence of CPLs and pulsed loads. The stability of CPL can be analyzed by small-signal analysis approaches. Due to the mismatch between source-side lightly damped filters and the load-side tightly regulated power converters, approaches such as active damping and linearization via state feedback are used to suppress the impact of CPLs. As for the pulsed loads, the parameters of the pulsed signal may affect the performance. The instability caused by pulsed loads has to be analyzed by large-signal methods in the nonlinear model.

Protection of DC-SMGs meets many technological challenges in terms of standardization, grounding system design, protection devices, system reconfigurations, and so on. IEC 60092-101:2018 and IEEE Std. 1709 provide standards and recommendation on the requirements of the protection system. The grounding system for bipolar DC-SMGs can be realized by resistance grounding or solid grounding to the hull. Fault management that including fault detection, fault isolation, and reconfiguration are reviewed. The pulsed loads bring challenges in fault detection and localization methods, and advanced methods are required to achieve this task. Existing protection schemes generally use a combination of fuses, isolators, breakers, and converter control to effectively protect the system. Reconfiguration after faults can be achieved by optimizing the bus architecture and load shedding according to various advanced and optimal algorithms and load importance, respectively.

Finally, commercial cases of DC-SMGs are introduced. Various ship types have already installed DC-SMGs, such as cruise ship, ferry, PSV, and destroyer. Currently, for ships less than 1MW, low voltage DC system architecture is usually adopted; while for larger ships that demand more than 10MW, MVDC architecture is required, and generators with different rated power are equipped to coordinate in various operation modes.

The future research trends of DC-SMGs from the aspects of coordinated control, stability analysis, and protection design may be developed from the following points:

1) Characteristics of energy storage devices need to be more comprehensively and thoroughly considered in coordinated control to achieve more stable control performance and longer lifetime of ESS. Different kinds of ESS with different dynamics and costs will coexist in the SMG, such as batteries and fuel cells, to name a few. Coordinated control may consider the different dynamics and costs, as well as constraints, to allow proper operation, this may impact the coordination control levels corresponding to the secondary and tertiary hierarchical control levels.
2) The mechanism and the impact of shipboard pulsed loads still need further detailed study. Afterward, effective and efficient methods that mitigate the instability of pulsed loads should be studied to ensure stable operation of the DC-SMGs.
3) Future researches may aim at providing accurate and fast fault detection methods that can distingue fault current from normal current feeding pulsed loads are necessary for reliably and safe operation of DC-SMGs. In current studies, fault detection distinguishing the normal condition when activating pulsed loads and the faulty condition is still a challenge in DC-SMG protection. Besides, coordinated protection and reconfiguration are necessary for higher survivability.
4) The leakage protection in the shipboard application is necessary but still limited. Considering the grounding system in DC-SMGs, corresponding real-time leakage current detection methods need to be further studied.
5) Although the survivability assessment criteria are vital for improving the SMG systems, it is still an immature field of research. Existing studies on the DC-SMG survivability are mainly from the viewpoint of topological survivability and resilience to sensor faults. Quantitative survivability assessment is expected in the future.

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