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Next-Generation Shipboard DC Power System

Introducing smart grid and dc microgrid technologies into maritime electrical networks.

In recent years, evidence has suggested that the global energy system is on the verge of a drastic revolution. The evolutionary development in power electronic technologies, the emergence of high-performance energy storage devices, and the ever-increasing penetration of renewable energy sources (RESs) are commonly recognized as the major driving forces of the revolution. The explosion in consumer electronics is also powering this change. In this context, dc power distribution technologies have made a comeback and keep gaining a commendable increase in research interest and industrial applications. In addition, the concept of flexible and smart distribution has also been proposed, which tends to exploit distributed generation and pack together the distributed RESs and local electrical loads as an independent and self-sustainable entity, namely a microgrid. At present, research in the area of dc microgrids has investigated and developed a series of advanced methods in control, management, and objective-oriented optimization that would establish the technical interface enabling future applications in multiple industrial areas, such as smart buildings, electric vehicles, aerospace/aircraft power systems, and maritime power systems.

Maritime power systems can be traced back to the 1880s, starting with the earliest record of a dc-based onboard power system on the *SS Columbia*, where Edison's dc lighting system was first installed. In the last century, maritime power systems have been greatly developed along with the increasing demand of onboard electrical loads. During this development, shipboard power transformed from Edison's dc power system into Tesla's ac power system, as the use of electricity extended from the initial lighting to almost every aspect aboard a vessel where it was necessary to build upon the advances in the ac distribution infrastructure. In recent years, government regulation of emissions has become increasingly strict, while customers' fuel-efficiency requirements have risen. This has resulted in the current trend toward more efficient ships, the most emblematic of which is the all-electric ship (AES), which exploits an electrical propulsion system instead of the conventional mechanical system. One of the significant features of the AES is the concept of the integrated power system (IPS), which minimizes the number of generators in a ship by incorporating intelligent methods for meeting load demands through multiple paths and dynamically matching generational capability to loading needs. In broad terms, the shipboard IPS can be regarded as a large-scale, onboard microgrid with specific requirements. In recent studies, the current IPS research trend is turning to dc power distribution systems. This has resulted in advanced research outcomes in the dc microgrid field, especially in its advanced control, management, and optimization methods, all of which can be attributed to a wide body of AES research.

DC Power Architecture

The *Queen Elizabeth II*, the world's first cruise vessel with an electric propulsion system, is a high-profile example of an existing ac shipboard power system. The power architecture of its shipboard power system is shown in Figure 1. The vessel, originally steam powered, was built in 1968 and was converted from steam to diesel-electric propulsion in 1987. The ship was refitted with nine diesel generator sets rated 10.5 MW at 10 kV. The electric power plant is connected with the vessel's main bus, driving the two major 44-MW electric propulsion systems. The auxiliary loads and the hotel service loads are powered through transformers and power electronic converters. The conversion to a diesel-electric power system was expected to improve fuel efficiency by up to 35% at the vessel's service speed of 28.5 kn and save £12 million a year in fuel costs. However,

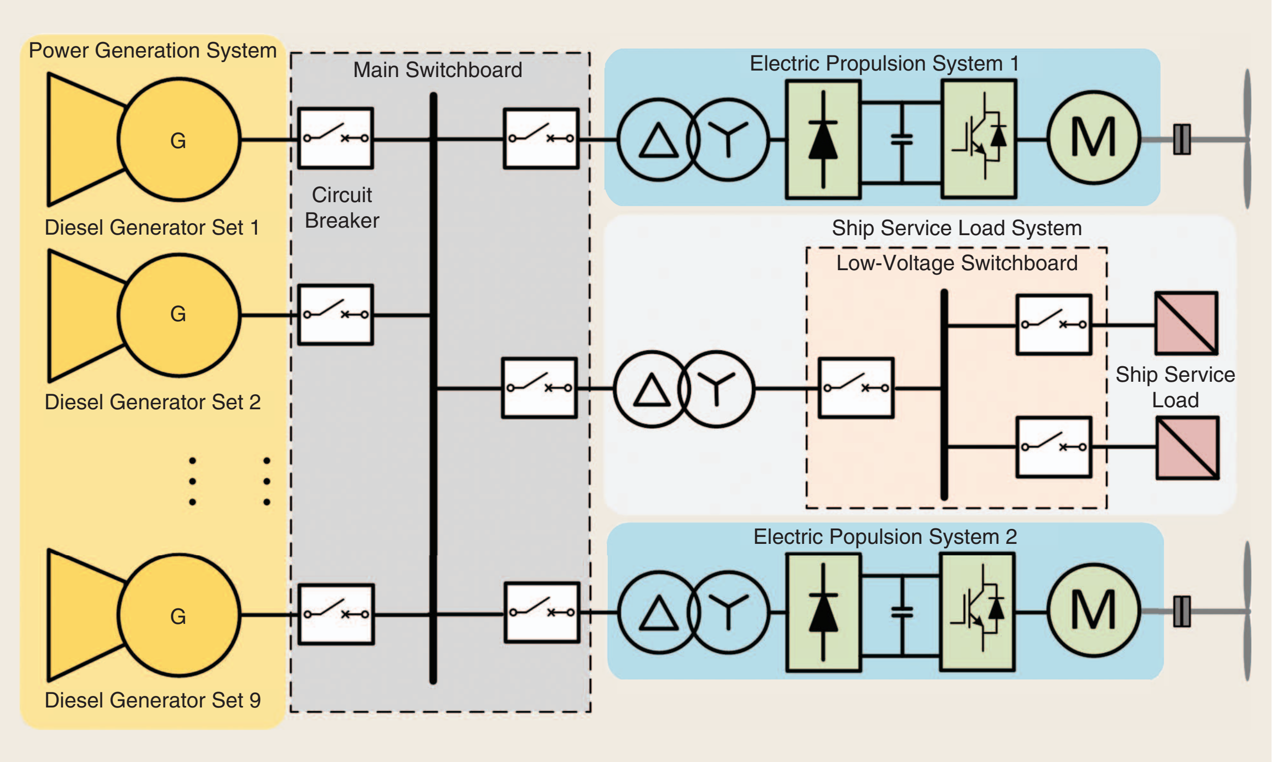


Figure 1. The diesel-electric shipboard power system of the *Queen Elizabeth II*.

as studies have progressed, researchers and engineers have noticed inadequacies in the ac power architecture that can be summarized as follows:

- generator sets have to work in fixed speed and thus limit further improvement in fuel efficiency
- the ac power architecture introduces unwanted reactive power flow and power quality problems (e.g., three-phase imbalances and harmonic currents)
- the bulky conventional transformers occupy too much valuable space and weight onboard
- there is a potential risk of systemic disintegration when supporting emerging pulsed electrical loads.

These problems also plague terrestrial power distribution systems, resulting in the current trend toward returning to dc-based power distribution systems. Edison's dc power system has once again led the second Industrial Revolution and brought a new era of light as well as electrification to humankind. It was overshadowed for more than a century after losing the famous "battle of the currents" due to its inherent inability (at that time) to change voltage levels without the addition of multiple motor–generator sets, thus making the system uneconomical to operate compared with the ac power system (which had at its disposal the simple transformer for changing voltage levels). But thanks to the rapid development of modern power electronic technologies, the high-frequency dc–dc converter has already qualified for taking on the role of transformer in dc systems. It therefore may allow Edison's invention to change the world once again. Just as Edison once strove to prove, it is becoming clear that the dc power system has several major advantages over the ac system, and even some newly recognized advantages, such as

- replacing bulky ferromagnetic transformers with compact power electronic converters
- easier parallel connection or disconnection for dc power sources
- elimination of harmonic and imbalance problems
- elimination of synchronization problems
- elimination of reactive power flow.

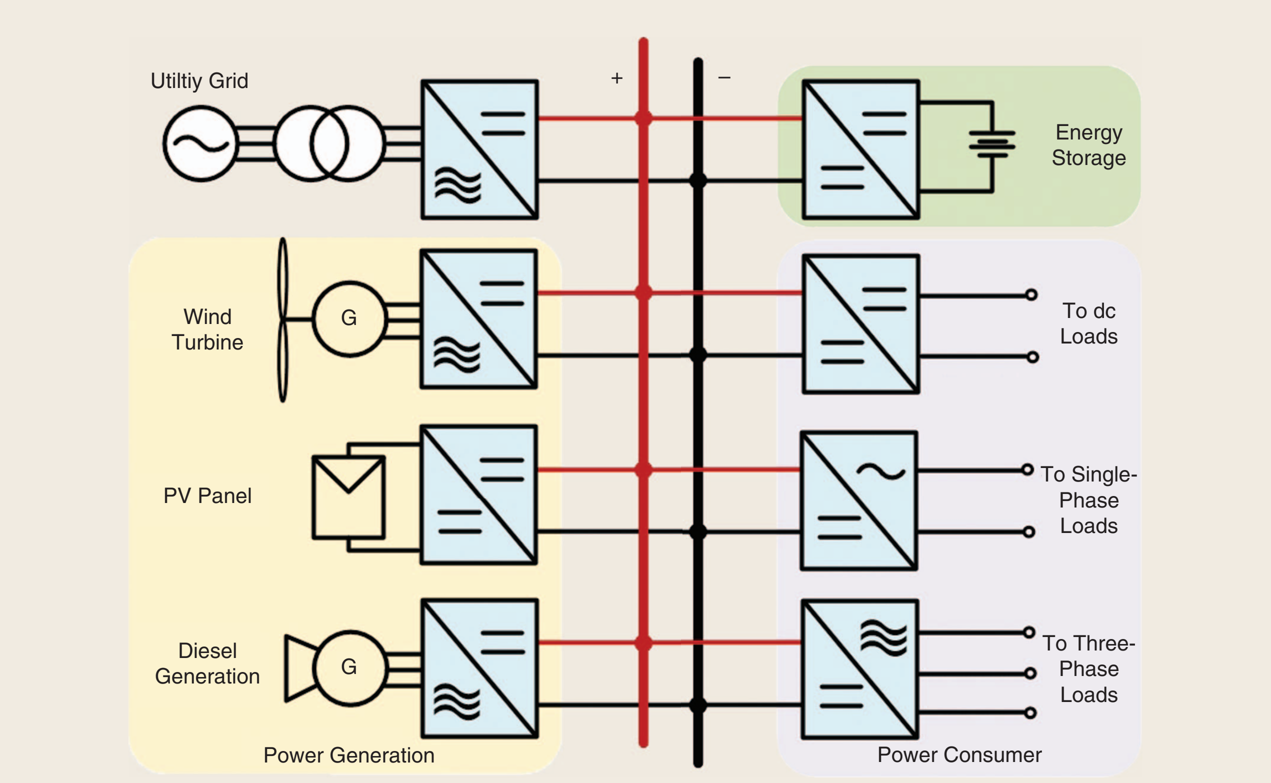
Just as Edison once strove to prove, it is becoming clear that the dc power system has several major advantages over the ac system, and even some newly recognized advantages.

Additionally, considering the specific needs of shipboard power systems, the dc-based IPS could bring a broad range of advantages for both commercial and mission-oriented ships. Generally, the dc power architecture will eliminate bulky low-frequency transformers and reduce the rating of switchgear, thus reducing the occupied space and overall weight of the whole system, which may result in extra cargo space. The commercial sector focuses on the 15% fuel saving due to allowing variable-speed diesel generators, whereas the military sector is interested in support for advanced electrical equipment and weapons, which are characterized by high-power pulsed loads. For these vessels (mainly warships), meeting these objectives requires a highly secured power supply. Moreover, a dc power architecture could provide better survivability, limitation of fault current, and reconfiguration capability. Besides that, the integration of advanced high-speed, high-efficiency diesel generation (i.e., gas turbine generation) could also be easily achieved within the dc power architecture, which could effectively improve the fuel efficiency of the system. Due to the higher power levels required in AES applications, the only available design option for a dc-based IPS is the medium-voltage dc (MVdc) solution with a dc bus voltage above 1 kV.

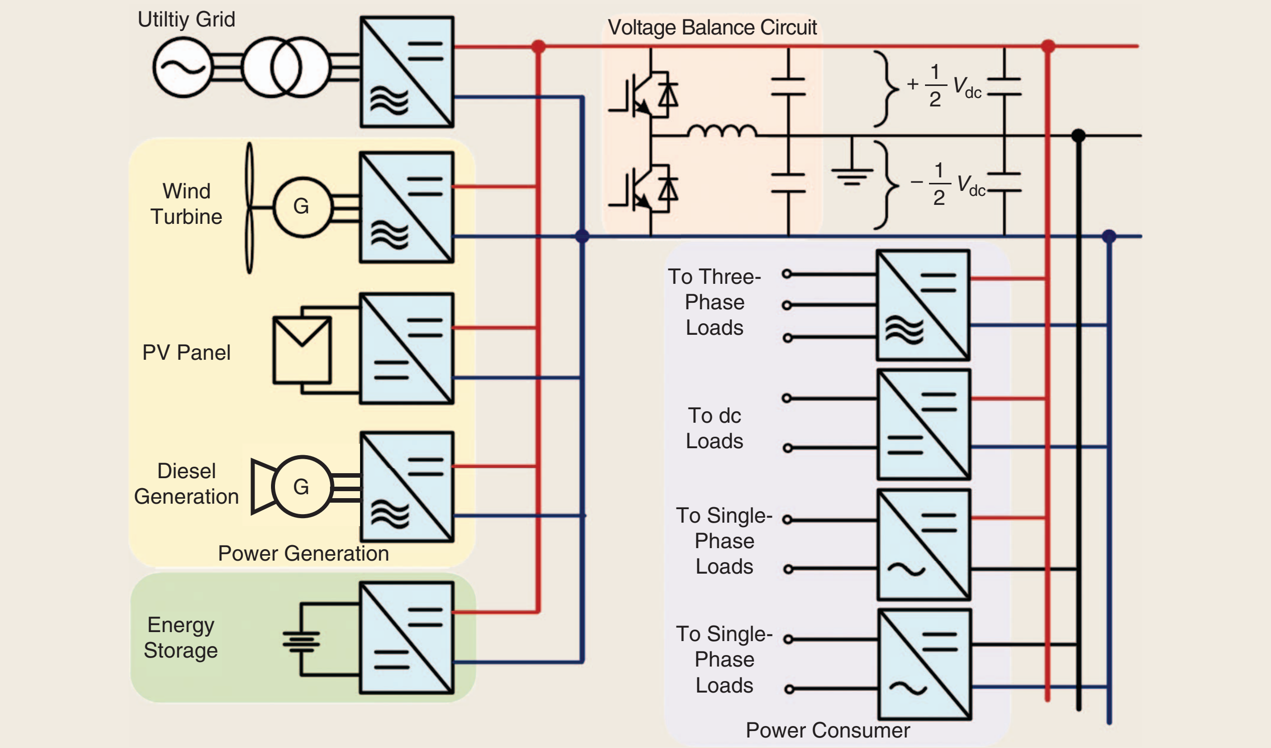
The typical power architecture of terrestrial dc microgrids is shown in Figure 2(a), where the RESs, energy-storage systems (ESSs), and local electrical loads are packaged together with the dc bus to enable islanding operation, which makes the system fully resistant to major blackouts in the main grid. The elimination of reactive power and synchronization problems makes the whole system much simpler to design, control, and coordinate. Moreover, with a well-selected nominal bus voltage, the overall efficiency will be generally higher than its ac counterpart. The three-wire, bipolar-type dc microgrid power architecture is shown in Figure 2(b). The architecture evolves from Edison's three-wire dc power distribution system, which was initially designed to save conductors. Compared with the typical architecture, the positive bus and negative bus can work independently if a fault occurs, which result in inherent redundancy and higher reliability. Moreover, it allows using a neutral bus with a low rated current if the loads on the positive bus and negative bus are roughly equal.

Figure 3 shows a ring-bus-based dc microgrid power architecture proposed for a critical load with higher security requirements (e.g., a data center). The ring bus allows energy flows along either the shortest path or a suboptimal path. That is, wherever a single fault occurs in the system, it can be isolated by switching off the nearest circuit breakers, allowing other parts to work as normal. This feature guarantees system survival from single-point failures. In addition, the ring bus allows the critical load to obtain energy from multiple nodes by applying either a conventional multiple-contact point switch or multiterminal converters. Accordingly, the critical load is highly secured to achieve uninterrupted operation.

A similar architecture can apply to the maritime power system, but the inner part of the system will be



(a)



(b)

Figure 2. Typical power architectures of a single-bus dc microgrid: (a) a common architecture and (b) a bipolar architecture. PV: photovoltaic.

divided into electrical zones corresponding to the feeds, and it will typically be laid out with generational sources on the two sides, designated as port and starboard and with a simple cross-connect in the forward and aft parts of the system, as shown in Figure 4(a). Such a system is commonly referred to as a dc zonal electrical distribution

Figure 3. A ring-bus-based dc microgrid.

system (ZEDS). Figure 4(b) shows the layout of the equipment in an electrical zone. Note that a large number of the loads in the zone are fed from both sides of the ship to enhance survivability. As opposed to a terrestrial power system, a maritime power system is inevitably restricted by the cabin structure of the vessel or offshore platform, so the size and weight of the overall system are important. To minimize the dc cabling size, voltage levels of greater than 6 kV are proposed for future combatants. For architectures as in Figure 4(a), the switches around the ring bus are there to isolate faults that may occur on the buses that distribute power to the zones. There are two approaches: breaker-based and unit-based. With breaker-based architectures, the switches must be actively controlled solid-state circuit breakers (SSCBs) combined with fast-acting no-load isolating mechanical switches. Such systems have the potential to provide a high quality of power during fault events (i.e., minimal power interruption), but the SSCB at these levels are still items in development that carries with it considerable risk. Intercommunication between adjacent SSCBs is necessary to isolate the fault because the dc ZEDS must be able to provide the same current from any direction.

With unit-based architectures, the power converters that interface with the electrical sources to the port and starboard buses play the primary role of driving the current to a fault on the bus to zero. The switches are all no-load switches. To be unit-based, the architecture in Figure 4(a) cannot have cross-tie switches between buses (i.e., where the battery-interfacing converters are), because when a fault occurs on a bus system, operation requires that critical loads within the zones autonomously shift their power sources to the healthy opposite bus. This is accomplished by diode auctioneering of power sources fed from both sides of the ship into the loads. Intercommunication between the switches and converters is necessary to determine where to isolate the fault. Once a switch isolates a fault, the power converters on the effective bus are reenergized, and all but the faulted part of the system is restored to operation. Communication is considerably more complex with the unit-based system, but the risks of implementation and system cost will be much lower when compared to the breaker-based model. The system in Figure 4(c) is an alternative architecture that utilizes SSCBs of different current rating levels on two buses and may be able to isolate faults using SSCBs but with minimal intercommunication. If generators are distributed between buses, this architecture provides an opportunity for operation with a high power quality bus on the inside, dedicated to feeding the low-voltage systems in the zones under normal conditions, and a lower-quality bus on the outside that is dedicated to high power loads and pulsed loads. These two buses can operate independently of each other if the SSCBs have reverse current-blocking capability. The architecture offers an opportunity for efficiency improvement in the ship by allowing the output bus to operate at a lower voltage than the inner bus when it is not necessary to operate at full propulsion speed.

These different power architectures are all feasible choices for the design of onboard dc power systems. However, there are always tradeoffs between reliability and complexity. Complicated power architectures require much more sophisticated control and coordination strategies, which need to be carefully evaluated during early-stage design. Generally, the crucial guidelines for power architecture design and selection should be the reliability and redundancy requirements and the shipboard mission requirements.

Onboard Distributed ESSs

Enabling Smart Grid Technologies

Due to the soaring price of fossil fuels and the practical need to integrate intermittent renewables into the future energy system, energy storage technology has been one of the hottest research directions in the last decade. With the presence of highly intermittent energy sources and

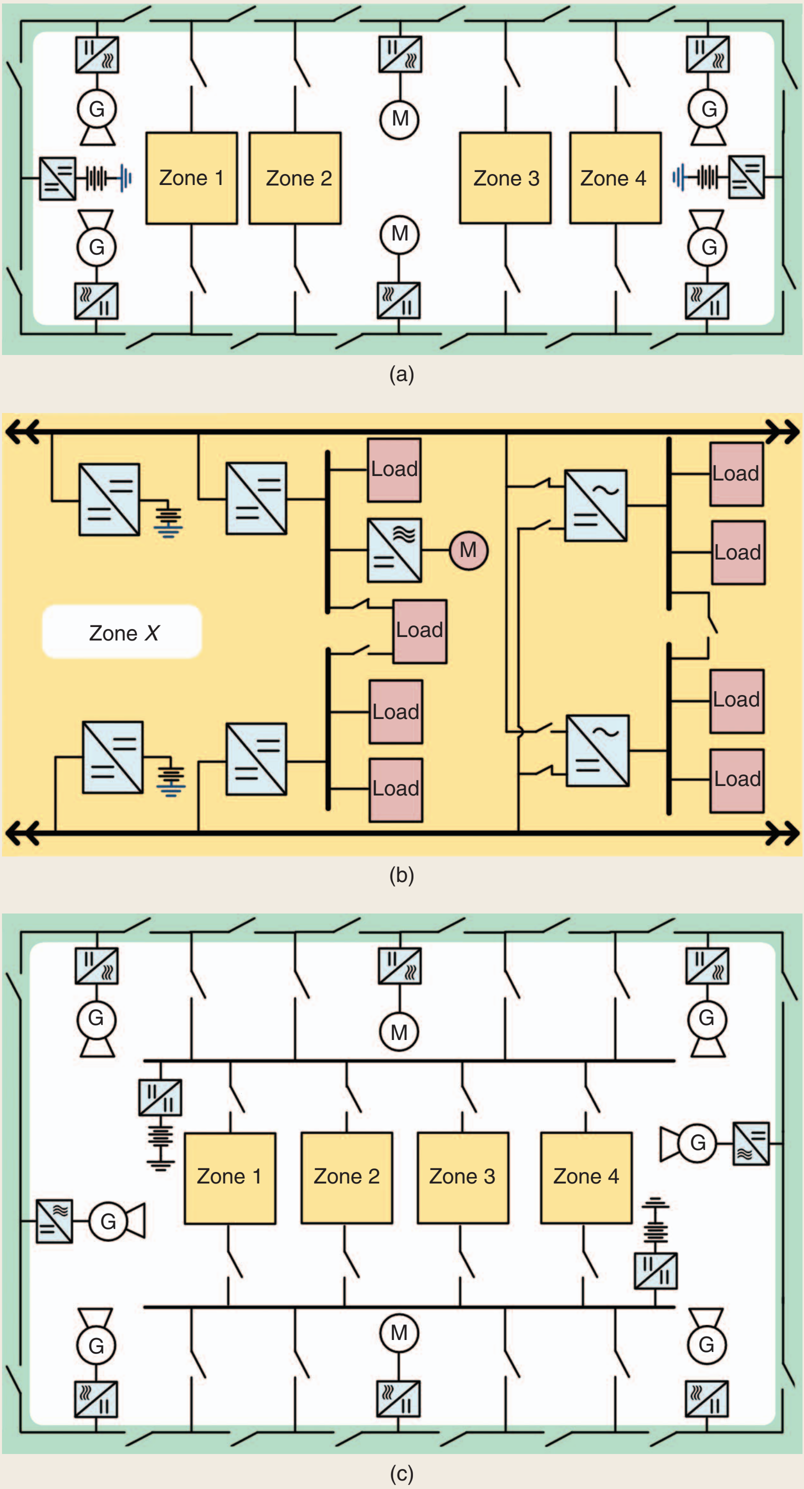


Figure 4. Typical power architectures of ZEDS-based dc power distribution systems: (a) dc ZEDS, (b) zonal load center, and (c) dual-ring-bus dc ZEDS.

loads, ESSs are necessarily needed to guarantee reliability, security, stability, and desirable power quality, especially under islanding operation. However, ESSs were seldom a concern in traditional power systems. In recent studies, the importance of ESSs in microgrids, especially in islanding ones, is being gradually elevated due to their potential to introduce a range of benefits. ESSs can be directly controlled as the master unit in the microgrid, and therefore they ensure the uninterrupted operation of the entire system. In addition, the ESS charge–discharge cycle can be optimally scheduled according to variable energy prices, consumption prediction, and weather forecasts, aiming at achieving economic objectives.

In the case of maritime applications, onboard ESSs are taking on a pivotal role in the IPS of the next-generation AES. For U.S. Navy surface combatants, the main reasons for an ESS are twofold: 1) to enhance survivability and 2) to enable high-energy pulsed loads. Congressional funding for research and development on the AES is motivated by the advent of and need for high-impact electric weaponry. Without an ESS, the shipboard generators would need to be significantly oversized to support the high-energy, pulsed nature of electric weapons. Even with an ESS, the growth of auxiliary loads and the capacity needed to support electric propulsion necessitates a capability to utilize the reserve capacity of online generators and the ESS to deliver the right amount of power to the right place in the ship at the right time—which is enabled by the IPS.

As for the commercial sector, fuel economy is the major concern. Considering the fact that diesel generation is still the major power source for all maritime applications, its efficiency characteristic in fixed-speed operation is as shown in Figure 5. In general, engineers will intentionally design and make the diesel generator sets work in their high-efficiency area and modulate the number (K in Figure 5) of running engines to achieve optimal load matching. However, instantaneous fluctuations in the demand side (e.g., dynamic positioning) will break the balance between power generation and power consumption, thus reducing fuel efficiency. The presence of the ESSs can inject bidirectional, controllable power flow into the system to achieve load conditioning. Such a fact enables modifying fuel efficiency with the help of onboard ESSs. In this way, it is possible for diesel generator sets to work constantly with the modified fuel efficiency.

Along with the development of energy storage devices, a range of commercially available storage device options for stationary or mobile terrestrial applications have already appeared. A comparison of their instantaneous power density and energy density is shown in Figure 6. Heretofore, batteries, especially lithium-ion batteries, became the preferred choice for electric vehicles and hybrid electric vehicles. Electrical double-layer capacitors [(EDLCs) or, informally, supercapacitors] have been applied for peak power shaving. Flywheels have found application in improving the low-voltage ride-through ability for wind farms. Besides that, there are several references involving sodium-sulfur (Na-S) batteries and superconducting magnetic energy storage (SMES), even though they have extreme-temperature requirements. Since the AES IPS is a large-scale system with complex loads, one potential solution will be distributed ESSs, which is based on a cluster of large or small ESSs using different kinds of energy storage devices. At present, the most promising, dominant energy storage devices for maritime applications are batteries, EDLCs, and flywheels. With proper allocation and configuration, the onboard ESSs will be able to enable multiple functions, such as power backup, peak power shaving, and braking energy recovery.

From the perspective of control and decision making, the integration of ESSs also introduces a new dimension into the control and management of shipboard power systems, where efficiency and the emissions from the onboard generation could be actively optimized. By cooperative control of onboard ESSs and generators under the complex load conditions, the optimization toward lowest fuel consumption and/or lowest emissions, as well as the need to service highly dynamic load demands and pulsed energy requirements, can be achieved simultaneously. Currently, a new trend of installing PV panels and wind turbines on board vessels to reduce the cost of sailing is drawing industrial attention. Such an optimization between ESSs and generational sources would be more effective and necessary with the integration of onboard RESs in the near future.

Control and Coordination of the Microgrid-Based Power System

Hierarchical Control: The Future Smart Power System's Interface

Despite the benefits offered by the dc-based IPS, it is still a challenging task to simultaneously achieve voltage regulation in a vessel's highly dynamic load condition (especially in dynamic positioning operation) and real-time optimization of fuel economy. According to IEEE Standard 1709–2010, the shipboard dc power system needs to fulfill the following control objectives:

- *power system stability*: the ability to maintain autonomous equilibrium in normal conditions and regain a state of operating equilibrium after being subjected to a physical disturbance
- *power quality*: the ability to maintain or restore the common dc buses at their nominal voltage with acceptable voltage tolerance
- *power management*: the ability to optimize systemic efficiency by intentional scheduling or intervention without affecting the maximization of the power supply to the demand side.

In terrestrial applications, dc microgrids also face similar challenges. According to the IEEE Standard 1547 series standards, microgrids should be able to

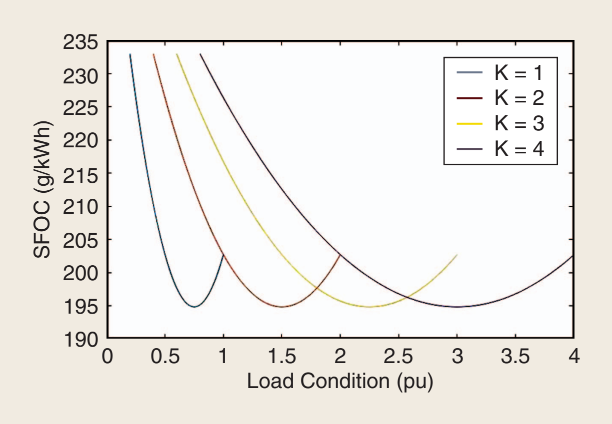


Figure 5. A schematic diagram of the fuel efficiency characteristic of diesel generation (at a fixed speed). SFOC: specific fuel oil consumption.

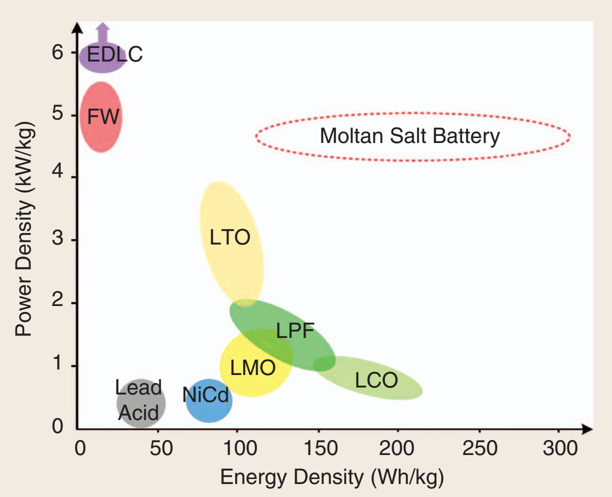


Figure 6. The power and energy densities of different energy storage devices. FW: flywheel; NiCd: nickel-cadmium; LMO: lithium manganese oxide; LPF: lithium ferrophosphate; LCO: lithium cobalt oxide; and LTO: lithium titanate.

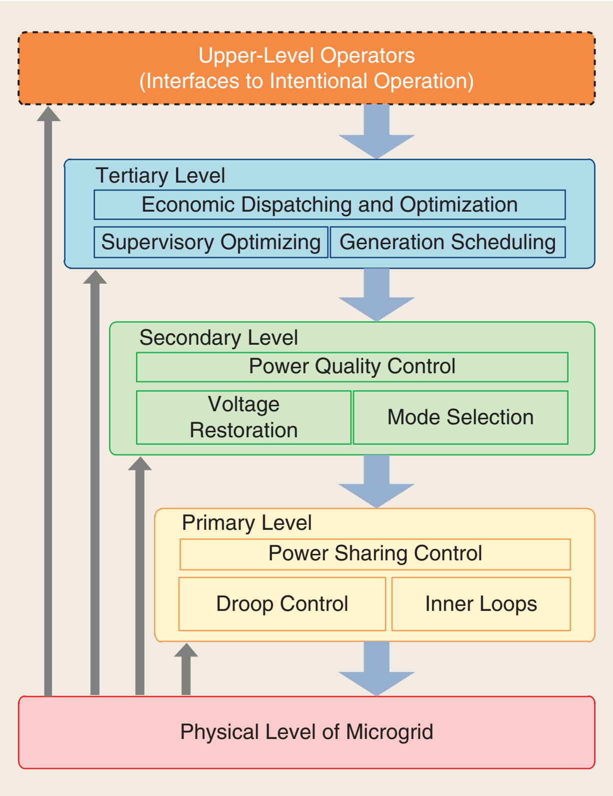


Figure 7. Different levels in hierarchical control.

operate both in grid-connected and islanded modes. Power flows are also expected to be managed at the same time. With the active research and development in recent years, a series of advanced control and coordination techniques have been investigated for dc microgrids. One of the most representative ones is the hierarchical control scheme, which is an adaptation of the International Society of Automation ISA-95 grid operation standard in microgrid control. Generally, to effectively achieve different control functions, the hierarchical control scheme is proposed, with the following typically defined levels:

- *Level 0 (inner control loops)*: the fundamental control loops to regulate the output voltage and/or current within each power electronic converter connected to the microgrid.
- *Level 1 (primary control)*: the control methods to emulate the physical behaviors that make the system stable and more damped power sharing.
- *Level 2 (secondary control)*: the control methods to ensure that the major variables of the system are within the required values.
- *Level 3 (initial tertiary control)*: the control methods to manage and control the power flow among the upper-layer grid and/or other microgrids.
- *Upper levels (extended tertiary control)*: the control and decision-making methods to achieve extra targets (such as practical economic benefits).

Figure 7 shows a typical scheme of hierarchical control. At present, mature power electronic converters are designed precisely to ensure that they remain stable and controllable under the worst working conditions. For this reason, hierarchical control of the microgrid is allowed, concentrating on system-level control, references as primary, secondary, and tertiary control. Generally, the primary control performs the local control of output voltage and current of the power electronic interfaces, following the setting points of the upper control levels. The secondary control that appears above the primary control deals with voltage or frequency restoration and the management of power quality. Additionally, the secondary control is in charge of power exchange with the external grids in the same layer (e.g., other microgrids). The tertiary control is conventionally issued with the task of managing the power exchange between the microgrid and its upper-layer grid. In recent studies, there is a trend to integrate the upper control levels, which are initially issued to achieve extra targets in the tertiary control. To this end, the tertiary control is to introduce intelligence to the microgrid and optimize the microgrid operation based on specific interests—normally efficiency and economics.

For large-scale dc microgrids, hierarchical control is often a preferred choice since it offers decoupled behavior between different control layers.

Figure 8 shows a typical control architecture applying hierarchical control in a generalized dc microgrid. Droop control can be installed as the primary control method for active power sharing purposes. In recent studies, either output power or output current could be selected as the feedback signal in the droop control. The droop coefficient can be regarded as a virtual internal resistance. In this case, the droop control consists of the physical connection of dc sources, and it therefore simplifies the design of the parallel converter systems in the dc microgrid. A small voltage deviation will be introduced by droop-based primary control. Therefore, a secondary control is introduced to compensate for the voltage deviation. In most cases, a straightforward proportional-integral controller can be employed to meet the need of tracking nominal voltage reference. However, adaptive droop control that uses adaptively changing droop coefficients instead of fixed ones has also been introduced to some high-requirement systems using decentralized coordination. It differs from primary and secondary control in that the tertiary control is providing optimization functions.

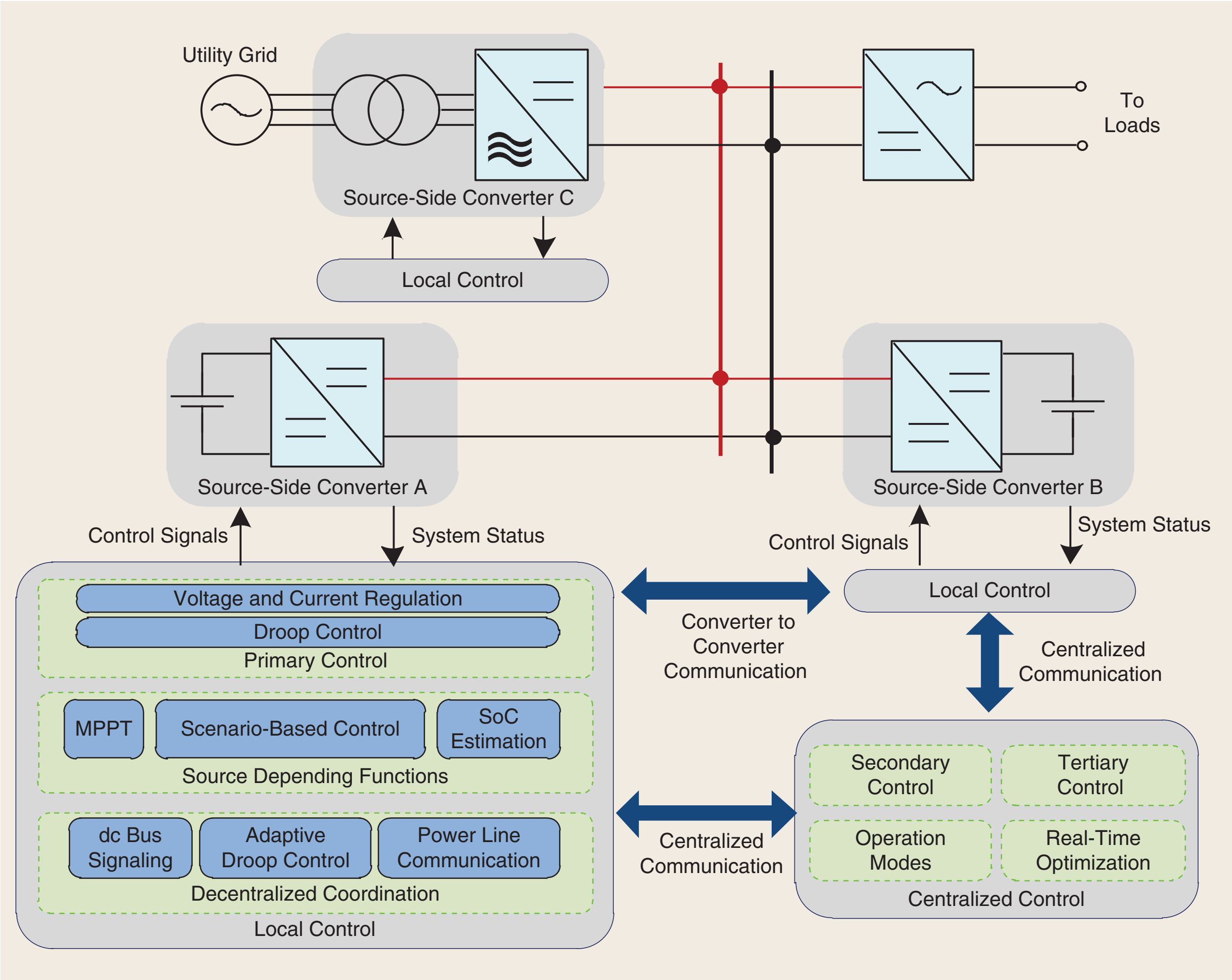


Figure 8. Hiearchical control in a practical dc microgrid.

Thus, not only the controller itself but also decision-making methods have been proposed to achieve specific optimization objectives.

Centralized, Decentralized, or Distributed Coordination: Scenario-Based Choices

For large-scale dc microgrids, hierarchical control is often a preferred choice since it offers decoupled behavior between different control layers. However, hierarchical control is achieved by simultaneously using local control of the power electronic interfaces and the coordinated control of all these components. The secondary and tertiary control levels rely on the cooperation of several or all local controllers. For this reason, the coordination in the microgrid will also impact on system stability, reliability, and performance. According to their different communication modes, coordination methods can be divided into three categories: centralized, decentralized, and distributed. Figure 9 shows the different operating principles of these three coordination methods.

Centralized coordination control can be implemented in dc microgrids by employing a central controller and a communication network, as shown in Figure 9(a). In small-scale dc microgrids, each unit can be directly regulated by the central controller via high-bandwidth communication using the master/slave method. It should be noted that centralized control provides the best foundation for the advanced control functionalities and system-level optimization, since all relevant data can be collected and processed within a single controller. However, the cost and difficulty of implementing centralized control increases nonlinearly with the increasing number of accessed components. Moreover, the most obvious drawback is that the control architecture has to face the potential failure of the central controller and/or key communication links, which may block the transmission of the commands and result in a systemic failure. In addition, the emerging issue of cyber-attack also needs to be considered, especially for some mission-oriented applications.

Decentralized coordination control is achieved exclusively by the local controllers, as shown in Figure 9(b). The obvious advantage of decentralized coordination is its independence from the communication and central controller, allowing this architecture to offer higher flexibility and

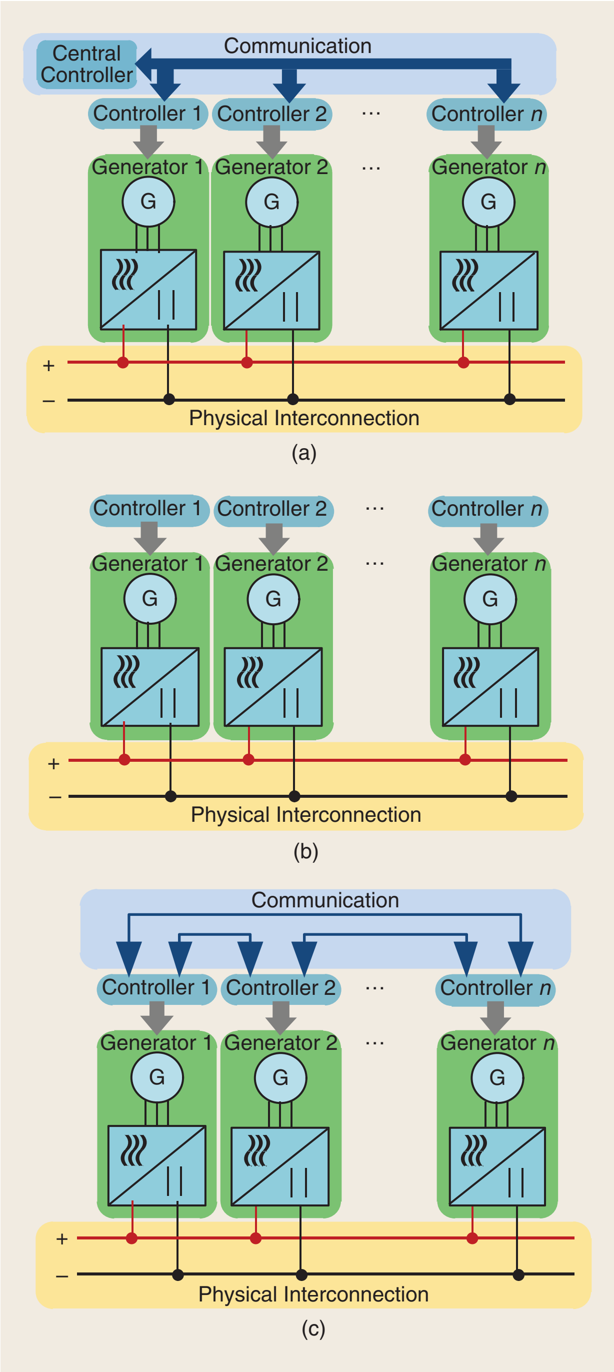


Figure 9. The operating principles of different coordination methods.

exemption from single-point failure. In recent studies, decentralized coordination can be achieved in several ways, such as by the dc bus signal (DBS) and power line signal (PLS) methods. These methods exploit the information-carrying potential of global variables (i.e., dc bus voltage) to achieve coordinated operation. Meanwhile, master/slave control and multimode control strategies are commonly used to coordinate the energy sources to achieve comparable performance. However, decentralized coordination methods have their own drawbacks, the most important being the lack of global information awareness, which will result in inherent performance limitation, especially when performing optimization. In addition, the major methods of decentralized coordination are based on the response to specific global variables; the accuracy of measurement thus impacts the effectiveness of the entire system.

Therefore, instead of centralized coordination control or decentralized coordination control, distributed coordination control can be seen as a good compromise between both approaches, where a central controller does not exist but where local controllers are able to communicate with each other. The most important distributed coordination method is the multiagent system (MAS), in which each local controller could be regarded as an intelligent agent, with all agents together composing the MAS. By applying a consensus algorithm, it could achieve information awareness comparable to that of centralized control and offer the possibility of applying wider functionalities than decentralized control. Meanwhile, it maintains a reliability comparable to decentralized control. The MAS is also considered to be an effective way to achieve global optimization objectives (e.g., overall efficiency improvement). However, it requires a complex interaction network among the local controllers, and its main limitation is the complexity of the analytical performance analysis, especially in nonideal environments (e.g., communication time delays and measurement errors).

Smart Grid Technologies, the Key to the Smart Onboard Power System

The common trend of power systems is moving toward higher intelligence and efficiency. As one of the major objectives of the future smart grid, the concepts of intelligent management (e.g., supervisory energy management) and smart protection (e.g., adaptive reconfiguration) have been introduced to the microgrid as an extension of the conventional hierarchical control architecture. These concepts can also be introduced to the IPS to achieve an efficient and reliable shipboard power system for the future smart AES, and therefore contribute to the further improvement of fuel efficiency, limitation of greenhouse gas emissions, and fault-tolerant character of the shipboard power system.

Smart Coordinated Management for Lower Cost and Reduced Emissions

Under normal conditions, the voyage or mission of a vessel can be divided into several operating scenarios, such as docking, acceleration, deceleration, and cruise. These scenarios will not transfer in random order—for example, the vessel will not dock directly after acceleration. Based on this important fact, preplanned onboard energy management and its optimization would be applicable to coordinate the onboard generation and ESSs for optimal fuel efficiency. In recent years, the International Maritime Organization has promoted the Ship Energy Efficiency

Management Plan (SEEMP) to encourage emissions limitation, and it may be required for each vessel in the near future. To design a SEEMP, it is possible to employ advanced offline optimization algorithms to improve the fuel-saving effect with reasonable assumptions (i.e., the fuel efficiency is affected only by engine speed and load). However, the practical operation of a vessel may be influenced by innumerable contingencies (e.g., unexpected travel distance due to wind and waves), which make the offline predesigned SEEMP result in suboptimal fuel efficiency. To maximize fuel efficiency and/or minimize emissions, a potential method is to combine scenario-based multimode control and real-time optimization, in which real-time optimizing could be done within the constraints given by the tertiary level of hierarchical control (i.e., the energy management level) and according to the detailed system status (i.e., the overall state of charge information from the ESSs and the operation mode).

> ***In small-scale dc microgrids, each unit can be directly regulated by the central controller via high-bandwidth communication using the master/slave method.***

To implement a SEEMP, joint management, on both the generation side and demand side, is required. From the perspective of generation, a dc distribution system allows each prime mover to operate independently in a variable-speed mode without the limitation of synchronization. Figure 10 shows an experimental result of the specific fuel oil consumption (SFOC) in g/kWh under the full operating range of a typical shipboard diesel generator. It indicates that fuel consumption is a nonlinear function of the engine speed and load condition and has a high-efficiency area. Generally, the generation-side management tends to keep the onboard generators either working in their high-efficiency area or working in idle speed. In this way, the SFOC is maintained at its lowest point. However, the onboard generation is not stand-alone; it always depends on the power demand.

The traditional demand-side management method in power systems is based on load shedding methods. However, the onboard loads are usually mission oriented, and the major energy consumer will be the electric propulsion system in the future AES. Thus, conventional load shedding will result in unwanted performance degradation in mission-oriented function or the propulsion system, which makes the methods unsuitable for such coordinated management. With the help of ESSs, the dynamic active power balance can be achieved by properly and bidirectionally managing the power flow between ESSs and the dc bus. Thus, an equivalent demand-side management can be achieved in this way, which allows highly flexible operation of the other onboard electrical equipment. At the same time, the major optimization objectives, such as maximum fuel efficiency and support of emerging pulsed mission-oriented equipment, can also be achieved.

The role of ESSs in the SEEMP is extremely important due to their invaluable bidirectional characteristic. The presence of ESSs breaks the conventional dependency between the generation side and demand side, thus significantly improving the flexibility of the SEEMP. In addition, it is noteworthy that the electric propulsion could also act as generation while doing regenerative braking. The traditional method is not able to deal with such bidirectional loads, and the excess energy has to be dissipated on dumping resistors to maintain the stability of the power system. With the help of ESSs, this part of the energy can be partly or fully stored, thus helping to reduce the overall cost. ESSs are also able to take the role of the primary energy resource during short-term voyages (e.g., in-port moving) or emergency conditions (i.e., auxiliary generation), which may significantly reduce the environmental impact and enhance reliability.

Smart Protection and Reconfiguration for Fault-Tolerant and Highly Reliable Systems

The protection of dc power systems, especially those with complex dc ZEDS configurations, is a challenging task requiring the development of SSCBs suitable for MVdc solutions and complex coordination between power converters and protective functions. Moreover, compared with conventional transformers, the instantaneous overcurrent capability of power electronic converters must be limited to avoid equipment damage, whereas conventional transformers inherently carry a reserve inertia to sudden transient electrical events. As a result, an adequate shipboard IPS, which delivers power through power electronic converters, usually leads to overdesign of the power electronic equipment, which is a problem when considering space

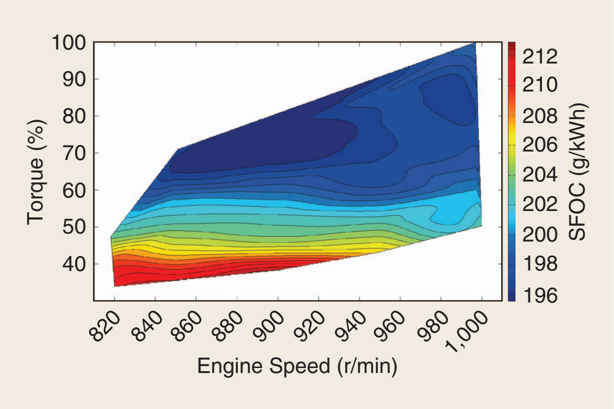


Figure 10. The SFOC of a typical diesel engine at variable speed and torque.

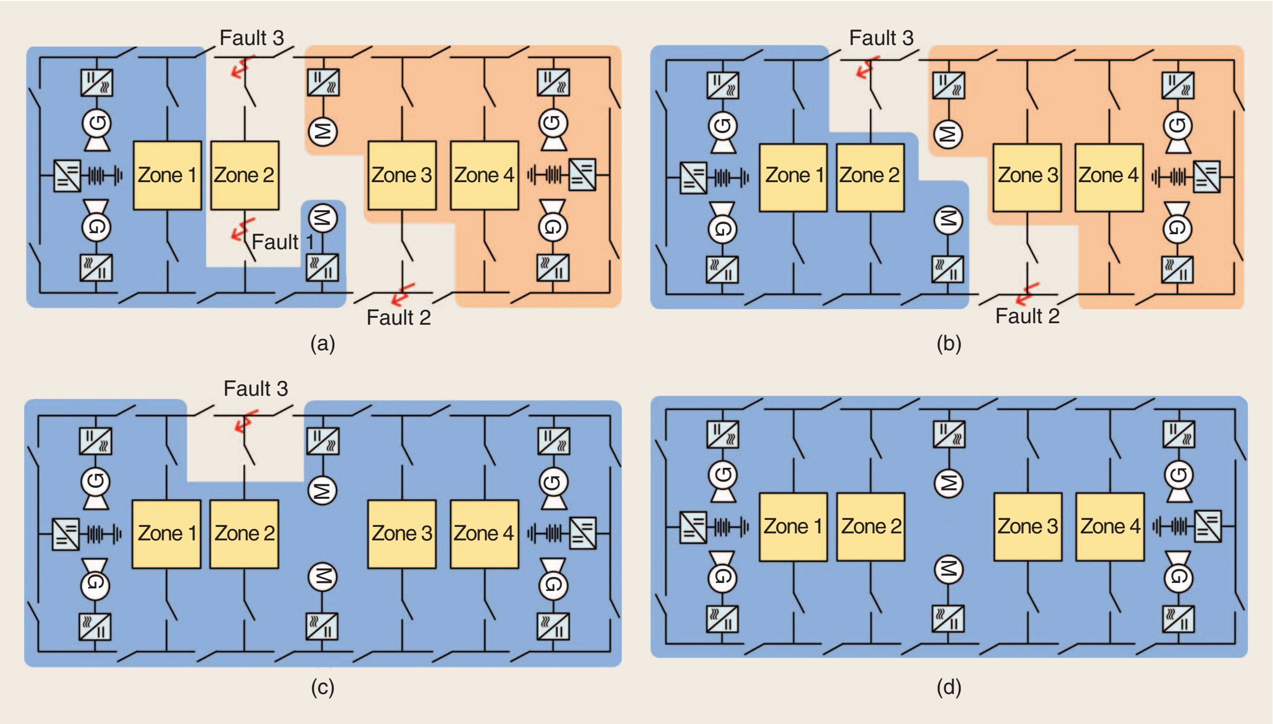


Figure 11. The process of sectionalization and reconfiguration based on the self-healing method: (a) faults occur, (b) fault 1 clear, (c) fault 2 clear, and (d) fault 3 clear.

constraints. Also, considering dc ZEDS, since zones are normally interconnected, there may be scenarios where a single failure might spread and cause a regional failure or systemic crash if the protective architecture is not designed to address the potential for such scenarios. Hence, effective fault protection and fault-point isolation are considered as the major challenges for ensuring the safety of the MVdc IPS.

The reconfiguration capability is one of the most promising advantages of the MVdc IPS for the future AES, especially for naval applications.

A considerable research and development effort has been made to enable the protective function by using power electronic converters. However, there are still several challenging points, such as communication delays and measurement failures. In recent studies, measurement failures can be overcome by using outliner data detection and reconstruction algorithms. Expert system concepts have also been introduced into dc microgrids to achieve prognosis of fault sections and to guide effective protective activities when faults occur.

The reconfiguration capability is one of the most promising advantages of the MVdc IPS for the future AES, especially for naval applications. However, the nonlinear multiconnectivity and high-dimensionality of the onboard power system make it difficult to achieve fast and efficient reconfiguration. Returning to the dc ZEDS discussion related to Figure 4, several advanced concepts have been introduced to address the protection dilemma. An essential approach is the self-healing reconstruction method, which first subdivides the power system into several zonal microgrids and then reconstructs from microgrids when a fault is cleared. The sectionalizing aims at the minimization of the isolated area while at the same time maintaining the power supply to healthy zones. Further, the sectionalized zonal microgrids will attempt to connect with each other and form networked microgrids, which can improve the operation and reliability. In this way, the power system will recover from the fault in several steps and isolate the fault location at the same time. Figure 11 shows the process of sectionalization and reconfiguration based self-healing when three faults occur in different positions.

Conclusion

In this article, we examined dc microgrid-based maritime onboard power systems and outlined the need for and potential benefit of employing both smart grid technologies and the MVdc IPS for the future AES to enhance the controllability and efficiency of shipboard power systems. We introduced a series of technical outcomes from research on terrestrial dc microgrids, such as dc power architecture, the application of ESSs, hierarchical control, and different coordination methods. We also presented objective-oriented coordinated management methods and protective functions for future MVdc IPSs, which are to meet the specific need of maritime applications using methodologies from dc microgrids.

In the last decade, there were several prototypes of ships on the low-voltage dc level, while, for the MVdc IPS, there are still technological challenges and de-risking studies to be performed. However, it is foreseeable that the advanced technologies from terrestrial dc microgrids are potentially applicable in the MVdc IPS of the future AES. Thus, such a combination will contribute to the implementation of high-performance MVdc IPSs for both commercial and mission-oriented vessels in the near future.

For Further Reading

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