An Application of Modular Design in the Refitting of a Hybrid-electric Propelled Training Ship

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***Abstract*—Nowadays specific ships are used to train students as sailors. As historical vessels are conveniently employed to this aim, the average age of these ships is usually high. In order to amortize operating and maintenance costs, the training ships' ownership (except for naval ones) is shared among multiple entities and schools. Moreover, generally these vessels are used in coastal navigation. The consequent operational profile imposes the need to rearrange the ship internal spaces according to the shipowner who will use it. Considering all these reasons, a modular design approach can be adopted in the refitting process, while reverse engineering techniques and integrated design tools should be used for the reconstruction when the original technical documentation is not available. In this context, hybrid-electric propulsion systems can be proposed as effective to enable the Zero Emission Mode, thus reducing the vessel's environmental impact during the training. By doing this, three goals are achieved to extend the ship operational life: ease of rearrangement of the internal spaces for different uses, reduction of operating/maintenance costs and eco-sustainability in coastal navigation. In this paper, after a description about modular design and hybrid electric technologies, the refitting project of the M/N "Umberto d'Ancona" is discussed. The latter is the training ship of "Tomaso di Savoia Duke of Genoa", the nautical institute in Trieste, Italy.**

***Keywords*—modular design, reverse engineering, integrated design, hybrid-electric propulsion, DC power system, Zero Emission Mode**

I. Introduction

The use of ships within education and training for sailor students is a common practice: onboard, students can exercise with navigation operations and tools, so vessels must be outfitted in a proper way. However, it is worth noting that usually training ships are shared between multiple owners, in order to amortize operating and maintenance costs. Each owner can require a diverse operation mode and consequently different necessities as regards the vessel outfitting. For this reason, rearranging the ship internal spaces based on the current purpose must be an undemanding procedure. In this framework, the modular design concept fits perfectly. Indeed, it allows to adapt a unit to different operational profiles and provides numerous advantages [1]-[3]. In addition, another important aspect to consider is the ship propulsion system. Since training ships are usually historical vessels, the latter can be obsolete and low-performing. Given the coastal-navigation aim, to reduce polluting emissions many technological solutions can be obtained from the pleasure craft market [4], however hybrid-electric propulsion systems offer one of the best solutions. Indeed, they can reduce noise and environmental impact, by assuring a Zero Emission Mode (ZEM) navigation [5]. By adopting a modular design approach and replacing the propulsion system, training vessels can be refitted in a proper and effective way and their operational life can be extended. Nevertheless, refitting such vessels could not be simple, due to the lack of design documents. Reverse engineering techniques can help in the process, since they allow the recreation of the original technical documentation and give information regarding the current conditions of the vessel.

In the paper, the above-mentioned design approach and technologies are described and applied to a case study, i.e., the M/N "Umberto d'Ancona", a training ship belonging to "Tomaso di Savoia Duke of Genoa", the nautical institute in Trieste, Italy.

II. Modular Design

The modular design enables to create flexible units capable to change rapidly their operative characteristics and modes. In maritime industry, modular design has been mainly applied in naval sector, where it ensures fast refitting procedures and an increased capability to face new threats [1]. Hence, by allowing easier integration of new technologies and new components, modular design reduces both the time and the costs of refitting procedures, extending the operative life of a naval vessel [2]. Nevertheless, modular design can be applied also to the design and retrofit of civilian vessels in order to ease a good balance of a wider range of design conditions and constraints [3]. The modular design is based on two key elements: modularity and flexibility [6]. Modularity consists of design functionally partitioned blocks, containing all the means for their connection with other blocks. A system or a structure is then partitioned adopting functional analysis and identifying the key interfaces, which are usually designed according to the industry standards. Two main design categories can be defined by applying modularity:

- *Structural modules:* the ship construction is partitioned in blocks including all the outfitting and the connections to contiguous blocks. This construction process enables a reduction of building cost and time since all the outfitting is installed in a workshop during the block construction instead of onboard.
- *Modular installations:* the vessel can accommodate different types of payload modules connected to the other onboard systems by means of defined interfaces. Within the module, there are all the required spaces and equipment to satisfy a specific operation. This approach can allow also a fast rearrangement of ship internal spaces due to the required operational mode.

On the other end, flexibility is the capability to adapt the vessel purpose and capabilities through future rearrangements, modernisations and upgrades. While modularity implies fixed boundaries and defined interfaces, flexibility allows both to change. A module has usually some flexibility degree, however, a flexible ship shall also expand boundaries and modify interfaces. To this end, considering small size vessels, a viable solution is the adoption of flexible infrastructures. Flexible infrastructures permit to rapidly change or rearrange the ship internal boundaries within a defined space. Keeping fixed the external bulkheads, the internal ones are mounted on tracks allowing different configurations of internal rooms. Within flexible infrastructures, standard connections to power, cooling and communication can be fitted in order to satisfy multiple arrangements of equipment and systems. Both the modularity and flexibility can be applied in the retrofit of a small vessel, in order to obtain a multipurpose unit designed to operate in a large set of different conditions. The new vessel shall be easily and rapidly rearranged to carry out different kind of operations with acceptable performances. To this end, the modular design offers a good framework to assure refitting success, and allow easy future upgrades of the unit extending its operative life.

III. Design Constraints

The application of the modular design to the refitting of an existing unit is more challenging than the application since the concept design of a new vessel. Indeed, the existing constraints, in particular the watertight boundaries, limit the application of flexible solutions during a retrofit. Anyway, before applying the modular design pattern, it is mandatory to define the new "mission" of the vessel. Means to define the operational configurations and profiles, which are required to design an efficient powering system.

A. Operational Configurations and Context

Here, the objective is to refit a small craft in order to obtain a multipurpose vessel capable to operate as a research/training vessel or passenger ship. The vessel is intended to operate mainly in the North Adriatic region, including the natural reserves. The research vessels are usually medium/small units fitted with all the equipment to carry out research at sea. Research activities might include seismographic studies, hydrographic studies, oceanographic research, fisheries research or geological studies [7]. Often, especially during measurements, the ship is required to follow strictly a predefined route. Hence, research vessels are usually equipped with DGPS devices and dynamic positioning systems [8]. Moreover, during research activities requiring the adoption of hydrophones or other acoustic devices, it is required to limit the noise emission from the propulsion system. To this end, a viable solution is the adoption of a ZEM navigation at low speed without running the Diesel engines [5]. Moreover, a research vessel shall be capable to launch, tow and recover instruments, dredgers and/or nets. In this study, the refitted vessel shall be capable to train undergraduates and researchers in the fields of environmental science, geology and biology. The ship is intended as a mobile multipurpose laboratory to be used during curricular courses by Italian universities. The expected research activities of the ship are mainly: bathymetric, morphologic and stratigraphic analyses of the seabed, samples collecting for sedimentological, chemical, biological analyses. Moreover, the ship shall be capable to accommodate a ROV for medium-high depth and all the means for scientific fishing. Eventually, if necessary the vessel shall be capable to accommodate 7 people and 2 crew members for multiple days research campaigns.

It is expected that the vessel will operate as research ship only for limited periods, since the laboratory and training activities are related to the academic calendar. Hence, in order to maximise the vessel operation over the year, especially during summer, a viable solution is to design the ship as a multipurpose ship capable to operate also as passenger ship. In the North Adriatic region, there is a strong interest in improving coastal tourism. In particular, Friuli-Venezia Giulia has included this topic as a key objective in regional tourism planning [9]. The refitted ship shall be capable to easily change operational configuration, removing the research equipment and offering to 21 passengers the spaces and services required for one day trip. They should include refreshment areas, open and sheltered seats to admire landscape and a silent propulsion system to increase the onboard comfort. To this end, the ZEM navigation offers a good solution for slow and environmentally friendly tourism in coastal areas [10]. Eventually, the passenger vessel configuration will require some spaces for additional life-saving appliances. In detail, life jackets and life-rafts shall be available at both the sides for the 100% of the people onboard.

Finally, some navigation restrictions in North Adriatic area shall be considered. In detail, the navigation is not allowed within 250 m from the shore in bathing areas and 200 m for other coastal areas. A speed limit of 10.0 knots is adopted within 500 m and 1000 m from the shore in Trieste and Grado respectively. Moreover, the speed limit in Monfalcone port canals is 5.0 knots and 6.0 knots for the main canals of Grado and Marano lagoon. Thus, a 10.0 knots design speed has been chosen, since the refitted vessel is expected to operate mainly in the coastal areas and within the lagoons in passenger configuration and at reduced speed during research operations.

B. Operational Profiles

In order to assure a successful refitting of the powering system of the vessel, it is mandatory to define in more detail the expected operational profiles. As already mentioned, the speed limitations and the different kind of operations carried out by the vessel require the definition of several modes with a speed ranging from 3.0 to 10.0 knots and a different source of power. A hybrid-electric solution has been considered the most flexible solution to satisfy the design conditions. In fact, in hybrid-electric powering systems, the power demand from propulsion and other onboard systems can be provided by the Diesel engines or by the battery packs. Based on the above considerations, the following operational profiles can be defined for a hybrid-electric vessel in order to meet all the already mentioned design requirements:

A. *Navigation at full speed*: in an emergency condition, all the available power onboard is absorbed by propulsion system reaching the vessel maximum speed (12.0 knots) for a limited period.

B. *Navigation at cruise speed:* this condition allows the vessel to reach the cruise speed of 10.0 knots in unrestricted waters with the Diesel engines.

C. *Navigation at cruise speed with battery charge*: this condition is the same of profile B but the remaining power from Diesel engines is used to recharge the battery packs.

D. *ZEM at cruise speed:* in this condition, all the power is supplied by battery packs allowing the zero-emission navigation. In this condition the ship can reach 8.0 knots in unrestricted waters.

E. *ZEM at medium speed:* this condition is the same as C but the speed is reduced to 6.0 knots. This profile is mainly used in natural reserves.

F. *ZEM at low speed:* this condition is the same as C but the speed is reduced to 3.0 knots. This profile is mainly used during research operations in order to minimise the noise coming from the propulsion system. Moreover, it is also representative of manoeuvring and berthing operations.

G. *Berthed*: it is possible to recharge the batteries and supply the onboard users by a shore connection. The available power in this profile depends on onshore infrastructure and it is here assumed equal to 43.8 kW.

All the profiles are to be considered in the refitting process and combined with operational configuration.

TABLE I. MAIN CHARACTERISTICS OF THE ORIGINAL VESSEL.

Symbol	Characteristic	Value	Unit
L_{OA}	Length overall	24.20	m
L_{WL}	Length on waterline	21.50	m
L_{PP}	Length between perpendiculars	20.97	m
B	Breadth	5.00	m
T	Draught	1.40	m
Δ	Displacement in weight	76.38	t
GT	Gross tonnage	82.00	t
NT	Net tonnage	58.00	t
V_C	Cruise speed	10.00	kn
P_B	Installed propulsive power	2 x 145	kW
P_E	Diesel generators power	2 x 50	kW

IV. THE VESSEL RETROFIT

In the present work, the vessel selected for the refitting is the ship Umberto d'Ancona (Fig. 1 and 2), a research ship built at Riva Trigoso shipyards in 1967. The main characteristics of the original design are provided in Table I. The ship, after 30 years service in Venice CNR, has been acquired by the Trieste nautical school Tomaso di Savoia Duca di Genova. After maintenance, the ship has carried out in 2013 a hydrographic campaign in the Trieste gulf devoted to students training. The current general arrangement of the ship is provided in Fig. 2. The ship, it is considered suitable for multipurpose refitting since the large open deck in the aft part of the ship and the quite large flybridge can be easily rearranged to accommodate tourists in the passenger configuration, without requiring costly structural alterations.

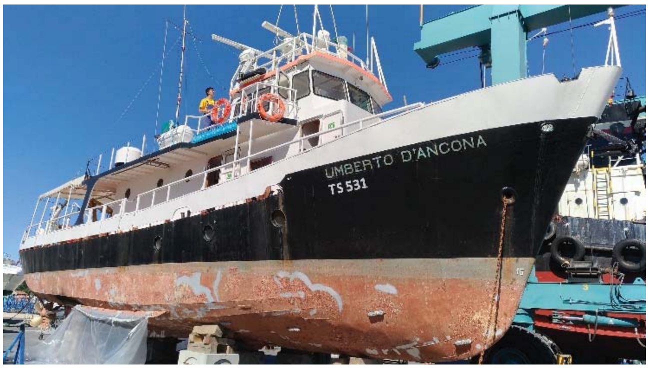

Fig. 1. The *Umberto d'Ancona* during ordinary maintenance works.

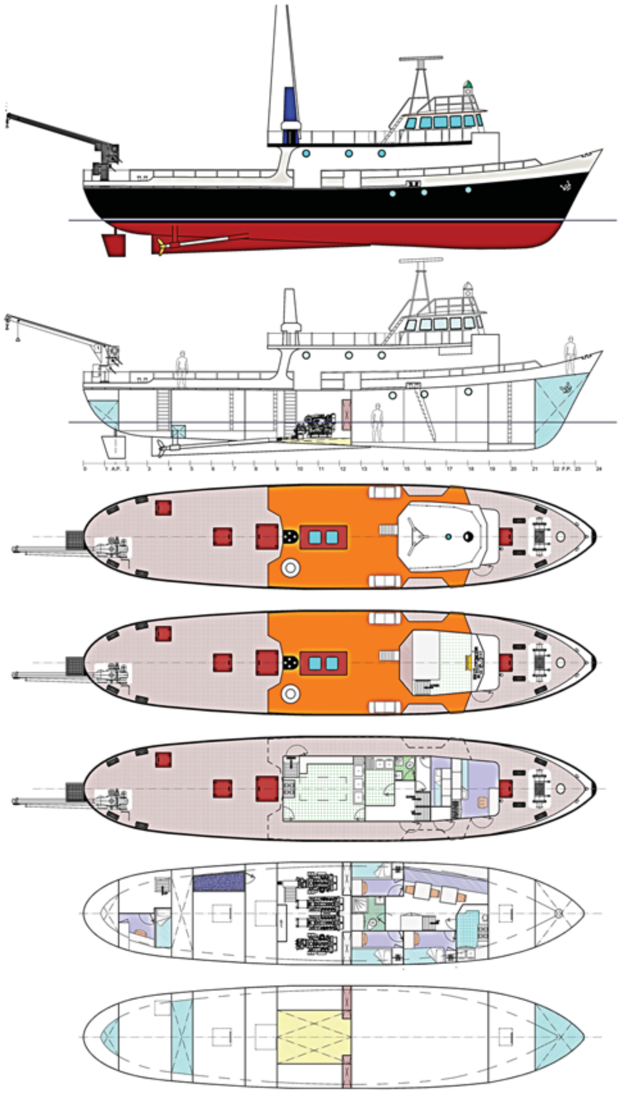

Fig. 2. The original general arrangement of the vessel.

The ship is still equipped with the original main engines and Diesel generators. During the ship life the increased electric power demand is slightly above 50 kW, thus requiring both the gensets running at a non-optimal load. In the unit refitting, the generators have been consequently removed thus the main propulsion engines are employed in hybrid-electric configuration. The aim is to reduce the environmental impact of the unit, while enabling the ZEM navigation.

A. Modular Refitting

Due to the vessel age, no digital drawings where available and only limited paperwork information were present onboard. Thus, the original general arrangement of the ship has been reconstructed adopting a reverse engineering process. Then the ship 3D CAD model has been developed to be the base for application of modular design. In the original arrangement, in the lower deck there are two holds used as workshop and storage. Abaft there is also a cabin accessible only from the open deck. In the midbody is located the engine room and, in the forebody, the remaining accommodations for the researchers are fitted. On the main deck there are two laboratories (14 m^2) and the master and chief engineer cabins. At the extreme stern, the ship is equipped with a crane to support all the research operations. On the fly-deck there is the bridge and the life-saving appliances.

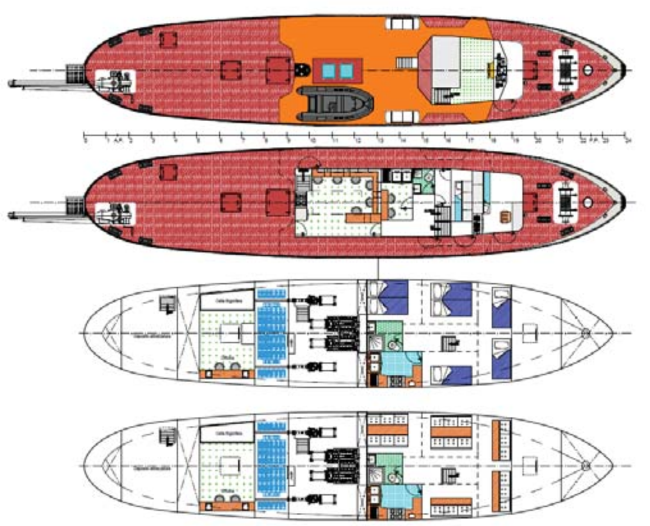

Fig. 3. The new general arrangement for research vessel configuration.

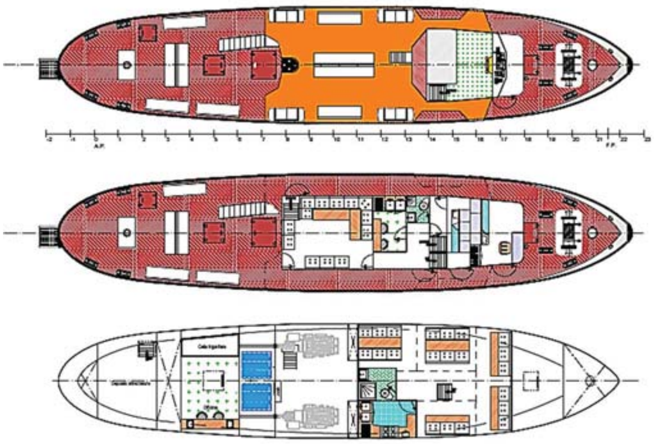

Fig. 4. The new general arrangement for passenger vessel configuration.

The Fig. 3 shows the new proposed research vessel configuration. The installation of the hybrid powering system requires a proper segregated space for the battery packs. Hence, the store has been moved abaft the workshop, removing the aft passenger cabin. In addition, the accommodations on the lower deck have been redesigned using the flexible installation pattern. All the cabin bulkheads are mounted on tracks and can be removed to obtain an open-space for fitting tables and seats can be fitted. Both these sub-configurations are in Fig. 3 and can be adopted due to research campaign duration. On the main deck, the spaces have been not changed, but all the equipment and furniture in the laboratories is modular in order to be easily removed. Moreover, the vertical stair connecting the aft deck with the fly-bridge has been replaced by a more conventional one, in order to ease the reconfiguration as passenger ship.

The Fig. 4 shows the passenger ship configuration after modular refitting. The most relevant changes regard the main deck and flybridge. On the main deck, the crane and the laboratories' equipment have been removed in favour of modular seats for passengers located on open deck and inside the superstructure. Other seats have been fitted on the fly-deck, containing also the additional life-rafts for passengers. In place of the tender boat installed in research vessel configuration, additional life rafts are installed on both sides of the flybridge (Fig. 5). The lower deck is arranged with the open-space sub-configuration.

Fig. 5. Ship 3D model for new passenger vessel configuration.

B. *Power Balance*

In the design of the new hybrid-electric powering system, both the series and parallel configurations have been tested. The parallel solution provided the best results for the vessel design conditions, hence it is here described in detail. In such a configuration, both the thermal engine and an electric motor can be physically connected to the shaft lines through a reduction gear and clutches. The parallel configuration enables to use both Diesel engines and the electric motors in full speed condition, allowing a more flexible solution compared to the series one. In the power balance, all the power users installed on the vessel have been included. The users have been grouped in the following categories:

1. Propulsion power from the Diesel engines
2. Propulsion power from the electric motors
3. Power required to charge battery packs
4. Navigation systems (radar, echosounder, GPS, lights, etc.)
5. Research system and instruments (refrigerating cell, crane, etc.)
6. Other users (HVAC, pumps, etc.)

For each category, the absorbed power has been evaluated in all the operational profiles. In particular, the propulsion power, i.e. the main element in the power balance, has been estimated considering the resistance in calm water, the air resistance and the mean added resistance due to waves in the North Adriatic region. These data have been also considered to choose the propellers particulars. The resulting power balance is provided in Table II. Such a balance is the starting point for dimensioning all the components of the new hybrid-electric powering system.

TABLE II. POWER BALANCE FOR THE DIFFERENT OPERATIONAL PROFILES (A-G).

		User categories (kW)						
		1	**2**	**3**	**4**	**5**	**6**	**TOTAL**
Operational Profiles	**A**	252.0	66.0	0.0	4.2	3.0	5.8	331.00
	B	95.0	0.0	0.0	4.2	7.0	8.3	114.50
	C	95.0	0.0	18.0	4.2	7.0	8.3	132.50
	D	0.0	40.0	0.0	4.9	7.0	8.3	60.20
	E	0.0	15.0	0.0	4.9	7.0	8.3	35.20
	F	0.0	2.0	0.0	4.9	7.0	8.3	22.20
	G	0.0	0.0	36.6	1.0	3.0	3.2	43.8

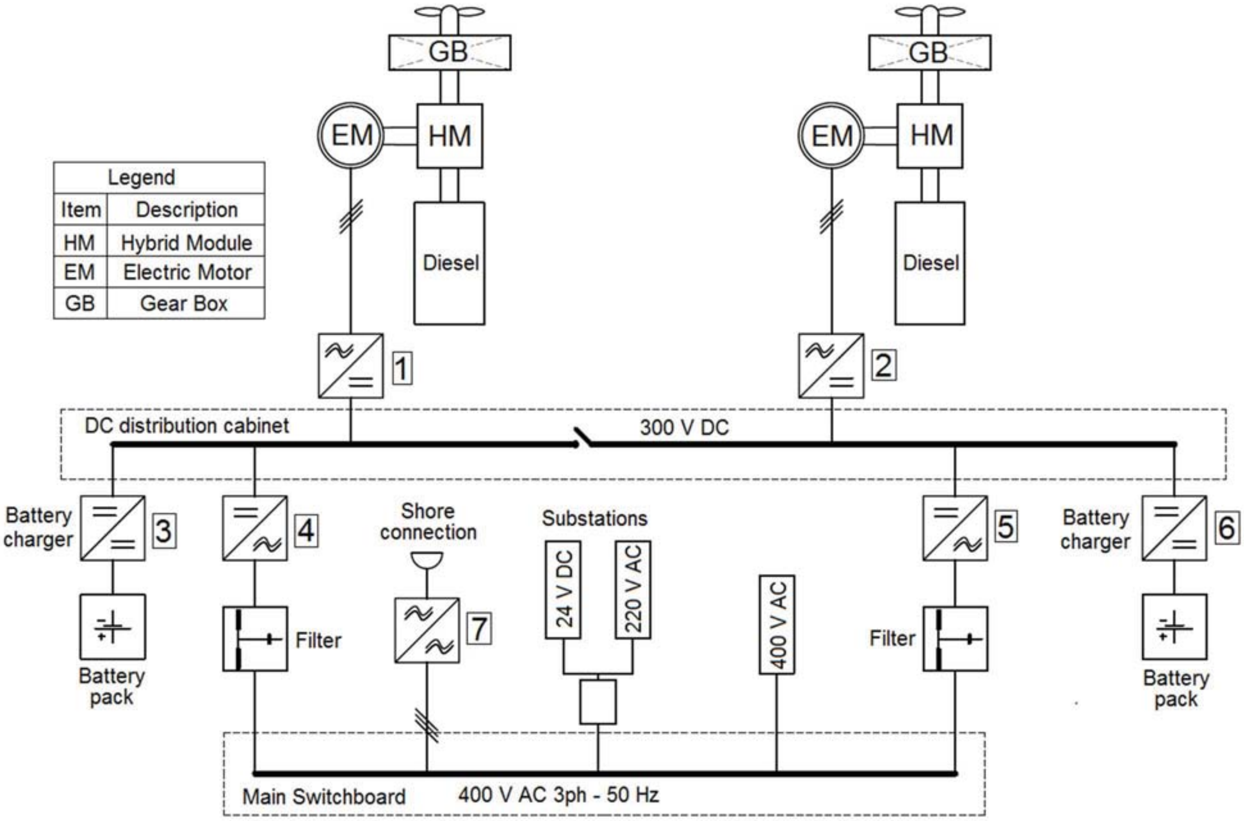

Fig. 6. DC distribution system for the parallel hybrid configuration.

C. Hybrid Propulsion System

In the last years, the hybrid-electric propulsion has been proposed as powerful solution in largely reducing the environmental impact of marine transportation. This trend is observable both in leisure yachts [11]-[12] and in multipurpose-small passenger crafts [13]-[14]. As well known, in these hybrid systems electric motors and Diesel engines are cooperating in decreasing the vessel carbon footprint, thus enabling the ZEM operative profiles in restricted areas. For the training ship under design, the parallel hybrid configuration appears to be the most convenient, as it is able to satisfy flexibility and redundancy while meeting the operational profiles expressed in Table II. In particular, the DC distribution [11]-[14] in Fig. 6 has been chosen to power the six user groups, thus at the end ensuring the correct ship operation in the different scenarios. In such a distribution, the 300 V DC bus (higher section) is supplied by several sources by means of power electronics converters. While in the lower part, the main switchboard provides 400 V AC 3ph-50 Hz for feeding the shipboard users. In this DC distribution, central role is the one covered by the hybrid system (Fig. 7). The latter foresees a strong collaboration between Diesel engines and electric motors to suitably ensure the ship operation and the loads supply. As each Diesel engine and electric motor are interconnected by the HM (i.e. Hybrid Module), not only the two machines are able to collaborate in the propellers movement (i.e. Boost operation, EM behaves as motor), but also they can supply the DC system when the EM works as generator. Evidently, such a hybrid configuration can operate only in presence of a storage system (i.e. battery packs) interconnected to the DC cabinet by power converters. The batteries indeed supply the EM during the Boost configuration, while they store the energy during the standard Diesel configuration.

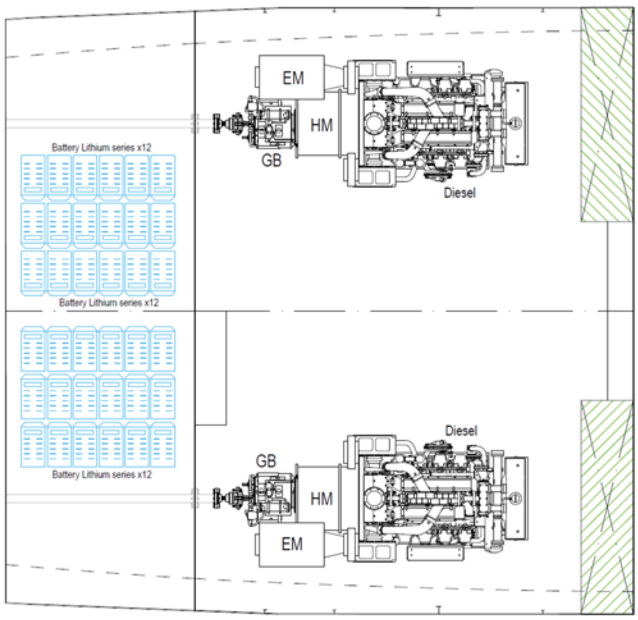

Fig. 7. Hybrid arrangement in parallel configuration.

D. Interface Power Converters

Only a smart employment of electronics converters can make feasible the DC hybrid configuration for the research/training/passenger ship. In this regard, the power scheme of Fig. 6 highlights seven power converters. From the lowest number, it is possible to notice the converters 1 and 2 behaving as bidirectional interfaces. During the Boost operation, they work as DC-AC controlled converters to supply each EM, rated 50 kW in power. Conversely, during the reverse functioning they interconnect the EM generators to the 300 V DC bus while providing the AC-DC rectifying operation. Converters 3 and 6 are the ones dedicated in DC-DC interfacing the storage systems, thus offering the battery recharge. Such an interface behaves as a step-up boost converter when the storage supplies the system (i.e. power flow towards the DC bus), while step-down buck converters if the batteries are to be refilled (i.e. power flow from the DC bus). In Fig. 7, the 36 Lithium battery packs (one ton is the total weight) are series/paralleled connected to store 181 kWh, thus making possible 3 hours of navigation in ZEM at 8 kn. Both the autonomy and the ship speed are notable, thus confirming the potentiality expressed by the parallel hybrid refitting. It is important to observe that the proposed solution is commercially available on the market. Therefore, both storage sizing and system voltage definition are determined as outputs of a classical designing procedure. Important the function covered by the converters 4 and 5. During the standard vessel operation, they supply the main switchboard, indeed making available the AC 400 V distribution from the DC bus. This means that these two power converters behave as DC-AC inverters. Conversely, when the ship is moored at the port for the shore to ship supply, converters 4 and 5 have to reverse their operation, thus recharging the battery packs in AC-DC operational mode. Actually, in this particular case the converter 7 is responsible for the cold ironing thus adapting the AC terrestrial grid voltage to the main switchboard value (400 V-50 Hz). Although in Fig. 6, the last converter is represented as an AC to AC block, in reality two subsystems are usually adopted. The AC source voltage is previously transformed into a filtered DC output (i.e. rectifying functionality). Then, such a DC voltage is finally converted into the AC voltage output, thanks to a classical inverter operation. By smartly managing these seven converters, not only the training ship can efficiently navigate, but also the onboard loads (i.e. 24 V DC, 220 V AC, 400 V AC) are powered by the two filtering stages.

V. Conclusions

The paper has presented an innovative concept for refitting a historical training ship, the M/N "Umberto d'Ancona" now located in Trieste (Italy). To amortize both the operating and maintenance cost of the vessel, the modular design is aimed at creating flexible units capable to change rapidly their operative characteristics and modes. This point is noteworthy as it guarantees the easier integration of new technologies, while at the same time it simplifies the refitting procedure by reducing time and costs. Moreover, the ships ownership can be shared among multiple entities, thus subdividing the effort in managing the vessel. As the electrification earns day-by-day more importance even in the marine industry, a hybrid-electric propulsion has been adopted in the presented refitting, whereas the designed DC power system is able to proficiently power the loads and the propulsion boost. In particular, the described parallel configuration can offer a long time in zero-emission navigation, while maximizing redundancy and flexibility. By adopting the new modular design approach in the hybrid refitting, four are the important goals achieved. Firstly, the ship operational life is extended and operating/maintenance costs reduced. Then, the internal spaces can be easily rearranged for different functionalities, whereas the eco-sustainability is largely increased. For all the reasons here expressed, the modular design in hybrid retrofit appears to be an efficient solution when old ships are finding a new use.

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