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Procedia Computer Science 200 (2022) 962–968

Procedia Computer Science

www.elsevier.com/locate/procedia

3rd International Conference on Industry 4.0 and Smart Manufacturing

The future developments of Hybrid and electrical propulsion for small vessel, according to new possibilities offered by Industry 4.0.

Valerio Ruggiero *

Dipartimento di Ingegneria, Università di Messina, 90100 Messina, Italy

Abstract

The electrical propulsion was used at the beginning in the first years of XXth century for cars and ships, then the developments of traditional engines made this solution less used.
Nowadays we are seeing a new renaissance with small vessels for public transportations, yachts, etc using hybrid propulsion.
The paper aims at giving a study of new technologies and possibilities, not only like having a small passenger vessel completely propelled by batteries, but also examining the situation under the profile of accidents, of solutions to increase safety, and how the project should probably change completely the approach from the traditional design "spiral" starting from dimensions to a new one starting from the profile of mission and consequentially the logistic of power source available ashore to recharge the batteries. Combining all the above elements the paper aims at defining the directions for new development in manufacturing new small vessels with cleaner propulsion and also show how, as consequence of developments in batteries it is now possible to adopt electrical propulsion for several existing small vessels.

Keywords: Passenger vessels, yachts, small vessels, hybrid propulsion, batteries

* Corresponding author. Tel.: +39-335-6369213.
E-mail address: vruggiero@unime.it

10.1016/j.procs.2022.01.294

Nomenclature

P_E	Effective power (kW)
P_B	Brake power: Power at flange of engine/motor, considering the hull efficiency and the propeller open water efficiency (kW)
Loa	Length over all (m)
Δ	Displacement (t)
η	Propulsive efficiency

1. State of art

Actually the hybrid electric propulsion is used especially in small passenger vessels and in yachts, with an overall length of about L.o.a. 50 m.

The most diffused utilization is the hybrid electric propulsion, with traditional diesel generators as main power source and battery packs as power source for limited trips[1-2].

North European Scandinavian countries are increasing the development of full electric propulsion, starting to use vessels with power fully provided by batteries.

The number of vessel equipped with hybrid electric propulsion of full electric propulsion is constantly increasing, the Tab.1 shows some samples of the most recent realization in the field, the help to introduce the topic of the article.

Table 1.: Recent samples of ferries.

Country	Name	L.o.a. (m)	Passengers	Power source
Taiwan	Qi Fu 1	25	150	Battery
Norway	Basto	139	600/200 cars	Battery
Norway	Ampere	80	360/120 cars	Battery
Italy	Liuto	24.75	230	G.E. + batteries
Italy	Topazio	32	200	G.E. + batteries
Norway	Ytteroyningen	49.8	160/38 cars	G.E. + batteries

As can be seen, a differentiation between two types of propulsion can be outlined:

- units with "hybrid" propulsion with the propeller (propeller with traditional shaft line or azimuth thrusters) driven by electric motors powered by electricity produced on board by traditional generators, with the possibility of resorting, for navigation of limited duration, to the use of batteries installed on board and recharged or from shore current during stops or from the main generators.
- units "full electric" where the electric motors are powered by packs of batteries, of significant capacity, charged exclusively through the earth current during stops.

The fundamental limitation of both types is linked to two factors:

- battery charging capacity, linked to the power that can be supplied by the charging station.
- battery capacity taking into account the current battery technology and consequent decay of the useful life of the batteries, based on the discharge cycles and the percentage of discharge.

Of course, in the global assessment of the environmental impact of the unit, especially when it comes to units with "full electric" propulsion, it is also necessary to take into account the environmental cost of the energy produced on board.

In fact, a first schematization can take into account the following aspects:

- Energy produced by generators installed on board: in this case a loss can be estimated, therefore a higher cost of the energy produced on board, equal to 10% more than the direct drive with the internal combustion engine of the propeller.
- Energy produced on the ground and used to charge the batteries: in this case the main problem, in terms of the "ecological cost" of energy, is related to the way energy is produced. In fact, some nations are still linked to the use of hard coal or hydrocarbons for power plants, or to the use of nuclear power with all the related problems of perception by public opinion.

2. Dimensioning propulsion

Wanting to hypothesize a short simple calculation scheme to evaluate the sizing of the battery pack, it is possible to hypothesize the following:

Required Power: P_B + PH
Where P_B (kW) = Power brake for propulsion
PH (kW) = Power for hotel and ship services: air conditioning, light, etc
T (h) = Time of navigation with batteries propulsion

Energy provided by batteries = EB (kWh) , the Energy provided can be expressed with Eq.1)

$$EB = \left(P_B \quad + PH\right) * T \qquad 1)$$

Example: 15 mins of navigation at 5 knots
15 mins correspond to 0,25 h
P_B = 50 kW
PH = 30 kW
The total energy request can be calculated with Eq. 2)

$$EB = (50 + 30) * 0{,}25 = 20\ kWh \qquad 2)$$

Dimensioning the capacity of battery packs for 20 kWh we will have a complete discharge each trip of 15 min., but we must consider now the life of batteries compared and related with the Depth of discharge and Discharge cycles, in the last years the life cycle of batteries increased significantly his performances as in the following Table presenting a summary of average data obtained in literature:

Table 2.: Life of batteries in relation with discharge.

Depth of discharge	Discharge cycles
100% DoD	350-550
50% DoD	1100-1600
25% DoD	2000-2500
10% DoD	3700-4800

In this way is possible to have an estimation of the life of the battery packs and the design spiral need to be revised, at this point, taking in consideration as first station the average time between complete substitution of the battery packs.

This calculation is obvious and very basic and simple, but leads to some interesting conclusion in the new possibilities offered by the market, and this is the aspect where the “Industry 4.0” [3-6], with continuous cohoperation between different branches of engineering, like the possibility of monitoring the residual capacity of the battery packs can be of extreme interest, aiming at a “smart monitoring” of the use of the energy on board [7-8].

But, anyway, it is already possible to foresee the possibility to adopt full battery propulsion in larger field of applications, only remembering different aspects, like fire risk and pollution, not yet completely investigated [9].

This because there is a massive drop in the cost of batteries and this drop is continuing so is possible nowadays to imagine to realize completely new routes for internal waters on short distances with energy for propulsion fully provided by batteries.

In fact, for example, the paper considers that a vessel with L.o.a. = 33 m (Fig.1) , capable to carry 210 passengers, with a P_E at 8 knots of 35 kW (obtained from Tank test and measured with torque meter on board) can require a total P_B+PH of 100 kW assuming a propulsive efficiency of $\eta = 0.5$, meaning with 3 tons of batteries considering a density of 130 kWh/t can navigate 10 hours, covering the complete need of energy and recharging at night the battery pack with an average life of the battery packs of 500-600 cycles, so 2-3 years.

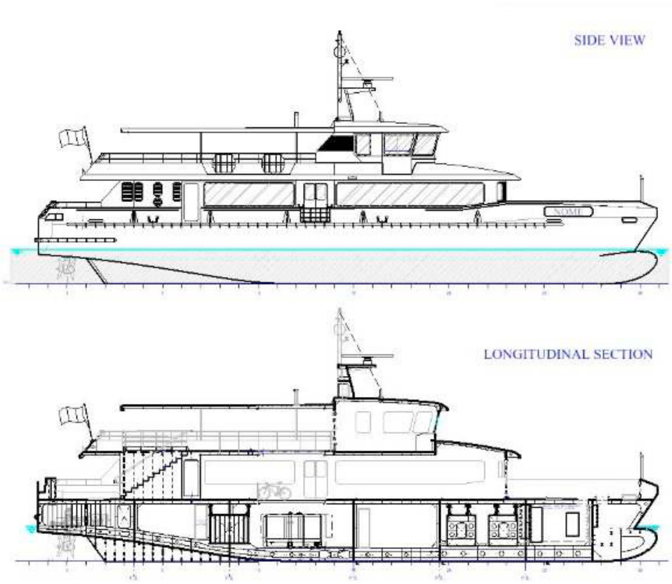

Fig. 1 – View of case study 33 m passenger ferry

But these data, originally studied for an use of electrical propulsion only in limited amount of time, can be used to change the approach at the project, realizing a full electric propulsion, as will be described.

Basically it s now important to understand that the main limitation in the electric propulsion for ships is not the simple “weight” of the batteries but the ratio between the weight of the batteries and the weight/displacement of the vessel. Of course 100 kW of power, for 10 hours, if provided by traditional diesel engines with a specific consumption of 0,21 kg/kWh can be guaranteed by a tank of about 210-240 kg of fuel, instead of the 3 t of batteries, but the 3 t of batteries must be compared with the 200-210 t of displacement of the ship.

Nowadays the energy density of batteries is presenting the following values, increasing yearly:

Table 3. Type of batteries energy density.

Type of batteries	Energy stored
Lithium based (Tesla)	260 Wh/kg
Lithium based marine use	150 Wh/kg
Sodium based	120 Wh/kg

3. New possibilities and developments

According to all the above data, the paper wants to focus on the situation of small vessels, also because the limited size of electrical motors is now making possible a successful retrofit of existing vessels for the low speed, where the request of P_E is limited.

In fact the paper considered the case study of a vessel of 33 m L.o.a. usually operating a speed of 10 knots (see Fig.1), based on similar vessels realized, so all the data regarding the weight on board and the P_E are real and tested. The vessel has been originally designed to operate with diesel electric propulsion and using batteries only for the approaching /departing from pier, but the recent developments in battery life and cost, will allow a redesign with complete battery fed propulsion.

The full load displacement of the vessel is 200 t., and Tab.4 will show the items that can be removed in case of full battery solution:

Table 4. Results of tank test – Passengers vessel Δ = 200 t.

Items	Weight (t)
GG.EE.	9
Fuel tank structure	1
Fuel piping (vents, filter, pumps)	1
Cooling system for GG.EE.	1
Engine room Ventilation systems	0.7
Total	12.7

The above mentioned total is 12.7 t. without considering the weight of fuel loaded (9 t) and considering in some cases like the E.R. ventilation system the difference from the normal ventilation of the compartment.

At this point is necessary to study the results from tank test, validated by the fact that the vessel reached the corresponding speed with a power request from electrical motors corresponding to the tank test, and proceed to the sizing of an appropriate battery pack.

Assuming to navigate 14 h continuously at a speed of 10 kn , severe assumption, because the required speed is less, and with a continuous hotel load of 50 kW for light, vents, air conditioning etc, the Tab.5 shows the following results: P_E = 81 kW , with a P_B of 148 kW (better detailed propulsive efficiency obtained trough self propulsion test at Tank facilities according to ITTC procedure) , and a total request of Power as calculated with Eq. 3)

$$148 + 50 = 198\ kW \tag{3}$$

This produce a size of battery, for electric propulsion, assuming an energy density of 150 Wh/kg of 2800 kWh equal to 18.7 t. , assuming to have a discharge of 90% it is possible assume to install 21 t of batteries.

Table 5. Results of tank test – Passengers vessel Δ= 200 t .

Speed (kn)	P_E with appendages (kW)
8	35
8.5	45
9	56
9.5	67
10	81

10.5	96
11	116
11.5	144
12	181

The difference of weight as consequence of the substitution of GG.EE. with batteries shows an increase of about 8 t but we must consider also the fact that will not be installed on board fuel (diesel oil) for a total of 6 t.

The calculation and the simulation, according to data obtained from existing vessel, shows the possibility to realize full electric propulsion for an important part of public transportation in inland waters or coastal water, recharging the batteries during night time with a complete zero emissions during navigations.

At this point an important critic could arise regarding the firesafety and risk installing on board such large amount of battery packs, in consideration of the overheating risk of batteries and the consequences of contact of water with Lithium or Sodium. This problem has been examined in several studies [10-14] and there is now evidence that traditional firefighting system, also with use of water can be used to contain risk of fire for Lithium based battery packs, furthermore is possible now to consider the use of Sodium based batteries, with performances not too far from Lithium but significantly less expensive.

In fact, as reported by [15-17] is now expected a severe increase of the request of expensive materials but must be also considered the development of batteries using Na.

4. CONCLUSIONS

The conclusions of this paper is that now, with a deep cohoperation among Industry in all the fields: Battery, Propulsion systems, management systems is possible to increase the amount of full electric vessels for operating in different situation, not only in closed waters, realizing zero emissions vessels at a reasonable cost.

An important contribution from the Industry 4.0 can be the real time monitoring of the battery and propulsion [18-20] systems, in order to optimize the energy consumption, for the propulsion and for the loads on board such as air conditioning, ventilation, etc, increasing significantly the performances and life of batteries.

It is important to underline that the “turning point” in this kind of project is consequence of the developments of better batteries with higher density of power and also of the drop in terms of costs of batteries.

In terms of future challenges for Industry 4.0 is expectable and highly recommended a deep investigation aiming at solve the problem of recycling and waste management of the used batteries in order also to face the need of critical minerals.

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