Design of Minimum Fuel Consumption Energy Management Strategy for Hybrid Marine Vessels with Multiple Diesel Engine Generators and Energy Storage

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Abstract—**The paper presents an analytical method for estimation of the fuel saving potential resulting from installation of energy storage on-board of marine vessels equipped with multiple diesel engine generators. The method is based on quasi-steady-state assumptions and does not require precise a-priori knowledge of the operating cycle of the vessel. The method also gives insight about the expected energy throughput of the storage system that can be directly related to its expected lifetime. Simple procedures are proposed for favorable trade-off between fuel saving and storage lifetime. The paper also shows how the off-line method can be extended to design high-level power flow control and energy management strategies for the engines and storage. Time-domain simulations with several load profiles having different characteristics are presented, showing the validity of the proposed approach.**

I. Introduction

Increased focus on pollution and emissions from marine activities requires technology and operation strategies that can contribute to reduced fuel consumption.

The use of on-board electrical energy storage to reduce fuel consumption in vehicles such as cars, buses and trucks has become common practice, following the commercial success of the first hybrid power trains introduced around the turn of the century. A similar trend is now emerging in the maritime sector [1]. Several new builds and retrofits are now being equipped with battery energy storages as supplement to internal combustion engine-based generators (ICEG). There are also examples of vessels that charge in harbor (similar to the ground-based Plug-in Hybrids) and even some that are sailing with batteries as their only on-board source of energy [2].

The process of designing a hybrid power plant for a vessel, meaning choosing type and size of energy storage, as well as rating, number and type of ICEGs to achieve minimum fuel consumption is strongly application-dependent [3]. The expected operating cycle of the vessel must be taken into account and - what is often overlooked - the power management strategy must be included in the early stage of the design process. In its essence, the power management strategy defines how to share power between the alternative sources available on-board and how to choose the best time to store energy.

Although there is a vast scientific literature related to optimal power sharing strategies for hybrid vehicles such as cars, buses and trucks [4][5], many of the concepts cannot be applied directly to hybrid marine vessels due to several marked differences. Marine auxiliary engines designed for direct generation of 50/60Hz AC voltage must run at fixed speed, while hybrid vehicles can adjust speed to maintain a high efficiency at different loads due to the action of gearshifts and/or to the possible mechanical decoupling between generator axle and driving axle. On the other hand, most marine vessels have more than one engine, while hybrid vehicles typically have only one. Regeneration of kinetic energy, while being one of the main factors for increased fuel efficiency in hybrid vehicles, is only relevant for ships with large cranes and drilling draw works, especially in combination with heave compensation. Besides these technological aspects, rules, regulations and operational procedures used to ensure safety at sea will typically pose restrictions on the operation of the vessel power plant. The energy management strategy must therefore take such operational constraints into account, especially for vessels in critical maneuvers and during dynamic positioning (DP) where the vessel is to retain its maneuverability after any single failure.

The most common operating constraints imposed by regulatory aspects are related to spinning reserve, meaning that a certain amount of power and energy is required to be instantly available in case of a contingency. Moreover, spinning reserve is typically required on each power bus bar present on-board. Typically, a modern vessel has at least two power bus bars. In some cases, further requirements exist concerning the minimum number of generators that need to be online and running at all times.

The problem of optimum fuel consumption has been studied in detail for vessels without energy storage [6][7] and to some extent also for vessels with energy storage. In [8] a simple load leveling strategy is used, [9][10][11] and [12] utilizes different online optimization techniques, [13] uses load prediction for the optimization while [14] and [15] utilizes offline optimization.

It is pointed out in [16] that the use of on-board energy storage in marine vessels can contribute to reduce fuel consumption in several different ways. This paper will focus on two aspects: strategic loading and spinning reserve. Strategic loading indicates the use of storage to shift the operation point of ICEGs to minimize fuel consumption. Storage-based spinning reserve refers to the use of storage as backup source that can immediately be deployed in case of contingencies, allowing the vessel to be operated with reduced number of running ICEGs while still fulfilling the redundancy requirements.

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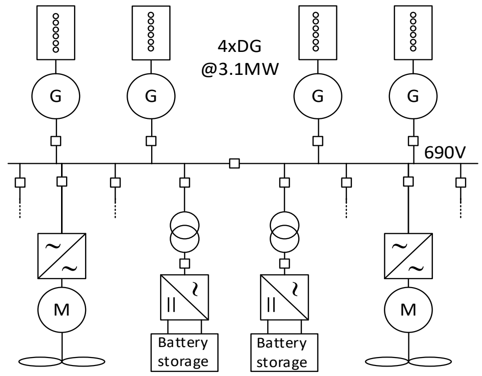

Fig. 1 The hybrid system. Parameters for the system are reported in Table III.

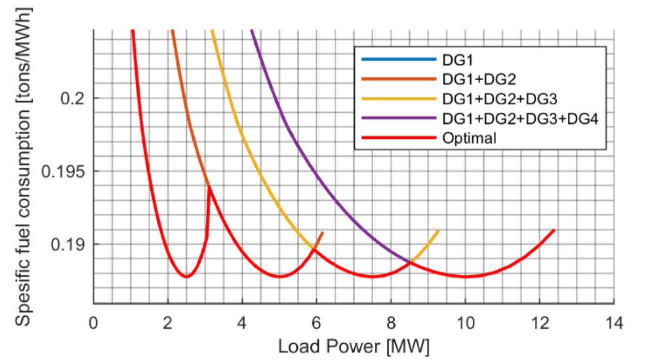

Fig. 2 Specific fuel consumption (tons/MWh) for 1-4 engines. Red line shows best operation without storage and without spinning reserve.

The paper presents a systematic method to map equivalent fuel consumption resulting from cycling energy in and out of a battery-based energy storage in hybrid vessels, considering the operational and regulatory aspects described above. The basic assumptions and methods for the mapping are related to those found in [12][13][15]. The mapping is used to develop rule-based energy management strategies for minimum fuel consumption.

It is noted that an improperly designed energy management strategy, besides increasing fuel consumption, can also accelerate the degradation of the energy storage system. Manufacturers of battery storage systems usually specify the expected lifetime of their components in terms of number of equivalent full charge-discharge cycles. It is therefore also important to take the cycling into consideration in the design of energy management strategies. The paper shows a possible way to take the cycling effect into consideration.

II. Case Study

To illustrate the principles, the proposed methodology is applied to the hybrid system shown in Fig. 1, consisting of an energy storage and four identical diesel engines, each rated for 3.1 MW and optimized for 80% of maximum continuous operation (MCO). The specific fuel consumptions for one to four diesel engines running in parallel are shown in Fig. 2. Shown in the same figure is also the minimum specific fuel consumption (SFC) achievable by selecting the number of running engines n according to the load level, assuming no required spinning reserve:

$$SFC_{DG,opt}\left(P_L\right) = \min_{n=1,\dots,4}\left(SFC_{DG}\left(n,P_L\right)\right) \tag{1}$$

The two battery storage systems in Fig. 1, storage converters included, are treated as an aggregate system whose operating losses while charging and discharging are expressed as:

$$\begin{aligned} P_{l,C} &= f_1(P_{B,C}) = p_{l,0}\cdot P_{B,rated} + p_{l,C}\cdot P_{B,C} \\ P_{l,D} &= f_2(P_{B,D}) = p_{l,0}\cdot P_{B,rated} + p_{l,D}\cdot P_{B,D} \end{aligned} \tag{2}$$

where $P_{B,C} \geq 0$ and $P_{B,D} \geq 0$ are the charging and discharging power, respectively and $P_{B,rated}$ is the rated power of the battery storage. All the other storage parameters, as well as the engine parameters are reported in Table III.

In the following, it is assumed that operation with storage only (no running engine) is acceptable. The presented method can however be easily extended to include a constraint on the minimum number of running engines.

III. Storage Used for Strategic Loading

In theory, with an infinitely large, lossless storage it will be possible to operate the engines at their best efficiency at all times, store energy as needed and obtain an equivalent specific fuel consumption equal to the lowest possible SFC of the engines. A practical energy storage system will however have a limited storage capacity and non-negligible losses. Consequently, it will not be optimal to cycle power through the storage at all loads. It will also not necessarily be optimal to always operate the engines at their lowest SFC.

Determination of the optimum strategy starts from considering steady-state operation at a specific load level $\overline{P}_L$. When the load is constant, average fuel consumption of the system in Fig. 1, is minimized by selecting the optimal storage cycle. In steady state, the energy supplied to and delivered by the battery $W_{B,in}, W_{B,out}$ are related by:

$$W_{B,out} = W_{B,in} - P_{l,D}\cdot T_D = \left(P_{B,C} - P_{l,C}\right)\cdot T_C - P_{l,D}\cdot T_D \tag{3}$$

Charging and discharging time T_C, T_D are consequently related to the charging and discharging power as:

$$\begin{aligned} \frac{T_C}{T_C+T_D} &= \frac{P_{B,D}+P_{l,D}}{P_{B,C}+P_{B,D}-P_{l,C}+P_{l,D}} \\ \frac{T_D}{T_C+T_D} &= \frac{P_{B,C}-P_{l,C}}{P_{B,C}+P_{B,D}-P_{l,C}+P_{l,D}} \end{aligned} \tag{4}$$

Due to power balance, the total power from the engines during storage charge and discharge is expressed as:

$$\begin{aligned} P_{DG,C} &= \overline{P}_L + P_{B,C} \geq 0 \\ P_{DG,D} &= \overline{P}_L - P_{B,D} \geq 0 \end{aligned} \tag{5}$$

The equivalent specific fuel consumption of the overall system, taking the battery cycling into account is therefore:

$$SFC_{Sys} = SFC_{DG}(n_C, P_{DG,C})\cdot\frac{T_C}{T_C+T_D} + SFC_{DG}(n_D, P_{DG,D})\cdot\frac{T_D}{T_C+T_D} \tag{6}$$

where n_C, n_D are the number of engines running during charge and discharge, respectively. $SFC_{Sys}(\overline{P}_L)$ can now be written in terms of four independent variables $P_{B,C}, P_{B,D}, n_C, n_D$ by

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combining equations (4), (5) and (6). The optimization problem is then formally stated as:

$$SFC_{Sys,opt}\left(\overline{P}_L\right) = \min_{\substack{P_{B,C},P_{B,D},\\ n_C,n_D}} \left(SFC_{Sys}, \left\{ \begin{array}{l} 0 \le P_{B,C} \le P_{B,\max,C}, \\ 0 \le P_{B,D} \le P_{B,\max,D}, \\ 0 \le n_D \le 4, \\ n_D \le n_C \le 4 \end{array} \right\} \right) \tag{7}$$

The results of the optimization process performed for all possible load levels between zero and maximum system load are reported in Fig. 3, Fig. 4 and Fig. 5. Fig. 3 shows the optimal charging and discharging power of the storage, $P_{B,C,opt}\left(\overline{P}_L\right)$ and $P_{B,D,opt}\left(\overline{P}_L\right)$ respectively. Fig. 4 shows the optimal load on diesel engines while charging and discharging the storage, $P_{DG,C,opt}\left(\overline{P}_L\right)$ and $P_{DG,D,opt}\left(\overline{P}_L\right)$ respectively. Fig. 5 shows the optimal number of DGs running during storage charge $n_{C,opt}\left(\overline{P}_L\right)$ and discharge $n_{D,opt}\left(\overline{P}_L\right)$, respectively.

As can be seen, there are large operating areas where:

$$\begin{cases} P_{B,C,opt}\left(\overline{P}_L\right) = P_{B,D,opt}\left(\overline{P}_L\right) = 0 \\ P_{DG,C,opt}\left(\overline{P}_L\right) = P_{DG,D,opt}\left(\overline{P}_L\right) = \overline{P}_L \\ n_{C,opt}\left(\overline{P}_L\right) = n_{D,opt}\left(\overline{P}_L\right) \end{cases} \tag{8}$$

The condition in (8) states that for such values of $\overline{P}_L$, it is optimal to have all the load energy supplied directly from the engines without using the storage for strategic loading. This stems from the fact that when the engines are loaded close to their optimum operating point, the additional losses resulting from the use of the storage and from the starting of an additional engine during storage charging overcome the gain of operating the engines exactly at their point of minimum SFC. Fig. 4 also shows that even when the storage is used to shift the loading point of the engines, optimum system SFC is in general not obtained by loading the engines exactly at their lowest SFC point.

The resulting optimum equivalent specific fuel consumption for the overall system at different system loads is shown in Fig. 6 together with specific fuel consumption for engines only.

The fuel saving (Δfc) per hour operation at each constant load level $\overline{P}_L$ can then be expressed as:

$$\Delta fc\left(\overline{P}_L\right) = \overline{P}_L \cdot \left(SFC_{DG,opt}\left(\overline{P}_L\right) - SFC_{Sys,opt}\left(\overline{P}_L\right) \right) \tag{9}$$

Fig. 7 shows the amount of fuel saved per hour of operation at different constant load levels. For comparison, the potential saving using a lossless storage is also shown. As expected, the fuel saving potential will be less due to the storage losses. What is also very clear from Fig. 7 is that fuel saving is very dependent on the system load. The consequence is that fuel saving estimations based on an arbitrary load cycle defined in the time-domain will be extremely sensitive to what is the dominating load power levels in the analyzed profile, making the results difficult to generalize to different time-series.

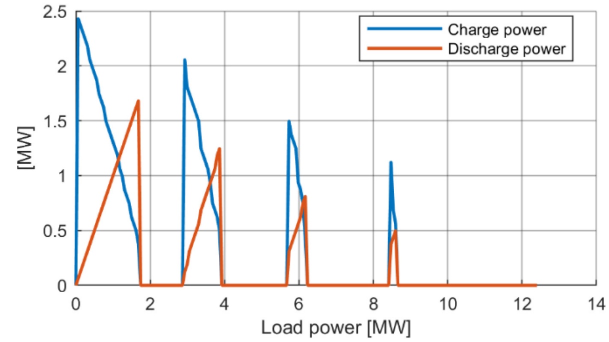

Fig. 3 Optimal charge and discharge power ($P_{B,C,opt}$ / $P_{B,D,opt}$) at different load levels

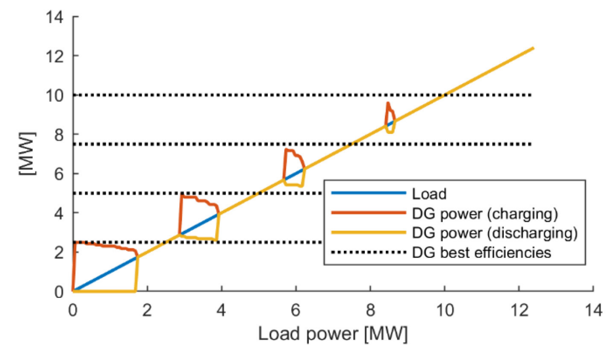

Fig. 4 Optimal load ($P_{DG,C,opt}$ / $P_{DG,D,opt}$) on diesel generators during charge and discharge for different system loads P_L. No storage usage in intervals where DG power for charge and discharge are equal to the load power

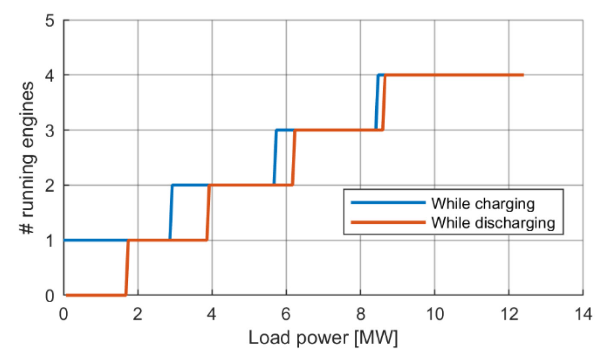

Fig. 5 Optimal number of running engines ($n_{C,opt}$ / $n_{D,opt}$) for system with storage. No storage usage at load levels where $n_{C,opt}$ = $n_{D,opt}$.

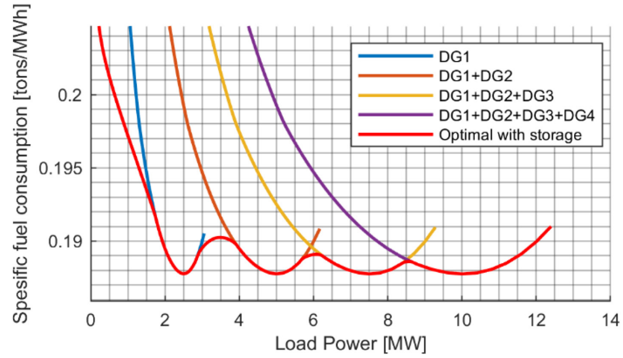

Fig. 6 Specific fuel consumption (tons/MWh) for 1-4 engines. Red line shows best operation with storage and optimal charge/discharge strategy for strategic loading of DG units.

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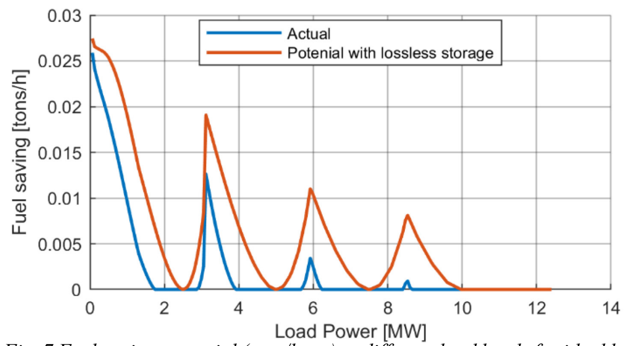

Fig. 7 Fuel saving potential (tons/hour) at different load levels for ideal lossless storage and for the real storage of the example system.

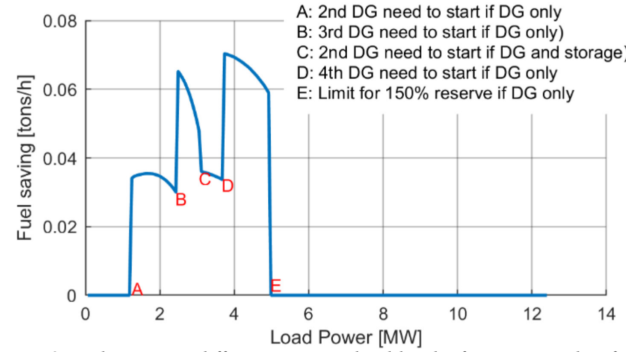

Fig. 8 Fuel saving at different constant load levels if storage used to fulfil a 150% spinning reserve requirement.

IV. Storage Used as Spinning Reserve

It is common practice in vessel power systems to avoid loading the DGs to their absolute maximum. A certain reserve (spinning reserve) is maintained to prevent overloading the DGs in case of a step increase in load power demand. Additional spinning reserve is required in redundant DP operations. Spinning reserve implies that at some load levels, more DGs are required to run than what is strictly needed to supply the load power, resulting in the power plant being operated less efficiently than what would otherwise be possible. In the general case the required spinning reserve will be a function of the load.

The minimum specific fuel consumption of a system operated at load level P_L and spinning reserve $P_{SR}(P_L)$ is expressed as:

$$SFC_{DG,SR,opt}(P_L, P_{SR}) = \min_{n=1,\dots,4}\left(SFC_{DG}(n, P_L), \{n \cdot P_{DG,\max} \geq P_L + P_{SR}\}\right) \tag{10}$$

where $P_{DG,\max}$ is the maximum power that can be generated by a single engine.

If a given amount of power capability of the storage system $P_{B,SR} \leq P_{B,\max}$ and $P_{B,SR} \leq P_{SR}$ is reserved for spinning reserve, the system SFC becomes:

$$SFC_{Sys,SR,opt}(P_L, P_{SR} - P_{B,SR}) = \min_{n=1,..,4}\left(SFC_{DG}(n, P_L), \{n \cdot P_{DG,\max} \geq P_L + P_{SR} - P_{B,SR}\}\right) \tag{11}$$

The fuel saving in tons per hour resulting from the use of storage as spinning reserve will then be:

$$\Delta fc_{SR}(P_L, P_{SR}, P_{B,SR}) = P_L \cdot (SFC_{DG,SR,opt}(P_L, P_{SR}) - SFC_{Sys,SR,opt}(P_L, P_{SR} - P_{B,SR})) \tag{12}$$

Fig. 8 shows calculated fuel saving if the requirement is 150% spinning reserve at each load level ($P_{SR} = 1.5 \cdot P_L$) and all the reserve is covered by the storage ($P_{B,SR} = P_{SR}$). It can again be seen that saving depends very much on the load levels. The origin of the observed discontinuities in fuel saving potential is explained in the figure.

A spinning reserve as high as 150% can be realistic for redundant DP operations, but note that fuel saving potential in redundant DP operations can be significant larger than shown in Fig. 8, since redundant DP operations without storage requires minimum two running engines even for the lowest load levels. Further, in some cases only an even number of running DG's will satisfy the requirements. The same approach can, with modification of (10) and (11), be used to find fuel saving potential for these more restrictive cases as well, by replacing n=1,..,4 by n=2,…,4 or by n=2,4 for the strongest requirement.

V. Fuel Saving Potential for an Actual Load Profile

The calculation of the optimal loading strategy presented so far requires no a-priori knowledge of the load profile. Fuel saving potential resulting from an actual load profile is estimated by using a load distribution that describes the typical operating cycle of a particular vessel. An example is given in Fig. 9. Although not originating from a real measured profile, such load distribution is synthesized to be representative for a dynamic positioning emergency response and rescue vessel (ERRV). These vessels will typically have over-sized power plants due to redundancy requirements and they spend most of the time at rather low load compared to maximum installed power. It is noted that load distribution can be easily extracted from a real load profile given in time-domain. Vice-versa, a given load distribution can describe an infinite number of time-domain profiles.

Fuel consumption is first determined for given load distribution assuming no use of storage, no spinning reserve requirements, optimal number of engine running for each load and no additional fuel consumption for start and stop of engines. The given load distribution results in a total energy demand of 11530 MWh for one year of operation. Fuel consumption for one year of operation was found to be 2322 tons. In comparison,

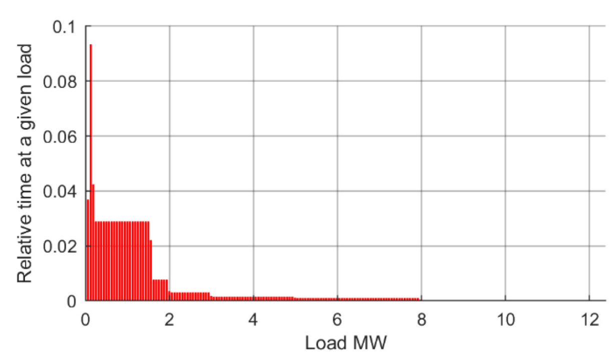

Fig. 9 Expected relative time the example Vessel will operate at different load levels

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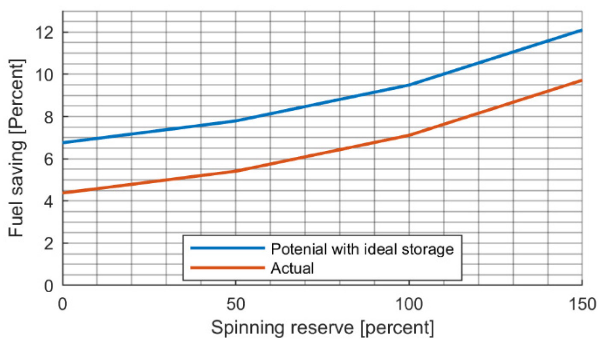

Fig. 10 Percent fuel saving for different spinning reserve requirements for the load profile in Fig. 8 (sum of saving for spinning reserve and strategic loading).

fuel consumption if power plant is operated with 150% spinning reserve and no storage was found to be 2446 tons per year.

The load distribution can be used to directly estimate total fuel consumption reduction over one year of operation simply by summation of the fuel saving potential at each load level weighted by the relative time spent at each load level and multiplied by the number of hours in one year. The contribution from spinning reserve and strategic loading can then be added to find the total fuel saving potential. Fig. 10 shows the expected fuel saving for different levels of required spinning reserves over one year of operation of the example vessel for a loads distribution as given in Fig. 9.

It is to be noted that the criticality of a vessels activities will typically not be the same throughout the year. The required spinning reserve can for instance be quite different during a redundant DP operation compared to when vessel is in transit or at quay. To take this into account one may use different load distribution curves, each combined with individual spinning reserve requirement, and then perform a weighted summation to find the yearly fuel savings.

VI. Energy Storage Cycling and Consequences for Storage Expected Life-Time.

Expected lifetime of a battery, when operated within specified conditions, is mostly affected by the amount of energy cycled (the so-called throughput). The latter can be predicted by the steady-state method presented so far.

Fig. 12 shows the average energy throughput per hour at different load levels P_L for the case study. Throughput per unit of time is determined by combining (4) and:

$$\frac{W_{cycle}}{T_{Cycle}}(P_L) = P_{B,D,opt}\left(P_L\right)\cdot\frac{T_D}{T_{Cycle}} \tag{13}$$

Where $T_{Cycle} = T_C + T_D$ is the number of hours to complete a full storage charge/discharge cycle following the chosen operation strategy at a constant load, P_L and T_D is the time used for discharging in the same full charge/discharge cycle.

The average throughput per hour in Fig. 12 can be used in combination with the load distribution in Fig. 9 to find expected energy throughput in the same way as for calculation of yearly fuel saving. The throughput can be used as key input to a life-time model of the battery storage in order to determine expected life time for different alternatives of storage type and size. Total cost (OPEX+CAPEX) can then be optimized taking cost of

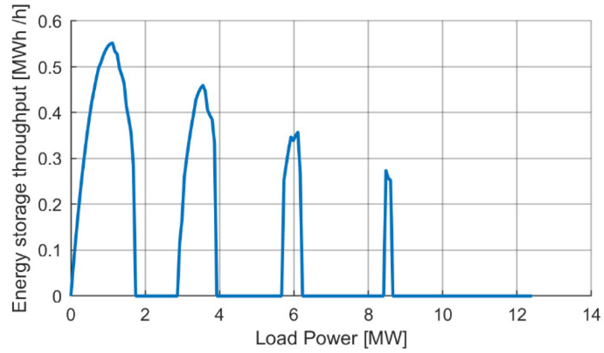

Fig. 12 Average MWh energy throughput per hour of operation at different constant load levels when optimal charging strategy is applied.

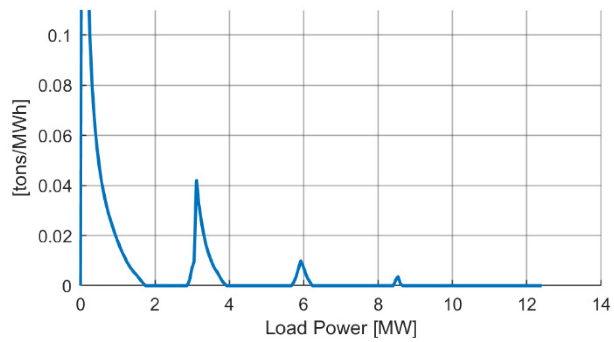

Fig. 11 Fuel saving per MWh energy cycled through the energy storage if the optimal loading strategy in Fig. 4 is used

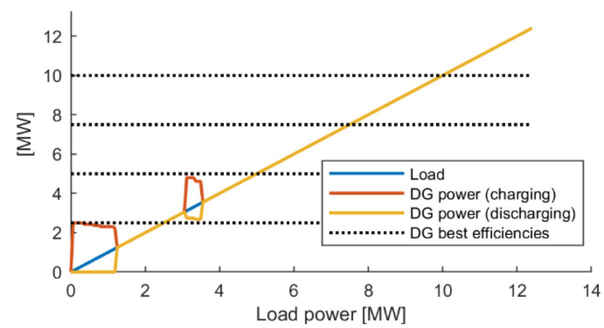

Fig. 13 Illustration of modified operation strategy for reduced use of energy storage (case with minimum yearly saving of 0.01tons/MWh cycling).

storage and cost saving due to reduced fuel consumption into consideration.

It is also possible to use the energy throughput calculation to modify the energy management strategy such that storage energy cycling is prioritized for the load levels that give the largest payback in terms of fuel saving. To that aim, fuel saving per cycled energy at different load levels can be determined by dividing the fuel saving (Fig. 7) by the energy throughput (Fig. 12) at each load level. The result is shown in Fig. 11. It is then possible to set a minimum threshold for the yearly tons of fuel saving per MWh cycled energy below which the storage is not to be used, as it is deemed that the savings will be marginal compared to the detrimental effects on storage lifetime.

As an example, the resulting operation strategy for minimum yearly saving of 0.01 ton/MWh is shown in Fig. 13. Compared to the original situation in Fig. 4, storage is now used in a smaller portion of the operating region. Both yearly fuel saving and throughput will necessarily be reduced. The effect on fuel saving and throughput can be found by recalculating those quantities without including the contribution at the load levels

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where one no longer choose to use the storage. Table I shows the consequences of setting different thresholds for minimum fuel saving per MWh throughput. The relationship between fuel saving and throughput is depicted in Fig. 14. Such results can be useful when having to compromise between storage size, storage life-time and fuel saving. It can for instance be observed that by sacrificing 5% fuel saving, one can reduce storage cycling by as much as 28% for the given load distribution profile.

TABLE I
TRADEOFF BETWEEN STORAGE USAGE AND FUEL SAVING

Set minimum yearly tons of fuel saving per MWh routed through storage	Resulting storage MWh throughput per year		Resulting tons of fuel saving per year	
0	2814	100%	101.6	100%
0.01	2026	72%	96.8	95%
0.025	1181	42%	82.6	81%
0.05	473	17%	57.9	57%

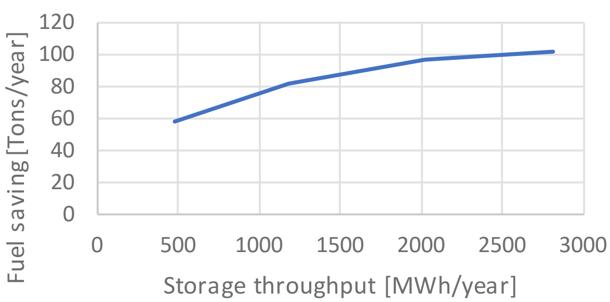

Fig. 14 Relationship between yearly fuel saving and yearly storage throughput

VII. REAL-TIME ENERGY MANAGEMENT BASED ON PROPOSED STRATEGY

A simple real-time energy management strategy can be derived by applying the results presented in section III. The strategy will consist in starting and stopping the engines according to the illustration in Fig. 5 while controlling the power flow of the energy storage according to Fig. 3, so that engines are loaded as prescribed in Fig. 4.

Although the optimal sharing between engine power and storage cycling at each load level is defined, due to the steady-state assumption no clear prescription is given on whether the storage should be charged or discharged at a given point in time. Here, a simple method based on monotonous state-of-charge (SOC) variation between preset upper and lower limits is used. More specifically, the method consists in always discharging the storage with a load-dependent power calculated following the red line in Fig. 3 (discharging mode) until the lower bound of the SOC is reached. From this point in time, the storage is always charged with a load-dependent power calculated following the blue line in Fig. 3 (charging mode). When the upper bound of the SOC is reached, the operation is switched back to discharging mode and the cycle continues.

Such basic strategy can only be guaranteed to approach optimality if the underlying assumptions of quasi-steady-state conditions are fulfilled. Moreover, the number of required engine start/stop operations should be small, making the additional fuel consumption and engine wearing negligible.

In the next sections, time-domain simulations with variable loads will be used to assess the validity of both the off-line estimation of the long-term fuel-saving potential and of the proposed real-time energy management.

VIII. VALIDATION OF METHOD

The real-time energy management strategy presented in the previous section has been implemented in a Matlab time domain energy flow simulation model, with system parameters reported in Table III. The load power profile has been synthesized from the load distribution shown in Fig. 9 that was previously used to illustrate the proposed steady-state method for off-line estimation of potential fuel saving. As already mentioned, there exists an infinite number of load series that comply with the given distribution. For the validation we have chosen first to use the simplest possible load series, built by sequentially applying all the load levels from zero to the maximum system load for a duration proportional to the corresponding probability. This obviously results in a profile characterized by a minimum variability. Such profile is shown by the blue curve in Fig. 15, assuming a total duration of the time series of 24 hours. This basic time series was then used to synthesize load profiles with more variability, in order to challenge the method. The synthesis process consisted in slicing the basic time series in intervals of fixed duration. Half of the slices where then reverted in time, and finally all slices where stitched together in a random sequence to form a new time series. An example of the outcome of this process is illustrated by the red curve in Fig. 15, where a 24-hour sequence is built starting from 1-hour time slices. This same method was used to synthesize load series of different characteristics by changing the two parameters T, T_{Rand} representing the duration of the time series and the duration of the single slices used for randomization. Some selected combinations are reported in the first three columns of Table II and are used as input to the time-domain simulations. Variations marked as *A* and *C* corresponds to time series with no randomization (the blue curve in Fig. 15). Variation *G* is the case featuring the highest load variability, as shown in Fig. 17.

In general, the time series generated with this method tend to give an exaggerated load variability, since there is no correlation between average load in adjacent slices. For most vessels the load would be more correlated.

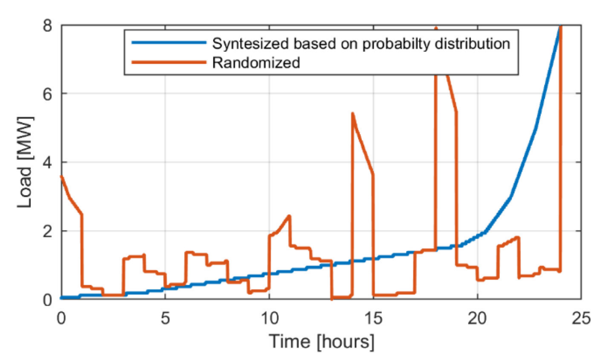

Fig. 15 Synthesized time series of load power with same distribution as shown in Fig.9. The blue curve will be closest to the constant load assumed in the steady state method. The blue corresponds to variant A defined in Table II while the red is one possible time series for variant B defined in same table.

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In order to validate the real-time strategy presented in section VII, ten instances of each load series variant were generated with different seed for the randomization. The results of time-domain simulations in terms of fuel saving and energy throughput were analyzed and compared to the predicted values obtained by application of the steady-state method of section III. The influence of the randomization for time series characterized by the same parameters T, T_{Rand} is shown in Fig. 16. The effect is rather small for all the analyzed cases except for variant *B*, where both fuel saving and throughput have noticeably different values for different seeds used in the randomization. This is due to the short duration of the simulation compared to the randomization period.

Values of fuel savings and throughput averaged among the ten cases for each variant of the load time-series are reported in Table II. As expected, the relative difference between such values and those calculated off-line by the steady-state method is small for the minimum variability load series (*A* and *C*). The difference increases as the duration of the time slices is reduced and variability increases, but is still within an acceptable range, with a maximum deviation of 11% for time slices of 5 minutes. The difference in storage throughput is larger (29% for variant *G*). This is however also considered to be acceptable, taking into account the rather extreme variability introduced.

IX. Proposed Loading Strategy versus Natural Loading Strategy

Starting from the steady-state assumptions, the problem of finding a suitable loading point for the engines by cycling some energy through the storage has an intuitive solution consisting in using the storage to always achieve operation of all the necessary engines at their optimal SFC point. This corresponds to the load-dependent strategy for engine loading depicted in Fig. 18. This natural loading strategy is not optimal under ideal steady state conditions, as demonstrated in section III.

However, it is interesting to check how the natural strategy would perform, compared to the optimal one (Fig. 4), if used as basis for a real-time energy management system. To this aim, the same time-series used in the previous section are used, and average results of the ten runs for each load variant of the achieved fuel saving and throughput are reported in the last columns of Table II.

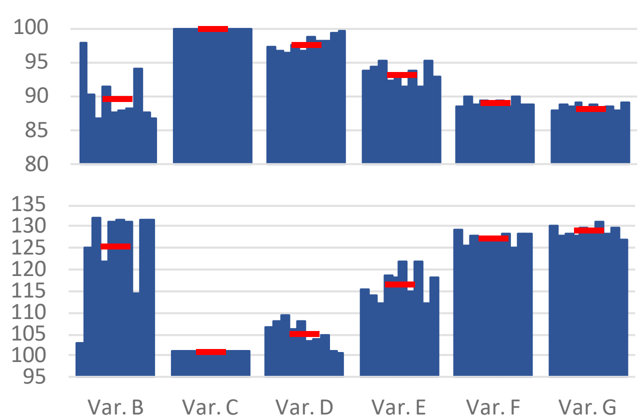

Fig. 16 Variation in fuel saving (upper) and throughput (lower) for 10 runs of time domain simulation of each variant B to G. Different seed for each randomization of the load time series are used for each of the 10 runs. Red markers are placed at average value for 10 runs.

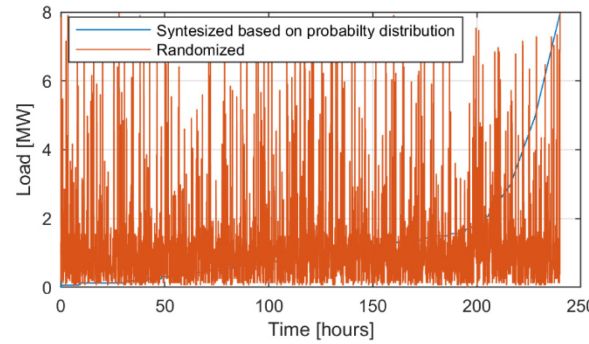

Fig. 17 240-hour randomized time series of load power with same distribution as shown in Fig 9 using 5 minutes time slices in the randomization (Variant G)

It is clear from the table that a strategy based on loading engines to their best SFC consistently gives less fuel saving and increased energy storage throughput and thus reduced storage lifetime, compared to the proposed one. In particular, while the achieved fuel saving may be comparable for some of the analyzed load series, the resulting throughput is always considerably higher, indicating that the storage is often used in conditions where the gain in fuel efficiency is marginal or negative.

X. Engine Start And Stop

Load-dependent start and stop of individual engines is the usual way of operating vessels to minimize fuel consumption. In principle, energy storage can be used to reduce the number of start and stops, thus reducing wear and tear of the engines. However, it is acknowledged that if storage is used for strategic loading of engines with the main aim of further improving fuel efficiency, then it is likely that the number of start and stops will increase rather than decrease. A strict use of the proposed strategy in combination with very dynamic load will probably cause too many start and stops of DG units. The energy management strategy will then have to be modified, e.g. by using hold-on and hold-off timers on the start and stop criteria, in a similar fashion of what is commonly done for vessels without storage. It is also possible to implement more sophisticated modifications that prioritizes keeping the same number of engines running when choosing whether to charge or discharge the storage rather than following the monotonous SOC variation or even rather than fulfilling the optimal loading strategy for minimum fuel. The consequence may then be somewhat less fuel saving in favor of reduced mechanical stress. The number of start and stops cannot easily be quantified using the steady state approach. This is a weakness of the proposed method.

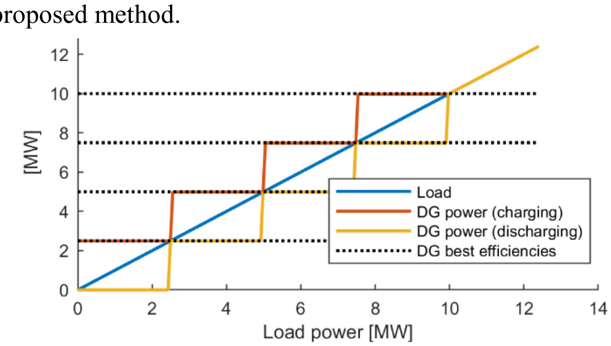

Fig. 18 The natural loading strategy where DG are loaded to their individual optimum

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TABLE II
COMPARISON STEADY STATE METHOD AND TIME DOMAIN SIMULATIONS WITH DIFFERENT LOADING STRATEGIES

Variant	T	T_{Rand}	Prediction by steady state method		Time domain simulation Load engines to system optimal as found by steady state (Fig. 4)		Time domain simulation Load engines to DG best SFC (natural load. strategy in Fig. 18)	
			Fuel saving Tons/year	Storage throughput MWh/year	Relative fuel saving	Relative throughput	Relative fuel saving	Relative throughput
A	1 day	(None)	101.6 (=100%)	2814 (=100%)	99 %	102 %	-	-
B	1 day	60 min			90 %	125 %	-	-
C	10 days	(None)			100 %	101 %	94 %	127 %
D	10 days	120 min			98 %	105 %	96 %	134 %
E	10 days	60 min			93 %	117 %	91 %	149 %
F	10 days	10 min			89 %	127 %	85 %	166 %
G	10 days	5 min			89 %	129 %	82 %	168 %

XI. CONCLUSIONS

The paper proposes a method for estimation of the fuel-saving potential resulting from the introduction and use of energy storage in the power plant of ships equipped with multiple ICE-based generators. The method uses a steady-state approximation in combination with basic statistical information about the load distribution, eliminating the need for precise a-priori knowledge of the load cycle.

Fuel saving resulting from both strategic loading and use of storage as spinning reserve can be quantified, taking into account most of the constraints found on real-world operations.

The method also gives insight about the expected energy throughput of the storage system that can be directly related to its expected lifetime. Simple modifications to the optimization procedure are also proposed for favorable trade-off between fuel saving and storage lifetime.

Besides giving an off-line estimation of the fuel saving potential for a given installation, the method can also be used for designing real-time energy management strategies for marine vessels with multiple diesel generators and on-board energy storage by introducing simple rule-based strategies.

Numerical time-domain simulations with several load series of different characteristics have been performed to show the validity of the proposed method.

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TABLE III
SYSTEM DATA FOR CASE STUDY

DG maximum continuous power	$P_{DG,max}$	3.1 MW
DG fuel consumption (generator losses included)		Fig. 2
Storage rated / maximum power	$P_{B,rated}$ /$P_{B,max,C}$/$P_{B,max,D}$	3.1 MW
Storage energy rating		3.1 MWh
Storage and converter charge loss coefficient	$p_{l,C}$	0.04
Storage and converter discharge loss coefficient	$p_{l,D}$	0.04
Storage and converter constant loss coefficient	$p_{l,0}$	0.001
Propulsion and hotel loads		Fig 9

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