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Battery Sources and Power Converters Interface in Waterborne Transport Applications

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***Abstract*—In recent years the electrification in the waterborne transport application is in noticeable development. To face the high battery cost, a proper design of the energy storage system is required. For battery sources, the solution worthy of investigation is the use of a hybrid energy storage system (HESS). HESS is composed of a power-dense battery and an energy-dense battery. The use of a HESS allows better optimization of the energy and power levels of the energy storage system. In the paper, the battery source requirements in the waterborne transport application are evaluated to achieve the best trade-off among energy, maximum power, and life cycle. Furthermore, the power converters selection, to balance the power flow among the batteries and the vessel electrical network is described.**

***Index Terms*—Marine vessel electrical transport, Waterborne electrical propulsion, Hybrid energy storage system, Energy battery, Power battery, Battery power converters selection.**

I. Introduction

Nowadays, electrification of waterborne transport propulsion is having a strong development with a target to reducing CO2 emissions for sustainable development in naval transports. The field of application involves the whole naval sector such as commercial and industrial cargo ships, navy ships, passenger cruise vessels, ferries, and small recreational boats [1]–[3]. For large ships, hybrid electro-mechanical arrangements are a viable solution since several years ago, while full electrification without prime internal combustion engines (ICEs) is a new challenge in more sustainable waterborne transport i.e., ferries, and luxury yachts [4], [5].

Hybrid propulsion systems for naval applications integrate combustion engines with battery source power electric motors for the best engine operation with emissions reduction. Another architecture is the electric propulsion system with hybrid power supply [7]. In this propulsion solution, there are several power sources with an energy storage management system to create a grid to energize electrical motors to drive the propellers. The auxiliary electrical loads are connected by power converters to the grid together with other renewable energy sources such as photovoltaic (PV) panels and/or wind power for boats [8]. The whole power sources and storage system compose the ship's electric power station. In Fig. 1 a general block diagram is shown considering different power sources as renewable sources, a DC bus architecture and the propeller with the main powered loads as requested in the naval sector. In a pure battery-electric propulsion system, (see Fig. 1) the propellers are connected to electric motors (EMs) of large power ratings [9], [10], which are nowadays shifting to induction or synchronous multiphase solutions [11], [12]. These EMs are driven by the energy stored in a battery storage system (BSS) that is typically charged from shore. Furthermore, in some battery-electric systems, a smaller diesel generator (or gas turbine, Fig. 1) is inserted to ensure safe and continuous operation in case of battery charge failures or to allow longer navigation. In the battery electric solution, the BSS has a crucial role in the autonomy of the waterborne transport system. The BSS is composed of the battery sources coupled to the power converters interface (Fig. 1). The BSS can be connected to the onboard grid or it can directly power the electric motor drive system. The full electrical marine propulsion requires a differ types of storage systems and several technologies are currently available. These technologies

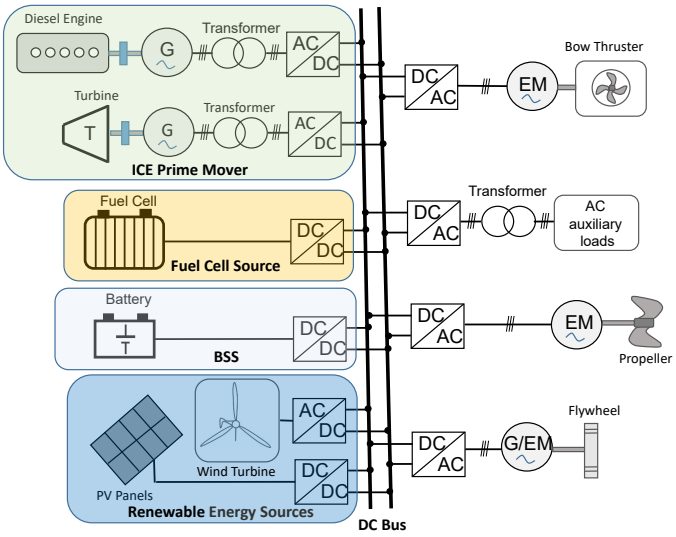


Fig. 1: Architecture of the electric power station with DC bus. The Power sourced depicted are the battery storage system (BSS), the fuel cell source [6] (further feasible naval propulsion energy source), the diesel engine and/or turbine as prime movers for the electric generators interfaced with the DC bus, and the renewable sources (PV panel and/or wind/turbine). The power sources supply a propeller, a bow thruster, and the AC auxiliary loads. Finally, a flywheel is considered.

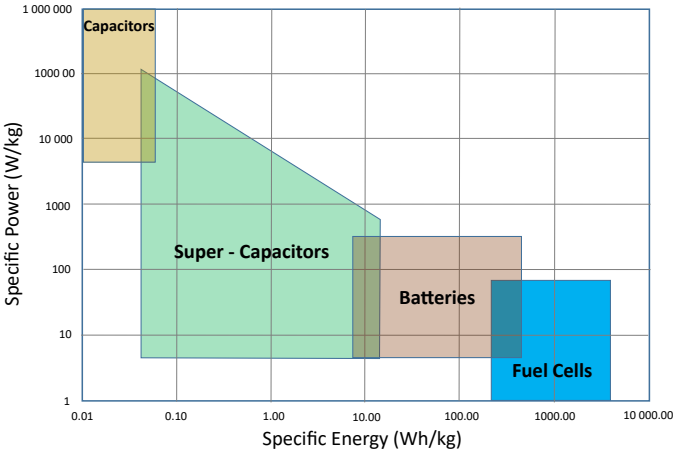


Fig. 2: Storage systems technologies clustered per specific power and energy.

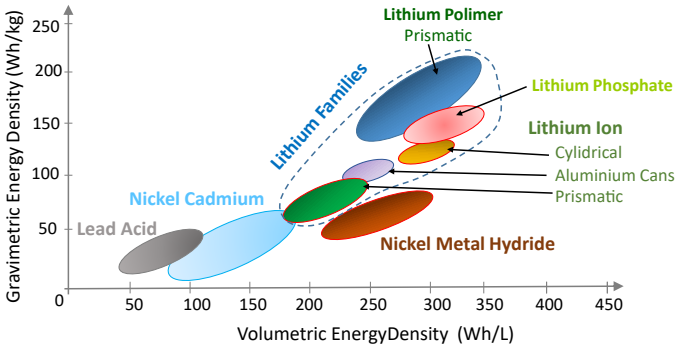


Fig. 3: Power and energy density of various battery chemistries with special focus on lithium ones.

include electrical (capacitors) and chemical storage (batteries and fuel cells [6]) and are available in various power and energy densities, as shown in Fig. 2. The working cycle of a vessel needs quite constant energy for the continuous operation combined with a high power rate in the thruster operation during maneuvers, therefore justifying the adoption of different storage technologies.

Furthermore, the converter topologies, that interfaces the battery sources can be selected considering the battery, the grid and the loads requirements to manage the energy flow and optimize the losses. First, in Section II the main battery sources characteristics for waterborne transport applications are described and analyzed. The energy storage requirement and management in a vessel working cycle are considered in Section III. Finally, the power converters selection to optimize the battery storage system are evaluated in Section IV.

II. Battery Source Requirement For Waterborne Transport Applications

The traditional batteries employed for shipboard were the lead acid type, based on a well-known technology they show low self-discharge rate, high response time and low cost. The life span is around 1500 cycles for 80% depth of discharge (DOD), while the main drawbacks are the low energy density and the presence of lead that requires a complex decommissioning process. A viable solution for nowadays applications is the use of Lithium-Ion batteries mainly in the types of: Lithium-Iron Phosphate (reduced risk of thermal runaway), Lithium Nickel Manganese Cobalt (longer life cycle) and Lithium Manganese Oxide (higher charging rates and thermal stability but with lower life span). An overview of the available Li-ion solutions on the market are summarized in Fig. 3. The open circuit voltage of Lithium-Ion cells has a typical value between 3.2 and 3.9 V, the cells are series connected to get modules, that are the smallest group of cells that can be isolated from the on-board electric network during operation and maintenance. Several modules series and/or parallel connected, according to the voltage and current requirements, are a battery pack. To be practically used in marine applications the battery packs need a battery management system (BMS) and a thermal management system (TMS). The BMS is the connection block between the cells and power management system (PMS) of the whole ship, and it is essential to grant a proper use of the battery packs. The BMS, by measuring relevant electrical, mechanical and thermal parameters of the cells, controls the charge and discharge levels of the batteries up to the level of the single cell or group of cells. In this way the state of charge (SOC) and state of health (SOH) are monitored to grant a good behavior of all the batteries in the packs. The control of the SOC is essential to grant that all the cells in the pack are in the same conditions: following the information from the BMS the charge equalizers provide additional discharge from the cells with higher SOC using resistors (passive charge equalization) or transferring the charge to the elements with lower SOC (active charge equalization by means of electronic switches and capacitors). The temperature is a physical property that can heavily affect the battery performance, to keep under control the temperature information about the temperature of the cells is sent from the BMS to the cooling and thermal management system of the whole battery pack. Large battery packs, as the ones required for marine application, show the additional problem to keep under control the temperature of large volumes to a common value. Bearable battery temperatures, but higher than the design values, reduce the battery life span. In specific conditions, exothermal reactions, due to internal failures of the battery pack, can occur, and the sudden temperature increment, can destroy the battery in a short time. The BMS must operate to detect faulty cells before a thermal runaway occurs and the packs containing the cells with high temperature must be disconnected from the system before destruction.

Cooling systems for marine application can be based on air or liquid: air-based systems need larger spaces among the battery modules and in marine applications must face the high content of salt in air (filters for the inlet air are nearly mandatory to reduce the salt content), while liquid-cooled systems are more efficient and the related heat exchangers can be integrated in the heat management network of the whole ship. The whole system composed by the battery packs, the BMS, the cooling system and the power electronic components

to manage the electrical connections among the packs and with the external electric network is the battery storage system (BSS). In contemporary applications the power electronic converters and the ancillary electromechanical devices are designed to have a battery system that behaves, with the limits imposed by the SOC, as an ideal voltage source with maximum current protection. The power converter at the terminals of the battery system operates to keep constant the output voltage, and thus reducing the oversizing of the users that do not need to be designed for a variable voltage supply.

III. Energy Storage Requirements and Management

The sizing of the battery pack is defined considering three main requirements that must be evaluated in the specific environment operating conditions of the battery:

- Maximum power: the value of the maximum power required from the battery. Since voltage variation at the battery terminals during usual operation is known, the value of the maximum current is a proxy of the maximum power value if an average constant output voltage value is assumed, this approximation is usually accepted during the specification definition procedure.
- Minimum stored energy: minimum amount of the energy that is stored in the battery to grant the cycling between two consecutive partial or full charges.
- Number of required operating cycles: minimum value of the charge/discharge cycles the battery must withstand, keeping its capacity within the design range. This specification is directly correlated with the life of the battery and a viable use of the battery from the economic point of view.

Following the technology employed in the construction the batteries have defined values of maximum power and stored energy or more specifically: at assigned values of DOD, i.e., max DOD of 80%) and the maximum power can be assumed proportional to the stored energy, while the proportional coefficient depends on the cell technology.

The values of maximum power and stored energy required by the specific application are two fully independent parameters, to comply the load specification, a battery technology that allow contemporary achievement of power and energy specification can exist, but in general the battery is oversized for the value of maximum power or the value of stored energy. In usual waterborne application the required power is not constant and maximum power values occur for limited time intervals during the working cycle. The ratio between maximum power and average power has a wide range since the batteries can be used for several purposes and, moreover, emergency operating conditions, where additional power is required, must be considered in marine applications. To reduce the battery oversizing and the related cost, a solution based on a Hybrid Energy Storage System (HESS) composed by two (or more) battery packs with different characteristics can be adopted. Each pack is composed by batteries with a specific power over energy ratio and it is connected with the other

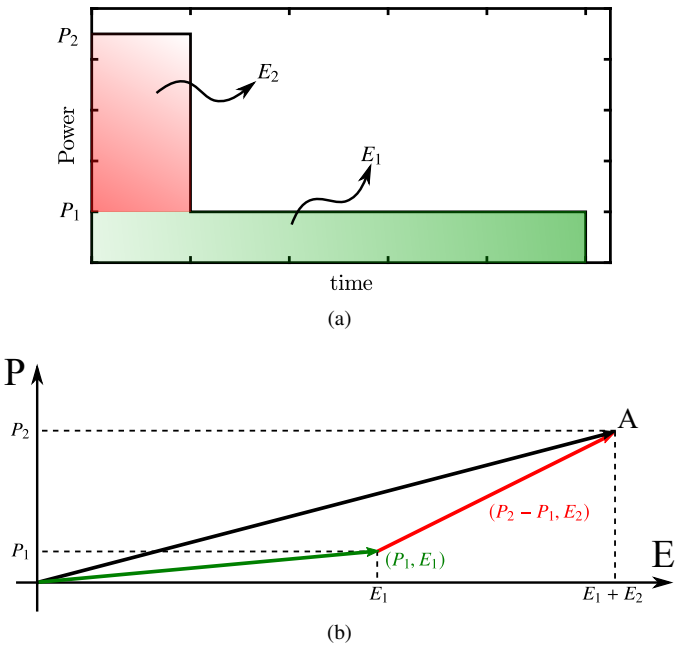


Fig. 4: From top to bottom: a) Simplified power requirement vs time. b) Battery requirements in the max power vs stored energy plane.

packs by power electronics converters. The result is a whole battery system composed by cells with different technology that can operate together due to their specific BMSs and interconnection converters. The specifications concerning the whole battery pack are fulfilled by different battery packs that individually complies with some but not all the specifications. Since the solution based on a HESS reduces the oversizing following the use of a unique battery type the total CAPEX can be lower even if the system is more complex. As an example if the power requirement vs time has the shape depicted in Fig. 4a, with two power value in the cycle. The load demand can be tackled by two storage technologies. One is in charge of the peak power demand P_2 (red area) and the other is rated only P_1 (green area E_1). These storage requirements can be represented by vectors in the max power vs stored energy plane by the point A (see Fig. 4b), that can be reached with a HESS composed by two different kinds of batteries, while the use of one battery type will carry to an oversizing of the ESS. Several different sizing of the two batteries in the pack will allow the solution of the problem and the selection of the couple of packs can be performed following cost minimization.

IV. Converter Topologies for Battery Interface

As mentioned in the Introduction, the integration of batteries in shipboard networks is not direct, but it requires a conversion stage between the BSS and the onboard grid. In general, the conversion stage should feature the following:

- Bidirectional operation, to charge and discharge the BSS;
- Galvanic isolation between the storage and the ship power network;

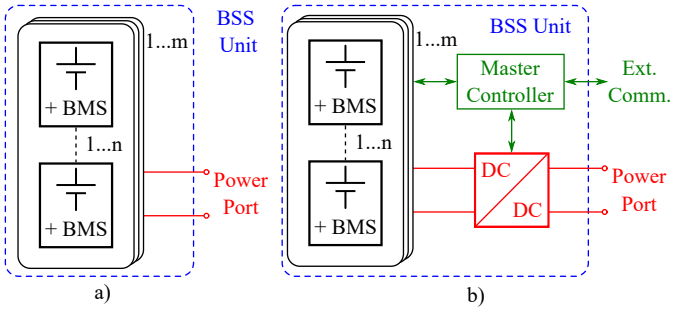


Fig. 5: Basic BSS integration solution: a) Direct connection of the battery to the converter. b) Battery integrated with a DC/DC converter for voltage/current adaptation.

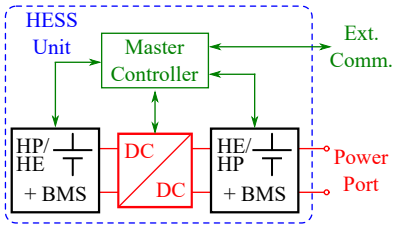


Fig. 6: Semi Active HESS structure. Only one storage technology is interfaced with an electronic converter.

- Enable optimal exploitation of the storage technologies to increase their lifetime;
- High conversion efficiency;
- Limited volume and weight.

Several battery integration structures are possible [13], [14] and have one or more of the mentioned features. The simplest structure involve monotype BSS units interfaced to the ship-board power grid. In this case, a simple and straightforward solution is the direct connection of the battery unit power terminals to a DC/DC or DC/AC converter for grid interfacing, as depicted in Fig. 5a. This solution minimizes the number of conversion stages and the system complexity. However, the variable state of charge (SOC) of the battery leads to a variable input DC voltage of the converter unit. Therefore, this requires power switches with a wider safe operating area and able to withstand both the maximum BSS voltage and load current at BSS minimum voltage [14].

A first advancement compared to the direct connection is the integration of a DC/DC stage into the BSS, as shown in Fig. 5b. This DC/DC stage regulates the output voltage of the BSS unit with the advantage of a direct connection to the network in case of a DC grid and a more optimized DC/AC converter design when interfaced to an ac network. Moreover, this conversion solution enables modular storage solutions, by stacking more BSS units in series or in parallel.

However, thanks to the degree of freedom offered by the electronic converters, it is also possible to mix different battery technologies to build up hybrid energy storage systems (HESSs) [15]. These HESSs enable finer optimizations of the battery part of the ship, by using the specific peculiarities of different technologies into the same storage system, i.e., high energy (HE) and high power (HP) batteries. Moreover, HESSs are not strictly limited to batteries, but can also adopt other

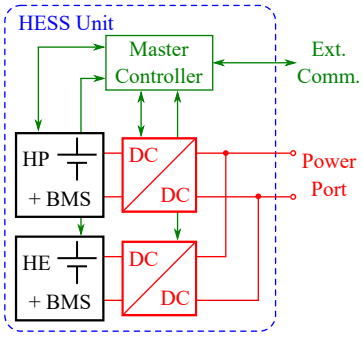


Fig. 7: Full Active HESS structure. All storage technologies are interfaced with an electronic converter.

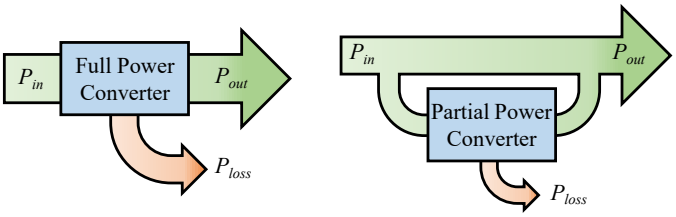


Fig. 8: Partial power processing concept.

storage technologies, such as supercapacitors and fuel cells [16]–[18]. Being HESSs potentially very flexible solutions, several connections and conversion structures are possible [14].

The HE and HP storage technologies can be coupled in various ways, leveraging the possibilities of static conversion. A first solution is called Semi Active (SA) [15] and it directly connects the HE or HP storage to the power terminals of the HESS, while interfacing the other technology with an intermediate DC/DC converter as depicted in Fig. 6. This solution allows a more optimized exploitation of the batteries, by putting the HP battery in charge of the peak power demands and the HE storage of the mean value of the load, thus leveraging the best features of both technologies. Moreover, the SA solution has the advantage of the reduced conversion complexity (single converter), but it cannot overcome the disadvantages of having a storage device directly connected to the power port. This leads to an external behavior as the basic system of Fig. 5a, with a largely variable output voltage, depending on the battery SOC.

A further increase of the HESS complexity leads to the full active (FA) HESS [15], schematically diagrammed in Fig. 7. In this case, each storage technology (HE, HP) is interfaced by a dedicated converter. The converters can then be connected in parallel to a common DC bus to increase the power rating of the system. The FA configuration allows an optimal exploitation of all the storage technologies, stress reduction and consequent lifetime extension. Besides, being each storage block interfaced with a converter, the output voltage of the HESS unit can be controlled to the rated value, mitigating the effect of SOC variation. However, the FA structure has the disadvantage of lower efficiency (more conversion stages), larger volume, weight and complexity with respect to the SA solution.

To mitigate the disadvantages of the FA solution, it is

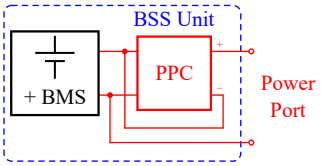


Fig. 9: Partial power converter (PPC) interfacing a battery.

appealing to employ more efficient and compact conversion solutions. A promising solution in this direction is the so-called partial power processing (PPP) concept [19]. This paradigm originates from the photovoltaic conversion field and the doubly-fed induction generators for wind turbines and it is becoming more and more appealing to interface batteries [20]. The idea behind PPP is that the converters only process a limited fraction of the plant power, while the rest is connected without further conversion stages. Therefore, thanks to the reduction of the power processed by the converter, also the overall conversion losses are reduced (see Fig. 8) and so is the converter size, being in first approximation dependent on its power rating. It is therefore possible to imagine a FA battery interface equipped with PPP converters, such as depicted in Fig. 9. This would enable more compact, efficient and lightweight converters appealing for maritime applications. It must be noted, though, that the PPP approach cannot provide galvanic insulation between the battery and the shipboard network. Therefore, it would be necessary to include this separation in a later conversion stage.

V. Conclusion

The electrification of waterborne transports is an emerging topic in the field of electric transport and the developments in the science and technology of batteries allow the possibility to employ both hybrid and full electric ships for specific application (i.e. ferries). The cost of the battery pack is a drawback for the development of electric maritime transport and solutions can be evaluated to get cost reduction. The paper presents the use of a HESS for waterborne transport based on two different battery packs with specific maximum power and stored energy, topologies for the power electronics converters used to connect the batteries between them and with the onboard grid are also presented.

Acknowledgment

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