Hybrid system design and performance based on actual vessel operational data

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Abstract. The recent trend of marine industry towards more efficient and versatile ships and lower emission has increased interest in hybrid solutions. However, the spread of this technology has been limited by several factors both economic and technical. Among these, a recurrent issue is the sizing of the Energy Storage System (ESS), which is strictly connected to the vessel typology, its operation and its control system. This paper presents an algorithm, developed within Wärtsilä Italia SpA, for the extraction of sequential operating modes from data recorded on board the vessel, in order to properly design a feasible ESS. The paper shows a technical economic analysis carried out on a small cruise vessel in order to identify competitive hybrid solutions compared to traditional configurations (engines running on conventional fuel or Liquid Natural Gas). Finally, the paper compares two case studies of a small vessel powered only by fuel cells (in place of conventional engines) and batteries, in order to prove the potential benefits derived from such innovative technologies with different operational profiles, also in hybrid mode.

Keywords. Environment protection, electric system and ship energy efficiency

1. Introduction

During recent years, two main factors have driven the marine industry towards an increase of the efficiency of on board power plants: the more and more pressing environmental regulations set by the International Maritime Organisation (IMO) and the worst economic crisis since the beginning of the century.

This stringent legislation is due to several factors: according to the third IMO Green House Gas (GHG) study in 2014 [1], from 2007 to 2012 the marine industry accounted for about 2.8% of global greenhouse gas emissions, producing about 1 billion tonnes of GHGs annually, along with 15% and 13% of NO_X and SO_X, respectively.

IMO MARPOL annex VI[2] sets main regulations in the sector, introducing:

1. Limitations on the nitrogen oxide (NO_X) and sulphur oxide (SO_x) emissions for diesel engines with an output of more than 130 kW.
2. The introduction of the Energy Efficiency Design Index (EEDI) for new ships, which takes into account the amount of CO_2 emissions that a ship produces per tonne of goods and per mile.[3]

Among all the available technologies that are capable of increasing system efficiency, hybrid systems (referred to as a power generating set with Energy Storage System, ESS) are rapidly growing also due to the following factors:

- *Validated technology*: this technology has been studied since 1980 and we already have some applications that can prove its advantages [4].
- *Possible refitting*: integration with already built vessel's engine room is easy thanks to stack modularity and according to the degree of hybridisation.
- *Growth of battery market*: this is linked to the automotive sector, where hybrid systems have spread over the last ten years. The price of ESS is decreasing [5], allowing the introduction of this technology into the marine sector.

In this paper a brief review of hybrid system design and relative control is made in section 2, while section 3 shows an algorithm to extract significant data from the operating data recorded on board ship used to simplify the design process. Section 4 employs this algorithm in order to assess a feasibility study for a small cruise vessel, while in section 5 two different control strategies are compared to prove the advantages of hybrid systems even with future technologies, in particular fuel cells.

2. State of the art of design and control of hybrid system

In accordance with the complexity of the system, an increasing number of data is required for the preliminary design of the engine room from a technical and economic point of view. In a first stage the size of the engine room is established from the knowledge of all the consumers' rated power (electrical or mechanical) and their partition between propulsive and hotel power. However, in order to identify the size and number of the power producers, which could supply this amount of power, an analysis of the operation of the vessel must be performed, requiring the knowledge of power and energy required from the most frequent operating modes of the vessel.

The introduction of an ESS raises several problems in this first stage: in order to access a proper design, it is important to understand how and why to use batteries. From a general point of view, we can distinguish between the following functionalities:

- Back-up source of energy;
- Safe return to port;
- Reduce load fluctuations (also called peak shaving mode);
- Optimise load of the power producers.

From the point of view of normal engine room operation, only the third and the fourth usage mode of batteries are relevant. In fact the third mode can reduce undesired fast transient loads on the engines that might affect fuel consumption. Moreover, batteries and connected power electronics could help to stabilise the electrical network of the vessel, increasing redundancy, which is a crucial aspect in the marine field. In fact, by increasing the level of redundancy of the system, the engine margin employed during the design phase could be reduced, improving performances and allowing installation of fewer cylinders. The latter solution for the employment of batteries is more challenging from the point of view of design and control, but nonetheless it constitutes the most promising alternative, because it could seriously affect the entire engine room design and operation, providing the best benefits.

In [6] control strategies for this kind of system are analysed in depth: the core element of the more advanced architectures is the Energy Management System (EMS), which performs the so-called tertiary control. The EMS sets the power delivered by different power producers depending on load demand, the State of Charge (SoC) of the batteries and the energy drawn or supplied to them.

According to [6], there are different possible control strategies: the heuristic controllers, which are rule based, and Equivalent Consumption Minimisation Strategies (ECMS), which solve an optimal control problem to minimise fuel consumption, are the most common in the literature. From this review, ECMS seem to be more interesting especially when the operating profile is unknown. However, the effect of this kind of controller is hard to determine in the pre-design process, because it requires complex transient simulation like those performed by [7], [8] and [9].

Among possible implementations of the EMS in [10] several different strategies are compared on a vessel powered only by fuel cells: in this paper a multi-scheme EMS that combines and integrates different strategies is presented in order to increase efficiency but also to reduce FC stress, which is particularly likely at fast load fluctuations.

3. Operational data analysis

3.1. Reasons for the employment of vessel's data in engine room preliminary design

In order to properly size the batteries for the engine room preliminary design, it is mandatory to have operating data of a similarly designed vessel and the minimum amount of data needed for this purpose is strictly related to the complexity of the engine room.

Different approaches and algorithms have been developed in order to optimise the engine room during operation, thus reducing the OpEx. Nonetheless, the present cost of batteries (even if it is decreasing) poses a great problem from the CapEx point of view: comparing the Total Cost of Ownership (TCO) of traditional and hybrid machinery it is hard to identify a feasible solution.

In the following, a design approach derived from Wärtsilä experience is presented. This method considers the analysis of the vessel type, its operational profile and its specific requirements in order to assess a technical economic simulation of different engine room configurations and identify a feasible design of ESS. For this purpose, it is of primary importance to fetch data of actual vessel operational data and create a sequence of representative operating modes (e.g. harbour, manoeuvring, sailing at 14knots), in order to simplify the usage of batteries and thus their sizing, but preserving the knowledge of the sequential energy flows.

3.2. Algorithm for extraction of sequential operational modes

In order to extract a representative sequence of the operating modes, knowledge of the following data is required:

1. **Total generated power**: that is the sum of power produced by the generators (e.g. engines, gas turbines, batteries, fuel cells);
2. **Thruster power demand**: sum of the electric power delivered with all the thrusters;

3. **Representative data of propulsion condition**: it could be the speed of the vessel or the propulsive power.

The latter datum is of primary importance for the algorithm because it is used to create the different modes. The datum to be used is related to the type of vessel: for example tug boats greatly change their propulsive power if they need to generate bollard pull or are in free sailing, but the two conditions can not be distinguished by vessel's speed only. Cruise vessels, on the other hand, must respect a time schedule, therefore their speed is meaningful to distinguish different load conditions.

Figure 1 describes the algorithm, which could be resumed as follows:

1. *Identifying and splitting between manoeuvre, harbour and sea condition*: creation of a first level of cluster labels, in order to separate non-contiguous sea conditions;
2. *Identifying and splitting of different sea operating modes*: this is the core of the algorithm and is repeated for each sea cluster:
    (a) *Splitting of the data according to kernel density estimation of the propulsion relevant data*: an estimation of the probability density function is made in order to split the data into sub clusters according to all density minima;
    (b) *Cleaning of the cluster*: all the clusters that do not satisfy certain conditions (e.g. shorter than a selected threshold) are conveniently merged. If ramps are relevant to the analysis, they could be identified in this stage.
3. *Calculation of average power and deviation*: propulsive, thrusters and hotels power (if it is possible to make such a distinction) are averaged in the aforementioned clusters and standard deviation is calculated in order to have a measure of the fluctuations;

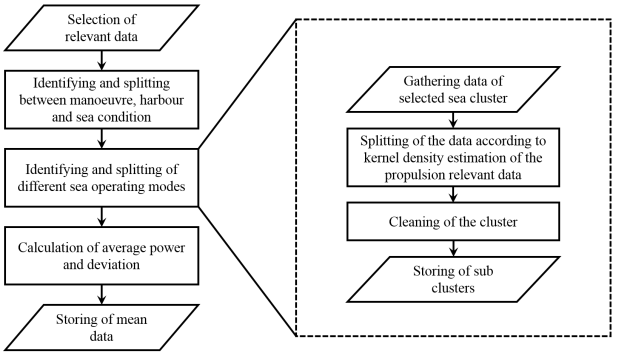


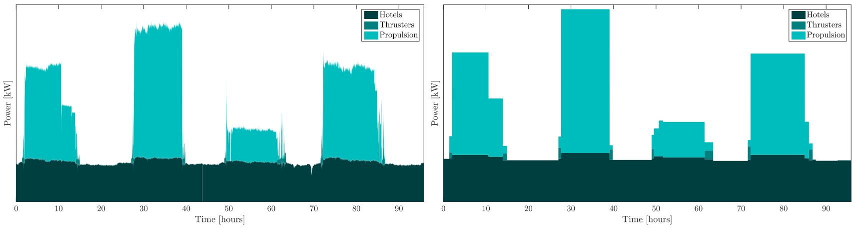
Figure 1. This diagram shows the procedure followed by the proposed algorithm.

The output of such algorithm can be used for different purposes:

- *feasibility study of hybrid system*: during the pre-design of an engine room many details are unknown and a transient simulation to assess hybrid system performance is not possible, while with this approach an acceptable amount of data is retained, as shown in section 4;
- *EMS design*: if an EMS that follows a heuristic control strategy is selected, this algorithm could be used for an initial tuning of the controller (see section 5).

4. Application of the algorithm in a feasibility study of engine room design

The algorithm explained in the previous section has been employed for the pre - design of the engine room of a small cruise vessel: figure 2a shows a representative time trace of the power recorded on board on similar vessel and figure 2b shows the extracted operation profile.



(a) Original data.

(b) Extracted data.

Figure 2. Comparison of the original data and the extracted profile for this case study.

4.1. Compared configurations

The aim of this case study is to compare different hybrid solutions to traditional solutions: table 1 reports data of the different simulated configurations. The different ESS sizes are selected with the aim of comparing benefits brought by a peak shaving strategy and those brought by strategies that seek to optimise engine loads. Because the latter strategy greatly depends on battery size, two different sizes are employed: this has the aim of identifying a solution where those batteries are too large compared to the savings it could bring. Finally, a solution with shore connection has also been examined in order to show its benefits with a hybrid system.

Table 1. Details of the different configurations analysed.

Name	Cylinder installed	ESS Capacity $[MWh]$	Shore connection installed
DE	40	-	no
DEDF	44	-	no
DE 1MWh	36	1	no
DEDF 1MWh	40	1	no
DE 2.5MWh	36	2.5	no
DEDF 2.5MWh	40	2.5	no
DE 5MWh	36	5	no
DEDF 5MWh	40	5	no
DEDF 5MWh SC	40	5	yes

In the simulations, both Dual Fuel engines and Diesel engines are employed in order to compare the effect of hybridisation of the vessel to the choice of the fuel: for this reason LNG (a low-price fuel with high LHV) and MGO (high price fuel with a lower LHV) have been employed.

In both comparisons, the reference case is designed and simulated employing an engine margin of 15%, while in hybrid configuration the engine margin is reduced to 10%: this allows installation of fewer cylinders without any loss in redundancy, which is of primary importance to decrease the cost of the ESS.

If ESS is not used only for peak shaving (as in the simulation with only 1 MWh), it is employed to optimise power load (thus loading all the engines at about 85% MCR) and to reduce engine running hours (achievable shutting off one or more engines): this makes it possible to increase system efficiency especially during slow steaming conditions and manoeuvring. The solution with shore connection has the additional benefit of shutting off all the engines in port and set the SoC of the ESS at predefined value.

4.2. Results

Figure 3 shows the OpEx of the selected configurations: one can observe a non-linear increase in savings with increased size of batteries, more relevant for Diesel configuration than the Dual Fuel (DF) one.

In particular, hybrid configuration savings come from:

1. Reduced fuel consumption;
2. Reduced running hours;
3. Reduced lube oil consumption;
4. Reduced urea consumption (only for Diesel configuration with SCRs).

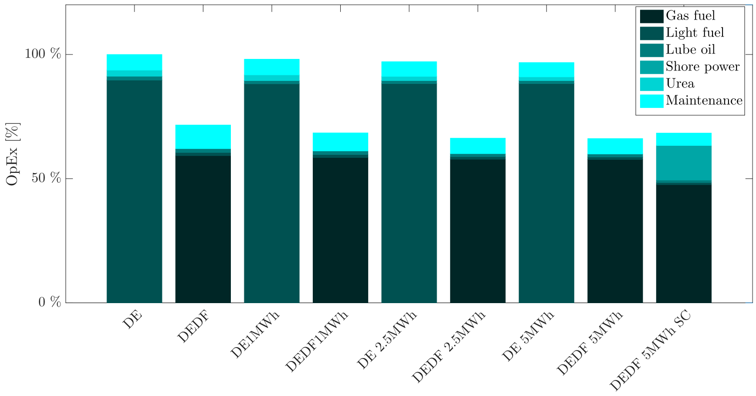


Figure 3. This graph shows the OpEx of the investigated configuration (values are dimensionless using the OpEx of the DE case as reference).

A rough estimation of CapEx relative to the different configurations is depicted in figure 4 (including engines, ESS, electrical and automation equipment and LNG tanks): these data are necessary to assess a Total Cost of Ownership (TCO)analysis, visible in figure 5, which takes into account a variable yearly cost of maintenance (that includes both spare parts and labour cost) and ESS replacement.[1]

These figures lead to the following conclusions:

- As expected hybrid solutions could provide savings that increase with size of ESS, nonetheless these benefits do not grow with the CapEx, therefore there will be an optimal choice: among Diesel solutions the most interesting solution is the one with an ESS of 1 MWh, while among DF solutions it is the one with 2.5 MWh;

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[1] According to ESS producers, battery stacks must be replaced after 12000 cycles or 10 years after installation, even if a lot of factors (e.g. depth of discharge, temperature, humidity) not taken into account here influence the ESS's lifetime.

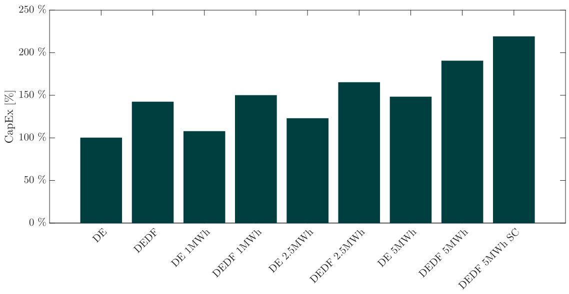


Figure 4. This graph shows a preliminary estimation of CapEx of the investigated configuration (values are dimensionless using the CapEx of the DE case as reference).

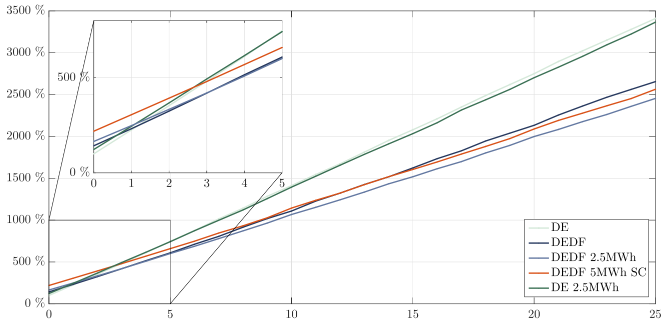


Figure 5. This graph shows the accumulated TCO of the investigated configuration upon the years (values are dimensionless using the CapEx of the DE case as reference).

- Because of the great difference of price between MGO and LNG and the higher LHV the choice of DF engines, it is more advisable from both an economic and environmental point of view;
- Even if the configuration that fitted the shore connection is the one with the highest efficiency and the lowest OpEx, the additional CapEx makes this configuration less convenient than a traditional one.

Considering an accumulated TCO of 10 years, the solution that allows the best savings is the one with DF engines and an ESS of 2.5 MWh, with a gap of half the initial reference CapEx with respect to DF traditional configuration and of more than 4 times the reference CapEx with respect to a traditional Diesel configuration.

5. Simulation of a fuel-cell-powered vessel

From the previous analysis it is clear that the major benefits of hybrid systems comes from the employment of the right controller with the selected size of the batteries: the aim of these simulations is to underline the effect of the controller in coordination with ESS on the performance of the vessel.

In particular, two simulations have been performed on a small vessel powered only by fuel cells, in order to prove that this kind of system could also be adopted with the next generation of power producers, improving their performances.

5.1. Dynamic Model

In order to compare the advantage given by the knowledge of the operating profiles in terms of performance, two dynamic simulations have been performed in the MATLAB/Simulink environment and in particular employing the Simscape Power Systems (SPS) toolbox [11]. Both the simulations have the same electric load (that has been distinguished by hotel, thrusters and propulsive load) and the same FC installed, but with different ESS size enabling different control strategies (as explained in section 5.2).

The model, visible in figure 6, is composed of the following components:

- 2 PEM fuel cells;
- 1 Energy Storage System;
- 3 electrical loads (representing propulsive, thrusters and hotels load);
- 1 DC switchboard connecting energy producers and consumers;
- control system in order to balance the plant.

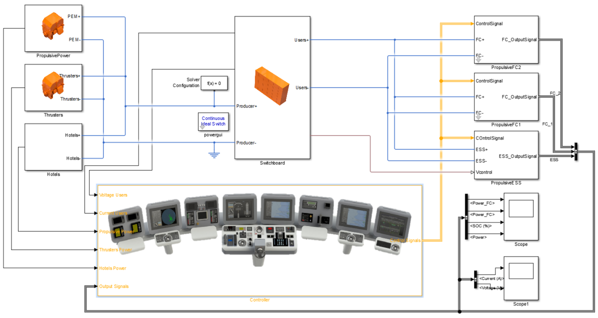


Figure 6. Scheme of the system in Simulink environment.

The electric grid is DC because energy producers supply DC current, the low power transmitted enables one to employ a Low Voltage network and a DC bus could feed the electrical motors (whose speed is controlled thanks to a variable frequency inverter) without the necessity for any rectifier or transformer.

Figure 7 shows the load applied that is representative of two different voyages of a very small vessel, lasting about 24 hours.

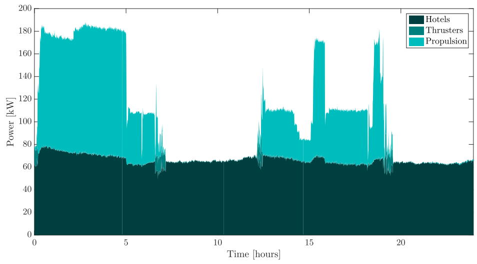


Figure 7. Electrical loads applied to the system.

5.2. Adopted control strategy

For the simulations two strategies have been implemented:

1. *Peak shaving strategy*: the simulation goal was to eliminate fast load fluctuations that could reduce the expected lifetime of the FCSs and oversize it;
2. *Multi-scheme strategy*: in this simulation a simple multi-scheme approach is tuned in order to improve system efficiency by means of ESS using FCSs to provide base load (at low power), reducing FCSs degradation and fuel consumption.[12]

The EMS is based on a state machine that is able to detect the current operating condition, selecting the suitable usage of batteries that could be:

- *Peak shaving*: in this mode the ESS is used as low band pass filter of the total required power;
- *Charging/ Discharging*: the FCs are forced by a PI controller to charge/discharge the batteries at a predefined value.

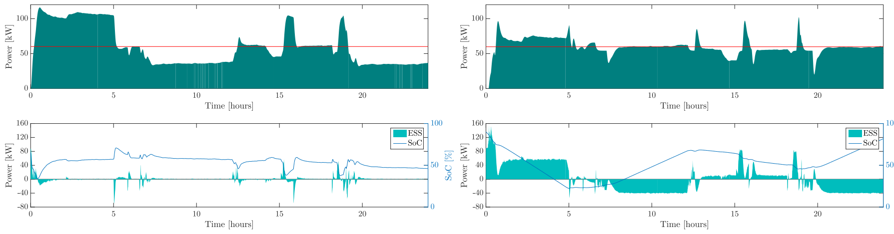
The transitions between the states and modes associated with them were selected analysing the output of the aforementioned algorithm. For this model, 5 states were implemented: harbour, manoeuvring and 3 different sea conditions.

As explained before, because the rationale behind the two control strategies was different, the size of ESS was also different in the two simulations: for the first configuration 20 kWh were sufficient in order to maintain the SoC between 30 and 90%, while for the second an ESS with 200 kWh was employed.

5.3. Compared simulations

Figures 8a and 8b report the load of the two FC employed, the power to/from the ESS and its SoC relative to the two simulations, underlining the following aspects:

- in the first simulation, in which ESS performs only peak shaving, FCs follow the load and therefore experiences great fluctuations, while in the second one the FCs have a more stable and lower load.
- as expected with peak shaving strategy the ESS is active only to cover fluctuations and ramps, while in the other it is extensively used for the balancing of the plant.



(a) Peak shaving simulation (red line corresponds to mean load of $61kW$).

(b) Multischeme simulation (red line corresponds to mean load of $59kW$).

Figure 8. Power extracted from FC and ESS and SoC of ESS.

This has an impact on hydrogen consumption: using the multi-scheme strategy the FCSs works at a more stable and lower load thanks to the charging/discharging of batteries, allowing them to consume 59.2 kg of hydrogen for each fuel cell, while with only peak shaving the consumption is 61.6 kg (which means a reduction of 3.9%).

6. Conclusions

This paper describes an alternative approach used in the preliminary design of an engine room that might fits an ESS. This allows us to assess its techno-economic effect on ship design from its operational data and to identify the best size for the ESS.

Two transient simulations of a vessel powered only by fuel cells with different size of batteries are performed, in order to understand the advantages brought about by different control strategies of hybrid systems also with highly efficient technology.

A future development for the presented algorithm is the integration with both optimisation algorithm, with the aim of defining the best engine room operation and size of the ESS, and simulation tool, in order to speed up the design process.

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