Optimal Sizing of Energy Storage Systems for Shipboard Applications

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***Abstract*—The recent worldwide effort on the environmental issue has led to new regulations on greenhouse gases emissions (GHG), both for land and marine applications. Nowadays, the extensive electrification of transportation systems is a promising choice for this purpose. In this perspective, algorithms for the optimum sizing and management of energy storage systems (ESSs) integrated into already operating shipboard power systems are proposed in this work. The main aim of this method is reducing the power generation system fuel oil consumption, GHG emissions and management costs. This is applied to two case studies (i.e. a ferry and a platform supply vessel), of which load power profiles are available from the on-board integrated automation system (IAS). The results yielded show remarkable savings close to 6% and 32% along the whole ship's life horizon for the ferry and the platform supply vessel, respectively. These results prove that an optimal sizing combined with an optimum management of ESSs may significantly reduce the operative costs of shipboard power systems.**

***Index Terms*—Energy storage systems, optimal size, energy management systems, shipboard power systems, battery energy storage systems**

I. INTRODUCTION

THE maritime transport of goods accounts for more than 70% of the world trade in terms of value and 80% in terms of volume [1], [2]. According to recent studies, the international shipping emitted in 2012 about 796 million tonnes of CO_2, which is close to 2.2% of the total emission for that year [3], [4]. However, the mid-term forecasting shows that by 2050, an increase between 50% and 250% in CO_2 emissions due to shipping is possible, depending on the future economic growth and energy development. It is to be noted that shipping is one of the major human activities and the main transport system of goods. Therefore, the public interest on its environmental footprint has led to increasingly stringent regulations on greenhouse gases (GHGs) emissions [5], [6].

In the perspective to globally reduce these polluting emissions, two possible solutions are available today. The first one involves the concept of "energy efficiency", which has become a very important topic affecting human behaviour everyday. In this context, energy efficiency does not mean reducing a service in order to save energy, but rather use less energy to provide the same service by adopting practices and technologies aimed to this purpose (e.g. smart meters, energy management plans, demand side management, etc.) [7]. The second option involves the adoption of high efficiency devices together with the massive electrification of transportation systems, home appliances and industrial machines.

In order to decrease the environmental footprint due to shipping and the energy waste, already since 1983, the International Maritime Organization (IMO) has released regulations in order to minimize pollutant emissions [5] - [8]. Nevertheless, it is only since 2011, with the *62nd* session of the IMO's Maritime Environmental Protection Committee (MEPC), that stringent mandatory measures have been adopted to reduce emissions of GHGs from both new buildings and already operating ships [6] - [11]. These rules have encouraged all stakeholders involved in the maritime industry to adopt innovative solutions to improve ship's efficiency.

In this context, as already stated, the extensive electrification of transportation systems has become an appealing technology compared to the traditional fuel-driven ones, even for marine applications, where the widely known all-electric ship (AES) solution would allow to introduce many technologies and practices already adopted in land-based applications [12] - [16]. Technologies such as energy storage systems (ESS), variable frequency drives (VFDs) and practices such as unit commitment (UC), power system dispatch (PSD) and demand side management (DSM) have been barely introduced in most cases, [17] - [21].

A key aspect of all these technologies, is the need to know the load power profile or the ability to predict it. However, almost every ship presents a different load profiles due to the large amount of power required for the propulsion system, which can significantly vary in relation to weather conditions and operational requirements. As a result, an increase in costs, fuel consumption and emissions is often observed.

Therefore, as it happens in many land-based applications, where significant uncertainties related to the power generation profile due to weather conditions occur (e.g. wind and solar power generation plants), the installation of energy storage systems can be advantageous to cover the fluctuating load variations and increase the ship's operative efficiency, reliability and flexibility [22].

Several works in literature have addressed the problem of the shipboard power generation system optimum management. In [23], two energy management system (EMS) algorithms are proposed. The first one is based on a *"if/else"* logic approach

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and the second one on a mixed-integer linear programming optimization. Three different power plant configurations are considered and compared, including fixed-speed, variable-speed gensets and implementation of an ESS. Therefore, these two algorithms and three power plant configurations are tested on three case studies based on the operational efficiency, in terms of fuel savings and reduction in genset running hours. However, the size of the ESS for each case study are decided *"a priori"*. Therefore, the size of the ESS is not considered in the optimum problem proposed. Moreover, it is to be highlighted that the total number of start-ups and shutdowns of diesel generators is significantly high (e.g. close to 19 starts and stops per hour). In [24], an EMS algorithm is developed based on bond graph models in conjunction with a particle swarm optimization (PSO) algorithm. This method optimizes the configuration of the power system based on actual data. Moreover, it has been validated using a real operating profile of an hybrid roll-on/roll-off vessel. On the other hand, the ESS size selection is not considered in the optimization problem and the storage system output is controlled depending on its state of charge (SoC) limits, without considering the aging effects of this control on it. In [25], an EMS scheme based on model predictive control (MPC) is implemented and deployed in order to optimize the coordination between the ESS and gensets under high-power ramp rate loads. The model is applied and validated in a reduced scale shipboard power system. Nevertheless, aging effects on ESS depending on its management and the resulting optimal sizing are topics not covered in this work. On the other hand, the optimal ESS size selection depending on the management strategy is studied in [26]. In fact, authors formulate a dynamic dispatch problem (DDP) to find the optimal loading strategy for DGs and ESS, validating the method on a case study. However, the control on the ESS has been performed only avoiding the ESS to violate the SoC limits. In addition, the aging or efficiency effects on the optimal management of the ESS and on its size are not studied. Furthermore, the best size for the ESS is determined with a "brut-force" method. The problem of optimal sizing and location of ESS on-board ship is studied in [27], where the authors describe an approach to evaluate their impact on ship survivability and quality of service (QoS). A multi-objective optimization is used to obtain a Pareto optimal solution considering QoS and survivability. However, the optimum management and aging effects of the ESS are not considered in this work.

This work is aimed to propose an approach to select the best size of an ESS (e.g. battery, flywheel or super-capacitor) based on the knowledge of a typical shipboard load power profile. This optimal selection and sizing should also consider the optimum management of the power generation system and its aging effect on the storage system. It is to be noted that in order to properly select the optimal size for the storage the diesel generators should work as close as possible to their most efficient loading conditions. Furthermore, the ESS working behaviour should guarantee an acceptable life duration of the system itself (i.e. the life duration of an ESS depends on its management). Therefore, the proposed method should verify the goodness of all the possible solutions depending on the power generation system optimum management. In this way is possible to evaluate all the possible solutions under the same conditions. Due to the complexity of the issue, the optimum problem is decomposed in two main sub-problems (i.e. as shown in Fig. 1). The first algorithm solves the problem of finding the best size for the ESS. The second one, searches the best energy management for both the DGs and the ESS. The best size is defined considering as objective function of the problem the sum between the power system management cost (e.g. due to the fuel oil consumption), installation costs for the ESS and its power inverter and replacement costs for the ESS (i.e. depending on the size and the aging effects on the storage). These assessments have been proposed over the vessel life time horizon, which is usually considered equal to 25 years, in order to account of the total number of replacements required for the ESS.

This paper is organized as follow: Section II describes the problem of finding the optimal size for an ESS, whereas Section III describes in detail the formulation developed in this work for this aim. Section IV proposes and describes the case study ships. In Section V, results are analyzed and commented. Finally, Section VI draws some conclusions.

II. PROBLEM STATEMENT

The problem of finding the optimal size of an energy storage system is strictly related to the dispatch and scheduling for both DGs and energy storage modules (ESM). In fact, in order to select the optimal size of an ESS, it is required to perform the optimal scheduling and dispatch for the whole power generation system. This work aims at establishing a methodology to optimally select the size of an ESS for a shipboard application, when real load power profiles data are available for the on-board consumers. Therefore, the proposed method solves the problem of the optimum energy management of the power generation system (e.g. considering DGs and ESS) and adopts its results in order to test the goodness of the possible sizes for the ESS.

A. Algorithm to find the optimum sizing of an ESS

The problem of selecting the optimal size for an ESS and obtaining the optimum energy management strategy for the power generation system involves a large number of variables, parameters and specific information. As proposed in Section I, several methods in literature only partially address this problem [23] - [27]. Therefore, this work is focused on finding a global solution to these two problems, when the load power profile is available. An energy management system (EMS) is proposed in this work. Such systems consider events in the past, in the present and perform forecasts on the future. Typical results of an EMS algorithm are for example: the energy supplied, the number of charging and discharging cycles in the time horizon considered, the state of charge (SoC) of the storage, the power supplied by generators and their fuel oil consumption. In the perspective of selecting the optimal size of an ESS, these results are useful information.

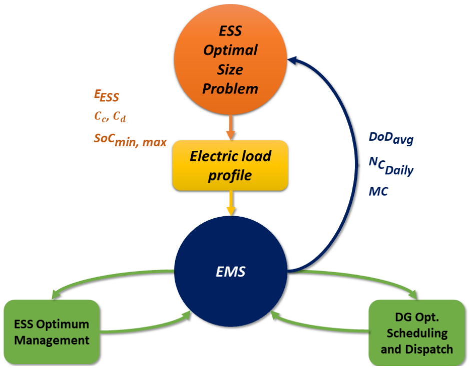

Fig. 1. Problem decomposition

In fact, combining these results with input information such as load power, power system characteristics and ship operating conditions, it may be possible to optimally select the size of the storage system and its main features. In fact, different size of the storage means different performances of the power generation system and different energy management strategies to be applied. This problem can be formulated as a mixed-integer non linear programming (MINLP) problem and solved by adopting heuristic methods such as genetic algorithms (GE) or particle swarm optimization (PSO). In fact, it involves both integer (e.g. the generator's state) and continuous variables (e.g. the power supplied by generators or the ESS). Moreover, it is to be noted that the non linearity of the problem is mainly due to the product of variables into the objective function and constraints of the problem [28]. However, in spite of the easy formulation allowed by these solvers, very long computational time are required, which does not ensure a more accurate result, if compared to other formulations. With the purpose to adopt a different formulation of the problem, the whole problem has been decomposed into two main sub-problems, as shown in Fig. 1. These sub-problems interacts between them exchanging information and results. The first sub-problem (e.g. in orange in Fig. 1) solves the selection of the optimal size of the ESS and it has been formulated as a non-linear programming problem (NLP). Furthermore, it provides important information used as inputs for the second sub-problem (e.g. in blue in Fig. 1). These information are for example the nominal size E_{ESS}, current rate C_{ESS}, minimum SoC_{min} and maximum state of charge SoC_{max} of the ESS. On the other hand, the second sub-problem has been formulated adopting a mixed integer linear programming approach (MILP) and should find the optimal scheduling and dynamic dispatch for the DGs as well as finding the optimal management for the ESS considered in the first sub-problem. The resulting optimum management supplies information such as the average depth of discharge DoD_{avg}, number of daily cycles $NC_{D_{aily}}$ and mission cost (MC), which are vital information in order to properly select the size of the ESS. In fact, the management strategy for the ESS has direct effects on the aging of the system (e.g. depending on the average DoD and number of daily cycles) and, as a result, on its life-time horizon and total number of replacements required.

III. PROBLEM'S FORMULATION

The energy management and optimal sizing problems for the power generation system and the storage have been developed in General Algebraic Modeling System (GAMS) and Matlab environments, respectively. The whole problem has been divided into the ESS optimal sizing and the generation system optimum management problems.

A. *Algorithm for ESS optimal size selection*

This problem aims to find the optimal sizing of the ESS and provides information on the storage system main features that may be used for its optimal management.

1) Problem's input: inputs can vary depending on the energy storage technology considered (e.g. batteries, super-capacitors, flywheels etc.). Main information are the technology selected, the rated current in charge C_c and discharge mode C_d, the maximum depth of discharge allowed DoD, the rated power in charge P_{ESSc} and discharge P_{ESSd}, the maximum E_{ESSmax} and minimum E_{ESSmin} size for the storage, the initial state of charge SoC_0 and the final state of charge SoC_f, the nominal cost per kWh of the storage system C_{inst}, the relation between the DoD and the number of charge and discharge cycles $NC_{T_{ot}}$ guaranteed in the ESS life and the storage efficiency η_{ESS}.

2) Problem variables: the only variable is the ESS size. The solver selected to perform this optimization is fmincon that is available in Matlab. This solver is able to find a solution for NLP problems and requires, as input, the starting point for the search.

3) Objective function: objective function of this problem is the total cost TC calculated over the whole ship life-horizon (i.e. 25 years) as the sum of the installation costs (IC) for the energy storage system and its power converter and the power generation system management cost (MC) obtained by solving the second sub-problem, as reported in equation (1).

$$TC = IC + MC \tag{1}$$

Where, IC is equal to the sum of the installation costs C_I for both the ESS and its power inverter and the replacement costs C_R of the ESS, as proposed in equation (2).

$$IC = C_I + C_R \tag{2}$$

The installation cost for the ESS is defined as the product of the nominal cost of the storage $C_{inst_{ESS}}$ and its nominal size E_{ESS}. The installation cost of the inverter, on the other hand, is defined as the product of the nominal cost of the inverter $C_{inst_{INV}}$ (e.g. that is modeled as a piece-wise linear function depending on the inverter size) and its rated power P_{INV}, as proposed in (3).

$$C_I = C_{inst_{ESS}} \cdot E_{ESS} + C_{inst_{INV}} \cdot P_{INV} \tag{3}$$

Furthermore, considering the ship's life horizon the replacement costs for the storage system C_R are strictly related to its main features (e.g. the number of cycles $NC_{T_{ot}}$ guaranteed in function of the depth of discharge DoD) and on the management strategy adopted (i.e. that affects the aging of the ESS), as proposed in (4). It is to be noted that the power inverter replacement is not considered in this formulation. This is due to the fact that the main features of the ESS does not change after each replacement.

$$C_R = C_{inst_{ESS}} \cdot E_{ESS} \cdot N_{replacement} \tag{4}$$

Therefore, in accordance with (3) and (4), the objective function proposed in (1) can also be formulated as proposed in (5).

$$\begin{aligned} TC = C_{inst_{ESS}} \cdot E_{ESS} \cdot (N_{replacement} + 1) + \\ + C_{inst_{INV}} \cdot P_{INV} + MC \end{aligned} \tag{5}$$

The number of replacements ($N_{replacement}$) for the ESS is defined combining results obtained from the EMS problem and variables of the ESS optimal sizing problem, as proposed in (9) combining equations (6)-(8). Where, $N_{C_{Daily}}$ is the total number of daily charging/discharging cycles of the storage system. This can also be seen as a daily *"aging effect"* on the ESS. Moreover, $E_{exchanged}$ is the total energy exchanged by the ESS in a typical daily mission after the energy management strategy has been defined. $N_{C_{Tot}}$ is the total number of cycles guaranteed by the manufacturer throughout the ESS's life. DoD_{avg} is the average depth of discharge performed in the mission according with the management strategy. a and c are constants of the exponential polynomial approximation for the total number of cycles and b, d are the exponents. Finally, $N_{Service_{Days}}$ is the potential number of service days for the ESS in accordance with the formulation.

$$N_{C_{Daily}} = \frac{E_{exchanged}}{2 \cdot E_{ESS}} \tag{6}$$

$$N_{C_{Tot}} = a \cdot e^{(b \cdot DoD_{avg})} + c \cdot e^{(d \cdot DoD_{avg})} \tag{7}$$

$$N_{Service_{Days}} = \frac{N_{C_{Tot}}}{N_{C_{Daily}}} \tag{8}$$

$$N_{replacement} = \frac{25 \cdot 365}{N_{Service_{Days}}} \tag{9}$$

Finally, for what concern the installation costs, it is to be noted that in equation (9) the numerator represents the total number of days the ship will be in service in its expected life, which is typically equals to 25 years.

The management costs MC are calculated according to the outputs of the EMS problem. These account for those costs related to the DG's fuel oil consumption, as proposed in equation (10).

$$MC = \sum_{i,j=1}^{G,S} [\alpha \cdot P_{gen_{ij}} \cdot SFOC_{ij} \cdot FC \cdot dt] \tag{10}$$

Where, $P_{gen_{ij}}$ and $SFOC_{ij}$ are the power delivered and the specific fuel oil consumption (e.g. in g/kWh) for the i-th generator at the j-th time step, respectively. Furthermore, FC is the cost per unit of the fuel oil (e.g. in \$/t) and α is a constant equals to 10^{-6} that is used to convert from grams to tonnes. Finally, dt represents the time step of the simulation.

B. Power generation system EMS algorithm

The EMS algorithm is formulated as an optimization problem, in which the main variables are the states of the DGs and the power delivered by each generator and by the ESS at each time step of the simulation. Involving both integer and continuous variables the EMS is formulated as a mixed-integer linear programming (MILP) problem. This formulation allows acceptable calculation time and a good accuracy of results. Results must guarantee the best management strategy for the power generation system according to the objective function and constraints of the problem. The problem has been formulated in GAMS environment, employing CPLEX as solver.

1) EMS inputs and variables: the main inputs and variables are those proposed and summarized in Table I.

2) EMS objective function: each term of the objective function proposed in this work is multiplied by a constant (e.g. a weight) to allow a normalization of its contribution to the total values assumed by the objective function. The first term of the objective function proposed in equation (11) accounts for the power delivered by each generator at each time step $P_{gen_{ij}}$ and it is multiplied by its weight w_{Pgen}. The second term and its weight w_{Su} identify the total number of start-ups of the DGs. The third term of the function is introduced in order to evaluate the goodness of the loading conditions for the diesel generators in accordance with the values assumed by the penalty function LF_n (e.g. proposed in Fig. 2) and the weight w_{LF}. This penalty function has been modeled as a piece-wise linear function and follows the behaviour of the specific fuel oil consumption curve of the DGs. This function has been formulated in GAMS as proposed in equations (12)-(15). Finally, the last term in equation (11) accounts for the ESS aging effects due to the selected management strategy. Specifically, it considers the average state of charge SoC_{avg} performed during the simulation (e.g. corresponding to the inverse of the average depth of charge DoD_{avg}), multiplied by its weight w_{SoC}.

TABLE I
EMS INPUTS AND VARIABLES

Parameter	Symbol
Inputs:	
ESS rated power in charge/discharge [kW]	P_{ESS_d}
ESS rated power in charge [kW]	P_{ESS_c}
ESS initial state of charge [%]	SoC_0
ESS final state of charge [%]	SoC_f
ESS maximum depth of discharge [%]	DoD_{max}
ESS current rates	C
Number of DGs	G
Number of simulation time steps	S
DG's rated power [kW]	P_{Grated_i}
DG minimum time up [min]	$DG_{min_{up}}$
DG minimum time down [min]	$DG_{min_{down}}$
Simulation time step [s]	dt
Variables:	
DG power delivered [kW]	$P_{gen_{ij}}$
DG start-up state	v_{ij}
DG shutdown state	w_{ij}
ESS power exchanged[kW]	P_{ESS_j}
ESS state of charge [%]	SoC_j

The signs in equation (11) are chosen in order to minimize the fuel oil consumption and find the best management strategy for the power generation system.

$$\begin{aligned} J_{object} = w_{Pgen} \cdot \sum_{i,j=1}^{G,S} P_{gen_{ij}} + w_{Su} \cdot \sum_{i,j=1}^{G,S} v_{ij} + \\ + w_{LF} \cdot \sum_{n=1}^{N} LF_{n} - w_{SoC} \cdot \sum_{j=1}^{S} \frac{SoC_{j} \cdot dt}{S} \end{aligned} \tag{11}$$

3) Penalty function: the penalty function proposed in Fig. 2 is introduced in order to evaluate the goodness of the loading conditions of the DGs and it has been formulated as a piece-wise linear function. Once the power delivered by a DG is defined, the penalty assigned depends on the corresponding value of the specific fuel oil consumption $SFOC$. This penalty has been modeled introducing auxiliary variables as the power delivered by the n-th step of the piece-wise linear function $P_{gen_{ijn}}$, which also depends on the i-th diesel generator considered at the j-th time step, with $n \in N$ (i.e. from 1 to N, where N is the total number of linear steps of the function). Moreover, z_{ijn} identifies the switch from one step to another one of the piece-wise linear function, as shown in Fig. 2. In addition the formulation requires to define some parameters of the piece-wise line such as m_{in}, which identifies the angular coefficient of the n-th line step considering the i-th diesel generator and C_{in} that is known. In equation (12), the total power delivered by the i-th diesel generator at the j-th time step is defined as the sum of the power delivered by all the n-th power ranges $P_{gen_{ijn}}$, defined by the piece-wise linear function. Further, in (13) the power limits of each step of the function are defined as P_{nom_n} and equation (14) states that it is not possible to work in the *(n+1)*-th step without working also in the previous n-th step. Finally, the corresponding penalty value is proposed in (15), where $P_{g\%}$ is the ratio between $P_{gen_{ijn}}$ and the product of z_{ijn} and P_{nom_n}.

$$P_{gen_{ij}} = \sum_{n=1}^{N} P_{gen_{ijn}} \tag{12}$$

$$0 \leq P_{gen_{ijn}} \leq P_{nom_n} \cdot z_{ijn} \tag{13}$$

$$z_{ij(n+1)} \geq z_{ijn} \tag{14}$$

$$LF_{n} = \begin{cases} \displaystyle\sum_{i,j=1}^{G,S} [C_{in} + m_{in} \cdot P_{g\%}] & n = 1 \\ \displaystyle\sum_{i,j=1}^{G,S} [C_{in} + m_{in} \cdot P_{g\%} - C_{in} \cdot z_{ijn}] & n > 1 \end{cases} \tag{15}$$

4) EMS equations: the SoC behaviour depends on the power exchanged by the ESS at the j-th time step, the initial state of charge SoC_{0} and the rated capacity of the storage $E_{ESS_{nom}}$ is proposed in equation (16). On the other hand, equation (17) accounts for the power limits of the ESS. Finally, equation (18) states that the difference between the diesel generator's state at the $(j-1)$-th time step $u_{i,j-1}$ and at the j-th time step $u_{i,j}$ is equal to the difference between the variables $w_{i,j}$ and $v_{i,j}$ describing the shutdown and start-up states, respectively.

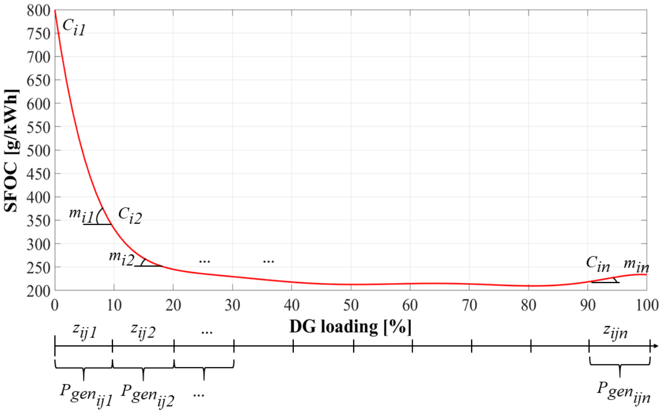

Fig. 2. DG fixed speed SFOC with penalty function LF_n

$$SoC_{j} = SoC_{0} - \sum_{j=1}^{S} [P_{ESS_j} \cdot \frac{\eta_{ESS} \cdot dt \cdot 100}{E_{ESS_{nom}} \cdot 3600}] \tag{16}$$

$$C_d \cdot E_{ESSnom} \leq P_{ESS_j} \leq C_c \cdot E_{ESSnom} \tag{17}$$

$$u_{i,j-1} - u_{i,j} = w_{i,j} - v_{i,j} \tag{18}$$

5) EMS constraints: constraints are all formulated as linear equality and inequality functions. In equation (19) the balance between the power demanded P_{load_j} and the sum of the power supplied by DGs $P_{gen_{ij}}$ and the storage P_{ESS_j} at each time step is guaranteed. Further, in equation (20) a reserve on the power available is guaranteed in case of failures [29]. This constraint is here named "spinning reserve", although it also considers power delivered by static sources such as energy storage systems. One of the main reasons for this unusual formulation is the need to consider scenarios where all generators are turned off at the same time and with all the load and reserve of power covered by the ESS. The reserve of power SR_{j} can be set depending on the ship's operating condition, i.e. for a supply vessel for example, this reserve can be increased in dynamic positioning (DP) in order to guarantee stringent level of reliability [30]. The minimum time for the DGs to be down and up are defined in equations (21) and (22). The final value of the state of charge SoC_{f} defined into the inputs of the problem is guaranteed by the equation (23).

Furthermore, inequality constraints are formulated in equations (24) and (25) in order to model characteristics such as minimum $P_{gen_{min}}$ and maximum $P_{gen_{max}}$ power available by the DGs, maximum SoC_{max} and minimum SoC_{min} state of charge for the ESS. Where, the SoC_{min} is equal to the difference between SoC_{max} and the maximum depth of discharge (DoD_{max}).

$$\sum_{i=1}^{G} P_{gen_{ij}} + P_{ESS_j} = P_{load_j} \tag{19}$$

$$\frac{\displaystyle\sum_{i=1}^{G} P_{Grated_i} \cdot u_{ij} + P_{ESS_d} - P_{loadj}}{P_{loadj}} \geq SR_{j} \tag{20}$$

$$u_{i,j} \geq \sum_{j=1}^{S} DG_{min_{up}} \cdot v_{i,j} \tag{21}$$

$$1 - u_{i,j} \geq \sum_{j=1}^{S} DG_{min_{down}} \cdot w_{i,j} \tag{22}$$

$$\sum_{j=1}^{S} [SoC_j - SoC_{j-1}] = SoC_f \tag{23}$$

$$P_{gen_{min}} \leq P_{gen_{ij}} \leq P_{gen_{max}} \tag{24}$$

$$SoC_{max} - DoD_{max} \leq SoC_{ij} \leq SoC_{max} \tag{25}$$

Finally, this formulation allows to set the initial state of some variables, which are defined as inputs. These, are the initial state $u_{i,0}$ for the DGs in equation (26) and the initial state of charge SoC_0 of the storage system in equation (27).

$$u_{i,j} = u_{i,0} \ for \ j = 1 \tag{26}$$

$$SoC_j = SoC_0 \ for \ j = 1 \tag{27}$$

The following section proposes and describes the case studies, the input information used in order to test this methodology and a comparison analysis of the data recorded from the on-board integrated automation systems (IAS).

IV. CASE STUDIES

Two different ships have been selected as case studies. These are a ferry and a platform supply vessel (PSV). Actual field data have been extracted from the on board IAS. These data have already been presented and analyzed in details in [23].

However, in order to allow a better comparison between the collected data and the results yielded applying the proposed method, these data are presented and analyzed in this section.

A. Ferry

Ferries present very stringent scheduled timetables. For this reason, they often show a cyclic load behaviour. However, for those ferries designed with an electric propulsion system, the electrical load profile is mainly affected by the power required for ship's propulsion, which is strongly dependent on weather conditions and cruising speed.

The case study vessel presents four fixed speed diesel generators (DG1, DG2, DG3 and DG4) as primary source of power, two of these are rated 1200 kW each (DG1 and DG3) and other two 640 kW (DG2 and DG4).

The electrical propulsion system is composed by two azipod propellers (AP1 and AP2) rated 1200 kW each, as shown in Fig. 3. An energy storage system composed by the storage and the power inverter have been integrated into the case study ship power plant. These storage and power inverter systems have been split into two storage packs (i.e. ESS1 and ESS2) in order to guarantee the power symmetry between the two main buses of the system.

The collected data have been extracted by the IAS with a sample frequency of 1Hz during a whole day of operation, which starts at 01:00 PM. The load power profile proposed in

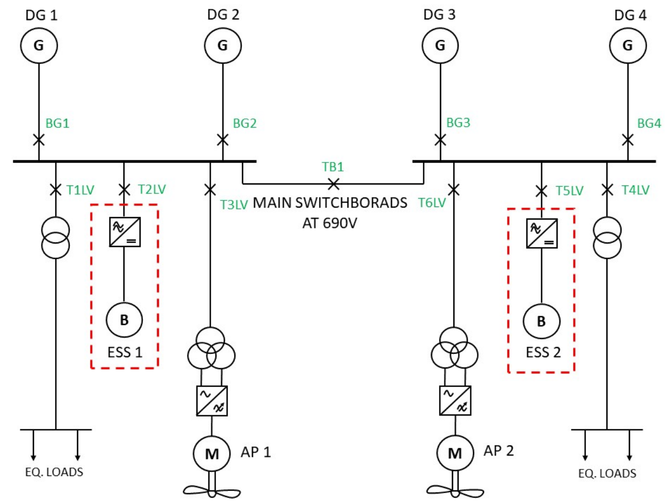

Fig. 3. Ferry, electrical power plant configuration with ESS

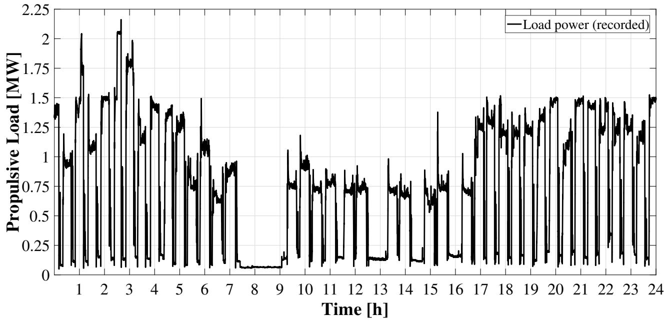

Fig. 4. Ferry, propulsive load power (recorded)

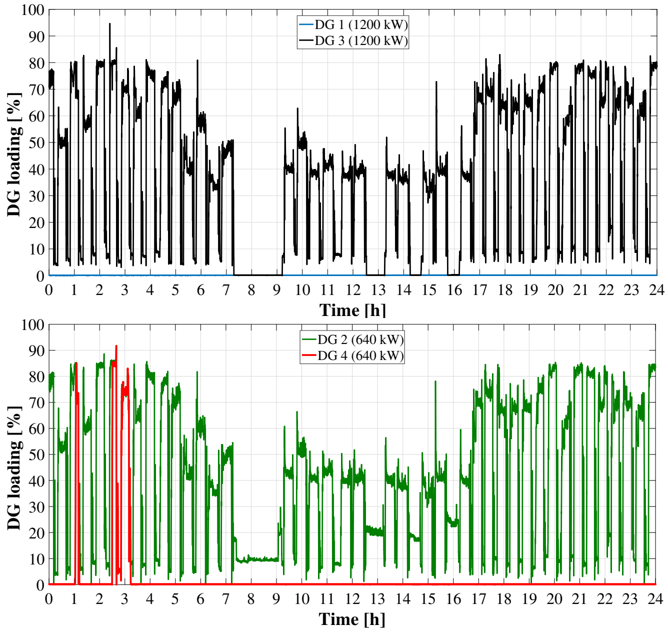

Fig. 5. Ferry, DGs loading condition (recorded)

Fig. 4 shows a cyclic behaviour according to the scheduled timetables of this ship.

Load peaks at the third hour of measurements (4:00 PM) are probably due to a mission delay. The power supplied by each diesel generator is shown in Fig. 5, where it is possible to highlight that DG1 is switched off for all the mission horizon. On the other hand, DG2 and DG3 are turned on for the most of the period, with a power delivered variable between the 3.3% and 91.7% and between 6.3% and 94.7% for DG2 and DG3, respectively. Their average loading conditions are equal to the 41.1% and 43.1% of their rated power, significantly far from their point of maximum efficiency and minimum $SFOC$ (e.g. close to the 80% of the rated power of a generator). The last diesel generator DG4 is turned on just in order to cover peaks for the first three hours of operation, with a minimum, maximum and average loading conditions equal to the 6.3%, 91.7% and the 55.5%, respectively.

Mission costs MC calculated by the recorded data applying the $SFOC$ curve proposed in Fig. 2 are equal to 2610\$. This corresponds to a total cost TC equal to 23817k\$, considering the ship's life horizon as reference.

B. Platform Supply Vessel

Typical platform supply vessels (PSVs) provide different services to off-shore installations. These ships exhibit stringent dynamic positioning (DP) capabilities in pumping or winching operations, with high values of load and power reserve in order to prevent dangerous black out conditions [30]. Therefore, generators often work at low load conditions with high level of fuel consumption.

The shipboard power system proposed in Fig. 6 consists of four fixed speed DGs, two rated 2350 kW (DG1 and DG3) and other two rated 994 kW (DG2 and DG4). The propulsion system presents two azimuth thruster propellers (MP1 and MP2) rated 2200 kW each, two bow (BT1 and BT2) and one azimuth bow retractable thruster (RT) rated 880 kW each. Furthermore, two energy storage system packs have been integrated into the on-board electric grid in Fig. 6.

The data have been extracted by the IAS with a sampling frequency of 0.2 Hz, during 6 days. The recorded total load power (Fig. 7) presents several peaks due to different ship's operating conditions, which are mainly affected by adverse weather conditions such as heavy wind, current and waves. For the first 20 and between 118 and 133 hours the load power is significantly low (i.e. close to 300 kW). In fact, at these time steps of the measurement the ship is in port condition and the propulsion system is off.

In the first plot of Fig. 8, the power delivered by DG1 and DG3 is shown. It is to be noted that DG1 is turned off for the whole mission horizon. The others diesel generators shown very different behaviours, with loading conditions ranging from 1.5% and 93.5% of their rated power. However, the average loading conditions for DG2, DG3 and DG4 are equal to 17.5%, 24.7% and 21.9% of their rated power, respectively.

These conditions lead to significantly high levels of fuel consumption and mission cost MC. This cost is equal to 19605 \$ per mission (e.g. 6 days for this ship). Furthermore, the total cost TC is equal to 30041.3k \$, considering ship's life as time horizon (i.e. 25 years of operation).

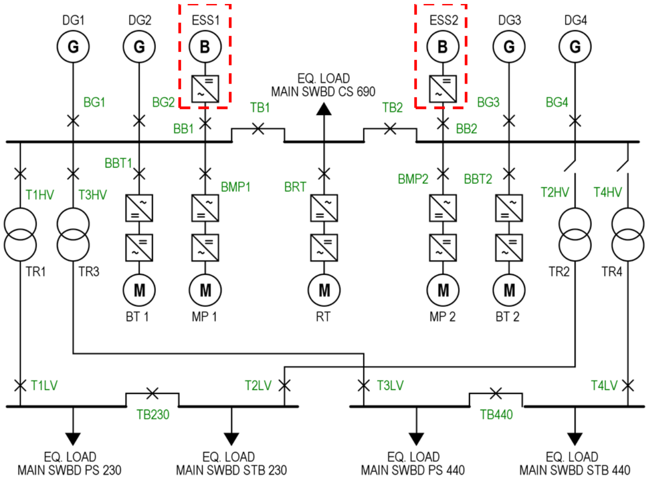

Fig. 6. PSV, electrical power plant configuration with ESS

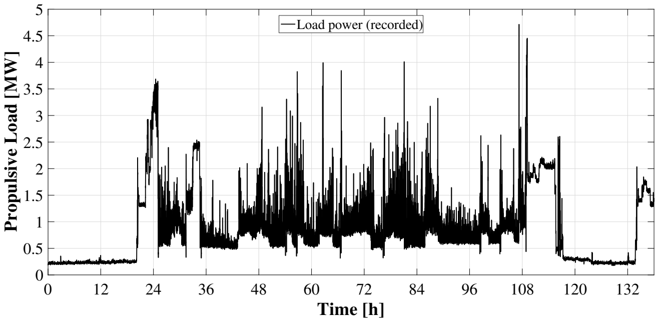

Fig. 7. PSV, total load power (recorded)

V. Simulations and Results Analysis

The proposed algorithm is here applied to the case studies and the main results are presented and analyzed. The main inputs for the simulations are summarized in Table II. The technology selected as ESS in this work, is a lithium-ion battery energy storage system (BESS) for marine application [31]. It is to be noted that, assuming the hypothesis that the load presents a cyclic behavior between the missions, it is possible to extend the calculations performed on a single mission to the whole ship life.

A. Sensitivity analysis

A sensitivity analysis on possible mission savings has been performed considering the influence of the current rate C of the BESS. Moreover, it should identify which is the best technical solution for the case studies between an "energy intensive" application and a"power intensive" one. The results of this analysis are proposed in Table III.

Where, $i - C$ means that a maximum current in charge and discharge equal to $i-$times the rated current of the BESS has been considered for the simulation.

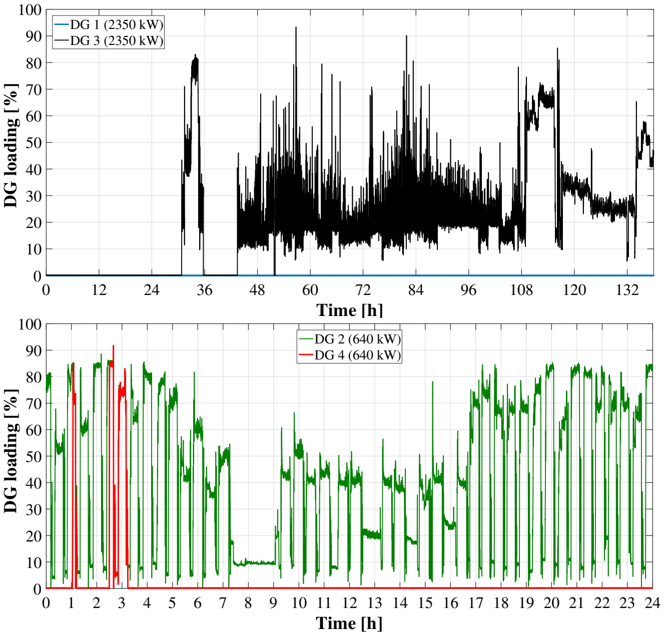

Fig. 8. PSV, DGs loading condition (recorded)

TABLE II
EMS PROBLEM INPUTS

Parameter	Ferry	PSV
Simulation characteristics:		
BESS technology - Lithium-ion		
BESS size range [kWh]	250 - 1000	300 - 2000
SoC_0 and SoC_f [%]	70	70
SoC_{min} and SoC_{max} [%]	20 - 100	20 - 100
η_{ESS} [%]	98	98
$P_{gen_{max/min}}$ [%]	110 - 5	110 - 5
SR_j [%]	10	50
Time horizon [days]	1	6
EMS objective function weights:		
$w_{P_{gen}}$	10^{-6}	10^{-6}
w_{S_u}	15	10^{-1}
w_{L_F}	10^{-2}	1
w_{SoC}	3	30
Recorded data costs analysis		
MC [$]	2610	19605
TC [k$]	23817	30041.3

Considering the ferry the maximum mission saving occurs for $4C$ case, where the mission savings MS are equal to 7.82%. On the other hand, the maximum total saving TS is observed for the simulation with the maximum current equal to $1C$ and it is equal to 5.64%.

For the PSV, the maximum mission MS and total savings TS are found for $4C$ and $2C$ simulations, respectively (e.g. equal to 42.37% and 31.9%). This is due to the irregular working behaviour of the PSVs and due to the stringent power redundancy requirement in DP conditions often sets equal to the 50% of the total load).

B. Ferry

In order to prevent from finding a local minimum (i.e. the problem is non-convex), tests have been performed over the feasible space of solutions. Moreover, it should be noted that the results reported Table III show that an "energy intensive" application is the most advantageous for the ferry.

TABLE III
RESULTS SUMMARY OF THE SENSITIVITY ANALYSIS

Results	Ferry		PSV	
BESS maximum current rate	*MS[%]*	*TS[%]*	*MS[%]*	*TS[%]*
$1C$	7.3	5.64	38.57	30.1
$2C$	7.4	4.15	40.7	31.9
$3C$	7.73	2.32	41.45	29.6
$4C$	7.82	0.21	42.37	27.2

TABLE IV
RESULTS SUMMARY

Results	Ferry	PSV
BESS characteristics		
E_{ESS} [kWh]	395	755
P_{INV} [kW]	395	1510
EMS results		
DGs start-ups/stops	25	195
DoD_{avg}	32	46.5
$N_{CD_{aily}}$	6.4	7.8
$N_{replacement}$	2	5
Mission costs analysis		
MC (recorded data) [$]	2610	19605
MC (optimized) [$]	2418.5	11632
Mission Savings [$]	191.5	8105
Mission Savings [%]	7.3	40.7
Total costs analysis		
ESS Installation costs [k$]	264.8	3150.9
TC (recorded data) [k$]	23817	30041.3
TC (optimized) [k$]	22473	20443
Total ship life savings [k$]	1343	9734
Total ship life savings [%]	5.64	31.95

This is mainly due to the different management strategies applied to the BESS compared to the "power intensive" application. Further, the results proposed in Table IV show that the best size of the BESS is equal to 395 kWh.

From the results presented in Fig. 9, it can be noted that DGs are often loaded at their point of minimum $SFOC$ (i.e. 90% of their rated power) and the number of starts and stops is limited to a maximum of 8 start-ups per day for each generator.

The mean, maximum and minimum loading conditions for DG1 are 76.9%, 110% and 30% of their rated power, for DG2, are all equal to 90%, for DG3 are equal to 77.4%, 108.4% and 30% and finally, for what concerns DG4, these are equal to 88.4%, 90% and 30%, respectively. Therefore, mission savings up to 7% have been pointed out.

Finally, one should note that in Fig. 10 the SoC is never below the minimum value SoC_{min} and it is often higher than 60%.

C. Platform Supply Vessel

For the PSV the results summarized in Table IV are referred to 6 days of simulation, instead of the single day considered for the ferry. The optimal size of the BESS is equal to 755 kWh. However, in contrast to the ferry, the sensitivity analysis proposed in Table IV shows that a "power intensive" is the best choice for this case (i.e. current rate equal to 2C).

In Fig. 11, the optimal loading conditions for the DGs are presented. It is possible to note that after the optimization

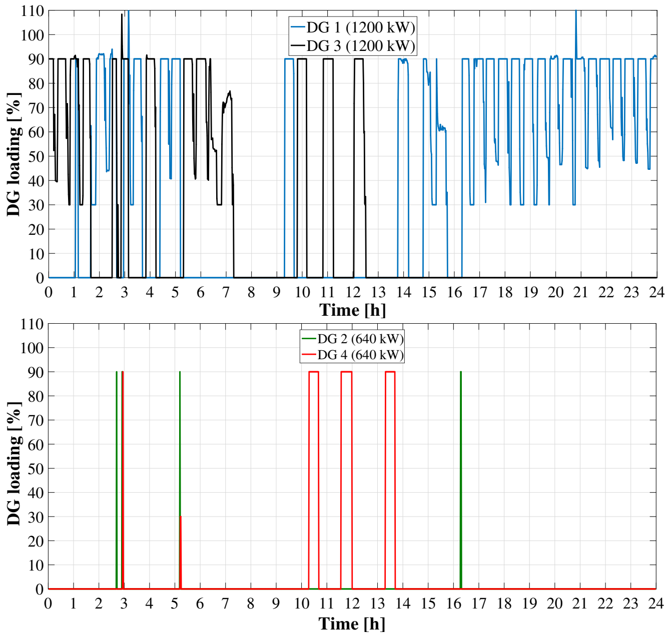

Fig. 9. Ferry, DGs loading condition (optimized)

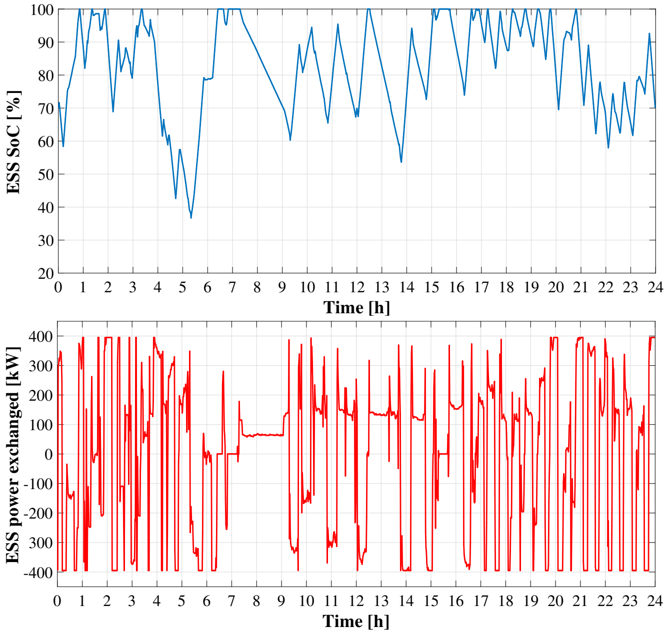

Fig. 10. Ferry, state of charge and power delivered (optimized)

DGs are loaded closer to their optimum load and the total number of starts and stops is limited to a maximum of 94 start-ups for DG1. The mean, maximum and minimum loading conditions for DG1 are 83.2%, 110% and 30% of their rated power, respectively. For DG2 and DG3, these values are all equal to 90%. Concerning DG4, the mean is equal to 82.1%, the maximum to 110% and the minimum to 30%.

Finally, the dynamic profiles of the state of charge SoC and power delivered P_{ESS} by the BESS are reported in Fig. 12 showing that the power through the inverter P_{INV} and the SoC limits are both respected (i.e. P_{INV} equal to 1510 kW and SoC equalt to 20%.

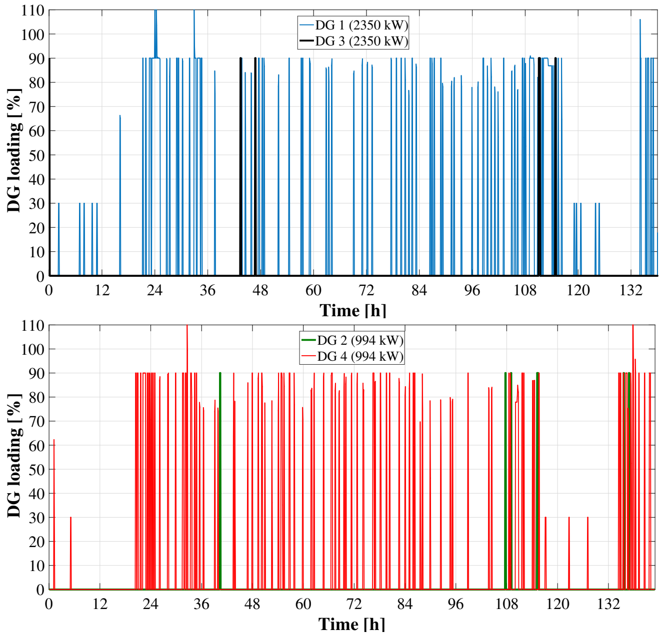

Fig. 11. PSV, DGs loading condition (optimized)

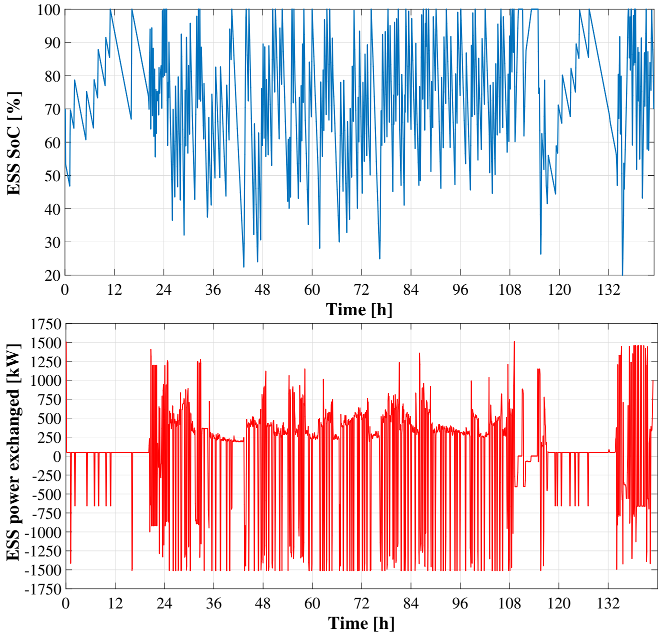

Fig. 12. PSV, state of charge and power delivered (optimized)

VI. CONCLUSIONS

In this work a method for the optimal selection, sizing and management of energy storage systems in the perspective of economic generation and utilization of the electrical energy for shipboard power systems has been presented. This method has been developed in a flexible and general way in order to be applied on several shipboard power system configurations and allow selection of different storage technologies (e.g. batteries, flywheels and super-capacitors). Application to the case studies have highlighted the possibility to improve the performances and increase the savings of traditional power generation systems by introducing a BESS, consequently.

Although significant savings have been observed for the ferry, i.e. close to 6% considering the net savings on the entire ship's life, the largest savings have been observed for the PSV (i.e. close to 42% and 32% considering a mission and a ship's life perspective) compared to those calculated with the recorded data. Future studies will consider the implementation into the EMS algorithm of a more complex efficiency model for the different energy storage technologies considered together with space and volume considerations.

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