Next generation Amphibious Vessel: an innovative power and propulsion system

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***Abstract*— The main purpose of Navy amphibious ships is to transport Marines, their weapons, equipment, and supplies toward distant operating areas to enable the conduction of expeditionary operations ashore. Although amphibious ships can be used to support Marines' landings against opposing military forces, they are also employed for operations in peace. This kind of vessel has large storage capability, which enables them to operate helicopters and landing crafts for the transfer of personnel and supplies from ship to shore without the need for port facilities. Thanks to their versatility, amphibious ships are in force in all major Navies. The main purpose of this paper is to carry out a study about the power and propulsion system of the next-generation Landing Platform Dock. This study proposes an innovative Integrated Electrical and Electronic Power System with a DC zonal power distribution system and full electric pod propulsion. The DC zonal power distribution will allow the installation onboard of innovative components and weapons (e.g., Laser Gun and modular fixed-face radar), while pod propulsion will improve the dynamic positioning capability, a key feature for this type of ship.**

***Index Terms*— DC zonal power distribution, Dynamic Positioning, Landing platform dock, Naval vessel, Pod propulsion.**

I. Introduction

According to NATO standard designations, a Landing Platform Dock (LPD) is defined as an Amphibious Transport Unit equipped with a floodable dock (well dock), designed to enable the landing of amphibious assault vehicles and troops in power projection operations. [1,2] The configuration of personnel and transportable vehicles may vary according to the type of mission. Here's an example: an assault company (200 forces with the related war and logistic equipment); up to 120 light-armored infantry carriers; 2 landing crafts (LC-23) capable of docking and beaching 2 armored vehicles at a time each; 2 medium helicopters (EH-101) on the flight deck equipped both to provide fire support to an amphibious operation and suitable for Heli landing actions. [3,4]

The high transport capacity mentioned above also makes the Unit very versatile for providing humanitarian aid, civil protection, and intervention in the event of natural disasters [5]. Indeed, these units can be easily adapted for tasks such as:

- the delivery of both medical and logistic healthcare;
- the transportation of special vehicles;
- the evacuation of civilians by sea and by helicopter.

The large spaces and the accommodation capacity also allow LPD to be used as a training ship for Academies' or Navy schools' cadet officers, thanks to the educational and specialist equipment placed onboard. Furthermore, an integrated command, control, and communications system, including satellite communications and computer networks for the distribution of information onboard, makes the Unit suitable as a command headquarters for naval and amphibious operations conducted by multinational and inter-force staff. Because of its versatility, LPD is a type of ship owned by all major Navies of the world. [6,7,8].

In addition, LPD, among other naval vessel types, is one of the most suitable to test and apply innovative solutions and systems [9]. The evolution of marine systems is mainly driven by changes in the available technologies, shipowner's requirements, and rules and regulations. In this context, the application onboard of Integrated Electrical and Electronic Power Systems (IEEPSs) is a good option to increase efficiency and reduce pollutants' emissions, moving towards an eco-friendlier design [10,11]. Thus, it is important to bear in mind that IEEPS can enable the integration onboard of innovative and high-energy-consuming weapon systems and sensors. In the future, they could also allow the implementation of combat systems which will require an increasing amount of electrical power [12]. As a consequence of the employment of IEEPS, it is nowadays possible to imagine a DC distribution. This leads to a considerable reduction in the overall weight of the vessel and consequently to an improvement in the vessel's performance [13].

To guarantee adequate maneuverability to LPDs, this paper proposes the use of a pod propulsion consisting of two main azimuthal thrusters and a retractile bow thruster. Their main feature is to combine main propulsion and steering functions with the advantage of removing the rudders while empowering ship maneuverability through direct rotation of the propeller [14,15]. The elimination of the rudder is not the only advantage of azimuthal thrusters. The far greater maneuverability provided allows the steering of large ships in narrow waters without tugs and, with an adequate number of azimuthing thrusters, the dynamic positioning of the vessel [16,17]. Furthermore, the possibility of transferring the power from the prime movers to the thruster via electric cables leads to saving space originally dedicated to the shaft lines and more comfortable fitting of the well dock (in the case of the LPDs). Therefore, this paper studies the power system configurations (DC zonal) and the propulsion system for an LPD. This work assesses their correct integration using 3D parametric models onboard since the early design stages and provides a comparison in terms of volume and weight.

In detail, two power and propulsion systems are here presented, describing the changes required to the ship to accommodate the new components, then the results are detailed and the most significant outcomes are discussed.

II. Methodology

Ship design is a complex process for a complex product. A single ship design passes hundreds of times through the hands of as many staff members before the launching of the final product. Naval ship design is an even more complex process. As a matter of fact, naval ship design teams have to take into account not only the issues related to the single vessel features, but also mission needs, effectiveness, cost/risk benefits, survivability, and integration with all combat systems. These aspects cannot be considered separately as they are closely interconnected since the early design stages [18].

To properly design a naval vessel, engineers must take into account not only each subsystem but also how they are interfaced with all the others onboard. Intending to have this aspect under control from the early design stages, it is possible to adopt innovative design tools called Computer Systems Integrators (CSIs). Such systems can interface with the tools usually employed during the naval design (Computer-Aided Design, Computer-Aided Manufacturing, Computer-Aided Engineering) also allowing an instant exchange of information. Thus, it is possible to continuously check the feasibility and the benefits of every single design choice. Hence, unfeasible solutions can be immediately recognized avoiding wasting time and rework during the next design stages [19].

A. Shipboard power distribution system

There are several different ways to distribute electric power onboard naval vessels. The electrical distribution schemes currently adopted are the radial and zonal types, both presenting specific pros and cons. Usually, the choice is driven by the ship's operational requirements and the applied rule framework. Nowadays, the majority of naval vessels adopt a radial electric power distribution system. This configuration counts two main power-generating stations, each composed of two or more generators. These can be driven by gas turbines, steam turbines, or diesel engines. Then, the two main power generating stations feed the secondary switchboards that in turn provide power to all the onboard users. Each user is classified as “essential” and “non-essential”. For the former, power supply shall be granted by both the main switchboard to secure the maximum continuity of service. On a naval ship, essential electrical loads include emergency lighting and communications, fire pumps, search radar, compartment ventilation motors, prime mover auxiliary pumps and blowers, steering gear auxiliaries, and weapons systems. The number of running generators can be decided based on the ship’s operational requirements while at anchor, at berth, at sea in normal conditions, during an emergency, or in combat mode. When necessary, the onboard automation system can even automatically switch off the “non-essential” users, providing power only to the “essential” ones.

The literature about onboard power distribution systems also proposes the above-mentioned zonal system [20]. This scenario leads to the sectioning of the ship into several electrical zones based on the physical subdivision of the vessel. The electrical zones are usually divided by watertight bulkheads, decks, or a combination of the two. The electrical power reaches each zone through two main buses. Usually, they are located one at starboard and one at the port side, one above the waterline and one under it to maximize the distance between them and, thus, the survivability of the ship. The pros related to the zonal architecture are that only the main buses (starboard and port ones) go through the watertight bulkheads and decks removing many switchboard feeder cables. This leads to other important benefits in the organization of the ship, such as the reduction of the weight of the electric distribution system and more space available for other essential naval systems. Furthermore, the adoption of the zonal system guarantees that all the cables except the buses are fitted in a single zone of the ship, enabling their installation as soon as the zone structural blocks are combined. This fact leads to cost/time savings and better management of ship production [21].

The onboard electric distribution system can utilize direct (DC) or alternating current (AC). There are several advantages regarding the distribution in DC which are mainly driven by the evolution and technological innovations in the field of electronic components. In addition to operating the power conversion, these are able to continuously monitor the health status of the network, allowing to instantly detect any fault and be capable to isolate it and ensure the continuity of service to all the other users. A second benefit connected to the electrical distribution in DC is the ability to precisely check the speed of rotation of the electric motors onboard by changing the power frequency to allow the functioning of this machinery at maximum efficiency. Note that this equipment is very usual onboard as all pumps and fans are powered by an electric motor. In addition, the considerable peak currents experienced when starting large motors can be limited, helping in maintaining a stable bus voltage. In some cases, a DC distribution reduces the number of stages of transformation of the electrical power. For example, combat system equipment requires power at 400 Hz. In AC systems, the installation of rotary converters is required to achieve this frequency. In a DC system, it is sufficient to install a converter that transforms the DC into an AC 400 Hz, without any intermediate passage. As shown by the previous examples, the adoption of a DC distribution system allows the elimination of a large number of transformers and converters with consequent savings in volume, weight, and costs. The volume gained allows the design team to allocate space to innovative weapon systems, which may require a significant amount of electrical power. Another advantage of DC distribution is that the generator frequency is independent of the distribution frequency requirements. In this case, the main engines can be designed and used so that they always operate at the most efficient speed to optimize fuel consumption and reduce emissions [22,23]. A drawback of the DC distribution is certainly related to the interface with the shore power supply. An additional conversion system should be designed to transform the ground power supply (generally 440V 60 Hz) into DC power to meet the ship's requirements.

B. *Electric pod propulsion*

Naval vessel propulsion systems are sized to reach the maximum speed and to have high efficiency at cruise speed. Traditionally, this was achieved through mechanical propulsion. Nowadays, the characteristics of this type of propulsion are well known: a main engine (gas turbine or diesel engine) mechanically coupled with the propeller through a shaft line and one or two gearboxes. Considering that naval vessels are often operating at very low speeds compared to the maximum speed, such "mechanical" engines might work off-design resulting in higher fuel consumption [24].

Recently, electric propulsion systems are becoming popular for naval ships. They changed the way of power transfer from the prime movers to the propeller as well as the way of managing and distributing electric power to both propulsive and non-propulsive loads. This propulsion system does not involve a variation of the primary source of mechanical power on board, which is usually still based on diesel engines, gas turbines, or steam turbines driving electric generators.

As far as electrical vessels are concerned, the electric power is transferred from the generators through electric cables towards the stern of the ship to the devices that modulate the frequency and the voltage for the Propulsion Electric Motors (PEM) so that these can operate at the required speed without using gearboxes. The electric propulsion system uses fixed-blade propellers that have higher efficiency than controllable pitch ones, required by 4-stroke engines' and gas turbines' direct coupling. The following points summarize the advantages of electric propulsion on naval vessels:

- Improved system efficiency;
- Reduced number, quantity, and complexity of prime movers;
- Improved vessel efficiency, ergonomics, and survivability due to the decoupling of shafts line from prime movers;
- The possibility to reduce the propulsion plant's noise signature;
- Eliminate the need for controllable pitch propeller and related equipment;
- Enhance performance at zero speed, improving the acceleration;
- Possibility to divert electrical power to other future main electrical loads during mid-life upgrade (e.g., railguns, advanced radars).

Electric propulsion equipment could be more expensive than mechanical one due to the acquisition costs of electronic drivers. However, it will be possible to recover these costs thanks to the fuel savings over the life of the vessel. A type of electric propulsion is pod propulsion. In the azimuthal electric propulsion based on pods, the PEM is placed outside the hull of the ship in a steerable housing called pod, which allows the direct coupling between the propeller and the electric motor, eliminating a long shaft line [25]. Transferring the propulsive power through electrical cables provides considerable flexibility in positioning the equipment where they offer the greatest advantages to the ship's functionality. The pods located outside the ship and immersed in water can rotate 360º around their vertical axis to provide thrust to the ship in any direction. Thus, the ship neither needs rudders, aft thrusters, or long shaft lines inside and outside the hull. Furthermore, this system reduces the resistance due to appendages (resulting in lower fuel consumption) as rudders, propeller brackets, etc. are removed. Moreover, since there is no longer the traditional shaft line, the propeller can be positioned closer to the stern, thus reducing vibration and noise levels.

Pod propulsion offers the following benefits:

- Carry out maneuvers in port without the aid of tugs;
- Eliminate the need for long shaft lines connecting prime motors with thrusters, promoting more flexible space allocation;
- Free positioning of the machine rooms to ensure good weight balance and maximum survivability;
- Eliminate the need for rudders to ensure the maneuverability of the ship;
- Reduce the maintenance and repair time, as pods can be disassembled and replaced by another one of equal size while the repair is carried out;
- Allow better maneuverability and seakeeping, allowing with the addition of an azimuthal bow thruster the dynamic positioning.

C. *Dynamic positioning (DP)*

DP capability is of considerable importance for an amphibious landing vessel. It allows to carry out launching operations of landing crafts also with a rough sea and successfully carrying out humanitarian aid operations even in remote locations without adequate port facilities to house a large ship. To ensure sufficient DP capability, preliminary calculations are required to demonstrate its effectiveness since the early design stage. In this context, the most common method is to adopt a quasi-static approach. This is the most suitable method for the early design stages because of its simplicity, as it is based on a balance between the external loads and the thrust generated by the ship. So it does not require too much input data (that might be uncertain at the beginning of the design project) nor a relevant computational power, allowing to compare multiple solutions to select the best one. At this stage of the project, the dynamic positioning calculations allow for estimating the maximum external loads that the ship can face with all kinds of thrusters installed onboard. The results of this study will be presented in capability plots, which are polar graphs representing the maximum wind speed the ship can face while maintaining the dynamic positioning for each heading angle [26-28]. The formula on which the calculation is based is the following:

$$\begin{cases} \sum_{i=1}^{N} F_{X_i} = F_{X_{ENV}} \\ \sum_{i=1}^{N} F_{Y_i} = F_{Y_{ENV}} \\ \sum_{i=1}^{N} M_{Z_i} = M_{Z_{ENV}} \end{cases} \quad (1)$$

Where N is the thruster number.

The environmental loads considered in a quasi-static calculation approach are mainly wind, wave, and current, here modeled according to DNV standards [29]. Usually, all environmental loads are acting in the same direction, without a specific offset angle between them. Only when particular operating conditions have to be tested, specific offsets are taken into account. Generally, the current is set with a constant speed, while the wind speed is systematically increased at each heading angle, thus varying the incoming wave according to the Beaufort Scale correlation. There are several ways to determine environmental loads, starting from simple regression equations through the formulas suggested by class societies, up to model tests or simulations with Computational Fluid Dynamics. At an early design stage, it is more common to follow the formulations suggested by class societies, as the necessary information is not available or not sufficiently accurate to carry out more complex tests or calculations.

III. Case study: Landing Platform Dock

A. Ship and requirements

LPDs perform the mission of amphibious transports and amphibious cargo ships by incorporating both a flight deck and a well dock that can be flooded and emptied to support landing craft or amphibious vehicles. LPDs also have hangar facilities for protection and maintenance. They can operate either alone, as isolated units, or in a convoy, therefore escorting other ships. In Navy operations, an LPD is commonly assigned to the following tasks:

- in "Transferring of Forces" and "Amphibious Operations" missions;
- to be fully equipped for the headquarter personnel that shall be managing those operations;
- to have the capabilities in terms of operational speed and agility, by transferring the amphibious vessels (Landing Craft Mechanized, Landing Craft Air Cushion, Landing Craft Vehicle Personnel and Assault Amphibious Vehicles) to the operation scenario;
- to have the necessary landing/takeoff and deployment facilities for helicopters and tilt-rotor aircrafts which are providing air support in Amphibious Operations;
- to provide disaster relief, humanitarian aid, and peacekeeping support operations.

As a consequence, an LPD needs to be flexible and efficient in all of its operations. Such a goal can be achieved only by adopting an integrated design approach, making it the most suitable ship to be analyzed for providing insights about the design methodology proposed in Section 2. After having drawn up a first general arrangement plan by following a high-level specification of the Italian Navy, it turned out that the main practical dimensions of the ship compatible with the above-mentioned requirements are those provided in Table I.

TABLE I Ship main dimensions

Displacement	10,500 tons
Length overall	141.6 m
Length between perpendiculars	136.6 m
Beam	23.0 m
Draft	5.6 m
Depth	18.0 m

The ship's displacement is about 10,500 tons and it has to reach a maximum speed of 20 knots. Moreover, at the 15 knots cruise speed, the ship shall have a range of 7,000 nm in sea state 5 (or even 6 if possible) and shall have autonomy of 30 days while accommodating 200 crew members and up to 400 additional people. The ship requirements also include the possibility of ensuring amphibious operations in rough seas.

Following the recent design trends of the Italian Navy, case study A proposes a CODLAD (COmbined Diesel eLectric And Diesel) propulsion system. This system allows reaching cruise speed using only the main diesel engines. Instead, the combination of prime propulsion engines with electric motors allows for reaching the maximum speed. In addition, when the ship is propelled with thermal engines at low speed it is possible to use electric motors as generators. In this way, some generators can be switched off (reducing their hours of motion while running active engines at the optimal load) or increase the electrical power available for additional electrical loads (e.g., weapons and sensors of the combat system). Case study B utilizes full-electric propulsion with pods. Depending on the speed required by the ship, it will be possible to keep in motion the minimum number of generators. Table II shows the main generation and propulsion characteristics for Cases Study A and B whereas Table III shows the assumed efficiencies.

TABLE II Generation and propulsion

	Electric generators	**Propulsion**
Case study A	4 Diesel generators (2940 KW each)	2 Main thermal engines (3800 KW each) 2 Electric motors (2700 KW each)
Case study B	8 Diesel generators (2495 KW each)	2 POD propellers (7350 KW each)

TABLE III Assumed efficiencies

	Thermal engines/ Diesel generators	**Gearbox**	**Shaft**	**Power Converters**
Case study A	0.86-0.96	0.92	0.98	//
Case study B	0.86-0.96	//	//	0.98

B. *Ship's hull form and propulsive power*

Two hull forms have been designed in order to meet the design requirements while assuring a good trade-off between resistance, seakeeping performances and weight distribution. The main difference between the two solutions is in aft boady: one shaped to accommodate two conventional shaft lines with rudders (Fig. 1), the other with a flat and almost horizontal segment to fit the pods (Fig. 2). Figures 3 and 4 show the pod positioning stern and top views. In both configurations an even keel set-up was guaranteed acting on the weight breakdown.

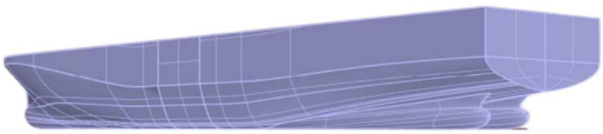

Figure 1 CODLAD hull

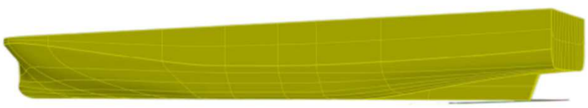

Figure 2 Podded hull

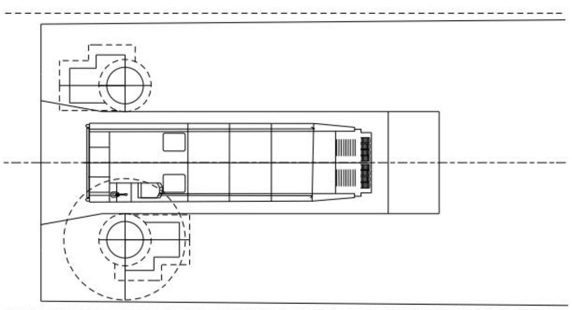

Figure 3 Top view pod positioning

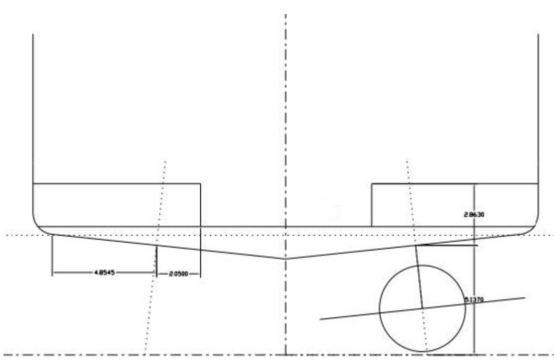

Figure 4 Pod positioning stern view

A specific tool for the creation of parametric 3D models has been used to model the ship as shown in Fig. 5 for the podded LPD. The midship scantling calculation was carried out referring to the Lloyd's Register Classification Regulations. The methodology used to estimate the weight of structural steel assumes that the longitudinal bending loads guide the

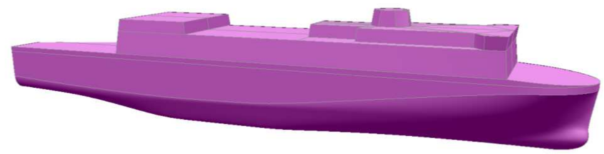

Figure 5 Ship 3D model of the full-electric podded LPD

longitudinal deformation. In particular, the Hughes method was applied to the structural response, with appropriate modifications by the authors.

The estimation of the propulsive power was carried out with the help of analytical and statistical models derived from the data collected with tests on extensive models performed by the main towing tanks (MARIN, INSEAN, DTMB, KSRC). In particular, the results obtained in calm water were corrected by using a non-linear method to obtain the prediction for a sea state 5 in head sea (design requirement) [30]. Figure 6 shows the required effective power as a function of the speed of the vessel.

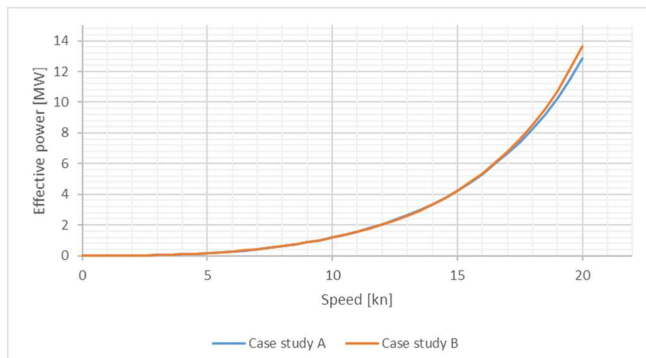

Figure 6 Effective power [MW - kn]

Given the required power, in the Case study A, two thermal engines of 3.8 MW each and two electric motors of 2.7 MW each were chosen. With a total installed power for propulsion of 13 MW the ship can reach the maximum speed. In the Case Study B, it was proposed to install on board two pods of 6.5 MW each, which allow the unit to reach maximum speed. In addition, on both solutions, an azimuthal retractable thruster has been fitted in the forebody to guarantee the survivability of the ship in case of failure to the main propulsion system, improve maneuverability during amphibious operations while avoiding issues when the ship operates in shallow water.

C. *Electric system requirements and electric balance*

The ships studied in the present work are subject to several requirements related to the electric system. In particular, the IEEPS system (Integrated Electrical and Electronic Power System) shall work at 60 Hz, 6.6 kV, according to the standards of the Italian Navy.

The first step of the project was to define the electric loads balance other than propulsion in order to assess the energy demand of the unit and define the power of the generation plants. Using data from similar vessels, the electric balance for the two test vessels has been defined in Tables IV and V for several operative conditions.

In the following rows, the electric loads related to the propulsion of the two configurations (A and B) have been added. Tables 4 and 5 show the results obtained.

TABLE IV Loads balance Case study A

OC/ Services	At berth [kW]	Prep. for sea [kW]	Cruising at 15 kn [kW]	Combat [kW]	Max speed [kW]
Total ship power w/o prop.	2100	3530	3260	4300	3570
Prop. system	//	2400	4250	12,800	12,800
Electrical power for prop.	//	2400	4250	5400	5400
Efficiency	//	0.88	0.91	0.89	0.89
Total electrical power	2100	6740	8260	10,900	11,300

TABLE V Loads balance Case study B

OC/ Services	At berth [kW]	Prep. for sea [kW]	Cruising at 15 kn [kW]	Combat [kW]	Max speed [kW]
Total ship power w/o prop.	2100	3530	3260	4300	3570
Prop. system	//	2400	4250	12,800	12,800
Efficiency	//	0.88	0.91	0.91	0.91
Total electrical power	2100	6740	8260	18,800	18,000

Comparing the data emerges that the pod propulsion solution is characterized by higher efficiency. For the maximum speed and during the combat the total electric power of the Case study A is lower than that of the Case study B as the power is provided by both the main thermal engines (7.6 KW) and the electric motors of propulsion (5.4 KW).

The following Fig. 7 illustrates the configuration of the electric distribution proposed for the Case study A. It is a traditional AC radial power distribution system, currently applied on many naval vessels. Since the total generation capacity is about 11.5 MW, it is deemed necessary to use high voltage to reduce the cross-section of cables.

Taking into account the power required in Case study B an innovative DC zonal power distribution system has been proposed (Fig. 8). Thanks to the integration within a 3D parametric model, it was possible to compare the AC distribution solution with the one that provides a DC distribution. Both solutions are feasible.

The radial DC configuration shows a reduction in weight and volume. This result takes into account the installation on board of the power electronics converters necessary for the DC distribution. As for cables, the DC solution reduces weights and volumes due to the use of two cables instead of three-phase distribution. The additional advantage of DC zonal distribution is caused by the reduction in the number of cables passing through the vessel from the main to the secondary switchboards [31]. In addition, a DC zonal distribution allows a more versatile integration of the innovative propulsion system. In the future, this solution will also allow the integration of weapon systems and innovative direct energy sensors, which now appear to be the new frontier in combat systems.

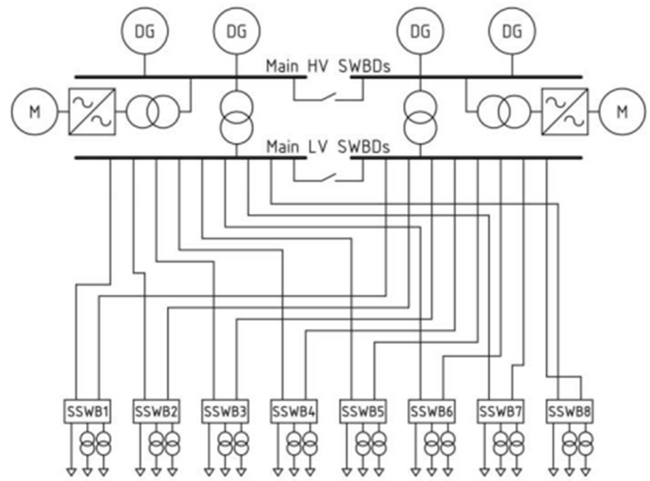

Figure 7 LPD AC radial Case study A

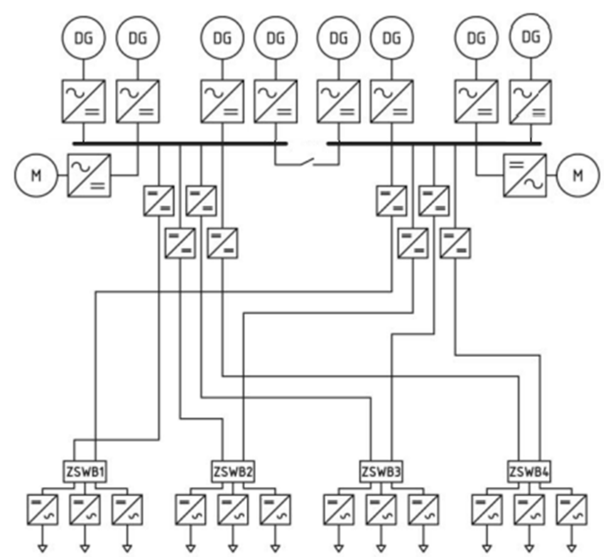

Figure 8 LPD DC zonal IPEES Case Study

D. *Dynamic Positioning*

In order to select which of the two proposals best meets the operational requirements of the unit, the dynamic positioning capabilities of the two options have been analyzed. For this purpose, a Matlab calculation code has been developed following a quasi-static approach. The code determined the wind speed at which the two proposals could keep dynamic positioning for each heading angle.

Fig. 9 and Fig. 10 capability plots summarize the results.

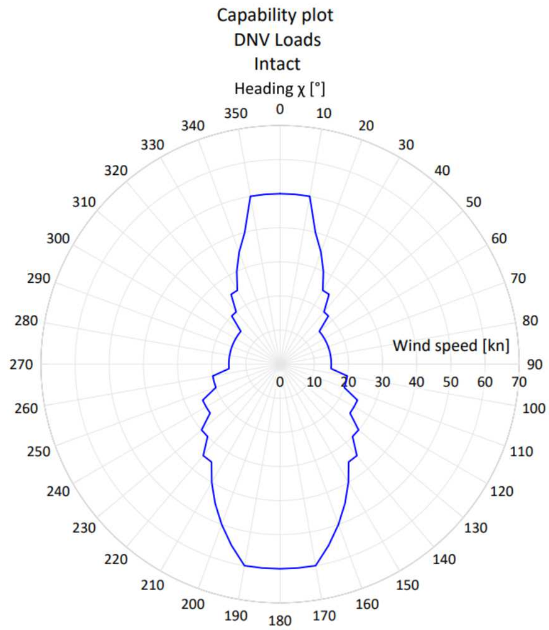

Figure 9 DP capability plot Case study A

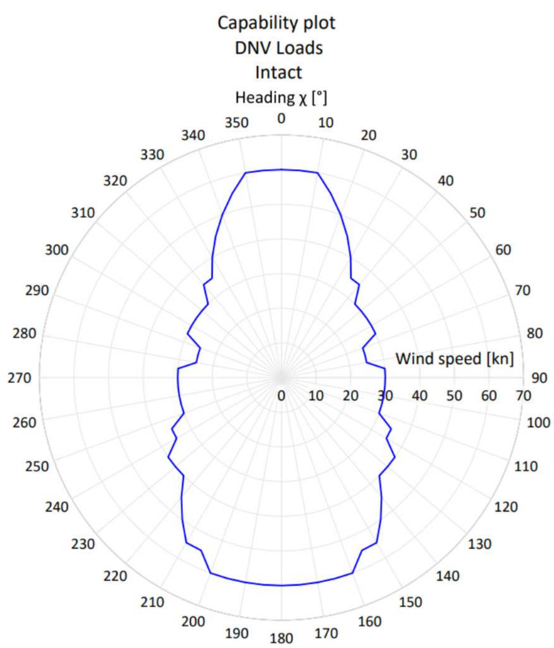

Figure 10 DP capability plot Case study B

It can be noticed that podded LPD (option B) can assure dynamic positioning up to 30 knots of transverse wind (worst condition), while the ship with traditional shaft lines withstands transverse wind up to 15 knots only. Hence, it is proved that the application of pods on an LPD can remarkably improve operability in harsh weather in non-sheltered water.

IV. Conclusion

This paper applied the integrated design methodology to carry out the preliminary design of an LPD. This enabled the integration of several innovative technologies relating to propulsion and energy management systems, evaluating their effect since the early design stage. This is possible thanks to the innovations introduced in the field by specific tools such as Computer System Integrators, which allow the integration of drawing tools with both complex mathematical models and the simulation of the real ship's working environment. This approach allowed determining a configuration that will ease the future integration of new weapon systems and sensors with higher electric power demand. During the present study, the hydrodynamic performance and the electrical and mechanical power demand were estimated with enough precision to draw fundamental conclusions about the most adequate design choices for the considered ship. It emerged that the best solution to fulfill the initial design requirements is Case study B: full-electric ship with pods.

The integration onboard of a DC distribution and the full-electric propulsion with azimuthal thrusters type pod brings several advantages:

- Rational use of on-board generators;
- Reduced fuel consumption and increased efficiency;
- Greater versatility in the distribution of spaces onboard;
- Reduction of weights and volumes dedicated to the energy distribution system;
- Reduction of the acoustic signature;
- Greater maneuverability, up to dynamic positioning capability;
- Possibility to integrate innovative sensors and weapon systems in the future.

Despite this, further investigation is needed, especially regarding the pod's ability to withstand shock loads caused by underwater explosions.

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