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Article

Energy Storage Systems for Shipboard Microgrids—A Review

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Abstract: In recent years, concerns about severe environmental pollution and fossil fuel consumption has grabbed attention in the transportation industry, particularly in marine vessels. Another key challenge in ships is the fluctuations caused by high dynamic loads. In order to have a higher reliability in shipboard power systems, presently more generators are kept online operating much below their efficient point. Hence, to improve the fuel efficiency of shipboard power systems, the minimum generator operation with N-1 safety can be considered as a simple solution, a tradeoff between fuel economy and reliability. It is based on the fact that the fewer the number of generators that are brought online, the more load is on each generator such that allowing the generators to run on better fuel efficiency region. In all-electric ships, the propulsion and service loads are integrated to a common network in order to attain improved fuel consumption with lesser emissions in contrast to traditional approaches where propulsion and service loads are fed by separate generators. In order to make the shipboard power system more reliable, integration of energy storage system (ESS) is found out to be an effective solution. Energy storage devices, which are currently being used in several applications consist of batteries, ultra-capacitor, flywheel, and fuel cell. Among the batteries, lithium-ion is one of the most used type battery in fully electric zero-emission ferries with the shorter route (around 5 to 10 km). Hybrid energy storage systems (HESSs) are one of the solutions, which can be implemented in high power/energy density applications. In this case, two or more energy storage devices can be hybridized to achieve the benefits from both of them, although it is still a challenge to apply presently such application by a single energy storage device. The aim of this paper is to review several types of energy storage devices that have been extensively used to improve the reliability, fuel consumption, dynamic behavior, and other shortcomings for shipboard power systems. Besides, a summary is conducted to address most of the applied technologies mentioned in the literature with the aim of highlighting the challenges of integrating the ESS in the shipboard microgrids.

Keywords: energy storage technologies; hybrid energy storage systems (HESSs); microgrids; shipboard power systems; power quality

1. Introduction

Electrification in commercial and military ships has been a trend in recent past in order to reduce emissions and to improve efficiency [1–4]. The International Marine Organization (IMO) in 2012 stated that global SO_x and NO_x emissions from entire shipping exhibits about 13% and 15% of global SO_x and NO_x respectively [5]. It further states that for international shipping total CO₂ emissions are around 796 million tons, which are approximately 2.2% of the global CO₂ emissions. The CO₂ emissions from ships all over the globe is found to be 2.6% of the global CO₂ emissions. Moreover, IMO predicts that by 2050, CO₂ emissions in case of international shipping could raise in between 50% to 250%.

IMO announced guidelines and regulations in Jan 2015 for Emission Controlled Areas (ECA) as a consequence of modifications applied in the International Convention of the Prevention of Pollution from ships [6]. The European Commission set forth a novel climate agreement (*the Paris Protocol*) with an elongated ambition of diminishing global emissions up to 60% by 2050 as compared to 2010 levels [7].

In past, cost of energy and environmental concerns were not of greater importance as of now in marine power systems. In order to save fuel and decrease emissions, several solutions have been proposed. For instance: substituting alternative fuels, exhaust gases after treatment, and using hybrid propulsions are the frequently applied approaches implemented to achieve environmental guidelines imposed by IMO. However, these solutions for reducing emissions (SO_x , NO_x , CO_2 , etc.) are not fundamental. Therefore, novel concepts such as hybrid energy storage systems (HESS) should be investigated in the shipboard microgrids.

There is an enormous evolvement over past few decades in shipboard microgrids due to their complex power architecture, power electronics interface based high power sources and loads. Hence, modern shipboard microgrids have become almost similar to terrestrial islanded microgrids, but due to the presence of high dynamic loads, complex control, and power management further complex the shipboard microgrids compared to terrestrial microgrids. Traditional power system relies on radial structure, which is used to have a separate generation for service and propulsion loads. However, due to the development of power electronics-based devices, the use of common power systems for both propulsion and service loads have been growing in the past few decades. Figure 1 depicts a single line diagram of the evolution of shipboard power systems.

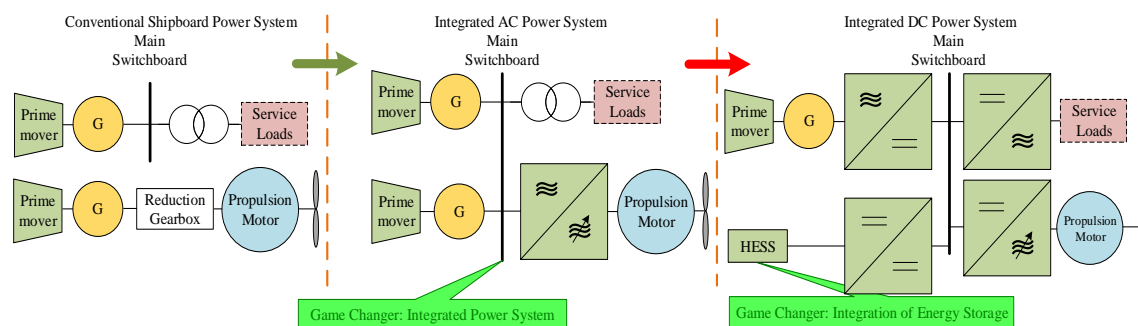


Figure 1. Evolution of Shipboard Power System.

The fast growth of electric and hybrid transportation systems open doors for further developments in ESS. Currently, the solutions are not technologically and commercially adequate in several features causing barriers to their broader usage. The ESS technologies vary from each other in terms of expense and technical aspects such as power density, energy density, charge and discharge time, operating temperature, lifetime, environmental impact, and maintenance requirement. Several works have been conducted in recent years, especially in the last decade, to improve ESS capacity. A typical single ESS technology, which can provide higher power and energy density, greater lifetime, and other such specifications, is not likely to be developed in near future. Therefore, in order to improve the capabilities, two or more ESS technologies can be hybridized.

Numerous modern technologies are being introduced in the maritime industry to meet the regulations imposed by various authorities. These technologies include liquid natural gas (LNG) as an alternative fuel, exhaust catalyst, hybrid propulsion, and so on. The implementation of Integrated Power Systems (IPS) have been firstly implemented in terrestrial Microgrid, then this application is extended to All Electric Ships (AES). The increased concerns over fuel economy and environmental issues have enforced maritime transport industry to hunt for fuel-efficient and lesser emission solutions. In marine vessels, power electronics offer a major role in fuel saving, particularly by the integration of ESS and electrification of propulsion systems through Variable Speed Drives (VSD). In order to

address fluctuations caused by propulsion loads, several solutions have been proposed such as the use of thruster biasing for ships with dynamic positioning systems [8]. A thruster biasing is a situation in which thrusters on a ship start to act against each other, using more power than it is necessary to generate the commanded thrust. The thrust allocation algorithms such as presented in [9] bias the thrusters in such a manner that it consume a particular amount of surplus power. Later on, this surplus power can be released in order to prevent from blackout when the power generation capacity is reduced due to faults. This approach is applied in dynamic positioning systems and mainly suitable for low-frequency fluctuations. The other well-known solution is the integration of energy storage system to smooth the load power [10–12]. Using a single ESS technology may result in increasing the size, cost, and weight of the operated electric ships [13]. Therefore, HESS is found out to be a promising solution to cater to transients in shipboard power systems in an effective and efficient manner. Lately, mostly ESS is being used as an emergency power supply in the shipboard power systems. It can be helpful especially for offshore vessels in a dynamic positioning (DP) operation where the occurrence of faults may leads to the blackout, hence, in this scenario, ESS can power the propulsion systems for a shorter duration and can reposition the vessel during the fault until the ship is re-powered. Thus, there is a greater possibility of using HESS in future shipboard power systems as a power generation source for load levelling, peak shaving, and for reducing voltage and frequency deviations, which consequently may contribute in enhancing the power quality of the electrical power system. Figure 2 shows future shipboard zonal power system with an integration of HESS.

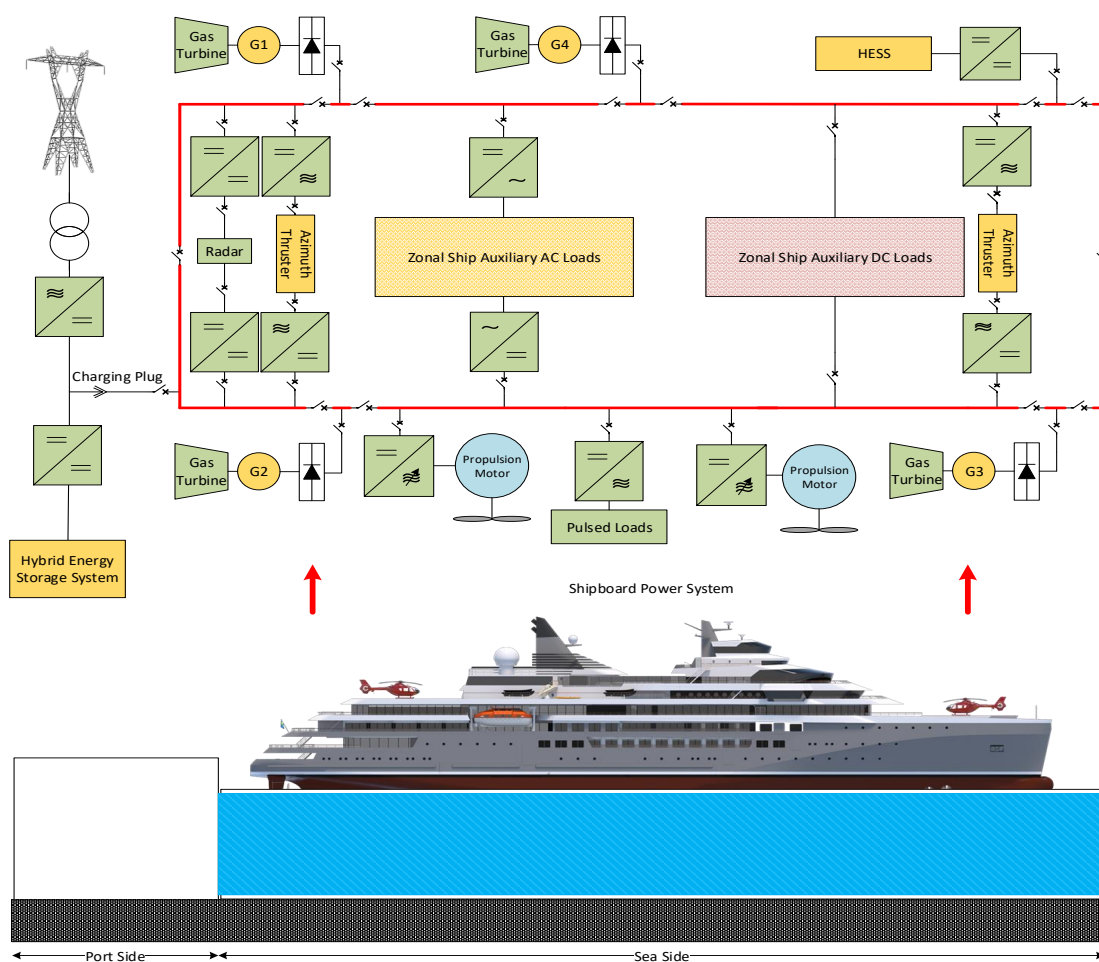


Figure 2. Typical single line diagram of the electrical power system for future ships.

The aim of this paper is to critically review

- Different types of energy storage devices such as batteries (lead-acid, Nickel Cadmium, Sodium Sulphur, Lithium ion), Ultra-capacitors, Flywheel, Superconducting Magnetic Energy Storage, and Fuel cells
- The energy storage devices that have already been used in marine vessels
- The most used hybrid combinations such as Battery-Ultracapacitors, Battery-SMES, Battery-Flywheel, and Battery-Fuel cell
- How the energy storage devices can enhance shipboard power systems
- What are the key challenges of integrating the ESS into the shipboard power systems

The rest of the paper is organized as follows: Section 2 presents an overview of different energy storage technologies. In Section 3, comprehensive analysis of the hybrid energy storage system are presented. Energy storage applications in shipboard power systems are discussed in Section 4. The challenges which occur while integrating an energy storage system in shipboard power systems are elaborated in Section 5. Finally, conclusion drawn from the study and authors opinion are presented in Section 6.

2. Energy Storage Technologies

An energy storage system comprises of an energy storage device, conversion of power and its control. Energy storage devices consist of secondary batteries, flywheels, capacitors, Superconducting Magnetic Energy Storage (SMES) systems, Fuel Cells (FCs), and pumped hydro. These devices differ from each other in terms of charge and discharge rate, life cycle, energy and power density, efficiency, etc. They are generally categorized into three groups with regard to the type of stored energy, i.e., electrical, chemical, and mechanical energy storage as shown in Figure 3.

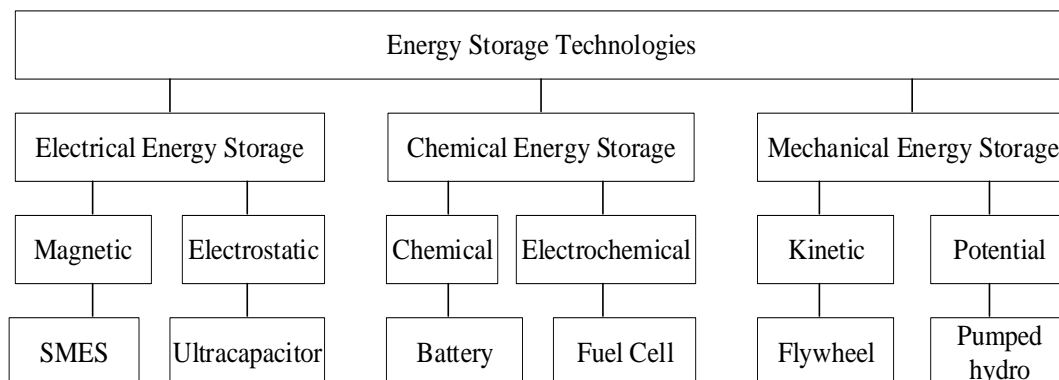


Figure 3. Energy Storage Technologies [14].

The maturity of different energy storage systems are depicted in Figure 4a, which are divided into three categories, mature, developed, and developing technologies. Lead-Acid is a mature technology, which has been used for over 100 years. NiCd, NaS, flywheel, ultra-capacitor, and SMES are the developed technologies that are commercially available. However, up till now, they are not used for large-scaled utility purposes. The fuel cell is still in the development phase as storing hydrogen is the key issue in this technology. The cycle efficiency of ESS is defined as $\eta = E_{out}/E_{in}$ where E_{out} and E_{in} is the output and input energy respectively. The efficiency of different energy storage technologies is depicted in Figure 4b, which shows that flywheel, SMES, and ultra-capacitor are highly efficient technologies.

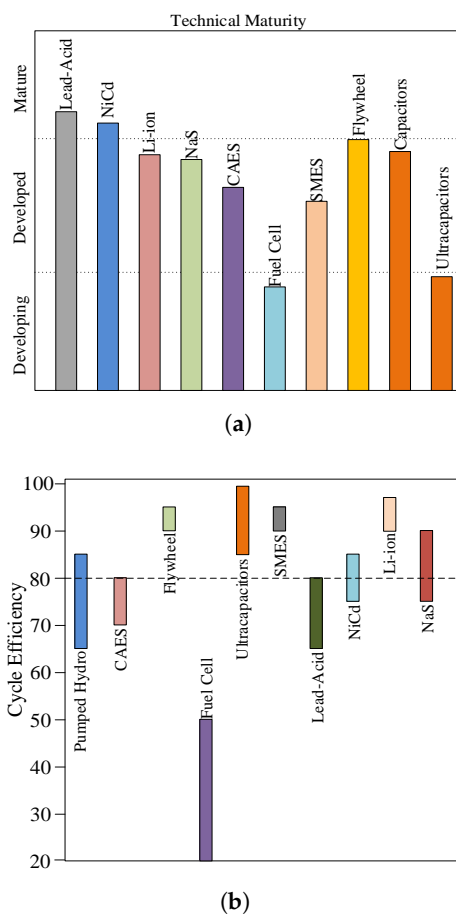


Figure 4. (a) Maturity and (b) Efficiency of different energy storage systems [15,16].

2.1. Batteries

Batteries are devices that transform chemical energy directly into electrical energy through an electrochemical oxidation-reduction reaction, and they are categorized as primary and secondary types of batteries. The former one cannot be charged electrically whereas the latter can. Lead acid battery is the most commonly used battery in the market. They are used in Uninterruptible power supply (UPS) [17–20], automobiles [21–23], etc. The increase in energy and power demands particularly, from hybrid electric vehicles results in large demand of batteries that are capable to produce higher energy density than lead-acid battery. The batteries that can provide an improved energy and power density are nickel metal hydride (NiMH) and lithium ion (Li-ion). Although their cost is high, still they are commercially adopted in various application, mainly in the automobile industry, cameras, medical instruments and in mobile phones.

Table 1 shows the different type of energy storage system with their power density, energy density, cost, efficiency, and lifetime, whereas Table 2 compares different type of energy storage technologies suitable for marine vessels. It can be seen that batteries such as lead acid, NiCd, NaS, and Li-ion are higher energy density devices, while flywheel, ultra-capacitor, and SMES are higher power density devices.

Table 1. Technical features of ESS [15,16,24,25].

System	Power Density (kW/kg)	Energy Density (kWh/kg)	\$/kW	Efficiency (%)	Life Time (years)	Response Time
Lead Acid	75–300	30–50	300–600	65–80	3–15	ms
NiCd	150–300	50–75	500–1500	75–85	5–20	ms
NaS	150–230	150–240	1000–3000	75–90	10–15	ms
Li-ion	150–315	75–200	1200–4000	90–97	5–100	ms–s
Fuel Cells	500+	800–10,000	10,000+	20–50	10–30	ms–min
SMES	500–2000	0.5–5	200–300	90–95	20+	ms
Flywheel	400–1500	10–30	250–350	90–95	15–20	ms–s
Ultra-capacitor	100,000+	20+	100–300	85–98	4–12	ms

Table 2. Comparison between different battery technologies.

Type of Battery	Advantages	Disadvantages
Lead Acid	Inexpensive Lead is easily recyclable low self-discharge (2–5% per month)	Shorty cycle-life (around 1500 cycles) Cycle life is affected by depth of charge Low energy density (about 30–50 kWh/kg)
Nickel Cadmium	High energy density (50–75 kWh/kg) High cycle count (1500–3000 cycles)	High degradation High cost Toxicity of cadmium metal
Sodium Sulphur	High energy density (150–240 kWh/kg) No self-discharge No degradation for deep charge High efficiency (75–90%)	Temperature of battery is kept between 300 °C to 350 °C
Lithium-ion	Very high efficiency (90–97%) Very low self-discharge (1–3% per month) Low maintenance	Very high cost Life cycle reduces by deep discharge Need special overcharge protection circuit

2.1.1. Lead Acid

Lead acid batteries are the most used batteries in the world since 1890s [26] and are still extensively used in cost-sensitive applications where limited life cycle and less energy density are not of greater concern [27]. Their application includes stand-alone system with photovoltaic (PV) [28], emergency power supply system [29], mitigating output fluctuations from wind power systems [30], and as a starter batteries in transportation such as in vehicles [31]. They have small daily self discharge rate, typically less than 0.3%, fast response time, low capital cost, and relatively high cycle efficiency. The cycle life is around 1500 cycles at 80% discharge depth and the efficiency ranges between 80 to 90%. Furthermore, lead-acid battery is a mature technology, available at lower cost, easy recyclability, and simpler charging technique [32]. However, the drawbacks of this type of battery lies in lower energy density and using lead (a hazardous material). Moreover, it is not suitable for discharges over 20% of its rated value as it further reduces the life cycle.

2.1.2. Nickel Cadmium

Nickel Cadmium (NiCd) batteries have been commercially in use since 1915s. The battery uses metallic cadmium at the negative electrode and nickel oxyhydroxide at the positive electrode. It has a greater number of cycles, higher power and energy density as compared to lead-acid batteries. The lifetime of NiCd batteries at deep discharge range from 1500 to 3000 cycles depends on the type of the used plate [33]. This type of batteries are featured by the ability of working even at a lower temperature ranging from -20°C to -40°C . Moreover, these batteries are currently implemented only in stationary applications, which is prohibited in Europe on consumer use due to the toxicity of Cadmium and higher cost [34]. The best performance is achieved when discharged between 20% to 50% of the rated value [35].

2.1.3. Sodium Sulphur

Sodium Sulphur (NaS) batteries consist of liquid sodium at the negative electrode and liquid sulphur at the positive electrode, in between these two materials there is beta aluminium tube acting as an electrolyte. The cycle life of NaS batteries is 4500 cycles which is a bit higher than lead-acid batteries and the efficiency is around 75%. It is being particularly used in Japan over 200 sites for peak shaving. The temperature of this battery is kept in range of 300 °C to 350 °C. In order to maintain this temperature within that range, a heat source is needed so that their performance can be improved using its own mechanism, which results in affecting their performance.

2.1.4. Lithium Ion

Lithium-ion batteries in recent times have been of greater importance since the start of 2000, particularly in the area of mobile and portable applications such as laptops, cell phones, and electric cars. It has been proved that these batteries have exceptional performance especially in medical devices and portable electronics [36]. The nominal voltage level of each cell is around 3.7 volts as compared to 1.2 volts in the case of NiCd batteries. Another advantage is its higher energy and power density as compared to NiCd and lead-acid batteries. The main obstacle in using it, is the high cost, which is more than 600 \$/kWh due to the overcharge protection and its specific packaging. Moreover, the efficiency of these batteries are quite high usually in the range of 95–98%, and the cycle life is around 5000. Safety is another severe issue in Li-ion batteries as most of metal oxide electrodes are unstable and may decompose at elevated temperature. Hence, in order to cater to this situation, the batteries are equipped with a monetizing unit such that to avoid over-discharging and over-charging.

2.2. Ultra-Capacitors

Capacitors store energy in terms of an electric field and generally known for their high symmetrical charge and discharge rates. Usually, capacitors have a quite low equivalent series resistances that enable them to supply the power efficiently. They are generally used in those applications where higher power is required for the shorter duration of time. The applications include camera flashes, filters, and compensation of reactive power. Capacitors are generally categorized by their dielectric medium, electrode material. They are further categorized as super-capacitors (also known as ultra-capacitors), electrolytic capacitors, and electrostatic capacitors. Figure 5 illustrates the individual structure of an ultra-capacitor. The key characteristics of ultra-capacitors are higher power density, faster charging and discharging due to lower internal resistance, enhanced life cycle, low voltage, and higher cost per Watt-hour (up to 20 times compared to Li-ion batteries). One of the main drawbacks of these ESSs is high sensitivity to over-voltage and, thus, overcharging. The other drawbacks include relatively low energy density, linear discharge voltage, high self discharge, and low cell voltage.

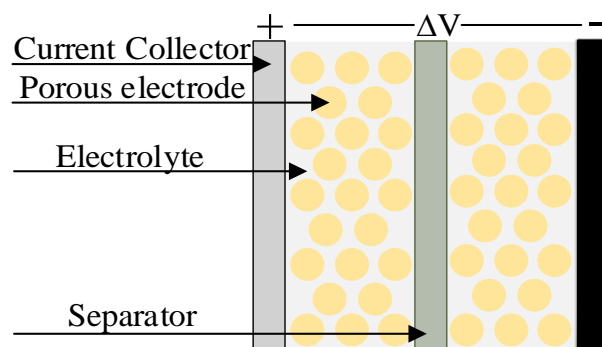


Figure 5. Individual Ultra-capacitor cell.

The life cycle of the battery is quite low in terms of charging and discharging cycles. Hence, in order to increase the lifetime of the battery and in particular to preserve system voltage above

the minimum threshold, ultra-capacitors are hybridized with batteries in hybrid vehicles [37–39]. The use of hybrid electric vehicles comprises of batteries and ultra-capacitors are suggested in [40,41] and a commercially available ultra-capacitor based electric bus developed by Sinautec Automobile technologies [42], the range is around 5.5 miles. The studies have proved that by hybridizing battery and ultra-capacitor results in improving the lifetime, performance, and cycle life of the battery for hybrid vehicles.

2.3. Flywheel

Flywheel stores energy in terms of kinetic energy in rotating mass or rotor. The measure of energy stored depends on rotor mass, location of the mass, and rotor's rotational speed. In case of a certain amount of energy is stored in a flywheel, this could lead to an accelerating torque, which consequently results a flywheel to speed up. Moreover, when the energy is provided it could lead to decelerating torque, which might results in slowing down the flywheel. The energy stored E in a high-speed flywheel is given by:

$$E = \frac{1}{2} I \omega^2 \quad (1)$$

where $I = \int r^2 dm$ ($\text{kg} \cdot \text{m}^2$) denotes the moment of inertia of flywheel rotor and ω (rad/s) is the angular speed of the flywheel. The basic layout of flywheel is shown in Figure 6. In order to transform rotational kinetic energy to electrical energy, a flywheel must include a generator and motor. Likewise capacitors, the flywheel may have charge and discharge rates equal. They can be useful in improving power quality, peak shaving, power factor correction, and load leveling. Flywheels have been used widely in different applications such as UPS [43], frequency response [44], smoothing wind power [45], and heavy haul locomotives [46]. As compared to ultra-capacitors, flywheel provides intermediate characteristics in terms of power and energy density. Flywheel technology caters with many shortcomings of prior energy storage technologies by having limited temperature sensitivity, chemical hazardless, the similar rate of charge and discharge cycle, higher life cycle, reduced space, and weight.

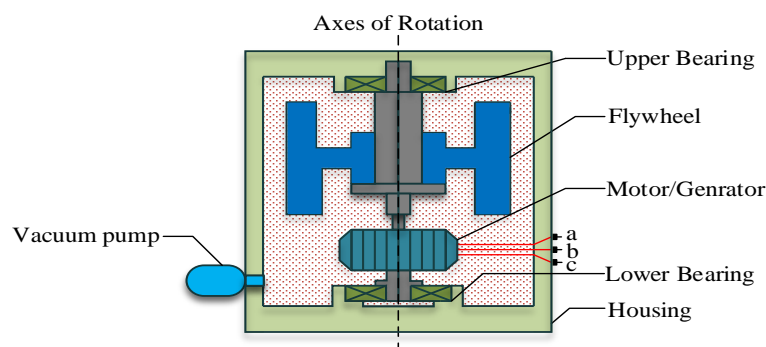


Figure 6. Basic Layout of Flywheel.

The study in [47] investigated and developed Flywheel energy storage system (FESS) for shipboard zonal power system. The main aim was to know where ESS can improve operation and/or reduce the maintenance cost. The applications where ESS can be beneficial includes “dark” start capability, system stability, pulse weapons, uninterruptible power supply, and load levelling. J. McGroarty et al. focuses “dark” start capability as an application of FESS in order to provide enough power capability and start opportunities to allow and help a gas turbine engine to come online from an off state. The optimization model for optimal sizing of FESS and dispatching controllable units economically for a drill-ship power system is presented in [48]. An optimization model of power management is proposed such that the optimization cost of vessel is minimized considering operational and technical parameters should not be violated. The proposed method further addresses

how much flywheel energy storage system required to be installed and scheduling of various power plants considering several mission profiles and loading levels.

In the future, due to the increase size of all-electric ships there will be large amount of power sharing among different high power loads. In order to evaluate it, a model of a power train has been developed and is implemented in [49] for an electric ship. By using this model, the behavior of rotating machine power source have been explored in three different ways for a shipboard rail-launcher. Firstly, the impact of rapid charging of rotating machine on the shipboard power system is discussed by charging the rail launcher through 5 MW motors. Due to this, there would be a voltage sag that can be managed using stored energy in rotating machine (conceptually a FESS) to an appropriate level. Secondly, stored energy in the rotating machine is then used to improve the power quality of shipboard power system. In this study, by using an appropriate power electronics, the stored energy in the rail launcher can be used to correct the power quality issues introduced by rest of ship's power system. Finally, the energy stored in rotor of an alternator can be used to power a free electron laser for ship's defense. The rail-gun's power system is shown in Figure 7; the prime mover for the system is mainly fed from the ship's main power grid. The drive motor uses the power from the power grid in order to accelerate the rotor, which results into an energy storage in the rotating mass. Conceptually at this instant, system is having active components similar to a FESS. The stored energy is then used to launch the rail gun instead of using it elsewhere in ship. A capacitor is then discharged via rotor winding and to bootstrap the system to its full power, the induced current in the stator is fed back to the rotor, it takes around 30 ms. After achieving full power, the alternator launches the rail-gun. The pulsed alternator systems have low impedance field windings that rely on positive feedback self excitation or boot-strapping action in order to energize the field winding. So, a capacitor is used for the self-excitation process, which is discharged directly into the field winding. Furthermore, the field initiation capacitor is recharged through ship's main power system by a bi-directional converter.

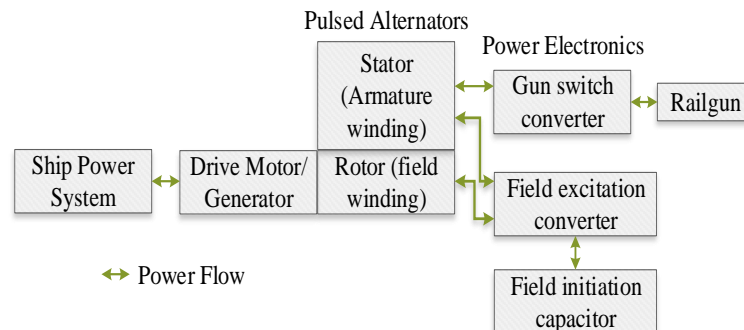


Figure 7. Basic block diagram of electromagnetic rail gun launcher.

The study in [50] addresses the use of high power FESS for DDG51 Arleigh Burke class destroyers to deal with high-power loads and to minimize the consumption of fuel. In the case of failure on one generator side, energy storage is responsible to power the critical loads up till another generator starts. The proposed study can mitigate transients in the system and provides a ride-through up to 10 min in order to start the backup generator. The study in [51] simulated FESS on the electrical power system based on offshore plants, which contains DP system such that to prevent from blackout, improve fuel efficiency, and mitigate voltage sags that usually take place in case of fault or the pulse loads. In the scenario, when there is an outage event of generator failure, the FESS will provide power until a backup generator starts. There are some particular rules specified for DP class, i.e., when the generator is operating at no load condition, at a nominal voltage level, and suddenly there is an additional loading, in this scenario the instantaneous voltage drop across the terminals of the generator should not be more than 15% of the nominal voltage. Furthermore, variations in the frequency should not exceed $\pm 10\%$ of the rated frequency and must be recovered within 5 seconds when the step load is turned off.

It is observed that by the use of FESS, the power system will overcome frequency drop and voltage sag within the limits to refrain from tripping other generators or blackout of power system. In [52], FESS is applied on the electrical network at the shipyard for powering the vessels from the shore distribution system such that to minimize fuel consumption on engines, avoid from blackout, and mitigate voltage sags. The simulation results show that there is around 15% drop in the rated voltage by the start of 2.25 HP motor in case when FESS is not integrated. On the other hand, by integrating FESS the voltage drop reduced to 4%.

2.4. Superconducting Magnetic Energy Storage (SMES)

Energy stored in SMES is in the form of a magnetic field created by superconducting coil. Initially, Ferrier introduced it in 1969 and originally it was anticipated as a load-levelling device [53]. It is an energy storage method based on the fact that current will remain flowing through a superconductor even after the removal of voltage across it because of zero resistance [54]. In order to have negligible or zero resistance, the superconducting coil is sustained below the critical superconducting temperature with the use of an external cooling pump. The stored energy in the superconducting coil can then be released by discharging the coil. SMES storage devices are found to be highly efficient, i.e., greater than 95% as compared to other energy storage devices. The power electronic interfaces are needed that produces 2–3% loss in either direction. It has tiny deterioration because of cycling however, it has a high rate of self-discharge because of mechanical stability issues and energy spent on cooling it with cryogenic liquid. The magnetic energy stored in a conducting coil is given by:

$$E = \frac{1}{2}LI^2 \quad (2)$$

where L is the inductance and I is the current. SMES system consist of three main components that are a super conducting coil, a cryostat system, and a power conversion system [55] as shown in Figure 8. US Navy is trying to pull out from a stage dominated with hydraulic, pneumatic, and mechanical-based devices to a stage governed by electromechanical-based devices and with full electric control [56]. Future naval electric weapons require higher power pulses of electrical energy [57]. It is predicted that 200 MJ pulse forming network is necessary for the Navy's railgun to attain the anticipated muzzle energy of 63 MJ² [58]. SMES is found to be an attractive technology for this application, as it exhibits high energy density, zero resistance, and an efficient stored medium. SMES can further be helpful in providing power for onboard submarines, ships, and for naval applications [59].

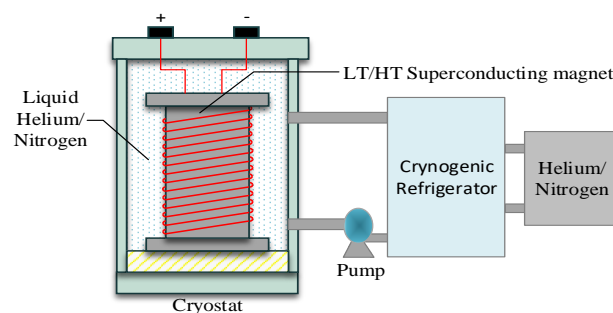


Figure 8. Superconducting magnetic energy storage (SMES) system.

2.5. Fuel Cell

Fuel cell transforms chemical energy directly into electrical energy and have the capability to be an alternative technology to the diesel engine, the individual structure of fuel cell is shown in Figure 9a. It has been proved to be more efficient as it produces lower or zero-emissions and functions cleaner as compared to a traditional gas turbine and an internal combustion engine. Polymer exchange membrane (PEM) fuel cell has been used to power Howaldtswerke-Deutsche Werft (HDW) submarines.

Nine Siemens PEM-based fuel cells were installed for propulsion purposes [60] ranging from 30–40 kW each. The first passenger ship to use fuel cell based propulsion is FCS Alsterwasser. The goal of the project was to test a ship that is free from emissions and to encourage the use of it for maritime applications [61]. The storage and hydrogen fuel distribution are the main challenging features for its wider use. As there are severe challenges to store hydrogen at a comparable energy density to hydrocarbon fuels such as liquid natural gas (LNG) or Marine Diesel Oil (MDO) [62]. It was suggested by Carlton et al. [63] that the technologies such as Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC) will be more favorable for ship propulsion as they use hydrocarbon fuels. The US energy department enlists several types of fuel cell [64] technology and are categorized as depicted in Figure 9b.

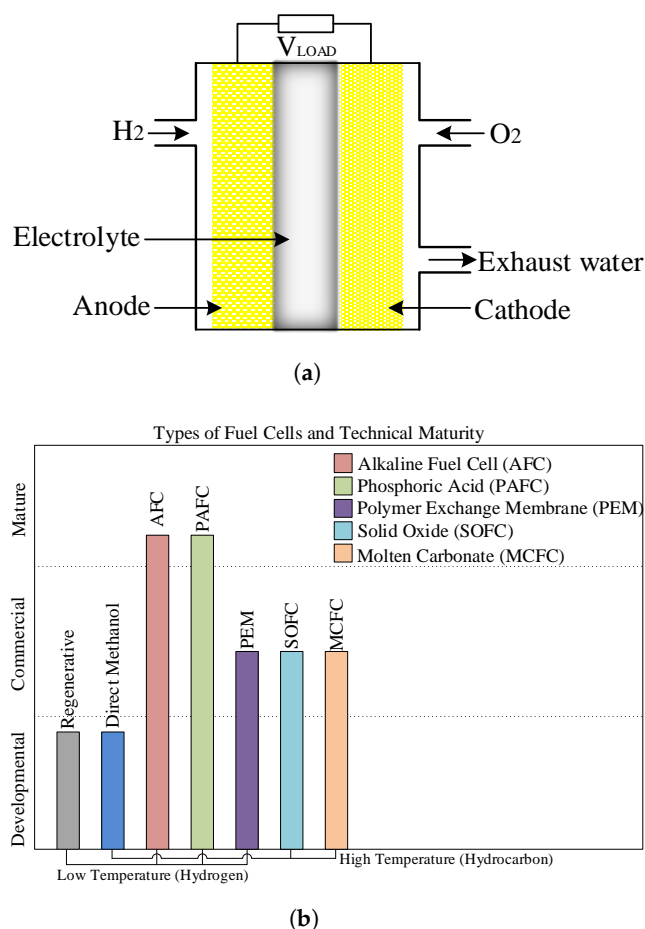


Figure 9. (a) Individual structure of Fuel cell and (b) Different types of fuel cell and their technical maturity.

Fuel cell for low emission ships (FellowSHIP), a research and development project with an involvement of industrial partners that comprises of Det Norske Veritas (DNV) (for the classification rules), Wärtsilä (for the energy), and Eidesvik Offshore (ship provider). The project is funded by Research council of Norway and its main goal was to integrate FC on offshore platforms and on-board vessels. In this research based project, a 330 kW FC is integrated with the *Viking Lady* as exhibited in Figure 10, an offshore supply vessel (OSV), the only commercially available vessel that uses fuel cell technology. It was docked in Copenhagen at the end of 2009 in order to replace traditional machinery to integrate fuel cell technology. The vessel is powered with dual fuel, i.e., liquified natural gas (LNG) and diesel-electric power plant. Four Wartsila based diesel engines and four main generators are installed to power the propulsion system and service loads. The vessel further uses molten carbonated

based fuel cell and LNG to meet all the power needs. The Molten Carbonate Fuel Cell (MCFC) generates approximately 320 kW power and is operated around 650 °C. Hence, the combined use of gas engine and fuel cell results in the reduction of nitrogen oxide, sulphur oxide, and carbon dioxide emissions [65], and the efficiency of FC generated electric power was found to be 52.1% [66]. The concept study based projects that used fuel cell in the shipboard microgrids is enlisted in Table 3.

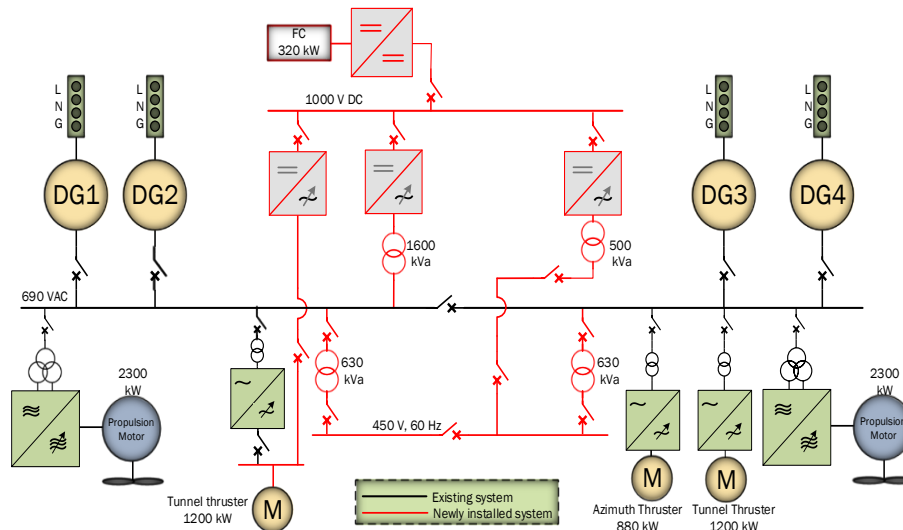


Figure 10. Fuel cell integration in *Viking Lady* [67].

Table 3. Summary of Fuel Cell based vessels and projects.

Vessel's Name	Type of Cell Used	Power Rating	Fuel Type	Reference
Viking Lady	MCFC	330 kW	LNG	[67]
Nemo H2	PEM	60–70 kW	Battery	[68]
ZemShip-Alsterwasser	PEM	100 kW	Battery	[69]
SF-BREEZE (Concept study)	PEM	2.5 MW	Liquid Hydrogen	[70]
PA-X-ELL (Concept study)	PEM	30 kW	Methanol	[71]
MV Undine (METHAPU Project)	SOFC	250 kW	Methanol	[72]
US SSFC (US Navy)	MCFC & PEM	2.5 MW	Diesel	[73]
MC-WAP (Concept study)	MCFC	500 kW	Diesel	[74]
MS Forester (SchIBZ Project)	SOFC	100 kW	Diesel	[71,75]
212 submarine U31	PEM	9(30–40) kW	H ₂ /Methanol	[76]
212 submarine (U32–36)	PEM	240 kW	H ₂ /Methanol	[75]
S-80 Class Submarine)	PEM	300 kW	Bioethanol	[77]
US Vindicator	MCFC	4 × 625 kW	F-76	[78]

3. Hybrid Energy Storage System (HESS)

The Hybrid Energy Storage System (HESS) is a combination of dissimilar energy storage technologies that have different characteristics with regard to energy capacity, cycle life, charging and discharging rates, energy and power density, response rate, shelf life, and so on. Figure 11 depicts the comparison of energy density, power density and their cost (\$/kW).

ESS technologies can be categorized further into higher energy and power technologies. Higher energy devices such as a battery, fuel cell, pumped hydro, and CAES can supply energy for the longer duration of time but their power is low. On the other hand, higher power devices such as a flywheel, super-capacitor, SMES, and higher power batteries can supply very high power but for a shorter duration of time. It is observed that battery technology can be employed in both categories due to their wide characteristics range. Hence, hybridization of higher energy density devices with higher power density device will yield to a better ESS. In this way, high-energy devices will provide long-term power

needs, whereas higher power devices will cater with short duration but higher power needs. Based on the above discussion, the possible combinations, which are extensively used in literature for different applications are depicted in Table 4.

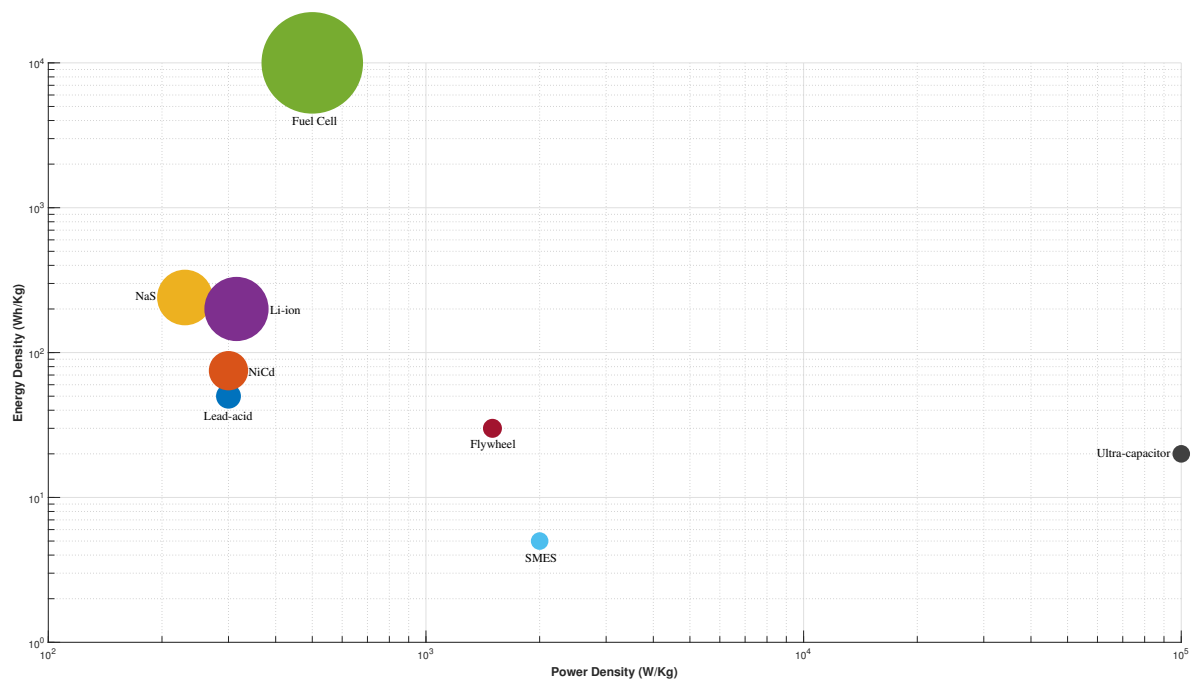


Figure 11. Ragone chart: Comparison of different energy storage technologies.

Table 4. Possible hybrid energy storage systems (HESS) configurations.

Energy Supplier	Power Supplier	References
Battery	Ultra-capacitor	[79,80]
	SMES	[81]
	Flywheel	[82,83]
Fuel cell	Flywheel	–
	SMES	[84]
	Ultra-capacitor	[85]
	Battery	[86]
CAES	Flywheel	[87]
	SMES	–
	Ultra-capacitor	[88]
	Battery	–

3.1. Battery-Ultracapacitor

Among all hybridized technologies, hybridization of ultra-capacitor and battery has been proposed in literature quite extensively. The rechargeable batteries are generally with high energy density and low power density normally below 1 kW/kg. The life cycle of the battery is quite low ranging from 1500 to 4500 cycles as compared to ultra-capacitors. In some literature, ultra-capacitors are named as supercapacitors and electrochemical double layer capacitors as well. This energy storage device has low energy density, typically below 10 kWh/kg and higher power density typically above 10 kW/kg. Furthermore, it possesses a high life cycle normally above 50,000. Generally, hybridization can be carried out via several methods, which can be categorized as internal and external hybridization [89]. In case of internal hybridization, the devices are developed by the hybridization of battery and ultra-capacitor on the electrode level as shown in Figure 12a. The hybrid battery

pack system “UltraBattery” [90] is an example of internal hybridization as shown in Figure 12b. It is the hybridization of lead-acid battery and ultra-capacitor and was developed by Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia. On the other hand, the hardwire connection between a ready available battery and ultra-capacitor is categorized as “external hybrid” as shown in Figure 12c. Among the methods mentioned above, the external hybrid method is the extensively used method in several applications.

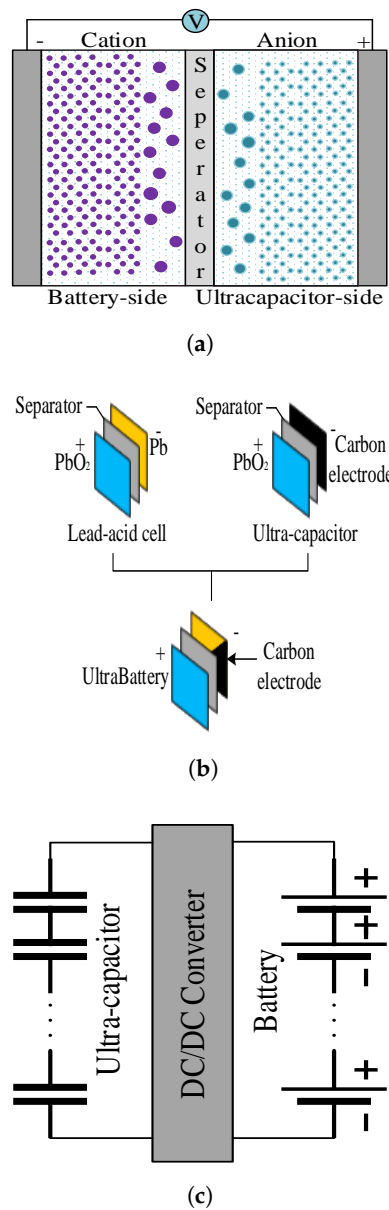


Figure 12. Possible approaches for hybridizing ultra-capacitors and batteries. (a) Internal hybridization, (b) Ultrabattery (c) External hybridization.

Yichao tang et al. [79] explores the feasibility by hybridizing battery and ultra-capacitor energy storage for naval applications. A dual active bridge based topology is proposed to control the bi-directional power flow through phase shifting for both charging and discharging ultra-capacitors and batteries. The topology is designed in such manner that it can meet the requirements of both 1 MW pulsed load and 100 to 500 kW propulsion system. Higher frequency switching devices were selected such that to achieve DC-DC conversion at higher power and voltage levels. The electric propulsion

system in vessel experiences large torque and power fluctuations on their drive shaft because of waves and rotational motion of propeller. Jun Hou et al. [80] explores novel solutions to address such fluctuations by exploring energy management strategies and integration of ultra-capacitor and battery. The two main objectives, i.e., mitigation of power fluctuations and HESS loss minimization are assessed at different sea conditions. The simulation results depict that substantial benefits can be attained in terms of reduction in fluctuations and losses. During navigation of ships at sea, it suffers from a constant rocking motion and is affected by ship navigation parameters and surrounding sea conditions, which further increases the uncertainty involved with the use of solar energy in ships. In [91], a mathematical model is considered for generating power through PV modules while considering both the sea conditions and movement of the ship. The rocking motion of vessels fluctuates the power typically for 10–20 s and it can reduce the lifetime of the battery to quite an extent. Hence, to cater to situation hybridization of ultra-capacitor with lithium-ion battery is proposed to improve the stability and reliability of the power system. The hybrid energy storage system based on ZEBRA batteries and ultra-capacitors modules for All-electric ships were considered in [92] to decrease the battery charge and discharge peak currents. Ultra-capacitor modules were considered in order to extend the expected life of the battery. Cohen et al. [93] presented an actively controlled Li-ion battery hybridized with ultra-capacitor for pulsed power applications aiming to maximize the energy density of Li-ion battery and also to maximize the energy and power density of Ultra-capacitor. Furthermore, the authors designed, constructed, and validated the hybrid model using commercial off-the-shelf technologies and it is observed that the generator's frequency and voltage deviations are massively improved.

3.2. Battery-SMES

The capacitor's nominal voltage is quite low ranging from 1 to 2.5 V due to the fact that the series connection of numerous units is required in order to provide higher voltages. However, connecting several units together in series can cause voltage imbalance. So, in order to balance the voltage, some protection circuits are required, these interfaces further may cause fluctuations in the power system, hence, step-down and step-up converters are further installed to adjust the output voltage. The change in output voltage in ultra-capacitors varies with its charge and discharge and is proportional to the stored energy. In contrast to ultra-capacitors, superconducting magnetic energy storage (SMES) does not require any step-down or step-up converters. It is basically a superconducting coil that stores energy in the form of a magnetic field. It has the capability to deliver from/to power system with outstanding characteristics such as high efficiency, high power density, fast response time, and higher life cycle. The implementation of SMES system is difficult, as it requires the refrigeration mechanism that is quite costly and involves complex maintenance. The special site requirements further limit its application that is stationary such as railway supply substation and renewable generation sites. Some researchers who proposed and investigated battery-SMES-based HESS system for transportation applications are as follows.

The demand for all-electric ships (AESs) amplified rapidly in recent times and load fluctuations in the system may lead to severe issues such as increased fuel consumption, voltage fluctuation, and environmental emissions. HESS comprising of a battery (higher energy density) and SMES (higher power density) proposed in [81] in order to cater to shiploads that cause sudden changes such as maneuvering and pulse loads. As the ramp-rate of vessel-generators such as gas-generators usually are in between 30–50 MW/min range and on the other hand, pulsed load require 100 MW/s ramp-rate that is far higher than the ramp-rate of generators [94]. Hence, ESS has become vital to deliver a huge amount of energy within a short period.

3.3. Battery-Flywheel

Jun Hou et al. [82] proposed a hybrid battery and flywheel energy storage system in order to isolate load fluctuations from the shipboard power network. The effectiveness and feasibility of the proposed hybrid system to mitigate load fluctuations for all-electric ships under various sea conditions

are shown through simulations. Li-ion battery was used due to their higher power and energy densities than other batteries.

In [83] the authors explored a novel solution by using flywheel and battery as a hybrid model in order to address fluctuations in load power. It is shown through simulations that with the use of battery-flywheel, the effectiveness and feasibility is quite high such that to mitigate load fluctuations, especially at high sea states. As power fluctuations may result into reduction in electrical efficiency, uncertain consumption of power, and most probably affect shipboard power quality. In [95] flywheels have been analyzed such that to address pulse power loads. The results depict that by using flywheel energy storage system, the stability of shipboard power system can be maintained during operation of pulse load. AT Elsayed et al. [96] presented a comparative study in order to determine the optimal hybridization of batteries, flywheel, and ultra-capacitors to minimize the frequency and voltage fluctuations, which are produced in a result of adding pulsed loads to the shipboard power system either on the AC or DC side. Hai Lan et al. [97] modeled a high-speed FESS in order to smooth the photovoltaic power fluctuations and hence improving the power quality of a large oil tanker. The sinusoidal pulse width modulation (SPWM) along with constant torque angle control method is proposed such that to control charging and discharging of a flywheel.

3.4. Battery-Fuel Cell

Hydrogen-based fuel cell presently has been of greater importance in the maritime industry which includes: Nemo H2, Hydrogenesis, Hydra, and fuel cell ship (FCS) Alsterwasser. Reduction in consumption of fuel, lesser emissions, negligible noise, lower maintenance requirements, and minimal vibration are the key features which led in developing maritime fuel cell technology. In 2008, Alster-Touristik GmbH developed FCS Alsterwasser, it was a first passenger tourist vessel that was entirely powered by fuel cells. FCS Alsterwasser can withstand up to 100 passengers operating at cruising speed of 8 knots, it has two 50 kW fuel cells powering 100 kW hybrid electric propulsion system in combination with lead-acid batteries [48]. Henderson further states that it is estimated that approximately 220 kg of SO_x, 77 tons of CO₂, and 1000 kg of NO_x is saved annually as compared to the traditional diesel-powered vessel. In December 2009, Nemo H2, a zero-emission canal boat was developed by Fuel Cell Boat B.V. It has the capacity of 87 passengers and 1 crew member operating at a cruise speed of 16 km/h. A hybrid propulsion system comprising of 60–70 kW PEM-based fuel cells with 30–50 kW batteries were installed. 24 kg of Hydrogen is stored in 6 cylinders at a pressure of 35 MPa [68].

The requirements of military submarines are quite severe, such as they longer underwater operation, low transfer of heat to sea water, low magnetic signatures, and low noise levels [98]. Traditional submarines are equipped with a diesel-electric based propulsion system and for underwater operations, battery energy is used (lead-acid). The batteries were charged using diesel generators during snorkelling period. Hence, fuel cells are found to be a possible alternative candidate in order to meet the specific requirements associated with air-independent propulsion (AIP) system [99]. In the 1980s, the German navy in collaboration with Siemens has tested 100 kW Alkaline Fuel Cell (AFC) system in an onshore laboratory and then in Class 205 submarine U1 [98] in order to judge the application of fuel cells for the submarine. The system consists of 16 × 6.2 kW Siemens modules of AFC, four modules each connected in series in order to correspond to battery's voltage and propulsion system. Later on, Siemens developed a 34 kW Polymer electrolyte fuel cell (PEFCs) module for German Class 212 submarines [100]. Submarine class 214 was launched in 2005, it uses two Siemens-based 120 kW PEFC modules [101]. It is connected to the main grid via DC to DC converter and has the efficiency of 56% on full load.

A hybrid fuel cell/diesel generator power system is proposed in [102] for propulsion and for test equipment on a research vessel. The PEM-based fuel cell system with a battery as backup and secondary energy source simulated in power system computer aided design (PSCAD). The secondary source is a lead-acid battery with a rating of 360 V and energy 82 kWh. The simulation-based analysis

depicts that the system has the capability to handle sudden load changes with minimal transients. Although FC's are a promising solution to reduce greenhouse gas emissions but their response time is not fast enough to cater to load transients that might occur in vessels at sea. Hence, higher density secondary batteries are needed to accomplish stability under transients and usually, dc/dc converters are needed for interfacing battery and FC into the DC link. Alireza et al. [103] presented an intelligent power strategy in order to improve the performance of FC without utilizing dc/dc interfacing converters. A new FC power management based strategy by using genetic algorithm proposed in [103] such that to guarantee the efficient performance of FC stack by preserving FC voltage within a required range in FC–battery hybrid system without the use of DC/DC interfacing converters.

The study in [104] proposed a hybrid system based on battery and PEM-based fuel cell to control power generation in a shipboard power system. The mathematical model for regulating active and reactive power is derived and integrated with PEMFCs in order to enhance the system dynamic response. Test results illustrate that injunction of hydrogen fuel into the fuel cells can be regulated automatically with fluctuations in loads. Furthermore, the batteries are used to compensate power in order to maintain operational security of the system.

4. Energy Storage Applications in Shipboard Microgrids

ESS can provide benefits to marine vessels as follows:

- Improves the stability of the system, which arises due to slow response of the engines to load demand.
- Decreases operational cost due to less engine maintenance and by optimizing fuel consumption.
- Minimizes the risk of blackout by installing an ESS as a UPS, such that it provides quicker response to a blackout as compared to emergency generators.
- ESS acting as an additional power reserve, hence provides power in case of failure of a generator. Furthermore, it can minimize the number of generators that have been online to improve the redundancy of the power system.
- ESS can also be helpful in peak shaving, load levelling, power smoothing, frequency and voltage fluctuations, and power quality.
- Decreasing thruster load ramp limits by adding inertia through ESS, which limits the power slew-rate and enables quick thrust force. Therefore, it enables quick response of vessel and boosts the capabilities of maneuvering.

Figure 13 illustrates the discharge timings of different applications of the stored energy. It can be seen that load levelling, peak shaving, and power smoothing are applications that take long time to discharge the energy, which has been stored in the ESS. Therefore, Li-ion batteries can be used for these applications. On the other hand, UPS and black start applications require high power density, so ultra-capacitors and flywheel are the most recommended ESS for these purposes. Table 5 compares different applications of energy storage devices in shipboard microgrids.

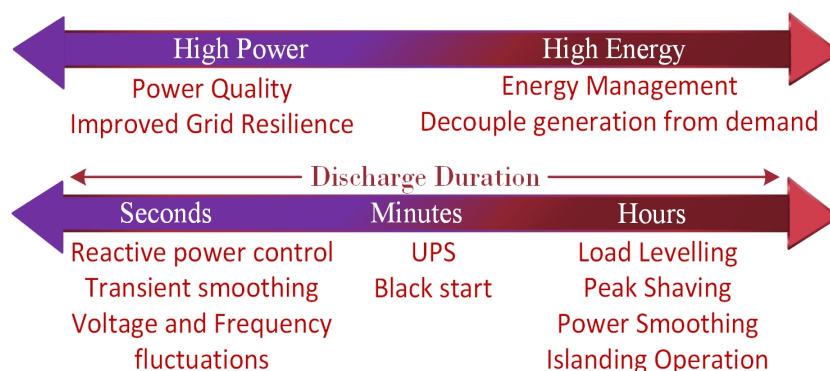


Figure 13. Energy storage applications and their discharge timings.

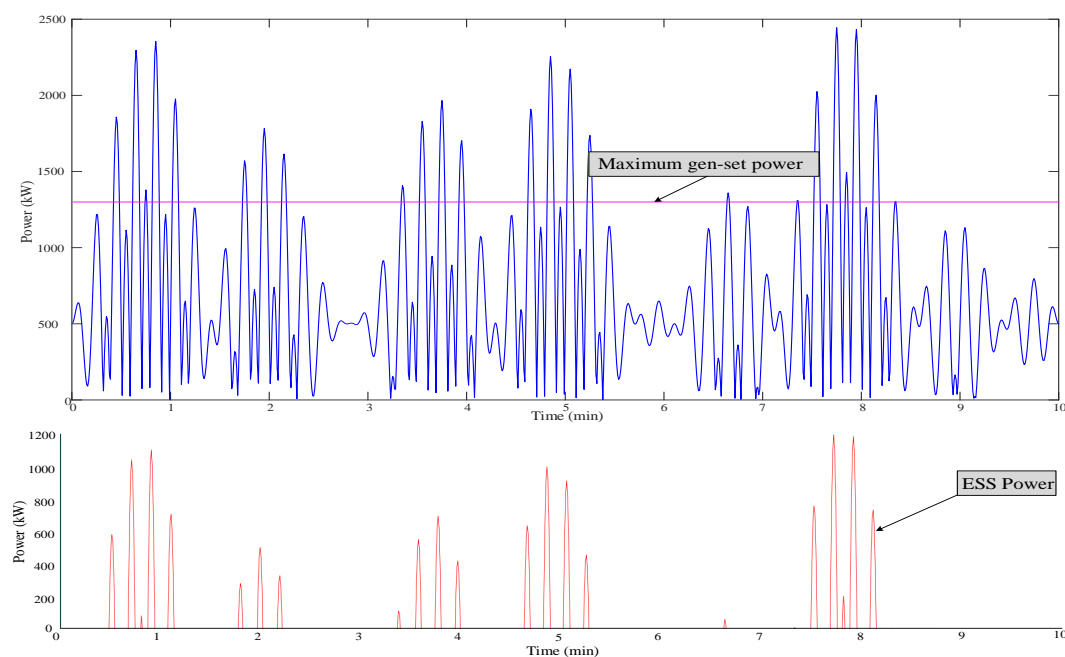
Table 5. Comparison between different applications of energy storage system (ESS).

Type	Functionality	Stored Capacity
Peak shaving	peak the shaves by energy storage or additional generators	Large
Power smoothing	smooth short term fluctuations by adding local energy storage system	Small
Power ramp-rate limitation	limit the power slew-rate by the addition of energy storage	Small
Load levelling	store energy to ESS when electricity is cheap or when there is light loading and delivers it when the electricity is expensive or when there is a high load demand	Medium

4.1. Load Levelling and Peak Shaving

Load levelling stores power when there is a light loading on the power system, then it delivers it during the period of high demand. When there is a high load demand, energy storage system supplies power and hence reduces the demand of load, which results in less economic peak generating facilities. On the other hand, moderate demands and reducing the peaks are called peak shaving. It is normally adopted at a higher scale by power companies in order to save money and sometimes by the commercial companies to sell the power and gain money, and thereby they purchase the power during low demand and sells it during high demand [105].

At present, ESS particularly Li-ion battery has been adopted to cater to variable loads in all-electric ships that are on shorter routes such as MF Ampere (route length 5.6 km), MF Folgefonn (route length 5.6 km), and Aero Ferry (route length up around 24 km). The cost-effective benefits are derived from peak shaving, spinning reserve, and load levelling functionalities [106]. Therefore, ESS can be useful in reducing the size and the number of generators to deal with variable loads by shaving the peaks or levelling the loads, which consequently reduces the emissions, fuel consumption, as well as wear and tear on the engines. In [107], distributed ESS contains a NaS battery that is utilized to shave the peak in order to mitigate the capacity constraints. In [108], 1 MW ESS based on Li-ion battery is installed at Nagasaki Shipyard for peak shaving operations. One prospect is to use ESS for peak shaving application as illustrated in Figure 14. When a marine vessel approaches near the harbor and is required with swift response in maneuvering, deprived of starting additional generators, ESS can be helpful in this scenario.

**Figure 14.** Peak shaving application in marine vessel.

The applications where lifting and lowering operations are required, for instance, in drillship and cranes there is a possibility to configure ESS in such a manner that it absorbs the regenerated energy instead of dissipating it in the dynamic braking resistors. This stored energy then can help to shave the peaks and in load levelling as shown in Figure 15.

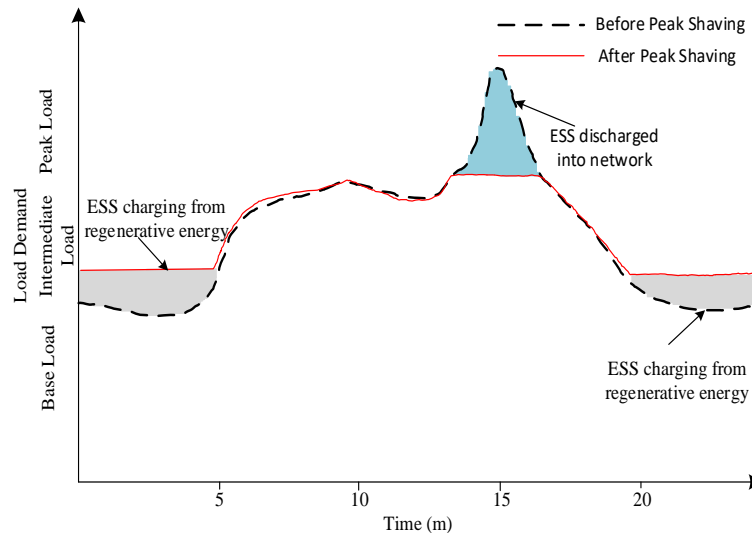


Figure 15. ESS application for peak shaving and load-levelling.

4.2. Power Smoothing

The battery-based power smoothing control in a shipboard microgrids based on using non-linear predictive control is proposed in [109]. In large vessels power fluctuations are quite high, which results in frequency fluctuations and can cause wear and tear of the source power plants. To cater to this issue, integrating batteries with DC/AC drive has been proposed by the same authors. However, due to the high fluctuations caused by the propulsion loads, which lead to an increase in temperature of the batteries, it is recommended to use a band pass filter with an optimized cutoff frequency parameters based on model predictive control. The energy storage systems such as batteries can also be added next to propeller motors to smooth the power oscillations as depicted in Figure 16. Power smoothing strategies have been utilized quite often in intermittent renewable energy such as in wind and solar energy conversion systems. Energy storage system can smooth the power by storing the energy from peaks and controls the ramp rate (MW/min) in order to eliminate rapid voltage and power fluctuations from the grid. Ultra-capacitor, fuel cell, battery, flywheel, and SMES are the energy storage technologies, which have been particularly used in wind energy for power smoothing applications. Therefore, these energy storage technologies can be helpful in smoothing electric power for shipboard microgrids as well.

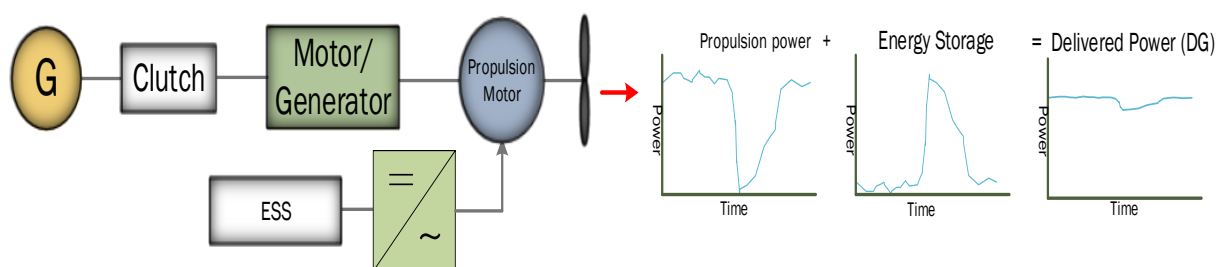


Figure 16. Power Smoothing utilizing energy storage technologies.

4.3. Frequency and Voltage Fluctuations

The heavy loads such as pulsed loads (propulsion motors, pumps, thrusters, etc.) can draw a large power in a short duration of time. If this amount of power exceeds certain limits, it might result in voltage and frequency fluctuations. In order, to avoid such voltage and frequency fluctuations, several standardization authorities have defined limitations for such fluctuations. Among these, IEC 60092-101 is an extensive standard, which defines the limitation for frequency and voltage fluctuations as depicted in Table 6. The other standards DNV [110] and Lloyds Register of Shipping (LRS) have the same limitations only for frequency, and for voltage fluctuations in case of a shorter period, they have set the limitation between -15% to 20% . In addition, in case of the steady state, DNV standards have limited the voltage fluctuations to $\pm 2.5\%$.

Table 6. Frequency and voltage permissible level as per IEC 60092-101 in shipboard microgrids.

IEC 60092-101			
	Steady State	Transient State	
	Magnitude	Magnitude	Duration
Voltage	-10% to $+6\%$	$\pm 20\%$	1.5 s
Frequency	$\pm 5\%$	$\pm 10\%$	5 s

ESS plays an important role in enhancing voltage and frequency fluctuations. In [111], a HESS based on improved maximum power point tracking (MPPT)-based algorithm is presented to enhance the performance of photovoltaic plant that is installed in the shipboard power system. This strategy helped to smooth and regulate the frequency oscillations. Besides, frequency hierarchical-based control algorithm is utilized to assign lower frequency oscillations to the battery and higher frequency oscillations to the ultra-capacitor. The improved MPPT algorithm further helps in reducing the installed capacity of HESS. The effectiveness of the proposed approach is verified under shipboard power system model.

Viknash Shagar et al. [112] utilized advance control strategies such as model predictive control (MPC) to minimize frequency fluctuations within the permissible limit as recommended by power quality standards in a shipboard power system. Moreover, battery-based energy storage system is directly connected to the DC link of the frequency converter as compared to traditional approaches in which battery energy storage system (BESS) is connected via DC-DC converters, hence reduces the complexity of ESS. It is further observed that the changes in service loads have a less impact compared to the changes in propulsion loads, which have a higher impact on bus bar frequency. Also, BESS has been integrated into a shipboard power system to mitigate these frequency fluctuations. The study in [113] utilized 1000 kW BESS with a DC-link capacitor and an active front-end (AFE) converter in order to boost the voltage and frequency quality together to suppress the grid harmonics as depicted in Figure 17.

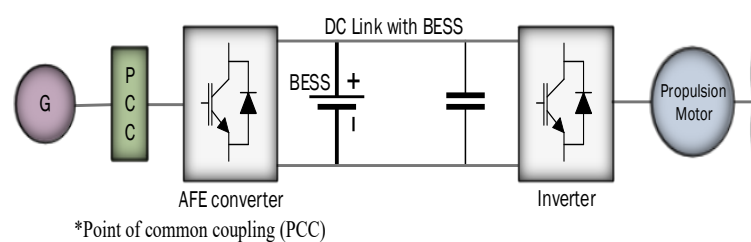


Figure 17. Integration of BESS with integrated power systems (IPS).

In order to verify the approach presented in [113], authors took a transient load that causes sudden change in the frequency of grid and ultimately trips the generator and pulse load (an active

and reactive power load), which causes sudden change in voltage and frequency of the power system. The overall load of 8.17 MW comprises of a trapezoidal load that consumes 5 MW of power for 200 ms, service load that consumes 1 MW with 250 kVar, and the propulsion load that consumes 2.17 MW. It is observed that with BESS compensation strategy the deviation of voltage at point of common coupling (PCC) was decreased to less than 10%, and the deviation in frequency was reduced to 2.5% as well, which satisfies the standards.

4.4. Power Quality

Nowadays, power quality has become a hot topic in shipboard microgrids. These power quality issues can be voltage dips, voltage and frequency fluctuations, harmonic contamination, and flickers, etc. Harmonic distortion is one of the main issues, which arise due to the presence of non-linear loads of the electric power system. The extensive use of non-linear loads in shipboard microgrids as compared to the terrestrial power system is a major concern, as these loads draw non-linear current while flowing through the power system resulting in distortion in the waveform of voltage, hence affecting the whole power system. The use of power electronic based converters in vessels such as in propulsion system, compressors, and thrusters has increased to a high level, for example, in the non-linear loads in navy and cargo vessels can reach up to 80% of the overall onboard capacity. The frequency variations and high extent of inter-harmonic distortion in a shipboard power system make it difficult to measure harmonics. Most used solutions for power quality issues in the terrestrial grids is the application of passive and active power filters [114,115]. Since the shipboard microgrids can be considered as a self-sufficient microgrid, the solutions applied to the terrestrial grids can be extended to shipboard microgrids as well. In regard to IEC 61000-4-7 standard, the maximum allowable synchronization error between power system frequency and synchronization should be within a range of $\pm 0.03\%$ of the nominal frequency of power system. In order to cope with this problem, several methods for estimating harmonics in a shipboard power system with the use of Fourier analysis by considering different synchronization methods and sampling windows is described in [116]. Different marine classification bodies, which include DNV, LRS, IEEE Std 45-2002, IEC 60092-101, and American Bureau of Shipping (ABS) have proposed limitation for power quality issues of a shipboard microgrids. As stated in IEC 60092-101, the Total Harmonic Distortion (THD) should not exceed more than 5% limitation considering no single harmonic should be greater than 3% of the fundamental voltage. The voltage harmonic distortion limitation from different classification bodies are depicted in Table 7.

Table 7. Harmonic voltage distortion limitation in shipboard power system.

	Different Standards				
	DNV	LRS	IEEE Std 45-2002	IEC 60092-101	ABS
Total harmonic distortion (THD)	8%	8%	5%	5%	5%
Single harmonic distortion	5%	1.5%	3%	3%	3%

To improve the power quality of shipboard power system FESS is utilized in [117]. This topology can store energy upto 80 MJ. An induction motor is considered as a propulsion motor with a power rating of 20 MW and a high power pulse electrical equipment with power rating of 2 MW is integrated as shown in Figure 18. It is observed that it has a huge impact on the power quality during the start of the high power pulsed load. However, the integration of FESS results in reducing the frequency fluctuations. In [118], a series voltage injection of FESS is presented for mitigating voltage sags in a shipboard power system for maximizing ship's survivability. The scheme basically comprises of a power electronic interface, a flywheel energy storage system coupled with an induction machine, and series injection-based transformer. The stored energy in a FESS, therefore, helps to mitigate voltage

sag problems, especially for critical loads. Modeling, simulations, and analysis of FESS interfaced with power converter using PSCAD/electromagnetic transients including DC (EMTDC) has been presented in the proposed approach. In [119] authors proposed multi-modular DC-DC converter-based HESS for shipboard power system, particularly for medium voltage direct current (MVDC) grid application. By using a virtual impedance based strategy, the cell capacitors of multi-modular converter are applied for implementing dc active power filter capabilities, which helps to improve the bus power quality without the use of auxiliary devices or even sacrificing battery lifetime. The study in [50] proposed FESS as a feasible approach to save significant fuel on the DDG51 Arleigh Burke class destroyers to support pulsed power based loads. The FESS allows the use of a single turbine generator close to a full load rather than using the traditional practice of running two turbine generators at less than a half load. In this strategy, it helps in saving the fuel, improves the reliability and power quality of the shipboard power system.

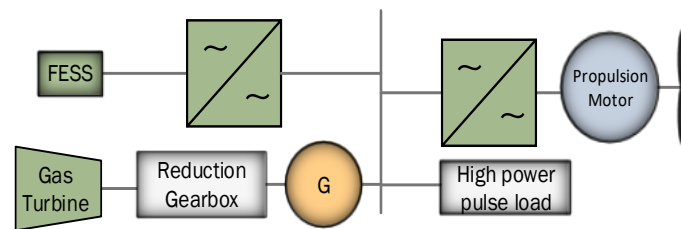


Figure 18. Integration of flywheel energy storage system (FESS) with IPS.

4.5. BESS Based Vessels

MF Ampere, the first zero-emission ferry operated by Norled AS, which sails on a 5.7 km crossing between the villages of Lavik and Oppedal, Norway. It has the capability to carry up to 120 cars and 360 passengers [120]. The vessel consists of two onboard motors, one of the motor is used to drive the thrusters, these motors are operated by lithium-polymer-based batteries [121]. The sailing time of the ferry is approximately 20 min and an extra 10 min are particularly specified for charging the batteries from the battery station located at shore side as shown in Figure 19. In order to recharge the batteries faster and not to put burden on the village grid, battery banks are installed on each side of shore to recharge the batteries. Approximately, one million litre of diesel per year is saved, 15 tons of nitrogen oxide and 570 tons of carbon dioxide emissions are reduced as compared to the same size of the vessels powered by traditional power sources operated on a similar route.

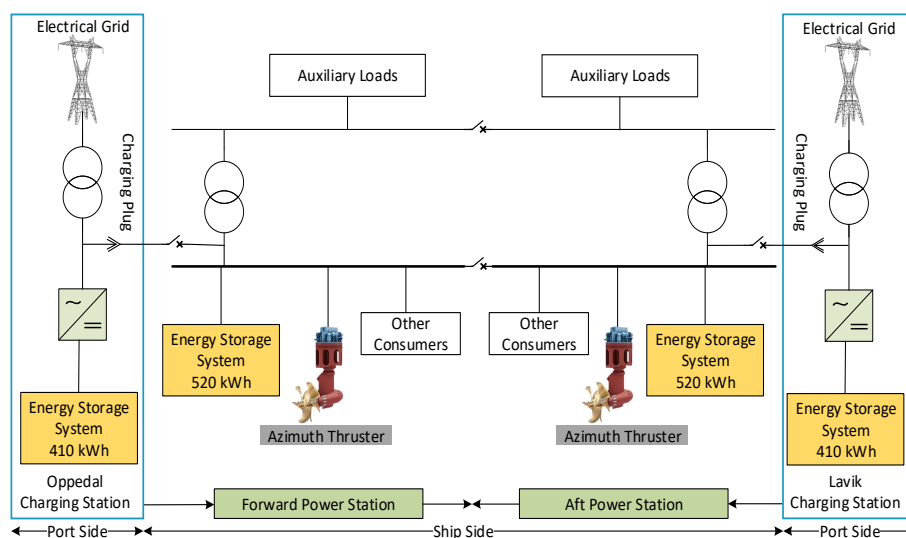


Figure 19. Schematic diagram of *MF Ampere*.

The first fully electric cargo ship was launched in Guangzhou by Guangzhou Shipyard International Company Ltd in 2017 to carry coal for thermal power generation along Pearl river. It is the first cargo ship to use Li-ion batteries with such a huge power rating of 2.4 MW and it takes approximately 2 h to charge these batteries [122]. The vessel carries up to 2000 tons of cargo can cruise up to 80 km when the batteries are fully charged at a maximum speed of 7 knots. The vessel is emission free and does not emit any greenhouse gases, hence contributing towards the pollution and fossil-fuel free future. *Greenline 33*, a hybrid yacht with diesel/electric propulsion system, the schematic diagram of this yacht is depicted in Figure 20. The yacht further consists of 6 solar panels, they are installed on the roof top of the yacht to charge the battery bank. Li-ion-based batteries are installed to run the yacht in an electric mode. It is observed that the yacht is emission free and the running cost in case of electric mode is reduced by 10 times as compared to the diesel engine. *Greenline 40* and *Greenline 46* are among the ongoing projects, which are based on fully electric propulsion system with Li-ion battery packs [123].

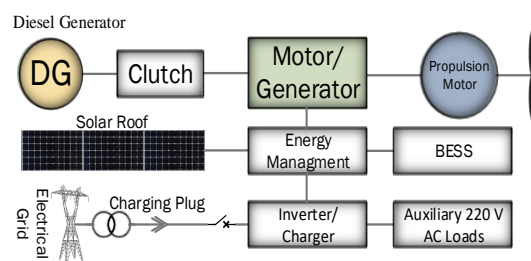


Figure 20. Schematic diagram of hybrid yacht by *Greenline 33*.

The Vision of the Fjords, a diesel-electric hybrid vessel owned and operated by the Fjords. ABB's onboard DC system is installed on the vessel that controls and manages the flow of energy between propeller, diesel engine, and the charging station [124]. The ferry carries around 400 tourists, it cruises between Flåm and Gudvangen, a distance of approximately 32 km. On the route from Flåm to the start of Nærøfjord, it works on a diesel engine with a speed of around 18–19 knots for a duration of around 30–40 min. From the Nærøfjord (UNESCO world's heritage-listed place) to Gudvangen, it will switch to a battery resulting in the speed around 8 knots such that people can enjoy the scenes in almost complete silence, the basic schematic diagram of the vessel is depicted in Figure 21. The power system in the vessel comprises of 2 main engines, 2 electric motors, lithium-ion-based ESS, and an onboard 825 V DC. The batteries are connected with a manual plug to the grid and it takes around 20 min to charge it. *Future of the Fjords* [125], a sister vessel of *The Vision of the Fjords* is fully electric vessel, which makes the vessel quiet, vibrationless, and emission-free. For charging the batteries a battery bank is installed in a floating glass at Gudvangen as the capacity of a nearby grid is quite limited. Two lithium-ion-based battery packs for the propulsion motors are installed. It is estimated that the ferry's electricity consumption is around 700 kWh per trip which is approximately equivalent to 80 litres of diesel.

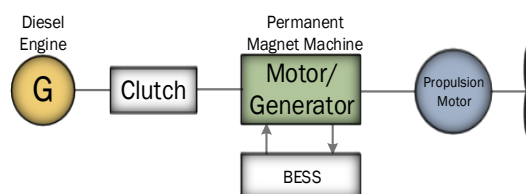


Figure 21. *The Vision of the Fjords* schematic diagram.

M/F Finnøy, a car ferry that was originally a diesel-electric ferry built in 1999 with a capacity of 350 passengers and 110 cars, the ferry runs on the crossing between Oanes and Lauvvik, Norway.

The vessel was upgraded in 2013 with an energy storage system, particularly a lithium polymer-based battery system is installed [126]. Presently, it is owned by Norled, which consists of Siemens based drive system, four diesel-based generators, a battery storage system, and main propulsion system as shown in Figure 22.

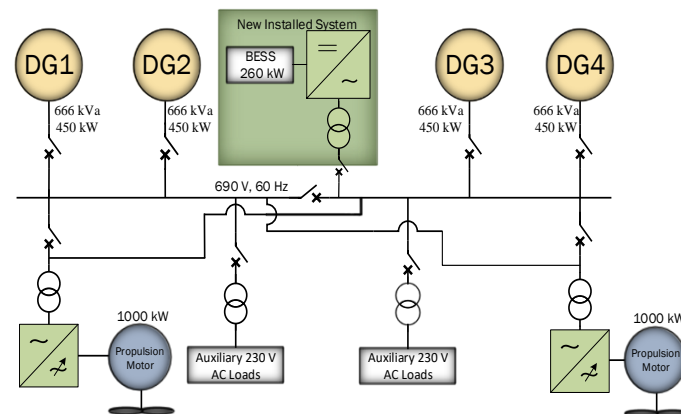


Figure 22. M/F Finnøy schematic diagram.

Tycho Brahe and *Aurora*, car ferries operated by HH Ferries group, which sails between Helsingør, Denmark and Helsingborg, Sweden, a distance of around 4 km. *Tycho Brahe* is sailing since 1991 and has the capability of carrying 1250 passengers, 240 cars, 260 trucks, and 9 passenger train coaches at a time. Previously, the ferry used to be powered with traditional power generation sources, i.e., diesel-based generators; 4 diesel engines were installed to cater to daily operations on the vessel. The ferry was docked in June 2017 to re-commission it as an entirely battery-powered vessel. The propulsion system and power for these two ferries are supplied by ABB, which comprises of batteries, an energy storage system, onboard DC grid technology, and control system [127]. The batteries installed on top of the ferry are 640 in number, having the energy density of each battery 6.4 kWh along with 2 deckhouses for transformers, cooling of batteries, and converters. Two generators out of four were removed from the ferry, rest of two generators act as a backup power source, i.e., not be used for daily operation purposes. Furthermore, ABB-based robotic arm is installed, which connects the batteries with the grid every time when the ferry is in port in order to optimize connection time. It is estimated that the emissions of carbon monoxide, carbon dioxide, and sulphur oxide are reduced by 50% [128].

Port-liner, a Dutch company builds an emission-free sailing barges, which are crewless and are operated from the ports of Amsterdam, Rotterdam, and Antwerp [129]. The company further develops an “e-Powerbox”, which is vibration and shock free. It can be easily swapped with the charged “e-Powerbox” when the barge is at the port. The electric motors of the barge will be powered by 20-foot batteries. As a consequence of these zero-emission barges, 23,000 trucks that are powered by diesel engines will subsequently be removed from the roads. As, presently in Europe, 74.9% freight is transported by roads, 18.4% by railways, and 6.7% by seaways according to Eurostat statistics. It is expected that five barges will be in operation soon, which have the capability to carry 20 containers, each container’s size is around 20 feet. These barges will be fitted with “e-Powerbox” that has the capability to provide power for 15 h. *FCS Alsterwasser*, a first passenger tourist vessel with zero-emissions was developed in Germany that operates on the Alster river. It has a hybrid electric propulsion system with two 50 kW PEM-based fuel cell and a lead-acid based battery system as shown in Figure 23. Table 8 summarizes the type and rating of BESS used in different vessels.

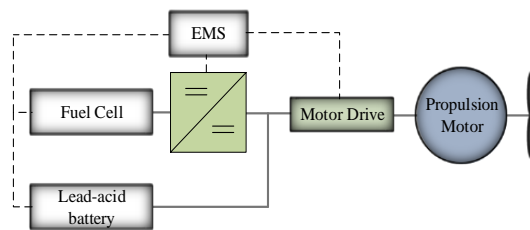


Figure 23. Fuel cell ship (FCS) alsterwasser hybrid battery/fuel cell system [130].

Table 8. Summary of BESS-based vessels.

Vessel's Name	Type of Battery Used	Power Rating	Generation Sources	Type of Ship	Reference
MF Ampere	Lithium-polymer	1040 kW	Battery only	Ferry	[120,121]
Guangzhou (Cargo Ship)	Lithium-ion	2400 kW	Battery only	Cargo Ship	[122]
Greenline 33	Lithium-ion	11.5 kW	Battery + Diesel generator	Yacht	[123]
Greenline 40	Lithium-ion	23 kW	Battery only	Yacht	[123]
Greenline 46	Lithium-ion	46 kW	Battery only	Yacht	[123]
The Vision of the Fjords	Lithium-ion	576 kW	Battery + Diesel generator	Ferry	[124]
Future of the Fjords	Lithium-ion	1800 kW	Battery only	Ferry	[125]
M/F Finnøy	Lithium-polymer	260 kW	Battery + Diesel generator	Ferry	[126]
Tycho Brahe & Aurora	Lithium-ion	4160 kW	Battery only	Ferry	[127]
FCS Alsterwasser	Lead-acid	200 kW	Battery + FC	Ferry	[69]

5. Challenges of Integrating Energy Storage System in Shipboard Microgrids

Electric ships experience immense propulsion load fluctuations on their drive shaft, particularly due to rotational motion of the propeller and waves, which affect the reliability and can cause wear and tear. Hence, modern shipboard microgrids are needed to be designed while considering challenging performance criteria and also considering the environmental concerns. These requirements demand to improve the design methods for vessels and their operation. The ESS can be considered either as the main source of power or as a redundant power source. In literature, there are several works where energy storage has been utilized in terrestrial microgrids to minimize the effects of changes in loads on the crucial parameters of the system. However, in shipboard microgrids, such approaches are yet to be applied at such level. Recently, control techniques being used are adaptive control, particle swarm optimization, proportional integral (PI) control, active and reactive power (PQ) control, etc. The abrupt changes in shiploads due to dynamic pulse loads such as high-power radars, an electromagnetic rail gun, laser self-defense system, etc., changes the power demand in a quick manner. These issues may reduce the efficiency of the whole power system if properly not handled.

Furthermore, ESS technologies are quite expensive and rely on power conversion devices depending on the power system either AC or DC. In this case, a solution might be to install ESS as part of motor drives as shown in Figure 17 in order to eliminate the requirement of additional power conversion devices, hence resulting in the reduction in the cost and weight. In this scenario, by installing ESS alongside with an AFE, the ESS can attain application flexibility, therefore can mitigate harmonics, peak shaving, etc. The battery packs are quite heavy and take a lot of space but can replace at least one prime mover from the vessel. The other issue with battery technology includes the lifetime, swift charging and discharging of batteries may result in heat, which further causes a reduction in the lifetime of a battery. Hence, there might be a possibility that batteries may be defected or died before they manage to cover the installation cost by reducing the consumption of fuel. To solve this problem, the involvement of ultra-capacitors, flywheel, fuel cells, etc., can be beneficial. They are installed with the battery packs to improve charge and discharge speed, increase lifetime, enhance power density and so on. In present, using a single energy storage system might not be a solution as batteries can only provide higher energy density whereas flywheel, ultra-capacitor can provide higher power density. Batteries further have a short life cycle as compared to higher power density-based energy sources. Hence, hybridizing two energy storage devices might be an interesting solution for future shipboard microgrids.

6. Conclusions

This paper reviews different hybrid combinations of energy storage systems for shipboard power systems which are applied in the literatures. The possibility of using energy storage systems in load levelling, peak shaving, power smoothing, and power quality improvement are briefly discussed. It is observed that ESS can be useful to flatten the vessel's load profile, to facilitate starting and stopping of generators, and reduces the number of online prime movers. Therefore, in low loading conditions, the ESS charges and during the high load demands, the ESS provides the stored power and hence discharges. Moreover, it helps the prime movers to run at their optimal fuel-consumption efficient point. ESS in peak shaving applications, further economizes the fuel consumption and therefore results in a reduction of emissions by reducing the number of online generators. Among the batteries, Li-ion is the most used battery for shipboard power applications, specifically for ferries that cruise on shorter routes. Furthermore, it can contribute in reducing the fluctuations caused by the propulsion loads. The hybridization of energy storage devices are expected to provide an extra support in future for larger cargo vessels and for larger routes as well. It is found that battery-flywheel and battery-ultracapacitors energy storage systems have been among the most used energy storage devices, particularly for the applications that are related to shipboard power systems. The hybrid battery-fuel cell is also among the frequently used technologies in literature, but efficiency and storing issues of hydrogen in case of fuel cells is still a major concern.

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Abbreviations

The following abbreviations are used in this manuscript:

IMO	International marine organization
ESS	Energy storage system
HESS	Hybrid energy storage system
IPS	Integrated power system
VSD	Variable speed drives
AES	All electric ships
SMES	Superconducting magnetic energy storage
FC	Fuel Cell
UPS	Uninterruptible power supply
PEM	Polymer exchange membrane
DP	Dynamic positioning
BESS	Battery energy storage system
FESS	Flywheel energy storage system
UPS	Uninterruptible power supply
MVDC	Medium voltage direct current

References

1. McCoy, T.J. Electric ships past, present, and future [technology leaders]. *IEEE Electr. Mag.* **2015**, *3*, 4–11. [[CrossRef](#)]
2. Zahedi, B.; Norum, L.E.; Ludvigsen, K.B. Optimized efficiency of all-electric ships by dc hybrid power systems. *J. Power Sources* **2014**, *255*, 341–354. [[CrossRef](#)]
3. Doerry, N. Naval Power Systems: Integrated power systems for the continuity of the electrical power supply. *IEEE Electr. Mag.* **2015**, *3*, 12–21. [[CrossRef](#)]
4. Doerry, N.; Amy, J.; Krolick, C. History and the status of electric ship propulsion, integrated power systems, and future trends in the US Navy. *Proc. IEEE* **2015**, *103*, 2243–2251. [[CrossRef](#)]
5. International Maritime Organization (IMO). *Third IMO Greenhouse Gas Study*; International Maritime Organization (IMO): London, UK, 2014.

6. International Maritime Organization: Prevention of Air Pollution from Ships. Available online: <http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/AirPollution.aspx> (accessed on 27 August 2018).
7. EU Commission. The Paris Protocol—A Blueprint for Tackling Global Climate Change Beyond 2020. Available online: https://www.eesc.europa.eu/sites/default/files/resources/docs/15_362-ppaper_changement-clim_en.pdf (accessed on 27 August 2018).
8. Johansen, T.A.; Bø, T.I.; Mathiesen, E.; Veksler, A.; Sørensen, A.J. Dynamic positioning system as dynamic energy storage on diesel-electric ships. *IEEE Trans. Power Syst.* **2014**, *29*, 3086–3091. [[CrossRef](#)]
9. Veksler, A.; Johansen, T.A.; Skjetne, R. Thrust allocation with power management functionality on dynamically positioned vessels. In Proceedings of the American Control Conference (ACC), Fairmont Queen Elizabeth, Montréal, QC, Canada, 27–29 June 2012; pp. 1468–1475.
10. Li, X.; Hui, D.; Lai, X. Battery energy storage station (BESS)-based smoothing control of photovoltaic (PV) and wind power generation fluctuations. *IEEE Trans. Sustain. Energy.* **2013**, *4*, 464–473. [[CrossRef](#)]
11. Hou, J.; Sun, J.; Hofmann, H. Interaction analysis and integrated control of hybrid energy storage and generator control system for electric ship propulsion. In Proceedings of the American Control Conference (ACC), Chicago, IL, USA, 1–3 July 2015; pp. 4988–4993.
12. Haseltalab, A.; Negenborn, R.R.; Lodewijks, G. Multi-level predictive control for energy management of hybrid ships in the presence of uncertainty and environmental disturbances. *IFAC-PapersOnLine* **2016**, *49*, 90–95. [[CrossRef](#)]
13. Hebner, R.E.; Davey, K.; Herbst, J.; Hall, D.; Hahne, J.; Surls, D.D.; Ouroua, A. Dynamic load and storage integration. *Proc. IEEE* **2015**, *103*, 2344–2354. [[CrossRef](#)]
14. Hemmati, R.; Saboori, H. Emergence of hybrid energy storage systems in renewable energy and transport applications—A review. *Renew. Sustain. Energy Rev.* **2016**, *65*, 11–23. [[CrossRef](#)]
15. Chen, H.; Cong, T.N.; Yang, W.; Tan, C.; Li, Y.; Ding, Y. Progress in electrical energy storage system: A critical review. *Prog. Nat. Sci.* **2009**, *19*, 291–312. [[CrossRef](#)]
16. Argyrou, M.C.; Christodoulides, P.; Kalogirou, S.A. Energy storage for electricity generation and related processes: Technologies appraisal and grid scale applications. *Renew. Sustain. Energy Rev.* **2018**, *94*, 804–821. [[CrossRef](#)]
17. Stan, A.T.; Swierczynski, M.; Stroe, D.I.; Teodorescu, R.; Andreassen, S.J.; Moth, K. A comparative study of lithium ion to lead acid batteries for use in UPS applications. In Proceedings of the Telecommunications Energy Conference (INTELEC), Vancouver, BC, Canada, 28 September–2 October 2014; pp. 1–8.
18. Nilsson, A.O. Nickel cadmium batteries in UPS design features. In Proceedings of the Telecommunications Energy Conference, San Diego, CA, USA, 30 October–2 November 1988; pp. 388–393.
19. Harrison, A.I. Batteries and AC phenomena in UPS systems: the battery point of view. In Proceedings of the Telecommunications Energy Conference, Florence, Italy, 15–18 October 1989; pp. 5–12.
20. Bekiarov, S.B.; Nasiri, A.; Emadi, A. A new reduced parts on-line single-phase UPS system. In Proceedings of the Industrial Electronics Society, IECON'03, Roanoke, VA, USA, 2–6 November 2003; Volume 1, pp. 688–693.
21. Zaghib, K.; Charest, P.; Guerfi, A.; Shim, J.; Perrier, M.; Striebel, K. Safe Li-ion polymer batteries for HEV applications. *J. Power Sources* **2004**, *134*, 124–129. [[CrossRef](#)]
22. Karden, E.; Ploumen, S.; Fricke, B.; Miller, T.; Snyder, K. Energy storage devices for future hybrid electric vehicles. *J. Power Sources* **2007**, *168*, 2–11. [[CrossRef](#)]
23. Burke, A.F. Batteries and ultracapacitors for electric, hybrid, and fuel cell vehicles. *Proc. IEEE* **2007**, *95*, 806–820. [[CrossRef](#)]
24. Zhao, H.; Wu, Q.; Hu, S.; Xu, H.; Rasmussen, C.N. Review of energy storage system for wind power integration support. *Appl. Energy* **2015**, *137*, 545–553. [[CrossRef](#)]
25. Chatzivassileiadi, A.; Ampatzi, E.; Knight, I. Characteristics of electrical energy storage technologies and their applications in buildings. *Renew. Sustain. Energy Rev.* **2013**, *25*, 814–830. [[CrossRef](#)]
26. Ibrahim, H.; Ilinca, A.; Perron, J. Energy storage systems characteristics and comparisons. *Renew. Sustain. Energy Rev.* **2008**, *12*, 1221–1250. [[CrossRef](#)]
27. Vazquez, S.; Lukic, S.M.; Galvan, E.; Franquelo, L.G.; Carrasco, J.M. Energy storage systems for transport and grid applications. *IEEE Trans. Ind. Electr.* **2010**, *57*, 3881–3895. [[CrossRef](#)]

28. Dufo-López, R.; Lujano-Rojas, J.M.; Bernal-Agustín, J.L. Comparison of different lead-acid battery lifetime prediction models for use in simulation of stand-alone photovoltaic systems. *Appl. Energy* **2014**, *115*, 242–253. [CrossRef]
29. Parker, C.D. Lead-acid battery energy-storage systems for electricity supply networks. *J. Power Sources* **2001**, *100*, 18–28. [CrossRef]
30. Mohod, S.W.; Aware, M.V. Micro wind power generator with battery energy storage for critical load. *IEEE Syst. J.* **2012**, *6*, 18–25. [CrossRef]
31. Lam, L.T.; Louey, R. Development of ultra-battery for hybrid-electric vehicle applications. *J. Power Sources* **2006**, *158*, 1140–1148. [CrossRef]
32. Olson, J.B.; Sexton, E.D. Operation of lead-acid batteries for HEV applications. In Proceedings of the Battery Conference on Applications and Advance, Long Beach, CA, USA, 11–14 January 2000; pp. 205–210.
33. Hadjipaschalis, I.; Poullikkas, A.; Efthimiou, V. Overview of current and future energy storage technologies for electric power applications. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1513–1522. [CrossRef]
34. Lukic, S.M.; Cao, J.; Bansal, R.C.; Rodriguez, F.; Emadi, A. Energy storage systems for automotive applications. *IEEE Trans. Ind. Electron.* **2008**, *55*, 2258–2267. [CrossRef]
35. Wehrey, M.C. What's new with hybrid electric vehicles. *IEEE Power Energy Mag.* **2004**, *2*, 34–39. [CrossRef]
36. Venkatesetty, H.V.; Jeong, Y.U. Recent advances in lithium-ion and lithium-polymer batteries. In Proceedings of the Battery Conference on Applications and Advances, Long Beach, CA, USA, 18 January 2002; pp. 173–178.
37. Khaligh, A.; Li, Z. Battery, ultracapacitor, fuel cell, and hybrid energy storage systems for electric, hybrid electric, fuel cell, and plug-in hybrid electric vehicles: State of the art. *IEEE Trans. Veh. Technol.* **2010**, *59*, 2806–2814. [CrossRef]
38. Cao, J.; Emadi, A. A new battery/ultracapacitor hybrid energy storage system for electric, hybrid, and plug-in hybrid electric vehicles. *IEEE Trans. Power Electron.* **2012**, *27*, 122–132.
39. Anstrom, J.R.; Zile, B.; Smith, K.; Hofmann, H.; Batra, A. Simulation and field-testing of hybrid ultra-capacitor/battery energy storage systems for electric and hybrid-electric transit vehicles. In Proceedings of the Applied Power Electronics Conference and Exposition (APEC), Charlotte, NC, USA, 15–19 March 2015; Volume 1, pp. 491–497.
40. Nájera, J.; Moreno-Torres, P.; Lafoz, M.; de Castro, R.M.; Arribas, J.R. Approach to hybrid energy storage systems dimensioning for urban electric buses regarding efficiency and battery aging. *Energies* **2017**, *10*, 1708. [CrossRef]
41. Kouchachvili, L.; Ya'ici, W.; Entchev, E. Hybrid battery/supercapacitor energy storage system for the electric vehicles. *J. Power Sources* **2018**, *374*, 237–248. [CrossRef]
42. Ultracapacitor Based Buses. Available online: <https://www.treehugger.com/cars/ultracapacitor-buses-work-as-long-as-you-have-lots-of-quick-charge-stations.html> (accessed on 27 August 2018).
43. Park, J.D.; Kalev, C.; Hofmann, H.F. Control of high-speed solid-rotor synchronous reluctance motor/generator for flywheel-based uninterruptible power supplies. *IEEE Trans. Ind. Electron.* **2008**, *55*, 3038–3046. [CrossRef]
44. Cheng, M.; Sami, S.S.; Wu, J. Benefits of using virtual energy storage system for power system frequency response. *Appl. Energy* **2017**, *194*, 376–385. [CrossRef]
45. Díaz-González, F.; Sumper, A.; Gomis-Bellmunt, O.; Bianchi, F.D. Energy management of flywheel-based energy storage device for wind power smoothing. *Appl. Energy* **2013**, *110*, 207–219. [CrossRef]
46. Spiriyagin, M.; Wolfs, P.; Szanto, F.; Sun, Y.Q.; Cole, C.; Nielsen, D. Application of flywheel energy storage for heavy haul locomotives. *Appl. Energy* **2015**, *157*, 607–618. [CrossRef]
47. McGroarty, J.; Schmeller, J.; Hockney, R.; Polimeno, M. Flywheel energy storage system for electric start and an all-electric ship. In Proceedings of the Electric Ship Technologies Symposium, Philadelphia, PA, USA, 25–27 July 2005; pp. 400–406.
48. Anvari-Moghaddam, A.; Dragicevic, T.; Meng, L.; Sun, B.; Guerrero, J.M. Optimal planning and operation management of a ship electrical power system with energy storage system. In Proceedings of the IECON 42nd Annual Conference of the IEEE Industrial Electronics Society, Florence, Italy, 24–27 October 2016; pp. 2095–2099.
49. Domaschk, L.N.; Ouroua, A.; Hebner, R.E.; Bowlin, O.E.; Colson, W.B. Coordination of large pulsed loads on future electric ships. *IEEE Trans. Magn.* **2007**, *43*, 450–455. [CrossRef]

50. Hebner, R.E.; Herbst, J.D.; Gattozzi, A.L. Pulsed power loads support and efficiency improvement on navy ships. *Naval Eng. J.* **2010**, *122*, 23–32. [CrossRef]
51. Jeong, H.W.; Kim, Y.S.; Kim, C.H.; Choi, S.H.; Yoon, K.K. Analysis on application of flywheel energy storage system for offshore plants with dynamic positioning system. *J. Korean Soc. Mar. Eng.* **2012**, *36*, 935–941. [CrossRef]
52. Jeong, H.W.; Ha, Y.S.; Kim, Y.S.; Kim, C.H.; Yoon, K.K.; Seo, D.H. Shore power to ships and offshore plants with flywheel energy storage system. *J. Korean Soc. Mar. Eng.* **2013**, *37*, 771–777. [CrossRef]
53. Boom, R.; Peterson, H. Superconductive energy storage for power systems. *IEEE Trans. Magn.* **1972**, *8*, 701–703. [CrossRef]
54. Hsomy, W.M.; Dodds, S.J. Applied superconductivity developments in Japan. *Power Eng. J.* **1993**, *7*, 170–176. [CrossRef]
55. Holla, R.V. Energy Storage Methods-Superconducting Magnetic Energy Storage—A Review. *J. Undergrad. Res. Univ. Ill. Chic.* **2015**, *8*. [CrossRef]
56. Beach, F.C.; McNab, I.R. Present and future naval applications for pulsed power. In Proceedings of the Pulsed Power Conference, Monterey, CA, USA, 13–15 June 2005; pp. 1–7.
57. Wolfe, T.; Riedy, P.; Drake, J.; MacDougall, F.; Bernardes, J. Preliminary design of a 200 MJ pulsed power system for a naval railgun proof of concept facility. In Proceedings of the Pulsed Power Conference, Monterey, CA, USA, 13–15 June 2005; pp. 70–74.
58. Miller, J.; Santosusso, D.; Uva, M.; Woods, K.; Fitzpatrick, B. Naval superconducting integrated power system (sips). In Proceedings of the 10th Intelligent Ship Symposium, Philadelphia, Pennsylvania, 22–23 May 2013.
59. Superconducting Magnetic Energy Storage. Available online: <https://apps.dtic.mil/dtic/tr/fulltext/u2/a338581.pdf> (accessed on 27 August 2018).
60. German HDW Submarine. Available online: https://www.naval-technology.com/projects/type_212/ (accessed on 27 August 2018).
61. Fuel Cell Ship Alsterwasser. Available online: <https://www.drewsmarine.com/en/references/passenger-ferries/fcs-alsterwasser> (accessed on 27 August 2018).
62. Symington, W.P.; Belle, A.; Nguyen, H.D.; Binns, J.R. Emerging technologies in marine electric propulsion. *Proc. Inst. Mech. Eng. Part M J. Eng. Marit. Environ.* **2016**, *230*, 187–198. [CrossRef]
63. Carlton, J.; Aldwinkle, J.; Anderson, J. *Future Ship Powering Options: Exploring Alternative Methods of Ship Propulsion*; Royal Academy of Engineering: London, UK, 2013.
64. Comparison of Fuel Cell Technologies. Available online: https://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/pdfs/fc_comparison_chart.pdf (accessed on 27 August 2018).
65. Viking Lady. Available online: <https://www.wartsila.com/resources/customer-references/view/viking-lady> (accessed on 27 August 2018).
66. Lloyd, G. DNV, Shipping Industry Eyeing Hydrogen Fuel Cells as Possible Pathway to Emissions Reduction. Available online: <http://www.greencarcongress.com/2012/09/h2shipping-20120907.html> (accessed on 27 August 2018).
67. Viking Lady. Available online: <http://maritimeinteriorpoland.com/references/viking-lady/> (accessed on 27 August 2018).
68. Fuel Cell Boat (Nemo H2). Available online: <http://www.opr-advies.nl/fuelcellboat/efcbboot.html> (accessed on 27 August 2018).
69. Henderson, K. Fuel Cell Vessel Back in Service. Available online: <http://articles.maritimepropulsion.com/article/Fuel-Cell-Vessel-Back-In-Service80232.aspx> (accessed on 27 August 2018).
70. SF-BREEZE. Available online: <https://energy.sandia.gov/transportation-energy/hydrogen/market-transformation/maritime-fuel-cells/sf-breeze/> (accessed on 27 August 2018).
71. Pa-x-ell. Available online: <http://www.e4ships.de/aims-35.html> (accessed on 27 August 2018).
72. METHAPU Prototypes Methanol SOFC for Ships. *Fuel Cells Bull.* **2008**, *5*, 4–5. 2859(08)70190-1. [CrossRef]
73. SFC Fuel Cells for US Army, Major Order from German Military. *Fuel Cells Bull.* **2012**, *6*, 4. [CrossRef]
74. Jafarzadeh, S.; Schjølberg, I. Emission Reduction in Shipping Using Hydrogen and Fuel Cells. In Proceedings of the ASME International Conference on Ocean, Offshore and Arctic Engineering, Trondheim, Norway, 25–30 June 2017; p. V010T09A011.
75. MS Forester. Available online: <https://shipandbunker.com/news/emea/914341-fuel-cell-technology-successfully-tested-on-two-vessels> (accessed on 27 August 2018).

76. 212A Class Submarine. Available online: <http://www.seaforces.org/marint/German-Navy/Submarine/Type-212A-class.htm> (accessed on 27 August 2018).
77. SSK S-80 Class Submarine. Available online: <https://www.naval-technology.com/projects/ssk-s-80-class-submarine/> (accessed on 27 August 2018).
78. Kumm, W.H.; Lisie, H.L., Jr. *Feasibility Study of Repowering the USCGC VINDICATOR (WMEC-3) with Modular Diesel Fueled Direct Fuel Cells*; Arctic Energies Ltd Severna Park MD: Groton, MA, USA, 1997.
79. Tang, Y.; Khaligh, A. On the feasibility of hybrid battery/ultracapacitor energy storage systems for next generation shipboard power systems. In Proceedings of the Vehicle Power and Propulsion Conference (VPPC), Lille, France, 1–3 September 2010; pp. 1–6.
80. Hou, J.; Sun, J.; Hofmann, H.F. Mitigating power fluctuations in electric ship propulsion with hybrid energy storage system: Design and analysis. *IEEE J. Ocean. Eng.* **2018**, *43*, 93–107. [[CrossRef](#)]
81. Alafnan, H.; Zhang, M.; Yuan, W.; Zhu, J.; Li, J.; Elsheikh, M.; Li, X. Stability Improvement of DC Power Systems in an All-Electric Ship Using Hybrid SMES/Battery, *IEEE Trans. Appl. Supercond.* **2018**, *28*, 1–6. [[CrossRef](#)]
82. Hou, J.; Sun, J.; Hofmann, H. Control development and performance evaluation for battery/flywheel hybrid energy storage solutions to mitigate load fluctuations in all-electric ship propulsion systems. *Appl. Energy* **2018**, *212*, 919–930. [[CrossRef](#)]
83. Hou, J.; Sun, J.; Hofmann, H. Battery/flywheel Hybrid Energy Storage to mitigate load fluctuations in electric ship propulsion systems. In Proceedings of the American Control Conference (ACC), Seattle, WA, USA, 24–26 May 2017; pp. 1296–1301.
84. Sander, M.; Gehring, R.; Neumann, H.; Jordan, T. LIQHYSMES storage unit-Hybrid energy storage concept combining liquefied hydrogen with Superconducting Magnetic Energy Storage. *Int. J. Hydrog. Energy* **2012**, *37*, 14300–14306. [[CrossRef](#)]
85. Kisacikoglu, M.C.; Uzunoglu, M.; Alam, M.S. Load sharing using fuzzy logic control in a fuel cell/ultracapacitor hybrid vehicle. *Int. J. Hydrog. Energy* **2009**, *34*, 1497–1507. [[CrossRef](#)]
86. Roda, V.; Carroquino, J.; Valiñ o, L.; Lozano, A.; Barreras, F. Remodeling of a commercial plug-in battery electric vehicle to a hybrid configuration with a PEM fuel cell. *Int. J. Hydrog. Energy* **2018**, *43*, 16959–16970. [[CrossRef](#)]
87. Zhao, P.; Dai, Y.; Wang, J. Design and thermodynamic analysis of a hybrid energy storage system based on A-CAES (adiabatic compressed air energy storage) and FESS (flywheel energy storage system) for wind power application. *Energy* **2014**, *70*, 674–684. [[CrossRef](#)]
88. Lemofouet, S.; Rufer, A. Hybrid energy storage system based on compressed air and super-capacitors with maximum efficiency point tracking (MEPT). *IEEE Trans. Ind. Appl.* **2006**, *126*, 911–920. [[CrossRef](#)]
89. Cericola, D.; Kötz, R. Hybridization of rechargeable batteries and electrochemical capacitors principles and limits, *Electrochim. Acta* **2012**, *72*, 1–17.
90. Cooper, A.; Furakawa, J.; Lam, L.; Kellaway, M. The UltraBattery—A new battery design for a new beginning in hybrid electric vehicle energy storage. *J. Power Sources* **2009**, *188*, 642–649. [[CrossRef](#)]
91. Liu, H.; Zhang, Q.; Qi, X.; Han, Y.; Lu, F. Estimation of PV output power in moving and rocking hybrid energy marine ships. *Appl. Energy* **2017**, *204*, 362–372. [[CrossRef](#)]
92. Balsamo, F.; Capasso, C.; Miccione, G.; Veneri, O. Hybrid Storage System Control Strategy for All-Electric Powered Ships. *Energy Procedia* **2017**, *126*, 1083–1090. [[CrossRef](#)]
93. Cohen, I.J.; Westenhov, C.S.; Wetz, D.A.; Heinzl, J.M.; Dong, Q. Evaluation of an actively controlled battery-capacitor hybrid energy storage module (HESM) for use in driving pulsed power applications. In Proceedings of the Pulsed Power Conference (PPC), Austin, TX, USA, 31 May–4 June 2015; pp. 1–5.
94. Vu, T.V.; Gonsoulin, D.; Diaz, F.; Edrington, C.S.; El-Mezyani, T. Predictive Control for Energy Management in Ship Power Systems Under High-Power Ramp Rate Loads. *IEEE Trans. Energy Convers.* **2017**, *32*, 788–797. [[CrossRef](#)]
95. Kulkarni, S.; Santoso, S. Impact of pulse loads on electric ship power system: With and without flywheel energy storage systems. In Proceedings of the Electric Ship Technologies Symposium, Baltimore, MD, USA, 20–22 April 2009; pp. 568–573.
96. Elsayed, A.T.; Mohammed, O.A. A comparative study on the optimal combination of hybrid energy storage system for ship power systems. In Proceedings of the Electric Ship Technologies Symposium (ESTS), Alexandria, VA, USA, 21–24 June 2015; pp. 140–144.

97. Lan, H.; Bai, Y.; Wen, S.; Yu, D.C.; Hong, Y.Y.; Dai, J.; Cheng, P. Modeling and stability analysis of hybrid pv/diesel/ess in ship power system. *Inventions* **2016**, *1*, 5. [CrossRef]
98. Mouritz, A.P.; Gellert, E.; Burchill, P.; Challis, K. Review of advanced composite structures for naval ships and submarines. *Composite structures* **2001**, *53*, 21–42. [CrossRef]
99. Han, J.; Charpentier, J.F.; Tang, T. State of the Art of Fuel Cells for Ship applications. In Proceedings of the IEEE International Symposium on Industrial Electronics (ISIE), Hangzhou, China, 28–31 May 2012; pp. 1456–1461.
100. Psoma, A.; Sattler, G. Fuel cell systems for submarines: from the first idea to serial production. *J. Power Sources* **2002**, *106*, 381–383. [CrossRef]
101. Sattler, G. PEFCs for naval ships and submarines: Many tasks, one solution. *J. Power Sources* **1998**, *71*, 144–149. [CrossRef]
102. Luckose, L.; Urlaub, N.J.; Wiedeback, N.J.; Hess, H.L.; Johnson, B.K. Proton exchange membrane fuel cell (pemfc) modeling in pscad/emtdc. In Proceedings of the Electrical Power and Energy Conference (EPEC), Winnipeg, MB, Canada, 3–5 October 2011; pp. 11–16.
103. Abkenar, A.T.; Nazari, A.; Jayasinghe, S.D.G.; Kapoor, A.; Negnevitsky, M. Fuel cell power management using genetic expression programming in all-electric ships. *IEEE Trans. Energy Convers.* **2017**, *32*, 779–787. [CrossRef]
104. Su, C.L.; Weng, X.T.; Chen, C.J. Power generation controls of fuel cell/energy storage hybrid ship power systems. In Proceedings of the Transportation Electrification Asia-Pacific (ITEC Asia-Pacific), Beijing, China, 31 August–3 September 2014; pp. 1–6.
105. Eyer, J.M.; Erdman, B.; Iannucci, J.J., Jr. *Innovative Applications of Energy Storage in a Restructured Electricity Marketplace: Phase III Final Report: A Study for the DOE Energy Storage Systems Program* (No. SAND2003-2546); Sandia National Laboratories: Albuquerque, NM, USA, 2005.
106. Energy Storage System for Ships-Work in Progress. Available online: <http://corvusenergy.com/work-in-progress/> (accessed on 20 September 2018).
107. Mattern, K.; Ellis, A.; Williams, S.E.; Edwards, C.; Nourai, A.; Porter, D. Application of inverter-based systems for peak shaving and reactive power management. In Proceedings of the Transmission and Distribution Conference and Exposition, Chicago, IL, USA, 21–24 April 2008; pp. 1–4.
108. Sonoda, N.; Matsunaga, H.; Gengo, T.; Minami, M.; Oishi, M.; Hashimoto, T. Development of Containerized Energy Storage System with Lithium-ion batteries. *Mitsubishi Heavy Ind. Tech. Rev.* **2013**, *50*, 36–41.
109. Bø, T.I.; Johansen, T.A. Battery power smoothing control in a marine electric power plant using nonlinear model predictive control. *IEEE Trans. Control Syst. Technol.* **2017**, *25*, 1449–1456. [CrossRef]
110. Det Norske Veritas. Rules for Classification and Construction. Ship Technology, Seagoing Ships, Electrical Installations of Ships. Available online: <https://rules.dnvgl.com/docs/pdf/DNV/ruleship/2012-01/ts408.pdf> (accessed on 27 August 2018).
111. Tang, J.; Xiong, B.; Huang, Y.; Yuan, C.; Su, G. Optimal configuration of energy storage system based on frequency hierarchical control in ship power system with solar photovoltaic plant. *J. Eng.* **2017**, *13*, 1511–1514. [CrossRef]
112. Shagar, V.; Jayasinghe, S.G.; Enshaei, H. Frequency transient suppression in hybrid electric ship power systems: A model predictive control strategy for converter control with energy storage. *Inventions* **2018**, *3*, 13. [CrossRef]
113. Kim, S.Y.; Choe, S.; Ko, S.; Sul, S.K. A Naval Integrated Power System with a Battery Energy Storage System: Fuel efficiency, reliability, and quality of power. *IEEE Electr. Mag.* **2015**, *3*, 22–33. [CrossRef]
114. Terriche, Y.; Kerdoun, D.; Djeghloud, H. A new passive compensation technique to economically improve the power quality of two identical single-phase feeders. In Proceedings of the IEEE 15th International Conference on Environment and Electrical Engineering (EEEIC), Rome, Italy, 10–13 June 2015; pp. 54–59.
115. Terriche, Y.; Golestan, S.; Guerrero, J.M.; Kerdoune, D.; Vasquez, J.C. Matrix pencil method-based reference current generation for shunt active power filters. *IET Power Electron.* **2017**, *11*, 772–780. [CrossRef]
116. Tarasiuk, T. Comparative study of various methods of DFT calculation in the wake of IEC Standard 61000-4-7. *IEEE Trans. Instrum. Meas.* **2009**, *58*, 3666–3677. [CrossRef]
117. Xie, C.; Zhang, C. Research on the ship electric propulsion system network power quality with flywheel energy storage. In Proceedings of the Power and Energy Engineering Conference (APPEEC) Asia-Pacific, Chengdu, China, 28–31 March 2010; pp. 1–3.

118. Samineni, S.; Johnson, B.K.; Hess, H.L.; Law, J.D. Modeling and analysis of a flywheel energy storage system for voltage sag correction. *IEEE Trans. Ind. Appl.* **2006**, *42*, 42–52. [CrossRef]
119. Mo, R.; Li, H. Hybrid energy storage system with active filter function for shipboard MVDC system applications based on isolated modular multilevel DC/DC converter. *IEEE J. Emerg. Sel. Top. Power Electron.* **2017**, *5*, 79–87. [CrossRef]
120. Ampere Ferry, World's First All-Electric Car Ferry. Available online: <https://corvusenergy.com/marine-project/mf-ampere-ferry/> (accessed on 27 August 2018).
121. Corvus Energy. Available online: <https://corvusenergy.com/tag/corvus-at6500/> (accessed on 27 August 2018).
122. World's First 2,000-Ton Electric Boat Launched. Available online: http://www.chinadaily.com.cn/china/2017-11/13/content_34470726.htm (accessed on 27 August 2018).
123. Greenline Yachts. Available online: <https://www.greenlinehybrid.si> (accessed on 27 August 2018).
124. Vision of the Fjords. Available online: <https://new.abb.com/marine/references/vision-of-the-fjords> (accessed on 27 August 2018).
125. Future of the Fjords. Available online: <https://www.braa.no/news/future-of-the-fjords> (accessed on 27 August 2018).
126. Finnøy, M.F. Available online: <https://corvusenergy.com/portfolio/mf-finnoy/> (accessed on 27 August 2018).
127. HH Ferries—Zero Emission Operation. Available online: <https://new.abb.com/marine/references/hh-ferries> (accessed on 27 August 2018).
128. Brahe, T. Available online: <http://sailwiththecurrent.com/> (accessed on 27 August 2018).
129. The Guardian: World's First Electric Container Barges to Sail from European Ports This Summer. Available online: https://www.portliner.nl/media/news/272284_the-guardian-world-s-first-electric-container-barges-to-sail-from-european-ports-this-summer (accessed on 27 August 2018).
130. Bassam, A.M.; Phillips, A.B.; Turnock, S.R.; Wilson, P.A. Development of a multi-scheme energy management strategy for a hybrid fuel cell driven passenger ship. *Int. J. Hydrog. Energy* **2017**, *42*, 623–635. [CrossRef]



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