OPTIMAL MANAGEMENT OF A DIESEL-ELECTRIC PROPULSION PLANT WITH EITHER CONSTANT OR VARIABLE DIESEL GENERATORS SPEED

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ABSTRACT

In recent years, diesel-electric propulsion has become a standard for many ship types. The traditional way to manage the electric flow onboard is by using AC distribution, and to run diesel generators at constant rotational speed to get the correct distribution frequency and to limit the weight and the size of the electric machinery. More recently, the current progress in DC field allowed exploiting the advantages of this technology, for instance, greater flexibility in the mode of operation of diesel generators in terms of rotational speed, with benefits in terms of efficiency. In this article, a pleasure craft, powered initially with a traditional propulsion plant, is repowered with two alternative diesel-electric propulsion plant layouts: a standard one, with AC distribution and torque controlled diesel generators at a constant speed, and a DC-link one with variable speed controlled generators. Variable speed diesel generators require a custom control system to manage the additional degree of freedom involved. For such a reason, the optimal working points of the diesel engines are assessed in design and off-design conditions by using a genetic algorithm, with the final aim of minimising the overall fuel consumption rate. The performance of the two analysed propulsion plants are evaluated and compared at different power levels. Eventually, the results are presented and discussed.

1. INTRODUCTION

With respect to the challenges of global warming, and the international regulations, such as the energy efficiency design index (EEDI) and ship energy efficiency management plan (SEEMP) [circolari IMO], the maritime sector was enacted to decrease the growth rate of fuel consumption and greenhouse gas emission. Thus, the requirement of designing energy-efficient and environment-friendly ships resulted in the development of several types of hybrid propulsion and power supply architectures [3,2] Among them, hybrid electric propulsive systems attract significant academic and industrial interest due to their potential for fuel saving [4] and greenhouse gas emission reduction [5] in partial load and dynamic load operation [1]. The IMO regulations [8,9] affect the commercial ships, while the pleasure crafts are exempt, whereas nowadays several yachts are propelled with diesel-electric power plants. The reasons are twofold, first, currently, in the pleasure craft world, the environmental awareness is increased, and second, the use of an electric propulsion motor in a pleasure craft decreases the noise and vibrations during navigation [13] that results in a higher comfort on board. In this worldwide panorama, several configurations of the hybrid propulsion system are present [15,6]. The traditional way to manage the electric flow on board is by using AC distribution, and to run diesel generators at constant rotational speed in order to get the correct distribution frequency: this option is not the best one to minimize the diesel engine fuel consumption, since the engine does not work at its maximum efficiency, as explained above. The idea presented in this paper is indeed to generate the electric energy with variable speed generators and then using a DC grid to distribute the power on board. In light of this, an optimisation methodology to the correct sizing of the diesel generator is presented. The performances of the two analysed propulsion plants are evaluated and compared at different power levels, and the results are presented and discussed.

2. METHODOLOGY

In the proposed approach, a diesel-electric power generation and propulsion system layout is considered, either with DC or AC electrical power distribution. In the first case, the diesel engines can be controlled at variable speed, while in the second, the revolution speed of the engines is constrained by the distribution frequency. Diesel-electric propulsion presents some drawbacks due to the presence of a higher number of energy transformations that affect the overall efficiency. In particular, in case of DC energy distribution, the presence of the power inverters adds an extra efficiency loss, which could be balanced by proper control of the diesel generators, that maintains the engine efficiency high both at high and low revolution speed.

In the evaluation process the following efficiency values have been hypothesised:

- Electric motors and alternators
  - $\eta = 0.97$ for power range 2.24 ÷ 1 MW;
  - $\eta = 0.96$ for power range 1÷ 0.4 MW;
  - $\eta = 0.95$ for power range < 0.4 MW;
- Inverters DC/AC (and viceversa)
  - $\eta = 0.99$ for power range 2.24 ÷ 1 MW;
  - $\eta = 0.98$ for power range 1÷0.4 MW;
  - $\eta = 0.97$ for power range < 0.4 MW;
- DC/DC a AC/AC converters
  - $\eta = 0.98$ for power range 2.24 ÷ 1 MW;
  - $\eta = 0.97$ for power range 1÷0.4 MW;
  - $\eta = 0.96$ for power range < 0.4 MW.

Diesel-electric propulsion, on the other hand, has several benefits in terms of layout flexibility, and engines' and propellers' revolution speed control, efficient load sharing between the diesel engines, permitting a more flexible operating profile.

In this paper, an optimisation-based approach is used to select the propulsion system layout and the engines' working points, to minimise the fuel consumption, ensuring at the same time that the available power is sufficient to reach the design speed. In particular, the following observations can be made:

- The propulsion system is diesel-electric, either with DC or AC electric power distribution, in the first case, both engines' revolution speed and power can be set, while in the second, the revolution speed is kept constant.
- Four different diesel generator models are considered with a nominal power of 2240, 1500, 746, 400 kW, respectively. The number of generators of each model is determined during the optimisation process.
- The selected propulsion layout is required to minimise the total fuel mass flow rate, while at the same time ensuring the ship to reach the design speed.

The propulsion system has been mathematically described [11,10,12], and an optimisation problem has been set up: the variables considered in the optimisation are the following:

- The number of engines per type
- The power of each kind of engine installed
- In the case of DC distribution, the revolution speed of each engine type.

The design speed requirement has been implemented as a nonlinear constraint. The problem has been solved using the Matlab implementation of the genetic algorithm [7,14].

Once the propulsion system layouts have been selected, the optimal propulsion configuration has been determined for several off-design speed conditions, upper bounding the number of engines of each type with the maximum number of engines available, i.e. the number of engines obtained by the design process. Summarising, the following two main results are obtained:

- The optimal amount of engines to be installed onboard, choosing between four different models and sizes, and their power and revolution speed to ensure the ship reach the design condition;
- The optimal number of running engines and their respective power and revolution speed to minimise fuel consumption in several off-design speed conditions.

3. CASE STUDY

The case study vessel is a pleasure craft whose main data are presented in Table 1.

The propulsion plant is conventional, and it is composed by two four stroke diesel engines that drive two fixed pich propellers trough two independent shaflines, in which two gearboxes are installed. Three diesel generators ensure the electric power generation with different power levels, and one additional diesel generator is used in emergency cases.

Table 1. Main data of analysed vessel

Variables	Symbol	Value
Length overall	LOA	70.000 m
Length @ 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		2525 bkW @ 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

4. RESULTS

The propulsion system layout optimisation has been performed considering a ship design speed of 17 Kn. Moreover, the optimal propulsion configurations have been determined for the following off-design speeds: 10 Kn, 14 Kn and 16 Kn.

The propulsion system layouts resulting from the optimisation process described in section 2 are presented in Figure 1 and Figure 2, in case of constant engine revolution speed (AC energy distribution) and variable revolution speed (DC energy distribution) respectively. As a result of the optimisation process, four engines of the same type, MTU12V 4000 M63 with 1.5 MW power output. A smaller engine, MTU 8v 2000 M61 with 400 kW power output, has been added to satisfy the hotel load when the ship is at anchor, as shown in Figure 1 and Figure 2.

Figure 3 and Figure 4 show the optimal working points of the two selected engine operating diagrams, both in constant and variable revolution speed case, at the considered speed conditions. The corresponding data are shown in Table 2. In Figure 3 and Figure 4 the specific fuel consumption (sfc) contours are normalized by dividing by the corresponding value at the maximum continuous rating (MCR). Figure 5 presents the engine efficiency, defined as follows:

$$\eta_E = \frac{P_B}{\dot{m}_f \, H_i} \qquad (1)$$

Where: P_B is the diesel engine brake power in kW, H_i=42800 kJ/kg is the fuel lower heating value, and $\dot{m}_f$ is the mass fuel rate in kg/s.

Figure 6 shows the fuel consumption in the function of the ship's speed in the considered cases. Note that the engines controlled at a variable revolution speed have higher efficiency, and, moreover, the efficiency is maintained high also at partial loads. In light of this, the DC distribution propulsion system has a lower fuel consumption rate compared with the AC distribution, as the higher engine efficiency compensates the additional energy loss due to the presence of the power inverters.

Eventually, Figure 7 presents the normalised difference between the two considered cases in terms of engine total power output, while Figure 8 shows a similar comparison in terms of engine efficiency and fuel consumption difference. The normalised differences are computed according to the following equation:

$$\Delta x / x\% = \frac{x_{VAR\ NE} - x_{CONST\ NE}}{x_{CONST\ NE}} 100\ [\%] \qquad (2)$$

Where: $x_{VAR\ NE}$ and $x_{CONST\ NE}$ are the general variables (x) associated with the propulsion plant working with variable and constant revolution rate, respectively.

The advantage of the DC distribution power plant with variable revolution speed control, especially at lower loads, is straightforwardly noticeable. The higher engine efficiency (up to 13%) allows the variable speed controlled propulsion to have a fuel consumption rate reduction up to 8% with respect to constant speed, despite the power output required to reach the same speed is slightly higher, up to 3%.

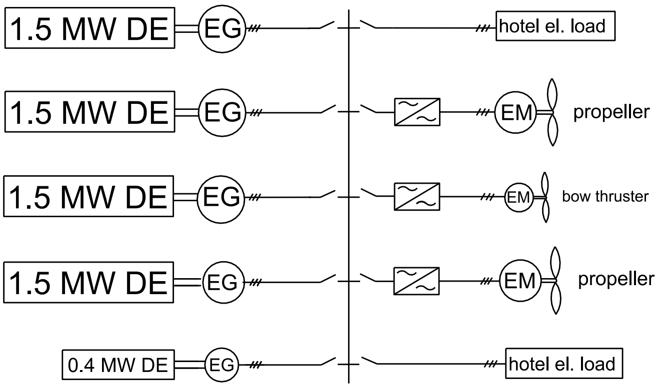

Figure 1. Constant rpm propulsive configuration.

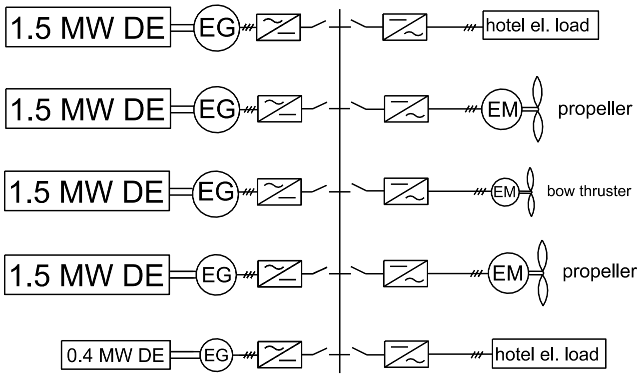

Figure 2. Variable rpm propulsive configuration.

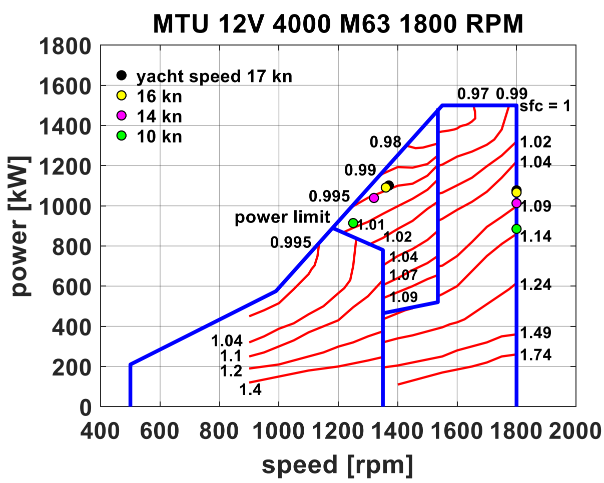

Figure 3. Engine operating diagram with normalized sfc contours and working points with constant and variable rpm propulsive configuration.

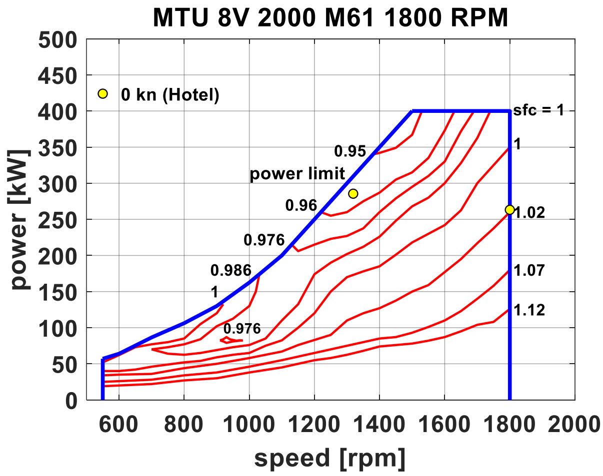

Figure 4. Engine operating diagram with normalized sfc contours and working points with constant and variable rpm propulsive configuration.

Table 2. Comparison of the different power generation plants.

Variables	Generation mode	Yacht speed [kn] 17	16	14	10	0
Required Power [Kw]	Constant RPM	4308	3198	2026	885	263.2
	Variable RPM	4407	3274	2078	914	285.5
Engine Efficiency	Constant RPM	0.389	0.388	0.384	0.370	0.384
	Variable RPM	0.421	0.421	0.420	0.417	0.409
Fuel consumption rate [kg/h]	Constant RPM	932	693	444	201	57
	Variable RPM	880	654	416	184	59

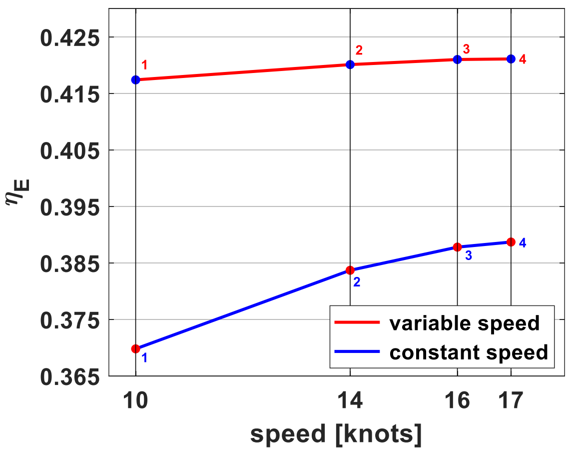

Figure 5. Comparison of engine efficiency between the two configurations. The numbers within the graph represent the number of running engines.

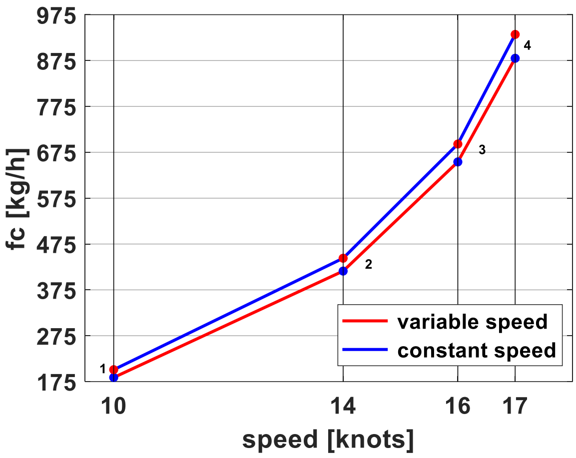

Figure 6. Comparison of fuel consumption rate between the two configurations. The numbers within the graph represent the number of running engines.

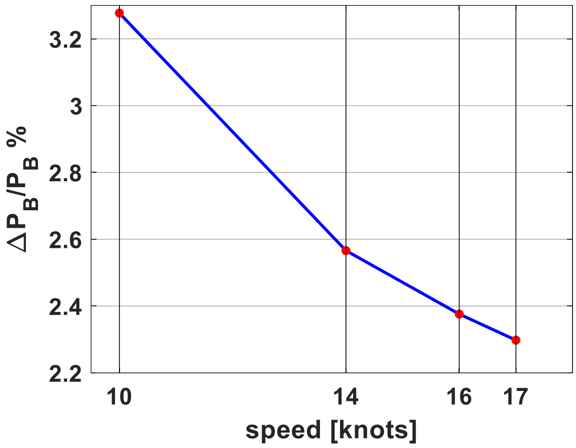

Figure 7. Normalised comparison of required power between the two configurations.

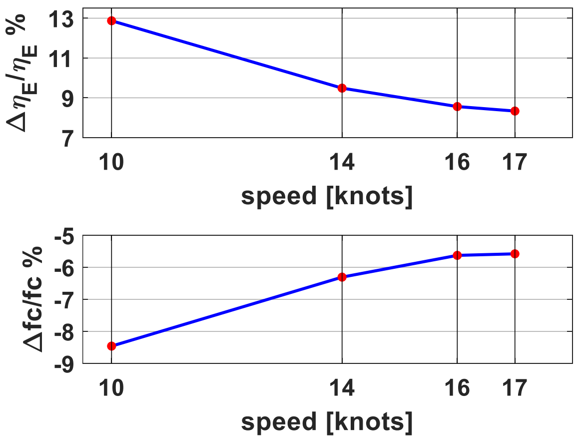

Figure 8. Normalised comparison of energy efficiency and fuel consumption rate between the two configurations.

Moreover a preliminary analysis of the total weight of the main components (thermal engines, electric motors, electric generators, energy conversion devices) has been carried out; in particular, the following weights have been estimated:

- AC distribution: 57.84 [t]
- DC distribution: 65.58 [t]

The results show that the DC power plant is 13.38% heavier than the other solution.

6. CONCLUSIONS

In this paper, a methodology to increase energy efficiency on board is presented, acting both from the design point of view by using an optimisation procedure to the correct sizing of the power plant, and form the operative point of view studying a variable speed energy generation. The results show that the major savings in fuel consumption can be higher than the 8% at partial load, while at maximum speed (full load) it is about 5%, compared with a standard diesel-electric power plant.

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