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Reduction of Fuel Consumption on Hybrid Marine Power Plants by Strategic Loading With Energy Storage Devices

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ABSTRACT Recent advances in energy storage devices (ESDs) technology have enabled new guidance strategies for power generation and distribution on hybrid marine power plants, supported by new class regulations. In this paper, a new model to calculate the fuel saving and emission reduction potential is derived based on the ESD maximum charge/discharge rate, engine efficiency, and specific fuel oil consumption (SFOC) curve. Several cases were analyzed with generator disconnection and also without it. Spline approximation for the discrete fuel oil consumption curve is used for numerical solution and later optimized using the Karush–Kuhn–Tucker method. A second approach is proposed, using linear interpolation, reducing the optimization process computational time. It is shown that fuel savings can be increased and emissions reduced by charging and discharging the energy storage device. This is denoted as strategic loading according to the proposed model. The cases with highest potential for fuel saving are shown to be cases where generators are disconnected.

INDEX TERMS Hybrid power systems, energy storage, optimization, fuel economy, smart grids, analytical models, numerical models.

Nomenclature

P_G	Generator power output.
P_L	Load mean power consumption.
P_B	ESD power output.
P_C	Generator power output while charging the ESD.
P_D	Generator power output while discharging the ESD.
E_C	Energy transferred to the ESD.
E_D	Energy transferred from the ESD.
η_C	ESD charging efficiency.
η_D	ESD discharging efficiency.
η_C	ESD charging efficiency.
η	$= \eta_C \cdot \eta_D$. Simplified equivalent efficiency.
Δ_C	ESD consumed power while charging.
Δ_D	ESD consumed power while discharging.
τ	Simulation time.
τ_C	Time charging the ESD.
τ_D	Time discharging the ESD.
τ_G	Generator time constant.
ω	Engine speed.
ω_C	Engine speed while charging the ESD.
ω_D	Engine speed while discharging the ESD.
$SFOC$	Specific Fuel Oil Consumption.
FOC	Fuel Oil Consumption.
F	Instantaneous fuel consumption.
λ	Lagrange multiplier.
$a\ b\ c$	Second order spline coefficients.

I. INTRODUCTION

The majority of marine vessels power producers are based on an engine (either gas engines or diesel engines) connected to a generator. The engine characteristics vary as a function of the amount of power being produced by the generator. Two of the most important characteristics of an engine is the efficiency (measured by the fuel consumption) as well as gas emissions.

It is intuitive to realize that the ideal scenario would be the case where the enabled engines are operating in a condition that leads to minimum fuel consumption. However, a challenge is that it is not possible to know a priori the power demand from the various energy consumers. The power demand will vary dynamically depending on the various enabled power consumers, operational profile as well as the environmental conditions. Since the electrical system is a so-called weak grid (which means that the consumers will have a great influence on the line voltage and frequency on power buses), the generators must constantly adapt their set-points to keep the voltage and frequency within the desired range. More details about shipboard electrical power systems can be found in [1] and [2].

One promising alternative to reduce fuel consumption is to use the newest technologies in Energy Storage Devices (ESD), which allow a marine system to strategically load the generator, according to a reference model, while keeping power production capacity. ESD is a device that stores energy and is able to consume and deliver power on demand.

ESD technology has been developed in an increased pace during the last decade. Mobile/embedded applications were one of the main motivations for the recent grow in technology. However more and more applications have a great interest in ESD due to its capacity to alter the effective power demanded to the generators.

The automotive industry focused on hybridization by installing fuel cells, ultra-capacitors and batteries to improve the system performance while reducing emissions and fuel consumption. A comprehensive discussion of the different ESD technologies can be found in [3]. Reference [4] presents the effects of hybridization on a conventional diesel bus, [5] presents an optimization strategy to minimize the equivalent fuel consumption for a system with a fuel cell, and [6] shows an optimization of a Power Management System (PMS) for a real vehicle with a fuel cell/super capacitor hybrid power system. Finally, a review on the Energy Management System (EMS) for an hybrid vehicle is described in [7].

Hybridization has been used in applications other than the automotive industry. Some examples include household applications [8], cranes, lifts and tooling machines as described in [9] and [10].

Hybridization in a power production is characterized by a system which contains at least two different power sources. It may be due to two different power producers, such as a gas engine and a diesel engine. For this paper, the focus will be on a hybrid marine power plant that contains a traditional power producer (engine + generator) and an ESD.

Hybridization in marine systems has many uses, which were described and explored in [11]. The most common ESD usage strategies are:

- Enhanced Dynamic Performance - It is known that generators loading should be gradually ramped up, since a large load step might lead to a system fault, such as a blackout, under voltage/under frequency, etc. The ESD can provide energy for the system during large load steps, and the generator will be loaded gradually, improving the overall electrical robustness when subject to load fluctuations and sudden steps. This methodology will contribute to improve safety.
- Peak Shaving - There are two approaches when it comes to peak shaving. The first one is that the generator-set power demand should be bounded between a lower and a higher limit. The second peak shaving strategy is a combination of the first peak shaving strategy with enhanced dynamic performance, where the generator-set load variation should not exceed a pre-defined magnitude. Peak shaving leads to reduction in fuel consumption, as shown in [12], since transient fuel consumption is higher than the steady state fuel consumption. Reference [13] shows that the fuel consumption reduction is marginal for fixed speed generator-sets. The main focus of this guidance system is to increase safety.
- Spinning reserve - Recent development in marine regulations [14] allows the usage of an ESD as a spinning reserve. It means that for redundancy purposes, less generators need to be connected to the bus at one point on time, increasing the load percentage per generator and thus reducing fuel consumption and emissions. ESD guidance system will be proposed and discussed in more details later on this paper.
- Strategic loading - By charging and discharging the ESD, it is possible to strategically load the generator. Through high/low engine load cycles, it is possible to lower the average fuel consumption, compared to a system without the strategic loading. A strategic loading guidance system model is the main contribution in this paper.
- Zero Emissions Operation - By shutting down the generators, it is possible to operate without any emission. A large ESD is required to supply the power demand from the vessel. This operation is interesting and might become an requirement in the future to reduce pollution close to highly populated areas, such as big city harbors. This methodology main focus is to minimize gas emissions.

A contribution in this paper is to model mathematically the generator-ESD interaction, as well as implementing strategic loading for the ESD system. The potential for fuel savings is the major motivation. The ESD efficiency will be taken into consideration. If the power output is low compared to the maximum rated power, the ESD system will usually present a high efficiency [15]. The main scientific contribution in this paper is the development of an ESD analytical model as the development of a numerical approximation for optimization method using Karush Kuhn-Tucker (KKT) and Lagrange multipliers to minimize fuel consumption given the ESD efficiency and operational parameters. Both analytical and numerical models are studied. The comparison between strategic loading with and without generator disconnection is also shown in this paper, analyzing fuel efficiency and discussing the boundary conditions necessary for each case.

Section II briefly describes the main components of an electrical system influenced by the newer technologies and the actual industry standard for each one of them. Section III describes the strategy that will be used to select the ESD desired set-point, and finally Section IV describes in details how the equivalent fuel consumption is derived. Simulation results and discussions are presented in Section V. The conclusions are summarized in Section VI.

II. ELECTRICAL SYSTEM

The standard vessel power plant, for medium to large all electrical vessels, consists of several diesel generators connected to an AC distribution system, separated by switch breakers and bus tie breakers. By connecting an ESD to a standard power plant, it is then classified as an hybrid power plant. One hybrid power plant example is shown in Fig. 1. The power distribution could be either through AC or DC.

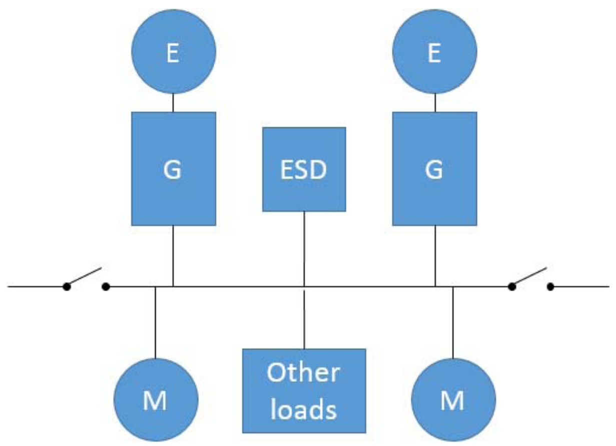

FIGURE 1. Hybrid power plant, showing one bus with two engines, two generators, two motors, one ESD, and other loads.

Fig. 1 shows a simplified power system with two diesel generator sets, one ESD, two thrusters and other loads.

The propulsion motors are usually the biggest power consumers in a marine vessel with electric propulsion, such as main thrusters, azimuth and tunnel thrusters. Besides the propulsion, there are usually several motors, frequency converters and transformers connected to the bus, that supplies energy to every electrical system in the vessel, such as hotel loads, drilling equipment, electrical equipment, etc.

In AC systems the line frequency on power buses should be fixed to either 50Hz or 60Hz, the same frequency of landlines, thus, forcing the generators to operate in a fixed frequency.

Redundancy is used to increase the overall safety by physically and electrically segregating into different branches as well as having more generators connected than the minimum required by the total load. Any single fault on the redundant system should not lead to a total loss of power.

The development of new technologies creates the possibility to implement power plants that were unavailable in the past. Both diesel and gas engines will be studied in the sections below.

A. GENERATOR-SET

The generator-set is a combination of an engine and a generator. The generator-set converts fuel into power, and the efficiency is given by how much fuel is consumed to generate 1kW per hour, this ratio is called Specific Fuel Oil Consumption (SFOC). If the fuel consumption is given in grams per hour, then the Fuel Oil Consumption (FOC) is measured. It is important to keep in mind that each generator-set will have a different SFOC, which depends on the engine and on the generator. One example of SFOC curve for a Perkins 2506C-E15TAG1 diesel engine retrofitted with a CAT C15 engine controller can be seen in Fig. 2.

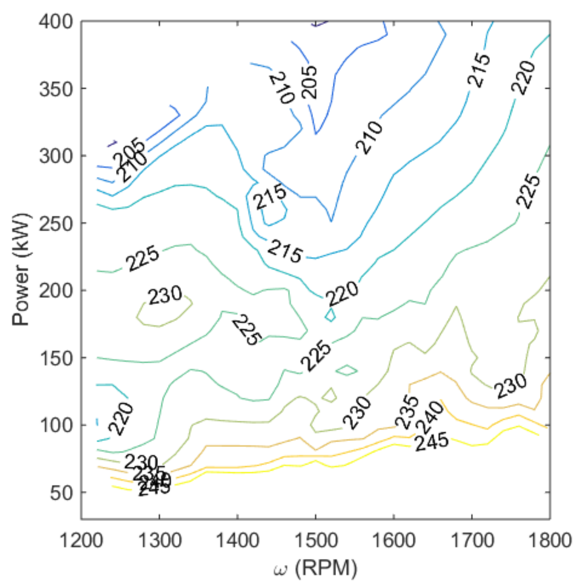

FIGURE 2. SFOC curve for a Perkins 2506C-E15TAG1 diesel engine with rated capacity of 460 kW.

This engine is designed to be operated in fixed frequency. Developments in DC-DC transformers made it viable to have DC transmission lines in the vessel. With DC distribution systems it is possible to operate the generator in any frequency, given that a rectifier will transform its output into DC voltage. The ideal case scenario would be with the generator running at the speed that leads to minimal fuel consumption, given any produced power.

It is possible to analyze the curves in Fig. 2 to show that by only switching from fixed frequency generators to variable frequency generators it can be expected to save up to 20% fuel. Fig. 3 shows the SFOC for the Perkins 2506C-E15TAG1 engine. Both curves are for the same engine, where in one case the SFOC is for fixed frequency and the other curve is given by the frequency which will lead to minimum SFOC for each power demand.

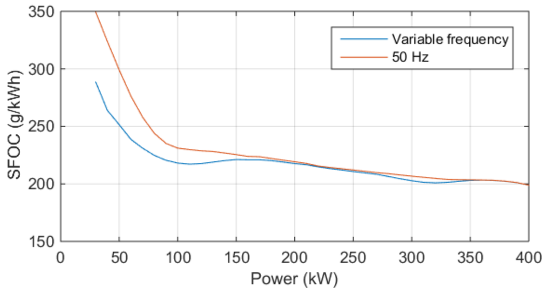

FIGURE 3. SFOC comparison for a Perkins 2506C-E15TAG1 diesel engine running with fixed frequency and variable frequency with rated capacity of 460 kW.

Redundancy is usually achieved by having more generators connected to the bus line than it is necessary, thus, leading to a low load scenario. It is known that the generator efficiency depends greatly on the engine and generator, but in general it is between 70% to 80% for diesel engines, as seen in Fig. 3. The efficiency curve of one generator operating in fixed frequency and the same generator operating in variable frequency will always have an equal or higher efficiency for the variable frequency. This difference tends to be higher for lower loads, which is the majority of the time during Dynamic Positioning (DP) operations, such as offloading, maneuvering, etc. DP operations are described in details in [16].

One downside of the variable speed engine operation is the fact that diesel generators can't operate at low speeds when high load is demanded. It must be assured that in cases with sudden load steps, the generator won't need to operate in a region that leads to shut down. One way to guarantee that the sudden load won't surpass the generator operational limit is by the use of an ESD with a peak shaving strategy, which will filter high power surges.

While varying the generator load and/or speed, the steady state temperature will vary as well, and the generator thermal response may alter the fuel consumption and emissions. This effect will be ignored in this analysis, but it is subject for further research.

It is possible to analyze how the ESD usage will affect the vessel emission, but is natural to expect the emission to be roughly proportional to the fuel consumption. An example of an specific emission curve can be seen in Fig. 4. This graph presents the Nitrogen Oxide (NOx) specific emissions provided by the FellowShip-III project, lead by DNV-GL (more details in [13]).

Notice that the curves presented in Figs. 3 and 4 are similar, with a lower specific fuel consumption and emission for a high power demand. So it is possible to utilize the strategic loading as a guidance system to minimize emissions instead of fuel consumption. The results may lead to minimization of both variables, but it will greatly depend on the generator that is being analyzed.

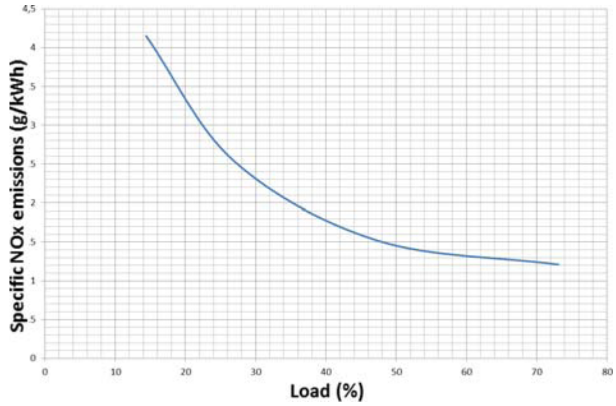

FIGURE 4. NOx specific emissions for the gas engine from the FellowShip-III project [13].

B. ENERGY STORAGE DEVICES

Several concepts for ESD may be used. We will on this paper consider batteries and ultra-capacitors. Batteries are characterized for having a higher energy density, but a lower power density than ultra-capacitors. A review on the main characteristics on both technologies is presented in [3]. On the downside, a marine vessel powered by ESD alone will have a shorter range, and higher cost.

Independently of the ESD type being analyzed, it can be operated in the same manner given some basic parameters such as its maximum charge and discharge power (Δ_C and Δ_C respectively) and charging and discharging efficiency (η_C and η_D respectively).

Since the electrical system dynamics ($\sim$ μs) is much faster than the mechanical system dynamics ($\sim$10s), it can be assumed that the ESD response time is instantaneous in the time scale of interest ($\sim$s). It is also assumed that the ESD inner controller is capable of providing the demanded power instantaneously and without fluctuations.

Given that the ESD have an ideal inner controller, then a guidance system must be designed. One guidance strategy that is easily implemented is the 'peak shaving', in which the generator will be responsible to produce the average power demanded by the load, while the ESD is responsible for the transient power.

With the ESD absorbing load fluctuations, wear and tear are reduced on the mechanical parts in the generators. The generator SFOC is also a function of the load derivative. Without load variation, all the fuel consumption due to transient power will be eliminated.

The second analyzed guidance system is referred as 'strategic loading' which will calculate the generator speed and power which leads to the minimum average FOC, based on the engine characteristics and give the correct loading set-point to the ESD.

Since it is only possible to continuously operate in a regime that will not deplete/overcharge the ESD, the strategic loading operation is divided in two phases, where the ESD is either charging or discharging.

The ESD will be charged so that the power demand on the engine is highly efficient. The discharging power is a parameter to optimize the overall power consumption, and will be analyzed in depth in the following sections.

ESD dimensioning is critical when designing a reference system for the controller, subject to maximum charge and discharge currents as well as maximum rated energy. Those parameters shall be taken into account during operations. Each type of ESD behaves differently. For instance, [15] and [17] show that operational parameters as charge/discharge current, depth of charge and temperature effects heavily the batteries cycle-life. Reference [18] shows batteries and ultra-capacitors efficiency under different State Of Charge (SOC), temperatures and charge/discharge currents.

There are three ESD operational strategies that will be relevant for this paper:

1) PEAK SHAVING

It is assumed that the ESD is capable to compensate all the load fluctuation. This leads to a more predictable and smooth power demand to the generators and thereby to the engines and will reduce wear and tear. It is assumed on this paper that there is an independent ESD performing peak shaving, so that only the mean load is seen by the generators.

2) SPINNING RESERVE

Since the ESD is capable of providing power instantly to the system, it is possible to disconnect a backup generator, increasing the load on the remaining connected generator, thus, reducing the SFOC. Another upside of this strategy is the fact that the number of engine and generator running hours is reduced, increasing the time required until a generator maintenance is necessary. An example of a hybrid system with and without the ESD as a spinning reserve can be seen in Fig. 5.

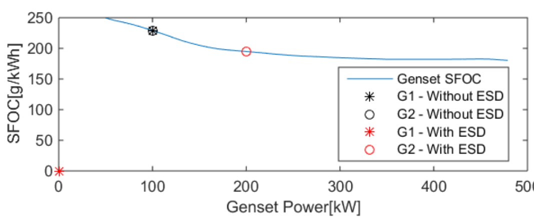

FIGURE 5. Variation in the generators SFOC for the case with the ESD connected (red markers) or disconnected (black markers).

3) STRATEGIC LOADING

The generator will cyclically charge and discharge the ESD, with the main objective being the minimization of the average fuel consumption as well as emissions reduction. This strategy is described in details in Section III.

III. ESD GUIDANCE STRATEGY

Since ESD can both provide and consume power from the system, it is possible to change the load being applied to the generator. It is well known that the generator SFOC has at least one local minimum, which is around 70% to 80% of the maximum load. In normal operations, the load tends not to stay above 80%, since more generators are connected due to safety reasons and class society requirements.

The potential for fuel savings is analyzed before developing a deep analysis about the system dynamics. The ESD reference system will change the effective load being applied to the generator.

If the transmission losses are disregarded, then the power produced equals the consumed power

$$P_G + P_B = P_L \tag{1}$$

where P_L is the average power consumed by the load, P_G is the generator power output, and P_B is the battery power output.

Since it is desirable that the average ESD SOC is not changed after one charge-discharge cycle, then it is required that

$$\begin{aligned}
E_C &= \int_0^{\tau_C} \Delta_C(t) \cdot \eta_C(t)dt && \text{(2a)}\\
E_D &= \int_0^{\tau_D} \frac{\Delta_D(t)}{\eta_D(t)}dt && \text{(2b)}\\
E_C &= E_D && \text{(2c)}\\
\Delta_C(t) &:= P_C(t) - P_L(t) && \text{(2d)}\\
\Delta_D(t) &:= P_L(t) - P_D(t). && \text{(2e)}
\end{aligned}$$

E_C is the energy stored by the ESD, and E_D is the energy produced by it. P_C is the power produced by the generator while charging the ESD, P_D is the power produced by the generator while the ESD is discharging, $\eta_C \leq 1$ is the charging efficiency, and $\eta_D \leq 1$ is the discharging efficiency. It is important to notice that the generator can be shut down during discharge if $\Delta_D \geq P_L$, leading to zero FOC

The variables P_C, P_L, P_D, Δ_C and Δ_D can be assumed constant during one charge/discharge cycle. Given the time to charge the ESD (τ_C) and discharge it (τ_D), the following simplification is derived:

$$\Delta_C \cdot \tau_C \cdot \eta_C = \frac{\Delta_D \cdot \tau_D}{\eta_D}. \tag{3}$$

The average fuel consumption ($\overline{F}$) is given by the following equation:

$$\begin{aligned}
\overline{F} &= \frac{\int_0^{\tau_C+\tau_D} P_G \cdot SFOC(P_G, \omega)dt}{\tau_C + \tau_D}\\
&= \frac{\int_0^{\tau_C} P_C \cdot SFOC(P_C, \omega_C)dt}{\tau_C + \tau_D}\\
&\quad + \frac{\int_{\tau_C}^{\tau_C+\tau_D} P_D \cdot SFOC(P_D, \omega_D)dt}{\tau_C + \tau_D}
\end{aligned} \tag{4}$$

where ω is the engine angular speed, and $SFOC(P_G, \omega)$ is the engine instantaneous SFOC.

If it is assumed that $SFOC(P_C, \omega_C)$ and $SFOC(P_D, \omega_D)$ are constant during the charge-discharge interval (for instance, for fixed frequency generators where ω is fixed), then, combining (3) and (4), and using the charge and discharge FOC ($FOC(P_C, \omega)$ and $FOC(P_D, \omega)$) result in

$$\overline{F} = \frac{FOC(P_C, \omega_C) \cdot \Delta_D + FOC(P_D, \omega_D) \cdot \Delta_C \cdot \eta_C \cdot \eta_D}{\Delta_D + \Delta_C \cdot \eta_C \cdot \eta_D}. \tag{5}$$

As shown in (5), if the assumptions are met, the resulting FOC is calculated by the weighted average of the points defined by $\Delta_C \cdot \eta_C \cdot \eta_D$ and Δ_D. This results show that it is simpler to estimate the potential for fuel savings based on a FOC curve instead of the SFOC curve.

The amount of fuel that can be saved without altering the number of connected generators is directly related to the FOC curvature. Concave areas present the largest percentual fuel saving potential. If the variables Δ_C and Δ_D are misplaced, the average fuel consumption might be increased.

Figs. 6 and 7 show the resulting fuel consumption divided by the fuel consumption for the case without the ESD, compared to the base value (fuel consumption of the system without ESD). In this case, $P_L = 30\%$, and the generator

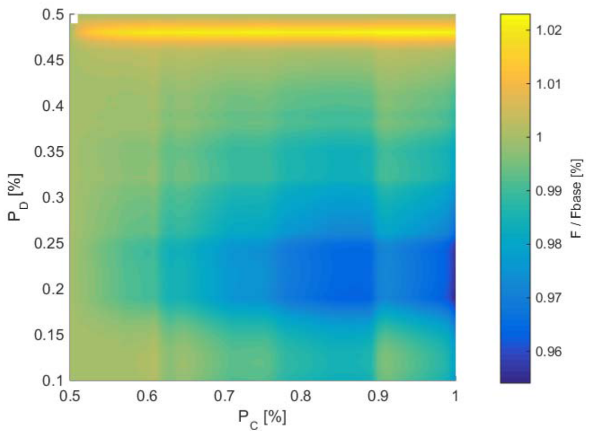

FIGURE 6. **Example of relative fuel savings for a motor with fixed speed, as a function of P_C and P_D. The base value is the same motor without the ESD.**

SFOC curve in Fig. 2 with fixed speed are assumed. It is important to reinforce that if the the selected operational points are incorrectly selected, the resulting operation might consume more power than in the case without ESD.

It is important to note that the generated power while charging the ESD (P_C) and discharging it (P_D) must meet the following conditions:

$$P_C > P_L > P_D. \tag{6}$$

It is worth mentioning that the ESD maximum energy capacity, Δ_C and Δ_D are directly related to the batteries cycle-life. The higher the charge and discharge current, the

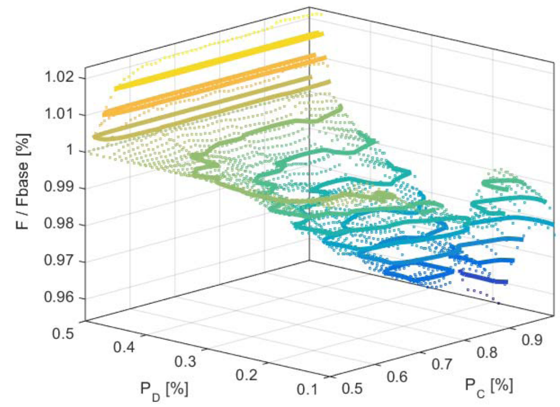

FIGURE 7. **3D view and isolines of the example illustrated in Fig. 6.**

faster the battery will degrade. Reference [19] shows lithium-ion batteries degradation as a function of number of cycles, and [20] demonstrates how the charging strategy influences the lithium-ion battery life.

It is assumed that the ESD inner controller is stable, meaning that by giving the reference set-point to the ESD, the low level controller is responsible for reaching the set-point within acceptable time limit. This problem is similar to the controller - observer problem, where the separation principle is applied. On the other hand, due to the system electrical characteristics, it is known that (1) is always true. This fact leads to the conclusion that, as long as the generator operation is within its operational limits, the system will be stable. The generator inner controller is also assumed to be stable, so, a step in the angular speed set point will lead to transient behavior, affecting the SFOC, but the stability is not compromised.

IV. FUEL CONSUMPTION OPTIMIZATION

It is desired to minimize the fuel consumption, both for environmental and economical reasons. Then, it is required to find the minimal $\overline{F}$, given the optimum Δ_C and Δ_D. This problem can be formally described such that

$$min\ \overline{F} \tag{7a}$$

$$\Delta_{Cmax} \geq \Delta_C > 0 \tag{7b}$$

$$\Delta_{Dmax} \geq \Delta_D > 0. \tag{7c}$$

The average fuel consumption variation as a function of the charging and discharging set-points is derived as follows:

$$\frac{\delta \overline{F}}{\delta P_C} = \frac{\frac{\delta FOC_C}{\delta P_C} \cdot (\Delta_D + \Delta_C \cdot \eta) \cdot \Delta_D}{(\Delta_D + \Delta_C \cdot \eta)^2} - \frac{(FOC_C - FOC_D) \cdot \eta \cdot \Delta_D}{(\Delta_D + \Delta_C \cdot \eta)^2} \tag{8a}$$

$$\frac{\delta \overline{F}}{\delta P_D} = \frac{\frac{\delta FOC_D}{\delta P_D} \cdot (\Delta_D + \Delta_C \cdot \eta) \cdot \Delta_C \cdot \eta}{(\Delta_D + \Delta_C \cdot \eta)^2} - \frac{(FOC_C - FOC_D) \cdot \Delta_C \cdot \eta}{(\Delta_D + \Delta_C \cdot \eta)^2}. \tag{8b}$$

For simplification purposes, the charging and discharging efficiencies are combined as one single equivalent efficiency $\eta = \eta_C \cdot \eta_D$.

A. ANALYTICAL SOLUTION

If we assume that it is possible to find a solution where the FOC curve is continuous and differentiable for the whole operational interval, then it is possible to solve the optimization problem in (7) analytically.

An analytical solution is found by setting $\frac{\delta \overline{F}}{\delta P_C} = 0$ and $\frac{\delta \overline{F}}{\delta P_D} = 0$, which requires the assumption that $\Delta_D > 0$ and $(\Delta_C \cdot \eta) > 0$, which simplifies (8) to

$$\frac{\delta FOC_C}{\delta P_C} = \frac{(FOC_C - FOC_D) \cdot \eta}{\Delta_D + \Delta_C \cdot \eta} \tag{9a}$$

$$\frac{\delta FOC_D}{\delta P_D} = \frac{(FOC_C - FOC_D)}{\Delta_D + \Delta_C \cdot \eta}. \tag{9b}$$

It is a common misconception that operating at the minimum SFOC will always lead to the minimum FOC in an operation with ESD, but 9 presents the correct conditions for optimization.

B. NUMERICAL SOLUTION

The main challenge with the analytical solution is the fact that the SFOC curves are not continuous, since the value is known only for a given set of points.

Hence is necessary to have a curve fitting algorithm, motivating a numerical solution for the optimization problem. Two methods are discussed in this paper, but the general idea can be extended for any interpolation method.

1) LINEAR INTERPOLATION

If a linear interpolation is used, it is known that the optimum P_C and P_D will be located in the sampled points. This is due to the fact that the objective function is a weighed average between two points. By inspecting the sampled points it is enough to calculate the optimum operational parameters as the set of points P_C and P_D that leads to the global minimum.

The main advantage of this method is that it will have finite calculation time, being promising for real-time applications. The drawback is the fact that the values between sampled data will be disregarded, and possibly the actual global minimum will not be found, leading to a local minimum instead.

A method to speed up the optimization problem is to solve the linear interpolation approximation, finding the candidates for a global solution. The solution for higher order methods can be done only on specific areas, reducing drastically the computational time. Fig. 8 shows in which direction the gradient for each analyzed area, thus, the potential minimum solutions are found. This example will be analyzed in details in the Section V.

2) SPLINES AND LAGRANGE MULTIPLIERS

A spline is a continuous and derivable curve that fits the data throughout all the measured interval. Methods for curve-fitting using splines can be further studied in [21]. Since the spline is continuous and has a continuous derivative throughout the whole valid region, it is possible to use advanced optimization methods, such as KKT [22] that solves bounded nonlinear problems.

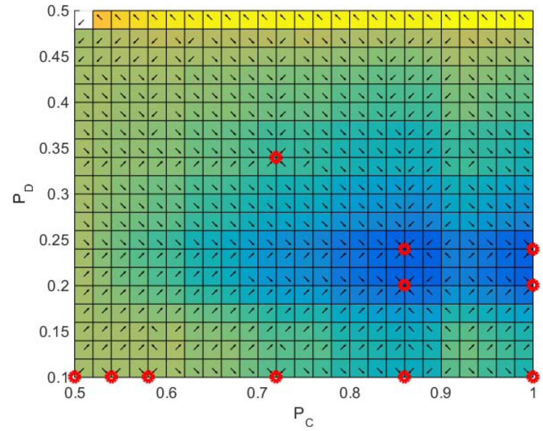

FIGURE 8. Gradient using the linear interpolation, where the arrows points to the direction with minimum fuel consumption for each section. The red circles are local optimum points. Keep in mind that the points where $P_C = P_L$ and/or $P_D = P_L$ are not taken into consideration. The simulated case is the same as shown in Fig. 6.

The main drawback with splines is that it has one equation for each interval between sampled points. Just like the linear interpolation method, it is necessary to calculate the minimum for each interval for each variable and calculate the global minimum as the lowest value found.

This methodology will have an increased calculation time, compared to the linear approximation, since one approximation problem will be solved for each P_C and P_D combination. If the computational time has strict requirements, then it must be assured that the non linear optimization method will have finite computational time. The advantage is that the global minimum will be better estimated, since the spline method will be closer to the actual SFOC curve.

Considering the second order spline equation, with coefficients a_1, b_1, c_1, a_2, b_2, c_2 for the P_C and P_D region respectively, then the $\overline{F}$ equation is simplified to

$$\begin{aligned}\overline{F} = &\frac{P_C^2 P_D(-a_1) + P_C^2(a_1 P_L) + P_C(b_1 P_L + c_2\eta)}{(P_L - P_D) + (P_C - P_L)\eta}\\ &+ \frac{P_C P_D(b_2\eta - b_1) + P_D(-c_1 - b_2 P_L \eta)}{(P_L - P_D) + (P_C - P_L)\eta}\\ &+ \frac{P_D^2(-a_2 P_L \eta) + P_C P_D^2(a_2\eta) + (c_1 P_L - c_2 P_L \eta)}{(P_L - P_D) + (P_C - P_L)\eta}.\end{aligned} \tag{10}$$

The KKT method uses Lagrange multipliers (λ) to define which boundary conditions are active, given the function to be optimized. The boundary conditions for each spline interval is

$$P_{Cmax} - P_C \geq 0 \quad (11a)$$
$$P_C - P_{Cmin} \geq 0 \quad (11b)$$
$$P_{Dmax} - P_D \geq 0 \quad (11c)$$
$$P_D - P_{Dmin} \geq 0. \quad (11d)$$

Function 10 have to be rewritten to be optimized, such that:

$$\begin{aligned} f(P_C, P_D, \lambda_1, \lambda_2, \lambda_3, \lambda_4) &= \overline{F} - \lambda_1 \cdot (P_{Cmax} - P_C) \\ &- \lambda_2 \cdot (P_C - P_{Cmin}) \\ &- \lambda_3 \cdot (P_{Dmax} - P_D) \\ &- \lambda_4 \cdot (P_D - P_{Dmin}). \end{aligned} \quad (12)$$

If the boundary condition is active, $\lambda_i \neq 0$, and if it is inactive, $\lambda_i = 0$. The solution will be optimal if $\lambda_i \geq 0, \forall i \in \{1, 2, 3, 4\}$.

By analyzing (11), it is possible to notice that the two first boundary conditions are mutually exclusive, as well as the two latter ones. Table 1 summarizes all possible combination of boundary conditions.

TABLE 1. Possible Lagrange multiplier combinations, where ≠ means that the boundary condition is active and = means that the boundary condition is inactive.

Case	λ_1	λ_2	λ_3	λ_4
1	=	=	=	=
2	≠	=	=	=
3	=	≠	=	=
4	=	=	≠	=
5	≠	=	≠	=
6	=	≠	≠	=
7	=	=	=	≠
8	≠	=	=	≠
9	=	≠	=	≠

For each case shown in Table 1, one equation per active boundary condition plus two equations are solved

$$\frac{\delta f}{\delta P_C} = 0 \quad (13a)$$
$$\frac{\delta f}{\delta P_D} = 0 \quad (13b)$$
$$\frac{\delta f}{\delta \lambda_i} = 0, \quad \text{where } \lambda_i \neq 0. \quad (13c)$$

The set (13) has a single solution, thus, it can be solved numerically.

V. SIMULATION RESULTS

Three cases were studied and simulated, consisting of a power plant with one and two engines, such as shown in Fig. 2, and a case with the engine from [13]. The goal is to show how the varying generator set point can be used to minimize fuel consumption, as well as how switching a generator on/off affects it.

The simulation conditions are summed up in Table 2.

TABLE 2. Simulations configuration.

Variable	Sim 1	Sim 2	Sim 3
$P_L[p.u.]$	Variable	0.21	0.5
$P_C[p.u.]$	Variable	0.7	Variable
$P_D[p.u.]$	0.81	0	Variable
$\eta[\%]$	90	100	100
Genset type	Diesel	Gas	Diesel
ω	750 RPM	Unspecified	750 RPM

A. MULTIPLE GENERATORS

Considering that multiple generators might be connected to the bus at the same time, it is also appropriate to investigate the potential for fuel savings where generators can be connected and disconnected over time. It will be considered that the generator connection and disconnection are instantaneous as well as the load can be applied without any load ramp. The main purpose here is to show how the redundancy requirements affect the fuel consumption. The simulation parameters are summarized in Table 2.

The reference system strategy is modified as well, since the load is greater than the optimum operation point. Instead of optimum operation while charging the ESD, it will be required that the optimum is achieved while discharging it. This case is particularly interesting, since it is possible to operate in the optimum set-point while the ESD is charged and discharged (just varying the number of generators connected). On the other hand, it may not be necessarily the best alternative, since the maximum fuel saving is due to generator disconnection. It has to be compromised how much the savings from varying the operational set-point and how often the generator set-point will be switched, since high values for Δ_C and Δ_D will reduce the ESD cycle life.

Fig. 9 shows that the effects of shutting down a generator during part of the operation leads to fuel savings much bigger than the simple fact of operating in the optimum set-point.

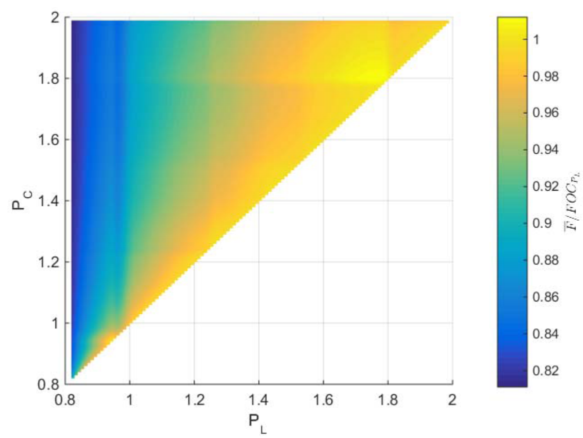

FIGURE 9. Resulting relative fuel consumption for the case with two generators and one ESD.

It is clear that the potential for fuel savings is greatly increased due to the possibility to reduce the number of online generators. In this case, assuming that the ESD is able to maintain the redundancy capabilities, then more than 19% of the fuel can be saved. The biggest savings are close to the point where the load is slightly over the optimum operational set-point, since both generators will share the power, and the resulting load per generator is way below the optimum set-point, leading to great savings.

Note that the graph presented in Fig. 9 presents only cases where $P_C \geq P_L$, according to the rules given by (6).

It is important to notice that the fuel savings in this case have a higher potential compared to the case in Fig. 6. Two factors contribute to the high potential, which are the fact that the P_L is variable in this simulation, as well as one engine being disconnected, thus, $FOC_D = 0$. By disconnecting the generator completely, the fuel consumption might be reduced even further.

B. DNV FellowSHIP-III

In this simulation, the effects of generators disconnection are analyzed for gas engines. The connection/disconnection time is disregarded.

Analyzing the DNV FellowShip-III engine data, presented in [13], it is possible to assess its potential for fuel savings.

Fig. 10 contains the FOC curves for the case with one and two generators connected. It is assumed that both generators will have equal load sharing due to simplification purposes.

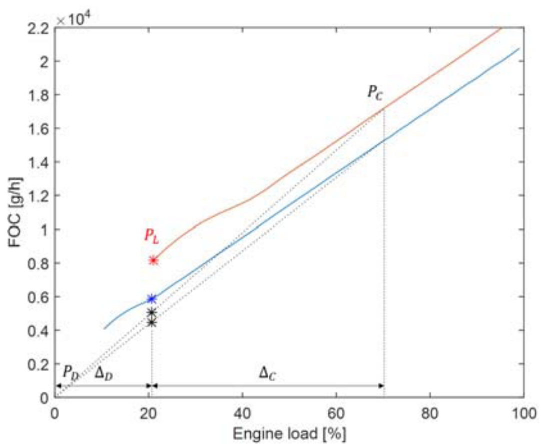

FIGURE 10. **FOC curves for the gas generators used in the DNV FellowShip-III [13]. The red line is the FOC for two generators with equal load sharing, while the blue curve is the case with only one generator. The x axis represents the engine load (where 100% means one generator maximum rating).**

Several configurations, shown in Table 3, were analyzed and compared. It is important to notice that it is only possible to completely disconnect both generators while the ESD is discharging if $\Delta_{Dmax} \geq P_L$. This requirement is mandatory in every case where generators will be disconnected.

TABLE 3. **Simulation V-B cases.**

Case	# of generators while charging	Strategic loading
Case 1	2	No
Case 2	1	No
Case 3	2	Yes
Case 4	1	Yes

The results for the analyzis using the data presented in Fig. 10 and 4 is shown in Table 4.

TABLE 4. **Simulation V-B results.**

Case	Fuel consumption [kg/h]	Fuel consumption reduction [%]	NOx Emissions reduction [%]
Case 1	8.14	0	0
Case 2	5.84	25	62.4
Case 3	5.04	38	76.6
Case 4	4.48	45	85.6

In this case, it shows that the emission reductions are even greater to the fuel consumption, making this strategy both economically advantageous as well as environmental friendly.

It is seen that the fuel consumption reduction is much higher by disconnecting generators instead of loading strategically the load. Both strategies can be used together, as shown in this case.

C. LINEAR AND NONLINEAR OPTIMIZATION

It was mentioned previously that the linear and nonlinear approximation methods can be combined to minimize the fuel consumption. For this analysis, the curve shown in Fig. 8 will be used.

Initially, all data points are analyzed using the linear interpolation method and the optimum candidates are selected. The ten local minimum are compared and the point with lowest average fuel consumption is chosen as the region in which the spline approximation is used. Table 5 presents the P_C, P_D and $\overline{F}$ for each analyzed point.

TABLE 5. **Simulation V-C results.**

Point	P_C [%]	P_D [%]	$\overline{F}$ [kg/h]
1	0.54	0.1	43.57
2	0.58	0.1	43.56
3	0.72	0.1	43.20
4	0.86	0.1	42.84
5	1.00	0.1	42.53
6	0.86	0.2	41.99
7	1.00	0.2	41.60
8	0.86	0.24	41.99
9	1.00	0.24	41.65
10	0.72	0.34	43.10

By optimizing the area around the point number 7 with spline interpolation, it is found that the solution is further refined, so that the new set-points $P_C = 99.43\%$ and $P_D = 19.43\%$ are found, leading to an average fuel consumption of $\overline{F} = 41.49 kg/h$.

From the computational perspective, using an average stationary computer takes 268ms to compute the solution for the linear approximation, 16.2s to compute the complete solution using only the spline method, and 325ms to compute the linear interpolation and KKT optimization around the initial guess.

The time between simulations can vary, but the presented values are an average of 5 tests.

VI. CONCLUSION

In this paper an introduction to ESD usage to reduce fuel consumption was given, as well as a deeper analysis for optimum set-point operation. It was shown that this methodology allowed potential fuel savings and emissions, but should be used carefully, since it may also have increased the fuel consumption if the charge/discharge set-point was not chosen correctly.

This methodology required deep understandings of the generator properties for every possible operation condition, which may be costly to obtain if not provided by the manufacturer.

Also, it is shown that the combination of optimum set-point operation combined with peak shaving was advantageous since it allowed the generator to operate under a smooth load as well as minimizing even further the fuel consumption, specially for low load scenarios.

The main conclusion is related to the disconnection of generators, where it was proven that the maximum fuel consumption saving is when generators can be disconnected ($\Delta_{Dmax} \geq P_L$) since the disconnected generator has zero FOC.

Since the SFOC and FOC curves are discrete measurements from engines, it is necessary to interpolate the measured values. The selected interpolation algorithm will influence the computational cost for the optimization process. It is noted that a simple linear interpolation leads to a solution close to the desired value, while not being computational demanding. On the other hand, with second order splines and KKT optimization, the optimization time is increased, and the optimum set-points for the guidance system are finely tuned. A proposed solution is to use a high order interpolation algorithm only around the optimum solution for the linear problem, greatly reducing the computational time, while leading to the same values.

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