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Hybrid Maritime Microgrids: A Quest for Future Onboard Integrated Marine Power Systems

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Abstract

The following is a comprehensive analysis which details potential ways for the maritime industry to begin to phase out AC power generation and distribution on new vessels over a short period of time. Therefore, the vessels of the future should consider transitioning into DC power generation and distribution. During the transition from AC shipboard systems to DC shipboard systems, there will be a time during which the vessels will be run by “hybrid” shipboard power systems, which utilize a mixture of AC and DC power. These systems are known as integrated marine power systems (IMPS) or hybrid maritime microgrid architectures, since they represent a distribution system or a part thereof. This study presents a state of the art of maritime systems, emphasizing on the design aspects of hybrid maritime microgrids, summarizing the advantages, disadvantages, and the challenges that planners may face when it comes to the vessels of the future. This study also reviews remedies that have been recently proposed in the literature to overcome such challenges. In addition, this work reports on the problem of service restoration of shipboard power systems and introduces directions on how to enhance the survivability of maritime power systems using techniques based on distribution system reconfiguration.

Keywords: integrated marine power systems, hybrid microgrids, maritime microgrids, distributed generators, renewable energy resources, power electronics, energy systems

1. Introduction

The dynamic evolution of the electrical loads aboard ships and vessels within the marine industry in the twenty-first century calls for further research and development of integrated marine power systems, with DC distribution and electrical propulsion components. The emerged IMPS comprise of the conventional AC generators and propulsion systems, in addition to DC distribution systems along with DC loads such as switchboards. The strong consideration of DC distribution systems in place of the commonly used AC within marine power systems has gained notice due to the much advancement in today’s power electronic circuitry.

The demands for sufficient electrical power in future ship designs varying from warships and naval aircraft carriers to oil tankers and transport vessels are

of main importance to current ship designers. From AC generators to the propellers, today's loads predominantly exist within the DC section of the system. With the introduction of advanced communication systems, electromagnetic aircraft launch systems, and electrical weaponry onto naval vessels, high-reliability integrated power systems that can meet varying electrical load demands are highly sought. Power system architectures are dependent upon load types, and the viability of DC distribution, such as medium- or low-voltage DC power systems, in meeting upcoming shipboard electrical demand forecasts is of focus. The paradigm shift of traditional AC system constructions to DC entails both operational benefits and, on the other hand, any accompanying risks. One form of system design does not by any means entitle an industry standard, as vessel functions vary from ship to ship and boat to boat. Ideal system configurations coincide with the shipboard loads and are characterized by high reliability, ease of maintenance, both fuel and payload efficiency, and lower costs and low, or optimally absent, emissions.

In [1], ABB has reported that an Onboard DC Grid can allow for fault current clearance within a time window of a maximum of 40 ms, as compared to 1 second for traditional AC circuits. Furthermore, because the speed of prime movers must be locked at approximately 60 Hz in AC marine systems, the lowest fuel consumption will be achieved operation about 85% of the rated load. Because DC buses are at no frequency, the prime mover speed can be adjusted according to demand, all the while correspondingly adjusting the generator excitation current in the same respects. Given this commodity of optimization speed, the operating window of the prime movers can be brought down to about 50% of the rated load with no increase in fuel consumption [2].

In recent years, there has been an increasing interest in the design and analysis of microgrids in general [3–5], with particular interest on the implementation of hybrid microgrids (*AC and DC microgrids*) within the maritime industry [6]. For instance, the Italian Navy, by the use of a system nicknamed naval package (NP), has successfully corroborated simulation results with experimental data in determining the validity of a medium-voltage DC shipboard IMPS with the use of dual three-phase 2.15 MVA generators. The results showed that the generator produced quality DC outputs with the introduction of faults and specified rectifier arrangements reduced performance degradation and increased system fault tolerance [6].

Several operations are constantly performed on shipboard power systems. Of these, service restoration and reliability improvement may be of most concern. Numerous marine power distribution systems are characterized by radial or weakly meshed topological structure. The unidirectional power flow in the radial distribution systems facilitates the coordination of the protective devices used at the distribution system level. Nevertheless, this radial topological structure makes distribution systems less reliable, compared to transmission systems, which are highly interconnected systems. Despite the unidirectional power flow in the radial distribution systems, the failure of any single component between the load point and the source node may cause service interruptions, which could lead to disconnection of several load points. Distribution systems are constantly equipped with two types of switches: sectionalizing switches and tie switches. The sectionalizing switches are normally closed; however, the tie switches are normally open but can be closed to routing the power and meeting the power demand during abnormal conditions. Distribution system reconfiguration can be used to minimize the duration and frequency of service interruptions and thereby enhance the reliability of the distribution system and the quality of service. By distribution system reconfiguration, we denote the process of changing the topology of the distribution

network by altering the status of sectionalizing and tie switches to achieve certain objectives [4]. Of these objectives, reliability improvement, service restoration, and survivability enhancement are of great concern. Generally speaking, reconfiguration and service restoration of marine power systems are carried out in a similar manner to that used for terrestrial power systems, with few restrictions and constraints.

In [7], a method for load sharing in hybrid microgrid systems using control loops is presented. A method for maritime microgrid reconfiguration is presented in [8] using genetic algorithms and heuristic techniques. The work presented in [8] is implemented on a small shipboard power system, and a modified CERTS microgrid system including distributed generators has been used. Methods for optimal feeder reconfiguration for terrestrial distribution systems using intelligent and heuristic methods are also proposed in [3–5]. In [9], a method for optimal sizing of renewable energy resources for next-generation seaports is presented. The renewable energy resources used in [9] are modeled using HOMER platform. A two-stage technique for isolated microgrid systems is introduced in [10]. The method proposed in [10] used graph theory and binary firefly algorithm to perform minimum load curtailment in the isolated microgrid. Methods for service restoration of marine power systems have also been presented in [11–13].

This study is organized as follows. Section 2 introduces a state of the art of modern power systems. Section 3 presents, discusses, and lists the unique features of next-generation marine power systems. Section 4 introduces the concept of maritime microgrids and discusses briefly the composition of such maritime microgrids. It also highlights the main differences between the conventional shipboard systems and next-generation maritime microgrid systems by giving examples and illustrations and single-line diagram of a maritime microgrid system. Section 5 presents modeling aspects for some of the marine power system components. Section 6 highlights feature studies for marine power systems followed by conclusions.

2. Modern marine power systems: state of the art

Modern ships consume a substantial amount of power due to a wide range of equipment needed to operate each vessel. Some of these equipment include cargo equipment (*such as cargo pumps and cargo cranes*) as well as other necessities including electric heaters, control equipment, and motors for pumps, compressors, or propulsion. Modern vessels always have a main switchboard and an auxiliary switchboard (*emergency switchboard*), which are connected via numerous circuit breakers (CB as in **Figure 1**). Usually the switchboards receive power from large AC synchronous generators. Both the main and emergency switchboards are interlocked with an automatic bus tie breaker that disconnects the two should power loss has been sensed on the main switchboard. The main generators are all connected in parallel to the main switchboard as depicted in **Figure 1**; however, only the emergency generator, not shown in **Figure 1**, is connected to the emergency switchboard. The emergency generator is periodically run in order to conduct weekly tests as well as monthly load tests; otherwise, the emergency generator is only powered up in the event of a power loss emergency. The main generators are connected to the switchboard one-by-one using circuit breakers as shown in **Figure 1** until there are enough online to power all electrical loads of the vessel. From the switchboards, power is then distributed to all appliances. There are multiple transformers on vessels used to step down the voltage for equipment,

which typically require less voltage. Much like landside power plants, automatic voltage regulators (AVR) and governors are implemented in order to control the generator's power, frequency, and voltage output. On most vessels, the only DC power is more commonly used to power computerized control equipment as well as the DC excitation of the synchronous generators, the general alarm, emergency lighting, and the electronic integrated circuits. Each of these systems use minimal amounts of power, which highlights the notion that modern marine power systems are almost entirely supplied by AC power. From the emergency switchboard, power flows through a rectifier which converts it from AC to DC, which trickle charges the batteries, such as battery bank (BT1 in **Figure 1**), that power the systems previously described.

One issue commonly found in AC distribution systems is the power loss that is almost inevitable due to the nature of the load and therefore the power factor. It is noteworthy to mention here that numerous vessels' power systems have extremely poor power factors, which should be corrected in order to increase efficiency. This can be accomplished using capacitor banks or synchronous condensers, which will bring a severely lagging power factor closer to unity. Unfortunately, such power factor correction devices will likely still waste resources, such as fuel, power, and money, which are never desirable. Section 5 briefly discusses modeling aspects of capacitor banks for power factor improvement of marine power systems.

As far as for DC systems, it is appropriate to highlight here that DC power is often inefficiently transmitted and distributed over large distances, which is one of the main reasons why landside AC power transmission is used. Fortunately, for

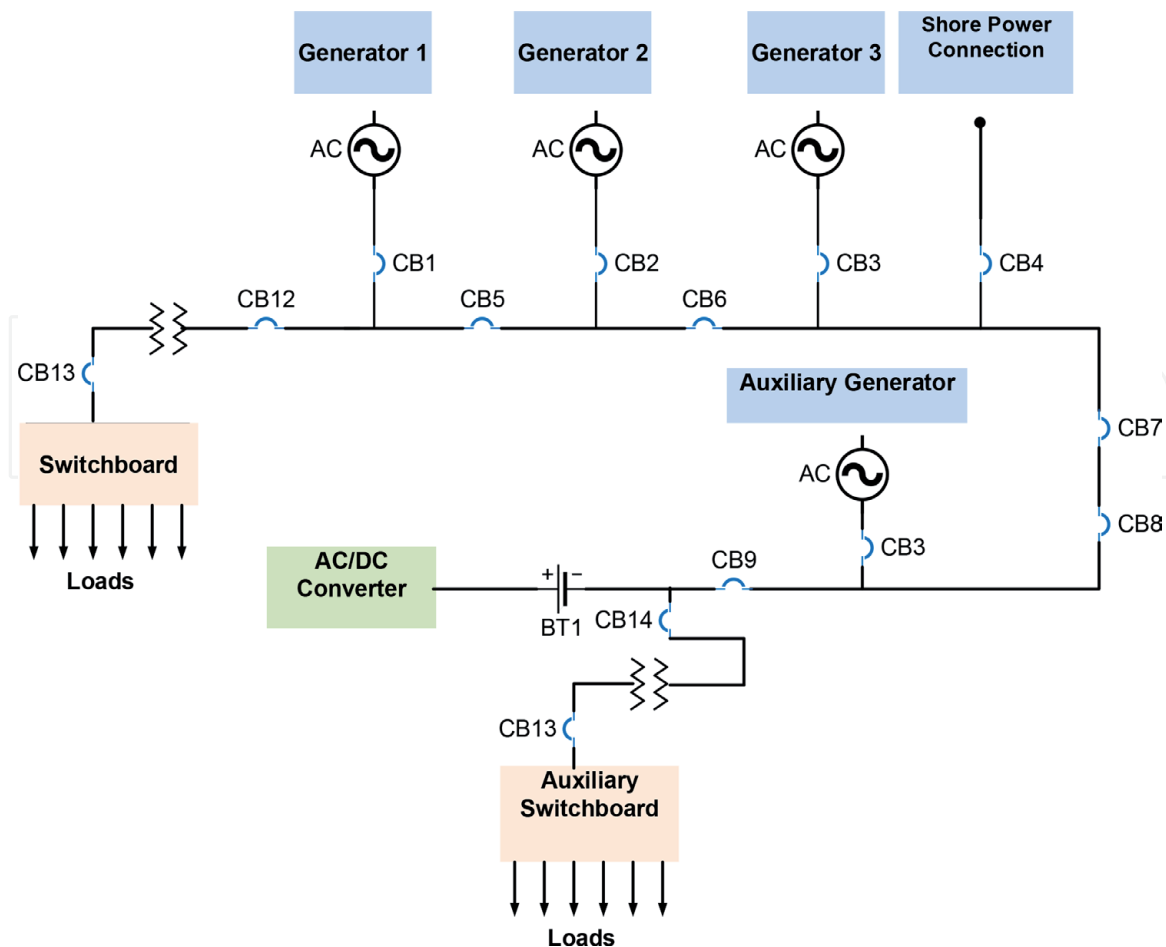


Figure 1.
Single-line diagram of a modern marine power system.

shipboard electric power systems, DC power distribution is a highly viable option. Unlike landside power generation and distribution, vessel power grids do not travel across massive distances. For example, one of the longest vessels ever made is only 1500 feet long, which is miniscule compared to the massive distances, or hundreds of miles, over which landside power companies are expected to transmit and distribute electric power.

3. Future marine power systems

Due to the added regulations regarding the increase in efficiency and decrease in pollution of all vessels, it has become evident why most companies desire and are actively searching for better shipboard microgrid architectures. The overall goal of future marine power systems would be to establish and use an almost completely DC marine power system. This is due to the numerous potential benefits it would allow in both efficiency and pollution if properly designed [14–19]. Numerous vessels now deploy diesel engine propulsion; however, they can likely be made more efficient in the future if they were to be switched to electric propulsion under the umbrella of all electric ships (AES). Electric propulsion may improve fuel consumption as well as the dynamic performance of the ship [14]. Since ships that use electric propulsion consume most of the power generated for propulsion, it is imperative to ensure that the shipboard microgrid of such a vessel is capable of handling the load dynamics, which are connected to electric propulsion as well as the immense amount of power needed to propel a vessel utilizing electric propulsion technologies.

With the use of energy storage systems (ESS), such as battery banks and fuel cells, synchronous generators can be operated at optimal speeds, which allow for improved efficiency and reduced pollution, as a result, allowing a greater reduction in distribution losses as well as increased reliability [7]. The use of energy storage systems is beneficial as they allow for continuous power flow to the connected loads in the event of a power generator failure.

Transformers, which are AC/AC converters, are used in conventional shipboard AC power systems. Such devices would be replaced with DC/DC power converters for the shipboard DC distribution systems of the future, which would allow the voltage to be stepped down (buck converters, for instance) or stepped up (boost converters, for instance), to the required levels. The voltage levels may also be stepped up and stepped down to achieve certain requirements by the means of buck/boost or buck converters. On the other hand and for specific AC loads, DC/AC inverters would be required. Benefits of using such converters may include increased power compensation and better frequency regulation.

It is appropriate to mention that the modern and future maritime systems have many similarities in structure; however, they also possess few differences. For instance, as shown in **Figure 2**, one of the major noticeable differences is that in future marine power systems, both the main and the auxiliary or emergency switchboards receive and distribute DC power as opposed to the AC power utilized on the modern marine power system example depicted in **Figure 1**. Another key difference is the use of an energy storage system, which powers the switchboard in the next-generation marine power systems as can be seen from **Figure 2**. Though only few ships are currently deploying electric propulsion, the ships of the future should solely use electric propulsion due to its higher efficiency. Some advantages of using DC-powered systems instead of the conventionally used AC systems on next-generation shipboard systems are summarized in **Table 1** [1, 2, 19, 20].

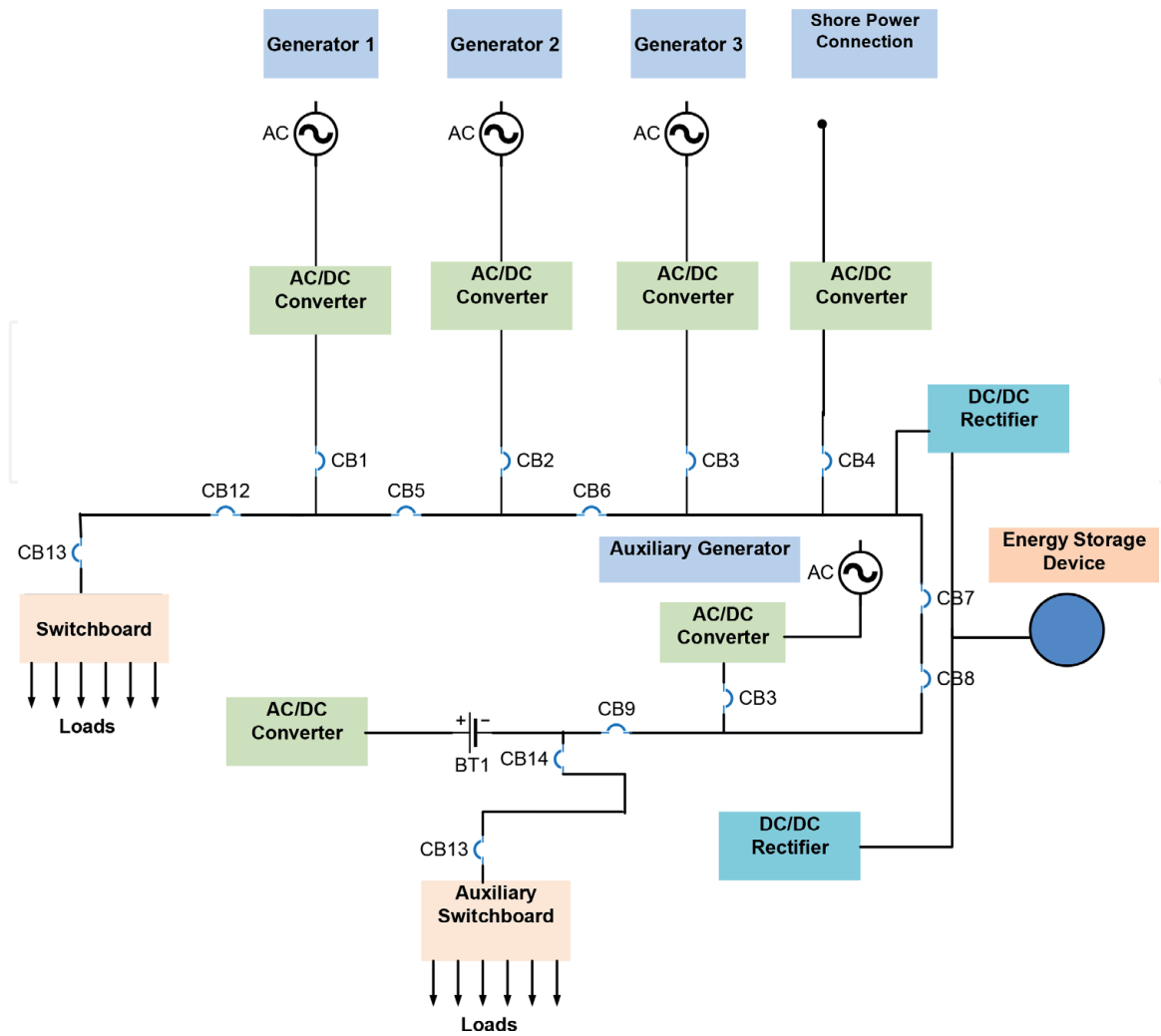


Figure 2.
Single-line diagram of a next-generation marine power system.

| Item | Advantages of using DC systems vs. AC systems |
|------|--|
| 1 | Eradication of frequency-related issues and synchronization of sources |
| 2 | Proper control of drive systems over a wide range of speeds due to the advancement in power electronic devices |
| 3 | Potential reduction in overall size and rating of switchgear |
| 4 | Generators operate at or near unity power factor; and thereby reactive power compensation may be controlled properly |
| 5 | Overall reduced system size in general, allowing for larger cargo space |
| 6 | Virtual inertia of power electronic devices may be deployed to enhance the overall system stability |
| 7 | Replacement of large distribution transformers with small-sized power electronic converters |

Table 1.
Advantages of using DC-powered marine systems.

4. Maritime microgrids

In general, DC microgrids characteristically are self-sustaining given the ability to work given a grid-connected or islanded-mode condition. The feature of these self-thriving distribution systems emanates from the connected renewable energy resources and energy storage devices. The general architecture of the emerged

maritime microgrids is depicted in **Figure 3**. As shown in **Figure 3**, most maritime microgrids consist of conventional generators, several power electronic circuitries, and numerous AC and DC loads such as the propellers and propulsion system as a whole.

In **Figure 3**, the maritime microgrid system under study consists of two synchronous generators operating in parallel and connected via a sectionalizing switch. The switch is normally open and can be closed during harsh conditions, as in case of breaking, for example. The hybrid maritime microgrid system shown in **Figure 1** is driven by power electronic circuitry, which is mainly consisting of the following:

- AC/DC full-bridge inverter system.
- Energy storage system EES, and in our case we assumed a battery system.
- DC/DC boost converter(s).
- DC/AC inverter(s). One of the main functions of the DC/AC inversion systems is to feed the propellers.

A lot of research is being conducted to optimize the operation of maritime microgrids such as enhancing reliability and survivability, improving stability using virtual synchronous generators, and minimizing power curtailment. References [1–13, 20] provide literature on some of these techniques.

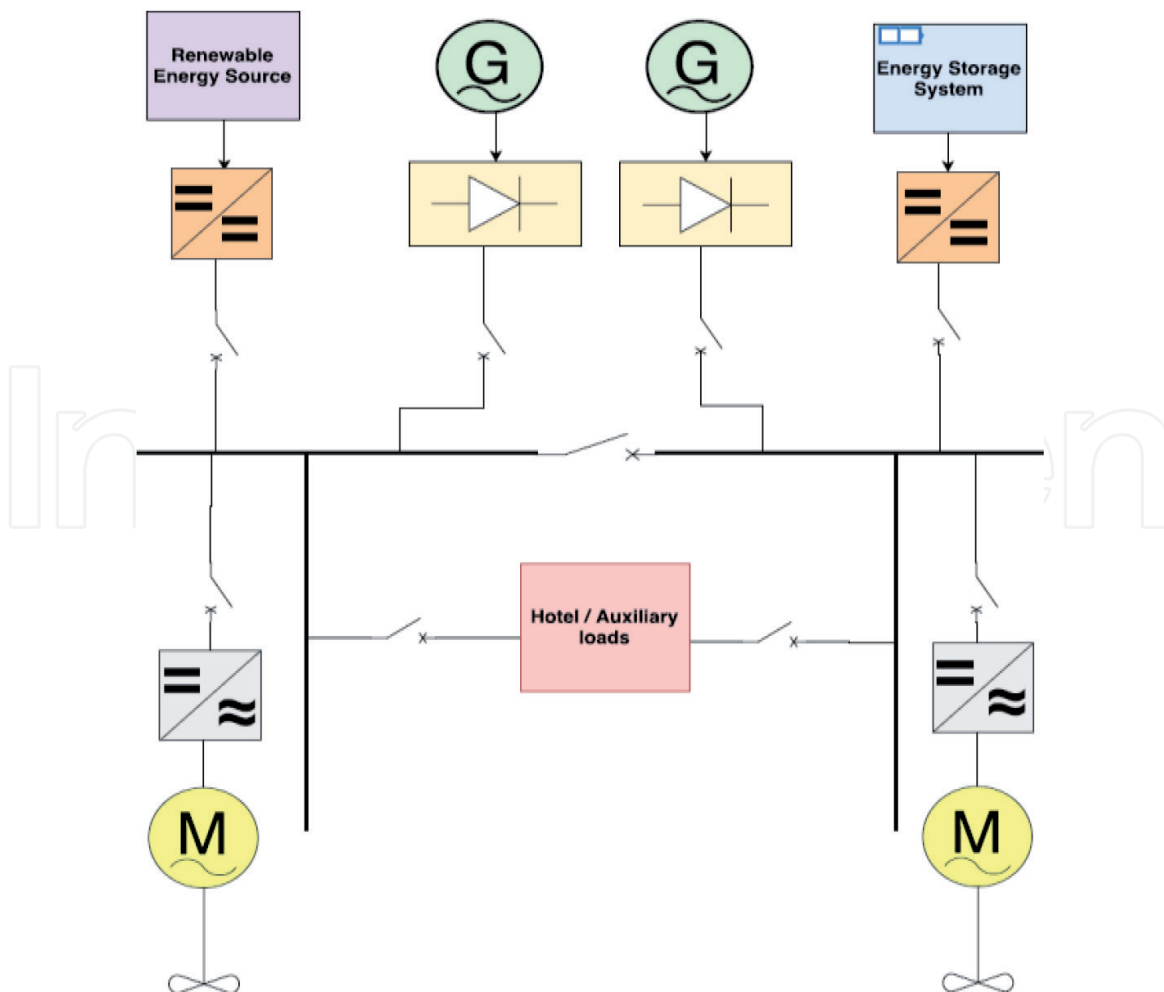


Figure 3.
Hybrid maritime microgrid system.

5. Review of marine power system components

In the subsequent section, modeling aspects of some components used on most of the current and future marine power systems are reviewed and briefly discussed.

5.1 Load model

The active and reactive power loads on distribution networks can be represented as constant power, constant current, constant impedance, or a mixture of these types. Hence, the load model in distribution systems can be generally represented as by an exponential form as

$$P_k = P_{ref} \left(\frac{V_k}{V_{ref}} \right)^\alpha \quad (1)$$

$$Q_k = Q_{ref} \left(\frac{V_k}{V_{ref}} \right)^\beta \quad (2)$$

where V_{ref} is the reference bus voltage; V_k is the operating voltage at bus k ; P_{ref} and Q_{ref} , respectively, are the active and reactive power consumptions at the reference bus; and α and β are exponents on which the load characteristic can be determined. That is, constant power load model can be found by setting α and β equal to 0. Further, constant current model is obtained by setting α and β equal to 1. Moreover, constant impedance load model is obtained by setting α and β equal to 2.

5.2 Cogeneration model

Cogenerators or distributed generators are small-scale sources of energy used at distribution level to increase the reliability and security of the system. Cogenerators can be modeled either as constant power nodes or constant voltage nodes. However, according to the IEEE standard 3636, cogenerators are modeled as constant power loads. Therefore, in several studies, particularly planning studies, it might be appropriate to adopt modeling of cogeneration such as photovoltaic, for instance, as constant power loads.

5.3 Static VAR model

As was mentioned earlier in Section 2, capacitor banks and other types of static VAR compensators (SVC) are utilized on maritime distribution systems to boost bus voltages and keep reactive power limits in the desired range. Capacitor banks can be modeled as constant capacitance devices and may be represented by current injections to the node to which they are connected.

5.4 Transformer model

Transformers are modeled using their per unit synchronous reactance. Using per unit system makes including transformers in power system analysis much easier as the problem of transferring reactances on both sides of the transformer is eliminated.

6. Future studies

Based on our discussion so far, we have concluded that maritime power systems are somewhat different from their typical terrestrial counterparts. In particular,

| Item | Challenges |
|------|---|
| 1 | The penetration of intermittent renewable energy resources and storage devices has increased in nowadays shipboard systems. Consequently, accurate models need to be developed to accommodate such an increase |
| 2 | To ensure reliable operation of next-generation shipboard systems, numerous studies should be carried out in a real-time frame using high-computation facilities and parallel computing |
| 3 | More innovative techniques for optimal load flows, service restoration, and reconfiguration need to be developed. This requires the development of more testbeds, particularly for large-scale realistic marine power systems |
| 4 | Frequency-related issues of power electronic devices are another area of research for future shipboard systems. Effective inverter topologies that minimize stress ratios and switching losses constitute another research path for future maritime systems |
| 5 | For stabilize operation of the hybrid power systems, more work needs to be carried out in the area of power system stability using the concept of virtual inertia. Proper control design and innovative communication protocols would help utilizing the concept of virtual synchronous generators to maintain the stability limits of a given marine electric system |

Table 2.
Examples and challenges of future research in marine systems.

generally speaking, maritime systems consist of generation and distribution, but no transmission, which is very distinct from the territorial electric power systems. The generation and distribution are coupled with distribution feeders in order to transfer the power from the synchronous generators to the loads. Hybrid maritime distribution systems (*hybrid maritime microgrids*) consist also of several power electronic devices such as converters, inverters, rectifiers, and switchboards. Instrumentation and control circuits are used on ships to ensure safe operation of the ship. A typical maritime power system is in fact an isolated power system, which is largely different from the terrestrial power systems. Therefore, survivability of such a system during abnormal circumstances is of great concern for marine power system planners. Enhancing reliability and survivability through feeder reconfiguring of marine distribution systems, however, needs flexible and reliable techniques to accommodate all of the aforementioned characteristics of modern marine power systems. In order to perform studies on any marine power system, a power flow solution is constantly required. Nonlinear power flow and DC power flows are commonly used in the literature to carry out optimization studies on terrestrial and shipboard systems. In recent literature, enhanced linearized power flows [21, 22] have also been used as they compensate for most of the drawbacks of the conventional DC power flows. A lot of research needs to be performed in order to secure transition from AC marine power systems to hybrid and then DC-powered marine power systems. This research may include developing methods for enhancing reliability and survivability, improving stability using virtual synchronous generators, and minimizing power curtailment on ships using real-time data and testbeds. **Table 2** summarizes some challenges and also lists examples of research that need to be carried out in order to accommodate the emerged maritime power systems.

7. Conclusion

This study has detailed some potential ways for the maritime industry to begin to phase out AC power generation and distribution on new vessels over a short period of time. Over short distances, DC power provides less power loss, no harmonics, and more control over equipment, which are some of the major reasons

why many industry officials are conducting vast research in this specific area. Therefore, the vessels of the future should consider transitioning into DC power generation and distribution. Nonetheless, during the transition from an AC shipboard power system to a DC shipboard power system, there will be a time during which the vessels will be run by a hybrid shipboard power system, which utilizes a mixture of both AC and DC power. These hybrid systems are known as integrated marine power systems or hybrid maritime microgrids.

Some advantages of hybrid maritime microgrids include higher efficiency, optimum fuel consumption, improved reliability, and more importantly improved survivability. This book chapter provides a quest for future maritime microgrids and integrated marine power systems. Though the power system literature is rich for terrestrial microgrids, it has fallen behind in providing a solid background for the future maritime systems. One of the main objectives of this review study is to pave the way for the researchers by supplying them with recent technologies, visions, and applications for future maritime microgrids. This study has presented a state of the art for maritime microgrids, emphasizing on the design aspects of hybrid maritime microgrids and summarizing the advantages, disadvantages, and the challenges that planners face when integrating renewable energy resources into existing marine power systems. Moreover, this review study has paved the way for mariners and researchers by supplying them with recent technologies, visions, and applications for future maritime integrated power systems and maritime microgrids. This work has also presented and discussed issues associated with the design and control of future maritime microgrids as envisioned by the US Navy near-term development plan of 2025 and the long-term plan of 2035. In addition, this study presented some of the challenges that both current and future IMPS are facing and reviewed some of the remedies that have been recently proposed in the literature to overcome such challenges. This study has also reported on the problem of feeder reconfiguration and service restoration of shipboard power systems and introduces directions on how to enhance the reliability and survivability of maritime power systems using distribution system reconfiguration.

Acknowledgements

This project represents a part of an ongoing research at the undergraduate level at the State University of New York, Maritime College. The corresponding author is grateful to Cadets Thomas Caravella and Christopher Austell for the time and effort they have dedicated to work on this project beside their regimental obligations. The corresponding author is also grateful for Dr. Taha Selim Ustun for the kind invitation to contributing to this book. His insightful comments and timely feedback of the revised chapter have revamped the quality of this work.

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