Feasibility Study of a DC Hybrid-Electric Catamaran for River Navigation

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***Abstract*—The sustainable growth is becoming every day more present and even mandatory in the framework of global decarbonization and Green House Gases (GHG) reduction. In such a context, electric powering offers important advantages while offering reliable and greener solutions for private-public urban transport. By considering this scenario, in this paper, an electric catamaran equipped with a DC hybrid module is proposed as effective in passenger transport along the Po river, in the Turin urban environment. The study encompasses many challenging aspects, which, in the end, improve the overall ship performance. For instance, the vessel shall be suitable for a quick hauling to the land in case of emergency with a crane truck. Secondly, the DC voltage distribution must provide safe power delivery by maintaining low weights. In this paper, the design is presented, along with the scenario constraints that have defined the peculiarities and addressed the technical choices.**

Keywords— electric propulsion, inland navigation, passenger vessel, electric catamaran design, DC power distribution, concept design, zero-emission ships

I. Introduction

In the framework of global decarbonization, the progressive development of electric mobility solutions makes them reliable and scalable to different operating scenarios, playing nowadays a crucial role. Effective benefits in terms of Green House Gases (GHG) cut and protection of human health derive from reducing air pollutants emissions in high-density urban areas. Electric powering must be implemented for both individual and public transport, not only for wheeled vehicles but also for waterborne traffic [1]. Inland waterways offer a viable alternative for the transportation of goods and people, in terms of specific propulsion power required to transport an amount of cargo also reducing road traffic and the consequent pollution impact. Short-distance people transport in urban areas can be successfully carried out by specifically-designed passenger vessels. The total capacity, overall dimensions, service speed are variables that significantly influence the success of a design. The environmental scenario, in inland transports, should not be neglected, as it strongly affects the entire project. It shall include also the weather and river-state conditions, in terms of precipitations, water level, and stream velocity, among others.

Even if bad weather conditions do not affect inland navigation in terms of wave-induced motions, they can seriously compromise the navigability of a branch of a canal or river: on the one hand by reducing the flowrate and the depth in dry seasons, on the other hand by increasing the stream, transporting heavy debris, when the river is in spate. In the worst scenario, there could be a risk of loss of vessels. Extreme weather events are generally increasing in number and severity in the central-southern Europe zone [2], thus, measures must be taken to avoid damages and injuries, minimising economic losses, too [3, 4]. For instance, a severe weather event dominated by high rainfall occurred in November 2016 [5] in the north-western regions of Italy, which caused extended damages in large areas of the Piedmont region, including river floodings in several countryside zones. The catastrophic event caused the loss of the two passenger crafts that sailed the branch of Po river in the city of Turin, capital of the Piedmont region. The boats, named Valentino and Valentina, respectively, have been unmoored by the river stream and floating debris, which pushed them on a dramatic course that was stopped by the pillar of a bridge. The tragic event culminated with the loss of both the vessels. The demand for new vessels led to the design of a lightweight catamaran, made by aluminium alloy, propulsed with a DC hybrid-electric system. The catamaran must be easily hauled in case of emergency, according to a defined rescue protocol, which is based on official forecasting systems [4, 6, 7].

In this paper, the feasibility study of the catamaran is presented. The design has been focused on the requirements related to the operative scenario, which is characterised by environmental constraints and utmost safety standard. The catamaran must be fully compliant with the EU Directives on Inland Navigation [8, 9].

II. Operating scenario

The design of the passenger catamaran has been focused on the peculiar operating scenario, as the environmental constraints strongly influence almost every aspect of the project. The request of abt. 60 passenger, the compliance with the Italian and European directives, the on-board comfort requirements are constraints to be considered in the feasibility study, concurrent to the design of the preliminary General Arrangement Plan, which is depicted in Fig. 1.

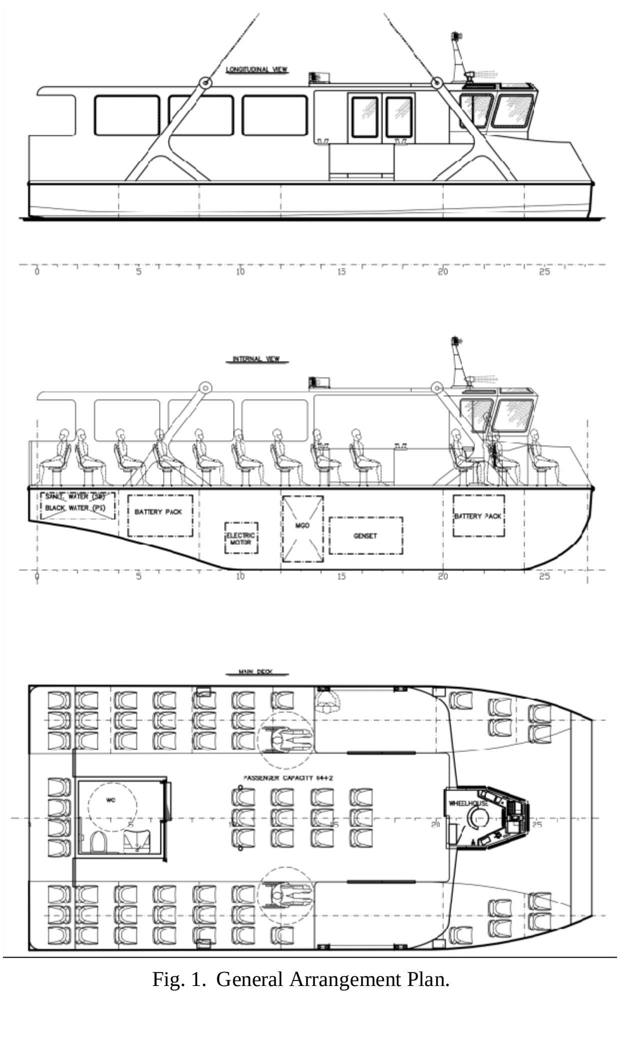

Fig. 1. General Arrangement Plan.

First, it has to be noted that the branch of the river where the vessel will operate is comprised in the urban structure, confined by notable bridges and rapids. Along with the boats of the famous rowing associations, they will be the only vessels that navigate in that section of the Po river. Thus, the highest reliability is mandatory in the catamaran design, as a safe return to a mooring point even in the unfortunate event of a failure that partially compromises the propulsion or the steering system, has to be achieved with no other means but its own, as no other vessels can assist.

The urban route is five kilometres in length, one-way navigation requires almost one hour, passing under three bridges:

- Umberto I Bridge, a stone bridge made of three arches measuring about 30 m in length, each.
- Principessa Isabella Bridge, with five semi-elliptical arches for a total length of 160 m, in brick and stone.
- Balbis Bridge, inaugurated in 1928, 147-metres long, built by three arches in reinforced concrete.
- Thus, the river environment is not a limiting factor for the overall breadth in a preliminary stage design, unlike other project requirements, as further explained.

Considerable changes in the water level are observed along the seasons: on the first hand, during the dry season, typically summer, shallow waters and sandbanks require reduced draught, whilst on the other hand, when the water level increase the consequent current must be accounted to correctly size the propulsion power. When the river is in flood, an emergency protocol has been developed to get to safety the vessel. Different levels of risks have been envisaged, depending on the water level and on the current velocity, based on the actual and forecasted river state.

The four classes of hazard are:

- Absent: No risk or hazard occurs.
- Ordinary: The river flow is enclosed in the whole width of the river bed with a water height tangibly under the countryside level. The probability of flooding is low, while attention must be paid to evolution.
- Moderate: The entire riverbed is full, the water height is close to the countryside level, high probability of flooding limited to the floodplain areas, moderate erosion phenomena.
- High: The river banks are not capable to contain the river flow, this implies a high probability of extended flooding and intense erosion.

When the worst flooding scenario occurs, the vessel is taken out of the river, rescued by a crane truck deployed on the riverside. The total weight of the vessel has thus to be limited as more as possible, allowing safe and fast lifting, even in bad weather conditions. As the operation's rate is of the utmost importance, a quick hooking system must be adopted, while the hauling is performed by special operators, specifically trained. The total breadth of the catamaran affects the lifting manoeuvring capabilities and influences the crane systems and vessel's cradles.

As mentioned, during sunny days the river is plenty of rowing boats and canoes that would suffer if the wave production is not adequately considered and minimised in an early-stage design. The narrow waterplane area coupled with the correct demihull separation does avoid an unexpected wave formation. The naturalistic environment of the river enters the urban territory of the city, requiring reducing emissions as more as possible, by means of DC electric propulsion. The boat must sail the entire route in full-electric mode, with Lithium batteries for energy storage. As recharging points are not yet operative in correspondence with the terminals nor the night dockings, diesel generators have been arranged, in case of low voltage of the batteries. It has been chosen to arrange twin diesel engines, one for each demihull, to ensure the full redundancy, that is the vessel has two propulsion engines that can be supplied by four different power sources. The above-mentioned design requirements represent the conflicting constraints, from which the main particulars of the catamaran are developed, as in TABLE I.

TABLE I. MAIN DIMENSIONS

Length overall	L_{OA}	13.90	m
Maximum breadth	B	6.60	m
Design draught	T	1.15	m
Full load displacement	Δ	20	t
Design speed	V_{des}	4	kn
Maximum speed	V_{max}	7	kn
Total electric power	P	2x30	kW
Passenger capacity	-	64+2	pax

III. POWER BALANCE, OPERATIONAL PROFILES

The sizing of the electrical power system is performed considering the actual power needs in different operational profiles[15], defined as:

A. Short-Time stop: the vessel is temporarily moored with only one line, just for the (dis)embarkation time of passenger, propulsion systems are running at low speed to avoid the risk of distancing from the dock.

B. Manoeuvring: While approaching the stops or during the turn to inverse the course, the catamaran requires a percentage of the propulsive power for the safe and correct manoeuvring, considering the presence of the river stream.

C. Downriver course: While navigating downriver, the propulsive power needs are lower than in still water condition.

D. Upriver course: As mentioned in case C, but with inversed proportion.

E. Full Speed ahead: Either during downriver or upriver course, the propulsion power that maximises the vessel's speed is provided by the motors at their Maximum Continuous Rating (MCR).

F. Emergency: in the unfortunate case of loss of the systems of a whole demihull, it is required for the vessel to safe sail to a stop for the disembarkation of all passenger, then to a permanent mooring, with a sufficient power margin.

Onboard users are divided into categories, following the below list:

1. Battery charger: When the battery voltage becomes too low, gen-sets are started to provide the recharge.
2. Electrical propulsion: The electrical power required for the propulsion motors is reported here.
3. Outfitting: The electrical needs for the lights, navigation instruments, and auxiliary are summarised.
4. HVAC: Heating, Ventilation, Air Conditioning and engine room ventilation systems require a proportion of the installed power that must not be neglected.

Operational profiles, as above mentioned, are associated with users power demand; TABLE II. summarising them.

TABLE II. OPERATIONAL PROFILES

Item \ Profile	A	B	C	D	E	F
Battery charger(*)	-0.0	-0.0	-0.0	-0.0	-0.0	-30.0
Electr. propulsion	5.0	20.0	10.0	40.0	60.0	20.0
Outfitting	2.0	4.0	2.0	2.0	2.0	1.0
HVAC	2.0	2.0	2.0	2.0	0.5	1.5
Total Power (kW)	**9.0**	**26.0**	**14.0**	**44.0**	**62.5**	**-7.5**

Fig. 2. Conceptual rendering.

IV. DC SHIPBOARD POWER SYSTEMS

This paper wants to explore the design of a hybrid electric catamaran for river navigation. Such a particular vessel can operate by exploiting a DC power distribution[16-1]. The reasons for implementing this power system are to be sought in the flexible use of source-storage-load. Moreover, the employment of several power converters is able to assure the ship operative profiles while maximizing the onboard space.

A. DC radial distribution

To supply the ship in the identified operational profiles, a distribution based on DC can be the best choice. Indeed, not only power generation from Diesel engine but also storage functionality are enabled thanks to this type of distribution. As made evident in the power scheme of Fig. 3, the main bus presents a DC voltage of 750 V, while two secondary distributions make available the low DC (24 V) and the AC (220 V-50 Hz). Evidently, if primary distribution interfaces the main power generation and propulsion, the other two are mainly adopted to supply the DC and AC loads. Similar solutions are also discussed in [10], [13] and [19]. The main power generation is obtained by coupling Diesel primary engines and AC electrical machines, while the use of several power converters is necessary for the interface function. In this regard, a detailed description is offered in the following, where the final supply to onboard loads is also described.

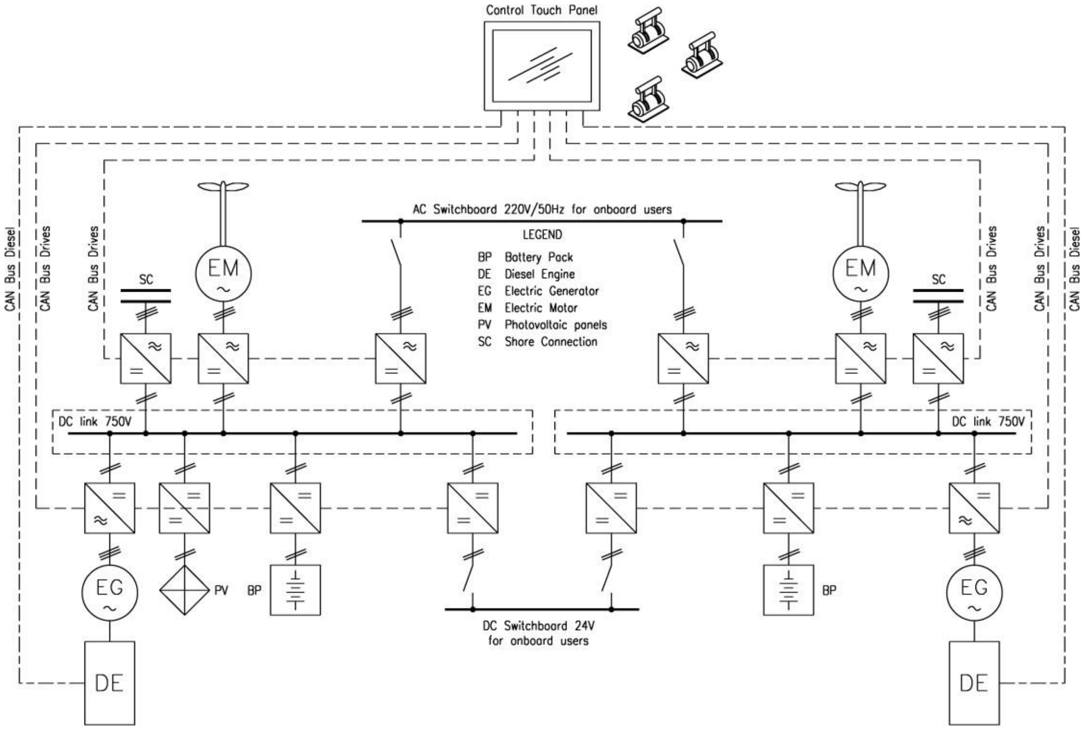

Fig. 3. DC distribution power scheme.

B. *Interface Power Converters*

As multiple are the employed power converters, the DC power system in Fig. 3 shows its complexity. By starting from the supply section, two AC-DC power converters are responsible for feeding the DC bus from the AC machines (600 V line-line voltage). Such converters are controllable rectifiers that can indeed regulate the DC bus, even in presence of large power demand. Secondly, each DC bus presents a Shore Connection (SC) input. Besides, in this case, AC-DC rectifiers are necessary as interfaces, when power the ship from the land electrical infrastructure. Moving towards the propulsion, DC-AC inverters are as usual in charge of controlling the torque-speed of propellers, thus enabling the vessel movement. Important the role covered by the DC-DC converters coupled to the storage system. Such power converters work in a bidirectional way to charge the batteries (abt. 200 Ah), but also to supply the ship in the no-emissions scenarios. Last converters are the ones to serve the low voltage. Thus, again two DC-AC inverters to power the AC switchboard, while unidirectional DC-DC converters to activate also the supply from 24 V DC bus. Evidently, such a large use of electronic converters can boost ship performance in terms of safe power delivery and low weights.

V. PRELIMINARY STABILITY CHECK

A preliminary intact stability calculation has been performed to check that an adequate metacentric radius (GM) and freeboard height are met in every loading condition. For preliminary purposes, the following load cases have been taken into account:

A. Full load displacement: the vessel is fully loaded with persons and provisions. It corresponds to the maximum loading condition.

B. No passenger condition: corresponds to the fully-equipped vessel, with fully-loaded tanks, ready for departing, with no passengers on board. This loading condition shall be considered for taking off in case of river floodings.

C. Passenger crowding: The passengers at full load condition are considered crowded to one side of the vessel, in the worst configuration, considering a density of 4 persons/m^2 if standing up. The resulting transversal centre of gravity of the passengers is located 2.021 m from the longitudinal plane, as defined in (RINA Inland Navigation [20]).

According to preliminary weight breakdown, hull forms and General Arrangement Plan, loading conditions are resumed in TABLE III:

TABLE III. LOADING CONDITIONS

	Full load [t]	**No pax [t]**	**Crowd. [t]**
Lightship	13.200	13.200	13.200
Passengers	4.950	0.000	4.950
Luggage	0.990	0.000	0.990
Crew	0.150	0.150	0.150
Gasoil	0.948	0.948	0.948
Fresh water	0.296	0.296	0.296
Black water	0.030	0.030	0.030
Total	**20.560**	**14.624**	**20.560**

Equilibrium conditions have been reported in TABLE IV.

TABLE IV. EQUILIBRIUM CONDITIONS

	Full load	No pax	Crowd.
Draft Amidships m	1.149	0.946	1.148
Displacement t	20.56	14.62	20.56
Waterpl. Area m^2	31.277	24.662	30.899
KB m	0.725	0.598	0.747
KG fluid m	1.344	0.787	1.386
BMt m	9.281	10.254	9.061
BML m	17.384	14.146	15.971
GMt m	8.661	10.065	8.421
GML m	16.764	13.957	15.331
Freeboard m	0.919	1.121	0.751
Heel deg	0.0	0.0	3.6

It can be observed that the catamaran relies on a high safety margin of initial stability, and the angle of heel at the equilibrium condition does not reach remarkable values, remaining in the framework of metacentric behaviour (less than 4° of heel or list).

VI. CONCLUSIONS

The challenging targets of reduction of carbon footprint and emissions shall be achieved by developing new applications and technologies in every industrial and urban context. Here, it is showed that the "green" alternative in urban waterborne transport is feasible and reliable. Indeed, the catamaran configuration gives intrinsic benefits in terms of redundancy, as all the essential equipment can be split and doubled into each demi hull, so having the reliability of two vessels at the same time. Further developments shall be promoted to improve the performances in both technology and naval architecture aspects, taking advantage of the DC power distribution and its ease of arrangement onboard. Moreover, the ability to take off the vessel while river flooding is forecasted makes them resilient to the environment in ever more frequent extreme weather occurrences.

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