SHIPBOARD DC HYBRID POWER SYSTEMS; PATHWAY TO ELECTRIFICATION AND DECARBONIZATION

Mehdi Zadeh[1] and Pramod Ghimire[1,2]

1. Norwegian University of Science and Technology (NTNU), Trondheim, Norway.

2. Kongsberg Digital (KDI), Horten, Norway.

E-mail: mehdi.zadeh@ntnu.no, pramod.ghimire@ntnu.no

Abstract

Ship power and propulsion systems are being electrified for several reasons out of which emission reduction, energy efficiency improvement, and ultimately reduction in operating expense (OPEX) are the main drives. The *electrification* can be described as transformation from the conventional transmission system to all-electric transmission system linking the energy source and generation units to the power consumers. Here, a marine energy system will be established based on a so-called hybrid power system composed by three main sub-systems such as power generation, load (mainly propulsion), and energy storage systems (ESS). In an electrified marine system, all the three main elements can be converted to electric by rotatory electric machines and solid-state devices such as power converters. The mainstem of the system is a power distribution system so-called switchboard which can be either AC or DC or a combination of them depending on the vessel mission and function. The connectivity, interoperability, and seamless functioning of such hybrid systems is provided with a hierarchical control system which includes a power and energy management system (PEMS) as well as low-level controllers, propulsion control systems, and dynamic positioning (DP).

Three key enablers can be seen at the forefront of the green shift, such as electrification of the powertrains and shifting to all-electric drive; hybridization of the onboard power systems with ESS; and alternative fuels and corresponding energy conversion technologies such as fuel cells and gas engines. The electrification has been realized based on the development of power electronics and onboard power systems among them shipboard DC grids. The recent trend of shifting from the conventional AC power system to onboard DC systems is driven by various factors including the energy efficiency, control flexibility, design flexibility, and fuel flexibility facilitating the integration of emerging power sources based on the alternative fuels such as H2 and other low-emission gaseous fuels. Here, the electrification shall be distinguished from battery installation and usage. The electrification in the general form is referring to all-electric powertrain with or without batteries. On the other hand, the hybridization of the onboard power systems is increasingly implemented due to the advancements in lithium-ion battery technologies. The batteries are contributing to different aspects of the system operation such as efficiency improvement and consequently fuel and emission saving, dynamic stability improvement, and zero-emission propulsion. In addition to the efficiency improvement benefits, power smoothing of the conventional engines is also a significant aspect as it reduces operational cost. Furthermore, the low or zero-emission fuel cell power systems are shifting the paradigm in shipboard power systems.

This chapter discusses watercraft systems from the perspective of power and propulsion system architectures and topologies. Furthermore, the strategies of control and load sharing are discussed mainly relevant to DC hybrid power systems. Besides, a few case studies are given to elaborate the efficiency aspect of the onboard DC power system.

Introduction

The significance of ocean space is increasing as it provides various opportunities and resources, be it food and minerals or the potential of renewable energy harvesting [1]. Further, it also provides a significant contribution to global trade as 80-90% of global trade takes place through maritime transportation [2]. Therefore, it is also considered as the *backbone of the global trade and economy* [3]. Further, the trend of global trade through maritime transportation is increasing. This upward trend increases not only the opportunities but also the challenges of *sustainability of the blue economy*. The major challenges come with energy efficiency improvement and emission reduction of the watercraft systems.

For the efficient utilization of resources and opportunities in the ocean space, various watercraft types are in operation based on the nature of the resources or the opportunities. In other words, various types of watercrafts are in existence to accomplish the dedicated tasks or purpose in the ocean space. These watercrafts propel through the power produced by the prime movers. The emission-free sails and oars were initially used for the ship's propulsion [4]. However, the controlled propulsion and navigation in many circumstances were challenging. Further, with the development of the prime movers like steam and diesel engines, the propulsion units were driven through the power produced by these prime movers [4]. The propulsion system is further divided into different types based on coupling between the prime movers and the propulsion unit, such as mechanical, electrical, and hybrid propulsion systems.

The propulsion unit has been conventionally driven through a gearbox or directly by the prime mover in the mechanical propulsion. In contrast, in the electric propulsion system, the propulsion unit is driven through an electric motor which is fed by an electric distribution system, so called switchboard, and the switchboard itself is fed by the source of electrical power which is usually a synchronous generator coupled with the prime mover which is usually a combustion engine. The coupled engine and generator system is also called engine-genset. In a hybrid mechanical-electrical propulsion, the propulsion unit is coupled mechanically to the prime mover and electrically to the electrical power generator and captures the positive aspects of both propulsion systems. The electrical power is used to accomplish various objectives on board a vessel. The commercial use of electricity in the form of light bulbs started in the vessel *SS Columbia* [5]. It has been followed by a series of innovative developments of the electrical equipment, machinery, and systems down the timeline, which is ever-increasing the electrical power demand onboard a vessel [6]. Some of the latest examples are autonomous vessels, fully electric vessels based on batteries and fuel cells, and hybrid power systems [7].

Shipboard Power System Architectures

As in the land-based power system, AC power system architecture has been dominating onboard a vessel. The dominance comes with the well-developed control and safety systems together with the major AC components such as electric generators and motors. On the other hand, thanks to the emerging use of energy carriers such as batteries, supercapacitors, and fuel cells, the relevance of the DC power system is increasing as all these carriers operate in DC systems.

The AC and DC power systems primarily differ with the physical positioning of the power converters. The development of efficient power converters has enabled the power conversion between AC and DC. Both AC and DC power systems onboard a vessel have merits and demerits. A general comparison of AC and DC systems is summarized in Table 1 [8] based on [6], [7], [9]–[14].

TABLE 1 COMPARATIVE ANALYSIS OF AC AND DC POWER SYSTEMS.

Characteristics	**AC System**	**DC System**
Reactive power	✓	✗
Voltage control	✓	✓
Frequency control	✓	✗
Synchronization	✓	✗
Harmonic distortion	✓	✗
Ripples	✗	✓
Variable-speed engine	✗	✓
Bulky components	✓	✗
Easy voltage transformation	✓	✗
Easy ESD connections	✗	✓
Fuel-saving potential	✗	✓
Well developed control systems	✓	✓
Well developed safety systems	✓	✗
Easy fault detection	✓	✗
Low maintenance	✓	✗
Better component availability	✓	✗
Proper standardization	✓	✗

AC Switchboards

In AC type onboard power system, the main switchboard is energized with the AC voltage of 50 Hz or 60 Hz. As the system frequency must be maintained, the prime movers in this system usually need to operate at a nearly constant speed. In addition to the system frequency, system voltage is also controlled in this system. The presence of reactive power increases complexity; however, it facilitates voltage regulation. Further, voltage, frequency, and phase synchronization are required in this system. A single line diagram (SLD) of a typical AC hybrid power system including the ESS is shown in Fig. 1. As batteries, supercapacitors, and fuel cells operate in a DC system, the connection of these energy carriers into the main switchboard requires power conversions, thereby reducing some flexibility. On the other hand, the voltage transformation is relatively more straightforward in an AC system, thereby increasing flexibility. However, the bulky AC components (voltage transformers and harmonic filters) increase the dead weight for the voltage transformation and reduction of harmonic distortions. Further, well-developed safety and control systems increase the robustness of the AC system. However, differential protection is increasingly used in AC systems, especially in complex systems with varying generator power ratings.

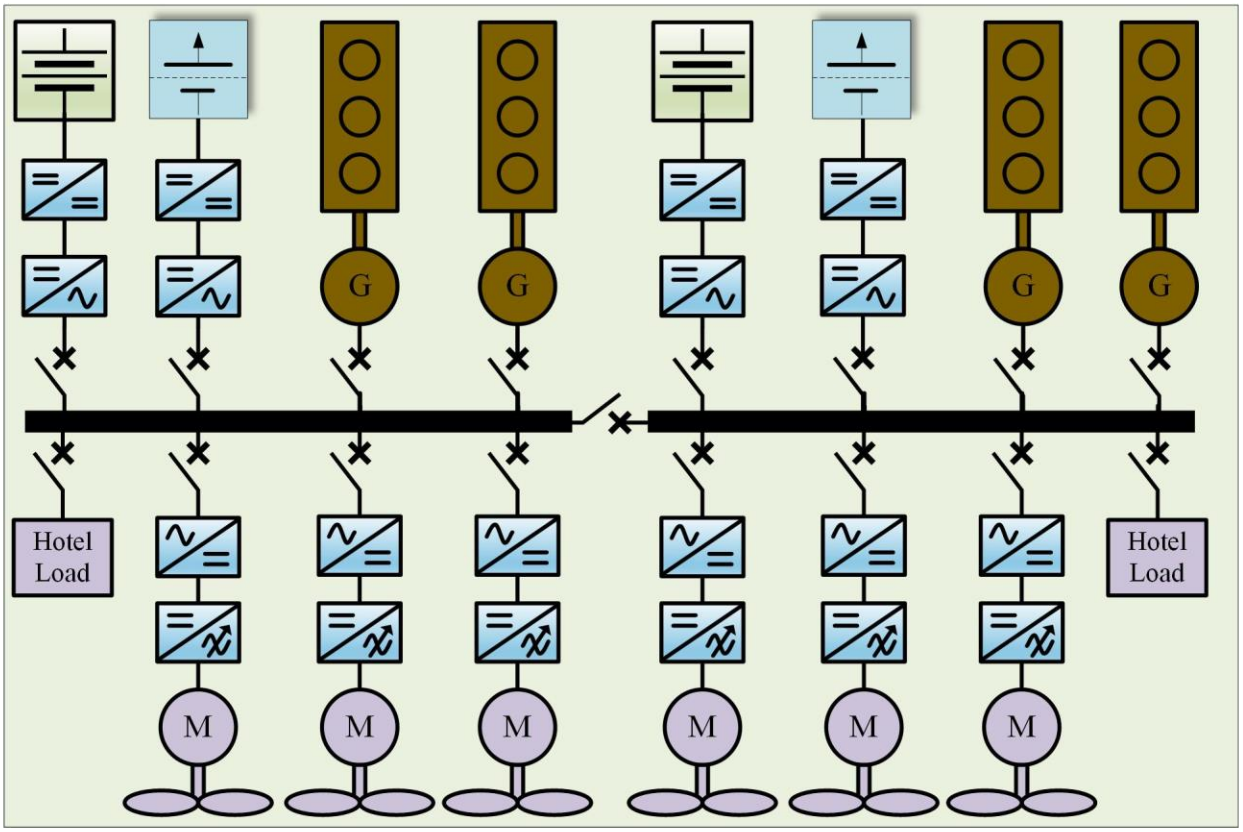


FIG. 1 TYPICAL MARINE AC HYBRID POWER SYSTEM ARCHITECTURE.

DC Power System

In the onboard DC power systems, the main switchboard is energized with the DC voltage. As the system is free of frequency, the prime movers are usually operated at a variable speed to attain optimal fuel consumption. This system is relatively simple as phase and frequency synchronization, and the harmonic filters are not required. However, the rectification of AC to DC may generate ripples that usually require capacitive filtering. SLD of a typical DC hybrid power system with the emerging energy carriers and ESS is shown in Fig. 2.

Renewable energy sources and emerging energy storages such as batteries, supercapacitors, hybrid energy storage systems, and fuel cells can be integrated into the DC system with less energy conversion as these sources are inherently DC. However, DC-to-DC converters may be required to adapt the voltage levels [34]. In commercial vessels, the major electrical power producers are still synchronous generators; the DC system requires the rectification of the AC voltages produced by the gensets. However, the rectification part of the variable speed drives of the propulsion units and other electric machinery are not required. The hotel loads are usually connected to an AC system that requires voltage inversion in the DC system. Though well-developed control systems for DC systems are available, the safety system (fault detection, location, and isolation) is still a major challenge for the DC systems with higher voltage levels.

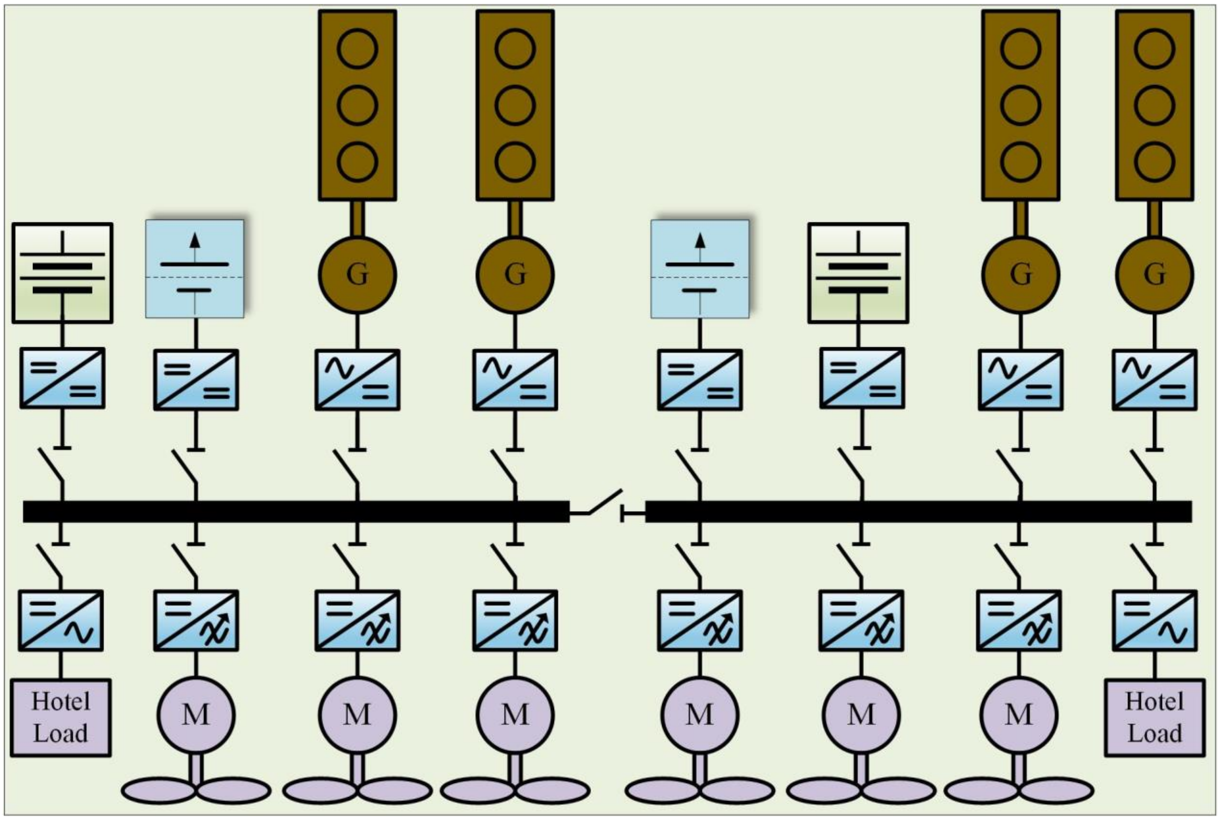


FIG. 2 TYPICAL MARINE DC HYBRID POWER SYSTEM ARCHITECTURE.

Hybrid AC-DC Power System

The major difference between AC and DC power systems comes down to the positioning of the power converters. Extra power conversion is required in the variable speed drives in the AC system, whereas it is required for the electrical generator output in the DC system. In the hybrid AC-DC power system, two main switchboards are maintained, one in the AC system and the other in the DC system, as shown in Fig. 3.

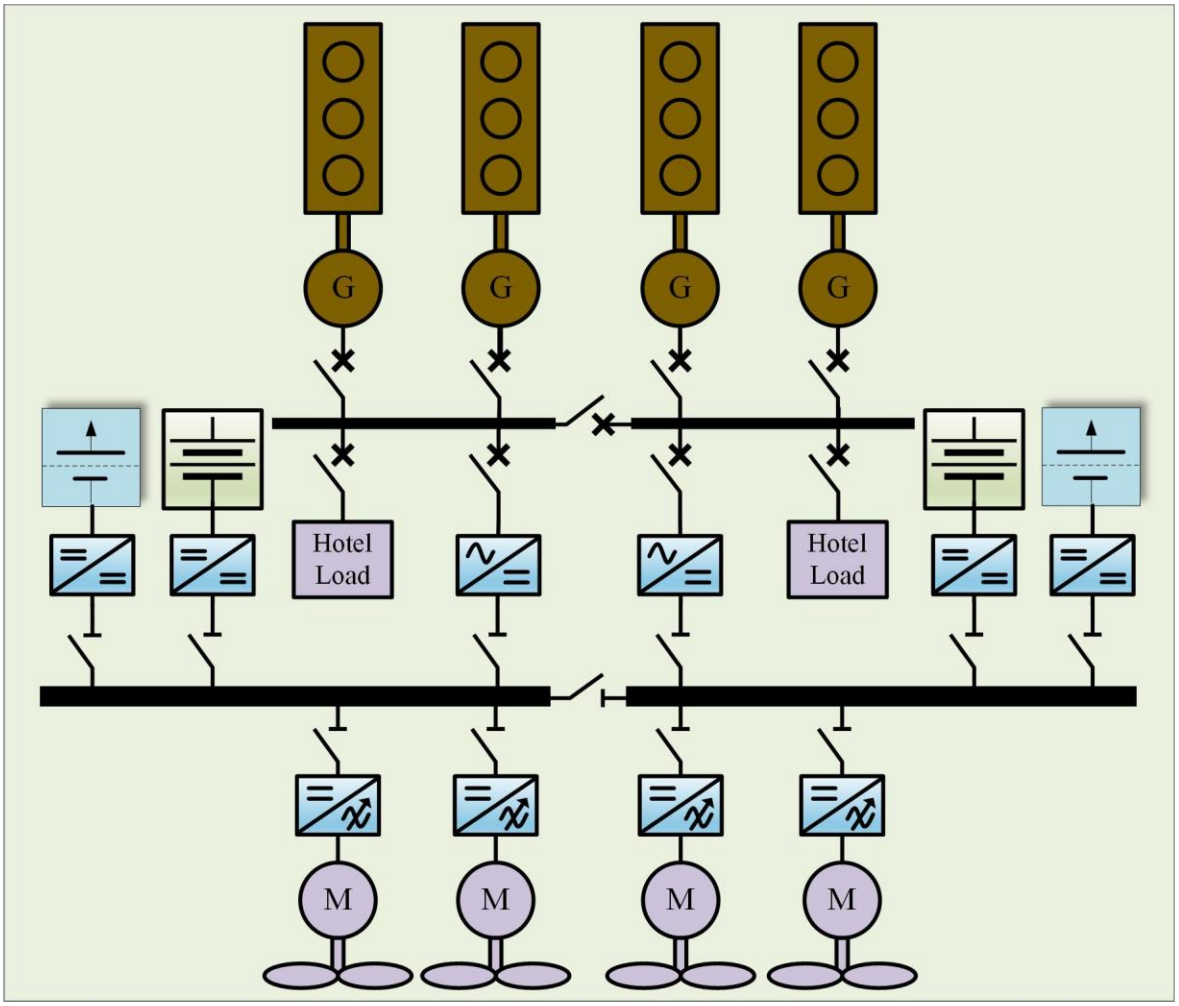


FIG. 3 TYPICAL MARINE AC-DC HYBRID POWER SYSTEM ARCHITECTURE.

These AC and DC switchboards or grids are then connected through a bidirectional power converter. The advantage of this architecture comes with minimal power conversions. The electrical generators and hotel loads can be combined in the AC system, whereas the propulsion loads, batteries, supercapacitors, and fuel cells can be connected to the DC main switchboard. However, the major benefit of the DC system due to the variable speed operation of the combustion engines is not realizable.

Shipboard DC Power System Topologies

As in marine AC power systems, different topologies can also be adopted in DC power systems. The selection of the bus topology depends on the high-level control and fault management design, requirement from the class society, and the functional requirement of the type of vessel itself based on the installed power. Some relevant DC bus topologies for the shipboard power system are introduced below with simplified illustrations based on [6], [15]–[21].

Fig. 4 depicts a simplified DC bus topology with a single main bus supplied by the generators, battery, and a fuel cell. The propulsion and hotel loads are also connected to the same bus. This topology is simple in nature and the high-level control can be relatively simple. However, the redundancy in the system is compromised as fault diagnosis and isolation become relatively complex. This type of topology can be suitable for smaller vessels.

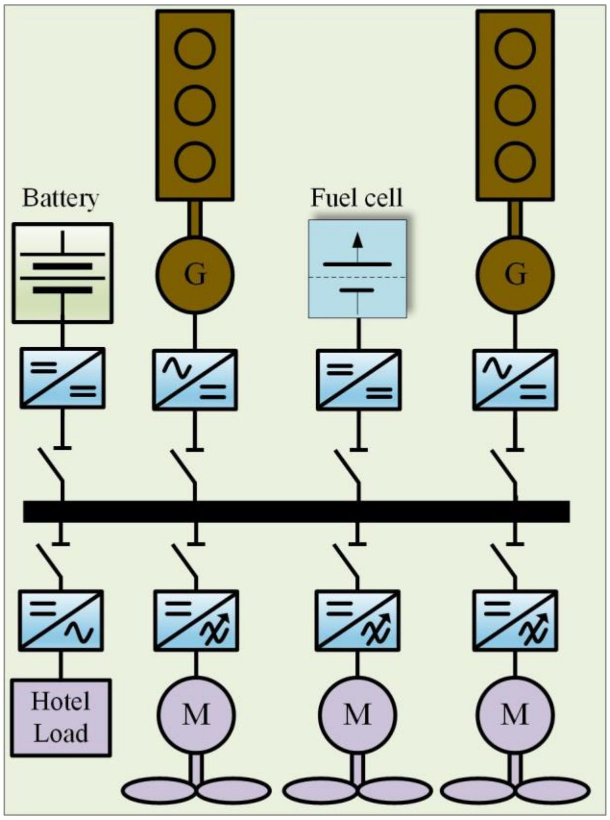


FIG. 4 SIMPLE DC BUS TOPOLOGY.

Zonal bus topology can be implemented to avoid the drawbacks of the simple DC bus topology. In the zonal bus topology, the main bus is divided into two or more zones using a bus-tie breaker. The power generators, energy storage devices, and loads are distributed to different zones. This enhances the redundancy and resilience of the onboard power system and enables to implement the protection selectivity in the DC system [35]. However, the high-level control system may be relatively complex as the control strategy for a common bus (bus-tie breaker closed), and sectionalized bus (bus-tie breaker opened) may be different. The common zonal separation of the bus can be based on the physical location onboard a vessel such as port, starboard, bow, and stern. Fig. 5 shows a typical zonal bus topology with each generator supplying the bus in each zone. The battery and fuel cell are connected to zone 1 and 2, respectively. Similarly, loads are also distributed to the bus in each zone. The number of zones can be designed based on the installed power and required level of redundancy.

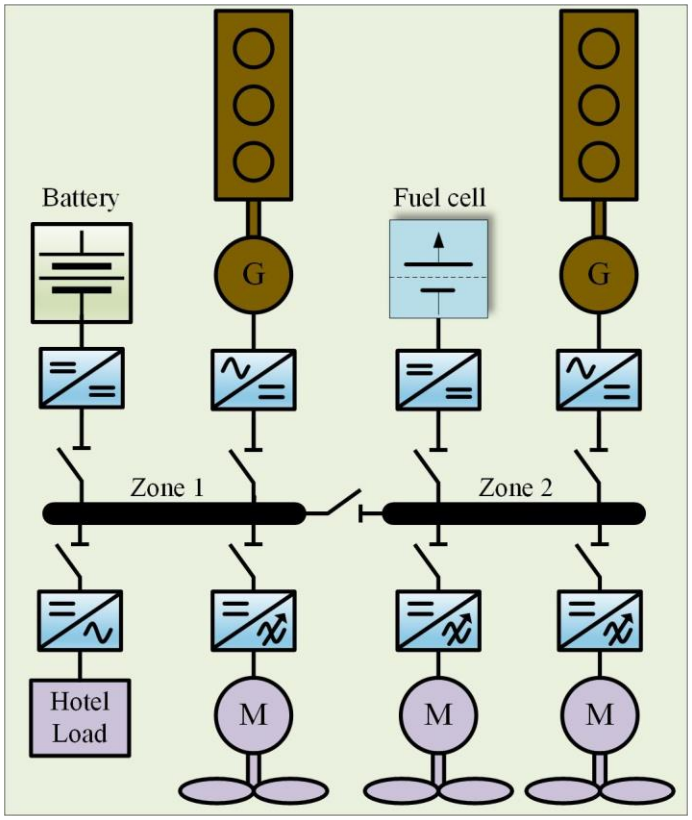


FIG. 5 ZONAL BUS TOPOLOGY.

To further increase the redundancy in the power system, the topology can be extended to a ring bus topology, where the buses are connected in a ring structure. The power generators, storage devices, the loads are then distributed to each bus. The high-level control of this topology is relatively complex; however, the degree of reliability is higher, or failure identification and isolation are relatively easier in this system. Fig. 6 presents the schematic of a ring bus topology. This type of topology can be implemented in the deep-sea vessels, which need to be also operating in harsh weather and sea conditions.

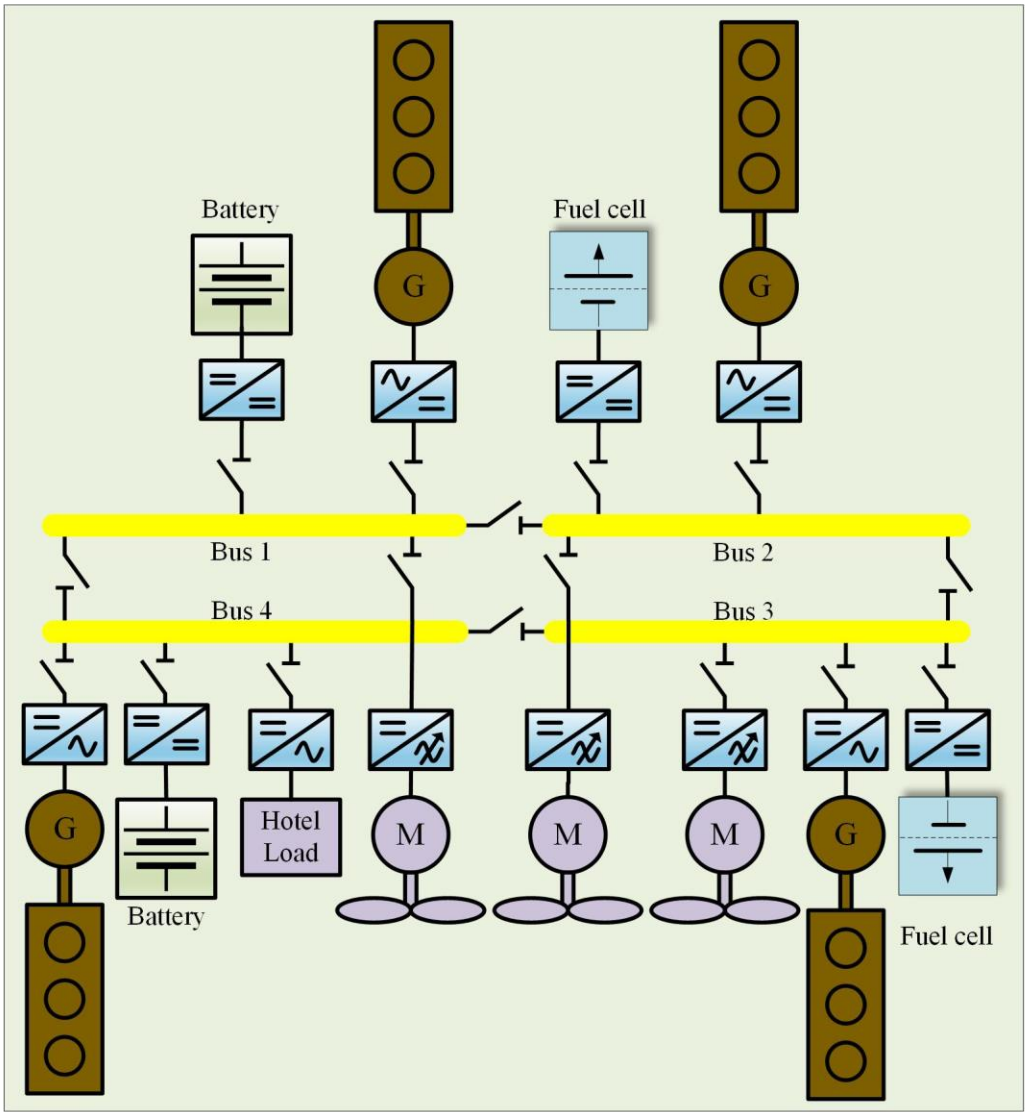


FIG. 6 RING BUS TOPOLOGY.

Fig. 7 illustrates the multi-voltage DC bus topology where zonal buses with two different voltage levels are connected through a common grid converter. The power generators can be operating in medium-voltage DC (MVDC), whereas battery and fuel cells can be working in the low voltage DC (LVDC). The load in the power system can also be segregated into different voltage levels based on their rated power capacity so that the current through the equipment can be in the range where safety and stability of the system are ensured. The segregated loads can then be connected to the buses with appropriate voltage levels.

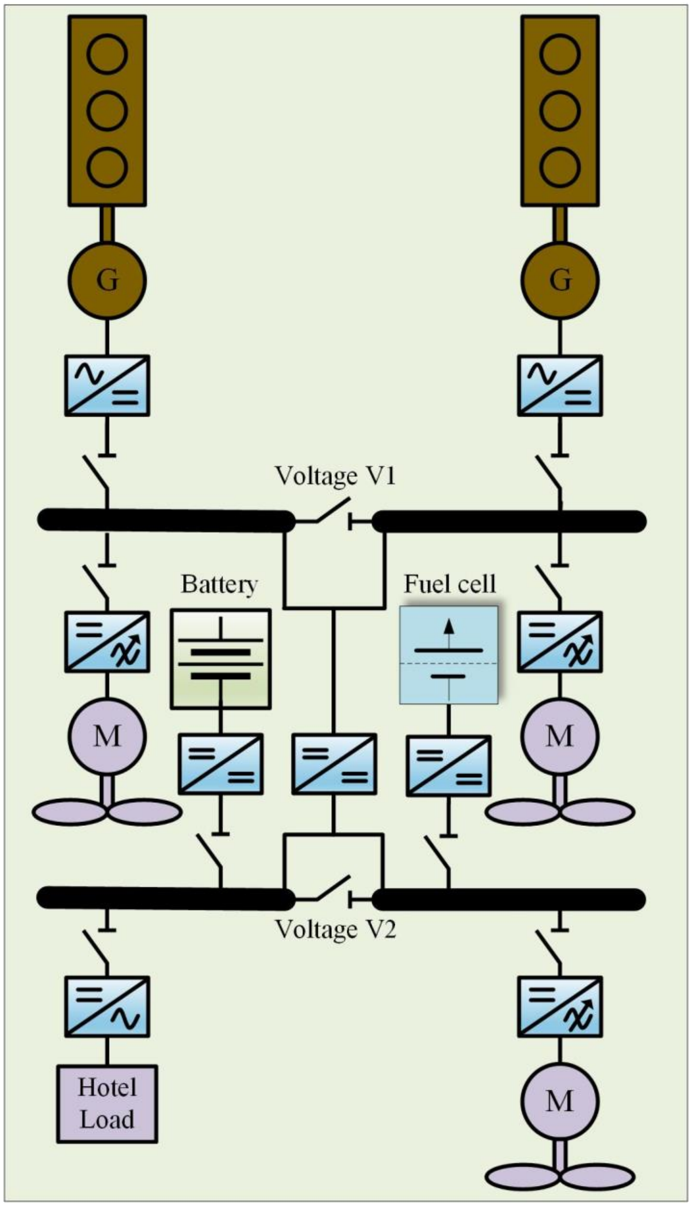


FIG. 7 MULTI-VOLTAGE BUS TOPOLOGY.

Energy Storage and Alternative Energy Sources in Shipboard Power System

Though green and renewable energy sources were initially used in historical watercraft [4], fossil fuels are the dominating source of energy in the watercraft systems. The green and renewable energy sources such as solar, wind, and wave energy include a high degree of uncertainty for the prediction, due to which controlled propulsion had been a challenge. On the other hand, advancements in the internal combustion engines turned out to be reliable energy conversion devices, due to which they have been widely used in watercraft.

The mission of the vessel defines its energy and power requirements which are usually represented by time series of load power so-called load profile. However, the ability of the energy storages and power sources to deliver the required power and energy depends on their gravimetric and volumetric power and energy density. These properties are defined by the weight and volume constraints of the vessels. For instance, renewable energy-based zero-emission propulsion with solar- and wind power is attractive in the green shift. However, producing the required power and energy demand by such power sources is not feasible for many vessel types. Therefore, the energy carrier selection in the watercraft is influenced by the energy and power requirement for the mission, the weight and volume constraints, as well as rules and regulations concerning ship design and operation.

The gravimetric energy and power density of the common energy carriers in the watercraft systems are presented in a Ragone plot in Fig. 8 [22], [23]. From the perspective of energy and power density, combustion engines can be considered a promising alternative. However, alternatives to combustion engines are considered due to the harmful emissions from fossil fuels and relatively low efficiency of the engines. Therefore, a fuel cell is considered as an attractive alternative [24] where reliable control and safety systems are under development, though the fuel cell propulsion can still be considered premature both in terms of power or energy capacity and fuel transportation. Batteries are considered a good option; however, they lack sufficient energy content for all vessel types. On the other hand, supercapacitors can only provide high power for short time intervals. Therefore, to achieve emission reduction and efficiency improvement in the watercraft, the combination of these power sources is considered as the most viable option with the available technologies in the field [6], [8], [25].

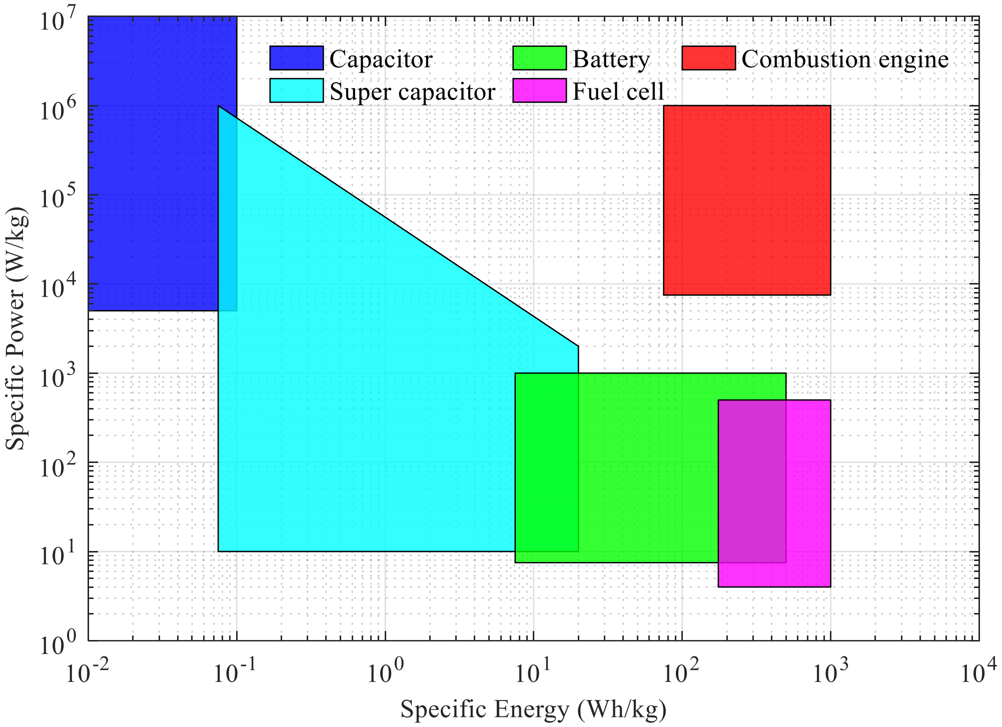


FIG. 8 RAGONE PLOT SHOWING TYPICAL GRAVIMETRIC ENERGY AND POWER DENSITY RANGES FOR ENERGY CARRIERS.

Energy storage devices such as batteries and supercapacitors are increasingly used in watercraft, mostly hybridizing the power system. Depending on the energy density properties, their use may vary a bit. However, batteries are mostly in use. Therefore, a high-level control system (power and energy management system) should include the defined control algorithm or strategies to achieve these functional applications of the energy storage devices. The major functional applications of the battery in watercraft systems are further described.

Fuel cell

Fuel cells (FC), as electrochemical power sources, convert the chemical energy of the fuel directly into electric power without a prime mover. Fuel cells are attractive for electric propulsion due to several main reasons such as the compatibility with H_2 and gaseous fuels, smooth efficiency profile and potentially higher energy efficiency compared to gas engines, low vibrations and mechanical impacts, and low maintenance requirements compared to rotatory machinery. On the other hand, FCs have often much lower lifetime compared to engines and even batteries.

Fuel cell systems are recently under development for marine propulsion based on both low-temperature FCs, e.g., proton-exchange membrane fuel cells (PEMFC), and high-temperature FCs, e.g., solid oxide fuel cells (SOFC) and molten carbonate fuel cell (MCFC). The low-temperature FCs are preferred in terms of safety, load tracking, and weight and space saving thanks to smaller auxiliary systems, while high-temperature FCs can provide higher electrical efficiency thanks to their high-temperature exhaust gas that enables combined heating and power (CHP) in a so-called co-generation system.

A typical fuel cell powertrain with DC power architecture is shown in Fig. 9. In this scheme, a DC-DC power interface is always required for isolating of the FC from the main DC grid, regulating the voltage on the DC bus independently from the FC, and boosting the output voltage of the FC which is usually very lower than the main DC bus due to the inherent low voltage of FC stacks [24].

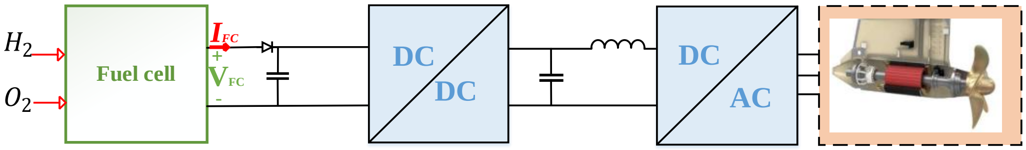


FIG. 9 SCHEMATIC OF A FUEL CELL POWERTRAIN.

FCs can also be integrated with the ESS (batteries and supercapacitors) via a three winding isolation transformer as shown in Fig. 10.

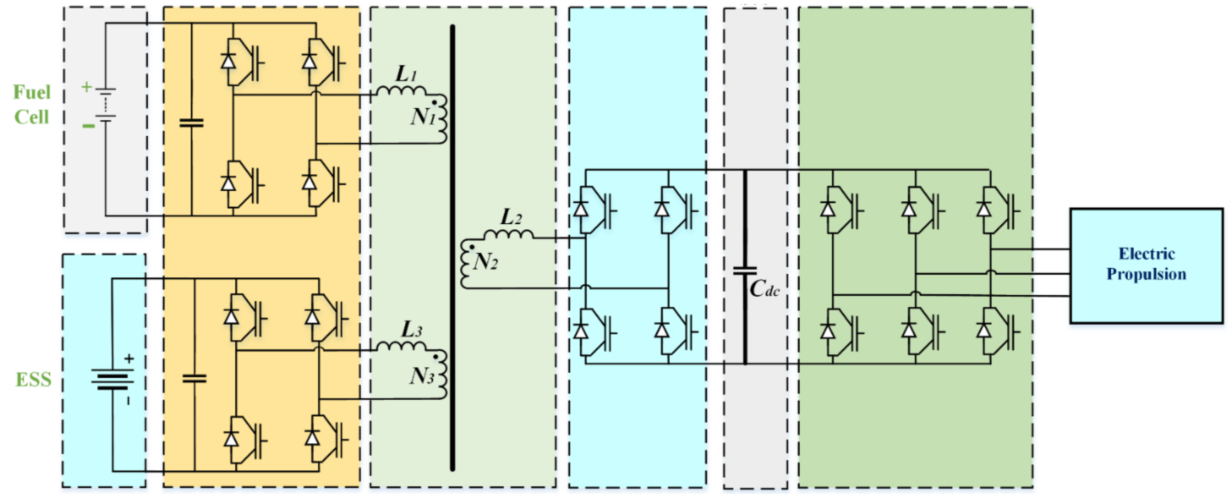


FIG. 10 INTEGRATED FC AND ESS TOPOLOGY.

High-Level Control of Energy Storage Systems

The energy storage system can act both as an energy supplier and consumer. It enables flexibility in the power system. The extra power generated can be stored in energy storage devices. On the other hand, energy storage systems can supply power when available power is deficient. However, they can neither store nor supply infinite power because of the size and capacity constraints. Therefore, implementing the proper strategies to manage the energy utilization in the storage devices is crucial. Some of those energy management strategies or high-level control approaches for the energy storage devices in the DC shipboard power system are discussed below based on [22], [26], [27].

Peak Shaving

The marine loads are usually fluctuating in nature due to different circumstances; the environmental condition is one. These fluctuating loads can make the power system parameters such as bus voltage, and engine load fluctuate. The fluctuating generator loads may lead to unnecessary start and stop of engine-generator sets when the load-dependent start-stop is activated. On the other hand, energy storage devices like batteries can shave the load peaks of the generator, as shown in Fig. 11. Depending on the loading conditions, the battery may charge or discharge. It ensures that the engine-generator sets operate between the predefined load limits.

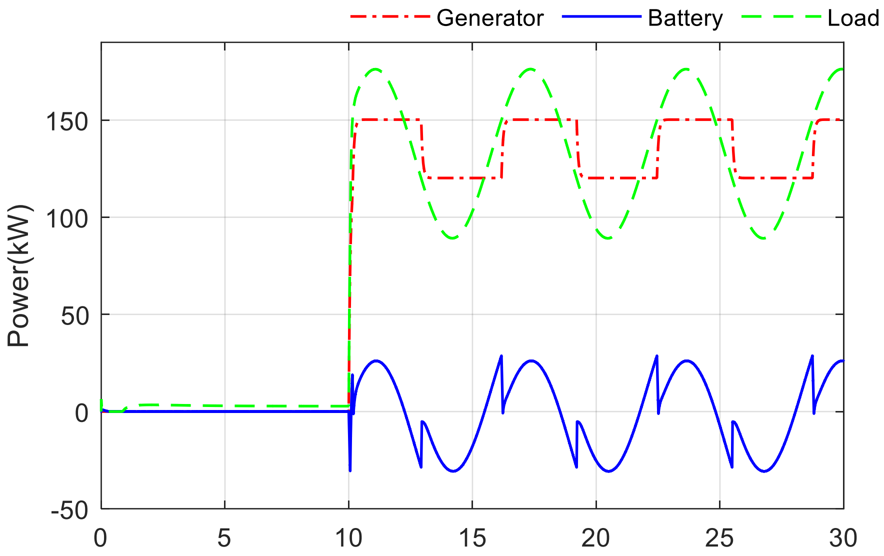


FIG. 11 LOAD SHARING THROUGH PEAK SHAVING STRATEGY.

Load Leveling

As in peak shaving, the objective of this control strategy is to avoid the fluctuating loading of the generator. In this case, the generator supplies the average load power. At the same time, the battery takes care of the load variations, i.e., battery charges if the load demand is lower than average load power and discharges if the load is less than the average load power, as shown in Fig. 12. It limits the fluctuations in the engine-generator sets; however, the battery capacity required to level the generator load is usually higher than in peak shaving.

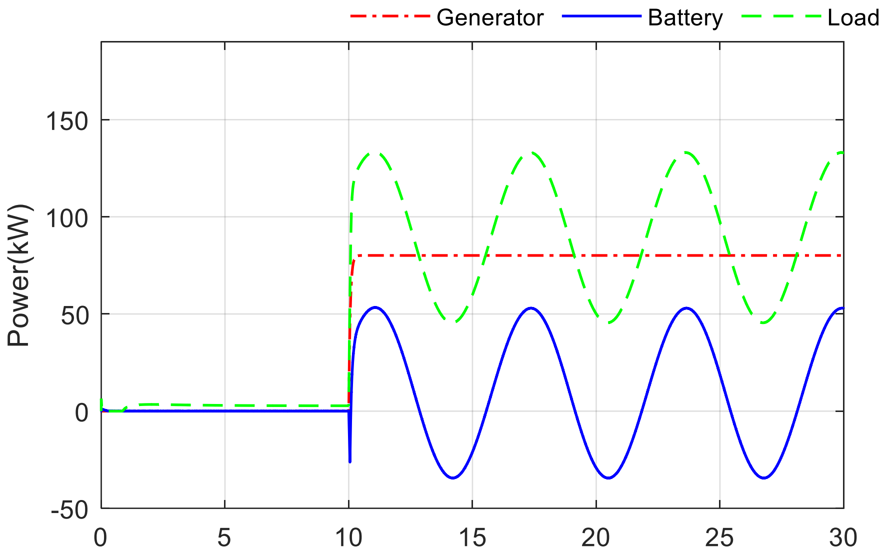


FIG. 12 LOAD SHARING THROUGH LOAD-LEVELING STRATEGY.

Zero-Emission

In the restricted areas where it is not allowed to operate fossil-fueled conventional engines, the batteries can be used to supply the total load demand in the vessel, zero-emission operating mode, as shown in Fig. 13. Usually, the battery has limited capacity compared to conventional engines. Therefore, it is crucial to design the battery and other component capacities such that they can provide power to the required propulsion and critical auxiliaries. In addition, the proper planning for zero-emission operation mode is necessary to ensure that the battery contains sufficient charge.

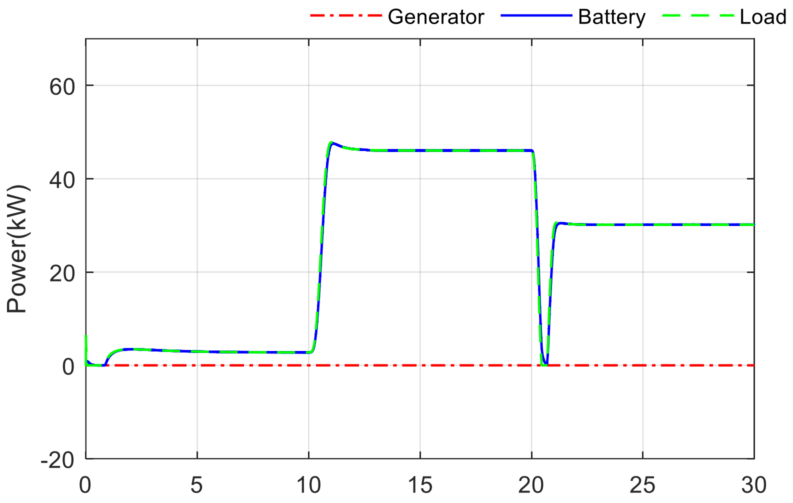


Fig. 13 Zero-Emission Operation.

Battery Charging

As the charge contained in a battery decreases with its discharging, it is essential to charge the battery, especially before zero-emission operation. Fig. 14 shows that the generator is supplying power not only to the load but also to recharge the battery.

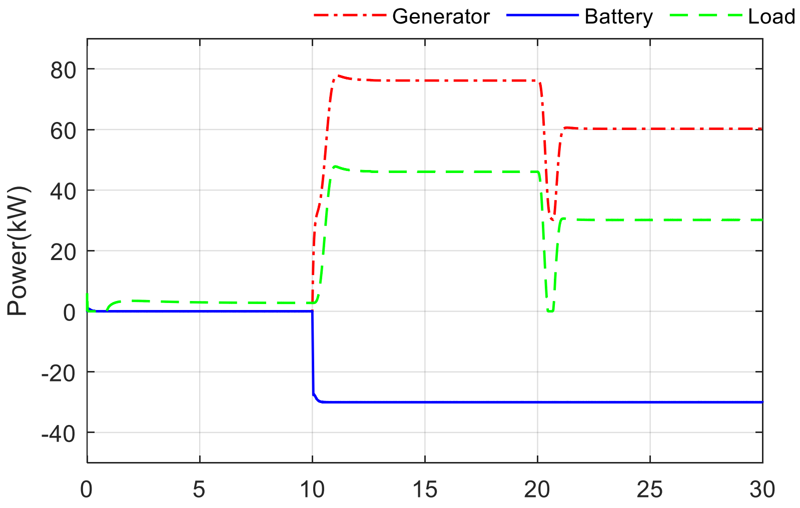


Fig. 14 Battery Charging Operation.

Strategic Loading

The batteries contribute to the load sharing with gensets. This battery function enables to reduce fuel consumption by allowing engines to operate in fuel-optimal regions. This is by the fact that the engine fuel consumption and efficiency are functions of the engine loading as maximum continuous rating (MCR). Fig. 15 shows the curve of the fuel consumption for a typical marine combustion engine namely specific fuel oil consumption (SFOC); the SFOC represents the consumption as gram of fuel per kWh energy generated and transferred through the engine shaft. The given curve indicates the SFOC as a function of engine loading in MCR percentage.

As shown in the figure, the consumption has a nonlinear relation with the loading and the high- or low-load condition may result in higher consumption and lower efficiency. The optimal efficiency may be associated to a specific loading which is in this case around 80% of MCR; this specific operating point results in minimum fuel consumption and maximum efficiency. Here, the battery can help to keep the engine loading in the optimal operating point or optimal region of operation by supplying the surplus load. The battery can then be charged in low-load conditions and can be discharged under high-load operation. In the figure, the overloading and underloading conditions are indicated by low and high MCR percentages, e.g., 35% and 100%, to elaborate the effect of the loading on the SFOC and efficiency. Compared to the green and purple ovals, on the red circle which is around 80%, the fuel consumption is obviously reduced. The so-called optimal operation point can be achieved thanks to the battery operation and strategic loading. This control strategy enables to reduce the fuel consumption and emissions [27], whereas the battery gets repetitive charge-discharge cycles [28].

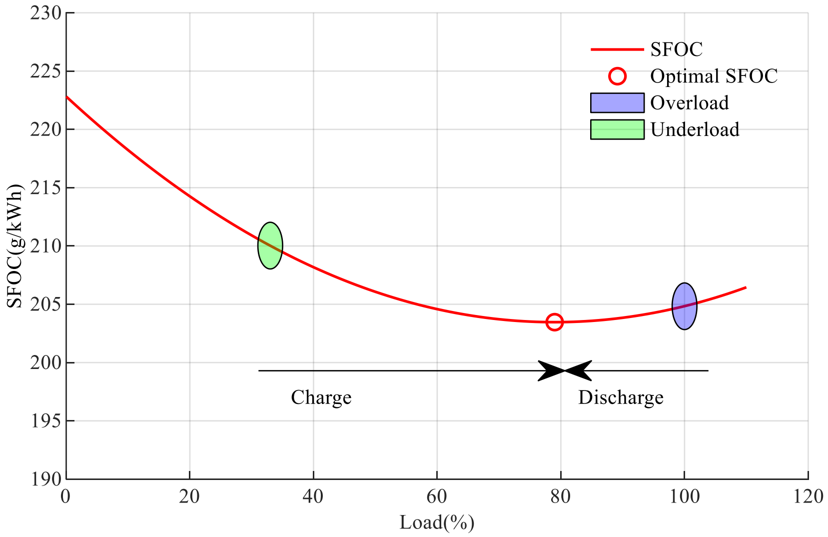


FIG. 15 STRATEGIC LOADING OPERATION.

Enhanced Dynamic Performance

Usually, the large engine high a slower response due to higher inertia. Similarly, gas engines and fuel cells also have a slow response. In contrast, marine loads fluctuate and can increase or decrease abruptly based on the mission profile or due to environmental conditions. This high load change can make the system unstable, leading to a blackout [27]. Therefore, the battery can compensate for the slower response of engines and fuel cells as it has a faster response and increases safety and robustness.

Spinning Reserve

Depending on the different classification from the class societies, the vessels need an extra level of redundancy. Therefore, additional generators are connected to the bus in a conventional power system to maintain redundancy levels. However, operating an extra generator reduces the generator load, which means the loading in all engine-generator sets becomes less than the fuel-optimal region. In contrast, the use of batteries as a spinning reserve increases robustness and decreases fuel consumption and emissions [27].

Load Sharing in DC Power System

Droop control is an established control technique in the shipboard power system. In an AC power system, active and reactive power are managed through frequency and voltage droop controls. However, the DC power system is frequency-free and does not require reactive power-sharing. But, the active power-sharing has to be performed and is usually done through the voltage droop control. The droop control is in principle a proportional controller that finds a voltage setpoint for the generator's automatic voltage regulator (AVR). This voltage setpoint is calculated based on the slope of the droop-line and the actual load in the generators. The droop control can be implemented in the distributed control for each generator. For equal load-sharing among the generators, the slope of the droop-line or droop sharing coefficient needs to be similar, as shown in Fig. 16 Fig. 16 Equal Sharing Through Droop Control **[22].**

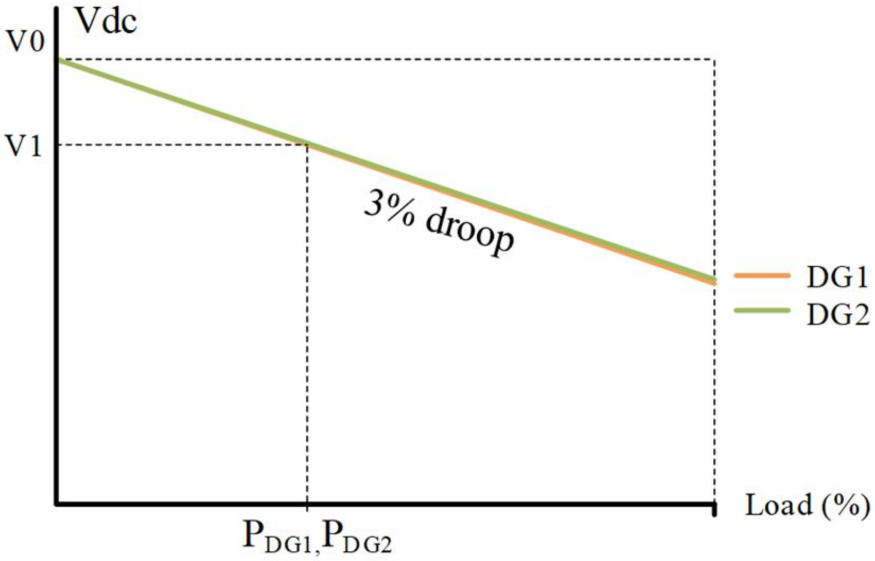


FIG. 16 EQUAL SHARING THROUGH DROOP CONTROL [22].

On the other hand, different droop coefficients for the generators make unequal power-sharing, as shown in Fig. 17. Further, it can also be extended for the sharing with the battery where the battery is charging when the power is negative and discharging when power is positive.

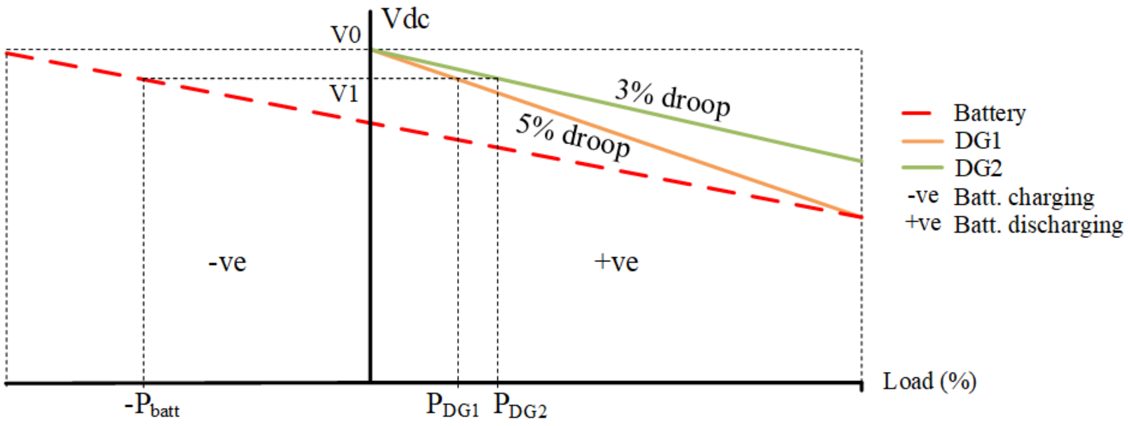


FIG. 17 UNEQUAL SHARING AMONG GENERATORS AND BATTERY USING DROOP CONTROL [22].

Efficiency Improvement and Emission Reduction Potentials

Energy efficiency quantifies the conversion of input energy to the intended output. For example, the chemical energy contained in the fuel is the input energy to the system. In contrast, the electric power consumption and mechanical energy output from the propulsion units are the output energy of the power system [8], [29]. Therefore, the energy efficiency is dependent on the fuel consumption, and the lower the fuel consumption for intended output, the higher is the energy efficiency. Therefore, the vessel's energy efficiency has been one of the crucial factors during the selection of new technology or the comparison with other technologies. At the same time, regulatory bodies are making stringent rules and regulations to reduce emissions from the maritime sector and improve energy efficiency [22]. Therefore, energy efficiency improvement also makes the industry competitive with other transportation sectors and reduces emission, a function of fuel consumption.

The system efficiency can be determined based on the power or energy in the system. The power efficiency is an instantaneous efficiency of the system, whereas energy efficiency is the time average of the power efficiency as presented in Eqn. (1) and Eqn. (2), where P_0 is output power, P_i is the input power, η_p is power efficiency, and η_e is the energy efficiency.

$$\boldsymbol{\eta_p(t) = \frac{P_0(t)}{P_i(t)}} \qquad (1)$$

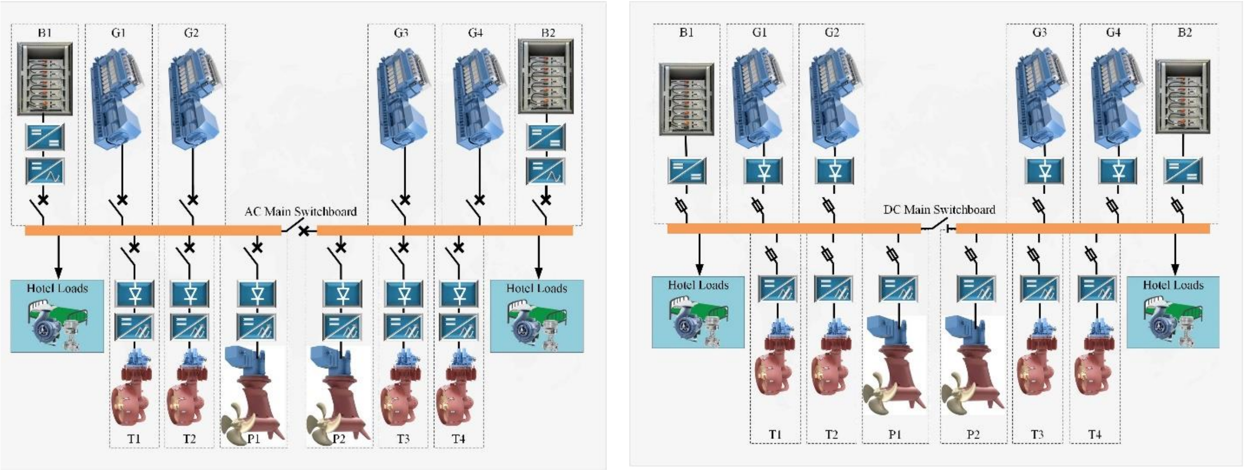
$$\boldsymbol{\eta_e(t) = \frac{\int P_0(t)dt}{\int P_i(t)dt}} \qquad (2)$$

Conventionally, the rated efficiencies for the components have been used to determine the power system efficiency [30]. On the other hand, loading conditions for the components impact their efficiency [31]. Therefore, the losses or efficiency determination for the components and the complete power system needs to be dynamic with the loading conditions [8], [29]. In addition, to make a fairly realistic estimation, the availability of an actual load profile is essential.

Further, one of the benefits of the DC power system in the maritime industry is improved efficiency. Operating the engines in variable speed operation helps reduce fuel consumption, especially in low-load conditions [32]. The comparative study of energy efficiency in different power system architectures in a cruise ship shows that the DC power system with variable speed engines provides slightly improved efficiency compared to the AC system [8]. It also showed that the DC power system is slightly more efficient than AC in both calmer and rough sea conditions. The improvement in the efficiency reflects less fuel consumption to do the intended work than AC, which means less emission and improved decarbonization from the maritime industry.

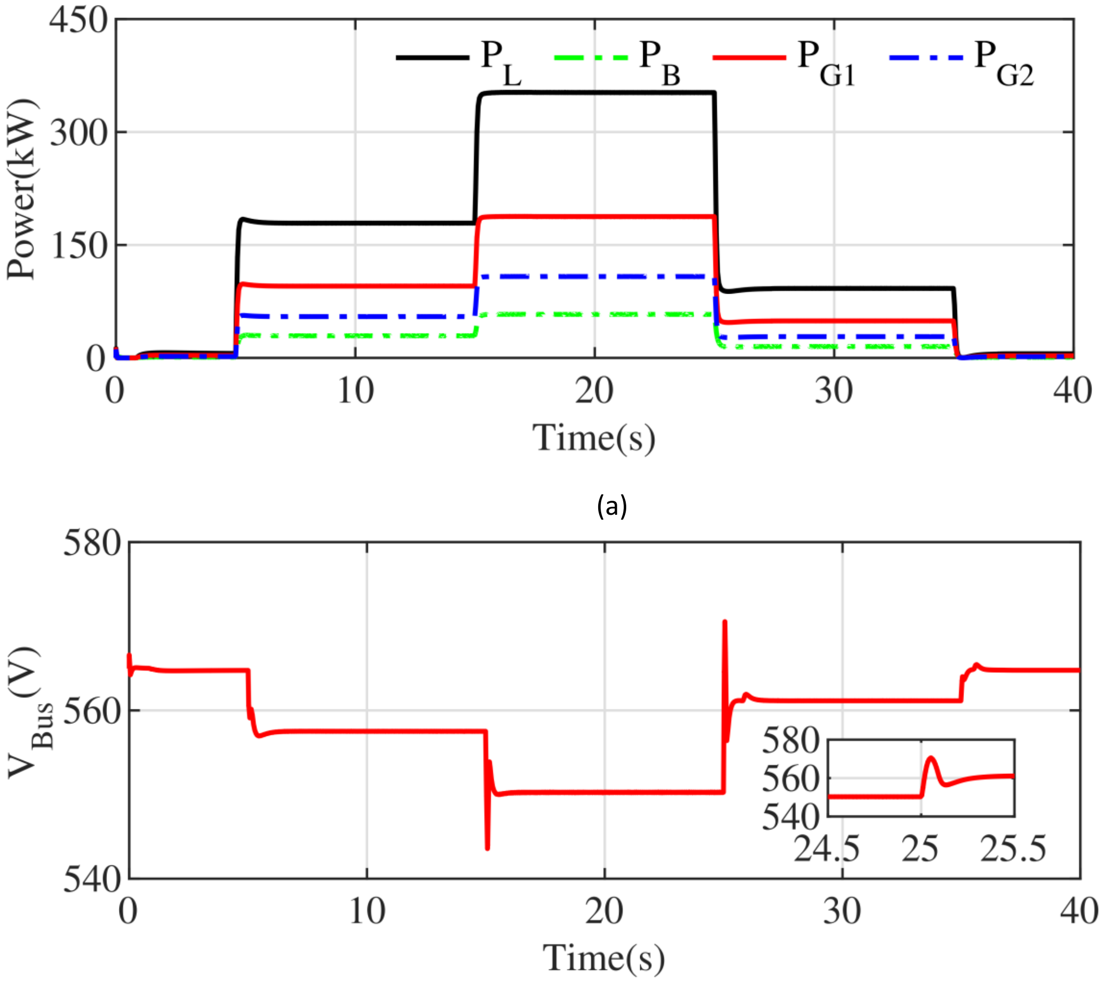
Case study

A case study is presented in this section to elaborate the efficiency aspects of the onboard power system. A typical hybrid power system with AC and DC switchboard is shown in Fig. 18. As shown in the SLD, the switchboard is split into two sections for the sake of redundancy and improved resilience. Based on the vessel classification, it can be also split in 3 or 4 sections. In the sectionized switchboard, the sections can be connected through switchgears namely bus-tie breakers. A typical vessel load profile is shown in Fig. 19 (a) with the load sharing between gensets and the battery on one DC bus section. Fig. 19 (b) also demonstrates the DC bus voltage variations on the main DC switchboard. In this case the rated DC voltage is assumed to be equal to 565 V and the voltage at the battery end equal to 346 V [25].



(a) (b)

FIG. 18. TYPICAL ONBOARD HYBRID POWER SYSTEM; (A) AC SWITCHBOARD. (B) DC SWITCHBOARD.



(a)

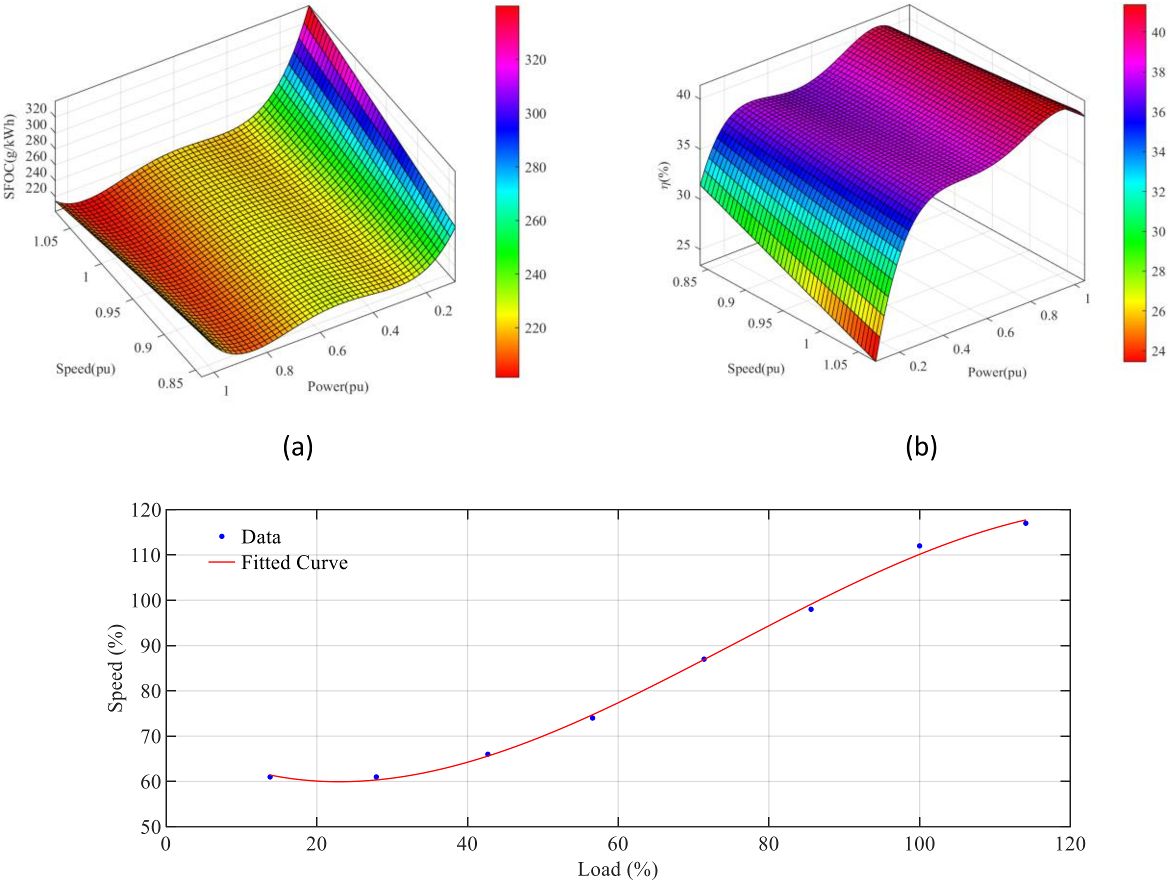
(b)

FIG. 19 (A) TYPICAL LOAD PROFILE WITH POWER DISTRIBUTION BETWEEN GENSETS AND BATTERY. (B) DC BUS VOLTAGE ON THE MAIN SWITCHBOARD AND FLUCTUATIONS CORRESPONDING TO THE LOAD CHANGES.

To analyze the energy efficiency, the whole vessel powertrain shall be considered including the power sources (gensets and battery), power distribution system, and the propulsion load. The efficiency of the engine-genset can be estimated with the SFOC of the engine as a function of the engine loading and shaft speed. An example of the SFOC surface with the two variables deduced from experimental data is shown in Fig. 20 (a); the corresponding surface of energy efficiency is also given in Fig. 20 (b). As shown in these graphs, the fuel consumption and hence, the efficiency, is a function of the output power and the shaft rotational speed. Therefore, the efficiency of the engine-genset can be optimized by keeping the engine loading and speed within the optimal range. Certain engine speed needs to be maintained to attain engine operational parameters such as torque limit. An example of the engine speed setting based on the engine loading is given in Fig. 20 (c); the experimental data are fitted to a continuous curve based on the Eqn. (3).

$$\Omega(L) = -0.0001L^3 + 0.02396L^2 - 0.9323L + 70 \qquad \textbf{(3)}$$

where the angular velocity Ω is given in percentage of the rated speed, and the load L is given in percentage of the MCR.



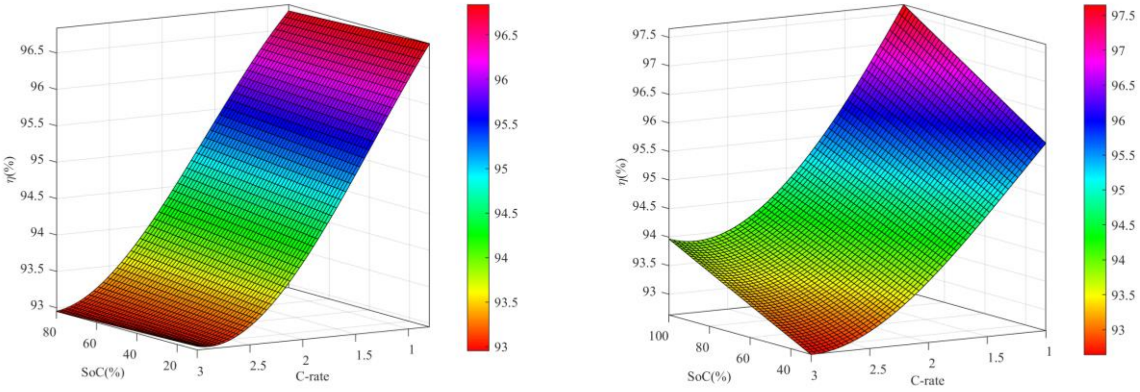
(a)

(b)

(c)

FIG. 20 ENGINE OPERATIONAL CHARACTERISTICS; (A) SOFC. (B) FUEL EFFICIENCY. (C) ENGINE SPEED VARIATION AND LOADING.

Besides, the battery efficiency is also a function of the battery state of charge (SoC) and C-rate as demonstrated in Fig. 21. Usually, the battery charging efficiency is different from discharge efficiency, as given in Fig. 21 (a) and Fig. 21 (b). From system point of view, the ESS can provide higher efficiency by shifting the engine operating point of the engines towards the optimal region.

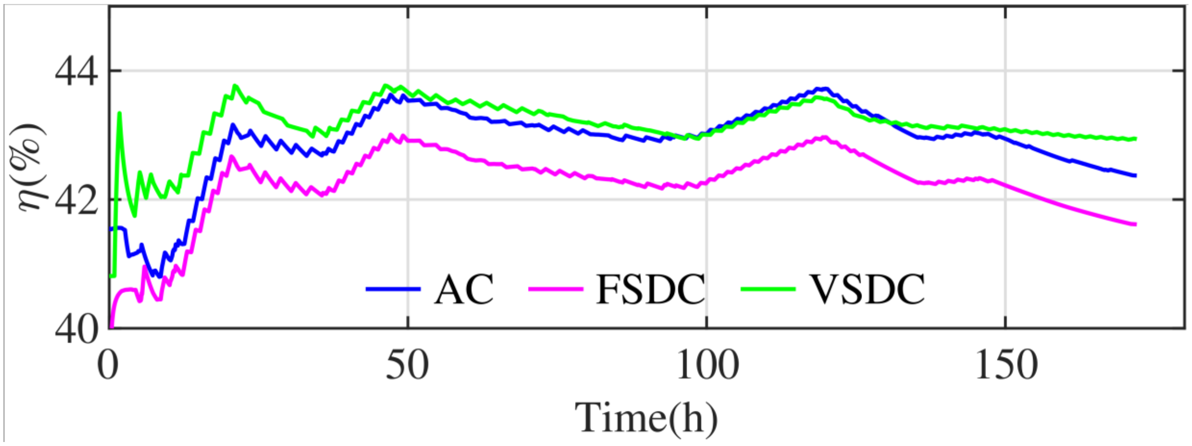


(a)

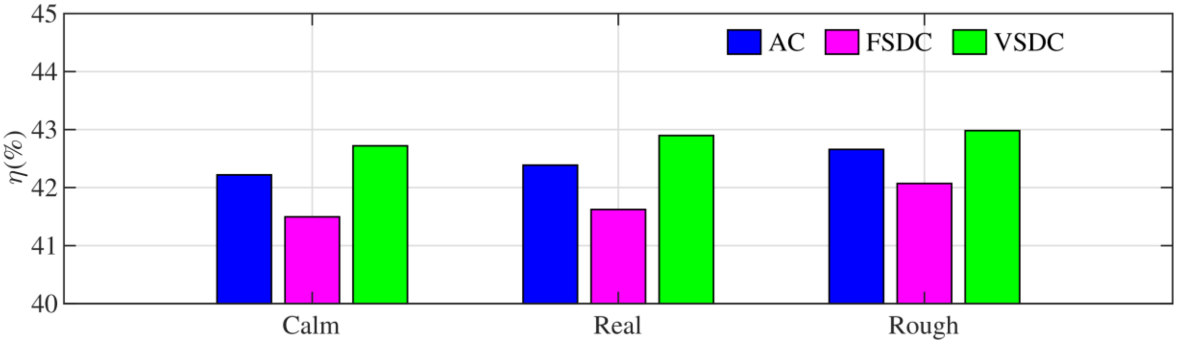
(b)

FIG. 21. EFFICIENCY OF THE BATTERY SYSTEM AS A FUNCTION OF SOC AND C-RATE; (A) CHARGING. (B) DISCHARGING.

A case study of a cruise vessel with hybrid power systems and an extended load profile (170 hrs.) is given in the Fig. 22 [8]; here, the dynamic energy efficiency of the total ship electric powertrain is given with the measured load profile and the power system architecture presented in Fig. 18. Here three main cases are compared such as AC switchboard (AC), DC switchboard with fixed speed engines (FSDC), and DC switchboard with variable speed engines (VSDC). An instantaneous power efficiency curve is given in Fig. 22 (a) while the energy efficiency for the whole profile and extended for various environmental conditions is given in Fig. 22 (b). It is seen that a marginal efficiency advantage is achieved with the variable speed engine and DC power system. This is due to the load correction of the engine-gensets with the variable speed. Regarding the weather conditions, the energy efficiency trend for the power system architectures is similar in all three cases, which shows that all power system architectures are similarly affected by the weather conditions. Therefore, the weather condition itself cannot be the deciding factor for selecting power system architecture. Further, it is observed that the energy efficiency for all three architectures in the calm sea condition is slightly less than in the real case. In contrast, it is slightly higher in the rough sea condition than in the real case. It signifies that the varying loads due to weather conditions are well handled by the battery such that diesel engines are less affected by the load fluctuations, which is one of the significant benefits of hybridization.



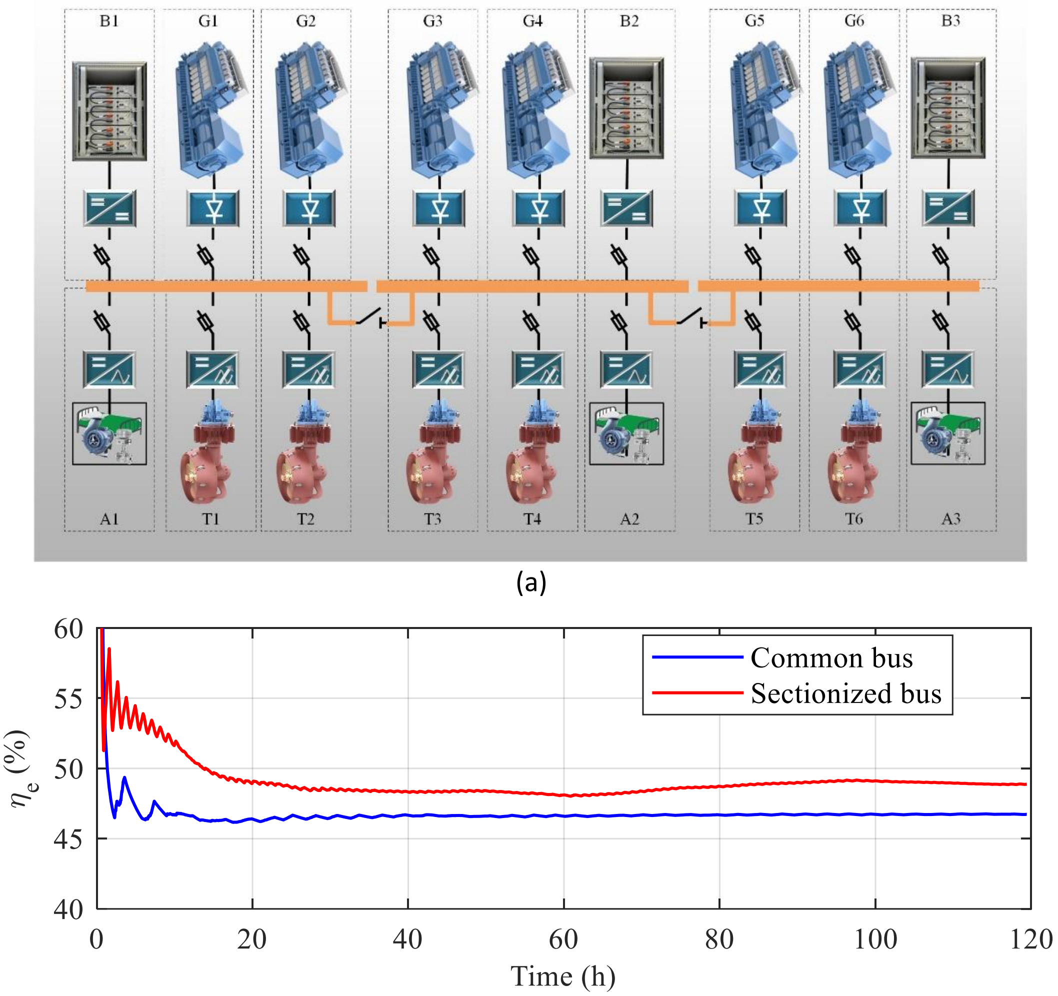
(a)



(b)

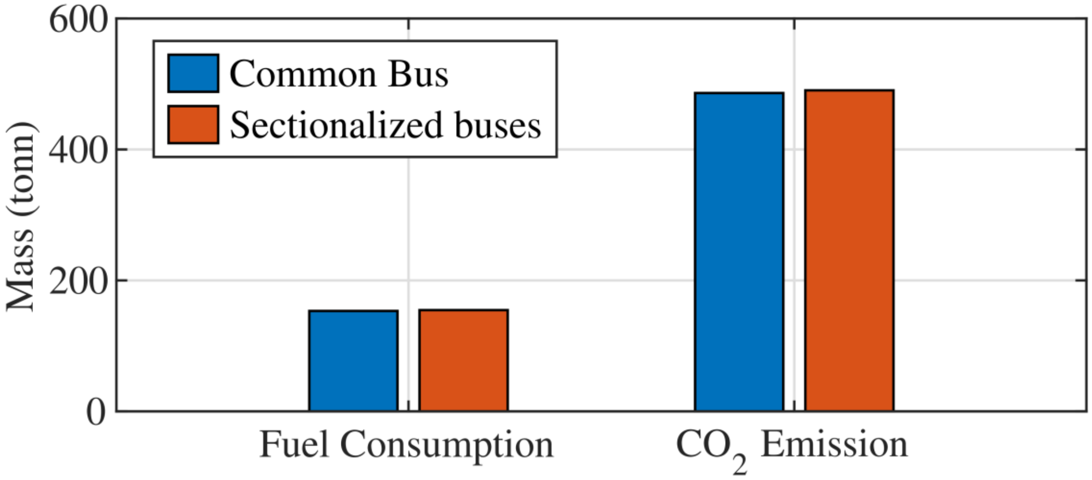
FIG. 22 EFFICIENCY ANALYSIS OF THE CRUISE SHIP WITH THE HYBRID POWER SYSTEM AND VARIOUS POWER SYSTEM ARCHITECTURES. (A) INSTANTANEOUS POWER EFFICIENCY (B) ENERGY EFFICIENCY OF THE STUDIED POWER SYSTEM ARCHITECTURES IN DIFFERENT SEA CONDITIONS.

Another case study for an offshore support vessel (OSV) with battery hybrid power system is performed with a measured load profile for almost 120 hrs. [33]; the corresponding SLD is shown in Fig. 23 (a). In this case, the simulations are performed for two different cases namely "common bus" referring to the case that the bus-tie breakers are closed, and "sectionized bus" referring to the case that both bus-tie breakers are open, resulting in separated DC bus sections. The efficiency analysis has been performed considering the entire electric powertrain from the source to the load; the averaged efficiency or energy efficiency during the total simulation period and with the common- and sectionized bus is shown in Fig. 23 (b); then, the total fuel consumption and corresponding CO2 emissions are presented in Fig. 23 (c).



(a)

(b)



(c)

FIG. 23 LOAD PROFILE-BASED EFFICIENCY AND EMISSIONS ANALYSIS (A) SLD OF THE DC HYBRID POWER SYSTEM FOR THE OFFSHORE VESSEL. (B) ENERGY EFFICIENCY VARIATION AGAINST TIME. (C) THE TOTAL ACCUMULATED FUEL CONSUMPTION AND CO2 EMISSIONS.

The average energy efficiencies calculated for the total load profile are approximately 46% and 48% for the common and sectionized bus, respectively. However, the fuel consumptions and CO2 emissions for both cases are similar. It indicates that the battery in the sectionized bus supplies more energy compared to the one in the common bus. Therefore, the battery SoC is dropped during the operation with sectionized bus. It is important to equalize the battery SoC during the operation in order to have a fair comparison of energy efficiency. In this case the equalization is applied to the fuel and emission calculation, hence, a realistic picture is obtained. An essential aspect of hybridization is battery sizing, meaning that the capacity of the battery and its maximum C-rate shall be chosen based on the battery function and consequently energy and power demand. An oversized battery may result in higher losses and reduced efficiency in addition to the higher investment cost.

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