D3.1 Design tools including power systems models and chosen architectures

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Summary

1 Introduction

The increasing sensibility to environmental issues and emission reduction is largely influencing the marine world [1]. More restrictive regulations on pollutants are suggesting the adoption of alternative propulsion systems and advanced energy generation systems. To this end, the onboard electrification is a promising solution to reduce pollution, giving also well-received flexibility on the strategy to use for the onboard system. In addition, a hybrid-electric system can be combined with the exploitation of green fuel, then increasing the potential reduction of total emissions. However, the final efficiency, both in term of emission reduction and expected operative expenditure, is strongly influenced by the operative profile of the vessel. This is of utmost importance both in case of a newly designed vessel and in the retrofitting of an existing one. Evidently, the great advantages of ship electrification are strongly dependent on the presence of energy storage systems. Among the different possibilities for the onboard storage, Supercapacitors and SMES are among the most promising ones since more than 20 years [2]. This project is aimed at investigating these two technologies taking into account both the two single storage units and also the DC power system architecture to host them. The research project is aimed at demonstrating that the two storages can provide their important role on a passenger ship.

As a matter of fact, the utilization of SMES and Supercapacitors is strongly dependent on the adoption of an onboard controlled DC grid, as they are conventionally interfaced to an input/output DC stage. In the nowadays shipboard context, the Direct Current (DC) technology is one of the most interesting possibility to renew the shipboard power system of both large All Electric Ships (e.g. cruise liners or navy vessels) and hybrid ships. This new concept not only can enable the use of SMES and Supercapacitors, but also it is capable of achieving valued advantages. To give some examples, simplified system integration, modularity and system efficiency, together with an expected reduction of the space devoted to technical system [3]. Therefore, this deliverable provides an initial overview on a possible DC redesign for marine applications, to both ensure the DC pros as well as the storage functionality of SMES and Supercapacitors applications.

2 Shipboard DC power systems

This Section wants to give the initial knowledge on DC systems in marine context. From a general treatise on the expected advantages, the Section wants to explore the IEEE standard guidelines as well as the possible system architectures. The standards are actually necessary to understand advantages, challenges and drawbacks. Conversely, the last part of the section wants to discuss about a standard radial distribution as well as about a new advanced one, the zonal DC distribution.

2.1 Introduction on DC power distribution for marine applications

In marine applications the DC concept has been firstly proposed for the redesign of large All-electric ships or navy vessels (near 2008). Then, in recent years the same idea has been transferred to smaller ship, usually adopting hybrid solutions. Then, a short recap on the initial considerations can help the reader in understanding the evolution towards DC ships. As proficiently described in [4], in recent times the most advanced navies in the world are adopting the AES (All Electric Ship) concept for their new vessels through the installation of medium voltage AC Integrated Power Systems (IPS). This concept foresees that the electric onboard power is used for both hotel loads and electric propulsion. To successfully design such ships, navy designers have drawn largely from the knowledge gained in the merchant field. Due to this, in such ships the design effort has been put mainly on achieving high levels of reliability and to improve mission capabilities, starting from a well-known design base. Examples of the most recent naval vessels built using AES concept are the U.K. Navy Type 45 series and the aircraft carrier HMS Queen Elizabeth. Moreover, the increasing use of hybrid propulsion (achieved through a combination of both mechanical and electrical propulsion systems) instead of a purely mechanical one is foreseen by most navies, exploiting their interest in the AES concept. However, the current adoption of medium voltage AC IPS is only the starting point for navies. To achieve even higher performance, the new concept based on MVDC distribution is under evaluation [5]-[6]. Focusing on large ships, the IEEE Std. 1709 [7] gives the guidelines to design Medium Voltage DC systems (voltages in the range of 1–35 kV) for marine applications. As a matter of fact, such a standard is mainly focused on high-power and high-voltage systems. However, it constitutes the common starting point where also conceiving smaller DC voltage systems for marine use. The interest in MVDC technology is major, due to the advantages that it can give to shipboard power systems (significant mainly for naval vessels, but commercial applications are promising as well). Yet, some relevant issues are still present, whose solving requires both academic and industrial research effort. This section is mainly devoted in showing some criticalities in using MVDC systems. While the next one wants to show the important expected advantages. Most of the MVDC distribution advantages are related to the high amount of electronic power conversion systems needed in dc power systems to allow their proper operation. However, such a pervasive electronic power conversion presence leads to the main technical issue of MVDC power systems. The so-called constant power load stability issue, thus the possible destabilizing interaction between a high-bandwidth controlled converter and the LC filter stage at its input. In addition, the MVDC distribution grid presents other relevant issues, which need to be solved prior to their common adoption as onboard systems. For example, another relevant issue in the adoption of MVDC technology is related to the utilization of power converter-dense power systems. They determine an inertia lack on one hand (i.e. absence of mechanical elements), the complexity in managing high shortcircuit current on the other. Again, one of the most significant obstacles to the adoption of such power systems is the lack of an established industrial base, being MVDC systems an insignificant commercial market nowadays. The absence of industrial partners able to supply validated/derisked MVDC components leads designers to generally ignore such a solution for onboard distribution. As a consequence, this in turn discourages suppliers' investments in this sector. Luckily, nowadays some major power component suppliers start to invest in industrial research related to MVDC application, with the aim of opening new business.

2.2 Background from IEEE Standard 1709-2010 on MVDC shipboard power systems

In the following, the starting point from IEEE Std. 1709 [7] to understand benefits and potentialities of MVDC shipboard applications. Recent successes in the development of fast switching medium-voltage power semiconductors made it possible to realize the following:

a) Simplifying connection and disconnection of different types and ratings of power generation and electrical energy storage devices.
b) Limiting and managing fault currents and enabling reconfiguration.
c) Eliminating reactive voltage drop.
d) Reducing power system weight by using high speed generators because there is no need for all generators to output a synchronous ac voltage.
e) Enabling higher power ratings for a given cable size due to reduced skin effect losses.
f) Improving control of power flows, especially in transient and emergency conditions.

g) Improving efficiency when energy storage and power conversion from batteries, fuel cells, and emergency generators is required.
h) Eliminating the need for phase angle synchronization of multiple sources and loads.

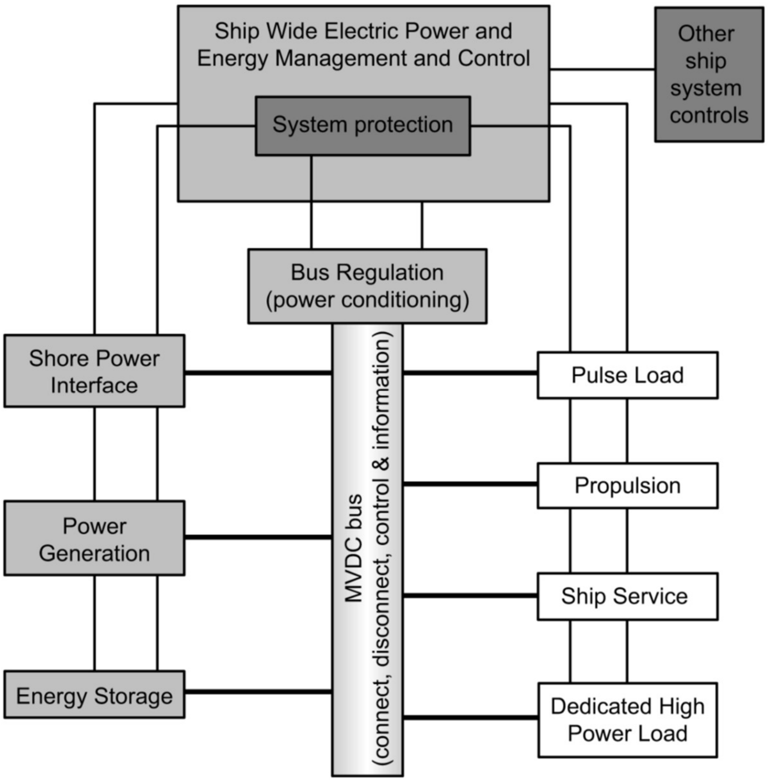


FIGURE 1. FUNCTIONAL MVDC BLOCK DIAGRAM [7].

Some elements in the MVDC notional functional diagram of Fig. 1 are fundamental to characterize the main benefits of a distribution based on DC current. The brief description in the following [7] is mainly oriented in describing the main elements of a shipboard DC distribution.

A. Shore Power Interface is primarily a power source that adapts electric energy from the utility system on shore to MVDC (e.g., interface transformer + rectifier). This may or may not be capable of bidirectional energy flow.
B. Power Generation is primarily a power source that converts prime energy from fuel into MVDC (e.g., gas turbine + generator + rectifier).
C. Energy Storage is a standalone power source (discharging) or is load (charging) whose purpose to provide power to the system when needed but also to draw power from the system to recharge (e.g., battery or a capacitor bank with a bi-directional dc/dc converter).
D. Pulsed Load is a stand-alone load center that primarily draws intermittent pulses of power from the system [e.g., electromagnetic aircraft launch system (EMALS)].
E. Propulsion is a load center that primarily draws power from the system for vessel propulsion (e.g., a motor drive inverter + propulsion motor). It may also generate power during certain maneuvers such as crash back whereas the energy must either be dissapated or converted for use on the ship's distribution bus.

F. Ship Service is a load center that primarily draws power from the system to power ship service within zones [e.g., dc/dc converter for in-zone distribution of low-voltage dc (LVDC), dc/ac inverter for inzone distribution of low-voltage ac (LVAC)]. Note that “ship service” modules may take power from either the MVDC bus or from in-zonal energy storage systems.
G. Dedicated High-Power Load is a stand-alone load center that draws 1 MW or more of power in steady-state operation (e.g., 3 MW radar sensor array). A dedicated high-power load could also be a pulse load.
H. MVDC Bus is a functional block that allows interrupting and isolating sections of the MVDC system (e.g., mechanical disconnect, solid-state dc breaker). In addition, each functional block in the system can connect, disconnect, and isolate itself from the system through its own means (e.g., a “power generation” module should have at least a disconnect switch at its dc output).

To better explain each block into the MVDC concept, additional description are required. Again, from the IEEE Std. 1709 [7], the main blocks of an MVDC power distribution are described as follows:

I. Shore Power Interface: Three-phase ac shore power is made available to the ship MVDC distribution bus by stepping its voltage up or down to the MVDC bus level with a transformer and rectifying the result with an ac/dc converter.
II. Power Generation: In this example, MVDC power is generated onboard the ship through the use of both gas turbine-driven and diesel motor-driven generator sets. In order to meet the total installed power requirement, two large-capacity “main” generator sets (e.g., 36 MW) can be supplemented with two or more small-capacity “auxiliary” generator sets (e.g., 4 MW). For example, high-speed permanent magnet (PM) ac generators can employ simple, low-cost, diode rectifiers to supply dc power to the MVDC distribution bus. If bi-directional (active) rectifiers are employed, adequate protection and control should prevent reverse power flow (from the system into the generator sets) from exceeding the prime mover’s reverse power withstand curve. Unidirectional fuel cell systems, which provide electrical power from fuel, are classified as power generation.
III. Energy Storage: Since the dynamic response time of generator sets to power fluctuations is inadequate to respond to some loads, sudden demands or rejections in dc bus power caused by step-loads changes from pulsed load devices or the loss of a generator set or shore power are met through the use of quick response energy storage devices. Furthermore, energy storage devices may be used to enable a dark ship system restart. All energy storage devices such as capacitor banks or flywheels charge from, and discharge to, the MVDC distribution bus via bi-directional dc/dc converters. Note that only bidirectional fuel cell systems, which also allow the generation of fuel from electricity, may be classified as energy storage devices.
IV. Pulsed Load: The pulse-charging circuits or pulse-forming network required to provide the pulse power required of high energy devices such as EMALS, rail guns, lasers or other directed energy weapons in military ships would draw power from the MVDC distribution bus via dc/dc converters. Note that these circuits may include an energy storage element or even a power generation element such that they could provide power back into the MVDC system, if required.
V. Propulsion: Ship propulsion motors are driven from the dc distribution bus through variable speed drive inverters. These inverters may be bi-directional to allow regenerative power created during

ship crash-back maneuvers to be absorbed by other ship loads on the MVDC distribution bus or dissipated in resistive load banks.

VI. Ship Service: Ship service loads are supplied by the MVDC bus via dc/dc or dc/ac converters. In military vessels, where continuity of power to vital loads is paramount, the concept of zonal regions along the ship served from alternate (e.g., port and starboard) MVDC buses may be employed. Continuity of power within each zonal load center is enhanced by automatically switching input power between port and starboard buses with automatic bus transfer switches. Some ship service loads, such as variable speed drives of large motors and most electronic equipment, may operate directly with dc power delivered from the dc/dc converters. For ac loads, such as smaller pump and fan motors and most "hotel" loads, dc/ac converters change the dc power to low-voltage, single-phase- or three-phase ac power. Bi-directional dc/dc converters may connect the charging/discharging circuits of load center uninterruptable power supply (UPS) systems to the dc distribution bus.

VII. Dedicated High-Power Load: The power supplies of high-power loads such as certain military radar arrays, large thrusters or compressor drives (typically requiring several MW of operating power) are supplied directly from the MVDC distribution bus via dc/dc converters.

VIII. Ship-Wide Power and Energy Management Control: The centralized or distributed shipwide power management control communicates with all power sources and major loads to prioritize and optimize the power flows throughout the ship. This power controller maximizes the continuity-of-service of vital loads during reconfiguration operations.

IX. System Protection: AC power subsystems, such as the ac generators and the shore power interface, can be protected against damage from faults by the traditional use of circuit breakers. In Figure 3, converters connect to the dc distribution bus via dc disconnect switches. System protection is achieved through a combination of converter's control and other dc circuit breaking devices, e.g., solid state dc breakers.

2.3 Onboard advantages by applying the MVDC technology

As a result of a technological evolution started 30 years ago [3], the totality of cruise ships are nowadays endowed with an Integrated Power System (IPS). The latter is conceived to ensure an enhanced system efficiency and a remarkable fuel saving. To this aim, the IPS is designed to supply both propulsion system and hotel loads, allowing redirecting the electric energy where there is power demand. Thanks to the undeniable advantages given by electric propulsion and IPS adoption, the All Electric Ships (AESs) concept has become a recognized standard for modern cruise liners. In last fifteen years, the AES concept gained popularity not only in large cruise ship applications, but also in naval vessels. Indeed, the world's major navies have proposed research projects and innovative designs based on AES architecture. Some relevant examples of these military applications are the UK Type 45, the Italian-French FREMM and the US DDG 1000. These modern vessels are equipped with electric propulsion and Medium Voltage Alternating Current (MVAC) IPS in order to guarantee the same desirable advantages typical of large all-electric cruise liners (among others, considerable dynamics of electric motors, lower vibrations of electric motors, rational way of positioning diesel generators). By considering that in a standard AES most of the loads are conventionally interfaced to the main bus through power converters, a new distribution concept has been conceived to enhance ever more power density and system's efficiency: the Medium Voltage DC (MVDC) distribution. Such a distribution system presents a DC bus (medium voltage: rated voltage higher than 1 kV) and it is based on the widespread use of power electronics equipment, both on generator and load sides. The most important benefits [3] of this new distribution are summarized as follows:

1. eliminating the need for phase angle synchronization;
2. simplifying the generators connection procedure;
3. eliminating large low-frequency transformers;
4. enabling reconfiguration after faults;
5. reducing power system volume/weight by using high speed generators;
6. improving control of power flows, especially in transient and emergency conditions;
7. reducing fuel consumption by allowing variable speed prime mover operation;
8. improving efficiency and power availability with energy storage.

Other outcomes are also expressed in [8]. A short summary is presented in the following:

9. replacing bulky ferromagnetic transformers with compact power electronic converters (like 3.);
10. easier parallel connection or disconnection for dc power sources;
11. elimination of harmonic and imbalance problems;
12. elimination of synchronization problems (like 1.);
13. elimination of reactive power flow.

If the previous benefits are reported on scientific publications, other pros are also highlighted on the IEEE Std. 1709-2010 [7]. What presented in the following can correspond of what already reported or can be a small addition of previous considerations. Expected advantages from onboard MVDC application:

a) Simplifying connection and disconnection of different types and ratings of power generation and electrical energy storage devices;
b) Limiting and managing fault currents and enabling reconfiguration;
c) Eliminating reactive voltage drop;
d) Reducing power system weight by using high speed generators because there is no need for all generators to output a synchronous ac voltage;
e) Enabling higher power ratings for a given cable size due to reduced skin effect losses;
f) Improving control of power flows, especially in transient and emergency conditions;
g) Improving efficiency when energy storage and power conversion from batteries, fuel cells, and emergency generators is required;
h) Eliminating the need for phase angle synchronization of multiple sources and loads.

As a matter of fact, by taking into account all these benefits, the MVDC application appears very interesting for renewing the passenger ships. If the large employment of controlled power converters on one hand enables advanced functionalities as well as the total control on an efficient power system, on the other possible problem are also activated by the controlled converters. On this regard, a specific subsection is proposed in the deliverable following to briefly explain the DC stability issue and how to evaluate it by a multi-model procedure.

2.4 Radial and zonal electrical distribution on MVDC technology

The competition in marine sector imposes changes in the ships power systems. In modern integrated power and energy systems the density of power electronics converters is continuously increasing. As an example, in actual large ships with electrical propulsion and ac distribution up to 85% of power is delivered to users through power electronics converters. This rate increases up to 100% in the case of integrated dc distribution systems [9]. Following this, the MVDC technology can play the role of enabler. Once hypothesized the presence of an MVDC system, the IEEE Std. [7] suggests two distributions as the most convenient. As in [10], the radial distribution is a conventional architecture that is recommended by [7] and has been applied to standard MVDC shipboard power system. The system configuration is depicted in the standard as Fig. 2, as well as in other research work (Fig. 3). Generally, two dc buses (rated values are in Fig. 3) distribute the power to consumers. Power sources, including generators and energy storage systems are distributed symmetrically and feed each dc bus. The port and starboard propellers are powered via two dc buses separately. The Integrated Power System is indeed based on radial distribution, where the two dc buses supply the onboard service loads for higher reliability. The radial scheme has the advantages of being simple and cost-efficient. Furthermore, since equivalent scheme has been used in the traditional mechanically driven ships and traditional MVAC ships, it is easier and more practical to redesign the system from the traditional ones to modern DC ones. The Zonal distribution [9]-[10] is another potential configuration according to IEEE Std. 1709-2010 [7]. This configuration has become the U.S. navy standard, while it is represented in Figs. 4-5. In zonal network, the shipboard loads are divided into *n* zones, each of which is fed by two connections from the buses and managed independently. The zonal distribution is typically arranged in the port-starboard sides along with the ship, and these two buses are connected at the stern-bow. This design enables redundant feedings for loads from two longitudinal dc buses. Each load center has connections with both the port and starboard buses, and when a fault occurs in one side, vital loads within the zones will autonomously shift their power sources to the healthy opposite bus. In naval vessels, specific high power loads like radars are set independently as the only equipment in a specific zone. Currently, few cases are using zonal architecture, while innovative studies are on hand increasing the theoretical knowledge [10]. On the other hand, new analysis have demonstrated how a zonal system can behave with better characteristic of flexibility and resiliency, even when very large load steps are applied [11]. There are many benefits in adopting zonal systems [10]. The survivability can be greatly enhanced for marine loads by feeding power from both port and starboard side dc buses. The vital loads can switch to the alternative one automatically or manually. The longitudinal bus architecture allows isolating faults with the minimum affected areas using coordinated protection systems via a communication network. Further information for designing the zonal distribution system is accessible in IEEE Std. 1826-2012 [12]. A qualitative comparison on radial and zonal distribution architectures and the key performances are shown in Fig. 5. Here, typical bus schemes, reliability, survivability, reconfigurability, and complexity are compared. The radial scheme requires least breaker and its structure is the simplest, while reliability, survivability, and reconfigurability are worst. On the other side, zonal scheme has the best performance in these three performance items, while the price is high system complexity and large numbers of breakers, especially for big ships. From this comparison, the radial scheme can be adopted for small ships with few components (e.g. short-distance ferries, or when the reliability requirement is not very high). For large ships with high requirement on reliability-survivability, zonal scheme may be preferable for better safety. Up to now, the radial scheme is mostly used in practical cases, since current electric ships are refitted from old ships, keeping the radial scheme still popular.

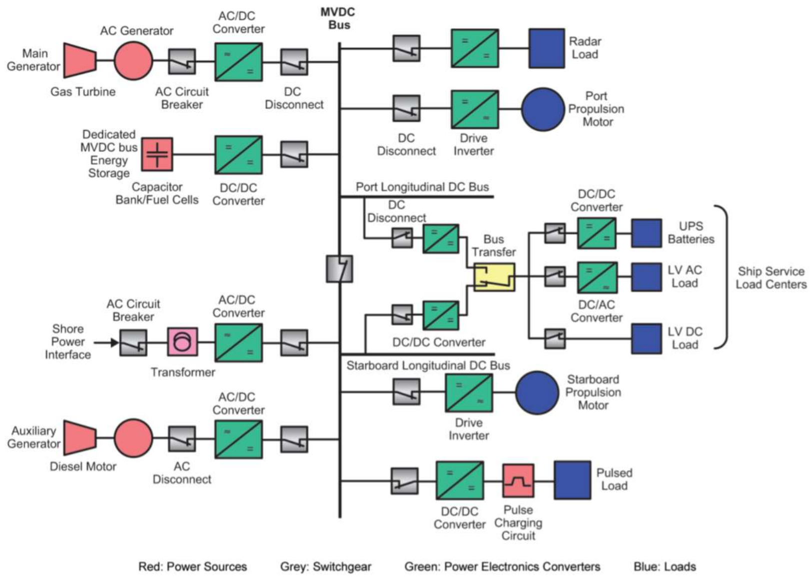
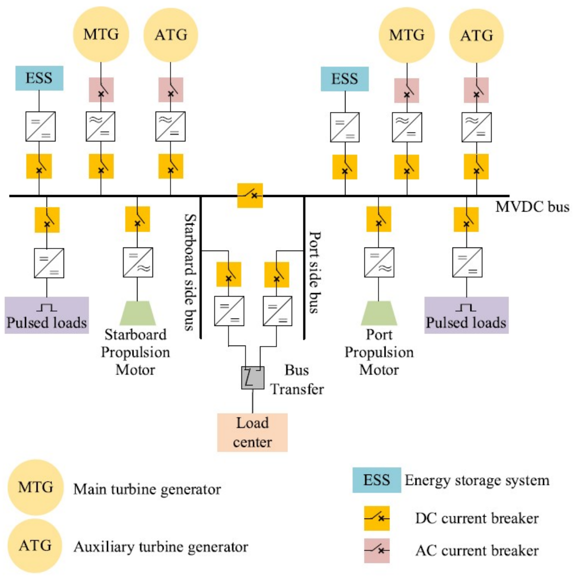


FIGURE 2. MEDIUM VOLTAGE DC POWER SYSTEM WITH STANDARD RADIAL DISTRIBUTION [7].



	MVDC Class	Nominal MVDC Class Rated Voltage	Maximum MVDC Class Rated Voltage
Already Established	1.5	1.5 or ±0.75	2 or ±1
	3	3 or ±1.5	5 or ±2.5
Future Design	6	6 or ±3	10 or ±5
	12	12 or ±6	16 or ±8
	18	18 or ±9	22 or ±11
	24	24 or ±12	28 or ±14
	30	30 or ±15	34 or ±17

FIGURE 3. MEDIUM VOLTAGE DC POWER SYSTEM WITH STANDARD RADIAL DISTRIBUTION [10].

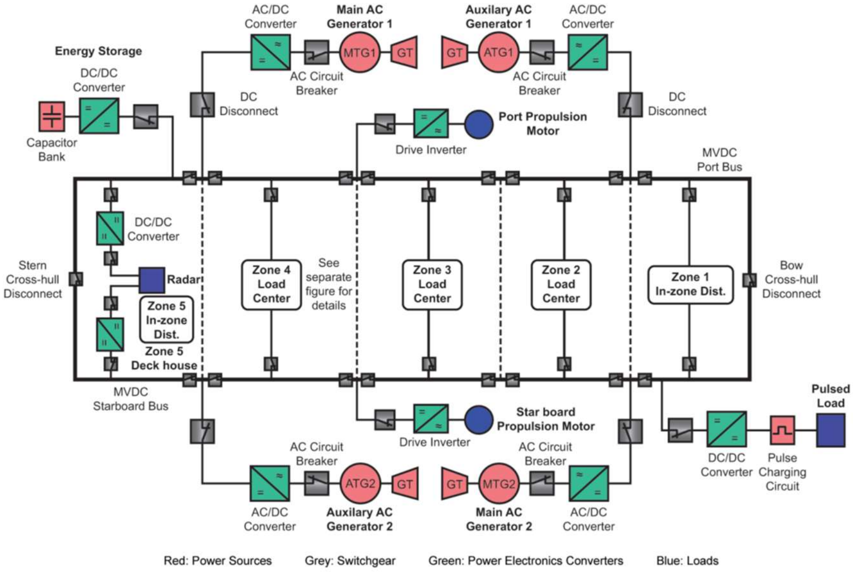
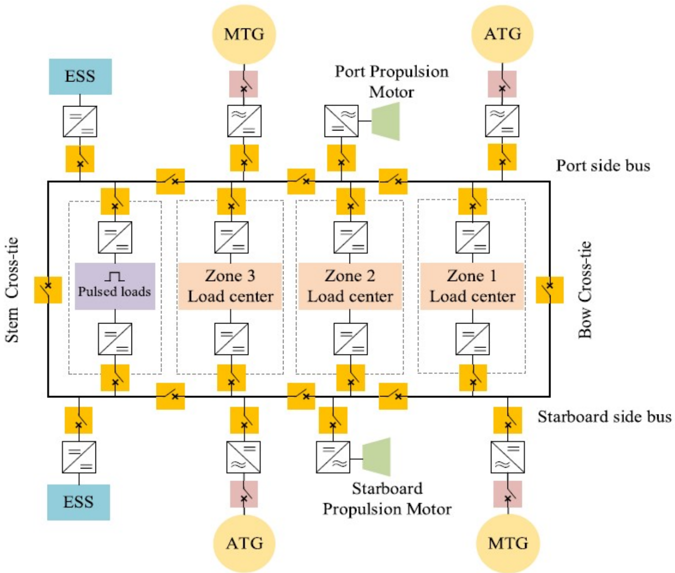


FIGURE 4. MEDIUM VOLTAGE DC POWER SYSTEM WITH HIGH-PERFORMANCE ZONAL DISTRIBUTION [7].



	Radial	Zonal
Bus scheme	Two buses connected by one breaker.	One ring bus with $2n$+2 breakers.
Reliability	Low	High
Survivability	Low	High
Reconfigurability	Low	High
Complexity	Low	High
Number of applied cases	Most	Medium

FIGURE 5. MEDIUM VOLTAGE DC POWER SYSTEM WITH HIGH-PERFORMANCE ZONAL DISTRIBUTION [10].

3 Shipboard applications

3.1 Load powers to be supplied

It is quite well recognized that the use of alternative EES (Energy Storage System) like ion-lithium battery technology has progressed significantly during the last years in domestic shipping such as national voyages (below 20 nautical miles from shoreline) and short international sea voyages (within 20 and 100 nautical miles from shoreline). Furthermore EESs oft are installed on deep sea vessels (oceanic voyages) to avoid blackout allowing optimized operation of the auxiliary generators dedicated to supply power for the hotel and cargo loads. As already well described in the SEABAT project (D2.1) nowadays the EESs are applied on board of ships for the following functions:

- load levelling for keeping the diesel engines of power generators running at their optimum conditions in order to increase the thermal efficiency
- power boosting to cope performance peaks
- spinning reserve to grant redundancy in the power supply
- peak shaving to cope with load fluctuations in power demand
- load smoothing similar to load levelling for frequency above 1 Hz
- ramp support for delivering instantaneous power for the required load step

The shipboard power to be available may vary a lot depending on the ship type and navigation service with required power from below 1 MW up to 12 MW as shown in the Fig. 6.

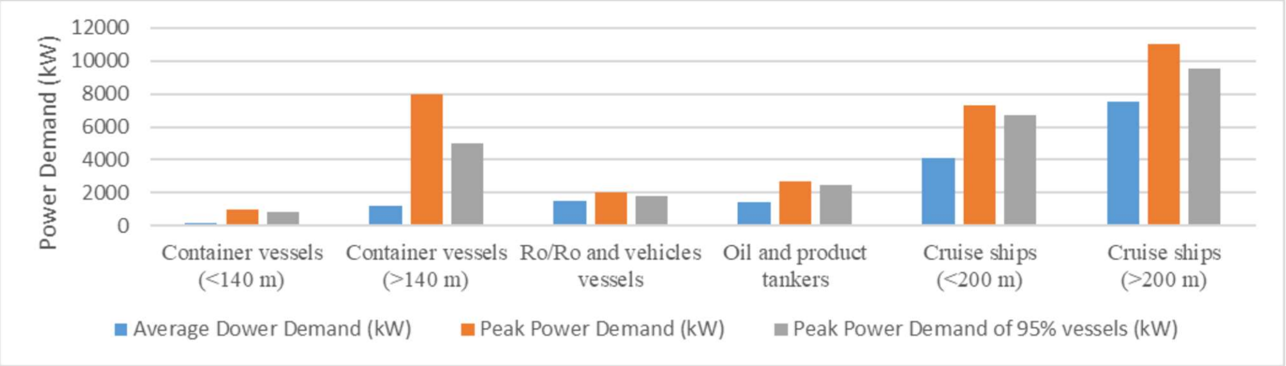


FIGURE 6. POWER DEMAND FOR DIFFERENT TYPES OF SHIPS.

The SEABAT project referenced by the T1.2 V-Access - "Ship types to identify Possible Application Cases" as well the Clarkson research (https://www.clarksons.com/research/shipping-trade/) confirms the trend that ferries (RO-Pax), offshore/platform support vessels (OSV / PSV), fishing vessels (Trawler) and Cruise ships are leading the demand of EESs in order to cut the GHG emissions to zero during port stay as part of the relevant shipping company´s sustainability strategy. For this reason it is important to focus the attention on such types of ship where the average load power levels may be resumed according to the Table 1 where the targeted ships have the following characteristics:

Ship 1: Cruise vessel with overall length of 240 m, breadth 32 m where fuel cell systems are installed and designed for compliance with SOLAS passenger ship requirements. This vessel is usually with diesel electric hybrid propulsion with low C-rate and very high energy.

Ship 2: Ferry vessel with overall length of 74 m, breadth 14 m, roll-on and roll-off type, double ended, fully electric propulsion with very high C-rate and nominal energy designed for compliance with European Directive 2009/45/EC as amended by as amended by 2016/844/EU.

Ship 3: Platform Support Vessel with overall length of 94 m, breadth 21 m, fitted with ESS used only for Dynamic Positioning (DP) operations with high C-rate and nominal energy.

Ship 4: Trawler Fishing Vessel with overall length of 80 m, breadth 17 m, fitted with hybrid propulsion and shaft generator (SG) and the ESS is used during trawling, transit and unloading in port.

	Ship 1: Cruise	Ship 2: Ferry	Ship 3: PSV	Ship 4: Trawler
Propulsion Power	10 MW	2 MW	3 MW (DP)	4 MW (Fishing)
Hotel Power	3,5 MW	500 kW	100 kW	100 kW
Cargo Power	-	-	-	600 kW

TABLE 1. AVERAGE POWER LEVELS WITH REFERENCE TO SHIP TYPE.

3.2 Operational profiles and operative modes

For the next generation of ships operating with alternative fuels and which may be fitted with fuel cell power system (FCPS) in addition to the traditional diesel generators (DG) the following ESS functions may be identified:

- **Support of Fuel Cell Power System** – where the ESS is requested to cope the hotel load variations and load demands and to store (e.g. charging mode) possible excess of energy generated by the fuel cell power system.
- **Peak Shaving in Sea Mode** – where during navigation on the sea (transit) the ESS can be used to avoid power generators or main engines running at not optimized loads delivering or storing energy in case of load variations. Furthermore the ESS supports the FCPSs which may a have very long response time if they are fitted with a reforming unit using LNG or Methanol or Ammonia as hydrogen carrier.
- **Peak Shaving in Manoeuvring Mode** – where the ESS supplies energy for load peaks and store energy during load drops supporting the diesel generators and additionally the fuel cell power system in manoeuvring mode.
- **Dynamic Performance** – where there is an high power request from network during loading/unloading or fishing operation, the ESS can be discharged with high power for a short time.
- **Blackout Prevention -** the ESS supplies power for a defined time for the whole ship, the ESS must always reserve the necessary capacity in terms of minimum State of Charge (SoC). The ESS will prevent the blackout condition by suppling the max. possible power to the network until the next engine is available. This power capacity cannot be used for other applications and the ESS has to take over the load with preferential tripping support in the main switchboard (MSB), until the generators are connected.
- **Forced Charging or Discharging –** where the ESS operation mode is imposed by operator due to other reasons not included in the previous modes.

The ESS SoC setpoint and the minimum setpoint for standby start of generators are adjustable from the Power Management System (PMS) which will have different SoC setpoints for the ESS, according to the power plant operation modes (e.g. Harbor, Navigation at Sea, Manoeuvring, Zero-Emissions Mode etc…). When the PMS is settled to a new mode, the SOC setpoint of the ESS for that mode will be communicated to the Energy Management System (EMS) of the ship. Additionally the EMS should receive information about the selected mode if the operator makes a change within a mode. Finally the PMS will receive the set SoC value from ESS as confirmation for the setpoint which is in use. The SoC value for standby start of diesel generators is common for all power plant modes.
The operating conditions and the functions for the PMS selectable modes may be described as follows:

Shore Power

For vessel fitted with Onshore Power Supply (OPS) according to IMO MEPC.1/Circ.794, in Shore Power mode the switchboard is supplied from shore power source via shore connection breaker. The ESS is available (by operator selection), operation in peak shaving mode and blackout protection. EMS/ESS is measuring the network load and is controlling the battery voltage via the frequency converter within the parameter limits. Operator may manually select "Forced Charging".

Harbor with Diesel Generators

Main switchboard is supplied by the diesel generators only and the ESS is available, operating in peak shaving mode, blackout protection and charging. In this case at least one diesel generator in online and connected.

Harbor with Diesel Generators, Fuel Cell Power System and ESS

Main switchboard is supplied by the DGs, with FCPS running stable on established load setpoint (operator adjustable). ESS is operating in peak shaving mode and a SoC setpoint is defined. The DG is running on a load setpoint that mainly covers the power difference between the service load and the FCPS power +/- ESS load/power. The Energy Management System (EMS) of the ESS is metering the service load and it is controlling the battery voltage via the frequency converter within the parameter limits taking into account that at least one DG is connected.

Harbor Zero Emissions

None of the DGs is connected to mains switchboard and the FCPSs are taking care of the ship service load. Here the ESS is active, supplying or receiving energy according to the difference between the power network requirement and the FCPS. The EMS of the ESS is metering the network load and it is controlling the battery voltage via the frequency converter within the parameter limits.

Manoeuvering with DGs

Two or more DGs are connected to the main switchboard and the ESS is available operating in peak shaving mode and supplying or receiving energy according to the difference between the power network requirement and the FCPS. The EMS of the ESS is metering the network load and it is controlling the battery voltage via the frequency converter within the parameter limits.

Navigation on the Sea

Two or more DGs are connected to the main switchboard and the ESS is available operating in peak shaving mode. The EMS of the ESS is comparing the network required load and the actual operation points of the DGs, supplying power to load peaks and storing energy in case of service load drops.

Navigation on the Sea with FCPS and ESS

One or more DGs are connected to the main switchboard with FCPS running stable on established load setpoint (operator adjustable) and the ESS is available operating in peak shaving mode. The EMS of the ESS is comparing the network required load and the actual operation points of the DGs, supplying power to load peaks and storing energy in case of service load drops within the applicable limits.

Navigation in DP

The operating conditions are similar to Navigation on the Sea where additionally the ESS may be used as redundant power source in order to grant enough energy in case of loss of one DG.

The duration of each operative mode is depending on the type of service and navigation as well specific request from shipowners however the Table 2 gives an approximate average of the time spent on each mode.

	Ship 1: Cruise	Ship 2: Ferry	Ship 3: PSV	Ship 4: Trawler
Shore Power	10%	10%	5%	5%
Harbor	45%	25%	20%	20%
Navigation on the Sea	40%	60%	40%	70%
Navigation in DP	-	-	30%	-
Manoeuvring	5%	5%	5%	5%

TABLE 2. TIME PERCENTAGE FOR EACH OPERATIVE MODE AND SHIP TYPE.

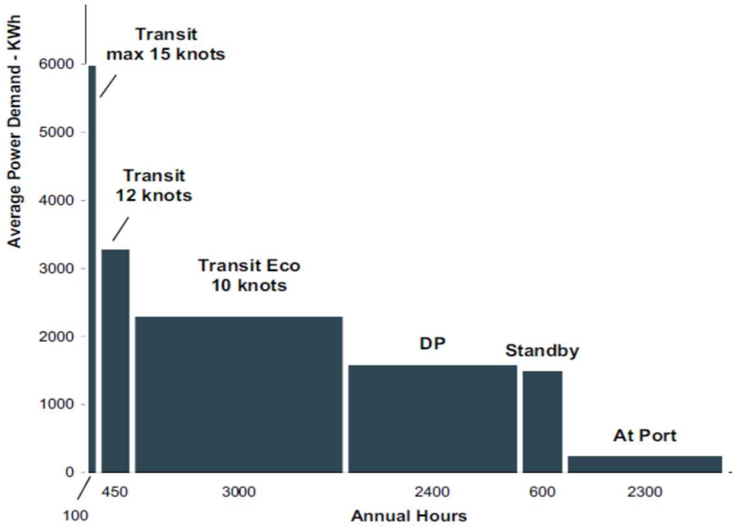


FIGURE 7. EXAMPLE OF THE ANNUAL OPERATIONAL PROFILE FOR A PSV.

As an example, the graph in the Figure 7 (Troms Offshore, 2015; in house data; Fagerholt and Lindstad, 2000) identifies the annual operational profile with the associated power demands for a PSV operating in the North Sea.

3.3 Generating subsystems and cold ironing interface

The power generation and distribution system may vary a lot from ship to ship depending on its service and navigation area however the one of a cruise ship may be considered as the most complex considering that several different machineries should be powered with the same network. Usually the next generation of cruise ships are fitted with four main diesel generators, an ESS and a fuel cell system supplying two medium voltage main switchboards which are normally located in separated compartments A60 fire insulated due to SOLAS Safe Return to Port requirements. As an example for the Ship 1 in subject the following electrical features can be identified:

Main Switchboard no 1 (11 kV/60Hz):

- ME1 Power 8.300 kWe, (ca 9.750 kVA)
- ME2 Power 4.100 kWe, (ca 4.850 kVA)
- Fuel Cells 4.000 kW, with two Frequency converters connected to one transformer

Main Switchboard no. 2 (11 kV/60Hz):

- ME3 Power 8.300 kWe, (ca 9.750 kVA)
- ME4 Power 4.100 kWe, (ca 4.850 kVA)
- Energy Storage System, 800kWh (max. power limit +/-2000kW) with one Frequency Converter connected to one transformer

Emergency switchboard ESB (690V/60Hz):

- EDG1 Power 1.500 kWe
- EDG2 Power 1.500 kWe

3.4 Reasons for embarking advanced storage technologies

ESS based on Li-ion battery cell chemistry is the present technology for full electric and hybrid electric vessels. The battery ESS (BESS) needs to be designed to meet the critical requirements of both high-energy missions (e.g., for maintaining cruising speed or spinning reserve function) and high-power peaks (e.g., fast charging and manoeuvring), which can vary significantly depending on the types of vessels and the intended functionalities of the BESS. For some marine applications, the power-energy requirements can overpass the battery technology limits if the BESS is designed for energy requirements only, leading to oversizing the BESS solution and consequent higher capital costs. Alternatively, a high-power ESS technology (like Supercapacitors or SMES) can be considered instead of batteries because they could offer better ratio between power and energy. However, the conditions can reverse, and the ESS may require to be designed to fit the required energy capacity despite the lower energy density compared to a BESS. This also implies higher capital costs.

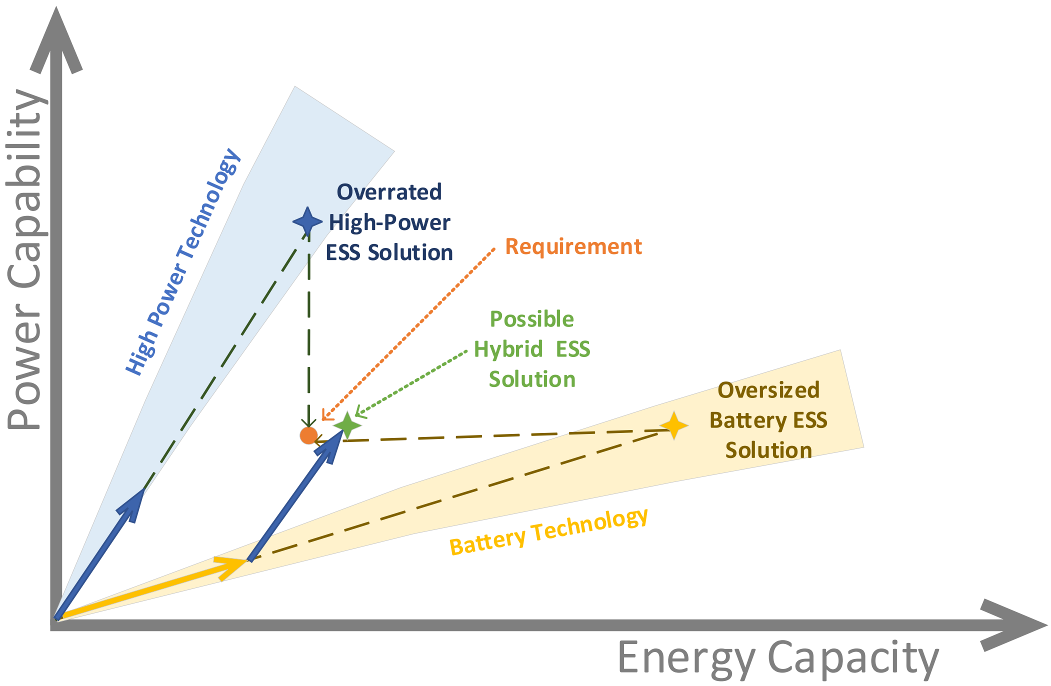


FIGURE 8 OVERSIZING AND/OR OVERRATING OF ESS TECHNOLOGIES TO MEET POWER AND ENERGY REQUIREMENTS.

Figure 8 illustrates the oversizing and/or overrating of ESS technologies to meet power and energy requirements. On top of that, cycling requirements are another factor to consider. Due to the exploitation of batteries to meet these requirements, the battery capacity can decrease greatly over time, so oversizing the BESS can also be necessary to compensate for battery pack degradation in some applications. It should be noticed in this sense that these high-power ESS technologies can withstand a much higher number of charge discharge cycles.

One promising solution is to adopt a hybrid topology, combing batteries with a high-power ESS technology in a hybrid ESS (HESS), so the total ESS can be downsized compared with a BESS by providing sufficient energy and power to the ship to meet the demands by the combination of two ESS technologies. Moreover, a hybrid topology can remove the high-current stress factor from the battery, resulting in a longer lifetime, smaller temperature peaks in the battery cells, and reducing the effect of a high depth of discharge. Especially the reduction in the power requirements may also lead to the selection of less performant battery configurations with lower associated costs. Figure 8 also illustrates how a possible HESS solution can meet power and energy requirements avoiding/reducing the oversizing of batteries and/or overrating of high-power ESS technologies by adjusting the proportion of different types of ESS technologies in the HESS. The efficiency, reliability, and flexibility of the marine power system could be possibly increased if an intelligent energy management system is implemented that optimize the use of the two storage technologies leveraging on their complementary performance characteristics. These factors could also result in a lower cost of the energy storage system over the life of the vessel.

4 DC power distribution for marine applications: design procedure

The present Section wants to design the MVDC shipboard power system where install and test two storage systems of interest (i.e. SMES and Supercapacitors). The ship under consideration is a passenger ship, where the All-electric concept is the right one to be installed. Indeed, in the hypothesized ship the hotel load can be important (some MW), therefore an alternative hybrid-parallel configuration is not convenient. The considered MVDC power system conversely will be based on the hybrid-series configuration, thus a structure that is quite correspondent to the classical configuration of cruise liners.

4.1 Selection of power distribution and bus voltage value

When designing a shipboard power system, the first stage regards the distribution choice. By considering the presence of advanced storage systems based on DC current, evidently the onboard power system will adopt the DC distribution. As demonstrated in previous sections, the DC concept has several important benefits that can increase the payload, therefore the ship value. By taking into account the vessel goal (i.e. passenger ship), the distribution type is consequent. A quite simple DC radial distribution like the one in Figs. 2-3 is proper for the considered application. By taking into account the classical loads of a passenger ship, a possible DC power system distribution is shown in Fig. 9. Second important evaluation the one about the bus voltage value. In such a case, it is important to take into account the installed power in order to understand if the total DC current is in accordance with the classical design criteria on power systems. By neglecting the presence of storage at this initial stage, the primary attention is put on potential loads. In the conceived ship, the main loads can be summarized as two electric drives (2 MW each), 2 controlled thrusters (0.25 MW each) and a hotel load of 1.5 MW. By hypothesizing an operational profile (i.e. the loads are not contemporaneously supplied, there is a contemporaneity factor), the supposed electric loads can be fed by only three DG Diesel Generators (each power is 1.6 MW), albeit four DGs are present at the same time. Conventionally, one DG is out for safety, resiliency and to assure the requested performance in event of bad sea state. From this consideration, it is consequent that a realistic maximum power through the main DC bus is near 4.5 MW. By taking into account previous experiences [11], a DC bus voltage of 1 kV is then imposed being the total current (4.5 kA) under the standard management of MVDC grids.

4.2 Interface power converters

Several power converters are installed in the MVDC distribution to supply the loads from onboard systems and to interface the storage. The ship design is related to a PSV in DP mode. In Fig. 9, the system architecture is depicted, where 14 power converters are hypothesized. For each interface, the rated power is in Table 3. Both C1 and C7 are the bidirectional DC-DC converters to interface the battery storage systems. The rated power (2.2 MW each) is chosen to ensure a green no-emission navigation (i.e. 1.1 MW in propulsion and 1.1 MW as hotel load) for 2 hours. The storage system (i.e. MWh data) is sized consequently. Four AC-DC converters (i.e. C2, C3, C5 and C6) interface the synchronous machines to the DC bus. Their rated power is 1.5 MW. Instead, C4 is the converter to the external supply from Cold Ironing (CI) during the stops in ports. The rated power is enough to feed the hotel loads. C8-C14 are the unidirectional DC-AC converters (2.35 MW each) of propulsion drives. Similar the work of C9-C13 (0.20 MW each), in charge of interfacing the AC thrusters. An equivalent hotel load (HL) is powered from the bus by the unidirectional converter C11 (i.e. 1.1 MW). Finally, C10 and C12 are the DC-DC bidirectional converters to interface the storage systems. The first is interfaced to the SMES (SM), while the second is the input/output stage of Supercapacitors (SC). The rated power of C10-C12 converters will be a project’s output, so it results Under Definition (thus “UD”) in Table 3.

TABLE 3. RATED POWER ON INTERFACE CONVERTERS.

Interface name	Input Output	Function	Power flux	Rated Power [MW]
C1	Battery storage	DC-DC	Bidirectional	2.20
C2	AC generator	AC-DC	Unidirectional	1.50
C3	AC generator	AC-DC	Unidirectional	1.50
C4	Cold ironing	AC-DC	Unidirectional	1.50
C5	AC generator	AC-DC	Unidirectional	1.50
C6	AC generator	AC-DC	Unidirectional	1.50
C7	Battery storage	DC-DC	Bidirectional	2.20
C8	AC motor (propulsion)	DC-AC	Unidirectional	2.35
C9	AC motor (thruster)	DC-AC	Unidirectional	0.20
C10	SMES	DC-DC	Bidirectional	→UD
C11	Hotel load	DC-AC	Unidirectional	1.10
C12	Super Capacitor	DC-DC	Bidirectional	→UD
C13	AC motor (thruster)	DC-AC	Unidirectional	0.20
C14	AC motor (propulsion)	DC-AC	Unidirectional	2.35

4.3 DC Power system architecture

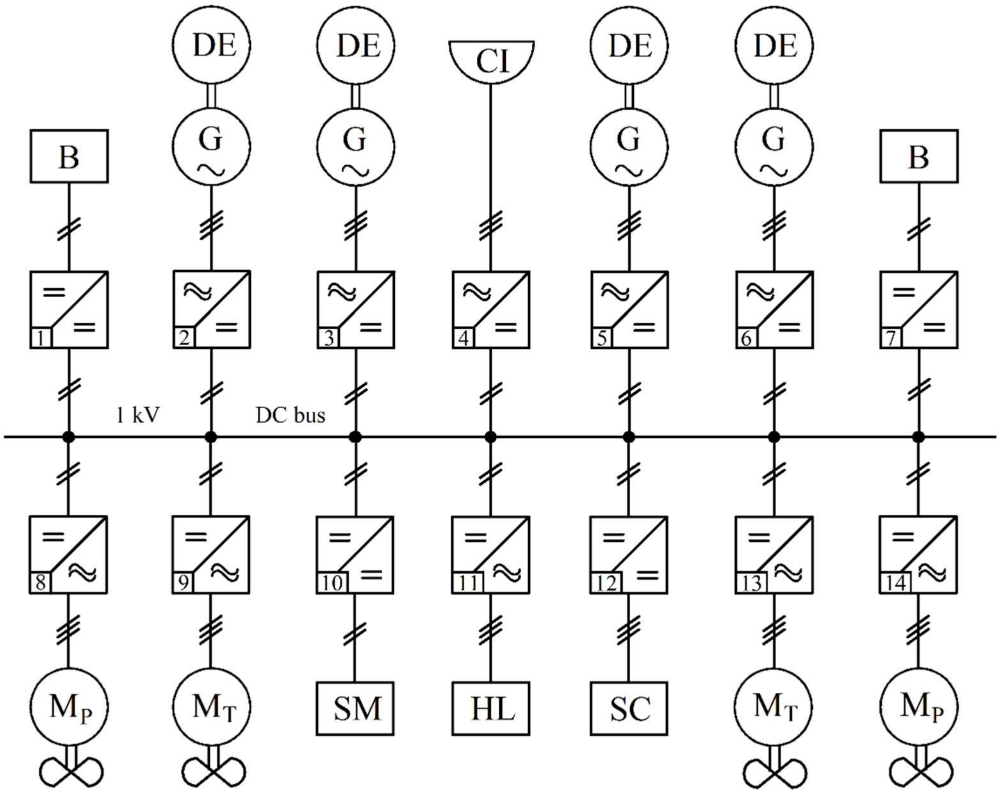


FIGURE 9. DC MICROGRID IN HYBRID-SERIES SOLUTION TO POWER A PASSENGER SHIP.

4.4 Power converters integration in the shipboard power grid

These devices must satisfy requirements about power density, which is an important factor in SPS design, and must have an high efficiency and reliability of operation. Moreover, the fault response of the converters have to be taken into account, due to the challenges in dc microgrid protection. Considering the input-output nature, the power converters can be categorized in ac-dc converters, dc-ac converters and dc-dc converters. Popular topologies of ac-dc converters are realized with diode, thyristor, or IGBT with freewheeling diode. In the former two cases, the power flow is unidirectional, while the IGBT-based converter allows bidirectional power flow. By adopting thyristors, bidirectional power flow is also possible, but inverting the voltage and not the current. Since in this power grid the voltage cannot be inverted, the power flow is thus unidirectional. In order to achieve higher voltage rating, modular topologies can also be employed.

DC-AC converters are used to feed the power to ac loads, such as the electric propulsion system. Popular dc-ac interfaces are represented by the VSI which can be realized with two-level or multilevel IGBT architectures [10]. DC-DC converters are key components for the integration of innovative energy storage system. These devices allow to adapt the input dc voltage to a different output voltage value. DC-DC converters can be categorized depending on the presence of galvanic insulation between input and output. Thus, non-insulated converters comprehend popular architecture such as buck, boost, bidirectional buck-boost and their corresponding modular versions [13]. Instead, insulated dc-dc converters comprehend a medium-high frequency transformer, which ensure galvanic insulation between input and output. The most popular insulated converter topology is the dual active bridge (DAB) converter, which is composed by two IGBT-based H-bridges, interconnected with a medium-high frequency transformer. Protection of dc microgrid represent a challenging task for ensure the reliability needed for the ship operations. Thus, it is important to understand the behavior of the power converters used under fault conditions.

5 Controlled DC system

In the following, important considerations are provided to understand the most important power electronics solutions in the design of a controlled DC system.

5.1 Introduction on DC power converters control

There are many types of DC-DC converters. In applications used by Vard the DC-DC converter is a 3 phase converter where the AC side is connected to the battery with a inductance or LCL filter between the battery and the converter. The dc side of the converter is connected directly to the dc link [14].

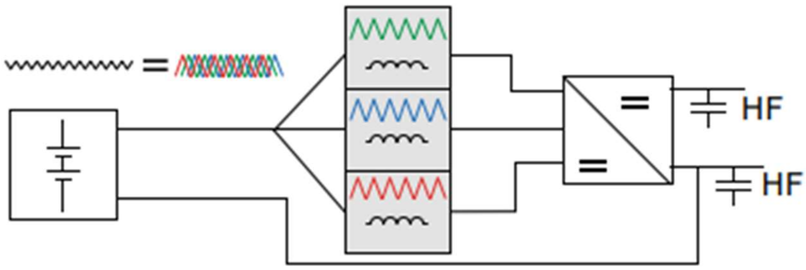


FIGURE 10. INTERLEAVED BRIDGE [14].

Each bridge leg is connected as a step down converter to keep a stable DC voltage as the voltage on the battery changes depending on the state of charge of the battery.

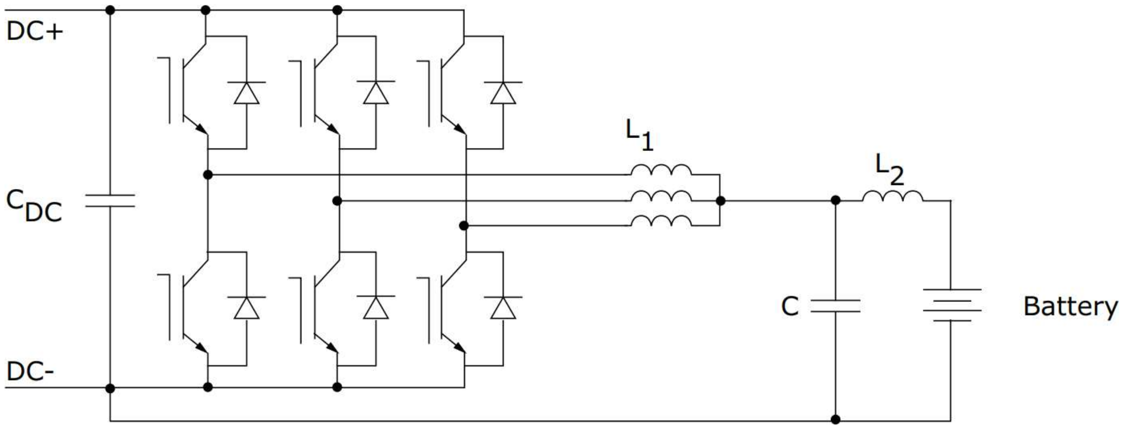


FIGURE 11. INTERLEAVED BRIDGE [14].

The 3 bridge legs are interleaved to reduce the ripple current in the battery.

5.2 Guidelines on the control of DC-DC power converters

The DC/DC converters have two different control modes, Current Control and Voltage control. In Current Control mode, there is the additional Under Voltage and Over Voltage controller which purpose is to maintain a functional DC voltage. The current control can only work within these limits [14].

CURRENT CONTROL MODE

This mode is used during normal operation of the ESS (Peek Shaving and Charge/Discharge mode). Load flow is regulated by imposing a current reference on the DC/DC converter's control, with limitation on maximum charge/discharge current and battery SOC.

The Over / Under voltage control will control the DC voltage to keep the voltage within the limits; this gives restrictions to the current control.

VOLTAGE CONTROL MODE

In this mode the DC/DC converters discharge or charge to keep the battery voltage at a fixed level [14].

5.3 Guidelines on the control of DC-AC power converters

The inverter processes represent the final stage in terms of converting the output voltage and frequency for AC voltage sections in the ship. It is essential for the equipment connected at the consumer end of the inverter that the distributed voltage and frequency is stable and within the accepted values, in order for the equipment to function properly and have an expected lifetime according to manufacturer estimates [15].

Inverters used by Vard are mostly constructed using transistors, making the inverters fully controllable switching units. The semiconductors in the inverter either conduct or block according to the signals generated by the control circuit. The variable voltages and frequencies are generated using two basic principles (types of modulation): Pulse Amplitude Modulation (PAM) and Pulse Width Modulation (PWM).

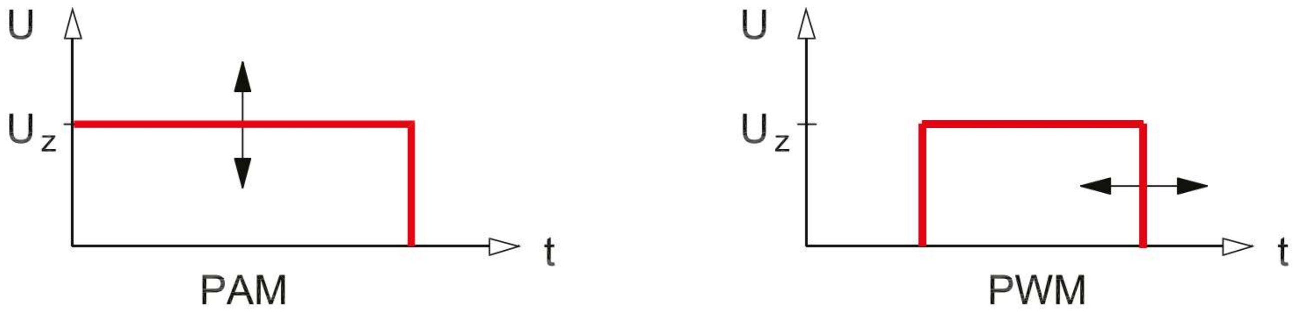


FIGURE 12. MODULATION METHODS [15].

Pulse Amplitude Modulation is commonly used in AC drives with variable intermediate circuit voltage or current. The intervals during which the individual semiconductors should be on or off are stored in a pattern, and this pattern is read out at a rate dependent on the desired output frequency. The semiconductor switching pattern is controlled by the magnitude of the DC-link variable voltage or current. If a voltage-controlled oscillator is used, the frequency always follows the amplitude of the voltage.

Using PAM can result in lower motor noise and very minor efficiency advantages in special applications like high-speed motors (10.000 – 100.000 RPM). However, this often does not overrule the drawbacks such as higher costs for the more sophisticated hardware and control issues like higher torque ripples at low speed.

As a result of the higher costs of PAM, Pulse Width Modulation has become the most widely established and best developed method for controlling AFEs. Compared with PAM, the hardware requirements for this modulation method are lower, control performance at low speed is better and brake resistor operation is always possible [15].

The motor voltage can be varied by applying the DC-link voltage to the motor windings for a certain length of time. The frequency can be varied by adjusting the positive and negative voltage pulses for the two half periods along the time axis.

Utilizing conventional PWM techniques, the control circuit can determine the on and off times of the semiconductors in order to make the motor voltage waveforms as sinusoidal as possible. Thus, the losses in the motor winding can be reduced and a smooth motor operation, even at low speed is achieved.

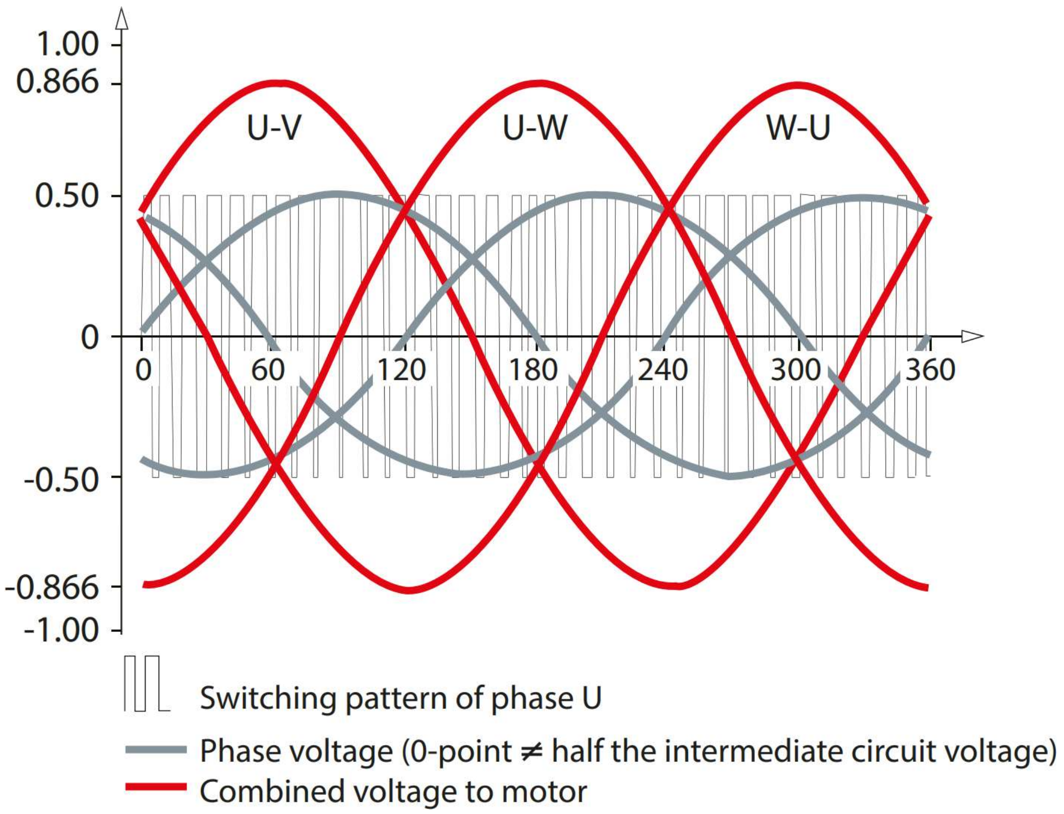


FIGURE 13. OUTPUT VOLTAGE PWM [15].

The output frequency is varied by connecting the motor to half the intermediate circuit voltage for a specific period of time. The output voltage is varied by dividing the voltage pulses of the AC drive output terminals into a series of narrower individual pulses with pauses in between. The pulse-to-pause ratio can be modified depending on the required voltage level [15].

A low switching frequency leads to an increase in acoustic motor noise. To limit the amount of noise produced, the switching frequency can be increased. The increase in switching frequency does however increase the losses in the drive. Therefore, there is always an evaluation to be done regarding losses in the drive due to high switching frequency and losses in the motor as a result of being fed a poorer sinusoidal voltage curve due to lower switching frequency. A PWM AC drive that relies exclusively on sinusoidal reference modulation can provide up to 86.6% of the rated voltage [15].

5.4 Guidelines on protections on DC grid design

The protection of dc microgrids is challenging for several reasons. Unlike ac systems, interruption of fault currents cannot exploit zero crossing, due to their dc nature. Capacitive filters and storage systems with high fault current rise time make the performances of conventional breakers not sufficient for these applications.

Other issues are represented by the multi-directional power flow, which imposes to identify flexible protection schemes that can manage faults currents with different directions.

The type of distribution is an important factor to take into account. The IEC 60092 - 201 [16] specifies the possible solutions, which are:

- Unipolar configuration - with one pole earthed but without structure or hull return system (TN-S);
- Bipolar configuration - with middle wire earthed but without structure or hull return (TN-S);
- Unipolar configuration - insulated (IT)
- Bipolar configuration - insulated (IT)

In the case of TN-S grounding configurations, [17] suggests to use an insulation transformer in the AC side of AC-DC converters, to ensure galvanic isolation, and to avoid possible current path between ground and neutral. For dc loads and sources, galvanic insulation can be guaranteed by using isolated power converters. Moreover, in TN-S systems, the corrosion of the hull structure must be considered, and countermeasures to reduce its effect have to be considered. In TN-S systems, the fault current can be high due to the low impedance fault path, which makes the detection easier. However, this grounding configuration cannot guarantee high fault tolerances, since after a fault the portion of grid under fault will be disconnected [18].

Considering IT grounding configurations, the fault currents find a high impedance path, thus its value is low, compared to the TN-S configuration. This means that after one fault the system is still able to operate, making the system more reliable. Then, if a second fault occurs, a large fault current will be fed to the fault. As a drawback, fault detection can be difficult much harder, and large transient overvoltages can occur [17]. For this reason, IT systems onboard ships are usually equipped with a high grounding resistor, whose value is selected to limit the fault current, while reducing the overvoltage and enhancing the fault current detection capability.

Considering the ac-dc and dc-ac converters, the fault response can be subdivided into three different stages [19]. The first stage is the filter capacitor discharge due to voltage drop in the dc-bus after the fault. The fault current rapidly increases and can reach values higher than 10 times the nominal current of the source, depending on the energy stored in the capacitor. After the dc-bus voltage has dropped below the voltage produced by the converter stage, the freewheeling diodes become forward biased and start to conduct the fault current, and the diode freewheeling stage begins. Normally, IGBTs have blocking mechanism for self-protection [20], but the diode cannot be protected, thus it is desirable to block the fault current before the diode freewheeling stage. If no intervention happens, the source starts to feed current to the fault, entering the grid-side current feeding stage.

In dc-dc converter the fault response depends on the topology. For the boost converter or the bidirectional buck-boost converter the fault response is again subdivided into the capacitor discharge state, the freewheeling diode conduction stage, and the grid-side current feeding stage. For a buck converter, the fault response is different, because there is an inductor in the grid side of the converter, which limits the value of the fault current.

The implementation of embedded protection functionalities, Fault Current Limiters (FCL), and Solid-State Circuit Breakers (SSCB) are today recognized among the most promising solutions to effectively realize dc microgrid protections [21]-[24].

5.5 Guidelines to model the controlled marine DC grid

Prior the installation of controlled MVDC microgrids for shipboard applications, a series of simulations and/or HIL emulations are to be developed to validate the system design. By considering the large presence of controlled converters and LC filtering stages (i.e. power quality's assurance), this initial evaluation is particularly necessary to conclude about the DC system stability. As well-known from the IEEE Std. 1709-2010 [7], the islanded DC systems with a large employment of controlled power converters can experience the so-called Constant Power Load destabilizing effect, that finally determine the ship blackout [25]-[27]. Therefore, it is important to model the controlled marine DC grid to successively provide the simulation tools. The later are usually adopted to establish about the system stability, both in steady-state condition and during the transients between different operating points. A convenient procedure is presented in this section to precisely model controlled DC systems and then establish the stability performance.

In the Std. 1709 [7], several studies are prescribed to model controlled DC grids and then perform the stability assessment, by taking into account both evaluations on Average Value Models (AVM) and on Switching Models (SWG). A procedure previously discussed in [28] is here proposed to study the stability of multi-converter MVDC shipboard power systems. As shown in Fig. 9, the microgrid under analysis presents four generating sources (AC diesel-generators), two Battery Energy Storage Systems (BESSs), two advanced storage systems (i.e. SMES and Supercapacitors), one hotel load and four drives for propulsion and thrusters. Each element is interfaced to a common DC bus via power electronics converters. This simple MVDC radial grid is selected as an illustrative shipboard distribution network. As this example serves only to validate the proposed stability assessment methodology, the multi-model approach can be applied also to more complex grids. A load increase in one of the load converters can behave as a perturbation to investigate the consequent effect on stability. Different control bandwidths can be selected to understand which combination can produce an unstable system response. Thanks to the proposed methodology, the arise of the unstable behavior can be predicted analytically. This aspect has an important value in the validation of the microgrid design. The proposed methodology consists in the implementation of three different models of the MVDC system. The first one is a circuital (SWG) model realized in PSCAD. It is the starting point of the analysis, but it serves also for the results verification. The other two are both AVM models implemented in Simulink: a nonlinear model (nAVM) and a linearized one (lAVM). By studying the lAVM, the linearized state-space matrix of the system can be obtained. The evaluation of the matrix's eigenvalues is the convenient tool used to assess the shipboard power system stability. The results of the Eigenvalues Based Method study can be then verified through numerical simulations in PSCAD environment. Dynamic comparisons between SWG and AVM transient responses can highlight the robustness of the proposed multi-model methodology.

A flowchart summarizing a convenient step-by-step procedure is represented in Fig. 14. This scheme can help in the comprehension of the steps to be performed when the DC system stability is under investigation. The proposed method consists of a series of subsequent comparisons. Particularly, each step can be executed only if the previous one is done correctly. In the flowchart of Fig. 14, different colors are used to separate and to identify the four different aspects of the multi-model methodology. Black squares are adopted for representing the modeling steps (e.g. switching model, linearized model). The green color is used for the system's settings (e.g. topology, inductances, control strategy), that are divided in System and Control Parameters (SCP) and Operating Points (OP). The blue lines represent the result of numerical simulations. The comparisons between results and consequent actions on models are depicted in red.

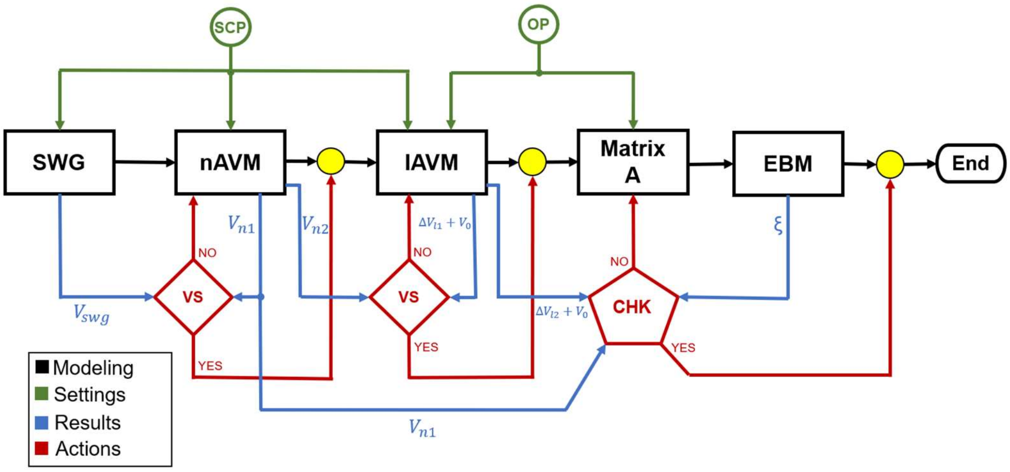


FIGURE 14. STABILITY ASSESSMENT PROCEDURE, FLOWCHART [28].

By starting from SCP (i.e. filters, control parameters, system topology), the SWG model is built as a starting point for the consequent modeling (nAVM, lAVM). The nAVM shows the nonlinear interactions at the basis of SWG, while the second model (lAVM) foresees a linearization in the equilibrium point (OP). Each modeling step is backward verified by comparing the blue responses (i.e. bus voltage). When the correspondence is confirmed in red blocks (VS), the transition across the checkpoints (yellow circles) is enabled. At the process end, the state-space matrix is the final output. The eigenvalues of this matrix are used to verify the system's stability. In the following, each step is specified in detail. For the radial topology, a circuital model can be obtained in PSCAD. Here, the converters are accurately modeled also considering their switching behavior. For the PSCAD model, the bus voltage dynamics response is identified in Fig. 14 as Vswg. This is used for the validation of the other models, as well as for the stability results. By starting from the SCP settings, the nonlinear equations of the system can be written down. These equations describe the AVM behavior of the system, once neglected the switching of power converters. By combining all the differential equations as in [28], a numerical model, named nAVM, can be built in Simulink. Its dynamic response Vn1 is thus compared to the one of the SWG model Vswg. This comparison is performed to evaluate if the nAVM transients are matching the average value of the SWG transients. When the check is successful, then it is possible to move on. Otherwise, it is necessary to check and correct the nAVM modeling. The third model is built starting from the nonlinear equations and from the data about SCP-OP. The result is an AVM model linearized around the operating points, called lAVM. To perform such a linearized modeling, the nonlinear equations are linearized in the equilibrium points, both before and after the system perturbation. To compare the nAVM and the lAVM models, a step down 10% bus voltage perturbation is applied to both models working at the equilibrium. If this comparison is successful, the two models are equivalent in the surroundings of the operating points and the linearized state matrix can be evaluated for stability purposes. Differently, the linearization procedure has to be checked and revised. The last step involves the linearized state space matrix. This is to be evaluated in the operating points that represent the system before/after the perturbation. By analyzing the eigenvalues of these two matrices, it is possible to investigate the small signal stability of the system before/after the load increase. For a stable evolution of the system, the eigenvalues' real part must be all negative. A single eigenvalue with a positive real part is sufficient for an unstable behavior. A cross-check on matrix and dynamics evolutions helps in concluding about DC system stability.

6 Conclusions

In regarding to the V-Access project, the D3.1 deliverable provides the “Design tools including power systems models and chosen architectures”. From some initial considerations on the report, the Section 2 introduces the topic of “Shipboard DC power systems” as crucial in the project development. Particularly, great attention is spent on the DC power distribution for marine applications (2.1) where the advanced DC technology is proposed for a possible passenger ship. In this regard, this new concept of totally controlled power grid is treated in detail in 2.2, where discussing on the IEEE Standard 1709-2010. The Subsection 2.3 is then more oriented on the expected advantages that are consequences of the massive adoption of power converters. Two possible distributions (i.e. radial and zonal) are proposed in Subsection 2.4, while pros/cons are investigated to select the most convenient for the hypothesized marine application. The Section 3 is focused on shipboard applications, from the load powers to be supplied (3.1) to the operational profiles (3.2). Generating subsystems and cold ironing interface are investigated in 3.3, while the reasons for installing advanced storage systems are in 3.4. The Section 4 constitutes the core of the present deliverable where the design procedure of “DC power distribution for marine applications” is introduced. Some initial remarks in the selection of power distribution topology and bus voltage value are presented in 4.1 to give the first operative considerations for then starting the system design. An important Subsection is the one in 4.2, being essential the function of controlled converters in DC distribution systems. In this part, the rated power of each interfacing converter is defined. The DC Power system architecture is finally introduced in 4.3, whereas 4.4 explores the power converters integration in the shipboard power grid. The Section 5 at the end discusses about the controlled DC system, by starting from an introduction (5.1) then following with some important guidelines. The Subsection 5.2 proposes the ones on the control of DC-DC power converters, while the guidelines on the control of DC-AC power converters are conversely provided in 5.3. The protections are properly investigated in 5.4, whereas the Section 5.5 offers the guidelines to model the controlled marine DC grid. The deliverable conclusions are in Section 6.

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