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(REVIEW ARTICLE)

Technical and economical comparison of optimized diesel-electric propulsion systems for a pleasure craft

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Abstract

The article compares between them three diesel-electric propulsion and power generation systems, characterized by a similar overall power but with diesel-generator sets very different in number and power; these systems are developed for the needs of an existing pleasure craft. In addition, each system configuration includes two versions, with diesel-generators operating at constant speed and other at variable one. Once defined the used diesel engines type, the characteristics of the six diesel-electric systems have been defined and optimized, by a genetic algorithm, in both design and off design ship speeds. The main performance, weight and cost of the generated systems, with both constant and variable speed diesel-generators, are compared between them and with the pleasure craft current mechanical propulsion system, for different vessel speeds. The comparison results are presented in graphical and tabular form and extensively commented.

Keywords: Simulation; Optimization; Ship diesel-electric systems; Ship propulsion plants comparison

1. Introduction

To reduce polluting emissions and combat global warming, increasingly restrictive International Maritime Organization (IMO) regulations have been enacted over the years [1,2,3,4]. The requirement of designing energy efficient and environment friendly ships resulted in the development of several types of hybrid propulsion architectures [5]. Nowadays several yachts are propelled with diesel-electric propulsion plants [6,7]. The increasing use of this yacht propulsion system type is due to the greater environmental awareness [8], greater comfort that the diesel-electric plants entail (noise and vibrations decreasing during navigation [9]) and their potential for fuel saving [10]. Based on a bibliographic survey, in a previous article [11] the author presented an extensive analysis and comparison concerning yachts and pleasure crafts with traditional (mechanical) and diesel-electric propulsion systems, these last with both constant or variable speed electric generators.

In the marine high-power diesel-electric plants, the propulsion and power generation systems currently used in large passenger ships, the diesel-generator number is rather standardized [12], while in the small ships, such pleasure craft and yacht, the number of diesel-generators and its optimal power distribution between them do not yet seem sufficiently defined. In the pleasure craft diesel-electric systems, due to propulsion and hotel low electrical power required, different layout configurations can be considered, ranging from plant schemes with few (two) high-power diesel-generators [6], to solutions comprising a greater number of lower power diesel-generators (generally no more than four [13]).

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In literature, different algorithms for ship propulsion and power generation systems optimization are presented [14-17]. As reported in an author previous work [11], for the diesel-electric ship propulsion systems optimization the approach based on the genetic algorithm [18,19] present interesting features.

Starting from different power marine diesel engines data, all suitable to be used on the pleasure crafts, by means of a genetic algorithm procedure also described in [11], a consistent number of diesel-electric systems schemes have been generated [11], all suitable to satisfy the power request of pleasure crafts. In the paper, starting by a previously defined number of diesel-generator groups in the diesel-electric (DE) system, the genetic algorithm is employed to generate and optimize different DE systems, all suitable to fulfil the propulsion and electric power request of an existing pleasure craft. Three DE basic systems have been configured, characterized by two, three and four main diesel-generators. Each DE basic system is developed and optimized in two variants, with the diesel-generator sets operating at constant or variable speed, as already reported in previous author articles [11,13].

Always using the genetic algorithm, the six defined DE propulsion systems have been optimized also at partial loads working conditions, depending to yacht speed.

The performances of the generated and optimized diesel-electric propulsion plants are evaluated, compared between them and with that of the yacht's original mechanical propulsion system, for different vessel speeds. The overall plant weight and cost of the six generated DE propulsion systems are determined and compared between them. Finally, the constant and variable speed diesel-generators solutions are compared between them.

2. Selected engines

To generate different schemes of DE propulsion systems, four MTU four-stroke marine diesel engines were selected, whose main characteristics are shown in Tab. 1 [20-23].

Table 1 Main feature of the considered four MTU engine models

Engines parameters	**16V 4000 M63L**	**12V 4000 M63**	**8V 4000 M53R**	**8V 2000 M61**
Brake power [kW]	2240	1500	746	400
MCR speed [rpm]	1800	1800	1600	1800
Cylinders number	16V	12V	8V	8V
Bore [mm]	170	170	170	130
Stroke [mm]	210	210	210	150
Displacement [l]	76.3	52.7	38.2	15.9
b.m.e.p. [bar]	19.6	19.0	14.6	16.8
Dry mass [kg]	8590	7240	5460	1790

All selected engines are suitable for mechanical and diesel-electric marine propulsion plants. As shown in the Tab. 1, the different powers of the selected engines allow to generate a large plants number configurations (especially if DE type), for medium-large yachts propulsion and electric load.

3. Case study

As case study a conventional mechanical propulsion plant of an existing pleasure craft is considered; Tab. 2 reports the ship main data. The current vessel propulsion plant is composed by two independent shaft lines, in each of which a four-stroke diesel engine drive, via gearbox, a fixed pitch propeller. Three diesel generators with different power levels are used to electric power generation. For emergency case one additional diesel generator is used.

Table 2 Main data of the conventional propulsion plant pleasure craft

Variables	**Symbol**	**Value**
Length overall	LOA	70.000 m
Length at weather deck level	L (w.d.)	60.800 m
Length between perpendiculars	Lpp	55.400 m
Moulded breadth	B	12.500 m
Overall Beam	BOA	13.200 m
Moulded Depth & weather deck	D	6.000 m
Mean Scantling Draft	T	3.400 m
2 x Main Engines		2 x 2525 kW at 1900 rpm
Gen-sets power		2 x 200 + 1 x 148 ekW + 1 x 69 ekW for emergency
Trial top intermittent speed:		16.0 Kn
Cruising speed, at ½ standard load		15.0 Kn
Passengers accommodation		12 persons
Hotel electric load		193.7 kW

4. Methodology

An also presented [11] genetic algorithm optimisation-based approach is used to select the DE propulsion system layouts and the engines working points, to minimise the cost function ($f\,(ndg, n_i, P_i)$) also defined in [11] and here reported:

$$f = \sum_{i=1}^{ndg} P_i bsfc(n_i, P_i) \quad \text{……………..(1)}$$

with: *ndg* the system diesel-generator number, P_i the i° diesel-generators brake power, *bsfc* the i° engine brake specific fuel consumption in the rotational speed (n_i) and brake power (P_i) working condition. Eq. (1) is applied with the constrain, also reported in [11], checking that the available system power is sufficient to reach the design and off design vessel speed. As regard the employed system optimization procedure, the following observations can be made:

- Among the numerous plant schemes generated by the genetic algorithm [11], three have been selected: one with two main diesel-generators (DG), another with three main DG and a third with four one.
- Four different diesel engines models, whose main characteristics are reported in Tab. 1, are considered for the selected DE propulsion system layouts.
- Each of the three selected plant schemes is characterized by the overall system minimum fuel consumption at 17 knots ship speed (the design one), each of them compared to other plants with the same number of main diesel-generators generated in [11].
- The three selected DE propulsion system are developed and optimized either with Direct Current (DC) or Alternate Current (AC) electric power distribution. In the first case, both engines revolution speed and power can be set; in the second one, the engines revolution speed is kept constant.

The DE propulsion systems numerical modelling has been described in previous authors papers [11,13,24,25]. For each main diesel engines selected numbers (from 2 to 4), the optimisation problem of electric-generators system minimum fuel consumption, to ship speed of 17 knots, has been set up: the variables considered in the genetic algorithm optimisation procedure are the following:

- The power of each installed engine kind.
- In the case of system with DC distribution, the revolution speed of each engine of the system.

The ship design speed requirement of 17 knots has been implemented as a nonlinear constraint. A genetic algorithm [11] Matlab implementation is used as problem solver.

In the propulsion systems optimization process the following electric components efficiency range have been considered:

- Electric motors and alternators: $\eta = 0.95 \div 0.97$.
- Inverters DC/AC (and vice-versa): $\eta = 0.98 \div 0.99$.
- DC/DC and AC/AC converters: $\eta = 0.96 \div 0.98$.

The lower efficiency values refer to the lower power electric components, while the opposite occurs for the higher power one.

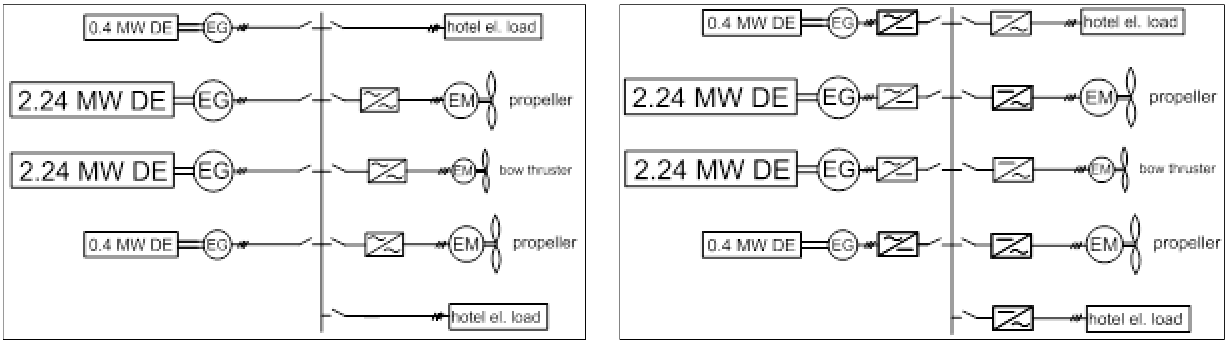
The diesel engines efficiency is determined by the specific fuel consumption contours on engine operating diagram.

For each of the six propulsion systems selected layouts, with a procedure similar that used to optimize the systems under design conditions (ship speed of 17 knots), the optimal propulsion systems diesel-generators active number and its working condition are determined also for several ship speeds. For each system layout, the off-design optimization genetic algorithm results are the optimal number of running engines and their respective power and revolution speed to minimise fuel consumption for different ship speeds.

5. Propulsion systems

Figs. 1-3 shows the six selected diesel-electric propulsion systems, among those generated by the propulsion plants procedure optimization [11]. The numerical codes used to plants identify shows the number of diesel engines in the system, in descending power order as reported in Tab. 1.

The plants of Fig. 1 named (2002) uses two 16V 4000 M63L diesel engines (the main plant engines type, 2240 kW each engine as shows in Tab. 1) and two 8V 2000 M61 diesel engines (400 kW each one), the latter are used almost exclusively for satisfying the hotel electrical load during stops in the harbor or at anchor. Fig. 1a shows the (2002) AC system scheme (constant speeds diesel-generators), while in Fig. 1b is visualized the (2002) DC system one (variable speeds diesel-generators).



a b

Figure 1 2002 plants scheme (a) DG constant speed (b) DG variable one

The propulsion systems reported in Fig. 2, named (0301), are composed by three main plant engines 12V 4000 M63 diesel engines (1500 kW each one) and one 8V 2000 M61 diesel engine (400 kW), this last is used mainly to hotel electrical load satisfaction when ship is stops in harbor or at anchor.

Finally, Fig. 3 shows the third selected propulsion systems, named (0221), that employ two 12V 4000 M63 and two 8V 4000 M53R diesel engines (all together constitute the main plant engines, with 1500 and 746 kW each engine power respectively), the 8V 2000 M61 diesel engine is employed almost exclusively for satisfy the hotel electrical load in harbor or at anchor. Similarly to the (2002) propulsion system, also these last plants ((0301) and (0221)) are developed in both AC (Figs. 2a and 3a) and DC schemes (Figs. 2b and 3b).

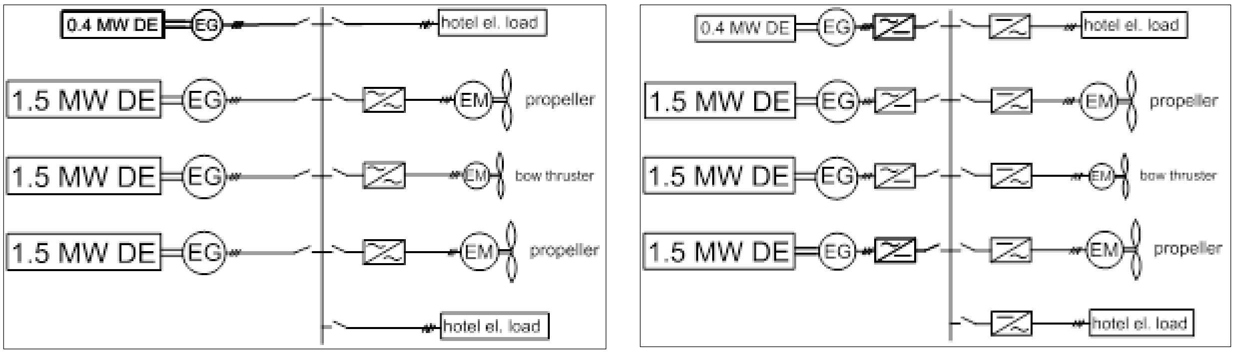


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Figure 2 0301 plants scheme (a) DG constant speed (b) DG variable one

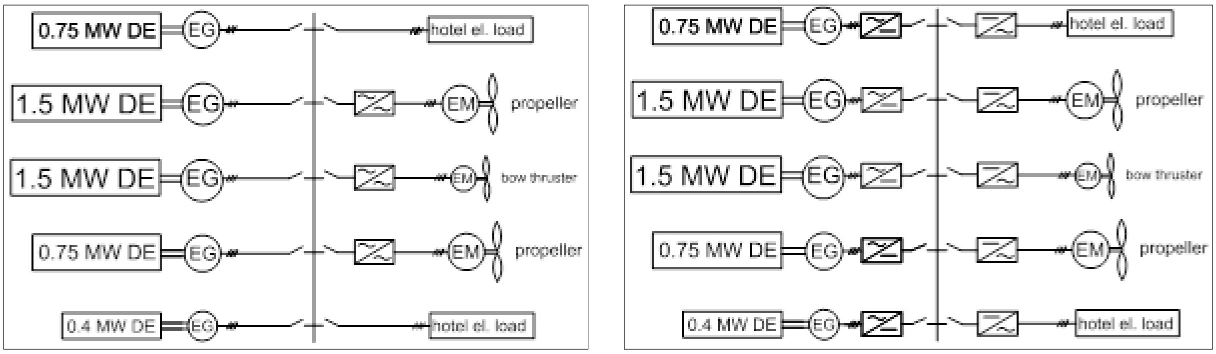

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Figure 3 0221 plants scheme (a) DG constant speed (b) DG variable one

The (2002) system is characterized by a reduced number (2) of main engines, while the (0221) one is composed of a greater number of lower power main engines (4). The system (0301) is an intermediate solution between the two previous ones, in terms of main engines number (3) and their power.

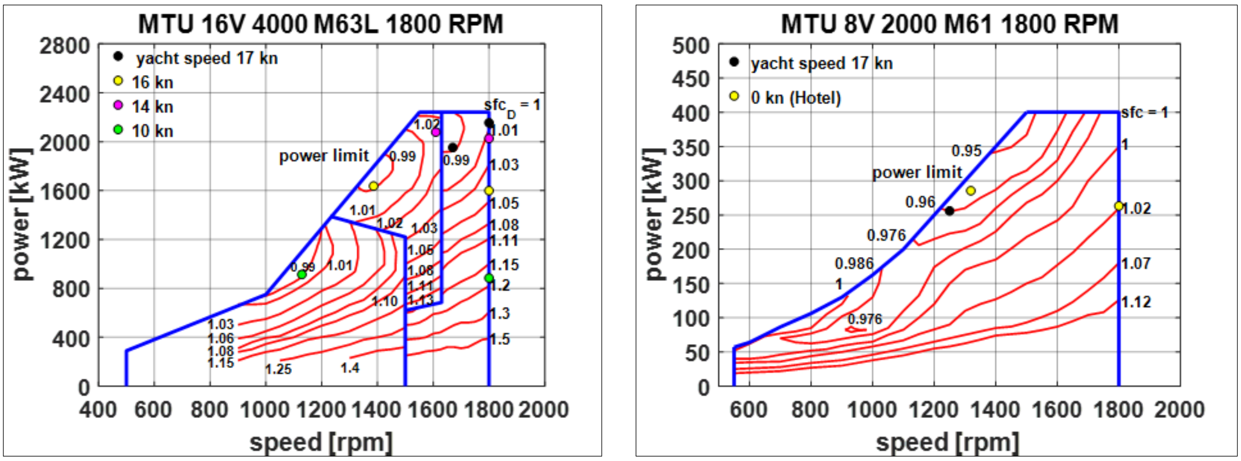
The total diesel engines power of the six selected propulsion systems is: 5280 kW the (2002) plant, 4900 kW the (0301) and 4900 kW the (0221) ones.

The 2002 system is more powerful than the other two, because it requires a second 400 kW diesel engine, as reserve in case of failure of the other same power one. Without it, the 2002 plant power would be similar that of the other two ones (4880 kW). The other systems (0301 and 0221) do not require a second 400 kW diesel generator, because in case of its failure, other engine-generators present in the system (the 1.5 MW one in the 0301, and the 0.75 MW one in the 0221one) can replace the 400 kW one. This is not possible in the 2002 system, given the considerable power of the main engines (2240 kW each one).

6. Systems optimization results

As earlier mentioned, for each of the six selected propulsion systems, with both AC and DC schemes, starting by the also defined engines number and type, to a defined ship speed, the genetic algorithm [11] determines the optimum system working conditions (number of DG actives and its power and speed percentage, referring the MCR of each diesel engine), to fulfil the ship propulsion and hotel load with the minimum electric generation system fuel consumption. 17 knots are considered as vessel design speed, while ship speeds of 16, 14, and 10 knots are considered for the off-design systems working conditions. To ship stops in harbor or at anchor conditions, a zero knots vessel speed is considered. In this case the only electrical load to be powered is the hotel one (Tab. 2 and Figs. 1-3).

For each propulsion system, its optimum working conditions, to different ship speeds, are obtained from the genetic algorithm, that determine the number of active DG and, for each DG, its working conditions (speed and load). The optimization results are shows in Figs. 4-6, where the engines working conditions are reported in the engines power-speed plan, for the selected plant system and ship speeds. The figures report the engines working conditions pertinent both AC and DC plants schemes.



a

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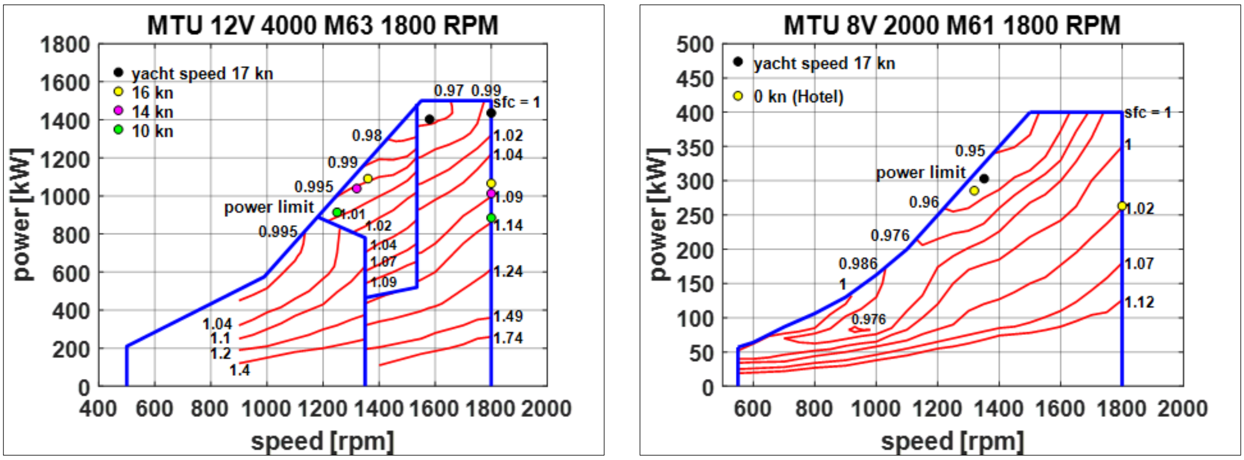
Figure 4 2002 AC and DC plants: 16V 4000 M63L (a) and 8V 2000 M61(b) engines working conditions on the power-speed specific fuel consumption plan to variable and constant DG speed vs yacht speed



a

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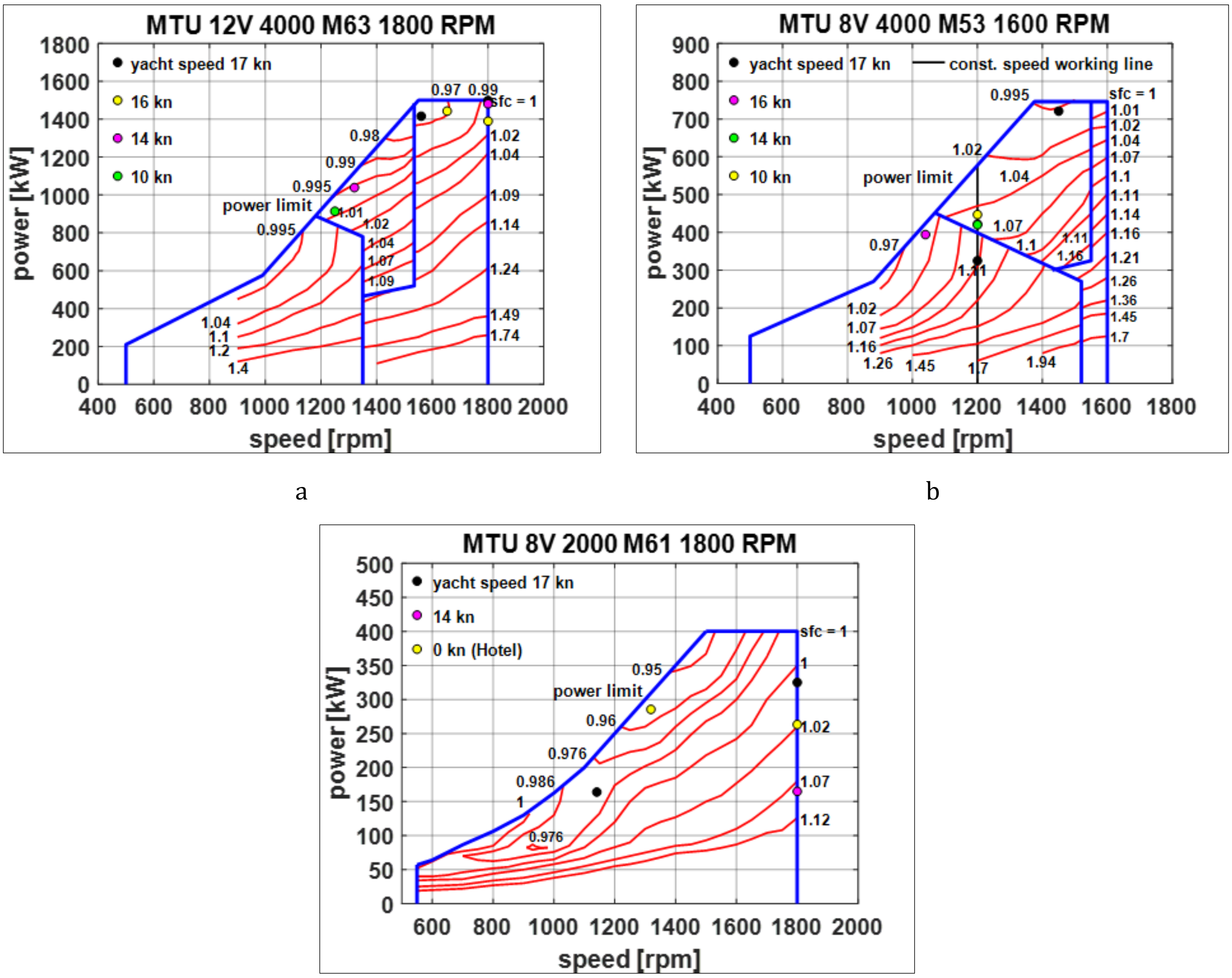
Figure 5 0301 AC and DC plants: 12V 4000 M63 (a) and 8V 2000 M61(b) engines working conditions on the power-speed specific fuel consumption plan to variable and constant DG speed vs yacht speed



a

b

c

Figure 6 0221 AC and DC plants: 12V 4000 M63 (a), 8V 4000 M53 (b) and 8V 2000 M61(c) engines working conditions on the power-speed specific fuel consumption plan to variable and constant DG speed vs yacht speed

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7. Systems comparison

The selected and optimized DE propulsion systems main data are compared with actual Numptia mechanical one, whose operating data for different working conditions are provided by the yacht manufacturer.

Fig. 7 shows the overall engines delivered power of mechanical and DE plants difference, determined by:

$$\Delta x/x\% = \frac{x_{DE} - x_{NUMPTIA}}{x_{NUMPTIA}} 100\ [\%] \text{ .... } (2)$$

where: x_{DE} and $x_{NUMPTIA}$ are the generic variables referred the diesel-electric system (with AC or DC plant schemes) and actual Numptia mechanical plants respectively.

Fig. 7 reports that at 17 knots ship speed the power supplied by the DE systems engines is greater than that of the mechanical one. This is due to the greater electric power transmission losses from engines to the propellers in the DE plants, due to the electrical energy conversion components present in these systems. At 16 knots ship speed this DE plants disadvantage is cancelled in the AC plants and strong reduced in the DC one, while for lower ship speeds the power of the mechanical system engines becomes greater. This trend is due to DE plants better propeller efficiency to the lower ship speeds. In the DE systems the propeller speed is independent to the DG engines one, while this does not happen in the mechanical plant.

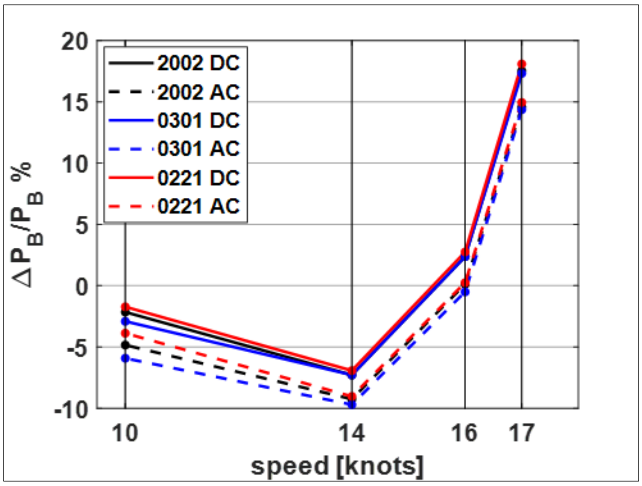


Figure 7 Variable (DC) and constant (AC) DG speed 2002, 0301 and 0221 plants diesel engines power vs Numptia mechanical one difference percentage vs yacht speed

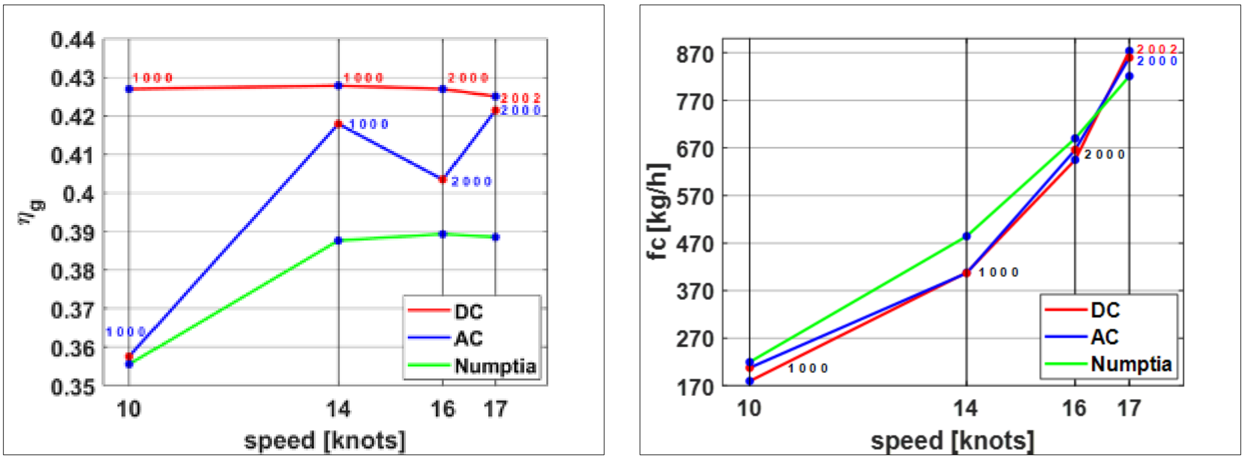
Fig. 7 shows also that the greater number of electrical energy conversion components present in DC systems (with variable speed DG), leads a lower efficiency in the electrical energy conversion and transport, compared to AC ones (with constant speed DG). The figure also shows a DE systems diesel engines overall brake power difference between the three considered DG number solutions, with the 0301plant advantage, followed by the 2002 and 0221 one. This difference, greater in the AC systems, is due to the electric components efficiency, above reported.

Fig. 8a reports the AC and DC 2002 DE systems and mechanical one overall engines plant efficiency (η_g) comparison, for the considered vessel speeds. This parameter is calculated with:

$$\eta_g \% = \frac{\sum P_{E\,act}}{\sum \left(M_f\, FLHV\right)_{E\,act}} 100\ [\%] \text{ .... (3)}$$

where: $P_{E\,act}$ is the active engines brake power; M_f e $FLHV$ the total fuel mass flow rate and its lower heating value respectively.

For the DE plants, Fig. 8, 9 and 10 also reports the number of active DGs, determined by the genetic algorithm optimization procedure, versus the considered ship speeds.



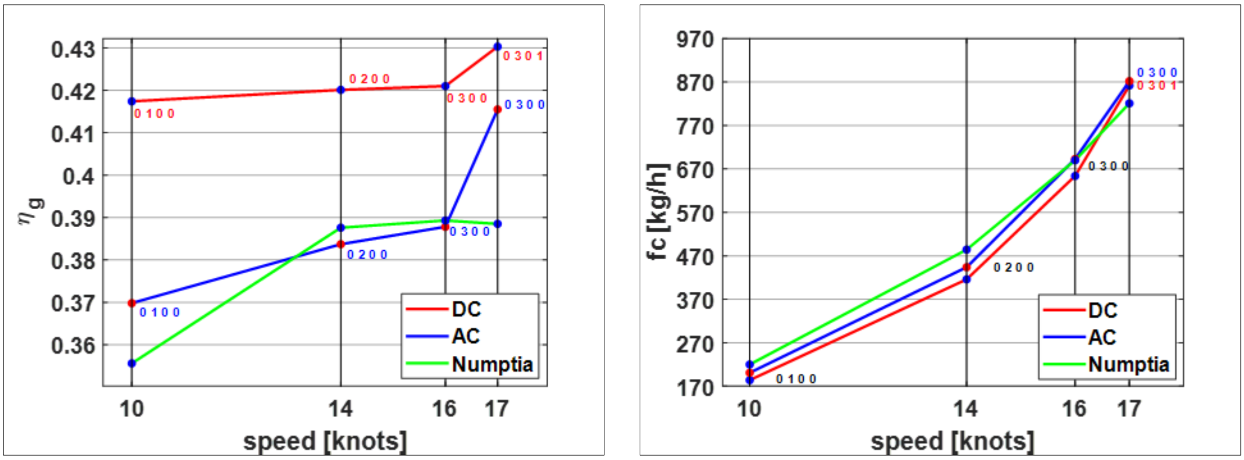
a b

Figure 8 2002 and actual Numptia plants overall efficiency (a) and fuel consumption (b) comparison for different yacht speeds

The 2002 DC system is characterized by high and almost constant overall engine efficiency (η_g) at all tested ship speeds (Fig. 8a), while in the AC system this efficiency is always lower and varies considerably according to ship speed. This difference is due to the DC system possibility to operate each active DG in the minimum specific consumption conditions at the required power (as shown in Fig. 4). Overall engines efficiency of the system is maximized by the genetic algorithm, which for a given overall engines required power (function of the ship speed), determines the number and type of active DGs, and the respective apportionment of power and speed. Fig. 8a shows the mechanical system lower efficiency compared to the DE ones, for all tested ship speeds. This depends to the fact that in the mechanical propulsion plant both engines are active at all ship speeds, and their speeds are proportional the propellers one.

At 17 knots ship speed, although the overall engines efficiency is considerably lower in the mechanical system (Fig. 8a), its fuel consumption (*fc* in Fig. 8b) is lower than that of the DE ones. This is due to the engines lower power required by the mechanical system, compared to that of DE ones, as shown in Fig. 7. To the vessel speed decrease, the mechanical plant fuel consumption becomes greater than that of DE ones. This fact is explained in the data shown in Figs. 7 and 8b.

In the 0301propulsion system, the DC one the overall engine efficiency (η_g) reduces of one percent to reduce ship speed from 17 to 16 knots (Fig. 9a), and remains approximately constant as ship speed decreases.



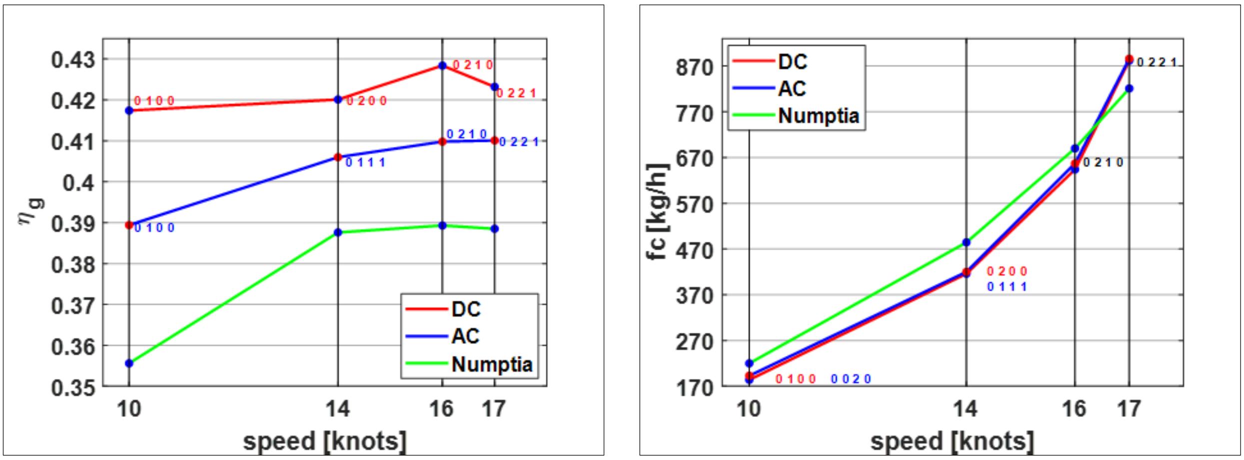
a b

Figure 9 0301 and actual Numptia plants overall efficiency (a) and fuel consumption (b) comparison for different yacht speeds

The same figure shows that the AC system engines overall efficiency undergoes a strong reduction in the passage from ship speed 17 to 16 knots. This efficiency reduction continues in a lesser extent to further vessel speed decreases. From Fig. 9a can be observed that at 16 and 14 knots of ship speeds the AC system efficiency is lower than that of the mechanical one.

The fuel consumption comparison between the three plants, reported in Fig. 9b, is similar to that of the 2002 plants (Fig. 8b), with the only difference that the 0301 DC system fuel consumption is always a little less than the AC one.

The overall engine efficiency (η_g) of the 0221 DC system is characterized by a variation, versus the ship speed, as reported in Fig. 10a.



a

b

Figure 10 0221 and actual Numptia plants overall efficiency (a) and fuel consumption (b) comparison for different yacht speeds

In the 0221 AC system the overall system efficiency is always lower than that of the DC one, and gradually 2% decreases from 17 to 10 knots ship speed. Fig. 10a shows also that in the actual Numptia plant this efficiency is 2-3.5% lover to that of the 0221 AC system, and about 3-6% lower than the DC one.

The fuel consumption comparison of the three plants, visualized in Fig. 10b, shows a trend similar to those already reported in Figs. 8b and 9b (referred to 2002 and 0301 DE systems and actual Nunptia mechanical propulsion plant), with the difference that in the case of 0221 systems (Fig. 10b) the fuel consumption is very similar between the AC and DC plants, in all tested ship speeds.

A more detailed analysis of the fuel consumption differences between the actual mechanical and the DE systems, also reported in Figs. 8b, 9b and 10b, is shown in Tab. 3, in terms of percentage difference, determine by equation:

$$\Delta fc = \frac{fc_{DE} - fc_{MECH}}{fc_{MECH}} 100 \; [\%] \;\ldots\ldots\ldots\ldots(4)$$

where: fc_{DE} and fc_{MECH} are the overall plants fuel consumption referred to DE and mechanical plants respectively.

Table 3 DE plants fuel consumption difference vs mechanical one for different ship speeds

DE system	**Energy distribution**	Δfc [%]			
		Ship speed			
		10 [knots]	**14 [knots]**	**16 [knots]**	**17 [knots]**
2002	AC	-5.45	-15.91	-3.48	4.75
	DC	-18.18	-15.70	-6.52	6.45
0301	AC	-8.64	-8.26	0.43	6.21
	DC	-16.36	-14.05	-5.22	4.99
0221	AC	-12.27	-13.22	-4.78	7.92
	DC	-16.36	-14.05	-6.67	7.43

Tab. 3 shows that at 17 knots ship speed the DE systems *fc* is greater than that of the mechanical one currently used. At lower vessel speeds all DE systems are characterized by a lower *fc* vs the mechanical one, particularly in DC energy distribution systems. The advantage of these plants type increase to the ship speed decrease. The 2002 DC plant scheme it allows a modest greater fuel saving compared to the other two DC schemes (0301 and 0221). Generally, starting from 16 knots ship speed and lower, the DE AC systems allow lower *fc* reductions (compared to the mechanical one) than those of the DE DC systems.

A preliminary DE plants main components (i.e.: thermal and electric engines, electric generators, energy conversion devices) overall weight estimation has been carried out by its main components manufacturer data [20-23,28,29]. For the six DE propulsion systems the determined weights are reported in Tab. 4.

Table 4 Estimated DE main components overall plant weight

DE system	**Main therm. engines numb.**	**Energy distribution**	**Overall weight [t]**	**DC vs AC plants weight diff. [%]**
2002	2	AC	54.97	14.33
		DC	62.85	
0301	3	AC	58.29	15.74
		DC	67.47	
0221	4	AC	54.22	11.42
		DC	60.41	

The fourth column of Tab. 4 shows that, to parity of system configuration (2002, 0301 and 0221), the total weight of the DC systems is always greater than that of the AC one, given the smaller number of electric components present in these lasts one, compared to the DC systems. Column five of Tab. 4 reports, for each system configuration, the DC vs AC systems weight percentage difference, determined by:

$$\Delta x = \frac{x_{DC} - x_{AC}}{x_{AC}} 100 \; [\%] \quad \text{..................} \; (5)$$

with: x_{DC} and x_{AC} the generic variables referred to DC and AC plants electric energy distribution respectively. The ratio between the heaviest DE system (0301 DC) and the lightest one (0221 AC) is 1.24 (see Tab. 4).

Tab. 5 shows the generated DE systems main components specific costs [12,16,26,27].

Table 5 Specific DE systems main machinery costs

Machinery item	**Specific cost range[€/kW]**
Diesel engine	365-425
Electric motor/generator	100-250
AC ↔ DC converter	150-300
Propeller line	105

In the table, for each component type, a range of values is reported, the lower one relates to the component characterized by the higher power, the opposite for the components with lower power among those used. Starting from the DE system schemes (reported in Figs. 1-3) and components characteristics, by Tab. 5 an overall cost estimation of the considered DE systems main devices is reported in column four of Tab. 6, for both AC and DC energy distribution schemes.

Table 6 DE systems main devices overall cost

DE system	Main therm. engines numb.	Energy distribution	Overall cost [M€]	DC vs AC plants cost diff. [%]
2002	2	AC	3.80	23.68
		DC	4.70	
0301	3	AC	3.60	25.00
		DC	4.50	
0221	4	AC	3.70	27.03
		DC	4.70	

The data reported in column four of Tab. 6 obviously show a lower cost of the AC systems, compared to DC ones, given the greater number of components present in these latter, to same system configuration. The same column shows that between the same electricity conversion-distribution plants type (AC or DC), the overall plants cost varies negligibly between the different system configurations (2002, 0301 and 0221). The percentage difference between the DC systems compared to the AC ones, to the same system configuration, determined by eq. (4) is displayed in the fifth column of Tab. 6; from the table can be observed that the AC systems overall cost difference, compared to the DC one, increases as the increases of the number of main engines presents in the system (this last parameter is shown in the second column of Tab. 6). The ratio between the overall cost of the most expensive DE system (2002 and 0221 both DC) and the less expensive one (0301 AC) is 1.3 (Tab. 6).

8. Conclusions

Starting by an existing pleasure craft data, in the paper its conventional propulsion plant is substitute, by simulation, with three diesel-electric systems characterized between them by different DG number and power. Each system layout employs both AC and DC electric power distribution. The six DE systems are generated and optimized by a genetic algorithm, employed also to DE systems efficiency optimization in different working conditions, these last defined by four vessel speed values.

The comparison results between the original pleasure craft conventional propulsion plant and the proposed diesel-electric propulsion systems can be summarized as follows.

To regard of overall plant efficiency:

- The DC systems get the highest and least variable values with ship speed (with the 2002 system having a near 1% higher value than the other two DE DC one);
- The AC systems obtain lower overall plant efficiency compared to DC one, with a consistent variation of this value to the ship speed variation. Plant 0221 achieves an average highest efficiency with minor variation to the ship speed variation, compared to the other two AC plants;
- The conventional propulsion plant is characterized by overall efficiency that are almost always lower than those of DE plants (especially with respect to DC), with a trend that decreasing as the ship speed decreases.

To fuel consumption regard:

- To 17 knots ship speed (the higher considered) the conventional plant is characterized by a lower fuel consumption compared to all the analyzed DE systems, which have very similar fuel consumptions to each other to this ship speed;
- At lower ship speeds (10÷16 knots) the DE systems have lower fuel consumption than the conventional plant. In particular, the three DC systems have the lower and very similar trend fuel consumption, while the AC systems are characterized by a similar or slightly higher consumption than the DC one, especially the 0301 system.

To overall plant weight regard:

- The DE AC systems are characterized by a global system lower weight, which varies between 11 and 16% approximately, compared to analogue DC systems. The three AC systems have a maximum weight difference of approximately 7% (with the 0301 system resulting the heaviest), while the maximum weight difference of the DC systems is approximately 12% (also in this case the heaviest system is the 0301);

To overall plant cost regard:

- All the AC systems have a very similar total cost, the same consideration also applies to the DC one. The DC systems higher cost compared to the AC one is about 27%.

Was not possible compare the DE systems weights and cost with respect to the conventional propulsion one due to lack of data relating to this latter.

The main conclusions drawn from this research are: the DE DC systems are characterized by a slightly less fuel consumption and a greater systems weight and cost compared to the AC one. Also the AC systems allow fuel savings compared to the ship's original mechanical one. The comparison between the DE systems, relative to the different main engines number did not provide clear indications on which is the best solution, being all DE systems characterized by fuel consumption, overall weight and plants cost with slightly different from each other, within their respective specifications (AC and DC). As regard to this last aspect, AC systems are characterized by significantly lower weight and system cost (especially this last) than DC systems, with fuel consumption only slightly higher than the latter. Considering that this ship type is generally characterized by a reduced number of annual navigation hours, AC systems seem preferable referring the DC one.

Abbreviations

AC	alternating current electric power distribution
DC	direct current electric power distribution
DE	diesel electric
DG	diesel-generator
P_B	diesel engine brake power

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare no conflict of interest.

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